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STATE-OF-THE-ART ON STEEL EXOSKELETONS FOR SEISMIC RETROFIT OF EXISTING RC BUILDINGS

Gianmaria Di Lorenzo[*1], *Eleonora Colacurcio*[1], *Agustina Di Filippo*[1], *Antonio Formisano*[2], *Alfredo Massimilla*[2], *Raffaele Landolfo*[1]

[1] Department of Structures for Engineering and Architecture, University of Naples "Federico II", Via Forno Vecchio 36, 80134 (NA), Italy

[2]Department of Structures for Engineering and Architecture, University of Naples "Federico II", Piazzale Tecchio 80, 80125 (NA), Italy

SUMMARY: *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 building use, but also because it can be effectively adopted, in cases of restructuring operations 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 of the main researches and applications on steel exoskeletons, their typological classification into families and the definition of the key project parameters, indispensable to both properly conceive and design such systems, have been performed.*

KEYWORDS: *Seismic retrofit, Existing RC buildings, Steel exoskeletons, Steel bracings, Integrated approach, Cataloguing of interventions*

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 issues (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, Montuori 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 use interruption of the construction is considered (FEMA, 2006). In this framework, admissible interventions are

Corresponding author: Gianmaria Di Lorenzo, Department of Structures for Engineering and Architecture, University of Naples "Federico II", Via Forno Vecchio 36, 80134 (NA), Italy
Email: gianmaria.dilorenzo@unina.it

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 biomimicry (Benyus, 2002), it is possible to call them as "exoskeletons", that is systems applied from outside 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 (Di Lorenzo et al., 2019a) 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., 2019b) 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 the 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).
For this reason, in Italy, the envelope renovation is promoted by the 2020 Balance Law, which provides a tax credit of 90% of the costs incurred for interventions dealing with envelope renovation of residential buildings. Therefore, the use of exoskeletons, which are integrated into the building envelope, becomes a cost-efficient solution, since in our country it is possible to have benefits from three different types of tax credits, namely *sismabonus*, *ecobonus* and *facciate bonus*. In this framework the current paper is located, which has 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 limited multiple storeys. 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.

2 Strategies for seismic retrofitting of existing reinforced concrete structures

Referring to civil engineering and architectural accomplishments, a planning to optimize resources and needs on resilience and sustainability requires 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 should be used even for existing buildings, which require a regeneration through upgrading or retrofitting interventions.

Figure 1- *Holistic approach in a life cycle way*

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 (Formisano, 2012; Formisano et al., 2016; Totter et al., 2018; De Domenico et al., 2019; Aiello et al., 2017; Preti et al., 2017).

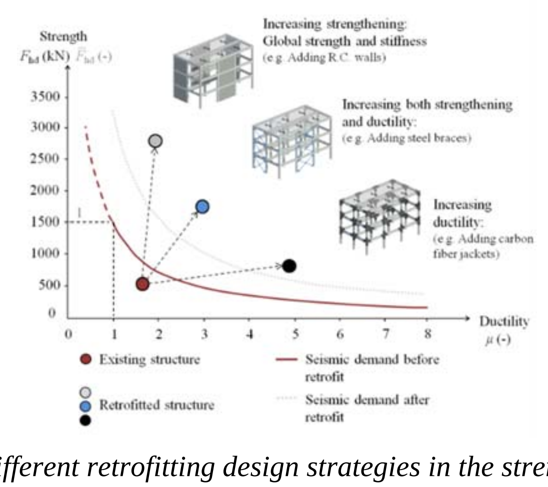

Figure 2 – *Effect of different retrofitting design strategies in the strength-ductility plane*

A successful and efficient choice of these strategies can be done by comparing demand (D) and capacity (C) within a strength-based design approach (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).

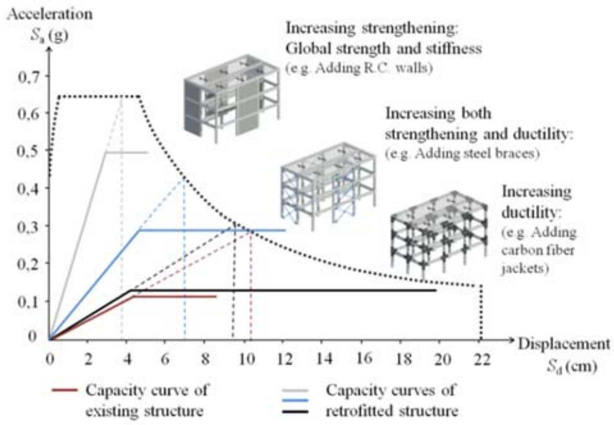

Figure 3 – *Effect of different retrofitting design strategies in the ADRS format*

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).

