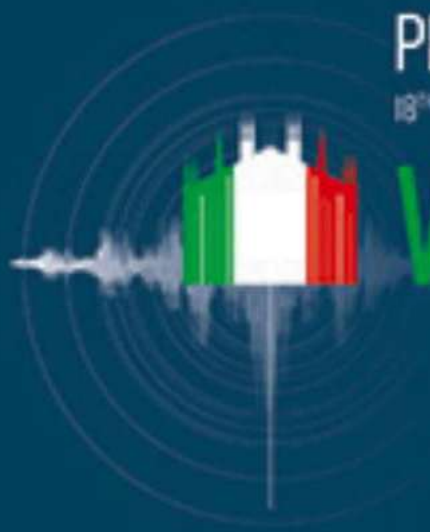


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RETHINKING THE ROLE OF THE CONNECTIONS TO IMPROVE THE SUSTAINABILITY OF THE RETROFIT ACTIONS

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Abstract: *Integrated interventions, possibly holistic and assembled outside the building, have been acknowledged as an effective solution to tackle the multifaceted needs of the existing buildings (structural, energy, and architectural). To guarantee true economic, environmental, and social sustainability throughout the building life cycle, besides mandatory objectives, such as energy efficiency and structural safety, other performance objectives must be targeted. LCSE principles, such as design for durability, reparability, for reuse-recycle, might remarkably improve sustainability. In this scenario, re-thinking the role of the connections, targeting standardization and modularity, might be key in improving the sustainability of any innovative and traditional retrofit actions. At the construction stage, the connection conceptual design should be aimed at reducing the construction time, facilitating the assembly of prefabricated components of the retrofitting exoskeleton, accommodating construction tolerances, and guaranteeing the envisioned stiffness and strength through modularity of its components. At the use stage, it should be aimed at lumping damage enabling the fast replacement in case of an earthquake (fuse of the structure), its possible adoption in the implementation of incremental rehabilitation retrofits and improving adaptivity to future uses of the building through plug-and-play installation and activation mode. At the end-of-life stage, connections could be fundamental in guaranteeing selective dismantling, and through standardization, they could effectively improve the reusability of the retrofit components. In the paper, the conceptual design of the existing building-to-exoskeleton connection is presented. A standardized, modular connection is proposed.*

1. Problem statement

The urgent need to foster sustainability has led to local and international policies being applied in the construction sector to renovate the existing building stock and reduce its emissions. Enormous resources have been invested yet such relevant effort may be a missed chance unless integrated retrofit solutions conceived in a Life Cycle Thinking (LCT) perspective are designed.

Integrated retrofit solutions are required since the uncoupled renovation is not sustainable from an economic, social, and environmental point of view. In the case of a strong earthquake, only upgrading the energy system in an unsafe building could result in the loss of investments, significant environmental damage, and most importantly, human casualties. On the other hand, the sole seismic retrofit may lead to unsatisfactory aesthetics and functionality, while neglecting energy efficiency might be a missed chance for tangible benefits associated with operational cost reduction.

When implementing a Life Cycle Thinking (LCT) approach, it is crucial to consider not only mandatory objectives such as energy efficiency and structural safety but also other performance objectives. Life Cycle Structural Engineering (LCSE) is the result of applying LCT in structural engineering and encompasses all LCT principles aimed at mitigating or eliminating the environmental impacts of buildings throughout their lifespan. These principles include, for example, designing for durability, reparability, and reuse-recycling.

Design choices, performance objectives, and construction details may thus be crucial in determining the impact of the building throughout its lifecycle. *In this scenario, re-thinking the role of the connections, targeting*

standardization and modularity, easy assemblage and demountability might be key in improving the sustainability of any innovative and traditional retrofit solutions.

Connections play a key role in every structural construction system. In literature, several authors discussed the importance of the connection in structural systems (Kelly et al. 1972, Whittaker et al., 1991, Xia et al. 1992, Fierro et al. 1993, Aiken et al., 1993, Tsai et al. 1992, Chan, 2008, Rodgers et al. 2006); not only connections are required to behave consistently with the structure, but they are often crucial in determining the structural features of the overall structure. However, the role of the connections in improving the sustainability of a retrofit solution needs to be further investigated since few authors discussed the importance of connections on the environmental impacts of buildings (Shilavantar et al., 2023, Burgan and Sansom, 2006).

This paper presents the conceptual design of an existing building-to-exoskeleton connection in full compliance with the LCT principles and proposes a standardized, modular connection. The proposed connection may be implemented in steel bracing walls, steel diagrid, or timber shell exoskeletons and was conceived to connect the exoskeletons to the RC perimetral chord of the existing building. The connection was supposed placed at the floor level of the existing building thus connecting the exoskeleton to the existing RC perimetral chord (Figure 1). The connections investigated in this paper connect the horizontal elements of the exoskeleton (e.g., steel bracing walls in blue in Figure 1) to the existing building RC chords (in black in Figure 1).

