

D13.3 End-user oriented guidelines for holistic retrofit



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1 Introduction

1.1 MULTICARE project

The built environment is ill-prepared for more frequent and increasingly intense climate-related extreme events. The current building stock is particularly vulnerable because it has limited or no capacity to adapt and recover from extreme events thereby leading to building failures that cause severe socio-economic losses and adversely affecting the health and wellbeing of people. Recent scientific and technological advances in the construction industry provide timely solutions for improving the resilience for specific single hazards (e.g. flood hazard or seismic hazard), but they are often not cost effective, rarely eco-friendly and nearly never address the multiple hazards present in many locations. This is hardly surprising because there is neither a clearly defined framework for quantifying the whole-life socio-economic-environmental impacts of extreme natural events nor tools for assessing the holistic climate resilience of buildings. Consequently, it is currently very challenging to develop/select optimal solutions for real-world multi-hazard scenarios.

MULTICARE will address this challenge directly by developing new multi-criteria decision-support frameworks and providing plug & play technological and digital solutions for improving the resilience of the built environment in a cost-effective, reliable and sustainable manner. The technological solutions consist of multi-functional low-carbon resilient technologies embedded in modular and prefabricated construction for the next generation of high performance and smart buildings, characterized by enhanced safety, energy efficiency, environmental-sustainability, improved quality of life, circularity, and scalability for a broad range of natural events and end-user. The plug & play technologies will be applied to either new multi-story buildings or existing structures by means of low-invasive external interventions. The digital solutions consist of a suite of multi-disciplinary digital services and tools for performing multi-hazard resilience assessment, design, operation and management across multiple scales (material, component, building, neighborhood/city). The new digital tools will enable stakeholders to make informed decisions in the selection of materials/solutions, including for heritage buildings, and support resilient supply chains. The effectiveness of the MULTICARE solutions will be demonstrated through large-scale pilots (3 buildings, 4 neighborhoods/district) in three different European countries carefully selected for their diverse local environmental, social and economic conditions (Italy, Netherlands, Romania). Banks and institutional investors will be engaged to better understand the financial risk reduction value of resilience and update existing and future “green finance” mechanisms that will help to leverage the project results. A user-center, inclusive and participatory approach will be consistently implemented throughout the project to engage citizens and extend the durability of MULTICARE impact.

To achieve these ambitious goals, MULTICARE brings together a unique interdisciplinary Consortium of 21 partners (Table 1) from 6 different EU countries with strong R&D and practical expertise, who are either established leaders in their sector or agile SMEs in emerging fields. Altogether, the Consortium members span across the whole technical and

value chain required for developing and implementing solutions in terms of design, digitization, manufacturing, construction and monitoring of resilient and sustainable buildings. The Consortium also includes partners with experience in social sciences, user engagement, and training to ensure the success and widespread application of new technologies in local communities. The Consortium will also support clustering activities with other relevant research projects to share knowledge and raise public awareness of building resilience. An international outreach and cooperation strategy will also be implemented to tackle the project challenges.

Table 1. Consortium

Number	Role	Short Name	Legal Name	Country
1	CO	TU Delft	TECHNISCHE UNIVERSITEIT DELFT	NL
2	BEN	PFE	PRIEDEMANN FASSADENBERATUNG GMBH	DE
3	BEN	IES R&D	IES R&D	IE
4	BEN	INCDFP	INSTITUTUL NATIONAL DE CERCETARE-DEZVOLTARE PENTRU FIZICA PAMANTULUI	RO
5	BEN	UNIROMA1	UNIVERSITA DEGLI STUDI DI ROMA LA SAPIENZA	IT
6	BEN	XLD	X-LAM DOLOMITI SRL	IT
7	BEN	STRESS	SVILUPPO TECNOLOGIE E RICERCA PER L'EDILIZIA SISMICAMENTE SICURA ED ECOSOSTENIBILE SCARL	IT
7.1	AE	UNINA	UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II	IT
8	BEN	AMS Institute	STICHTING AMSTERDAM INSTITUTE FORADVANCED METROPOLITAN SOLUTIONS(AMS)	NL
9	BEN	PMB	MUNICIPIUL BUCURESTI	RO
10	BEN	ASM	ASM - CENTRUM BADAN I ANALIZ RYNKUSPOLKA Z OGRANICZONA ODPOWIEDZIALNOSCIA	PL
11	BEN	RoGBC	ASOCIATIA ROMANIA GREEN BUILDING COUNCIL	RO
12	BEN	RINA-C	RINA CONSULTING SPA	IT
13	BEN	UTBV	UNIVERSITATEA TRANSILVANIA DIN BRASOV	RO
14	BEN	ACER	AGENZIA CAMPANA PER L EDILIZIA RESIDENZIALE	IT
15	BEN	Boom	BOOM BUILDS B.V.	NL
16	BEN	OMRT	OMRT BV	NL
17	BEN	ROTHO BLAAS SRL	ROTHO BLAAS SRL	IT
18	BEN	ARUP	ARUP BV	NL
19	BEN	Tecuci	MUNICIPIUL TECUCI	RO
20	BEN	Hölscher	DIPL.-ING. HPLSCHER GMBH & CO.KG	DE

1.2 Deliverable

As per Grant Agreement (Table 2), deliverable 12.4 will provide guidelines for implementing the proposed exoskeletons. It includes structural details for the load-bearing and connection systems and connection details for the building envelope. Moreover, it discusses possible strategies and techniques for flood risk mitigation, in view of a multi-hazard retrofit solution.

Table 2. Key deliverable information. Source: MULTICARE Grant Agreement.

Deliverable number and name	Work Package n°	Lead Beneficiary	Type
D13.3 – End-user oriented guidelines for holistic retrofit	WP13	5 – UNIROMA1	R – Document, report

2 The need for a holistic retrofit approach

Recent international sustainability requirements (e.g., Directive EU 2018/844, 2018) have further emphasized the need to enhance the energy efficiency of the existing building stock. The construction sector has been estimated as responsible for about 36% of total final energy use and 37% of energy-related CO₂ emissions (IEA, 2021; Figure 1). Reducing the environmental impact of buildings is therefore deemed a priority challenge, closely linked to the transition towards carbon neutrality and sustainable societies. Within this framework, the European Green Deal (EC, 2019) sets the ambitious target of making Europe the first climate-neutral continent by 2050. To reach this objective, the EU Member States must achieve by 2030 a reduction of at least 55% in both CO₂ emissions and energy consumption with respect to 1990 levels.

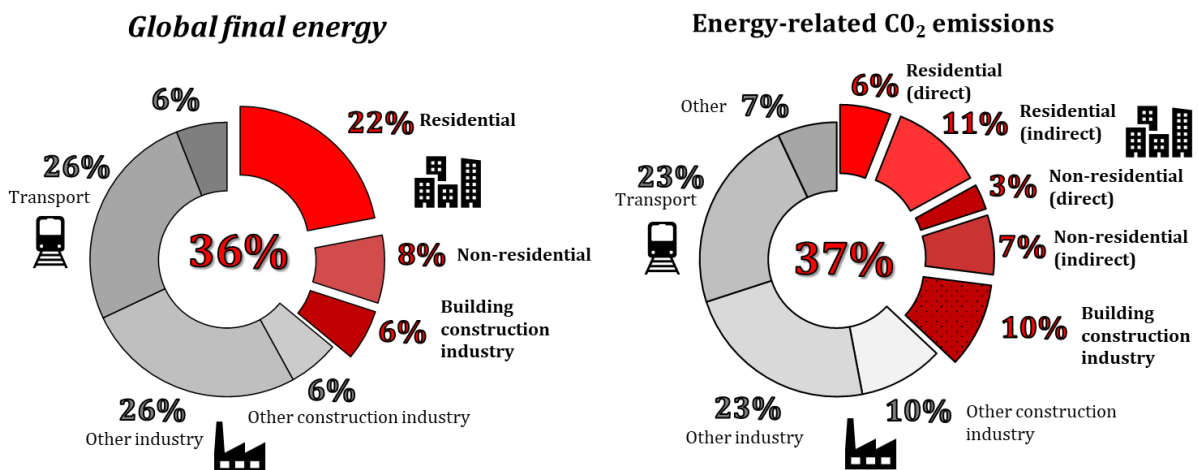


Figure 1. The environmental impact of the construction sector in terms of global final energy and energy-related CO₂ emissions (data source: IEA, 2021)

Moreover, in seismic-prone areas, focusing exclusively on energy efficiency is insufficient to ensure a resilient and resource-efficient built environment (e.g., Bianchi et al., 2022). To help the discussion, reinforced concrete (RC) frame buildings with masonry infills can be taken as a reference case. This construction typology is representative of a substantial portion of the building stock in Europe and the Mediterranean regions, and it will be the focus of this document. In these structures, RC elements such as beams, columns, and shear walls are

the primary load-bearing system, while masonry infills are generally considered as “non-structural” components and are designed mainly to ensure envelope-related functions (e.g., thermal and acoustic insulation). However, it is nowadays widely recognized that infills and the surrounding RC frames can have a strong interaction during seismic events. This infill-frame interaction can lead to significant damage to facade elements even during low-to-moderate earthquakes. Clearly, damage to infilled facades may also compromise the effectiveness of recently implemented energy retrofitting interventions, such as External Thermal Insulation Composite Systems (ETICS; Figure 2). For this reason, numerous works in the literature have highlighted the importance of adopting an integrated strategy for addressing both energy efficiency and seismic safety within a unified multi-performance framework/approach (Calvi et al., 2016; Belleri and Marini, 2016; Marini et al., 2017; Buornas, 2018; Di Vece and Pampanin, 2019; Menna et al., 2022; Bianchi et al., 2022; Pampanin, 2022; Clemett et al., 2023, Pedone et al., 2023, D’Amore et al., 2024; D’Amore, 2024; Sebastiani et al., 2024).



Figure 2. Example of observed damage to masonry infills and external thermal insulation (a: from Santarsiero et al., 2016; b: available online: <http://www.reluis.it/images/stories/webinar-23-11-20/Prota-daPorto.pdf>).

From a structural point of view, two main approaches are generally adopted for the seismic retrofit of reinforced concrete (RC) frame structures. The first consists of local interventions, aimed at improving the performance of individual members, such as beams, columns, or joints, and ensuring a desirable hierarchy of strength at the beam-column-joint subassembly level (e.g., Pampanin 2017). Possible solutions include fiber-reinforced polymer (FRP) jacketing (e.g., Akguzel and Pampanin 2012; Del Vecchio et al., 2014), concrete jacketing (e.g., Lizundia et al., 2006), the use of diagonal haunches (e.g., Pampanin et al., 2006), or selective weakening strategies (e.g., Kam and Pampanin, 2009). The second option is based on global interventions, intending to control the displacement demands through the addition of new lateral-load resisting systems, such as RC shear walls (e.g., Marriott et al., 2007), steel bracing systems (e.g., Rad et al., 2019), or exoskeleton structures (e.g., D’Amore and Pampanin 2021, 2025; Passoni et al. 2021; D’Amore et al., 2023, 2024; D’Amore, 2024).

In line with the above discussion, the role of non-structural components - and in particular of masonry infills in RC frame structures - must also be carefully considered. To mitigate the negative effects due to infill-to-frame seismic interaction, available retrofit strategies

are based on either decoupling techniques (e.g., Tasligedik and Pampanin, 2017; Preti and Bolis, 2017; Morandi et al., 2018; Tsantilis and Triantafillou, 2018; Marinković and Butenweg, 2022) or strengthening techniques (e.g., Facconi and Minelli, 2020; Bournas 2018).

By combining these strategies for both structural and non-structural components with common energy-efficiency measures (Figure 3), various combined seismic-and-energy retrofitting solutions can be defined (e.g., Di Vece and Pampanin 2019; Menna et al. 2022; Pedone et al., 2023).

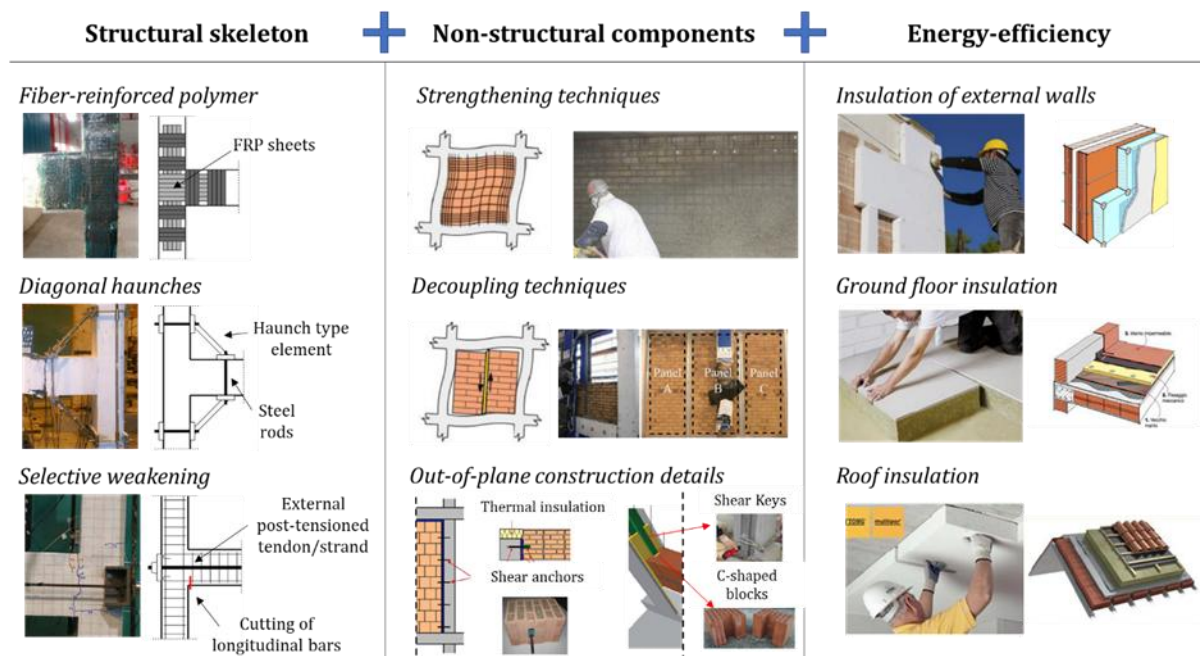


Figure 3. Examples of possible combined seismic-and-energy retrofitting solutions (from Pedone et al., 2023; structural skeleton: adapted from Kam and Pampanin 2009; Pampanin et al., 2006; non-structural components: adapted from Bournas et al. 2018; Di Vece and Pampanin, 2019; Tasligedik and Pampanin, 2017; Marinković and Butenweg, 2022; Morandi et al., 2018).

In this context, exoskeleton-based solutions have recently attracted growing interest in the integrated seismic, energy, and architectural refurbishment of existing buildings. This retrofitting strategy offers significant advantages from a life-cycle perspective, including standardization, disassembly, reparability, and potential reuse (e.g., Marini et al., 2017). Additional benefits include the possibility of performing the intervention entirely from the outside — thus minimizing disruption to occupants — and the opportunity to implement a multifunctional double-skin envelope, supported by the exoskeleton, that simultaneously addresses seismic, energy, and architectural performance.

By combining advanced low-damage technologies in eco-friendly materials for both structural and non-structural components with high-performance facade systems, the MULTICARE exoskeleton solution is intended to provide an effective and sustainable approach for the refurbishment of existing buildings. Further details on the proposed solution, along with practical guidance for its proper installation, are provided in the following sections.

3 The MULTICARE exoskeleton solution

The proposed exoskeleton solution is schematically illustrated in Figure 4, with reference to an existing RC building. Typically, the implementation of the proposed technology requires the following steps:

1. Replacement of outdated windows (if needed);
2. Implementation of a decoupling solution for infill walls;
3. Insulation of horizontal opaque surfaces;
4. Implementation of the low-damage exoskeleton (structural components);
5. Insulation of the vertical opaque surfaces through double-skin facade systems (supported by the exoskeleton's structural components)

Each step is discussed in more detail in the next sub-sections. Moreover, the last section will provide further insights for flood risk reduction strategies and techniques at building level, in view of a multi-hazard retrofit solution.

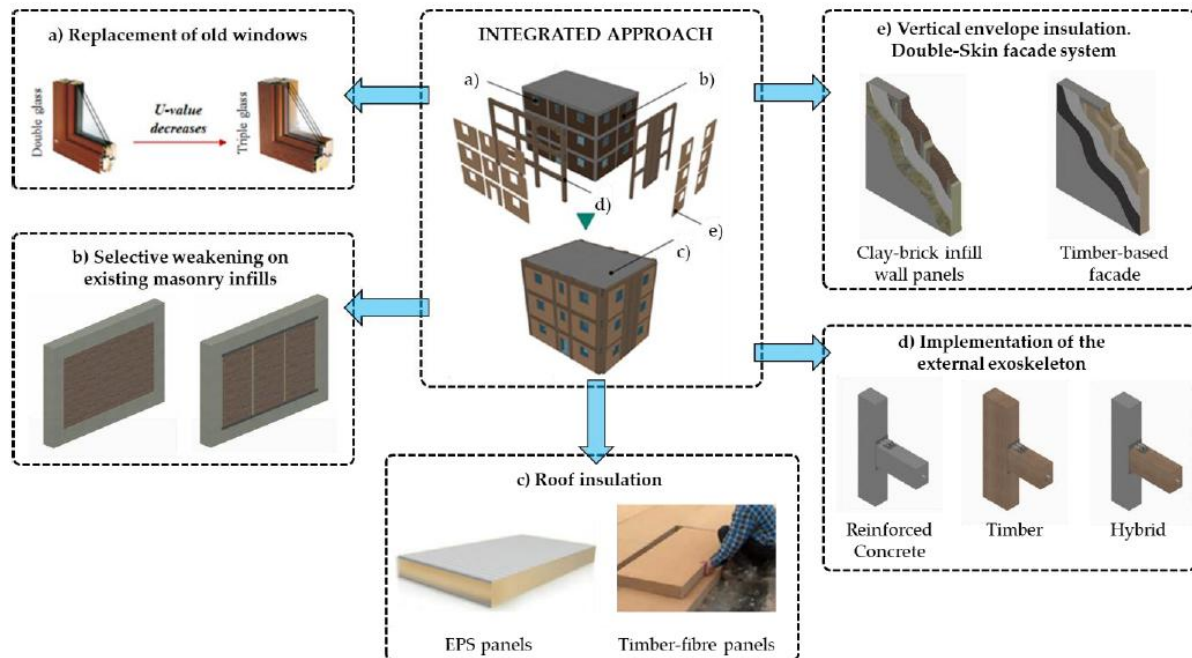


Figure 4. Integrated intervention based on the implementation of the MULTICARE exoskeleton (after D'Amore, 2024).

3.1 Replacement of outdated windows

Whenever necessary, the first step involves replacing outdated windows with new, high-energy-performance ones. The energy performance of glazed surfaces strongly affects a building's energy consumption; thus, particular attention must be paid to this component.

As an example, Figure 5 shows typical types of glazed components in existing Italian buildings. Common frame materials include aluminum, wood, and PVC, while single or double glazing is typically used.



Figure 5. Example of typical transparent vertical components with different types of window frames and single or double glazing.

An important parameter to evaluate the energy performance of transparent components is the thermal transmittance, referred to as U-value. The latter measures the heat flow through a surface (either opaque or transparent) per unit area and per degree of temperature difference between indoors and outdoors (i.e., the lower the U-value, the better the insulation performance of the building component).

In the case of glazed systems, the U-value is typically evaluated considering the characteristics of both the frame and the glass. To have an idea of U-values of glazed systems typically observed in existing buildings in Europe, the results of the TABULA (Typology Approach for Building stock Energy Assessment; Loga et al. 2010) research project can be considered. As an example, Figure 6 shows the expected U-value for the glazing systems of an existing building archetype in Italy. More specifically, the TUBULA webtool (<https://webtool.building-typology.eu/#bd>) is used to obtain the information, considering for the archetype a multi-family house located in a “Middle Climatic Zone” (Italian Climatic Zone “E”) and with construction period 1961-1975. It can be noted that the

resulting U-Value is equal to $4.90 \text{ W}/(\text{m}^2 \text{ K})$, which represents a poor energy performance if compared to the standard for new constructions (Table 3).

Window 1	surface area	97.2m ²
	type of construction / refurbishment measure	Single glass, wood frame Vetro singolo, telaio in legno
	picture	
	U-value	4.90 W/(m ² K)

Figure 6. Example of a typical grazing system in an existing RC building (from TABULA webtool: <https://webtool.building-typology.eu/#bd>).

The replacement of outdated windows with new ones must follow the requirements in terms of imposed U-values, depending on the building location. In Italy, the DM 26/06 (2015) defines the maximum U-values for glazed systems depending on the Italian climate zone, as reported in Table 3. Specifically, the whole Italian territory is subdivided into 6 different climatic zones (from “Zone A” to “Zone F”; DPR 412, 1993), based on specific ranges of heating degree days (HDD).