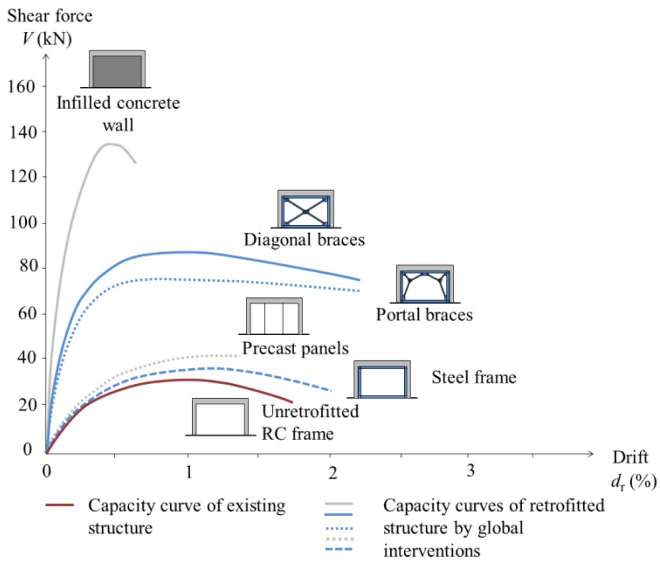

Figure 4 – *Typical experimental responses in the shear force-drift plane of r.c. frames strengthened with various global retrofitting techniques*

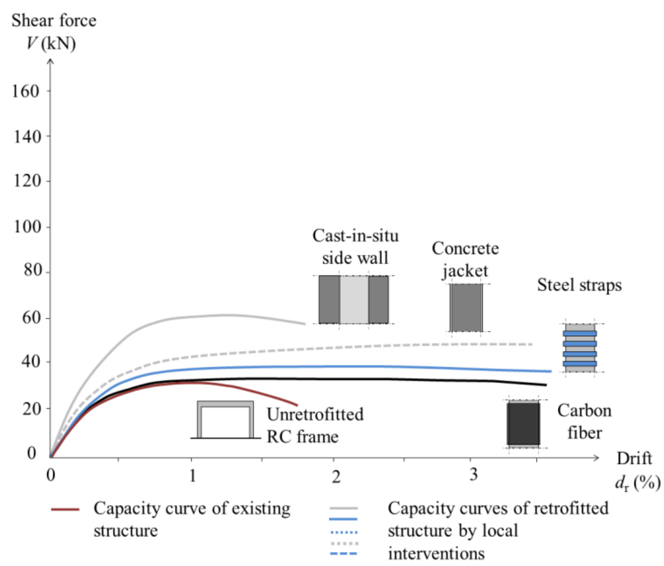

Figure 5 - *Typical experimental responses in the shear force-drift plane of r.c. frames strengthened with various local reinforcing techniques*

3 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).

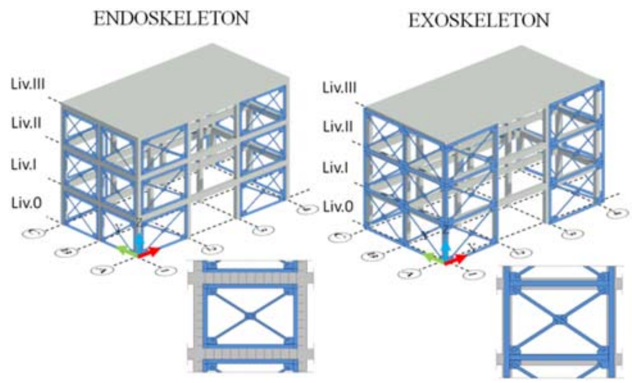

Figure 6 - *Differences between endoskeleton and exoskeleton*

In both cases there is a strength and stiffness increase, which permits the seismic upgrading of all those buildings characterized by low levels of security. The endoskeletons are used when it is not possible to operate from the outside for different limitations, such as physical/geometrical issues (i.e. townhouses), city-planning subjects (i.e. distance and volume limits) and architectonic matters (i.e. heritage buildings). This concerns especially old towns masonry buildings, where endoskeletons can be designed to absorb, partially or completely, both lateral actions and gravity loads. Instead, the exoskeletons, thanks to their external installation feature, highlight the possibility to avoid to interrupt the existing

building use. Referring to the Italian and European building stocks, the types of structure that are suitable to host exoskeletons are cast on site or precast r.c. buildings, as well as steel and timber framed buildings.
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).

