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Steel exoskeletons for seismic retrofitting of existing reinforced concrete buildings: State-of-the art and a case study

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ABSTRACT

Since '80s the use of external additive structures, commonly called exoskeletons, is considered one of the possible alternatives for seismic retrofit of existing r.c. structures with low dissipative capacity. The first Japanese and American codes dealing with structural rehabilitation issues, as well as many applications on the use of steel devices at the international level, are testimony of this trend, especially in high seismic hazard areas. Nowadays, the use of this intervention strategy has become of great actuality, not only because it can be implemented in a safe way without interrupting the operation/use of the building, but also because it can be effectively adopted, in cases of restructuring with lateral addition, for the integrated (formal, energetic and functional) retrofit of the entire construction. In the present work, after a thorough state-of-the art on the main researches and applications of steel exoskeletons, their typological classification (families) and the definition of the key project parameters, indispensable to both properly conceive and design such systems, have been performed. Finally, for illustrative purpose, it has been shown the application of steel exoskeletons to the case study of the P. Santini primary school in Loro Piceno, a district of Macerata.

1 INTRODUCTION

Nowadays, there are many strategies and intervention techniques to be adopted for seismic improvement and retrofitting of existing reinforced concrete constructions characterized by high vulnerability grade due to both the absence of seismic provisions and durability issues. Alongside the refinement of traditional techniques, the synergistic advances made by materials science and structural engineering, have allowed the spread of innovative systems. Since a lot of years the design of several of these systems has been codified at international level (JBDPA, 2001; CEB-FIB, 2003), so to be enclosed in the main rules and guidelines dealing with structural rehabilitation (Dolce and Manfredi, 2011). The advent of BIM and Industry 4.0 is encouraging the search for new solutions and choice methodologies to be used for the design of seismic risk prevention interventions in a Life Cycle-type perspective (Formisano et al, 2017; Vitiello et al, 2019).

The myriad of available alternatives to be adopted by designers for structural rehabilitation is drastically reduced when the important requirement of avoiding the interruption of use of the construction is introduced (FEMA, 2006). In this framework, admissible interventions are those carried out outside the building through additive structures linked sideways to the existing one and optionally having an independent foundation system. If interventions are extended to a significant construction portion, using a terminology derived from zoology and also transposed by bio-mimesis (Benyus, 2002), it is possible to name them as "exoskeletons", that is systems that, applied from outside, are able to protect the existing construction mainly by increasing its resistance and stiffness towards lateral actions (Foraboschi and Giani, 2017).

As evidenced by multiple recent workshops (Marini et al, 2015) and research projects (PRIN 2009; ReLUIS, 2019-21), the use of this intervention strategy is of great relevance, because it can be effectively adopted for the integrated formal, energetic and functional retrofit of the entire construction. Therefore, the exoskeleton, other than increasing the structural safety level of the existing construction with respect to the main limit states (Foraboschi and Giani, 2018), if used in an integrated design perspective (Feroldi et al, 2014, Marini, 2017), can become the support for a double skin capable of both improving the construction energy performance and, at the same time, providing an architectural makeover of the artefact (Caverzan, 2016). Returning to the purely structural issues, the double skin, protecting the areas most exposed to weather conditions, changes the environmental class of exposure or corrosiveness (Rizzo et al. 2019), increasing the construction durability. The integral type exoskeleton can also completely cover the construction, protecting it from environmental agents and improving the energy and structural performances of the roof (Terracciano et al., 2014). In a broader sense, the artefacts adopted for the protection of archaeological sites and monumental assets (Di Lorenzo et al., 2019) also fall into this category.

From the above considerations, it is therefore stated that, if the boundary conditions and urban/landscape limitations allow for their use, the exoskeletons, made of metal materials, assembled with dry technologies and integrated to existing constructions, become an effective intervention strategy aimed at increasing the resilience of the built environment in a sustainable and reversible way (Bellini et al., 2018). Applied to entire urban sectors, they can also promote the urban regeneration, redeveloping and re-evaluating, even economically, the existing building stocks, with particular reference to the suburbs and the most degraded areas (Angelucci et al., 2013).

In this framework the current paper is placed, it having the target to study a construction system/kit of metal carpentry exoskeletons for the preservation and/or retrofit of existing r.c. and precast r.c. buildings with either single storey or multiple storeys with limited height. Firstly, the concept of exoskeleton and its prerogatives have been defined and, secondly, a wide state-of-the art on the main researches and applications has been provided. Subsequently, their typological classification in archetypes or families has been made and the key parameters for designing these systems have been provided.

The literature review on these systems has been used for the concept-design and prototyping (virtual-BIM) of a construction system (kit) consisting of steel lattice shear walls to be applied orthogonally to the construction facade, without the presence of added dissipation devices.

Finally, a simplified design methodology for validation/control of design choices based on structural and economic criteria has been applied to the case study of the P. Santini primary school in Loro Piceno.

2 STATE-OF-THE ART AND CATALOGING OF EXOSKELETONS

2.1 *Strategies for seismic retrofitting of existing reinforced concrete structures*

Referring to civil engineering and architectural feats, a planning to optimize resources and bet on resilience and sustainability needs a holistic approach (Figure 1). It investigates the question in a multidisciplinary way analysing from the beginning all the different phases of the building life cycle (Zhang, et al. 2018).

In a holistic vision, structural and hazard mitigation issues must be related to those of energy performance and technological comfort. In addition, architectural and urban issues related to the formal and distribution aspects on small or large scale must be considered. This approach must be used even for existing buildings, which require a regeneration through upgrading or retrofitting interventions.

Figure 1 - Holistic approach in a life cycle key.

Once the structural gaps have been defined and the performance levels have been chosen, the possible intervention strategies can act on the capacity (C) increment and/or the demand (D) reduction through global and/or local interventions based on traditional or innovative systems and technologies.

A successful and efficient choice of these strategies can be done by comparing demand (D) and capacity (C) in terms of a strength-based design (Blume, 1960) (Figure 2) or in the Acceleration-Displacement Response Spectrum (ADRS) format, as usually done in the framework of a displacement-based approach founded on pushover analysis (Freeman, 1998; Fajfar, 1999) (Figure 3).