Table 3. Maximum thermal transmittance (U-value) of transparent elements (after DM 26/06; 2015)

Italian climate zone	Heating degree days (HDD)	$U \left[\frac{W}{(\text{m}^2 \text{ K})} \right]$
A	$HDD \leq 600$	3.00
B	$600 < HDD \leq 900$	3.00
C	$900 < HDD \leq 1400$	2.00
D	$1400 < HDD \leq 2100$	1.80
E	$2100 < HDD \leq 3000$	1.40
F	$HDD > 3000$	1.00

To match the required U-values, the use of high-performance windows with a thermal break is suggested. This typology of windows is designed to minimize heat transfer between the interior and exterior environments. They consist of frames with an insulating barrier (thermal break) between the inner and outer parts, which significantly reduces thermal bridging. Combined with low-emissivity glazing and efficient sealing, these windows provide improved energy efficiency, thermal comfort, and condensation control.

Figure 7 provides an example of high-energy-performance windows with a thermal break. Recent research by Pedone et al. (2023) on existing schools in Italy has further highlighted that glazed facade components may represent a weakness in the building envelope. Moreover, the authors emphasized that implementing an energy refurbishment intervention on glazed components alone could be very effective in many cases. However, in line with the philosophy of a holistic retrofit approach, they also stressed the importance

of not limiting refurbishment to energy aspects only, but extending the intervention to structural/seismic safety considerations as well.

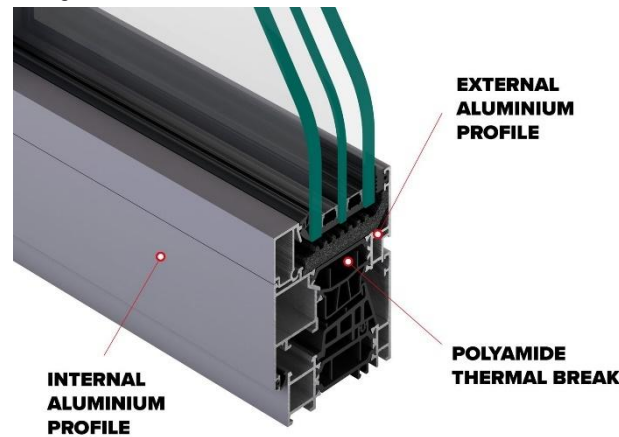


Figure 7. Example of high-energy-performance window with thermal break (available online: <https://www.metrabuilding.com/en/blog/thermal-break-aluminium-windows-doors-what-they-are/>)

3.2 Selective weakening of existing masonry infills

To achieve the objective of a holistic seismic-energy-architectural requalification of existing buildings, it is deemed fundamental to pay particular attention to the seismic performance of existing “non-structural” facade components. As previously mentioned in Section 2, damage to these components due to seismic infill-to-frame interaction can lead to a loss of functionality of energy refurbishment interventions, such as external thermal insulation systems.

In the case of seismic loading, partial detachment between masonry infill panels and the surrounding frame occurs. This leads to a concentration of compression at the diagonally opposite corners, resulting in the formation of a diagonal compression strut load path mechanism (Zamic and Tomazevic, 1984). Figure 8a conceptually shows this concept, while Figure 8b provides an example of results in terms of displacement incompatibility through a Finite Element Method (FEM) simulation.

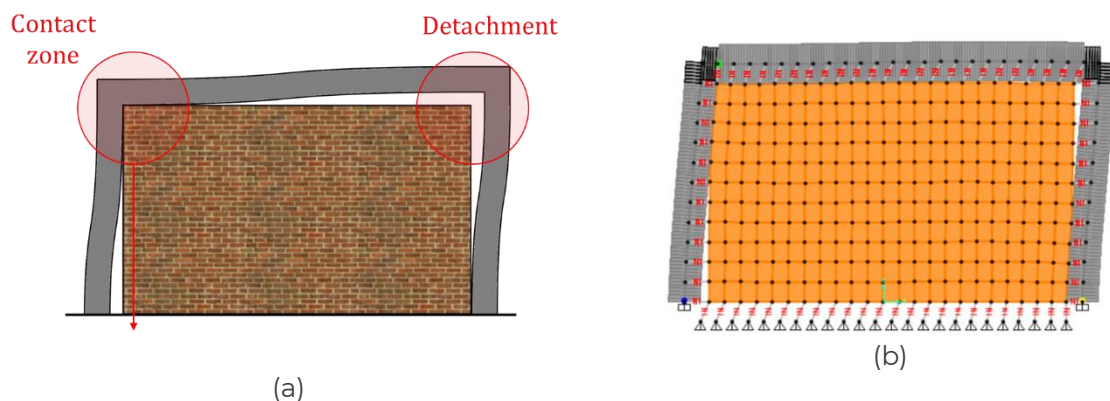


Figure 8. Infill-to-frame interaction during seismic shaking: (a) schematic illustration with indication of the contact and detachment zones; (b) example of numerical (software-based) results in terms of infill-frame displacement incompatibility (after Pedone and Pampanin, 2023).

To enhance the seismic performance of existing masonry infills, it is proposed to protect these components by “disconnecting” them from the surrounding RC frame. This type of intervention is commonly referred to as the “decoupling technique” (e.g., Tasligedik and Pampanin, 2017; Preti and Bolis, 2017; Tsantilis and Triantafillou, 2018; Morandi et al., 2018; Marinković and Butenweg, 2022). A possible practical solution consists of making vertical and horizontal cuts to create a gap between the infill and the frame (e.g., Marinković and Butenweg, 2022). The main objective is to avoid direct contact between the two elements and, consequently, to reduce their seismic interaction. The resulting gap is typically filled with elastomeric materials, which should exhibit low stiffness while at the same time ensuring adequate thermal and acoustic performance. An example of this solution is shown in Figure 9.

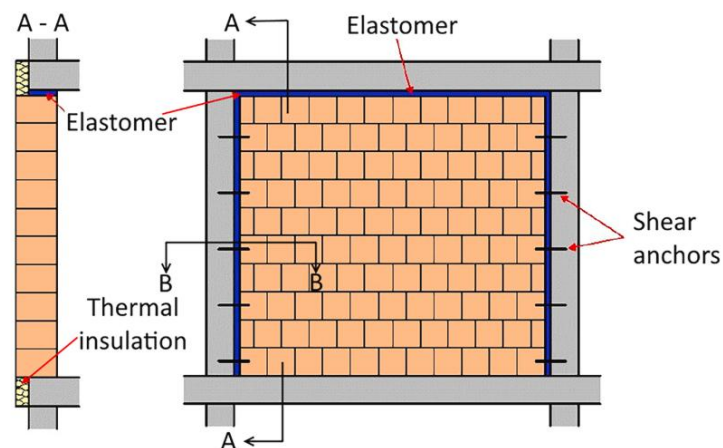


Figure 9. Schematic illustration of a decoupling technique for masonry infill walls (after Marinković and Butenweg, 2022).

Alternatively, it is possible to modify the monolithic behaviour of the infill walls and transform it into a series of discrete rocking panels (Figure 10). In this configuration, clay brick infills are able to accommodate significant drift levels before damage occurs. The effectiveness of this strategy was verified through quasi-static cyclic tests performed at the University of Canterbury (Tasligedik & Pampanin, 2017).

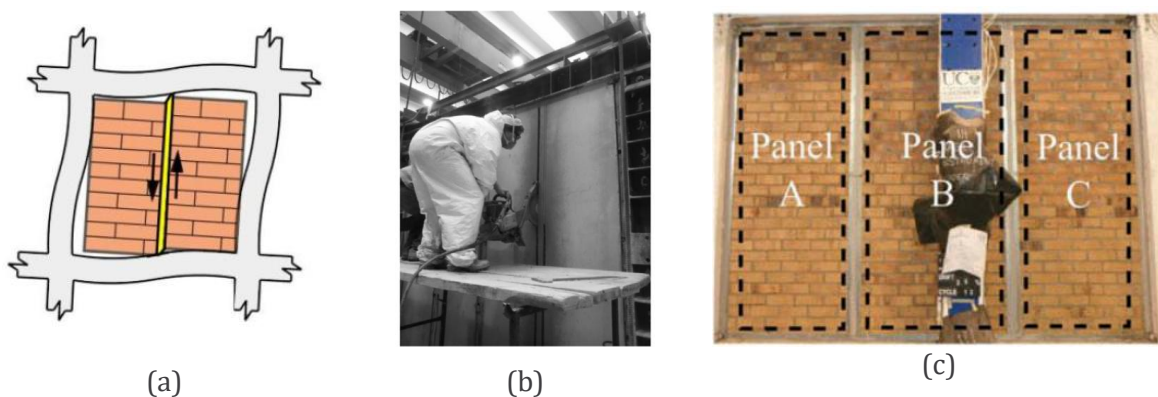


Figure 10. Decoupling technique based on vertical sliding joints for the infill panels: (a) concept; (b) infill cut operation (from Preti and Bolis, 2017); (c) example of final result (from Tasligedik and Pampanin, 2017).

An important advantage of this retrofitting technique is the possibility of implementing the intervention entirely from outside the building, thus minimizing disruption for occupants. This aspect was investigated by Preti and Bolis (2017), who tested masonry infill walls with vertical gaps similar to those adopted by Tasligedik and Pampanin (2017). In their approach, the infill-frame decoupling was obtained by performing cuts from one side only (Figure 10b).

In the case of a decoupling retrofit technique, it is critical to prevent out-of-plane failure mechanisms of the infill. For this reason, this retrofitting strategy also requires the installation of steel plates or shear anchors, possibly anchored to the beams above and below the infill wall (Figure 11). For the design of these improved construction details the concept of displacement incompatibility shape functions between masonry infill wall panels and reinforced concrete frame can be adopted, as suggested by Pedone and Pampanin (2023). Moreover, again, the gaps generated by the cuts must be filled with suitable materials, such as expanded polyurethane, to guarantee weather tightness and mitigate the formation of thermal bridges (Figure 11).

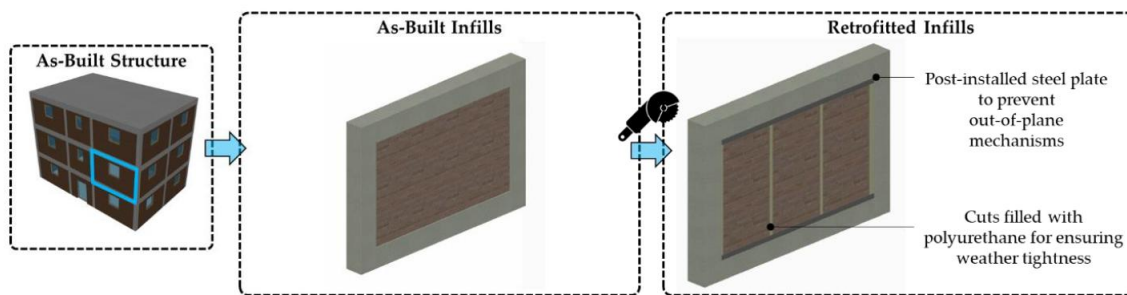


Figure 11. Decoupling technique for the existing masonry infills from the surrounding structural frames.

Finally, it is recommended to implement this intervention in combination with the replacement of outdated windows (Section 32), as this can minimize both the installation time and the costs associated with the operation.

3.3 Roof insulation

Proper roof insulation plays a key role in reducing the energy consumption of buildings. The roof is one of the most exposed components of the building envelope, and improving its thermal properties is essential to enhance energy efficiency, ensure indoor comfort, and reduce energy costs.

In line with the discussion on transparent components (section 3.1), the TABULA webtool (<https://webtool.building-typology.eu/#bd>) can be used to estimate the expected U-values of common horizontal opaque surfaces in existing buildings in Europe. As an example, Figure 12 shows the expected U-value for a multi-family house archetype in Italy located in a “Middle Climatic Zone” (Italian Climatic Zone “E”) and with a construction period 1961-1975. Again, it can be noted that the resulting U-Value is equal to 1.10 W/(m² K), deemed as representative of a poor energy performance when compared to the standard for new constructions (Table 4).


		Existing state
Roof 2	surface area	186.7m ²
	type of construction / refurbishment measure	Ceiling with reinforced brick-concrete slab Solaio latero-cementizio
	picture	
	U-value	1.10 W/(m ² K)

Figure 12. Example of a typical horizontal opaque surface in an existing RC building (from TABULA webtool: <https://webtool.building-typology.eu/#bd>).

As for the glazed components, the energy retrofit strategy consists of reducing the thermal transmittance of the roof in order to match the requirement of the building code. As an example, Table 4 lists the maximum allowed thermal transmittance (U-value) for horizontal opaque roof elements in Italy (DM 26/06; 2015).

Table 4. Maximum thermal transmittance (U-value) of horizontal opaque roof elements (after DM 26/06; 2015)

Italian climate zone	Heating degree days (HDD)	$U \left[\frac{W}{(m^2 K)} \right]$
A	$HDD \leq 600$	0.32
B	$600 < HDD \leq 900$	0.32
C	$900 < HDD \leq 1400$	0.32
D	$1400 < HDD \leq 2100$	0.26
E	$2100 < HDD \leq 3000$	0.24
F	$HDD > 3000$	0.22

Different techniques can be adopted to improve the energy performance of the roof. A possible option, commonly adopted, consists of using EPS (Expanded Sintered Polystyrene) panels for flat roofs. However, alternative eco-friendly materials can also be used (and are suggested) for roof insulation, such as timber-fibre insulation panels.



Figure 13. Roof insulation: (a) timber-fibre insulation panels and (b) example of in-situ installation (images available online: <https://www.betonwood.com/>).

3.4. Implementation of the exoskeleton

In the proposed holistic retrofit, the seismic safety of existing buildings is enhanced through the implementation of an exoskeleton. This strategy aims to increase the stiffness and strength of the existing structure by adding additional load-bearing systems, either in the form of frames or walls. However, differently from traditional solutions, the MULTICARE exoskeleton system is characterized by the use of low-damage solutions made of eco-friendly materials. Further details on the adopted low-damage technology and its possible use for retrofitting applications are given in the next sub-sections.

3.4.1. Low-damage technologies

The adopted low-damage technology is the PREcast Seismic Structural System, referred to as PRESSS (Priestley, 1991; Stanton et al., 1997; Priestley et al., 1999). The system was originally developed for precast concrete structures and is based on “jointed ductile” concepts with dry connections. The PRESSS technology was developed during an extensive research program conducted in the 1990s at the University of California, San Diego (UCSD), under the leadership of Professor Nigel Priestley as part of the US PRESSS program. The research effort culminated in a large-scale pseudo-dynamic test on a five-story prototype building (Figure 14a).

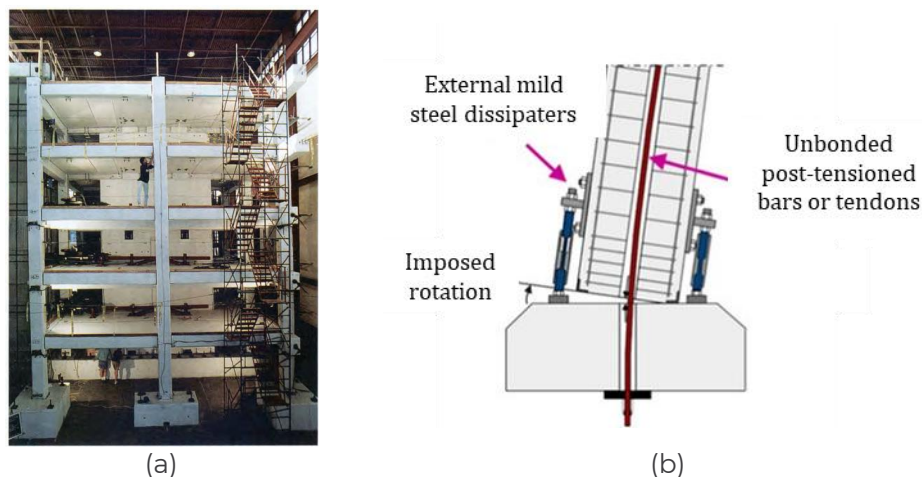


Figure 14. (a) The 5-storey large-scale low-damage specimen tested at the University of California, San Diego (Priestley et al., 1999); concept of a low-damage column-to-foundation connection with a controlled “rocking and dissipative” mechanism (after Marriot et al., 2008).

A key benefit of these innovative connections is the development of a controlled “rocking and dissipative” mechanism at the interfaces between structural elements - such as beam-to-column, column-to-foundation, and wall-to-foundation joints - which replaces the formation of traditional plastic hinges (Figure 14b). This way, the system can sustain large displacement demands without any substantial structural damage. The PRESSS technology relies on two main types of reinforcement (Figure 14b). The first consists of unbonded post-tensioned tendons or bars, which are designed to remain elastic during seismic shaking. Their role is to enable the re-centering capacity of the system, thus minimizing the residual displacement at the end of the seismic event. The second reinforcement involves energy dissipation devices. The latter consists of external fuse-type “Plug-&-Play” dissipaters, easily replaceable after the seismic event (Pampanin, 2005; Sarti et al., 2016).

The high versatility of the post-tensioned “rocking and dissipative” connection concept has also led to the development of alternative solutions based on other construction materials. Specifically, in the last decades, significant research efforts have been devoted to low-damage post-tensioned timber-based solutions, referred to as Pres-Lam (Prestressed-Laminated timber; Palermo et al. 2005). The Pres-Lam technology is the natural extension of the PRESSS technology to timber structures, and employs engineered timber elements/connections with unbonded post-tensioned bars (or tendons) and energy dissipation devices. The Pres-Lam technology has been widely validated through experimental campaigns (e.g., Newcombe et al., 2008; Smith et al., 2014) and successfully implemented in real new buildings (e.g., Brown et al., 2012; Holden et al. 2016; Figure 15). Recent research also proved the cost-efficiency of these low-damage solutions when compared to traditional technologies (Bianchi et al., 2021).

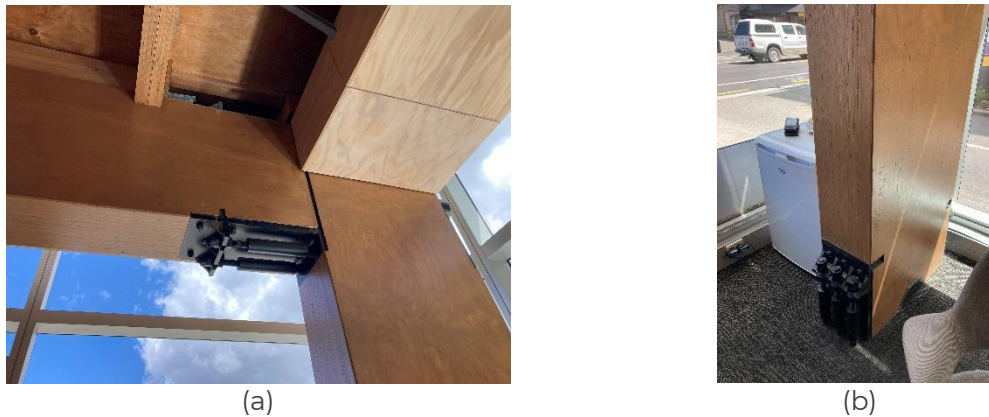


Figure 15. Example of a low-damage (a) beam-column connection and (b) column-to-foundation connection with external “Plug-&-Play” dissipaters in a real building (“Merritt Building”, Christchurch, New Zealand; pictures property of G. Formichetti).

Finally, hybrid concrete-timber post-tensioned solutions have also been experimentally investigated (Pampanin et al. 2023; Figure 16a) and implemented in real buildings (Figure 16b). One of the main advantages consists of replacing the timber column with a concrete one, which typically can provide the same stiffness capacity while reducing the size of the structural components.



Figure 16. Hybrid concrete-timber post-tensioned solutions: (a) experimental specimen (after Pampanin et al., 2023), and (b) example of implementation for a real building.

3.4.2. Low-damage solutions for retrofitting: key considerations

The MULTICARE project aims to investigate the promising use of low-damage technology, in the form of an exoskeleton, for seismic retrofitting applications (D'Amore et al., 2024; D'Amore and Pampanin, 2025). Compared to more traditional solutions, several key advantages can be highlighted:

- **Enhanced structural performance:** In addition to increasing stiffness and strength, the post-tensioned exoskeleton also provides re-centering capacity, thus minimizing residual displacements after a seismic event;
- **Damage limitation and reparability:** Low-damage technology ensures negligible damage to the exoskeleton itself during earthquakes. The use of external fuse-type energy dissipation devices allows for energy dissipation while ensuring the reparability or replacement of these sacrificial components;
- **Sustainability and adaptability:** The adoption of eco-friendly materials, such as engineered timber, improves the sustainability of the solution. Moreover, the use of dry connections - both between the structural components of the exoskeleton and between the exoskeleton and the existing structure - facilitates reparability, demountability, and reusability.