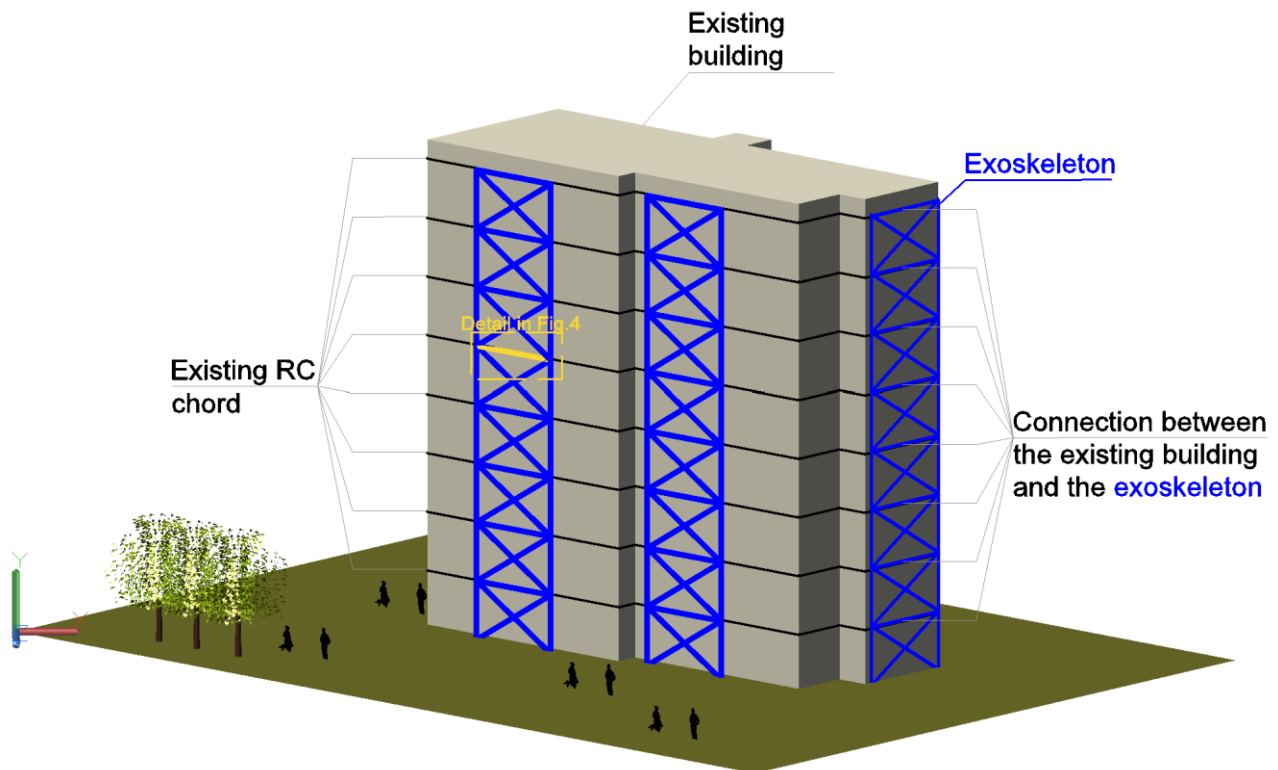


Figure 1. Sketch of the position of the connection proposed. In grey the existing building and in black are highlighted the RC chords; in blue the exoskeleton components.

In **Section 2** the approach and the design principles are presented. The discussion on the technological aspects of a possible connection between the existing building and the exoskeleton is presented in **Section 3**; while the paper contributions are summarized in **Section 4**.

2. Approach and LCT principles

In addition to mandatory structural objectives such as Life Safety performance, LCSE requires additional Design Performance Objectives (DPO) to be defined from the early stages of the design process, which are fundamental to conceive and design sustainable retrofit techniques, as discussed by Passoni et al. (2021). These supplementary design objectives are depicted in Figure 2, whilst those that drive the design of the existing building-to-exoskeleton connections are summarized in Table 1.