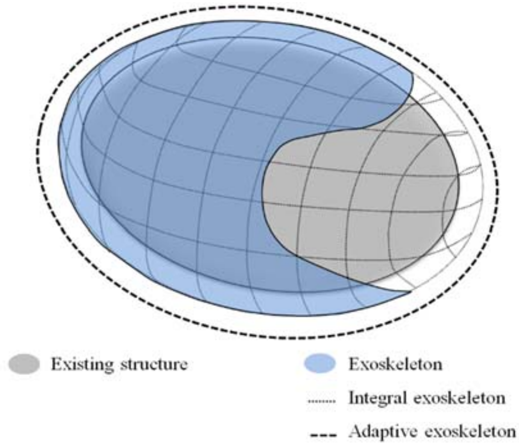

Figure 7 – *Concept of exoskeleton*

Due to morphological and right force transferring issues, it is considered as a real exoskeleton only the system applied on either most of the surface or on every sides of the building. 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 system. 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 potentiality 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 increases, necessary to improve safety levels at the collapse limit state, are provided.

4 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 for system design.

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 in the original structure, especially when a dry system is foreseen. If the exoskeletons are not well integrated in the structure, they are directly exposed to weather conditions and, therefore, need to be protected from corrosion. In terms of a life cycle approach, beside the non-alloy and low-alloy steels, which are the less expensive solutions, there are even more costly solutions based on stainless steels and aluminium alloys.

Once the material has been decided, the selection of the resistant scheme must be 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 bi-dimensional (e.g. shear walls) or three-dimensional (e.g. cores) elements. 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.

The connection to 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 effectively used 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 bi-dimensional systems, it is possible to adopt more expensive and efficient three-dimensional structures. Thanks to their own configuration of single 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 (usually indicated as diagrid) or multi-layer grids.

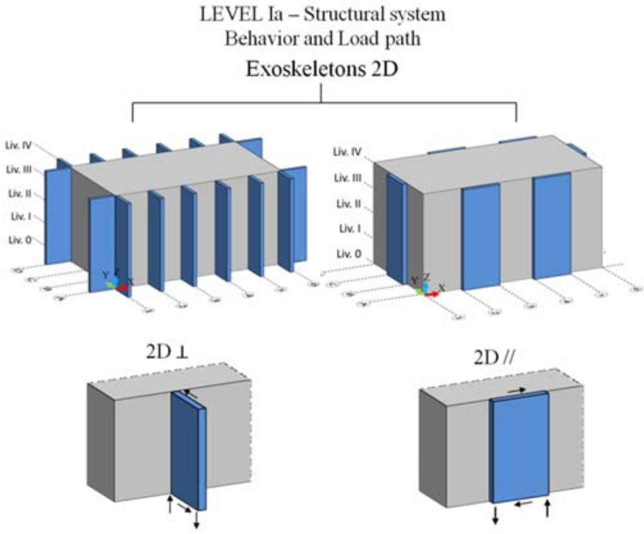

Figure 8 – *Level Ia typological choice: shear walls arranged perpendicular (2D⊥) or parallel (2D//) to the facade*