On the other hand, some practical recommendations should be followed to properly design and implement the proposed solution:

- Unlike new structures, the geometrical characteristics of the low-damage exoskeleton must be defined according to the architectural constraints of the existing building. This means that, for example, the number and length of bays, as well as the number of stories and the interstory height, are typically fixed;
- In line with the previous point, the choice between using a frame system or shear walls is often guided by the architectural requirements of the existing structure (e.g., for a facade with a high percentage of openings, a frame system may be preferred);
- Particular attention should be paid to the design of the structural components. Specifically, it is worth highlighting the need to minimize the width of beams and columns of the exoskeleton;
- The timber-based solution should be preferred to meet recently defined sustainability requirements. However, for some practical applications, mixed configurations with timber beams and RC columns may be adopted to ensure comparable stiffness capacity while minimizing the cross-sectional dimensions of columns (see previous point);
- The feasibility of the proposed solution must consider the maximum strength capacity of the floor diaphragm. If the maximum shear capacity required for the exoskeleton exceeds the diaphragm capacity, the latter must be reinforced;

- The exoskeleton requires a foundation. This may be an extension of the existing one or a new foundation, depending on the application;
- The implementation of the exoskeleton requires proper accessibility to the building, as well as the possibility of extending its volume.

The next subsection provides insights and practical recommendations for the proper implementation of the proposed solution, with particular focus on the timber-based configuration. For more details on the seismic design procedure of the exoskeleton, the reader is referred to Deliverable D12.4 - *Technical handbook for resilient structural systems*.

3.4.3. Construction details for the exoskeleton structural components and connections

As previously mentioned, the Pre-Lam technology relies on two main types of reinforcement (Figure 14b): (i) unbonded post-tensioned tendons or bars, which provide the re-centering capacity of the system; and (ii) external fuse-type “Plug-&-Play” dissipaters (Pampanin, 2005; Sarti et al., 2016).

The post-tensioned element must be designed to remain within the elastic range. Specifically, in a proper design of rocking and dissipative connections, yielding of the post-tensioned bars or tendons should be the last event in the strength hierarchy. These elements are crucial for the functionality of the low-damage system. Moreover, the gap opening of the rocking system (Figure 14b) is expected to increase the tensile force in the post-tensioned bar/tendon, and this effect must be considered during the design. It is also fundamental to account for all possible tension losses due to initial release and possible long-term effects. More details on the section design procedure can be found in Deliverable D12.4 - *Technical handbook for resilient structural systems*.

Concerning the external Plug-and-Play dissipaters, these are sacrificial devices that provide the energy dissipation capacity of the system. The main advantage of these components, compared to more traditional reinforcement of RC elements, lies in their easy demountability and replaceability after a seismic event. Figure 17a shows a schematic representation of a Plug-and-Play dissipater, while an example of a disassembled device is provided in Figure 17b. These devices are composed of:

- A fuse-type steel bar;
- An anti-buckling external tube, filled with epoxy or grout;
- Nuts and washers for the installation of the device

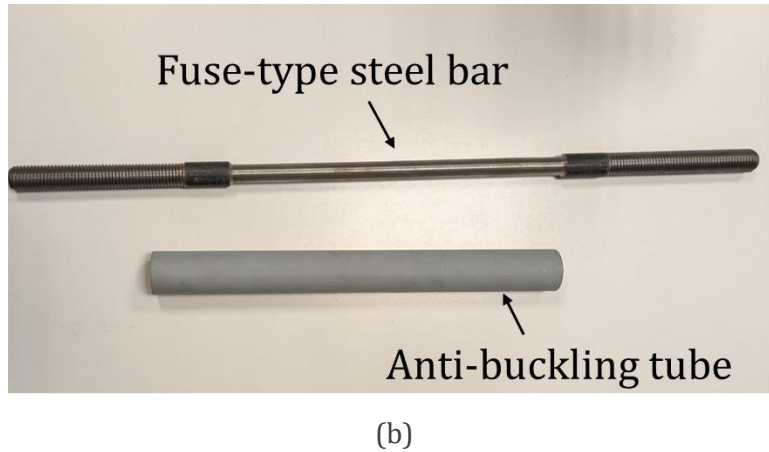
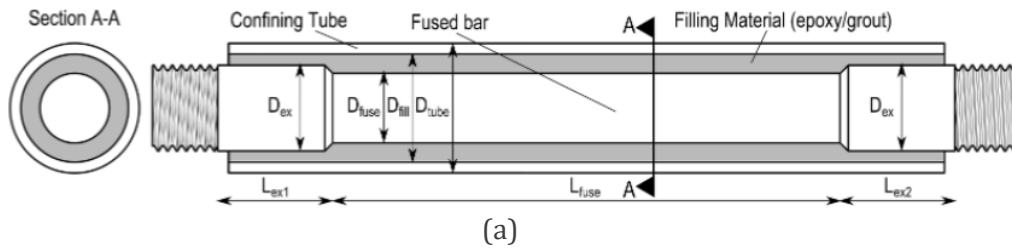


Figure 17. (a) Schematic illustration of the “Plug-&-Play” external fuse-type dissipater (Sarti et al., 2016); (b) example of a disassembled dissipater: fuse-type steel bar and anti-buckling tube.

For the correct design of the Plug-and-Play dissipater, an important parameter is the slenderness ratio of the fuse-type bar, λ_{fuse} . This parameter can be evaluated as (Eq. 1):

$$\lambda_{fuse} = \frac{4 L_{fuse}}{D_{fuse}}, \quad (1)$$

Where L_{fuse} and D_{fuse} are the diameter and the length of the fuse, respectively. Past experimental results showed that a fuse slenderness ratio equal to or lower than 60 is preferred to avoid buckling effects.

For filling the anti-buckling tube, either epoxy or cementitious grout can be used. Ideally, the filling material should be characterized by:

- High stiffness and strength;
- Plastic behavior, to avoid local failure due to stress concentrations;
- High flowability, since the gap between the fuse-type bar and the tube can be narrow.

An example of the filling operation for “Plug-and-Play” dissipaters with epoxy is provided in Figure 18a, while Figure 18b shows the assembled devices.



Figure 18. Example of (a) the filling operation for “Plug-and-Play” dissipaters with epoxy, and (b) the assembled devices.

For structural components, an engineered timber with high mechanical properties is suggested. In general, engineered timber may show similar or even higher mechanical properties than reinforced concrete, while significantly reducing the weight of the structural components (around 5 kN/m³ and 25 kN/m³ for engineered timber and concrete, respectively).

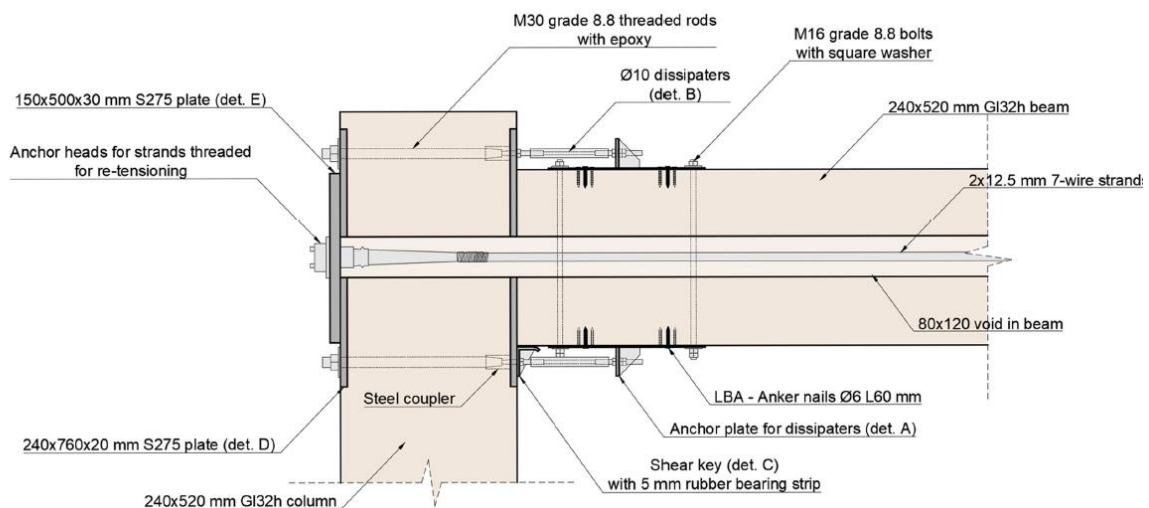
Typical timber materials used in Pres-Lam buildings are:

- **LVL (Laminated Veneer Lumber):** Widely adopted New Zealand and Australia, LVL is commonly made from sustainably-grown, renewable plantation forests of Radiata or Maritime Pine. It offers the highest strength capacity when compared to other engineered timber materials. LVL is produced by peeling 3 mm veneers and gluing them into billets (up to 1.2 m wide, 40–100 mm thick, and very long lengths). Billets are bonded with resorcinol adhesive under high pressure and temperature, then cut and assembled into beams, columns, floors, or walls with precise tolerances.
- **Glulam (Glue-laminated timber):** Glulam is made by bonding together layers of sawn timber boards with strong adhesives, usually with all grains parallel. This process allows large structural members to be fabricated with consistent properties and sizes beyond those available in solid wood. Glulam may be cheaper than LVL in some countries, while performing similarly to LVL.
- **CLT (Cross-Laminated Timber):** CLT consists of sawn boards glued in perpendicular layers, like thick plywood, forming large panels. CLT is mainly used in prefabricated walls and floors. Unlike LVL and glulam, it is bonded with polyurethane adhesive and vacuum clamped, which results in lower bonding pressures.

When dealing with timber structures, it is important to account for the lower compressive strength and elastic modulus perpendicular to the grain compared to those parallel to the

grain. In particular, in moment-resisting timber frames with horizontal post-tensioning, appropriate construction details must be provided for the timber joint panel.

Figure 19a shows a schematic illustration of a Pres-Lam beam-column connection, where a steel-based reinforcement is implemented. This is deemed as the best solution for the proposed exoskeleton, as steel plates and steel rods allow bypassing the timber beam-column joint, avoiding possible undesirable local deformations. An overview of connection detailing for post-tensioned timber frames can be found in Miliziano et al. (2020)



(a)



(b)

Figure 19. Pres-Lam beam-column connection with a steel-based reinforcement for the timber joint: (a) schematic illustration and (b) example of implementation for experimental tests part of the MULTICARE research project.

Construction details of these connections include:

- Steel plates for the timber joint (Figure 19a: detail D; Figure 20a)
- Threaded rods with epoxy: provide additional anchorage and transfer forces between the steel plates, avoiding local stresses in the timber joint; epoxy ensures proper bonding and prevents pull-out (Figure 20b).

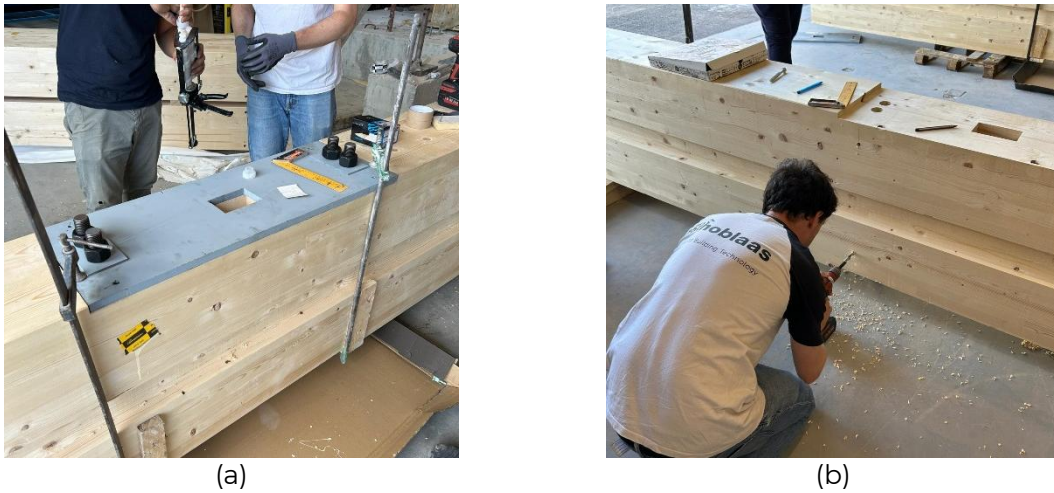


Figure 20. Example of (a) a steel plate for the timber joint and (b) epoxy injection for the threaded rods.

- Smaller steel plate for post-tension anchorage and load distribution (Figure 19a: detail E);
- Anchor heads for post-tensioned bars/tendons;
- Steel coupler for bolts and dissipaters (Figure 21);



Figure 21. Example of steel couplers for bolts and dissipaters

- Anchor plate for dissipaters, connected to the timber beam with both bolts and nails (Figure 19a: detail A).
- Shear key (Figure 19a: detail C) with rubber bearing strip, which provides additional support for the timber beam, improves shear capacity and allows for controlled rocking behavior.
- Void in the timber beam, necessary for the unbounded post-tension

Similar construction details are also provided for the column-to-foundation connection (Figure 22). In this case, particular attention should be paid to the steel plate at the base of

the column, which should include a proper shear key to avoid horizontal displacements of the column while allowing for the rocking mechanism (Figure 23).

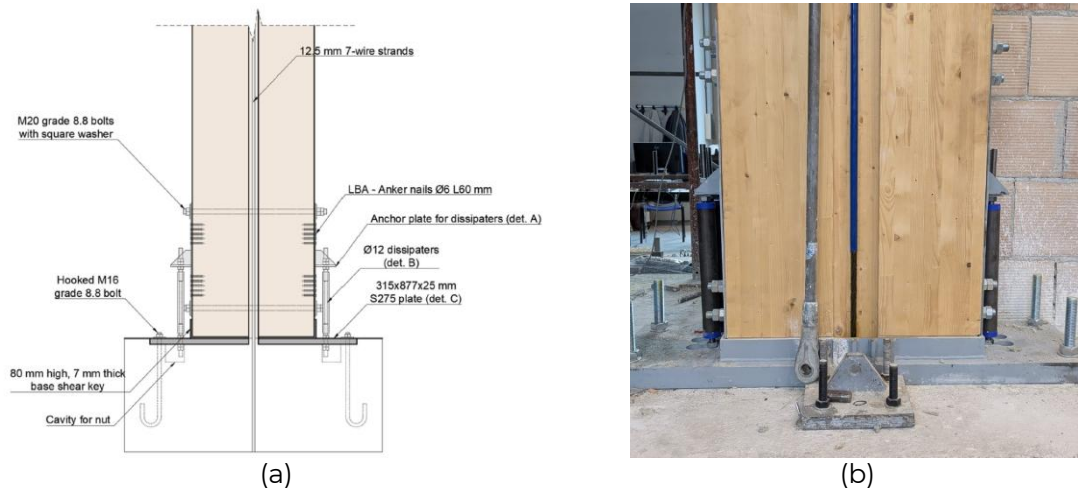


Figure 22. Pres-Lam column-to-foundation connection: (a) schematic illustration and (b) example of implementation for experimental tests part of the MULTICARE research project.



Figure 23. Example of a steel base plate realized for experimental tests as a part of the MULTICARE research project.

3.4.4. Connection of the exoskeleton to the existing building

The connection between the existing building and the Pres-Lam exoskeleton plays a fundamental role in transferring seismic forces and ensuring the proper activation of the exoskeleton itself. This connection is, in fact, the key component that allows the overall system to work as intended. Therefore, a reliable mechanism for shear transfer between the original structure and the newly added exoskeleton is essential. For this reason, the design of the connection system requires particular care.

The external system can be placed directly adjacent to the existing building or slightly detached, thereby creating usable intermediate spaces, as shown in Figure 24.

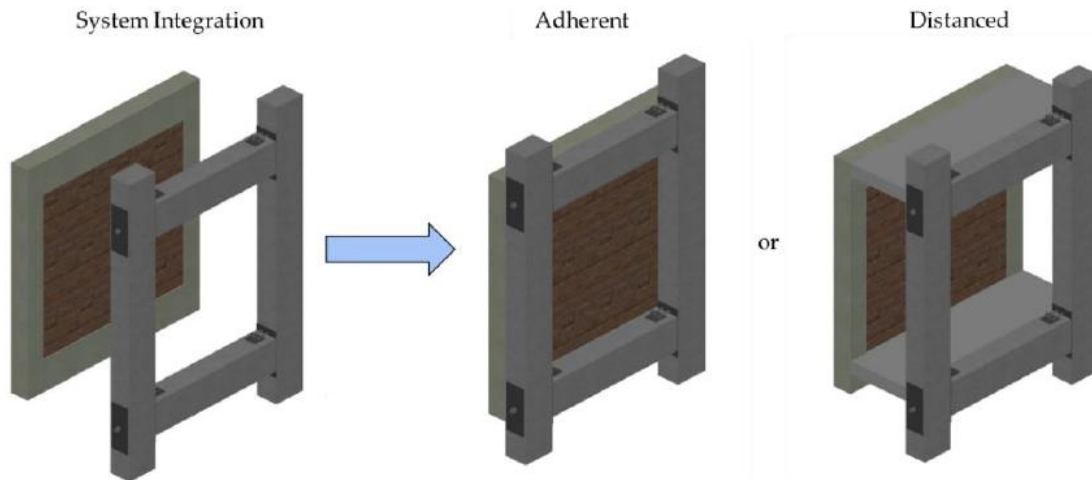


Figure 24. Schematic representation of both adherent and distanced exoskeletons.

The literature reports several possible strategies for the adherent configuration, including the use of anchor bolts, prestressing bars, or cast-in-place floor slabs that connect the two structures. A comprehensive review of these alternatives is provided by Cao et al. (2022). In earlier applications, anchor bolts represented the most common choice. However, subsequent studies investigated in more detail how the shear transfer mechanism depends on the construction details. In this respect, numerous contributions have shown that prestressing bars or bolts significantly increase friction at the interface and, consequently, improve shear transfer. Their use is particularly suitable when the exoskeleton is constructed in direct contact with the existing structure (Figure 25).

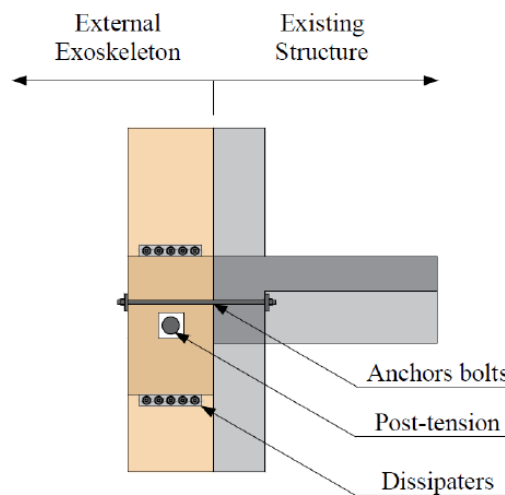


Figure 25. Example of a connection between the existing structure and an adherent Pres-Lam exoskeleton.

Conversely, cast-in-place slabs are more often adopted when balconies or new loggia-type spaces are introduced, as illustrated in Figure 26.

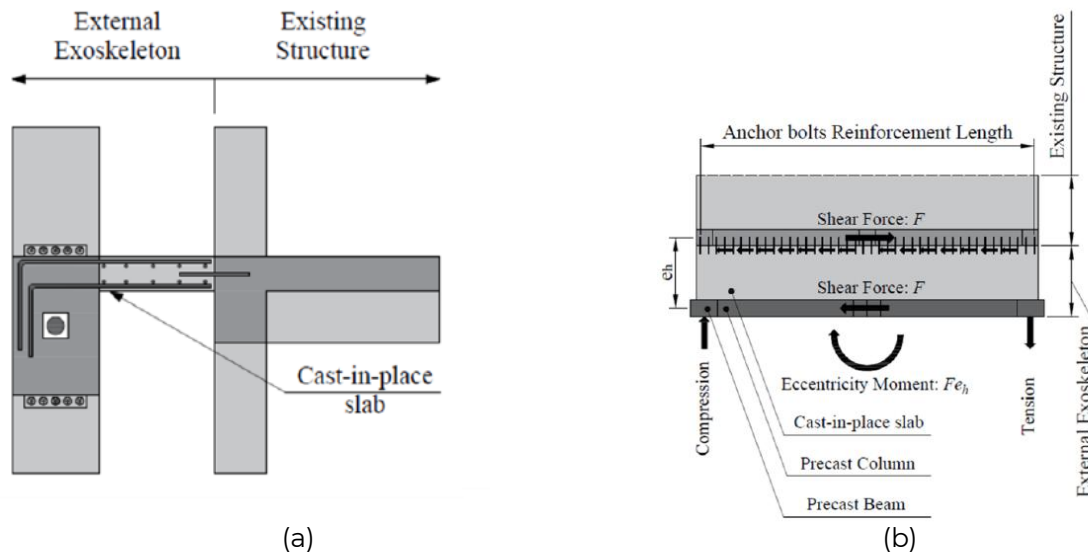


Figure 26. a) Details of a connection with a distanced low-damage exoskeleton; (b) shear transfer mechanism from the existing building to the distanced exoskeleton (after Takeda et al., 2013)

As noted by Takeda et al. (2013), prestressing bars require drilling through the beams, providing a fast and practical solution for the adherent configuration. On the other hand, when the exoskeleton is located at a distance from the building, the design of the connection system becomes more complex. In such cases, the eccentricity between the two systems induces bending effects, and the beams together with the end anchors experience both tensile and compressive forces, as shown in Figure 26b.