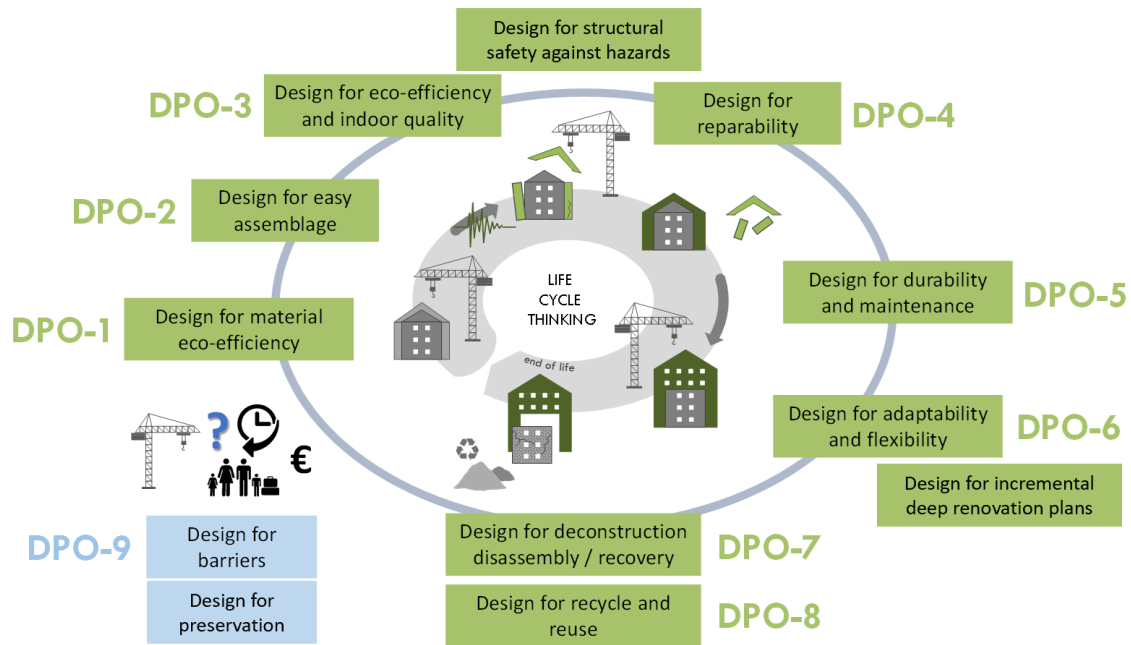


Figure 2. LCT-based Design Performance Objectives (DPO) (or design criteria) for the design of sustainable constructions. (Adapted from Marini et al. 2017 and Passoni et al. 2022).

As suggested by Passoni et al. 2021, to operationalize LCT-based Performance Design Objectives, specific strategies and technologies should be implemented. As for the connection design, compliance with the DPO should be ensured in various stages such as construction, use (maintenance/repair), and end-of-life (deconstruction).

At the construction stage, to allow for **Easy assemblage (DPO-2)**, **prefabricated** components could be used, and on-site construction **tolerances** should be managed. The existing building stock has inherent geometric irregularities, which must be taken into account when retrofitting solutions are designed since they may pose a threat to the assembly phase. These features should be reckoned with when designing connections to ensure a seamless and successful assembly phase.

At the use stage, connections can be designed to **lump damage** in specific components, making disassembly and repair works (**Reparability, DPO-4**) easier, whilst reducing waste and costs. **Standardization, dry assembly, and modularity** allow for improving adaptability and flexibility (**Adaptability and Flexibility, DPO-6**), which are required when implementing retrofit solutions through an incremental rehabilitation strategy (i.e., executing discrete actions over an extended period, FEMA P-420, 2009, Zanni et al., 2019).

Reparability must also account for the existing structure; in case of an earthquake, the existing structure should not experience excessive damage. For example, the maximum shear action in existing stiff elements, such as the staircase walls, should be limited to ensure that they can be repaired after an earthquake, while still being used as a safe means of egress. Similarly, the forces in the floor diaphragms and foundations must be controlled. To ensure the **safety and reparability** of the intervention, it's equally important to control the behavior of the retrofitted building at the Collapse Prevention Limit State. It's important to ensure that the retrofitted system exhibits a ductile failure mechanism. To achieve these goals, non-linear connections may be designed to limit the seismic action in the existing building, dissipate energy, and localize damage.

At the end-of-life stage, connections could be fundamental in guaranteeing selective dismantling, and could effectively improve the reusability of the retrofit components. **Deconstruction/Disassembly/Recovery (DPO-7)** may be enabled by dry assembly, while **Recycle and Reuse (DPO-8)** by standardization and modularity.

Table 1. LCT-based Design Performance Objectives and criteria/technological options to operationalize such DOP.

Stage	DPO	LCT principle
Construction	Design for Easy Assemblage (DPO-2)	Prefabrication On-site construction tolerances management
Use	Design for Reparability (DPO-4), Durability and Maintenance (DPO-5), Adaptability and Flexibility (DPO-6),	Dry assembly Modularity Lump damage
End-of-life	Design for Deconstruction/Disassembly/Recovery (DPO-7), Recycle and Reuse (DPO-8)	Dry assembly Standardization Modularity Lump damage

3. LCSE-designed connection between the existing building and the exoskeleton

Hypotheses and components

The following hypotheses were made at the beginning of the design process:

- 1) **The maximum length of the connection system should be less than 1.00m.** To use the connection between, among others, steel bracing walls and existing buildings, the module should have a longitudinal dimension shorter than a reasonable minimum distance between the columns of the bracing wall. From practice experience, distances shorter than 1.00m could lead to complications during the realization phase in positioning the thermal insulation layers. To enable hand management on site, each component weight must be smaller than 25kg.
- 2) The connection must be **both elastic and non-linear** and assembled using the **same components**.
- 3) Maximum design action on the connection is equal to 100kN. Such value was chosen based on the results of previous applicative cases (Labò et al., 2023) and the choice to incorporate existing fuses in the proposed connection. The fuses utilized were developed in (Zanni et al. 2021) and designing the connection for a maximum load of 100kN was deemed reasonable for these fuses when applied over a one-meter length.

The components are summarized in Figure 3. They **were kept to a minimum, standardized, and modular** to facilitate assemblage and the potential reuse at the end of life.