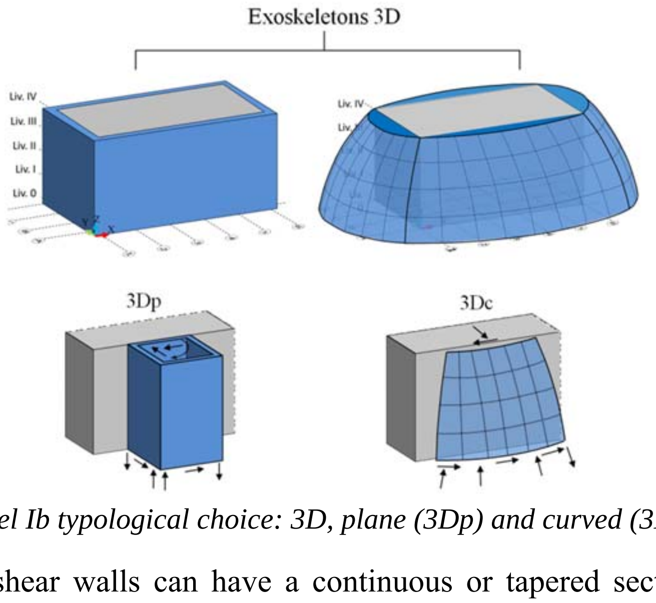

Figure 9 – *Level Ib typological choice: 3D, plane (3Dp) and curved (3Dc) structures*

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, namely Concentric Bracing Frame (CBF), Eccentric Bracing Frame (EBF), Buckling-Restrained Bracing frame (BRB) and Moment Resisting Frame (MRF) (Figure 11). Among them, the CBF configuration is preferable because of its more efficient design. The arrangement of diagonals in CBF systems can be usually done according to the St. Andrew's cross, Inverted-V, portal and K schemes (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, thanks to the rounded shape, combine high efficiency with aesthetic value, which make safe people in cases of accidental strokes.

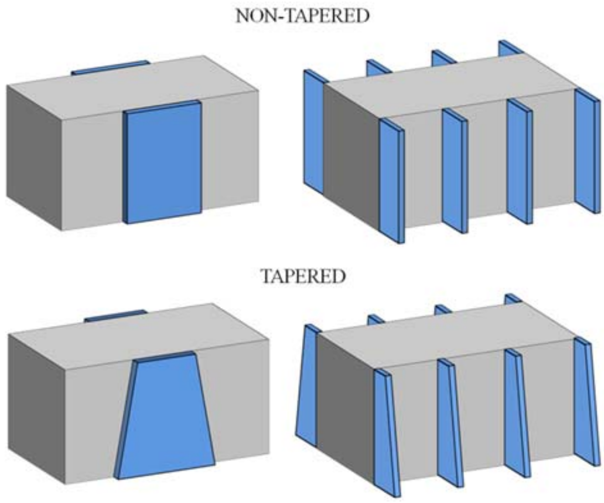

Figure 10 – *Non-tapered and tapered shear walls configurations*

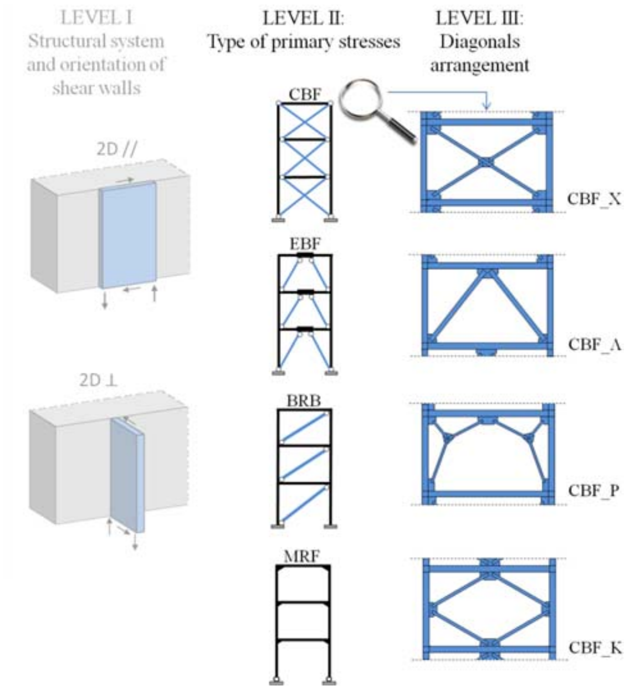

Figure 11 – *Type of primary stresses and arrangement of braces for CBF systems*

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. 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 (Sorace et al., 2019). 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.