In the framework of the MULTICARE project, an innovative connection solution is being developed and investigated, also with the contribution of industrial partners such as Rothoblaas. This connection consists of a post-installed threaded rod, fixed to the concrete using a chemical resin. The rod is linked to the timber exoskeleton through a steel plate, which is secured to the wooden beam with partially threaded screws for plates, such as HBS PLATE Rothoblaas. To improve stiffness, a specially designed thick washer is bolted between the rod and the plate.

Accordingly, the verification of the connection requires checking the following failure modes:

- Yielding and shear failure of the steel components;
- Anchorage capacity of the rod in the concrete;
- Load transfer in the plate-to-timber screw connection.

A representative construction detail is presented in Figure 27, while Figure 28 shows an example of the implementation of this solution for experimental tests in the MULTICARE project. For more details on the design of the proposed connection, the reader is referred to Deliverable D12.4 - *Technical handbook for resilient structural systems*.

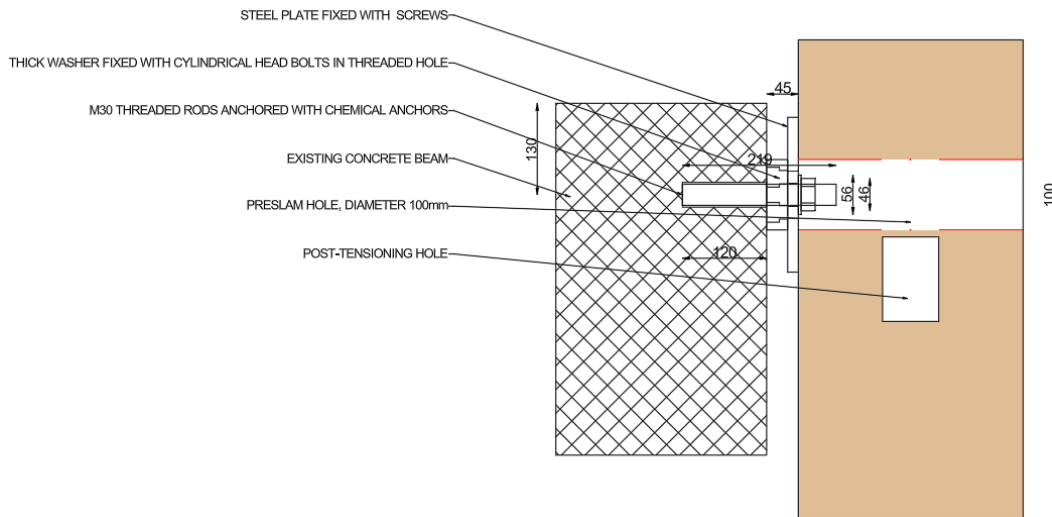


Figure 27. Schematic representation of the proposed solution for the connection between the existing building and the low-damage exoskeleton.

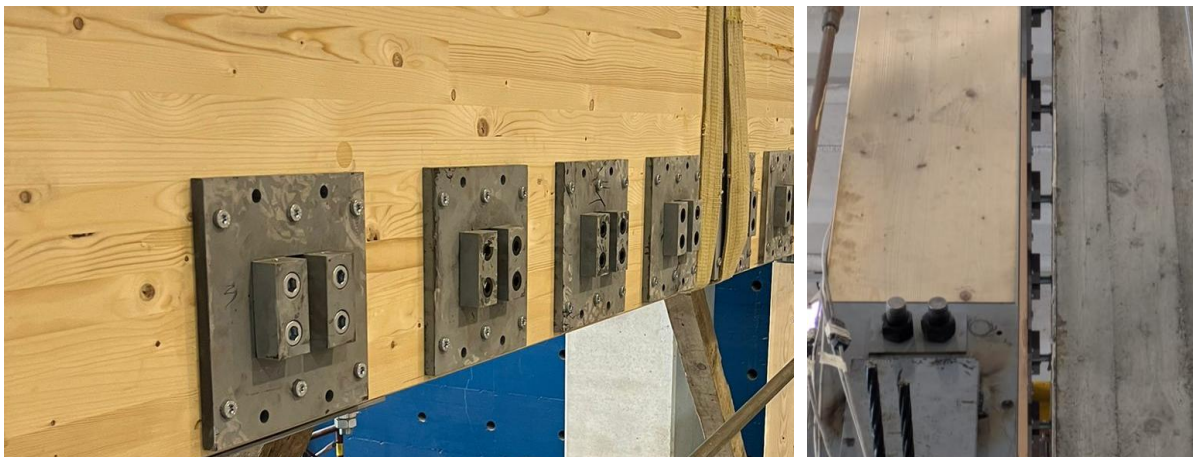


Figure 28. Example of the implementation of the proposed solution for the connection between the existing building and the low-damage exoskeleton as a part of experimental tests in the MULTICARE project.

3.4.5. Construction phases

The implementation of the timber-based exoskeleton follows a fast and controlled three-step process aimed at minimizing disruption to the existing building and its occupants. The main steps are illustrated in Figure 29 and are briefly discussed below:

1. **Assembly on the Ground:** Whenever possible, the prefabricated structural components are assembled at ground level. This step ensures high precision, safety for workers, and reduced time spent working at height.
2. **Lifting into Place:** Once assembled, the prefabricated exoskeleton is lifted by crane and positioned against the existing building. The use of large-capacity lifting equipment allows the entire exoskeleton to be installed in a single operation, significantly accelerating the construction process. It is worth noting that the

timber-based structural components are characterized by a reduced weight when compared to more traditional materials.

3. **Post-Tensioning:** After positioning, the structural components are post-tensioned to achieve the desired structural performance. This step guarantees the activation of the low-damage seismic-resilient mechanism, ensuring both stiffness and energy dissipation while maintaining the replaceability of damaged elements after an earthquake.

This construction methodology highlights the advantages of timber prefabrication - speed, precision, and safety - while enabling the implementation of innovative low-damage technologies for seismic requalification of existing buildings.

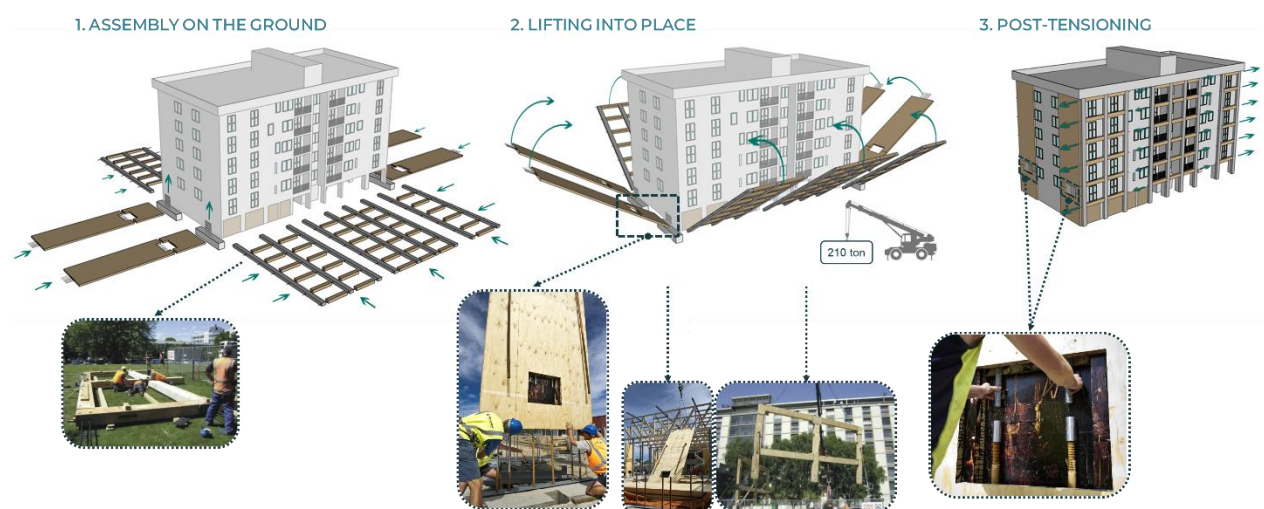


Figure 29. Construction phases for the low-damage timber-based MULTICARE exoskeleton

3.5. Low-Damage double-skin facade systems

In line with the concept of a holistic retrofit approach, the low-damage exoskeleton is intended to be used also as a support for the implementation of a double-skin facade system. This component is expected to improve the energy performance of the existing structures, as well as allow for architectural renovation.

Clearly, to avoid any damage to these components in the case of a seismic event, low-damage technologies must also be used for the double-skin facade system. Two different technologies can be adopted:

1. Low-damage infilled facade;
2. Low-damage cladding systems.

Each solution is discussed in detail in the next sub-sections.

3.5.1. Low-damage infilled facade

The first solution consists of a rocking cantilever system composed of clay brick infill-wall panels and multiple interconnected components (Figure 30a). The starting point is a light-gauge steel subframe, which is securely anchored to the exoskeleton. This subframe is made of C-shaped steel profiles arranged both horizontally and vertically. The horizontal members are fixed to the top and bottom beams of the exoskeleton, while the vertical profiles are friction-fitted. A deliberate gap is left between the vertical studs and the upper track, enabling the facade to slide under seismic loading.

The number of vertical profiles included in the subframe depends on how many independent rocking panels are to be installed. This, in turn, is determined by the aspect ratio of the panels, typically ranging between 1.5 and 2 (e.g., Tasligedik and Pampanin, 2017). Both the dimensions of the subframe elements and their connection details are designed according to the out-of-plane tributary load of the corresponding infill panels.

Once the steel subframe has been assembled, the clay brick rocking panels are mounted. Similar to the subframe, a horizontal gap is provided at the top of the panels to accommodate seismic movement and prevent damage. The vertical joints are then sealed with polyurethane, ensuring both airtightness and weatherproofing of the facade. At the same time, these joints maintain the required deformability of the system and allow for the functional integration of the individual panels. A schematic illustration of this low-damage infill-wall solution is presented in Figure 30a.

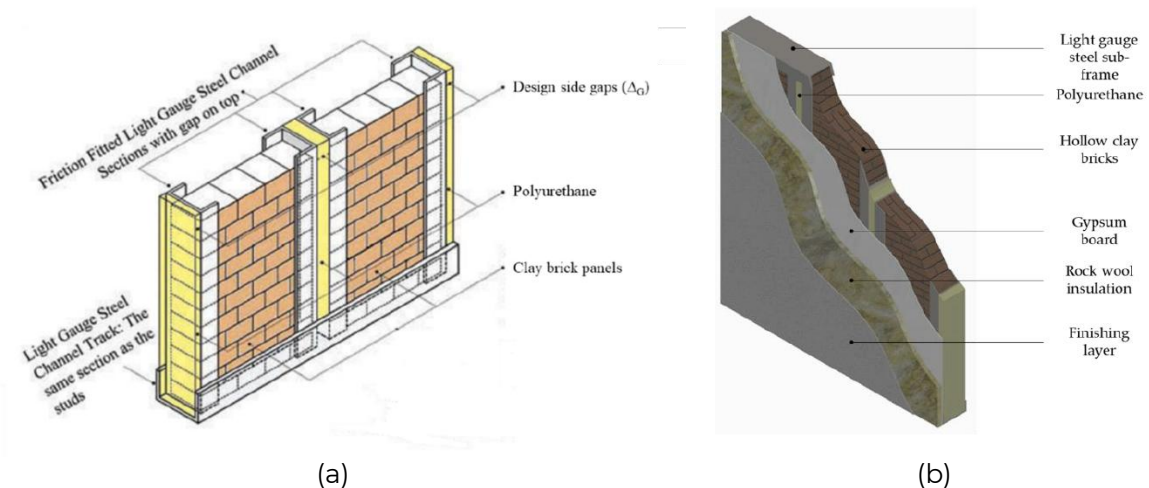


Figure 30. (a) Schematic representation of the low-damage infilled facade (from Tasligedik & Pampanin, 2017) and (b) illustration of the proposed double-skin system.

To ensure compliance with the thermal requirements prescribed by the code, additional layers of insulation material are also incorporated into the facade system to achieve the target U-values. As previously mentioned, the thickness of these layers is defined to satisfy the maximum transmittance values for vertical envelopes.

The insulation is complemented by a gypsum board and a finishing layer. The introduction of gypsum board plays a crucial role in limiting the impact of thermal bridges generated by the vertical gaps, both in the double-skin solution and in the retrofitted masonry infills.

However, the presence of vertical steel studs amplifies the effect of thermal bridging, owing to the high conductivity of metallic components. For this reason, advanced Finite Element Modelling (FEM) is suggested during the design phase to assess the overall transmittance of the facade. Figure 30b illustrates the schematic configuration of the low-damage, high-energy-performing facade system.

Alternatively, a timber-based system can also be adopted (Figure 31), similarly to the solution proposed by Tasligedik et al. (2015) for drywall partitions. From a seismic performance point of view, the structural mechanism is equivalent to the one previously described for rocking cantilever clay brick infill-wall panels. The system's effectiveness has been validated through experimental testing performed at the University of Canterbury, confirming its excellent seismic performance.

This facade system includes several components. Two steel tracks are first connected to the upper and lower beams of the exoskeleton, ensuring out-of-plane stability and providing the base for installing friction-fitted timber studs. A deliberate gap is left at the top of the studs, allowing them to accommodate horizontal displacements during seismic excitation. As in the previous solution, a vertical separation between the outermost stud and the surrounding frame is required to avoid interactions with the structural system. Within the stud framework, a Cross Laminated Timber (CLT) panel and a timber-fibre insulation layer are integrated.

To complete the facade system, additional layers are introduced: (i) a gypsum board, which mitigates the impact of thermal bridges associated with timber studs and gaps in the existing masonry infills, (ii) a vapour-open waterproof membrane, and (iii) an external finishing layer. The total thickness of the layers must be designed to comply with the thermal transmittance requirements for opaque vertical envelopes set by code.

The resulting stratigraphy of the timber-based double-skin facade is schematically illustrated in Figure 31.

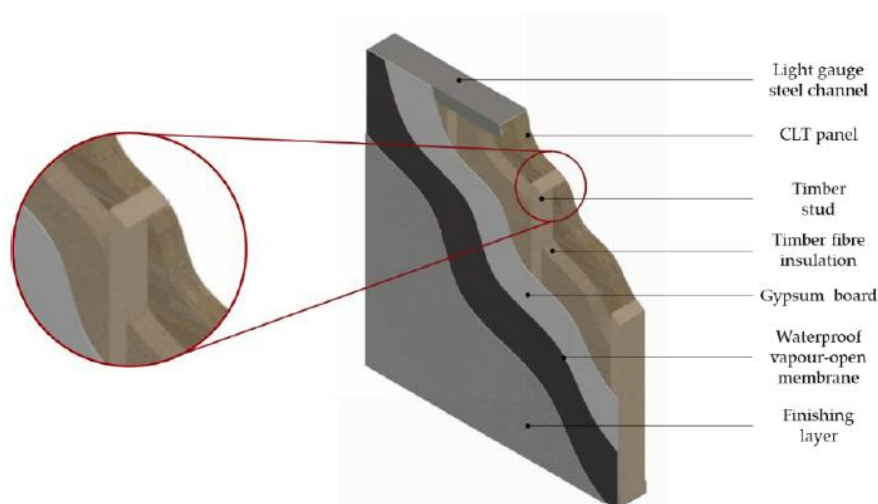


Figure 31. Low-damage timber-based double skin solution for the holistic retrofit.

3.5.2. Low-damage cladding systems

The second possible solution for the double-skin consists of low-damage cladding systems. Cladding systems can be designed using a wide range of materials and typologies, including curtain walls, stick systems, double-skin facades, spider glazing, monolithic claddings, as well as lightweight or heavy cladding panels. Similarly to infilled solutions, their seismic performance can be enhanced by carefully detailing the gaps and the connections with the structural frame.

A common strategy to minimize the interaction between the facade and the main (exo)skeleton involves the use of bearing connections at the bottom of the panels, which are designed to transfer only vertical loads. These are combined with tie-back or sliding connections at the top, which permit lateral displacements (Figure 32a). Such connections must be detailed with sufficient ductility and strength to avoid premature failure under seismic loading (e.g., Baird et al., 2011).

Since cladding panels can contribute to the overall lateral stiffness of the structure, their interaction with the building can also be mitigated by dissipative connections. These devices can absorb seismic energy without damage, thereby limiting the seismic demand on the panels. In this context, Baird et al. (2013) proposed a low-damage solution for precast concrete cladding panels, employing U-shaped flexural plate (UFP) connections (Figure 32b). These connections provide both energy dissipation and the ability to accommodate relative displacements between the structural frame and the cladding. The effectiveness of this solution to improve the seismic performance of new buildings has also been numerically demonstrated by Bianchi et al. (2021).

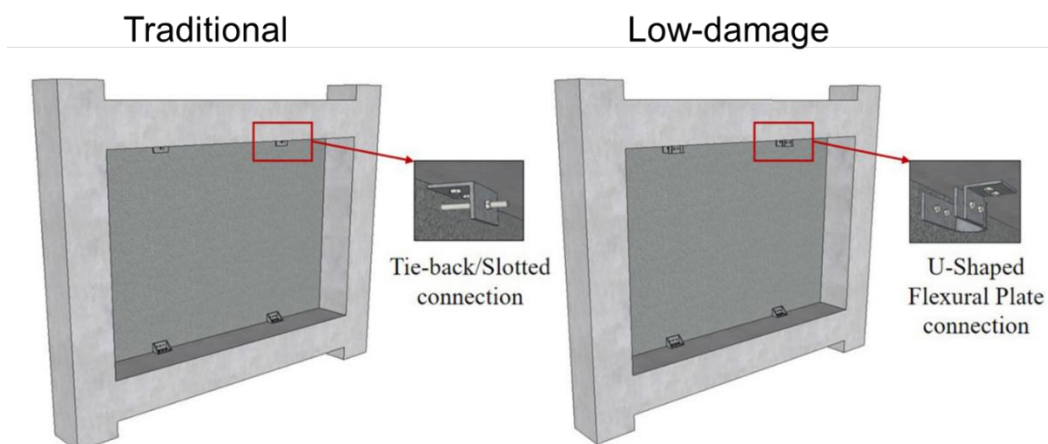


Figure 32. Comparison between more traditional and low-damage cladding systems (modified after Baird et al., 2013 and Bianchi et al., 2021)

Another interesting solution for improving the energy efficiency of existing buildings is the construction of a so-called ventilated facade (Figure 33). The ventilated façade is a multilayer system assembled “dry” using mechanical anchors, and it is characterized by the presence of an air cavity between the existing wall and the external cladding. This solution involves the application of insulation material directly to the vertical wall. However, unlike the external thermal insulation composite system (ETICS), the finishing layer is supported

by a substructure and detached from the insulation panels. This configuration creates an air gap that activates a “stack/chimney effect,” which provides several advantages: (i) protection of the structure from direct exposure to weather conditions; (ii) elimination of surface condensation; (iii) creation of a technical cavity for installations and ducts; and (iv) reduction of cracking risks in the cladding.



Figure 33. Example of a traditional ventilated facade.

In the case of a ventilated facade solution, it is possible to adopt appropriate construction details to achieve better seismic performance. Double-sided cladding systems equipped with a substructure are connected to the existing wall by means of special brackets, usually provided with slotted holes to allow adjustment in the three spatial directions (Figure 34). To enable the system to accommodate differential displacements between floors due to seismic loads, it is possible to implement movable connections by taking advantage of the slots already present in the brackets, thus ensuring an adequate displacement capacity compatible with the interstory drift expected for the design earthquake intensity.



Figure 34. Example of brackets commonly used for double-skin cladding systems.

Furthermore, it is possible to use advanced high-performance post-installed fasteners, such as the EQ-Rod (Quintana Gallo et al., 2018), for anchoring non-structural components to the exoskeleton. This solution is based on the use of a rubber ring around the anchor,

serving as a damper and isolator. Experimental studies have demonstrated that these systems are effective in reducing both the accelerations transmitted to non-structural elements and the forces acting on the anchors during seismic events (Ciurlanti et al., 2022). As a result, such technologies may also be applied in energy-efficient and architectural retrofitting solutions, including ventilated facades, to mitigate earthquake-induced damage (Figure 35).