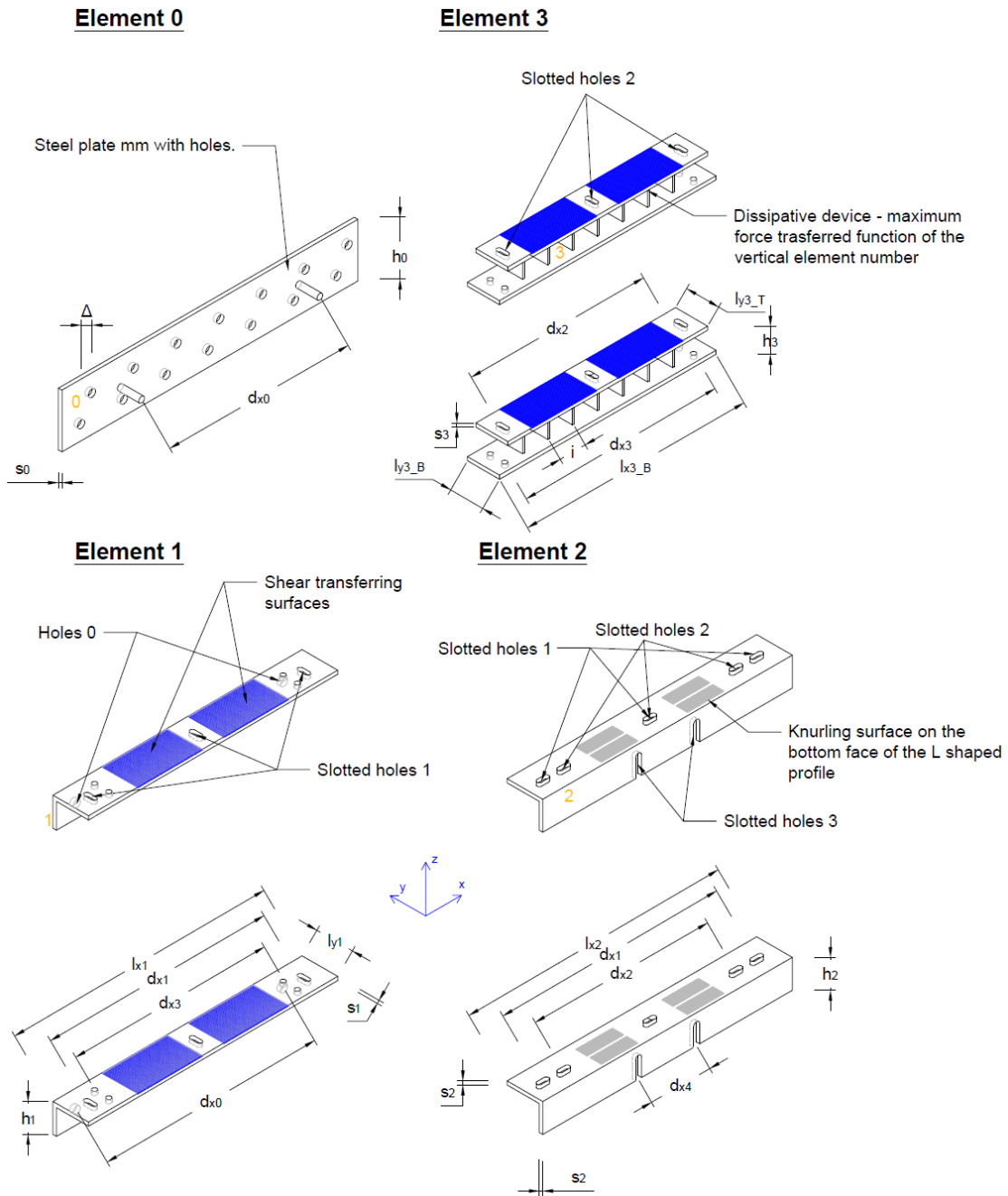


Figure 3. Components of the connection system: a) elastic, b) nonlinear.

Components: (Figure 3)

The connection system is composed of a pre-holed steel plate (**Element 0**), s_0 thick and h_0 high; the holes' bottom line is shifted by Δ respect to the upper one. On the steel plate are welded 2 bolts d_{x0} distant.

Element 1 is an L-shaped profile, l_{x1} long, h_1 high, l_{y1} width, and s_1 thick. It has two holes on the vertical surface, d_{x0} distant, and four round holes and two slotted holes on its upper surface. The slotted holes are d_{x1} distant. The upper surface of **Element 1** features a knurled texture complementary to that in **Element 2**.

Element 2 is identical in geometry to **Element 1**, with the same dimensions ($l_{x1} = l_{x2}$, $h_1 = h_2$, $s_1 = s_2$) and has slotted holes on both sides. On the upper side, there are two series of slotted holes (labeled slotted holes 1 and 2 in Figure 3) with the same dimensions as those in **Element 1**. Slotted holes 1 are located at a distance d_{x1} , while slotted holes 2 are located at d_{x2} . On the vertical side of the element, two "U" shaped holes (slotted holes 3) are realized d_{x4} distant.