Traditional retrofitting strategies of existing r.c. buildings can increase their capacity in terms of strength, stiffness and ductility towards lateral actions (Sugano, 1981; Fukuyama and Sugano, 2000).

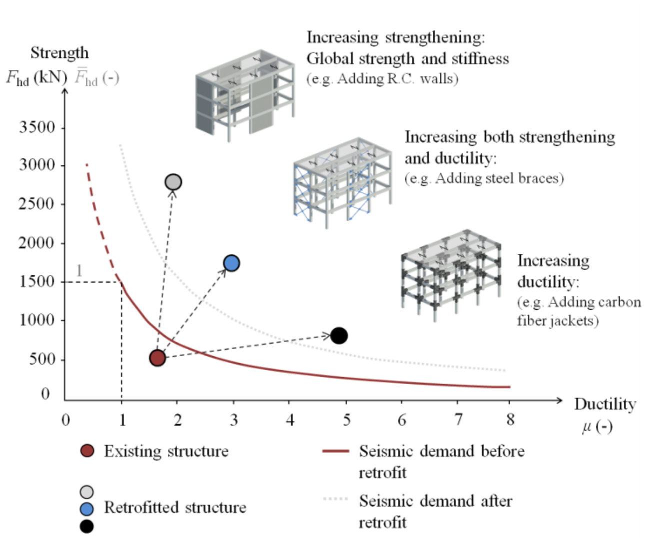

Figure 2 – Effect of different retrofitting design strategies in the force-ductility plane.

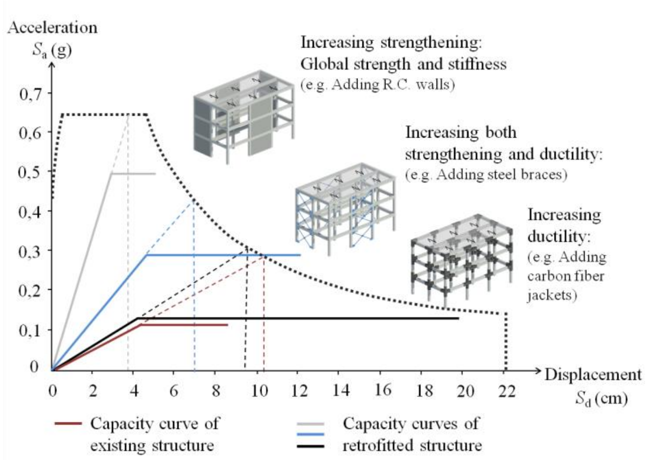

Figure 3 – Effect of different retrofitting design strategies in the ADRS format.

The first strategy is to add to the existing structure new components or earthquake-resistant systems able to modify its static and dynamic behaviour (global interventions) (Figure 4). Conversely, the second strategy is to apply interventions, like element jacketing or node stiffening, with the aim to increase the structure ductility (local interventions) (Figure 5).

2.2 Definition and structural features of exoskeletons

Global interventions consist in addition of earthquake–resistant systems which can be set inside or outside the existing building. Using a bio-mimicry language (Benyus, 2002), in case of internal additions, the system is called endoskeleton; contrary, in case of external addition, it is called exoskeleton (Figure 6).

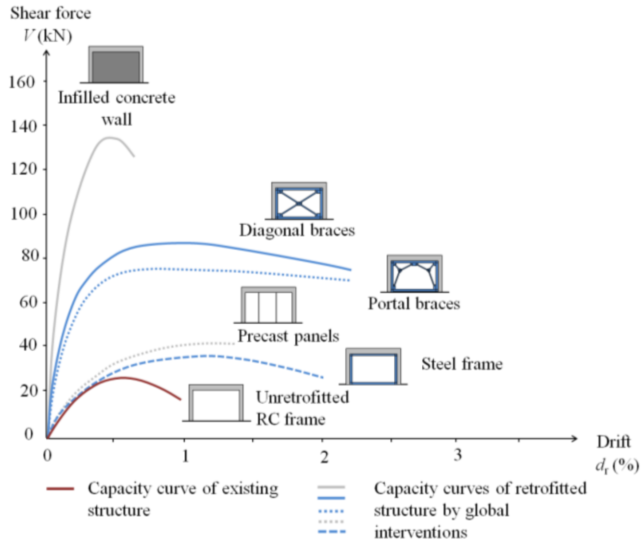

Figure 4 – Typical experimental responses in the shear force-drift plane of r.c. frames strengthened with various global retrofitting techniques.

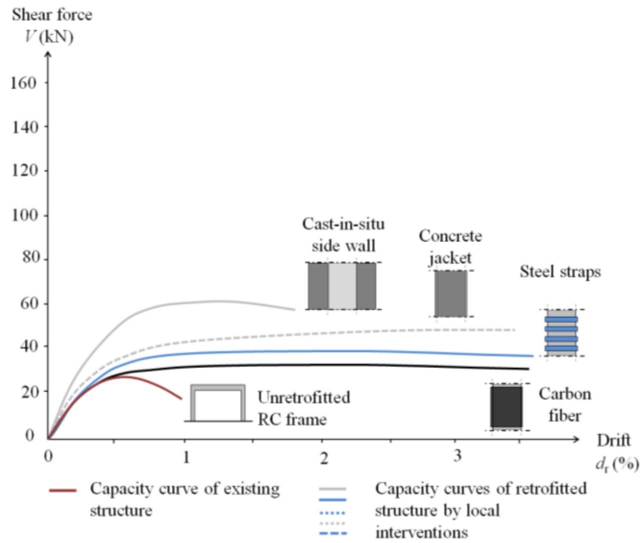

Figure 5 - Typical experimental responses in the shear force-drift plane of r.c. frames strengthened with various local reinforcing techniques.

The exoskeleton is an additive system, optionally even adaptive, which is connected to the existing building from outside. It has its own foundations, that are joined or linked to the existing ones (Figure 7).