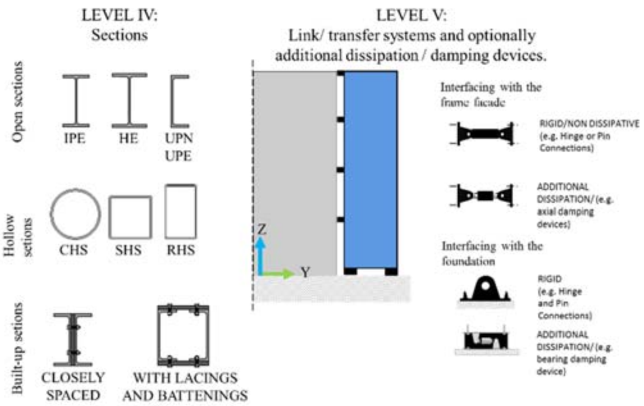

Figure 12 – *Typological choice: cross-sections of exoskeleton members and force transfer systems between the main structure and the additive system*

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 are taken from previous experiences of other designers on 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 indicates the ratio between the number of walls in each direction (i) and structural grid components (columns in plane and beams in elevation). With reference to a three-dimensional coordinate system (X, Y and Z), for example, F_X represents 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). Referring to the normal directions X, Y and Z, these indexes are called N_X, N_Y and N_Z. Spread (φ_i) index is a parameter specifying 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 the conceptual process for cataloguing exoskeletons and promoting their industrialization, it is reported the following nomenclature:

(EX) – (S R_{eH}-K_v) - (2D 3D) – (// ⊥) - (CBF-EBF-BRB-MRF) - (X-Λ-P-K)

where:

- EX indicates the exoskeleton;
- S R_{eH}-K_v is the structural steel (S) with grade (R_{eH}) and subgrade (K_v);
- 2D or 3D indicates the structural system type;
- // or ⊥ indicates the orientation of structural walls in case of 2D system;
- (CBF-EBF-BRB-MRF) are all the types of primary seismic-resistant systems;
- (X-Λ-P-K) are the possible diagonal arrangements in case of CBF systems.

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

5 Emblematic projects and cataloguing of interventions

Since the Eighties, all around the world, especially in those areas with very high seismic hazard, there were many cases of existing r.c. building retrofitted by exoskeletons (Figure 13). In the following, three emblematic cases of steel exoskeleton interventions are illustrated and described. These are presented by using cataloguing forms designed to map out the entire design process (Wenk, 2008). Forms are organized into two sections, namely part I ad part II, dedicated, respectively, to the building before and after retrofitting interventions.

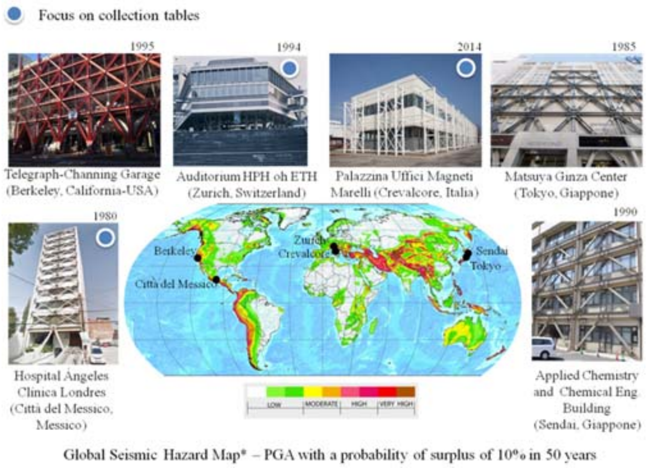

Figure 13 - *Exoskeletons applications over the world and Global Seismic Hazard Map*

Part I has four subsections regarding information about general building subjects (year of construction, building use, location, designers, construction cost), structural features (construction technology, structural type system, dimensional characteristics), safety assessment issues (level of knowledge, *ante-operam* security index, *ante-operam* seismic classification) and building deficiencies (previous damages, lacks). The most common deficiencies that can be found in existing r.c. buildings designed and built without seismic specifications are reduced global strength and stiffness towards lateral actions, in plan and in elevation irregularities, load path problems among elements and component detailing or foundations deficiencies. Other lacks that can be considered are problems related to non-structural elements, that can activate local collapse mechanisms, and those related to design and construction errors. Part II presents three subsections regarding general information (year of retrofit, designers, retrofit cost), design concept (retrofitting strategy, technology, typology, dimensional characteristics) and performance level achieved after retrofit (*post-operam* security index, *post-operam* seismic classification, damages after retrofit). Moreover, the design concept is summarized using the nomenclature previously exposed.
As many buildings after the retrofitting intervention were hit by earthquake, in the forms there is also a specific textbox, where it is reported a feedback on the structure real behaviour. This cataloguing form can be inserted into a specific database. In this way, useful suggestions can be offered to anyone wants to use this kind of retrofitting strategy. For the sake of example, the cataloguing forms of three case studies are reported as follows. The first form describes a 2D⊥