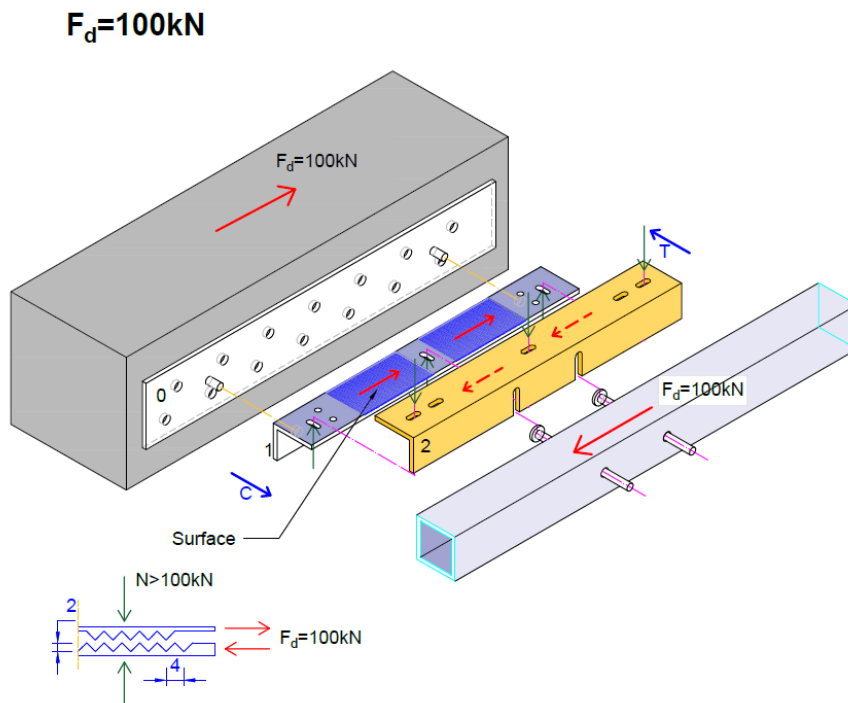
In the case of nonlinear connection, **Element 3** is introduced. **Element 3** is a dissipative device recently developed, which exploits the energy dissipated by the yielding of steel plates (see the “Adesa Fuse” in Marini Et al. 2015, Zanni et al. 2021). Pre-shaped steel plates are inserted into the pre-cut slots in the connecting plates and subsequently welded to these elements; this way is possible to calibrate the connection global resistance and stiffness by varying the number of steel plates or by modifying their sectional properties.

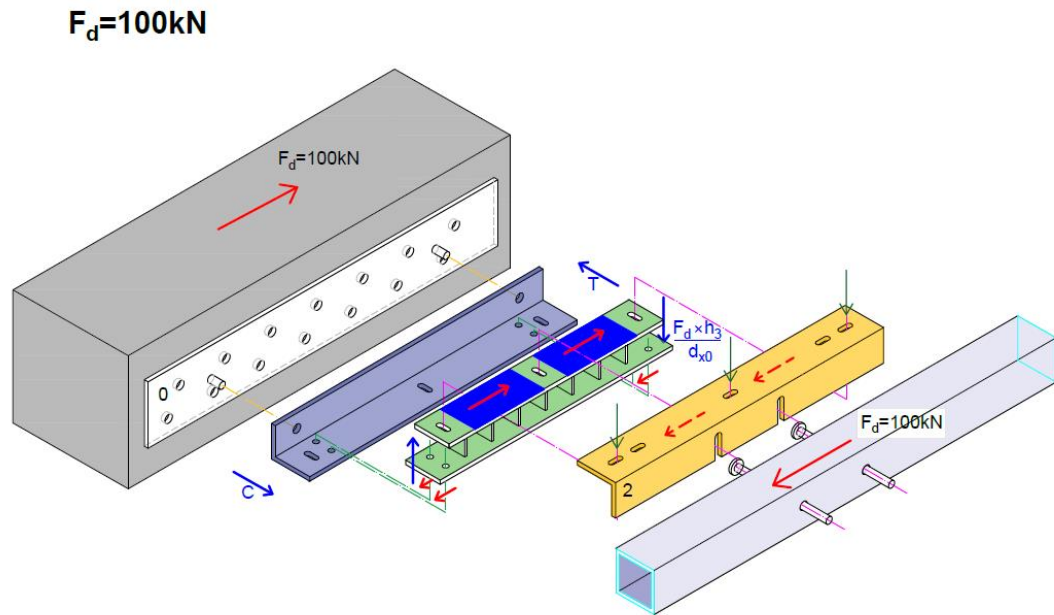
3.1. Conceptual design

- Elastic connections

The connection system is designed to transfer the inertia forces from the existing building to the exoskeleton, as shown in Figure 4a. Through the studs in the steel plate, and two cl. 10.9 M20 ($V_{rd}=98\text{kN}$ each), inertia forces are transferred from the existing building to **Element 1**. The shear actions are transferred thanks to the knurling surface on **Element 1** and its complementary surface on **Element 2**. To be effective, the vertical bolts between **Element 1** and **2** (three cl. 10.9 M12 bolt – $F_{r,t}=60\text{kN}$ each) must be tightened to a force (N) equal to the design force ($F_d=100\text{kN}$) times a safety factor of 1.5. From **Element 2** to the exoskeleton, forces are transferred by means of two cl. 10.9 M16 bolt ($V_{rd}=63\text{kN}$ each).

It is worth mentioning that additional forces arise due to the eccentricity between the applied load and the resisting force. Such forces are resisted, for example, by introducing two additional bolts placed in the columns of the steel bracing wall. It is worth noting that the bolts used to transfer the shear forces can withstand also the forces arisen from the eccentricity; however, decoupling of the soliciting actions was set as a design choice.





a)

Figure 4. Conceptual design of the connection system: a) elastic, b) nonlinear.

- Nonlinear connections

Similarly, to the elastic connection, in the nonlinear connection, forces are transferred from the existing building to **Element 1** (which, in this case, is rotated by 180°, Figure 3). Through four cl. 10.9 M16 ($V_{rd}=62.8\text{kN}$), forces are transferred by **Element 1** to the dissipative device which, thanks to the knurling surfaces on **Element 3** and its complementary on **Element 2** the shear actions are transferred.