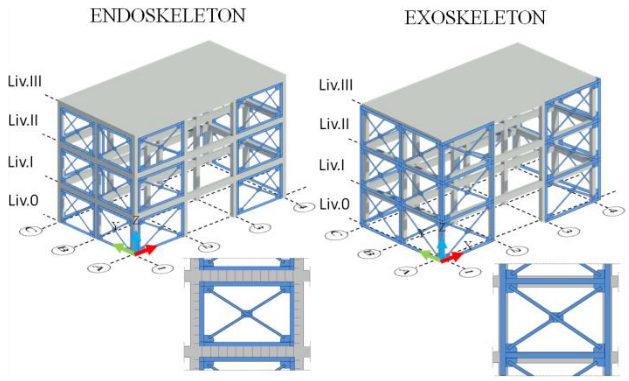

Figure 6 - Differences between endoskeleton and exoskeleton.

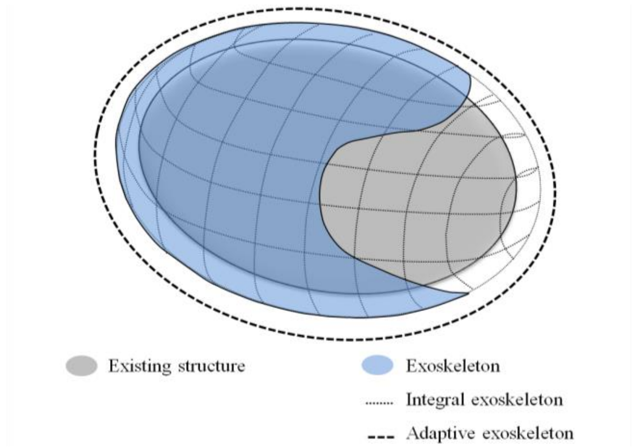

Figure 7 – Concept of exoskeleton.

Due to morphological and right force transferring questions, it is considered as a real exoskeleton only if applied on most of the building surface on every side. Moreover, it is defined as "integral" when it is applied on the total building surface. In this way, the exoskeleton is able to cover also the roof, so representing a simultaneous vertical and horizontal addition. It is possible to reduce the transferring of base shears to the new foundations using additional passive, active and semi-active control devices. They are inserted into the new foundation or applied between the superstructure and the substructure (Labò et al, 2016).

For its own configuration, the exoskeleton has the potential to combine itself with a new shell (cover) structure to be designed in a holistic approach, that combines structural (seismic and durability) issues with environmental (energetic) and architectonic (formal and functional) ones. When the building use cannot be interrupted, the exoskeletons are the only possible retrofitting solution because of their external application (FEMA, 2006).

Exoskeletons can be conceived to prevent seismic damage to the buildings, but if they are thought like a serial production kit, they can be also seen as safeguarding interventions before retrofitting operations.

According to the Performance Based Design principle, the main goal to pursue using exoskeleton is to design the seismic upgrading intervention of existing buildings at the life safety limit state. In this case, exoskeletons must undergo damages to prevent the premature failure of structural elements.

When the exoskeleton is appropriately fixed to foundations and in presence of rigid diaphragms, the lateral global stiffness increase allows to improve ultimate and serviceability limit state safety indexes (Foraboschi and Giani, 2017). In particular, the analysis of the serviceability limit state requires that acceleration of each floor should be monitored to prevent objects overturning and/or electronic devices functionality loss (Petrone et al, 2017). Calibrating local stiffness of each floor, it is possible to control these problems, which represent the main criticism when global interventions based on increasing load carrying capacity are of concern. Finally, inserting additional dissipation devices (Scuderi, 2016) or using the most common seismic-resistant systems, like steel bracing frames (Badoux and Jirsa, 1990), significant damping and/or global ductility increase, necessary to improve safety levels at the collapse limit state, are provided.

2.3 *Structural concept, typological families and proposed nomenclature*

Focusing on structural issues, any system concept should be thought on the basis of the following three sequential and successive parameters:

1. Technological choice, related to the structural material selection;
2. Typological choice, based on the seismic-resistant scheme selection;
3. Dimensional choice, related to the first attempt to size the system;

Referring to the first choice, the possibility to build light, resistant and reversible systems lead the designers to use metallic materials, which offer easy of transportation and simplicity of installation useful to be adapted to the original structure especially when a dry system is foreseen. If the exoskeletons are not well integrated with the structure, they are directly exposed to weather and, therefore, need to be protected from corrosion. In terms of life cycle approach, beside the non-alloy and low alloy steels, which are the less expensive solutions, there are even more expensive solutions based on stainless steels and aluminium alloys.

Once the material has been decided, the selection of the resistant scheme is done. The choice relays on geometric and mechanical properties of the building, as well as on the foundation type. Another important matter is the presence in the existing building of both rigid diaphragms and areas where systems or links can be inserted for transferring shears to the exoskeletons uniformly placed along the perimeter. Beyond structural issues, typological choice is influenced by formal and distributive features, i.e. how much useful space is available along the perimeter. In order to describe the new earthquake-resistant system, the typological choice is analysed at different levels. Referring to the global analysis of the system, transfer of shear may occur through bidimensional (e.g. shear walls) o three-dimensional elements (e.g. cores). In the first case (Figure 8) walls can be placed in perpendicular (2D⊥) or parallel (2D//) position to the façade, as stated by the first structural rehabilitation code (JBDPA, 1977). 2D⊥ systems, based on the concept of buttresses from gothic architecture, have the advantage of detaching from the structural grid to regulate the dynamic response of the existing building. They meet the demand in terms of stiffness and strength only by increasing the walls number and, therefore, they are suitable to be industrialized. 2D⊥ systems, thanks to their own shape, make the volume increase easier because of the simplicity of adding new floors and new shear transferring systems.