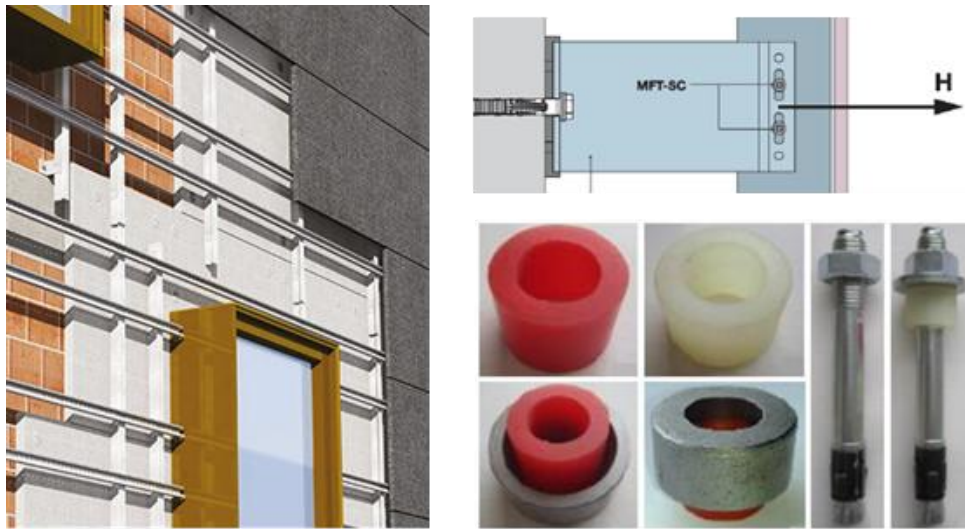


Figure 35. Concept of a high-seismic performance ventilated facade with proper construction details (EQ-Rod: adapted from Quintana Gallo et al., 2018)

It is important to highlight that a ventilated facade solution is deemed a demountable and replaceable intervention - thanks to its completely “dry” assembly system - with numerous advantages in terms of sustainability and resilience. In fact, following a seismic event, it would be possible to remove the facade elements, allowing intervention on the underlying structural components and subsequently reconnecting the removed panels.

An example of the possible implementation of a high-performance ventilated facade applied to the exoskeleton is presented in Figure 36. The system is conceived as a modular solution, designed to enhance the energy efficiency of the building envelope.

Several construction details are highlighted:

- A. Coping panel: upper termination of the facade system, ensuring protection and continuity of insulation;
- B. Corner connection: detailing of the joint between adjacent facade modules, allowing structural continuity and architectural integration.
- C. Cross section: representation of the multilayer system, including insulation and cladding elements.

- D. Window panel: integration of the facade system with existing window frames, ensuring thermal and acoustic insulation while maintaining architectural uniformity.
- E. Bottom section: lower termination of the system, designed to ensure durability, drainage, and ease of inspection.

At the center of Figure 36, a three-dimensional (3D) rendering of the retrofitted building (Acerra demonstrator) shows the overall architectural effect of the modular facade intervention, which combines energy efficiency with an architectural renovation. More details of the implementation of this solution can also be found in the deliverables specifically addressing the facade prototype for the Acerra demonstrator: (i) D11.1 – *Facade prototype for Italian demo*; (ii) D11.2 – *Guidelines for facade assembly – Italy*.

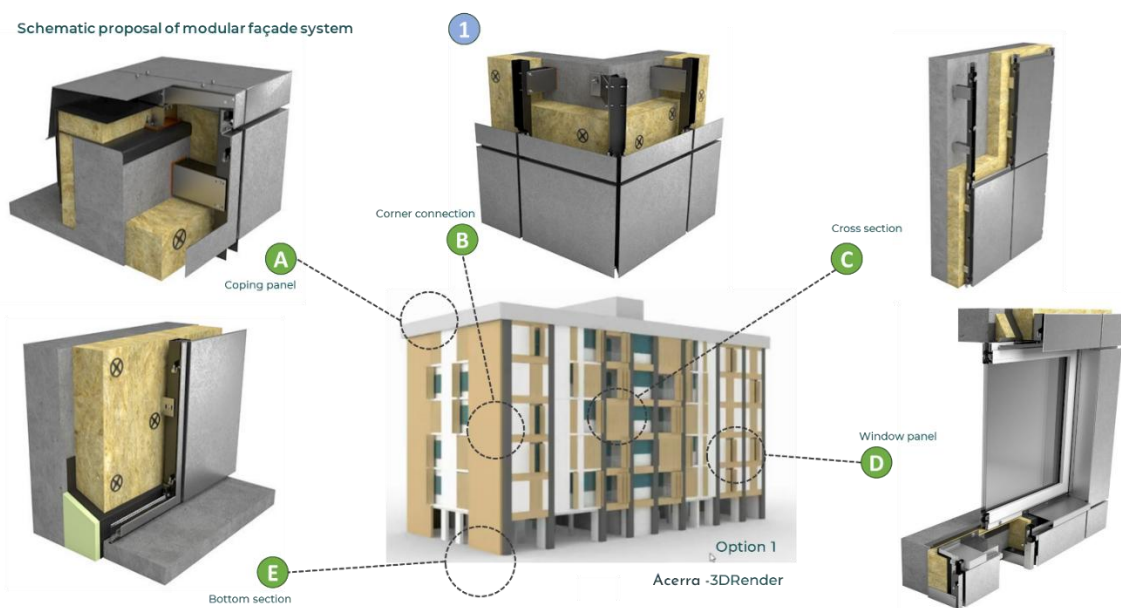


Figure 36. Schematic proposal of a modular facade system for the holistic retrofit solution (from WP5, WP8, and WP11 material: “Plug and play low-carbon resilient facade systems”).

4 Flood risk reduction solutions at building level

This chapter aims to review the most effective technical flood protection measures applicable at the individual building level. The focus will be on three essential areas:

- ✓ **Anti-flood barrier systems for doors** – practical, removable or integrated solutions that prevent water from entering the building.
- ✓ **Protection at the building foundation level**, including through lifting, waterproofing or efficient drainage, to reduce the risks of infiltration and loss of structural stability.

- ✓ **Flood damage-resistant materials**, selected and used strategically in exposed areas, to minimize degradation from direct or prolonged exposure to water.

In addressing the protection of buildings against floods, it is essential to align with a solid regulatory framework, which guides both the design, execution and maintenance of defense systems. Relevant norms and technical guidelines are issued by national and international institutions and reflect the experience gained from extreme hydrological events. Several concrete examples of relevant guidelines can be found in **Appendix I**.

4.1 Anti-flood barrier systems for doors

According to FEMA (2014), barriers are flood panels placed over openings in walls such as doorways and windows. Also, in the flood barriers at building level can be included the flood packing flood barriers (which cover a larger perimeter near the building) and also flood doors. Barriers can be made of several materials, depending on the size of the opening to be covered, and should include gaskets along their edges. If the flood depths are expected to reach the maximum allowable 0.6 to 0.9 m, barriers for openings wider than approximately 0.9 m feet must be made of strong materials such as heavy-gauge aluminum or steel plates (FEMA, 2014) (Figure 37). If the flood depth is below 0.6 m and the openings are smaller than 0.9, then lighter material can also be used for this type of flood defense solutions. Due to the possibility of the barrier collapsing, it is mandatory for a structural engineer to assist with the design of the barrier and evaluate the entire dry floodproofing system. Also, the engineer must evaluate the wall on which the barrier will be installed and recommend strengthening it to carry the flood loads associated with the flood barrier.

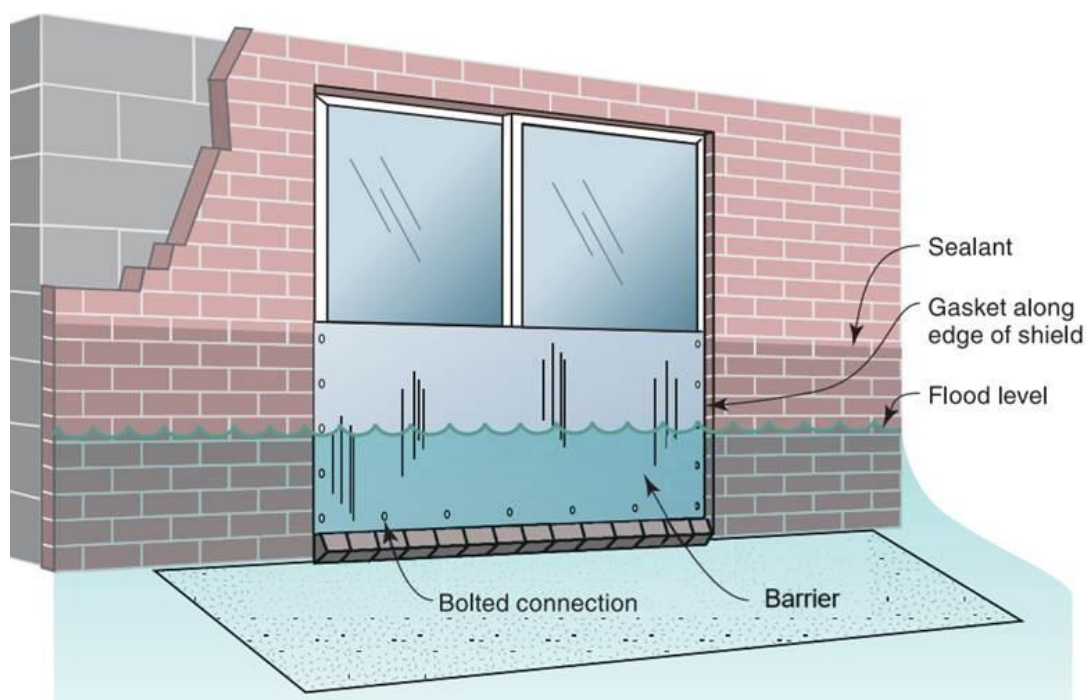


Figure 37. Heavy-gauge metal barrier over sliding glass door opening (source: FEMA, 2014)

Below are exemplified the main flood barriers types.

4.1.1. Removable panels

Flood barriers with removable panels are protective systems designed to prevent water intrusion during floods. They can be used at doors and windows level. These barriers consist of panels that can be installed in advance of a flood and removed when no longer needed, allowing for normal access and aesthetics during dry periods. They are widely used in both residential and commercial settings where permanent flood protection would be impractical or undesirable. In general, from the structure point of view these floods barriers include:

- ✓ **Horizontal or vertical panels**, often made of aluminum or steel, designed to withstand hydrostatic pressure.
- ✓ **Mounting tracks or brackets** that are permanently installed around doors, windows, or other openings. They contain an aluminum alloy groove.
- ✓ **Rubber strips** placed between the panels.
- ✓ **Sealing gaskets or compression systems** to prevent water leakage between panels and frame.
- ✓ **Fastening mechanisms**, such as stainless-steel screws, pressure cover adjustment block to securely hold the panels in place.

These components are shown also in Figure 38.

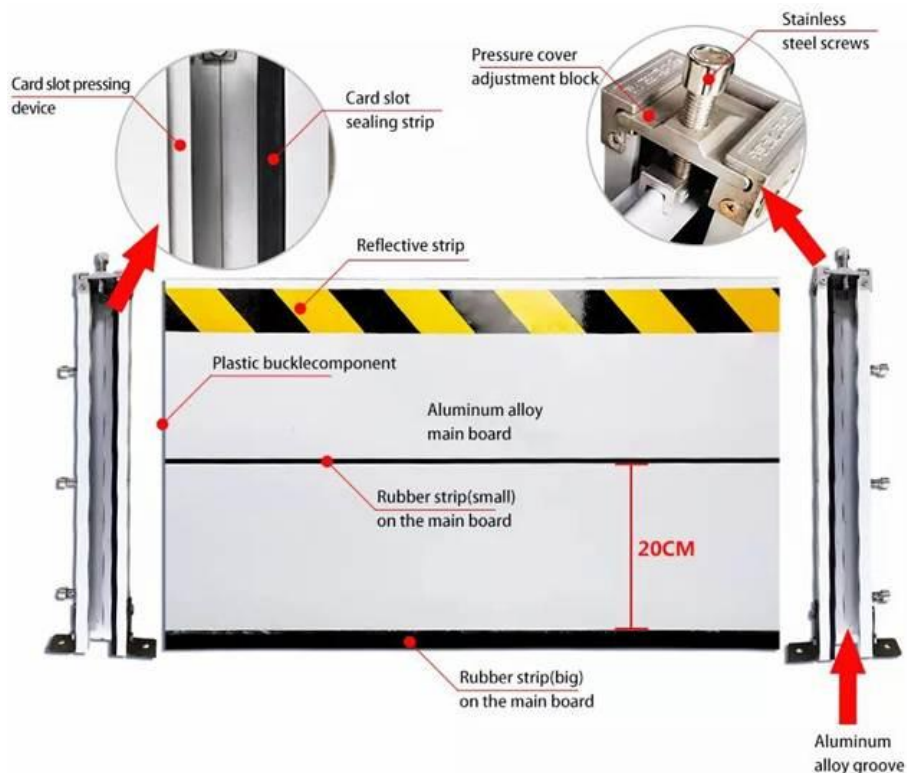


Figure 38. Structural components of aluminum flood barrier (source: <https://www.yiyindustrial.com/>)

More details regarding the installation steps and also other representative examples of flood removable panels can be found in **Appendix II**.

4.1.2. Packing flood barriers

Packing flood barriers (also called mobile aluminum barriers or modular flood protection panels) are temporary or semi-permanent defense systems that completely surround a building or entrance to prevent water from entering during a flood. thanks to its modularity, it allows installing specific modules for the openings, namely building entrances, in order to ensure their accessibility just before and after a flooding (not as it occurs) without compromising the functionality and potential reuse of barriers (Bignami et al., 2019). At the time of completion of the installation process, these barriers will constitute a line of defense in the form of a closed or semi-closed ring. The barriers will be sealed to prevent water from passing through. Also, they will be supported on the body of the buildings, its walls taking over an important part of the pressure exerted by the water at the time of the flood (Figure 39). To increase resistance to horizontal water pressure, a center post leg support can also be used to connect the barrier to the concrete structure next to the building.

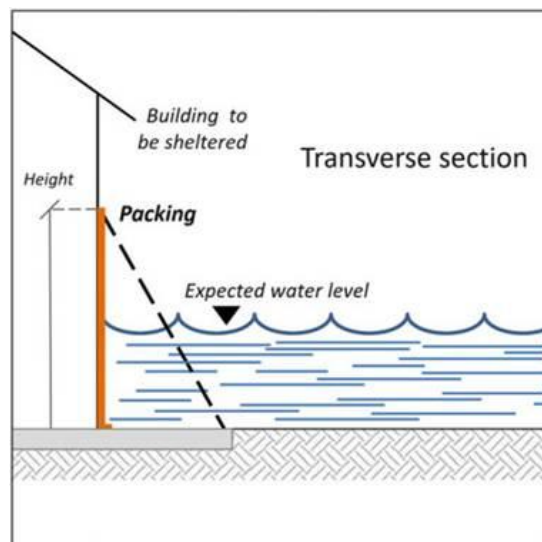


Figure 39. Working mechanism of packing technique, transverse section (by way of an example—drawing not in scale) (source: Bignami et al., 2019)

Additional details regarding the installation steps and also other representative examples of flood packing barriers can be found in **Appendix III**.

4.1.3. Flood doors

The flood-resistant door is a passive protection system designed to block water from entering buildings during flood events. It combines the function of a standard door with advanced sealing and reinforced structure, making it ideal for critical infrastructure, public buildings and industrial spaces (Figure 40).

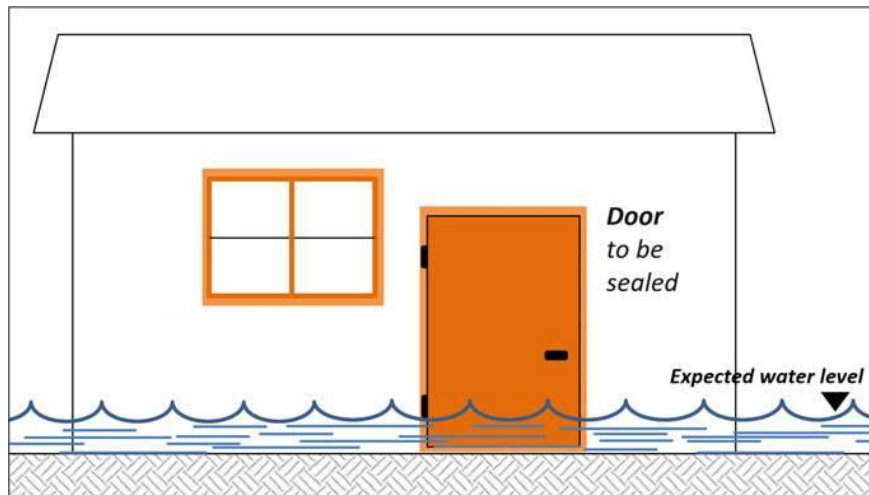


Figure 40 Schematic representation of flood doors at building level – front view (source: Bignami et al., 2019)

The main components of flood doors are (Figure 41):

- Structural frame – made of galvanized steel, stainless steel or extruded aluminum.
- The door itself – which is a very solid, reinforced construction, generally consisting of a door leaf with a thickness of between 2-5 mm.
- Sealing system – includes double or triple seals made of EPDM rubber, neoprene or industrial silicone.

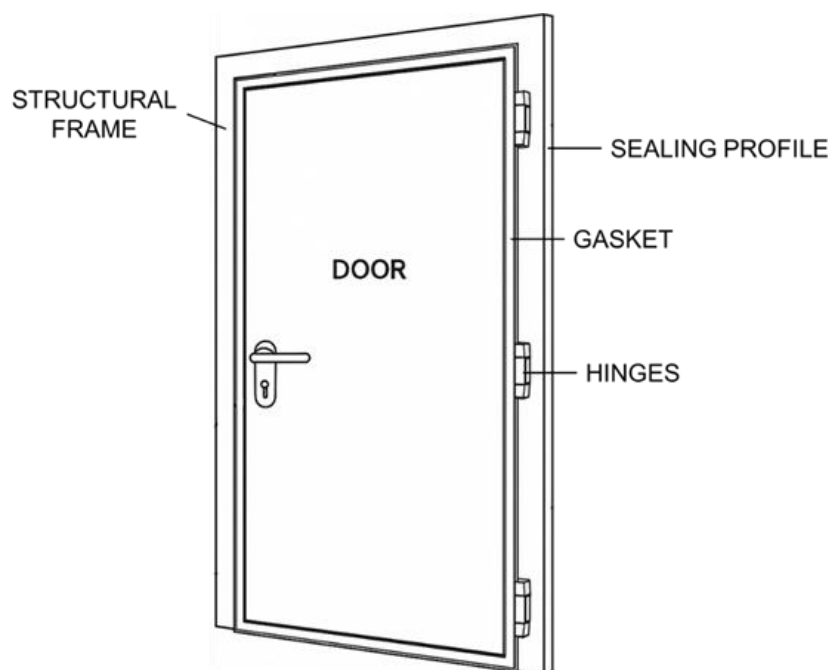


Figure 41. General components of flood doors

Appendix IV contains additional details of the installation steps for flood doors and some representative examples from real-world.

4.1.4. Smart Flood Barrier (SFB)

SFB is a device that includes an automatic barrier installed in front of the entrance door (Muñoz-Caballero et al., 2022). By hermetically sealing the door, this barrier manages to prevent water from entering the building. The biggest advantage of this type of flood barrier is that, being fully automatic, its beneficiary no longer has to install it before the flood occurs. The SFB components are listed in Table 5 and represented in Figure 42.

Table 5 SFB components (source: Muñoz-Caballero et al., 2022)

ID	Component	Description
1	Door	It is not directly part of the invention, but is fundamental to prevent water from entering the home.
2	Barrier	Hidden below the ground and which is automatically raised when there is a certain level of water.
3	Lateral Guides	Fixed to the pillars of the gate to be protected and has a peripheral chamber.
4	Lintel	Installed on the right or left side of the gate depending on the slope of the street or sidewalk.
5	Access	To be protected and which once fully raised closes in a watertight manner totally preventing the passage of water up to the gate.
6	Valves	Connects to a small pneumatic compressor.
7	Chamber	Installed perimetrically to ensure the sealing.

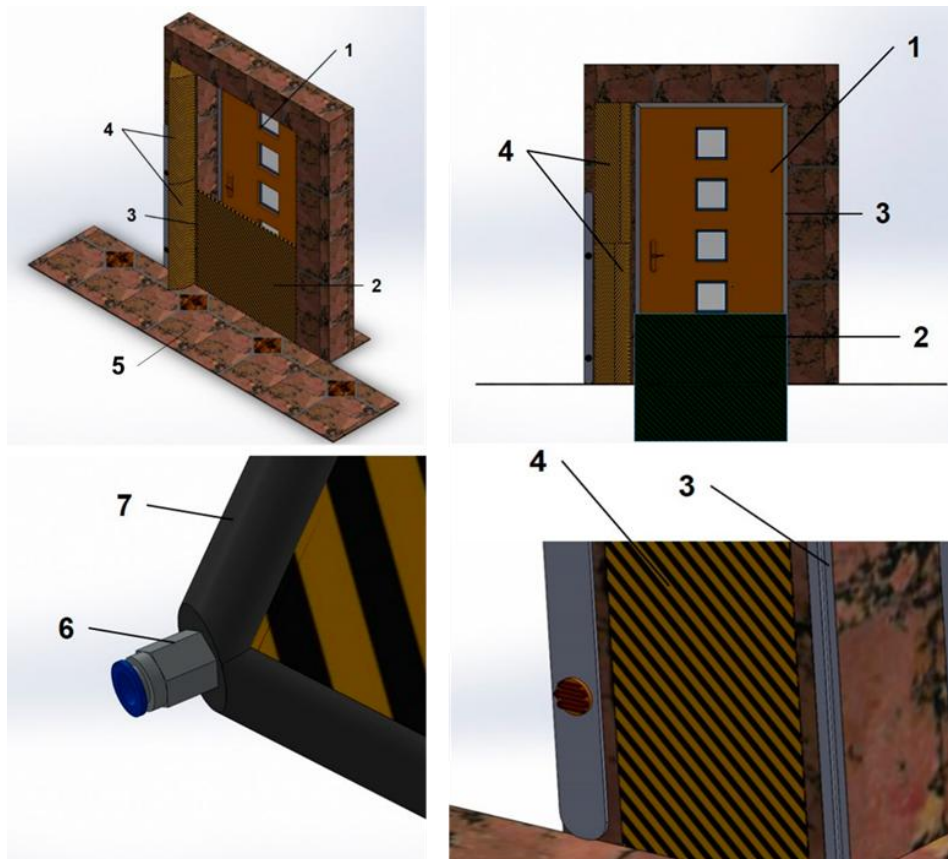


Figure 42. Overview of the Smart Flood Barrier (SFB) components (source: Muñoz-Caballero et al., 2022)

4.2. Protection at the building foundation level

Protective measures at the foundation level must ensure both waterproofing and adaptability to hydrostatic loads. **Elevating the foundation** and **Waterproofing foundations and basement walls** are the main 2 methods for the foundation protection against floods.