The dissipative device elastic stiffness and strength can be calibrated to the required design performances. The initial elastic stiffness of the vertical plates can be preliminary defined by assuming their end sections as fixed while their resistance can be modulated by locally reducing the resistant section, or the number of vertical plates. To effectively control the maximum force transferred by the dissipative device, the vertical plate cross-section may be notched at specific heights to force localization of the plastic hinge development (Zanni et al. 2021).

It is worth noting that in this case additional shear action must be resisted by the existing RC chord due to the vertical eccentricity between the applied forces; the additional shear force is proportional to the dissipative device height and inversely proportional to d_{x0} .

3.2. Construction stage

Design for easy assemblage/disassemblage – Dry assembly, on-site construction tolerance management.

The connection assemblage encompasses an ordered series of steps (Figure 5).

- **Step 0:** Connecting **Element 0** to the existing RC chord. **Element 0** must be placed horizontally where the bracing wall will be located. Pre-holes are at least double than those required for transferring the shear loads; holes are shifted by $+\Delta x$ (Figure 3) to account for the presence of stirrups in the RC chord which may inhibit drilling operation and insertion of the steel $\Phi 20$ studs at certain locations.
- **Step 1:** **Element 1** is connected to **Element 0** with bolt and nut. It is worth noting that the bolts are long enough to accommodate **Element 1** (10mm) and the nut thicknesses (16mm for an M20).
- **Step 2:** the exoskeleton (**EX**) is placed. In the horizontal element of the exoskeleton two cl. 10.9 M16 bolts are already introduced.

- **Step 3: Element 2** positioning. At this step, tolerances in both x and y directions are allowed thanks to the slotted holes 1. It is worth noting that the knurling surfaces are larger than required to transfer the envisioned actions; even the minimum superposition of the surfaces (according to the tolerances allowed by the slots) would be enough to transfer the design load.
- **Step 4: Element 2** and the **Exoskeleton** are brought into contact. It is worth noting that at this step bolts must not be tightened since friction between **2** and **EX** must be minimized.
- **Step 5:** Once all components are placed bolts and nuts that connect **Element 1** and **2** must be tightened up to a force (N) equal to the design force (100kN - 45° angles of knurling) times a safety factor equal to 1.5.

Similarly, the nonlinear connection can be assembled (Figure 6). In this case, **Element 1** is rotated by 180° around the y-axis (Figure 3) to host the dissipative device (**Element 3**), which is bolted by means of four cl. 10.9 M16 (Step 2 in Figure 6). Consequently, Steps 3, 4, and 5 of the elastic case became Steps 4, 5, and 6 in the case of nonlinear connections (Figure 6). As for the last Step, **Element 2** and **Element 3** are connected by means of bolts placed in the slotted holes 2 (instead of 1 as shown for the elastic case).