Connection with existing buildings can be done through rigid links or additional dissipation devices, possibly hinged on the inner system surface, to both avoid transferring bending moments and restrict the number of used anchor-bolts. On the other hand, due to dimensional questions linked to the wall maximum height, 2D⊥ systems can be used effectively to retrofit single-storey or low-storey buildings only. The limit in elevation of these systems lead to choose deep foundations to absorb bending moment and base shear in the walls. The most common solution is represented by 2D// systems, that are placed in parallel position to the facade. They are suited for multi-storey buildings but, because of their connection with the structural grid, appropriate devices for transferring shear to each floor are required.

As an alternative to bidimensional systems, it is possible to adopt more expensive and efficient three-dimensional systems. Thanks to their own configuration of single involving shells, these systems can absorb base shear in all directions independently from their orientation. Shells can be flat or curve (Figure 9) with single or double curvature. In both cases it is possible to adopt continuous systems characterised by simple or multi-layer grids. The simple grid solution is indicated as diagrid.

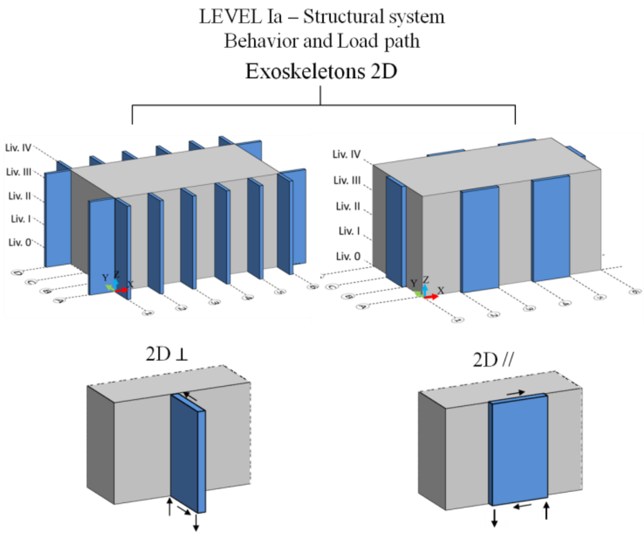

Figure 8 – Level Ia typological choice: Shear walls arranged perpendicular (2D⊥) or parallel (2D//) to the facade.

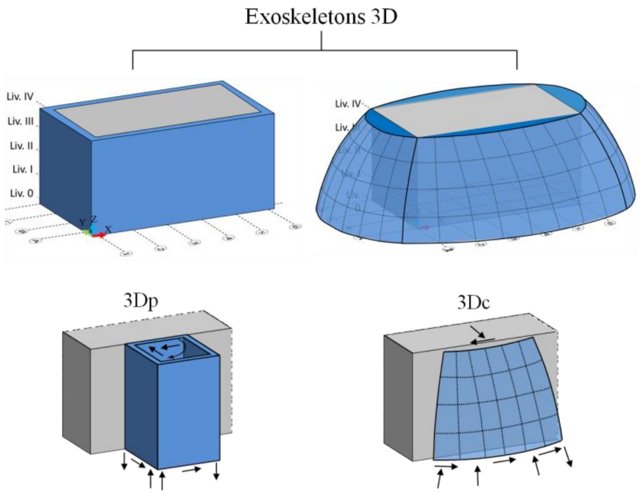

Figure 9 – Level Ib typological choice: 3D, plane (3Dp) and curved (3Dc) structures.

Focusing on shells, shear walls can have a continuous or tapered section (Figure 10), the latter following the shear and bending moment trends. When steel is used as basic material, there are different structural configurations of exoskeletons (Figure 11): Concentric Bracing Frame (CBF), Eccentric Bracing Frame (EBF), Buckling-Restrained Bracing frame (BRB) and Moment Resisting Frame (MRF). Among them, the CBF configuration is preferable because of its efficient design. The arrangement of diagonals in CBF systems can be of St. Andrew’s cross, Inverted-V, portal and K types (Figure 11). The most convenient option depends on the structural and architectural requirements.

Once the resistant system has been decided, the choice of cross-sections is made (Figure 12). The best choice depends on the adopted scheme configuration (Di Lorenzo et al, 2017). When axial stress regimen is predominant, the best solution is to use Hollow sections made of Hot-rolled ((HF-HS) or Cold-Formed (CF-HS) profiles. In particular, Circular Hollow Section (CHS) profiles combine high efficiency with aesthetic value thanks to the rounded shape, which makes safe people in cases of accidental strokes.

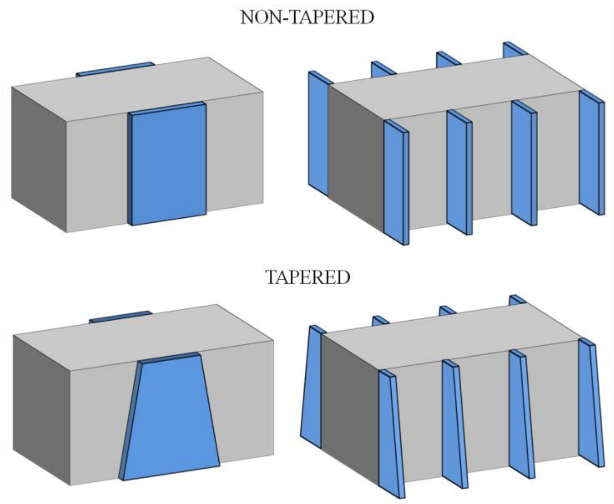

Figure 10 – Non-tapered and tapered shear walls configurations:.