retrofitting system applied to the office complex of Magneti Marelli in Crevalcore (district of Bologna, Italy) (Table1) The second one is a 2D// system applied to the Hospital Ángeles Clínica Londres in Mexico City (Mexico) (Table 2). The last case study is a 3Dp system applied to the Hörsaalgebäude Physik building in Zurich (Switzerland) (Table 3).

Table 1 - *Cataloguing form: Office complex of Magneti Marelli's headquarter*

Part I- Existing building		
General building information	Year of construction	1973 - 1974
	Building use	Office complex
	Location	Crevalcore (BO), Italy
	Designers	-
	Construction cost	-
Structural building system	Construction technology	r.c.
	Structural type system	MRF-2D
	Dimensional characteristics	Elevation from the street level: 9,3m - Rectangular plan with basement: 56m x 12,5m - First floor: 57,55m x 13,75m
Safety assessment	Level of Knowledge	LC2
	Ante-operam security index	0.2
	Ante-operam seismic classification	E_{IS-V}
Building deficiencies	Previous damages	Damages to non-structural elements and several damages to some columns and to the staircase during the 2012 Emilia Earthquake M_{w_max}=6.1
	Deficiencies	Transfer column and load path problems. Global strength and stiffness deficiencies in both longitudinal and transverse directions

Part II- Intervention		
General retrofit information	Year of retrofit	1980
	Designers	-
	Retrofit cost	20% of construction cost
Design concept	Retrofitting strategy	Strength and stiffness increase
	Technology	S275-355
	Typology	2D//-DIAGRID except from the ground floor 2D//- CBF_Λ
	Dimensional characteristics	F_Z 1_ F_X1_N20
Performance level achieved	*Post-operam* security index	> 1
	Post-operam seismic classification	-
	Damages after retrofit	No damages recorded during the 1985 Mexico City Earthquake M_{w_max} =8.0
photographic report	 	

Table 2 - *Cataloguing form: Hospital Ángeles Clínica Londres*

Part I- Existing building		
General building information	Year of construction	1970
	Building use	Hospital
	Location	Mexico City, Mexico
	Designers	-
	Construction cost	-
Structural Building system	Construction technology	r.c.
	Structural type system	MRF-2D
	Dimensional characteristics	12-storeys building
Safety assessment	Level of Knowledge	-
	Ante-operam security index	< 1
	Ante-operam seismic classification	-
Building deficiencies	Previous damages	Several damages to structural elements during the 1979 Mexico City Earthquake
	Deficiencies	Global strength and stiffness deficiencies in transverse direction

Part II- Intervention		
General retrofit information	Year of retrofit	Retrofit project 2012 Retrofit realization 2013-2014
	Designers	Teleios s.r.l
	Retrofit cost	€2.400.000 of which €700.000 for the structural elements
Design concept	Retrofitting strategy	Strength and stiffness increase
	Technology	S275-355
	Typology	2D⊥ - CBF_X
	Dimensional characteristics	F_Z2_ F_X1_ F_Y2_N2
Performance level achieved	*Post-operam* security index	> 1
	Post-operam seismic classification	A^{+}_{IS-V}
	Damages after retrofit	No significant event recorded
photographic report	 	

Table 3 - *Cataloguing form: Hörsaalgebäude Physik*

Part I- Existing building		
General building information	Year of construction	1970 - 1971
	Building use	Auditorium
	Location	Zurich, Switzerland
	Designers	Structure: Basler & Hofmann Architecture: Broggi & Santschi
	Construction cost	70 million CHF
Structural building system	Construction technology	r.c. - steel
	Structural type system	MRF-3D + r.c. shear walls
	Dimensional characteristics	Hexagonal plan that can be inscribed in a 74m x 69m rectangle
Safety assessment	Level of Knowledge	LC2
	Ante-operam security index	0.25 (SIA 160)
	Ante-operam seismic classification	-
Building deficiencies	Previous damages	-
	Deficiencies	Weak storey in the open entrance hall under the supporting floor of the auditoriums. Severe torsional stresses under seismic action caused by a large eccentricity between the centre of stiffness of the r.c. walls on the rear side of the ground floor level and the centre of mass of the overlying storeys.