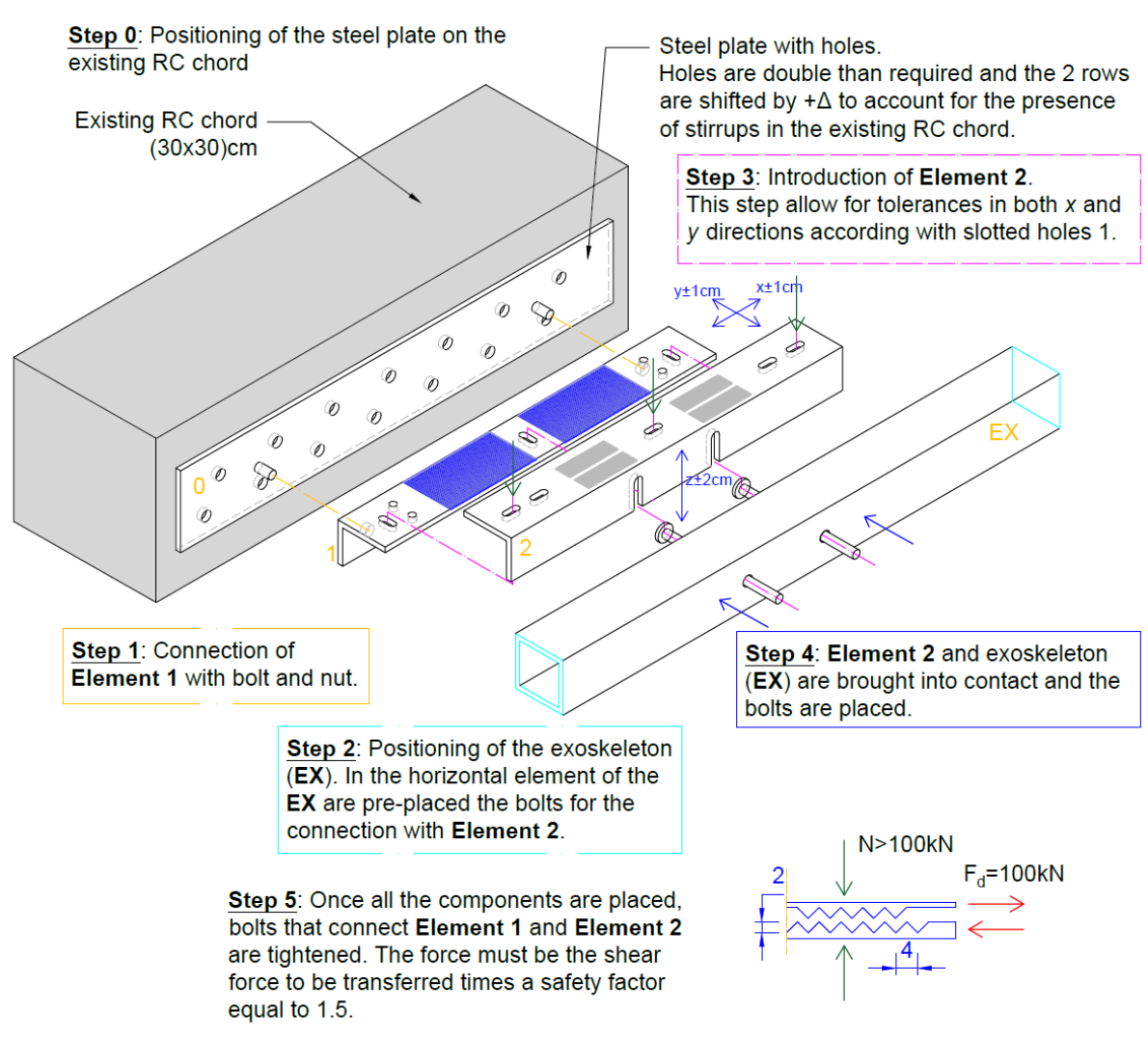


Figure 5. Construction stage for the elastic connection.

3.3. Use stage

Design for reparability/easy disassembly & Adaptability – Dry assembly, lump damage, modularity.

Unlike elastic connections which remain elastic in each load condition, in nonlinear connections damage is localized into specific elements to enable fast dismantling and repair/replacement after a major seismic event, thereby speeding the restore of the initial undamaged conditions.

During a seismic event, damages are localized in the dissipative devices which must be conceived as the weak link of the connection system and designed to have a lower yielding force lower than the other components. After an earthquake, being all these elements dry assembled, **Element 2** could be temporarily removed, and **Element 3** substituted.

To give another example, in some cases, it may be required to limit the forces transferred between the exoskeleton and the existing building; consequently, a low-yielding force of the dissipative devices could be set; yet it may be required to increase such a force after some time (e.g., after possible floor diaphragm strengthening). Thanks to the modularity of the system, **Element 3** can be replaced with another characterized by higher stiffness and strength.

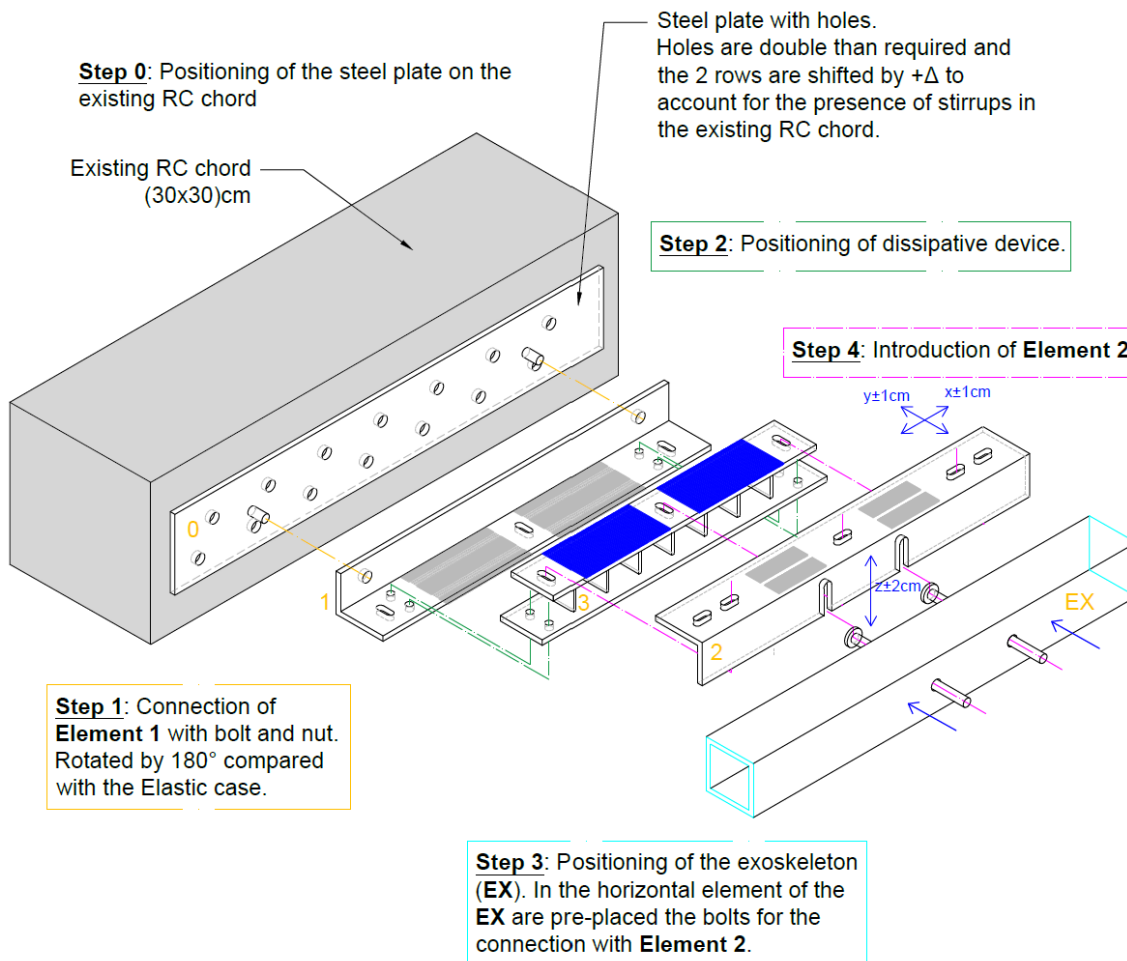


Figure 6. Construction stage for the nonlinear connection.