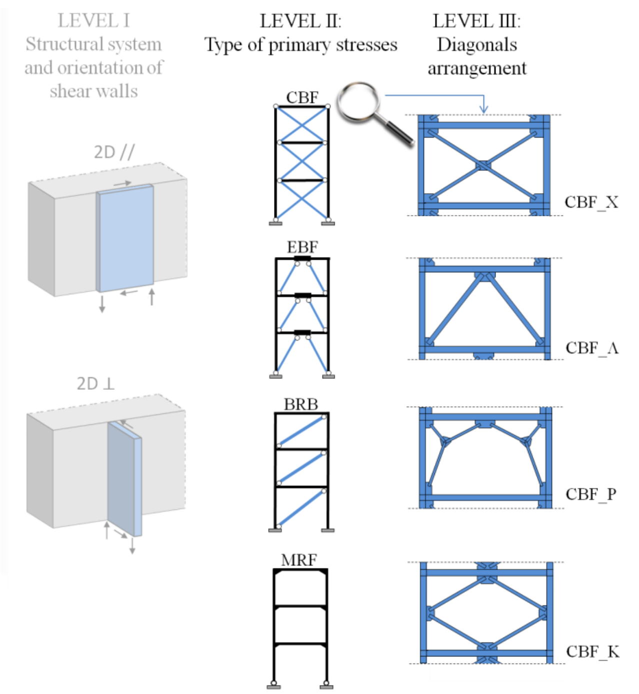

Figure 11 – Type of primary stresses and arrangement of braces for CBF systems.

The last level of typological choice regards the connection between the exoskeleton and the existing building, as well as the connection between the exoskeleton and the existing substructure (Figure 12). Additional dissipation or damping devices can be used to reduce loads acting on foundation. (Figure 12). This strategy demands to the existing structural system a large drift capacity, which often is not consistent with its own structural performances. Therefore, it is necessary to perform local interventions, that require to stop the building use, limiting a lot the benefits deriving from the employment of exoskeletons.

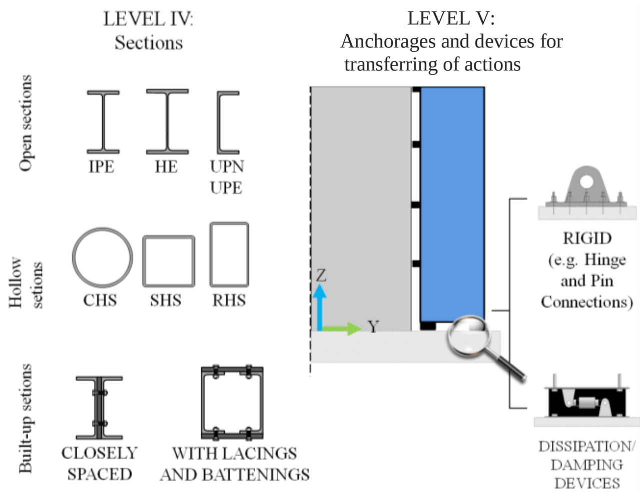

Figure 12 – Typological choice: cross-sections of exoskeleton members and force transfer systems between the main structure and the additive system.

Once the seismic-resistant scheme has been decided, the first attempt to size all structural components is performed. This phase consists in assigning a trial dimension to wall system and components using global (e.g. span/depth ratio) and local (e.g. length/depth ratio) shape factors. This preliminary dimensioning phase is based on the ratio theory, where shape factors were taken from previous experiences of other designers taken from similar buildings.

Other parameters to be considered are geometric indexes regarding the distribution of walls in the structural grid. As it is possible to have several walls on each side of the building, it is useful to introduce the frequency (F_i) parameter, that can indicate the ratio between the number of walls for each direction (i) and structural grid components (columns in plane and beams in elevation). This refers to a three-dimensional coordinate system (X, Y and Z). For example, F_X is related to the ratio along direction *x*. Contrary, the elements number index is referred only to the number of walls along a given direction *i* (N_i). With reference to the normal directions X, Y and Z, these indexes will be called N_X, N_Y and N_Z. Spread index (φ_i) is a parameter that specify the percentage of surface covered by the exoskeleton elements. It refers to a normalized surface related to the normal plan *i*.

With the aim to summarize concept process, facilitate cataloguing (§2.4) and promote exoskeletons industrialization, it is reported the following nomenclature:

(EX) – (S R_{eH}-K_v) - (2D 3D) – (// ⊥) - (CBF) - (X)

where:

- EX indicates the exoskeleton;
- S R_{eH}-K_v indicates the material. In case of structural steel, grade and subgrade are reported;
- 2D or 3D indicates the structural system type;
- // or ⊥ indicates the orientation of structural walls in case of 2D system;
- CBF indicates the type of primary seismic-resistant system;
- X indicates the diagonal arrangement.

To the above acronym it is possible to add the mentioned geometric indexes of frequency (F_X, F_Y e F_Z), elements number (N_X, N_Y e N_Z) and spread (φ_X, φ_Y e φ_Z).

3 DESIGN METHODOLOGY

3.1 *Design aims and expected performance levels*

The minimum safety standards (ζ_E index) to be respected for retrofit interventions are defined by Italian Technical Code NTC 2018 in Chapter 8. They change according to both the limit state (LS) chosen and to the building use class (C_U factor). The current standard requires that the seismic vulnerability assessment is done considering the Ultimate Limit States (ULS) at the Life Safety (LS) or Collapse Prevention (CP). Exceptions are for strategic buildings (use class IV), which it is required that the seismic vulnerability assessment is done even considering the serviceability limit state for (see §7.3.6 of the NTC 18). The same code foresees that performance levels of strategic buildings must be lower than those of the new ordinary ones. Referring to the school buildings (use class III) and to the use class IV buildings, the ζ_E index must not be less than 0,6. This index value is not applicable to the cultural heritage buildings, meanwhile for other use class III buildings and ordinary buildings (use class II) ζ_E must not be less than 0,1. However, the *post-operam* index value should be higher than the *ante-operam* one.

The retrofit of an existing construction by additive structures as exoskeletons can radically improve its seismic performance and structural safety levels with regards to both serviceability and ultimate limit states. The main feature and design aim of exoskeletons is the control of the global and local lateral stiffness of the existing structure. The increasing of lateral stiffness of the retrofitted structure leads towards smaller required seismic displacements. This is feasible for existing structures, which usually have a small displacement capacity. The stiffness control feature, if wisely applied, can be a design tool to correct the structural irregularities of the existing structure, so to lead towards a desiderated global failure mechanism.