Part II- Intervention		
General retrofit information	Year of retrofit	1994
	Designers	Basler & Hofmann Zwicky P. e Bachmann H.
	Retrofit cost	0.7% of the construction cost
Design concept	Retrofitting strategy	Strength and stiffness increase
	Technology	S355
	Typology	3D_DIAGRID
	Dimensional characteristics	$F_Z1\_F_H1\_N1$
Performance level achieved	*Post-operam* security index	1.00 (SIA 160)
	Post-operam seismic classification	-
	Damages after retrofit	-
photographic report	 	

6 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 safe way without stopping the building use, allowing at the same time to do an integrated structural, architectural and environmental retrofit.

This paper started with the state-of-the-art examination of main researches and applications about interventions with steel exoskeletons on existing r.c. buildings.

State-of-the art studies highlighted how the use of exoskeleton for the seismic retrofit is not a recent solution approach. Despite the amount of field researches, exoskeletons design is still not carried out following a holistic vision, that could take benefit from their natural feature to be well fitted with the building envelope to obtain a global structural, energetic and architectural retrofit. Conversely, most of these applications have focused only on the achievement of the building structural security after insertion of these systems.
Later on, the typological classification into families of exoskeletons and the definition of their key project parameters, indispensable to both properly conceive and design such systems, were performed.
Finally, a cataloguing form to be used for mapping the entire design process was proposed with the aim to create a database helpful to everyone would like to apply this kind of retrofit methodology. Moreover, it can be useful for seismic assessment studies aimed to the implementation of fragility curves.
In conclusion, the development of this retrofit strategy needs an integrated design approach, which requires a synergic collaboration among all stakeholders of the building sector. Strong relationships between industries producing structural and non-structural components should be required, as well as interventions with an integrated approach, using the BIM method and considering the whole building life cycle, should be planned.

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STATO DELL'ARTE SUGLI ESOSCHELETRI PER IL RINFORZO SISMICO DEGLI EDIFICI IN CEMENTO ARMATO

Gianmaria Di Lorenzo[1], *Eleonora Colacurcio*[1], *Agustina Di Filippo*[1], *Antonio Formisano*[2], *Alfredo Massimilla*[2], *Raffaele Landolfo*[1]

[1] Department of Structures for Engineering and Architecture, University of Naples "Federico II", Via Forno Vecchio 36, 80134 (NA), Italy

[2]Department of Structures for Engineering and Architecture, University of Naples "Federico II", Piazzale Tecchio 80, 80125 (NA), Italy

SOMMARIO: *Dagli anni '80 l'uso di strutture addizionali esterne, comunemente chiamati esoscheletri, è considerato una delle possibili alternative per il retrofit sismico di edifici esistenti in cemento armato a bassa capacità dissipativa. I primi codici giapponesi e americani che trattano di problemi di riabilitazione strutturale, così come molte applicazioni sull'uso di dispositivi in acciaio a livello internazionale, testimoniano questa tendenza, specialmente nelle aree ad alto rischio sismico. Oggi l'uso di questa strategia di intervento è diventato di grande attualità, non solo perché può essere attuato in modo sicuro senza interrompere l'uso dell'edificio, ma anche perché può essere efficacemente adottato, in caso di operazioni di ristrutturazione con aggiunta laterale, per il retrofit integrato (formale, energetico e funzionale) dell'intera costruzione. Nel presente lavoro, dopo un accurato stato dell'arte delle principali ricerche e applicazioni sugli esoscheletri d'acciaio, è stata effettuata una classificazione tipologica in famiglie e la definizione dei parametri chiave del progetto, indispensabili sia per concepire e progettare correttamente tali sistemi.*

Corresponding author: Gianmaria Di Lorenzo, Department of Structures for Engineering and Architecture, University of Naples "Federico II", Via Forno Vecchio 36, 80134 (NA), Italy
Email: gianmaria.dilorenzo@unina.it