4.2.1. Elevating the foundation

According to FEMA (2014), the elevating procedure consists of raising the entire building – including the exterior walls and load-bearing structure – above the minimum hydraulic safety level. This operation involves decoupling the building from its original foundation and constructing a new support system underneath it. It can be done using continuous footing or individual footing (Figure 43).

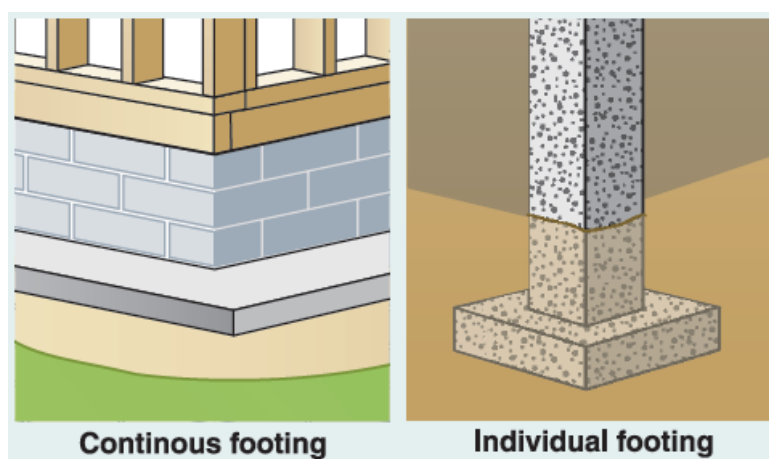


Figure 43. Footing types (source: FEMA, 2014)

These two methods are detailed in **Appendix V**.

4.2.2. Waterproofing foundations and basement walls

Foundation waterproofing is done on the outside of the basement walls. Below are the main conditions for waterproofing foundations and basement walls (source: <https://inundatii.ro/ro-floods/>):

- horizontal waterproofing will usually be single-layer and will be made with bituminous or polymer waterproofing membranes;
- horizontal waterproofing of the foundation elements can also be provided at the level of the foundation sole on the lightly reinforced leveling concrete of at least 10 cm thick;
- vertical waterproofing will be applied to a support made of plaster with cement mortar without the addition of lime, made of drywall;
- vertical waterproofing can consist of a bituminous or polymeric waterproofing membrane continuously glued to the support, mechanically fixed to the upper part or of at least two layers of homogeneous masses with film application, possibly reinforced, protected underground with semi-rigid boards, panels or sheets (simple, imprinted or cellular), masonry or clay screen compacted in successive layers and above ground with reinforced plasters made of cement mortar without the addition of lime or masonry.

Figure 44 shows a possible scheme for waterproofing the foundation of buildings, mentioning the components of this waterproofing solution (Table 6).

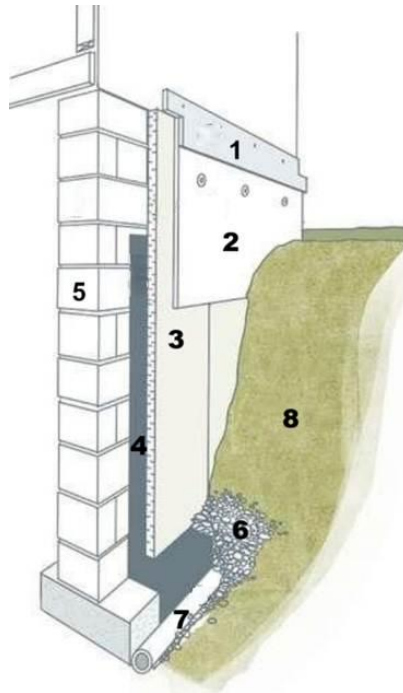


Figure 44 Possible foundation and basement waterproofing technique (source: <https://inundatii.ro/ro-floods/>)

Table 6 Components of foundation and basement waterproofing technique

No.	Component
1	base protection – waterproof material at the junction between the infrastructure and the superstructure of the house
2	root barrier
3	thermal insulation made of materials resistant to humid environments, protected against humidity by specific methods
4	waterproofing
5	basement wall sized by structural calculation, thermally insulated according to current regulations
6	coarse gravel or crushed stone filling
7	perimeter drainage pipe with a diameter greater than 80 mm equipped with a water discharge system to the outside
8	gravel filler

4.3. Classification of flood damage-resistant materials

The most well-known classification of flood damage-resistant materials is that made by FEMA in the work *Flood Damage-Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in accordance with the National Flood Insurance Program (NFIP) - Technical Bulletin 2 / August 2008* (FEMA, 2008). According to NFIP, “Flood [damage]-resistant material” is defined as “any building product [material, component or system] capable of withstanding direct and prolonged contact with floodwaters without sustaining significant damage.” The term “prolonged contact” means at least 72 hours, and

the term “significant damage” means any damage requiring more than cosmetic repair. “Cosmetic repair” includes cleaning, sanitizing, and resurfacing (e.g., sanding, repair of joints, repainting) of the material. It is mandatory that all building materials that are located below the Base Flood Elevation (BFE) to be flood damage-resistant.

In Table 7 are defined 5 classes of material resistance.

Table 7 Class descriptions of materials (source: FEMA, 2008)

	Class	Class description
Acceptable	5	Highly resistant to floodwater damage, including damage caused by moving water. These materials can survive wetting and drying and may be successfully cleaned after a flood to render them free of most harmful pollutants. Materials in this class are permitted for partially enclosed or outside uses with essentially unmitigated flood exposure.
	4	Resistant to floodwater damage from wetting and drying, but less durable when exposed to moving water. These materials can survive wetting and drying and may be successfully cleaned after a flood to render them free of most harmful pollutants. Materials in this class may be exposed to and/or submerged in floodwaters in interior spaces and do not require special waterproofing protection.
Unacceptable	3	Resistant to clean water damage, but not floodwater damage. Materials in this class may be submerged in clean water during periods of flooding. These materials can survive wetting and drying, but may not be able to be successfully cleaned after floods to render them free of most harmful pollutants.
	2	Not resistant to clean water damage. Materials in this class are used in predominantly dry spaces that may be subject to occasional water vapor and/or slight seepage. These materials cannot survive the wetting and drying associated with floods.
	1	Not resistant to clean water damage or moisture damage. Materials in this class are used in spaces with conditions of complete dryness. These materials cannot survive the wetting and drying associated with floods.

Appendix VI provides a comprehensive overview of various building materials evaluated for their performance in flood-prone environments.

5 Conclusions

This deliverable has provided end-user-oriented guidelines for the implementation of a low-damage exoskeleton for the holistic retrofit of existing buildings. The proposed solution combines structural, energy, and architectural objectives within a single integrated system, aiming to improve seismic performance while simultaneously reducing energy demand and enhancing the overall quality of the built environment.

The low-damage exoskeleton concept allows for the protection of structural and non-structural components by limiting damage during seismic events, thus ensuring higher resilience and reducing post-earthquake repair costs. At the same time, the integration of high-performance facade systems provides enhanced energy efficiency, supporting sustainability targets and contributing to a reduction in energy consumption and emissions. From an architectural perspective, the approach also offers the opportunity to

redefine the aesthetic quality of existing buildings, enabling modernization and functional adaptation without disrupting current construction practices.

Overall, the work highlights that the adoption of a holistic retrofit strategy based on low-damage exoskeletons is not only technically feasible but also economically and environmentally advantageous. Such interventions can represent a valuable solution towards sustainable and resilient urban regeneration, addressing structural/seismic safety, energy performance, and architectural renovation simultaneously.

Additionally, in view of a multi-hazard retrofit solution, the last section have highlighted three essential directions for protecting buildings against flood: (i) the implementation of flood barriers, (ii) the use of effective protection methods at the foundation level, and (iii) the choice of building materials resistant to prolonged contact with water.

References

- Akguzel, U., & Pampanin, S. (2012). Assessment and design procedure for the seismic retrofit of reinforced concrete beam-column joints using FRP composite materials. *Journal of Composites for Construction*, 16(1), 21-34.
- Baird, A., Palermo, A., & Pampanin, S. (2013, April). Controlling seismic response using passive energy dissipating cladding connections. In 2013 NZSEE Conference (pp. 1-8).
- Baird, A., Palermo, A., Pampanin, S., Riccio, P., & Tasligedik, A. S. (2011). Focusing on reducing the earthquake damage to facade systems. *Bulletin of the New Zealand Society for Earthquake Engineering*, 44(2), 108-120.
- Belleri, A., & Marini, A. (2016). Does seismic risk affect the environmental impact of existing buildings?. *Energy and Buildings*, 110, 149-158.
- Bianchi, S., Ciurlanti, J., & Pampanin, S. (2021). Comparison of traditional vs low-damage structural and non-structural building systems through a cost/performance-based evaluation. *Earthquake Spectra*, 37(1), 366-385.
- Bianchi, S., Ciurlanti, J., Overend, M., & Pampanin, S. (2022). A probabilistic-based framework for the integrated assessment of seismic and energy economic losses of buildings. *Engineering Structures*, 269, 114852.
- Bignami, D.F., Rosso, R., & Sanfilippo, U. (2019). Flood Impact on Buildings, in: *Flood Proofing in Urban Areas*. Springer, Cham, pp. 11–24. https://doi.org/10.1007/978-3-030-05934-7_2
- Bournas DA. Concurrent seismic and energy retrofitting of RC and masonry building envelopes using inorganic textile-based composites with insulation materials: a new concept. *Compos Part B Eng* 2018;148:166–79.
- Brown, A., Lester, J., Pampanin, S., & Pietra, D. (2012). Pres-Lam in practice: A damage-limiting rebuild project. In SESOC Conference.
- Calvi, G. M., Sousa, L., & Ruggeri, C. (2016). Energy efficiency and seismic resilience: A common approach. In *Multi-hazard approaches to civil infrastructure engineering* (pp. 165-208). Cham: Springer International Publishing.
- Cao, X. Y., Shen, D., Feng, D. C., Wang, C. L., Qu, Z., & Wu, G. (2022). Seismic retrofitting of existing frame buildings through externally attached sub-structures: State of the art review and future perspectives. *Journal of building engineering*, 57, 104904.
- Ciurlanti, J., Bianchi, S., Pürgstaller, A., Gallo, P. Q., Bergmeister, K., & Pampanin, S. (2022). Shake table tests of concrete anchors for non-structural components including innovative and alternative anchorage detailing. *Bulletin of Earthquake Engineering*, 20(8), 3971-3993.
- Clemett, N., Carofilis Gallo, W. W., Gabbianelli, G., O'Reilly, G. J., & Monteiro, R. (2023). Optimal combined seismic and energy efficiency retrofitting for existing buildings in Italy. *Journal of Structural Engineering*, 149(1), 04022207.
- D'Amore, S. (2024). *Enhancing Seismic Safety and Energy Efficiency of Existing Buildings through External Low-Damage Exoskeletons*. PhD Thesis, Sapienza University of Rome, Rome, Italy.
- D'Amore, S., & Pampanin, S. (2025). Displacement-based seismic retrofit of reinforced concrete buildings through low-damage exoskeletons. *Engineering Structures*, 322, 119209.
- D'Amore, S., Pedone, L., & Pampanin, S. (2023). Alternative retrofit strategies for seismic risk reduction: Studying the effectiveness of low-damage external exoskeletons. In *Proceedings of the 9th COMPDYN Conference*, Athens, Greece.
- D'Amore, S., & Pampanin, S. (2021). Seismic Retrofit of Reinforced Concrete buildings using low-damage external exoskeletons. In 2nd Fib Italy YMG. Symposium on concrete and concrete structures (pp. 1-13).
- D'Amore, S., Bianchi, S., Overend, M., & Pampanin, S. (2023). External timber-based low-damage exoskeletons for enhanced structural safety and energy efficiency. In 18th World Conference on Earthquake Engineering, Milan, Italy.

- Del Vecchio, C., Di Ludovico, M., Balsamo, A., Prota, A., Manfredi, G., & Dolce, M. (2014). Experimental investigation of exterior RC beam-column joints retrofitted with FRP systems. *Journal of Composites for Construction*, 18(4), 04014002.
- Di Vece, D., Pampanin, S. (2019). Combined retrofit solutions for seismic resilience and energy efficiency of reinforced concrete residential buildings with infill walls. In: *Proceedings of the 14th conf. on earthquake engineering in Italy*, ANIDIS, Ascoli Piceno, Italy.
- Directive (EU) 2018/844 (2018). Directive (Eu) 2018/844 of the European Parliament and of the council of 30 may 2018 amending directive 2010/31/Eu on the energy performance of buildings and directive 2012/27/Eu on energy efficiency. European Parliament and Council.
- DM 26/06/2015 (2015). Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici. *Gazzetta Ufficiale n.162 del 15-7-2015 - Suppl. Ordinario n. 39*, Rome, Italy. (in Italian)
- DPR 412 (1993). Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, in attuazione dell'art. 4, comma 4, della legge 9 gennaio 1991, n. 10. *Gazzetta Ufficiale n.96 14/10/1993*. Decree of the President of the Republic (DPR), Rome, Italy. (in Italian)
- EC (2019). The European green deal. Communication from the Commission, COM(2019) 640 final. Brussels, Belgium: European Commission (EC).
- Facconi, L., & Minelli, F. (2020). Retrofitting RC infills by a glass fiber mesh reinforced overlay and steel dowels: experimental and numerical study. *Construction and Building Materials*, 231, 117133.
- FEMA, 2008. Flood Damage-Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in accordance with the National Flood Insurance Program - Tech. Bull. 50.
- FEMA (2014). Homeowner's Guide to Retrofitting - Six Ways to Protect Your Home From Flooding FEMA P-312, 3rd Edition / June 2014.
- Holden, T., Devereux, C., Haydon, S., Buchanan, A., & Pampanin, S. (2016). NMIT Arts & Media Building—Innovative structural design of a three storey post-tensioned timber building. *Case studies in structural engineering*, 6, 76-83.
- IAE. (2021). Global status report for buildings and construction 2021. Paris: UN Environment and International Energy Agency (IEA).
- Kam, W. Y., & Pampanin, S. (2010). Experimental and numerical validation of selective weakening retrofit for existing non-ductile RC frames. In *Improving the seismic performance of existing buildings and other structures* (pp. 706-720).
- Lizundia, B., Holmes, W. T., Cobeen, K., Malley, J., & Lew, H. S. (2006). Techniques for the seismic rehabilitation of existing buildings. In *8th US National Conference on Earthquake Engineering 2006*.
- Loga, T., Balaras, C., Dascalaki, E., Sijanec Zavrl, M., Rakuscek, A., Corrado, V., et al. (2010). Use of building typologies for energy performance assessment of National building stocks. In: *Existent experiences in European countries and common approach*. Darmstadt/Germany: IWU—Institut Wohnen und Umwelt. First TABULA synthesis report
- Marini, A., Passoni, C., Belleri, A., Feroldi, F., Preti, M., Metelli, G., ... & Plizzari, G. (2022). Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: A proof of concept. *European Journal of Environmental and Civil Engineering*, 26(7), 2475-2495.
- Marinković, M., & Butenweg, C. (2022). Experimental testing of decoupled masonry infills with steel anchors for out-of-plane support under combined in-plane and out-of-plane seismic loading. *Construction and Building Materials*, 318, 126041.

- Marinković, M., & Butenweg, C. (2022). Experimental testing of decoupled masonry infills with steel anchors for out-of-plane support under combined in-plane and out-of-plane seismic loading. *Construction and Building Materials*, 318, 126041.
- Marriott, D., Pampanin, S., Bull, D. K., & Palermo, A. (2007). Improving the seismic performance of existing reinforced concrete buildings using advanced rocking wall solutions.
- Marriott, D., Pampanin, S., Bull, D., & Palermo, A. (2008). Dynamic testing of precast, post-tensioned rocking wall systems with alternative dissipating solutions.
- Menna, C., Felicioni, L., Negro, P., Lupíšek, A., Romano, E., Prota, A., & Hájek, P. (2022). Review of methods for the combined assessment of seismic resilience and energy efficiency towards sustainable retrofitting of existing European buildings. *Sustainable Cities and Society*, 77, 103556.
- Miliziano, A., Granello, G., Palermo, A., & Pampanin, S. (2020). Overview of connection detailing for post-tensioned dissipative timber frames. *Structural Engineering International*, 30(2), 209-216.
- Morandi, P., Milanese, R. R., & Magenes, G. (2018). Innovative solution for seismic-resistant masonry infills with sliding joints: in-plane experimental performance. *Engineering Structures*, 176, 719-733.
- Muñoz-Caballero, J., Vergara, D., Fernández-Arias, P., & Antón-Sancho, Á. (2022). Design of a smart barrier to internal flooding. *Inventions*, 7(4), 88.
- Newcombe, M. P., Pampanin, S., Buchanan, A., & Palermo, A. (2008). Section analysis and cyclic behavior of post-tensioned jointed ductile connections for multi-story timber buildings. *Journal of Earthquake Engineering*, 12(S1), 83-110.
- Palermo, A., Pampanin, S., Buchanan, A. H., Newcombe, M. P. (2005). Seismic design of multi-storey buildings using laminated veneer lumber (LVL). In: *Proceedings, New Zealand Society for earthquake engineering conference, Wairakei*.
- Pampanin, S. (2005). Emerging solutions for high seismic performance of precast/prestressed concrete buildings. *Journal of Advanced Concrete Technology*, 3(2), 207-223.
- Pampanin, S. (2017). Towards the practical implementation of performance-based assessment and retrofit strategies for RC buildings: challenges and solutions. In: *Proceedings of the 4th conference on smart monitoring, assessment and rehabilitation of civil structures, Zurich, Switzerland*.
- Pampanin, S. (2022). NextGen building systems-S4: Seismically safer, sustainable and smart-raising the Bar to enhance community resilience and sustainability. In: *Progresses in European earthquake engineering and seismology: third european conference on earthquake engineering and Seismology–Bucharest, 2022*. Cham: Springer International Publishing; 2022. p. 343–62.
- Pampanin, S., Christopoulos, C., & Chen, T. H. (2006). Development and validation of a metallic haunch seismic retrofit solution for existing under-designed RC frame buildings. *Earthquake engineering & structural dynamics*, 35(14), 1739-1766.
- Pampanin, S., Ciurlanti, J., Bianchi, S., Perrone, D., Granello, G., Palmieri, M., ... & Correia, A. A. (2023). Triaxial shake table testing of an integrated low-damage building system. *Earthquake Engineering & Structural Dynamics*, 52(10), 2983-3007.
- Passoni, C., Marini, A., Belleri, A., & Menna, C. (2021). Redefining the concept of sustainable renovation of buildings: State of the art and an LCT-based design framework. *Sustainable Cities and Society*, 64, 102519.
- Pedone, L., & Pampanin, S. (2023). Displacement incompatibility shape functions between masonry infill wall panels and reinforced concrete frames. *Bulletin of Earthquake Engineering*, 21(5), 2845-2875.
- Pedone, L., Molaioni, F., Vallati, A., & Pampanin, S. (2023). Energy refurbishment planning of Italian school buildings using data-driven predictive models. *Applied Energy*, 350, 121730.