The exoskeletons can be designed regarding to different seismic performance levels; for example, they can be designed in order that the existing structure will remain globally elastic and the damage is concentrated in the structural elements of the exoskeleton. Another performance level suitable for existing reinforced concrete structures is to design the exoskeleton in order to set the seismic required displacement of the retrofitted structure lesser than the displacement corresponding to the first shear failure; this choice permits to protect the existing structure from any significant damage.

3.2 *Proposed semplified design methodology*

All the design methodologies available in literature are developed for the design of traditional and/or dissipative steel bracings put inside or outside the existing constructions. Some of these methodologies were developed by Italian authors (Faella et al., 2004; Faella et al., 2008; Ponzo et al., 2010) and were contextualized in the framework of the so-called N2 Method (Fajfar, 2000), which is very suitable for professional applications.

The simplified methodology herein proposed is based on the N2 Method applied in the format of the Capacity Spectrum Method (N2-CSM). This methodology can be successful applied to exoskeletons without adding dissipating devices. Based on the results of a seismic performance assessment according to the N2-CSM method, imposing the displacement demand of the retrofitted structure Δ^*_{tar} , the global lateral stiffness of the retrofitted structure K_d can be evaluated with the following equation:

$$K_d = \frac{m^* \cdot S_{\mathrm{ADRS}}(\Delta^*_{tar})}{\Delta^*_{tar}} \qquad (1)$$

where m^* is the equivalent mass of the Single Degree of Freedom (SDOF) system and S_{ADRS} is the elastic spectral acceleration at the displacement Δ^*_{tar} . This formulation is valid under the hypothesis that the equivalent mass and the modal participation factor of both the existing construction and the retrofitted one remain the same. Furthermore, it is valid under the hypothesis that the yielding displacement of the bracing systems corresponds to the yielding displacement of the existing structure. As long as the retrofitted structure reacts locally and globally to the horizontal actions as the existing construction and the exoskeletons work in parallel, the global lateral stiffness of the exoskeleton in each main direction K_e can be evaluated with the following equation:

$$\mathrm{K_e} = \mathrm{K_d} - \mathrm{K_{ES}} \tag{2}$$

where $\mathrm{K_{ES}}$ is the global lateral stiffness of the existing structure, that can be evaluated as:

$$\mathrm{K_{ES}} = \frac{\mathrm{F}_y^*}{d_y^*} \tag{3}$$

where F_y^* and d_y^* are yielding force and yielding displacement of the SDOF system.

The choice of the target displacementΔ^*_{tar} sets the global seismic performance of the retrofitted structure. For example, as mentioned in §3.1, setting the target displacement equal to the yielding displacement of the existing structure, a globally elastic seismic behaviour is achieved. In order to protect the existing construction from brittle failures the target displacement can be set equal to the displacement corresponding to the first shear failure (Figure 13).

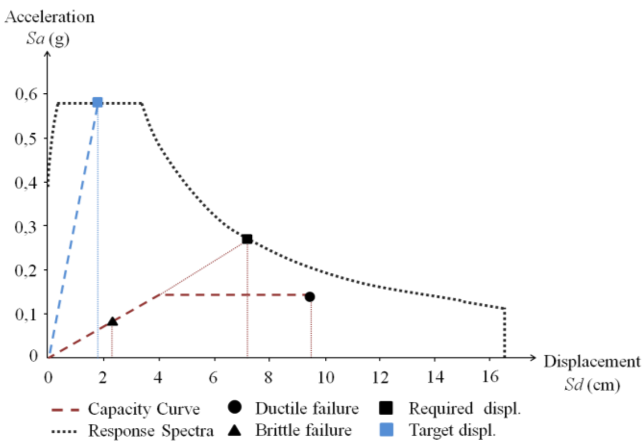

Figure 13 - Target displacement definition.

The global lateral stiffness of the exoskeleton is then distributed locally to each level by the following equation:

$$\mathrm{K_{c,i}} = r \cdot \mathrm{K_{ES,i}} \tag{4}$$

where $\mathrm{K_{ES,i}}$ is the local lateral stiffness of each level and r is the stiffness ratio, evaluated as:

$$r = \frac{\mathrm{K_e}}{\mathrm{K_{ES}}} \tag{5}$$

This local distribution have to be intended as a first attempt; indeed, it preserves the structural regularity properties of the existing construction. A regularization procedure (Ponzo et. al., 2010) can be applied to modify this initial distribution and to correct the possible structural irregularities of the existing construction.

4 CASE STUDY: THE SANTINI PRIMARY SCHOOL

4.1 Description of structural system

The case study building is the "Pietro Santini" primary school located in Loro Piceno, a district of Macerata. The building, dating back in the mid-sixties, is characterized by a rectangular plan with an offset floor on the East side (Figure 14).

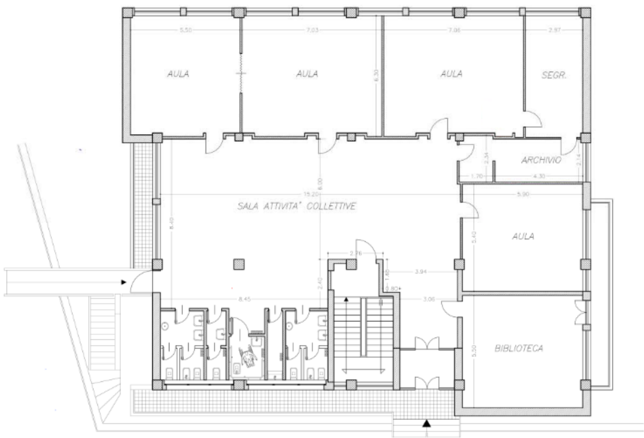

Figure 14 - Ground floor plan of the school building under study (source: Loro Piceno Municipality).

It is spread over three levels and it is placed next to an embankment, which goes along its Nord and East sides. The structure consists in a r.c. moment resisting frames (MRF) with reinforced concrete and hollow tiles mixed floors. It was designed to withstand the gravitational loads only. The structure is characterized by parallel MFRs disposed alongside East-West boundary directions and transverse MRFs placed at the building ends.