3.4. End-of-life stage

Design for reuse – Dry assembly, standardization, modularity.

When dry assembled with steel components, recycling the connection components is easy, as long as easy disassembly is guaranteed. However, the author believes that reuse should be the primary focus.

It is important to disassemble the connection components and reuse them once the building has reached the end of its life. For instance, the same components can be used to connect wood panels, as shown in Figure 7. By adding extra holes, **Element 1** and **2** can be nailed to the wood panels, connecting them to each other and to the existing building RC chord. However, this aspect requires further discussion which is postponed to future research.

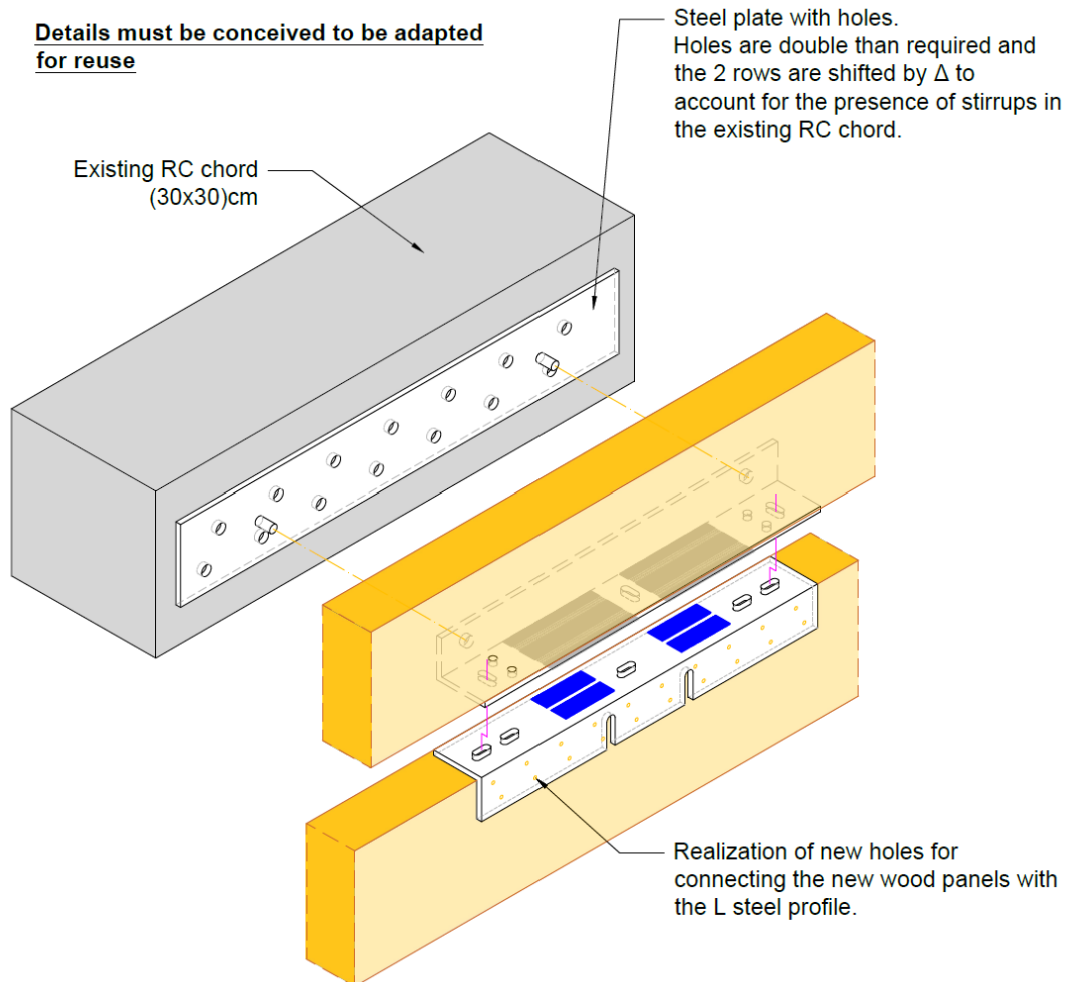


Figure 7. End-of-life stage: deconstruction, recycling, and reuse.

4. Discussion

This paper is an attempt to shift from a traditional design approach to a Life Cycle Structural Engineering approach in the conceptual design of exoskeleton to existing building connection. Among mandatory objectives such as safety, the connection should be easy to implement, account for on-site construction tolerances, be flexible, and reusable at the end of life.

An example of a standardized connection was proposed in this paper, and the main design steps were described. The connection system is made of steel prefabricated and modular components, is dry assembled, and allows easy management of on-site construction tolerances.

Further studies are needed to investigate the effectiveness of the connections particularly, attention must be paid to the additional forces that arise from the inherent eccentricity of the system. Future developments include finite element modeling and the development of a prototype to be tested.

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