- Preti, M., & Bolis, V. (2017). Masonry infill construction and retrofit technique for the infill-frame interaction mitigation: test results. *Engineering Structures*, 132, 597-608.
- Priestley, M. N. (1991). Overview of PRESSS research program. *PCI journal*, 36(4), 50-57.
- Priestley, M. N., Sritharan, S., Conley, J. R., & Pampanin, S. (1999). Preliminary results and conclusions from the PRESSS five-story precast concrete test building. *PCI journal*, 44(6), 42-67.
- Quintana Gallo, P., Moghaddasi, M., Pampanin, S., & Bergmeister, K. (2018). Shake table tests of post-installed anchors with supplemental damping. *ACI Structural Journal*, 115(3), 595-606.
- Rad, M. A., Pampanin, S., & Rodgers, G. (2019). Displacement-based retrofit of existing reinforced concrete frames using alternative steel brace systems.
- Santarsiero, G., Chiauzzi, L., Masi, A. (2016). Analisi del danneggiamento di edifici situati nella zona sud del comune di Amatrice (RI). Confronto pre e post sisma del 24/08/2016, Reluis report, Italy.
- Sarti, F., Palermo, A., & Pampanin, S. (2016). Fuse-type external replaceable dissipaters: Experimental program and numerical modelling. *Journal of Structural Engineering*, 142(12), 04016134.
- Sebastiani, I., D'Amore, S., Pinotti, R., & Pampanin, S. (2024). Integrated rehabilitation of reinforced concrete buildings: Combining seismic retrofit by means of low-damage exoskeleton and energy refurbishment using multi-functional prefabricated facade. *Journal of Building Engineering*, 95, 110368.
- Smith, T., Ponzio, F. C., Di Cesare, A., Pampanin, S., Carradine, D., Buchanan, A. H., & Nigro, D. (2014). Post-tensioned glulam beam-column joints with advanced damping systems: Testing and numerical analysis. *Journal of Earthquake Engineering*, 18(1), 147-167.
- Stanton, J., Stone, W.C., Cheok, G. S. (1997). A hybrid reinforced precast frame for seismic regions. *PCI journal*, 42(2), 20-32.
- Takeda, K., Tanaka, K., Someya, T., Sakuda, A., & Ohno, Y. (2013). Seismic retrofit of reinforced concrete buildings in Japan using external precast, prestressed concrete frames. *PCI journal*, 58(3).
- Taslighedik, A. S., & Pampanin, S. (2017). Rocking cantilever clay brick infill wall panels: a novel low damage infill wall system. *Journal of Earthquake Engineering*, 21(7), 1023-1049.
- Taslighedik, A. S., Pampanin, S., & Palermo, A. (2015). Low damage seismic solutions for non-structural drywall partitions. *Bulletin of Earthquake Engineering*, 13, 1029-1050.
- Tsantilis, A. V., & Triantafyllou, T. C. (2018). Innovative seismic isolation of masonry infills using cellular materials at the interface with the surrounding RC frames. *Engineering Structures*, 155, 279-297.
- Zamic, R., & Tomazevic, M. (1984). The behaviour of masonry infilled reinforced concrete frames subjected to cyclic lateral loading. In: *Proceedings of the 8th world conference on earthquake engineering*. Pren-tice-Hall, San Francisco.

Appendices

Appendix I: Guidelines and standards for flood risk reduction

Guidelines and standards in USA

Among the most relevant documents for the topic of this study, those written by FEMA (Federal Emergency Management Agency) and ANSI (American National Standards Institute) stand out. The most important such guides are briefly highlighted below:

- **FEMA Technical Bulletin 2 – Flood Damage-Resistant Materials Requirements:** classifies materials according to their behavior in contact with water and recommends what type of material for exposed areas.
- **FEMA P-348 - Protecting Building Utilities From Flood Damage:** *provides technical recommendations for the location, protection and elevation of essential installations (electricity, HVAC, water, sewage) in buildings at risk of flooding. The aim is to prevent disruption of building operations and damage to critical equipment.*
- **FEMA P-936 - Floodproofing Non-Residential Buildings:** *describes methods of sealing, structural reinforcement and active protection for commercial or industrial buildings. Includes solutions such as movable barriers, watertight doors and water-resistant materials, correlated with the risk level and flood zone classification.*
- **ASCE 24 – Flood Resistant Design and Construction** (developed by the American Society of Civil Engineers in collaboration with FEMA): fundamental standard for the design of buildings exposed to flooding, mandatory in the USA for buildings located in areas at risk.
- **American National Standard for Flood Mitigation Equipment** provides a comprehensive set of standards and technical requirements for the design, manufacture, testing, and installation of flood mitigation equipment. It was developed by ANSI and focuses on ensuring the performance and safety of flood protection systems, such as movable or fixed barriers, watertight doors, protective shutters, and backflow valves. The standard establishes clear criteria for equipment classification, acceptable materials, test methods, and manufacturing tolerances. It also defines maintenance and inspection procedures to maintain the efficiency of the systems over time. It is intended for use by designers, builders, local authorities, manufacturers and other parties involved in flood risk management. By adopting this guide, a uniform and safe approach is promoted for the implementation of technical solutions aimed at reducing the impact of floods on infrastructure and the population.

Guidelines and standards written and widely used in Europe

- **European Standard EN 13564 – Anti-flooding devices for buildings.** It is applied in the field of devices used to prevent the backflow of wastewater in buildings, especially in basements and cellars. The components concerned are: non-return valves, automatic valves, drainage systems with pumps. This standard provides a hierarchy of devices depending on the type of water (domestic wastewater, rainwater, etc.) and the degree of automation. It has a high importance because it is fundamental in areas where the risk of flooding through sewer networks is high.

- **Standard PAS 1188 (UK) – Flood protection products.** Developed by British Standards Institution (BSI), and widely used in Europe.

Sub-divisions:




- **PAS 1188-1:** Flood Protection products. Building aperture products.
- **PAS 1188-2:** Temporary and demountable flood protection products.
- **PAS 1188-3:** Buildings and building skirt systems.
- **PAS 1188-4:** Demountable products.






Performance tests: water pressure testing, wave exposure, forced penetration, wear durability.

Labeling: successfully tested products receive PAS certification, which is a guarantee of technical reliability.

Examples of manufacturers and products made according to the specifications of recognized guidelines (Table A 1)

Table A 1. Comparative details of products certified or compliant with different standards

Product / System	Protection Type	Certified/ Compliant Standard	Testing Criteria	Manufacturer / Country
 <p>FPS Barrier ®</p>	Removable door flood barrier	PAS 1188-1	Watertightness, mechanical load, leakage limit	Flood Protection Solutions / UK
 <p>Aquastop Door Barriers®</p>	Mechanical barrier for door frames	PAS 1188-1	Sealing under pressure, stress testing, reusability	Aquastop / Italy
 <p>SMART AirBrick®</p>	Manual cover for air bricks	PAS 1188-1	Impact resistance, seal integrity	UK Flood Defence Alliance
<p>PS Flood Barriers™ – Hydro1® Pedestrian Flood Door</p>	Permanent watertight door	FEMA P-936 tested	Static head, durability, corrosion resistance	PS Industries / USA

				
AquaFence® Wall System 	Deployable modular flood wall	FEMA guidance & PAS 1188-2	Load-bearing, time-to-deploy, real-world performance	AquaFence / Norway-USA
AquaFence® FloodBarricade 	FloodBarricade is tailor made to fit any opening	FM2510 compliant	Load-bearing, time-to-deploy, real-world performance	AquaFence / Norway-USA
IBS Technics® Mobile Barrier (MOBILDEICH®) 	Heavy-duty flood gate & door barrier	Tested to PAS 1188-1	Aluminum panel pressure testing, reuse, leakage rate	IBS Technics / Germany
Aquobex® Aluminium Slot-in Barrier 	Removable door flood barrier	PAS 1188-1 certified	Fully watertight, tested to static water load	Aquobex/UK

Appendix II: Installation procedure for removable panels

Installation of removable panels is usually quick and requires minimal tools. Also, generally the installation procedure implies 4 main steps detailed below and also represented in Figure A 1:

Step 1: Side channels installation

Permanently fix the side channels to the door or window frame using anchor bolts. They must be perfectly aligned vertically. Inside, rubber gaskets (EPDM/neoprene) are installed for sealing. The channels will guide the panels and ensure lateral sealing.

Step 2: Insert the Bottom Panel

The first panel (the bottom one) is inserted by sliding it between the side channels until it rests on the lower threshold. The person carrying out the installation process must ensure that the panel presses firmly against the gasket mounted on the floor for a correct seal.

Step 3: Fixing/securing the panels

The panel is secured in place with screws or levers. By tightening these, the rubber gaskets are compressed, providing a waterproof barrier. Advanced systems may have compression indicators.

Step 4: Install Additional Panels

The panels are installed sequentially from the bottom up. Each panel is provided with interlocking edges for secure joining. The fixing and sealing process is repeated for each level, up to the desired height.

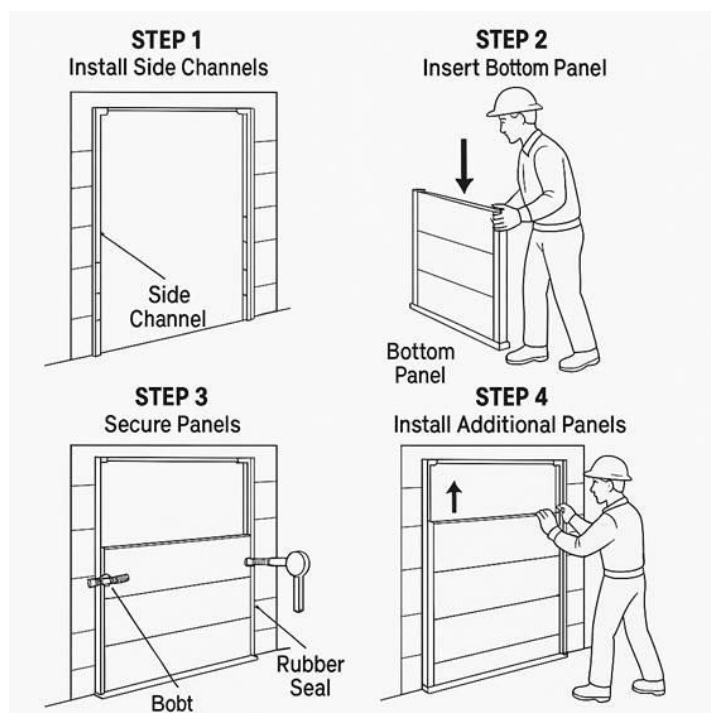


Figure A 1. Steps followed for flood barrier installation at door level

In Figure A 2 can be seen some examples of representative flood removable panels.



Figure A 2. Example of representative flood removable panels (source: Bignami et al., 2019)

In Table A 2 there are mentioned the main advantages and disadvantages of the flood barriers at doors and windows level.

Table A 2. Flood barriers advantages and disadvantages

Advantages	Disadvantages
Preserves normal building use and appearance.	Possible assembly or coordination errors between different systems may occur due to the human factor.
Can be less expensive, depending on site adaptation conditions.	Requires storage space, protected and, preferably, supervised, near areas prone to being affected by the hazard, for periods when not in use.
Easy to deploy with minimal labor.	They are mainly recommended for short-term flooding.
Can be used in conjunction with other methods to reduce damage during floods.	
Can be used on a large scale and in multiple ways, in different sites.	

Appendix III: Installation procedure for packing flood barriers

The general steps for mounting packing barriers structure against flooding are as follows:

Step 1: Preparing the area

Before installing packing flood barriers, it is necessary to clean the surface on which it will be installed so that the debris is removed. This step is necessary to ensure that the surface between the barrier and the material on the ground is sealed and water cannot penetrate.

Step 2: Installing side rails glued to the building

Vertical aluminum or stainless-steel bars are fixed to the walls of the building, to which flood panels will be attached. They are mounted in the ground with dowels, chemical anchors or expansion screws, depending on the material of the ground surface. For good tightness, the positioning of the metal bars must be perfectly vertical (Figure A 3).



Figure A 3. Installing side bars attached to the building

Step 3: Installing the modular panels between the side bars

They are inserted vertically. Each panel has a gasketed edge to prevent leakage between layers. The final height is determined by the anticipated flood risk (Figure A 4).



Figure A 4. Modular panels installed between the side bars

Step 4: Fixing braces for stability

Metal braces are installed from the ground towards the middle or top of the panels. They ensure the barrier's resistance to hydrostatic water pressure. They can be anchored to the ground (with metal plates, weights or fixing screws). For corners or long sections, the number of buttresses must be increased (Figure A 5).



Figure A 5. Fixing braces for stability

In Figure A 6 can be seen some examples of packing technique for building protection in the field.

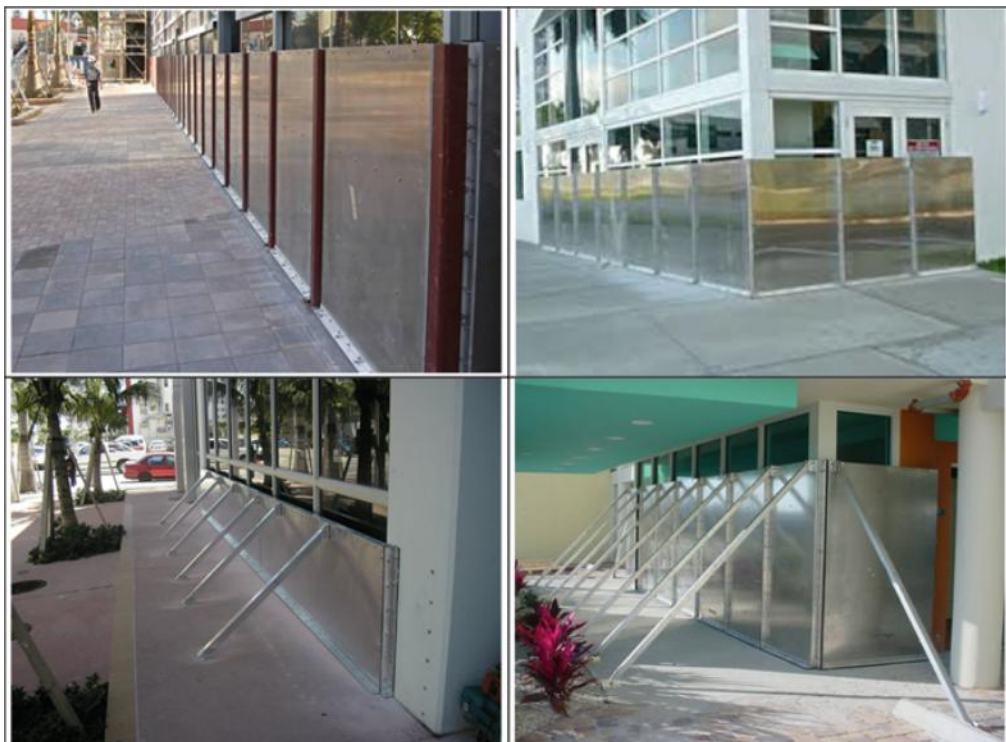


Figure A 6. Examples of packing technique for building protection (source: Bignami et al., 2019)

Appendix IV: Installation procedure for flood doors

The steps for installing a flood door are the following:

Step 1: Preparing the site and door

The installation area will be completely cleaned, including the threshold and edge of the opening. Ensure that the space around the opening is dry and free of impurities. This operation is necessary because such spaces or impurities can compromise the seal.

Step 2: Positioning the door frame in the opening gap

Insert the door frame into the designed location, checking alignment with the floor and wall. Use the level tool to ensure that the frame is positioned correctly both vertically and horizontally.

Step 3: Fixing the structural frame

The structural frame is fastened to the masonry (concrete, brick) using mechanical or chemical anchors. It is necessary that the tension of the elements is evenly distributed to avoid deformation. Extensions will be left for sealing gaskets (channels integrated into the frame).

Step 4: Installation of the door itself

The door leaf will be inserted into the fixed frame and the alignment will be checked by opening and closing it manually. Temporary fixing elements (optional) will be added to help with positioning before the final locking on the structural frame.

Step 5: Installing the sealing system

EPDM gaskets will be placed or silicone will be applied in the special channels in the frame. The compression will be checked, which must be uniform over the entire circumference between the door leaf and the structural frame. Any leaks could be detected by spraying water at the point of contact between the door leaf and the structural frame.

Step 6: Activating the multi-point locking mechanism

The central levers or bolts will be mobilized and in automatic models the electric/hydraulic system will be activated. This mechanism will have to pull the door leaf onto the structural frame, so as to achieve an optimal seal.

Step 7: Finishing and final check

Silicone or waterproofing foam will be applied to the corners and the area of contact with the ground. A controlled water test shall be carried out (if possible) to check the overall seal. Drainage will be provided in the vicinity, to avoid the accumulation of water on the threshold.

Flood doors can be used in the following areas of application:

- **Public buildings:** hospitals, schools, town halls, administrative headquarters
- **Commercial spaces:** shopping centers, underground parking lots
- **Critical infrastructures:** pumping stations, banks, data centers
- **Industrial areas:** warehouses, logistics halls, power plants
- **Historical buildings:** restorations with invisible protection requirements

In Figure A 7 can be seen some examples of flood doors for building protection in the field.

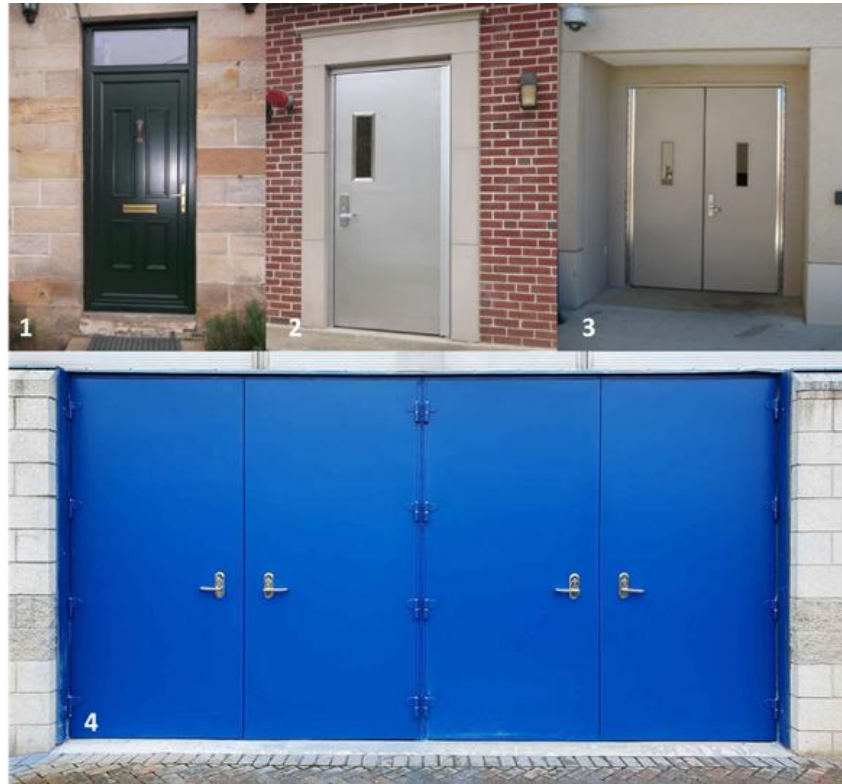


Figure A 7. Examples of flood doors for building protection (1. Residential type (source: <https://www.stormmeister.com/flood-doors-for-homes/>); 2. Industrial type (source: <https://www.psfloodbarriers.com/product/fire-rated-flood-door-single/>); 3. Industrial type (source: <https://floodcontrolinternational.com/secure-flood-doors/>); 4. Industrial type– double (source: <https://floodcontrolinternational.com/secure-flood-doors/>)

Appendix V: Flood protection measures at the foundation level

Method 1: Elevating on Continuous Foundation Walls

Open foundations should be considered as a reasonable mitigation option. After the home is detached from its foundation and raised on jacks, the existing foundation is often saved and the foundation walls are extended. The new portions of the walls are usually made of masonry block or cast-in-place concrete. Although this method may be the easiest way to elevate a home, it can involve some additional construction modifications or reinforcements. In Figure A 8 a technical draw of typical cross-section of home elevated on continuous foundation walls can be seen (FEMA, 2014).

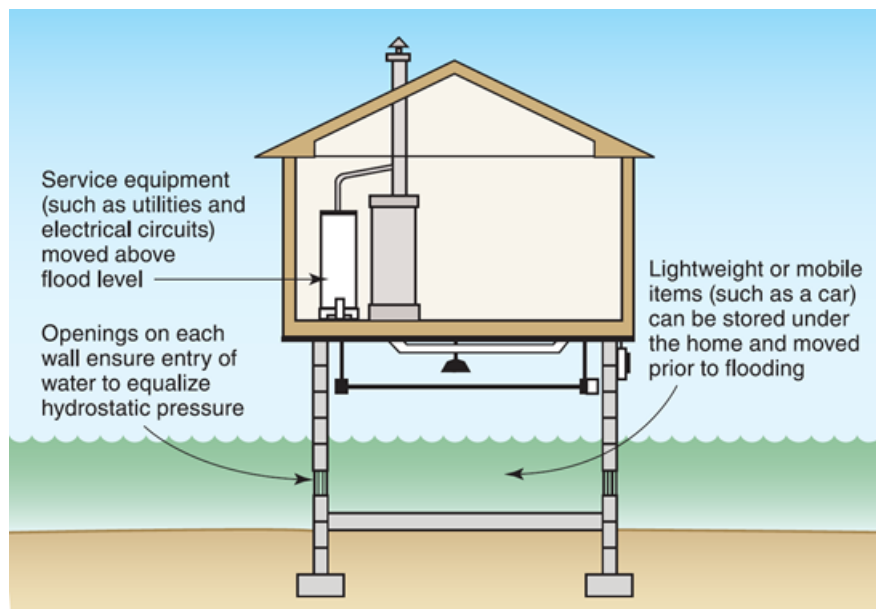


Figure A 8. Typical cross-section of home elevated on continuous foundation walls (source: FEMA, 2014)

A real-life building retrofitted using this elevation technique is presented in Figure A 9.