The staircase is located in an eccentric position. The r.c. walls hosting the stairs are disposed perpendicular to the main frames. This building configuration ensures a good distribution of the stiffness in main directions.

This case study is typical of the Italian built-up of Sixties designed to withstand vertical loads only. In fact, Loro Piceno was tagged as seismic area only in the early Eighties.

The information about the structural details were caught through both a diagnostic tests campaign and laboratory tests on materials. To gather more information, the results of the campaign were supplemented by a simulated project. It was done in compliance with calculation methods foreseen by the standard in force in the building erection period. Due to geometrical configuration, material properties and their degradation, a Level of Knowledge 2 (LC2) was considered according to the NTC 2018 standard.

4.2 *Structural assessment of existing building*

The analysis of the base shear-top displacement curve of the MDOF system shows how the first brittle failures occur in the elastic field for small displacements (Figure 15).

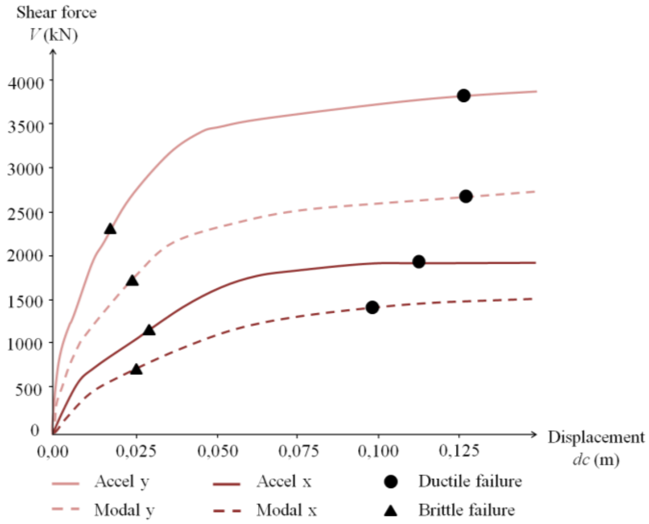

Figure 15 – Capacity curve of *ante operam* MDOF system.

However, ductile failures occur in the plastic region for large displacements. According to the approach codified in the NTC 2018, the seismic vulnerability assessment is done considering immediate occupancy and life safety limit states.

As a primary school, the case study is examined like an ordinary building with significant overcrowding, so to belong to the use class III. The current code foresees a nominal design life of 50 years for ordinary buildings and an use factor of 1,5 associated to this class of buildings.

The construction site has coordinates: 43,1652 latitude - 43,1652 longitude. The subsoil class is B and the topographic class is T1. According to these values, the seismic action reference period is set as equal to 75 years. Figures 16 and 17 show the safety assessment in the Acceleration Displacement Response Spectra (ADRS) format along directions *x* and *y*, respectively.

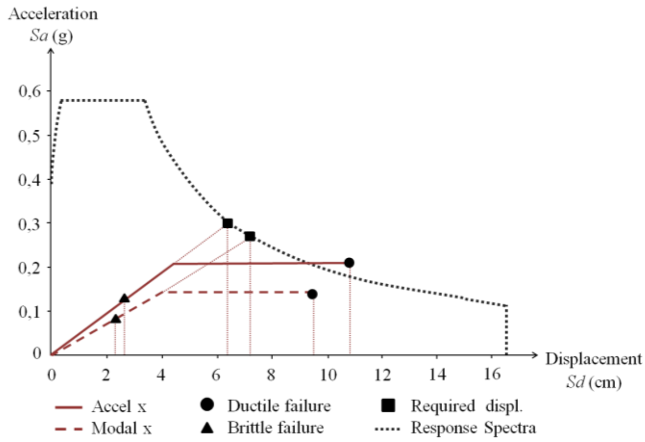

Figure 16 – Capacity curve of the *ante operam* structure in ADRS format in direction *x*.

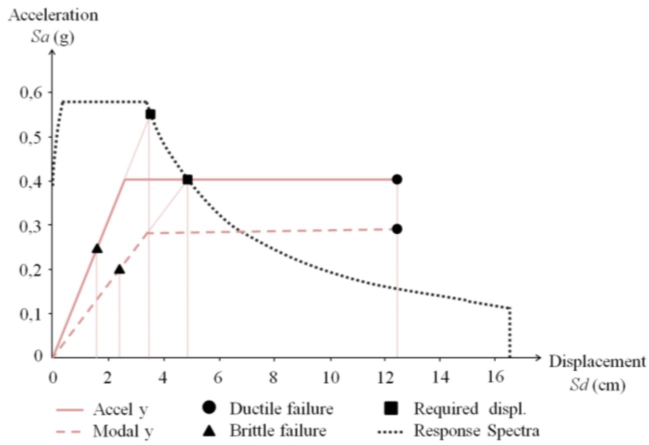

Figure 17 - Capacity curve of the *ante operam* structure in ADRS format in direction *y*.

As usual for r.c. buildings, taking the first ductile failure, the hazard index is higher than the unit. Nevertheless, the first brittle failure displacement is less than the required displacement and the hazard index is lower than the unit. As a consequence, the structure is unfit to meet the required displacement under the seismic action.

4.3 *Seismic deficiencies and design of the retrofit intervention*

Due to the embankment along the North and the East sides of the school, the first level typological choice has been directed towards the disposition of the exoskeleton in direction parallel to the facade. Concerning the second levels choice, a X-shaped Concentric Braced Frame (CBF-X) has been chosen. The braces adopted have been made of Circular Hollow Section (CHS) profiles. The nomenclature that identify this exoskeleton is 2D_//_CBF_X.

The placement of exoskeletons on each facade (Figures from 18 to 21) has been done considering architectural and functional limitations of the building.

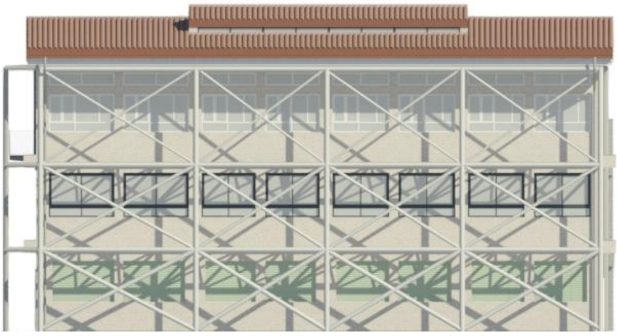

Figure 18 – Façade with exoskeletons in direction *x*. South Side: 2D_//_CBF_X_F_Z1_F_X1_N3.

Figure 19 - Façade with exoskeletons in direction *x*. North Side: 2D_//_CBF_X_F_Z1_F_X1-1_N3.

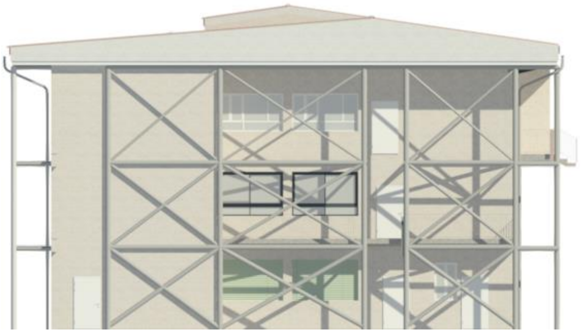

Figure 20 - Façade with exoskeletons in direction *y*. East Side: 2D_//_CBF_X_F_Z1_F_Y1-1_N3.

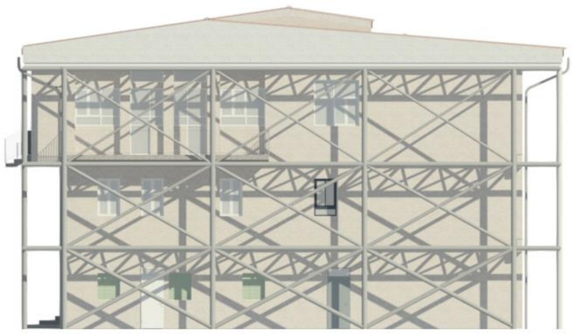

Figure 21 - Façade with exoskeletons in direction *y*. West Side: 2D_//_CBF_X_F_Z1_F_Y1-1_N3.

For these reasons, the exoskeleton has been placed in adhesion to the structure, when it is allowed by the building structural shape, or at a distance to allow for the regular use of both balconies and windows.

4.4 *Results and discussion*

Comparing the achieved results before and after the retrofitting intervention, it has been shown how the global lateral stiffness and strength are significantly increased (Figures from 22 to 24). After retrofit operations, it has been also detected that the seismic safety verifications are satisfied.

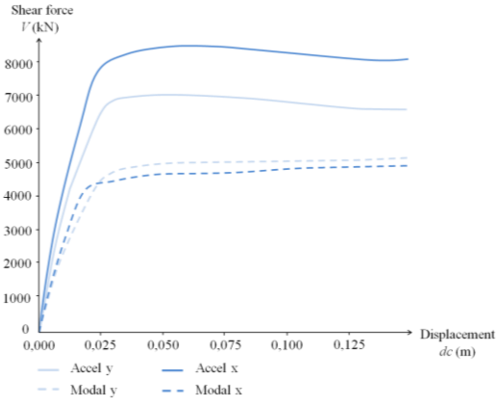

Figure 22 – Capacity curve of the *post operam* MDOF system.

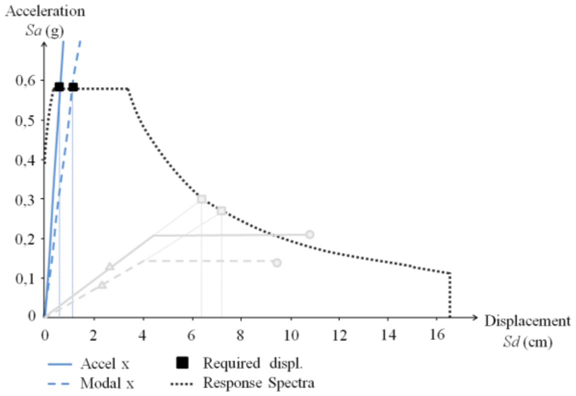

Figure 23 - Capacity curve of the *post operam* structure in ADRS format in direction *x*.

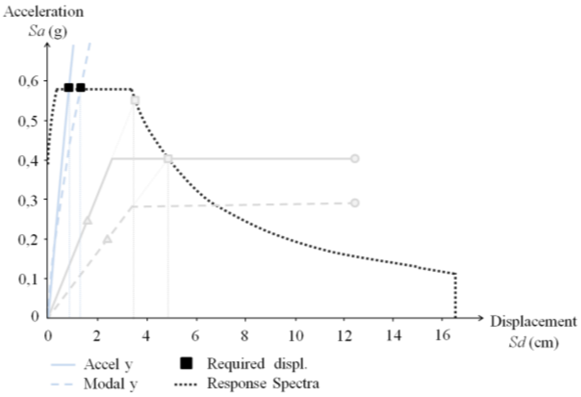

Figure 24 - Capacity curve of the *post operam* structure in ADRS format in direction *y*.

5 CONCLUSIONS

The use of external additive structures under form of exoskeletons for retrofitting existing r.c.

buildings is a very challenging and innovative technique in the field of seismic consolidation and rehabilitation of structures. This consolidation system represents the only strategy applicable in safety without stopping the building use, allowing at the same time to do an integrated retrofit from structural, architectural and environmental viewpoints. This paper started with the state-of-the-art examination on the interventions with steel exoskeletons. Then, the typological choices and the key-parameters for designing these systems were defined. At the end, a simplified design methodology to apply steel exoskeletons as additive retrofitting systems was proposed in the framework of the N2 method applied in the Capacity Spectrum Method format. Finally, the application of examined retrofitting systems to the case study of the "Pietro Santini" primary school in Loro Piceno (province of Macerata) showed that exoskeletons are effective systems in increasing significantly the performances of the original building in terms of base shear and stiffness.

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