Figure A 9 Before (left) and after (right) photos of a retrofitted home elevated on extended continuous foundation walls (source: FEMA, 2014)

Method 2: Elevating on Open Foundations

Open foundations are a structural solution commonly employed in flood-prone areas, particularly where wave action or high-velocity water flows are expected. Unlike continuous foundation systems, open foundations are composed of discrete vertical load-bearing members that support the structure at critical points. Their design allows floodwaters to pass underneath the building with minimal obstruction, thereby reducing hydrodynamic pressure and the risk of structural damage.

The most frequently used open foundation types are piers, posts, and piles. Each has distinct characteristics, applications, and installation methods:

1. Piers (Masonry or Concrete Columns)

Piers (Figure A 10) are vertical structural elements commonly constructed from concrete masonry units (CMUs), cast-in-place concrete, or occasionally steel or timber. Each pier is seated on a concrete footing that distributes the load to the ground.

In conventional construction, piers are primarily intended to support vertical loads such as the weight of the building. However, in flood-resistant applications, additional reinforcement is required. Piers are not inherently designed to resist lateral forces caused by water currents, wave impact, debris, wind, or seismic activity. As a result, they are most appropriate in areas where flood velocities and wave action are considered low to moderate, and seismic risk is minimal.

Design recommendations:

- Reinforce piers and footings with **steel rebar** to improve load transfer and resistance.
- Ensure that **piers are securely anchored to the footings** to prevent displacement under lateral loads.
- Use **strong mechanical connectors** between piers and the elevated structure to withstand uplift, wind shear, and flood forces.

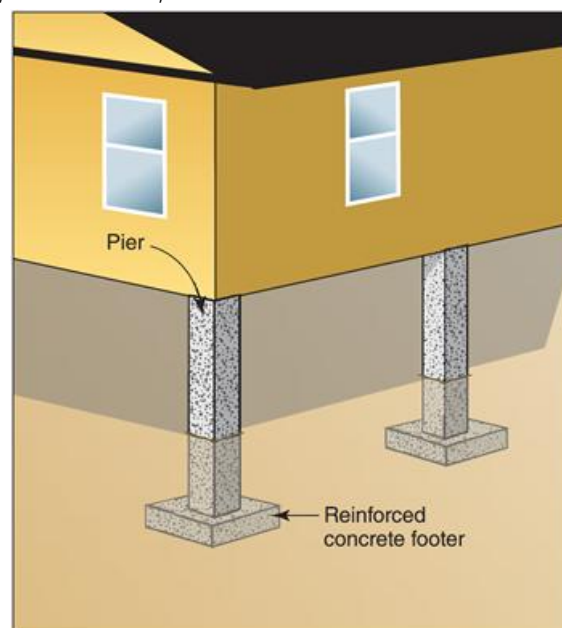


Figure A 10. Home elevated on reinforced concrete piers (source: FEMA, 2014)

2. Posts (Typically Timber or Steel)

Posts (Figure A 11) are vertical members typically made of **pressure-treated wood** or **steel**, and are either square or round in cross-section. Posts are set into excavated holes and supported by **concrete pads** or encased directly in concrete. After installation, voids around the posts may be filled with concrete, gravel, or compacted soil.

Due to their slender form, **posts require bracing** to improve lateral stability. Bracing systems may consist of wooden cross-members, steel rods, or tension cables, selected based on site-specific loading conditions, cost, and availability.

Like piers, posts are best suited for use in regions with **moderate or predictable flood conditions**. Posts generally have a **smaller cross-section** than piers and are often taller, which makes them **more flexible but also less stable**—hence the need for bracing.

Design recommendations:

- Install diagonal bracing between posts to increase resistance to lateral loads.
- Ensure post embedment depth and material selection are adequate for anticipated soil conditions and water forces.
- Use corrosion-resistant materials if posts are exposed to moisture or saltwater.

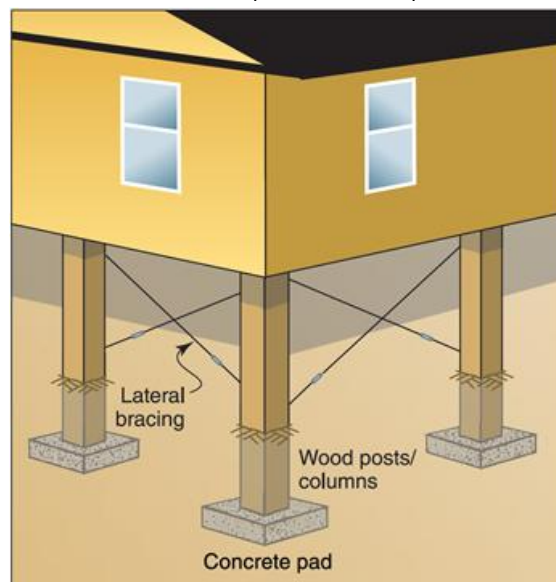


Figure A 11. Home elevated on posts (source: FEMA, 2014)

3. Piles (Driven or Jetted Foundation Elements).

Piles are long, slender columns made of **wood, steel, fiber-reinforced polymer (FRP), or precast concrete**, and are **driven or jetted deep into the ground** rather than placed in shallow excavations (Figure A 12). Because of their deep embedment, pile foundations are **the most resilient** among open foundation systems, offering superior resistance to erosion, scour, wave impact, and high-velocity flood flows.

Unlike piers and posts, **piles do not rest on concrete footings**. Instead, they rely on either:

- **End bearing**, where the pile reaches a stable layer such as bedrock, or
- **Skin friction**, where the pile's surface area interacts with the surrounding soil to support vertical and lateral loads.

Design recommendations:

- Select pile type and material based on soil geotechnical conditions and expected loading scenarios.
- Embed piles to a depth sufficient to resist vertical uplift and lateral water forces.
- Ensure pile caps and structural connectors are engineered to transfer loads effectively to the superstructure.

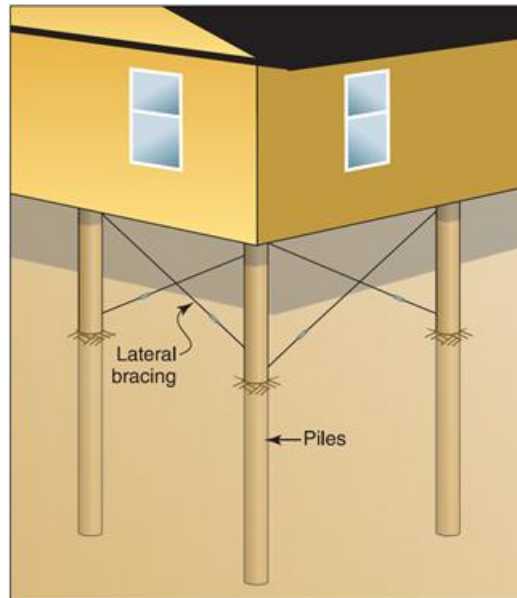


Figure A 12. Home elevated on piles (source: FEMA, 2014)

In Table A 3, a summary comparison of the three foundation types was done.

Table A 3. Summary comparison of the three foundation types

Foundation Type	Material	Installation	Best For	Structural Behavior	Flood Resistance
Piers	CMU, Concrete	Set on footings	Low/moderate flood areas	Strong vertical support	Moderate
Posts	Wood, Steel	Set in holes	Low/moderate flood areas	Flexible, needs bracing	Moderate
Piles	Wood, Steel, FRP	Driven or jetted	High flood / coastal areas	High lateral and vertical resistance	High

Appendix VI: Performance of building materials in flood-prone environments

The classification is based on the **type of material, specific uses in construction** (such as floors, walls, and ceilings), and whether the material is considered **acceptable** or **unacceptable** under prolonged exposure to water. The materials are grouped into three primary categories: **Structural Materials**, **Structural Building Components**, and **Finish Materials** (Table A 4).

Structural Materials

This category includes materials such as concrete, brick, cement board, stone, and other components used in core structural applications (e.g., floor slabs, beams, framing, subfloors, and sheathing). The table clearly indicates that certain materials perform exceptionally well when exposed to water or flooding:

- **Concrete (precast or cast-in-place)** is universally acceptable for both floors and walls/ceilings, making it one of the most flood-resilient materials.
- **Brick (face or glazed)** and **natural or artificial non-absorbent stone with waterproof grout** also show top performance, with full acceptability in structural applications.
- **Cement board/fiber-cement board, concrete block, and cast stone set in waterproof mortar** are also among the most reliable choices.

Conversely, materials that incorporate paper or other organic binders tend to be far less durable. For example:

- **Paper-faced gypsum board, greenboard, and plaster (non-Keene's types)** are generally unacceptable due to their water absorption and degradation tendencies.
- **Hardboard (all non-tempered types), mineral fiberboard, non-exterior grade OSB, particle board, and interior-grade plywood** are all deemed unacceptable, especially in flooring or structural wall applications.

This section underscores the importance of **material density, water resistance, and inorganic composition** as key factors in flood resilience.

Structural Building Components

This section focuses on engineered and load-bearing components such as **floor trusses, headers and beams, and wall panels**, fabricated from wood, steel, or engineered composites.

- **Steel components** (e.g., floor trusses, headers, beams, and wall panels) are widely acceptable due to their structural integrity and resistance to water damage—assuming proper corrosion protection.
- **Wood framing elements**, such as **solid wood (2x4s)** that are **decay-resistant or preservative-treated with ACQ or copper azole (CA)**, are considered acceptable.
- **Plywood and OSB**, if **exterior-grade or edge swell-resistant**, can also be used effectively. However, standard OSB or untreated materials are unacceptable due to swelling and breakdown when wet.

The table reinforces that **treatment and grading** are critical—materials that may otherwise be unsuitable can become viable with the correct enhancements (e.g., Borate-treated wood).

Finish Materials

Finish materials include floor coverings, wall and ceiling finishes, insulation, cabinets, doors, partitions, and windows. This is where the differences between acceptable and unacceptable materials are most striking.

- **Ceramic and porcelain tile** with **mortar set**, **concrete tile**, and **epoxy formed-in-place finishes** are considered flood-safe due to their impermeability and inert nature.
- **Non-ferrous metals** (such as aluminum, copper, and zinc tiles) and properly adhered **steel panels/trim** are suitable for both floors and walls.
- **Waterproof paint systems** (e.g., **polyester-epoxy**) are preferred over basic latex coatings, though high-quality latex is sometimes acceptable.

On the other hand, a wide range of commonly used finish materials are unsuitable in flood-prone areas:

- **Carpeting, linoleum, asphalt tile, mastic floor coverings, and rubber (except chemical-set types)** are all listed as **unacceptable**.
- **Vinyl tiles/sheets** with organic adhesives or on cork/wood backings are discouraged. Only **homogeneous vinyl** with **chemical-set adhesives** is considered acceptable.
- **Cabinets made of particle board, wood frame partitions, and doors with lightweight panel construction** also fall into the unacceptable category due to their susceptibility to moisture damage and warping.

Insulation materials vary widely in performance:

- **Closed-cell plastic foams (e.g., SPUF)** and **inorganic materials** like **fiberglass or mineral wool** are acceptable.
- **Cellulose, cotton, and open-cell plastic foams** are not suitable in flood situations, as they retain moisture and degrade quickly.

The commentary also notes the importance of **installation methods and adhesives**—a tile or flooring type may be acceptable only when installed with waterproof adhesives or mortar sets.

Classification of Acceptability

The table marks materials as "Acceptable" or "Unacceptable" for two key uses: **floors** and **walls/ceilings**. The materials marked with an "x" under both uses offer the most flexibility and durability in design for flood-prone areas.

Additionally, while the table contains columns for classifying materials into Classes 1 to 5, these ratings are not populated in the visible data. Still, their presence implies an evaluative framework—possibly based on metrics like durability under submersion, drying time, and maintenance requirements—which could be useful in future standardization efforts.

General Observations

- **Dense, non-absorbent, inorganic materials** are consistently more flood-resistant than porous, organic, or untreated wood products.

- **Material treatment** (e.g., chemical preservatives, waterproof coatings) significantly enhances resilience.
- **Adhesives and installation methods** are critical—materials that are inherently waterproof can fail if applied with water-sensitive adhesives.
- Components like **engineered wood, fiber-reinforced plastics, and metal doors with foam cores** show promise but require precise specifications to meet flood-resilience standards.

The document highlights the importance of using **flood damage-resistant materials** as defined by FEMA and other codes, especially in **Special Flood Hazard Areas (SFHAs)**. Selection based on both **material type** and **proper installation method** is vital for long-term durability.

Table 8 serves as a practical guide for selecting construction materials that can withstand flooding. It is particularly relevant for rebuilding efforts after flood events and for proactive planning in high-risk zones. The information supports evidence-based material selection, promotes structural resilience, and helps reduce recovery costs. It also emphasizes that **no single material is universally suitable**—the context of use, method of application, and protective treatments all contribute to a system’s overall flood resistance. Integrating this guidance into local building codes and architectural practice is essential for resilient, long-lasting construction in flood-prone environments.

Table A 4. Types, Uses, and Classifications of Materials (source: FEMA, 2008)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
	Floors	Walls/ Ceilings	Acceptable		Unacceptable		
			5	4	3	2	1
Structural Materials (floor labs, beams, subfloors, framing, and interior/exterior sheathing)							
Asbestos-cement board	X	X					X
Brick							
<i>Face or glazed</i>	X	X					X
<i>Common (clay)</i>	X		X				X
Cast stone (in waterproof mortar)	X	X					X
Cement board/fiber-cement board	X	X					X
Cement/latex, formed-in-place			X				
Clay tile, structural glazed	X	X					X
Concrete, precast or cast-in-place	X	X					X

Concrete block ¹	x	x					x
Gypsum products							
<i>Paper-faced gypsum board</i>	x			x			x
<i>Non-paper-faced gypsum board</i>	x		x				x
<i>Greenboard</i>	x				x		x
<i>Keene's cement or plaster</i>	x			x			x
<i>Plaster, otherwise, including acoustical</i>	x				x		x
<i>Sheathing panels, exterior grade</i>	x			x			x
<i>Water-resistant, fiber-reinforced gypsum exterior sheathing</i>	x		x				x
Hardboard (high-density fiberboard)							
<i>Tempered, enamel or plastic coated</i>	x				x		x
<i>All other types</i>	x					x	x
Mineral fiberboard	x					x	x
Oriented-strand board (OSB)							
<i>Exterior grade</i>	x				x		x
<i>Edge swell-resistant OSB</i>	x				x		x
<i>All other types</i>	x					x	x
Particle board						x	
Plywood							
<i>Marine grade</i>	x	x					x
<i>Preservative-treated, alkaline copper quaternary (ACQ) or copper azole (C-A)</i>	x		x				x
<i>Preservative-treated, Borate²</i>	x	x					x
<i>Exterior grade/Exposure1 (WBP – weather and boil proof)</i>	x		x				x
<i>All other types</i>	x					x	x

Recycled plastic lumber (RPL)							
<i>Commingled, with 80-90% polyethylene (PE)</i>		x					
<i>Fiber-reinforced, with glass fiber strands</i>		x					
<i>High-density polyethylene (HDPE), up to 95%</i>		x					
<i>Wood-filled, with 50% sawdust or wood fiber</i>				x			
Stone							
<i>Natural or artificial non-absorbent solid or veneer, waterproof grout</i>	x	x					x
<i>All other applications</i>	x				x		x
Structural Building Components							
<i>Floor trusses, wood, solid (2x4s), decay-resistant or preservative-treated</i>	x		x				x
<i>Floor trusses, steel³</i>		x					
<i>Headers and beams, solid (2x4s) or plywood, exterior grade or preservative-treated</i>	x		x				x
<i>Headers and beams, OSB, exterior grade or edge-swell resistant</i>	x				x		x
<i>Headers and beams, steel³</i>	x	x					x
<i>I-joists</i>					x		
<i>Wall panels, plywood, exterior grade or preservative-treated</i>	x		x				x
<i>Wall panels, OSB, exterior grade or edge-swell resistant</i>	x				x		x
<i>Wall panels, steel³</i>	x		x				x
Wood							
<i>Solid, standard, structural (2x4s)</i>	x		x				x
<i>Solid, standard, finish/trim</i>	x			x			x
<i>Solid, decay-resistant⁴</i>	x	x					x

<i>Solid, preservative-treated, ACQ or CA</i>	x		x				x
<i>Solid, preservative-treated, Borate²</i>	x		x				x
Finish Materials (floor coverings, wall and ceiling finishes, insulation, cabinets, doors, partitions, and windows)							
Asphalt tile ⁵							
<i>With asphaltic adhesives</i>				x			
<i>All other types</i>						x	
Cabinets, built-in							
<i>Wood</i>	x				x		x
<i>Particle board</i>	x					x	x
<i>Metal³</i>	x		x				x
Carpeting						x	
Ceramic and porcelain tile							
<i>With mortar set</i>	x		x				x
<i>With organic adhesives</i>	x				x		x
Concrete tile, with mortar set		x					
Corkboard	x				x		x
Doors							
<i>Wood, hollow</i>	x				x		x
<i>Wood, lightweight panel construction</i>	x				x		x
<i>Wood, solid</i>	x				x		x
<i>Metal, hollow³</i>	x		x				x
<i>Metal, wood core³</i>	x		x				x
<i>Metal, foam-filled core³</i>	x		x				x
<i>Fiberglass, wood core</i>	x		x				x
<i>Epoxy, formed-in-place</i>		x					

Glass (sheets, colored tiles, panels)	x		x				x
Glass blocks	x	x					x
Insulation							
<i>Sprayed polyurethane foam (SPUF) or closed-cell plastic foams</i>	x	x					x
<i>Inorganic – fiberglass, mineral wool: batts, blankets, or blown</i>	x			x			x
<i>All other types (cellulose, cotton, opencell plastic foams, etc.)</i>	x				x		x
Linoleum						x	
Magnesite (magnesium oxychloride)						x	
Mastic felt-base floor covering						x	
Mastic flooring, formed-in-place		x					
Metals, non-ferrous (aluminum, copper, or zinc tiles)	x			x			x
Metals							
<i>Non-ferrous (aluminum, copper, or zinc tiles)</i>	x			x			x
<i>Metals, ferrous³</i>	x		x				x
Paint							
<i>Polyester-epoxy and other oil-based waterproof types</i>	x		x				x
<i>Latex</i>	x		x				x
Partitions, folding							
<i>Wood</i>	x				x		x
<i>Metal³</i>	x		x				x
<i>Fabric-covered</i>	x					x	x
Partitions, stationary (free-standing)							
<i>Wood frame</i>	x		x				x
<i>Metal³</i>	x		x				x

<i>Glass, unreinforced</i>	x		x				x
<i>Glass, reinforced</i>	x		x				x
<i>Gypsum, solid or block</i>	x					x	x
Polyurethane, formed-in-place		x					
Polyvinyl acetate (PVA) emulsion cement						x	
Rubber							
<i>Moldings and trim with epoxy polyamide adhesive or latex-hydraulic cement</i>	x		x				x
<i>All other applications</i>	x					x	x
Rubber sheets or tiles ⁵							
<i>With chemical-set adhesives⁶</i>		x					
<i>All other applications</i>						x	
Silicone floor, formed-in-place		x					
Steel (panels, trim, tile)							
<i>With waterproof adhesives³</i>	x	x					x
<i>With non-waterproof adhesives</i>	x				x		x
Terrazo			x				
Vinyl asbestos tile (semi-flexible vinyl) ⁵							
<i>With asphaltic adhesives</i>		x					
<i>All other applications</i>						x	
Vinyl sheets or tiles (coated on cork or wood product backings)						x	
Vinyl sheets or tiles (homogeneous) ⁵							
<i>With chemical-set adhesives⁶</i>			x				
<i>All other applications</i>						x	
Wall coverings							
<i>Paper, burlap, cloth types</i>	x					x	x

<i>Vinyl, plastic, wall paper</i>	x					x	x
Wood floor coverings							
<i>Wood (solid)</i>						x	
<i>Engineered wood flooring</i>					x		
<i>Plastic laminate flooring</i>					x		
<i>Wood composition blocks, laid in cement mortar</i>					x		
<i>Wood composition blocks, dipped and laid in hot pitch or bitumen</i>					x		

Notes:

¹Unfilled concrete block cells can create a reservoir that can hold water following a flood, which can make the blocks difficult or impossible to clean if the floodwaters are contaminated.

²Borate preservative-treated wood meets the NFIP requirements for flood damage-resistance; however, the borate can leach out of the wood if the material is continuously exposed to standing or moving water.

³Not recommended in areas subject to salt-water flooding.

⁴Examples of decay-resistant lumber include heart wood of redwood, cedar, and black locust. Refer to Section 2302 of the International Building Code® (IBC®) and Section R202 of the International Residential Code® (IRC®) for guidance.

⁵Using normally specified suspended flooring (i.e., above-grade) adhesives, including sulfite liquor (lignin or "linoleum paste"), rubber/asphaltic dispersions, or "alcohol" type resinous adhesives (culmar, oleoresin).

⁶Examples include epoxy-polyamide adhesives or latex-hydraulic cement.