MITIGATING EARTHQUAKE VULNERABILITY OF MIXED URM-RC BUILDINGS AT THE URBAN SCALE

Characterization of mixed URM-RC building typologies

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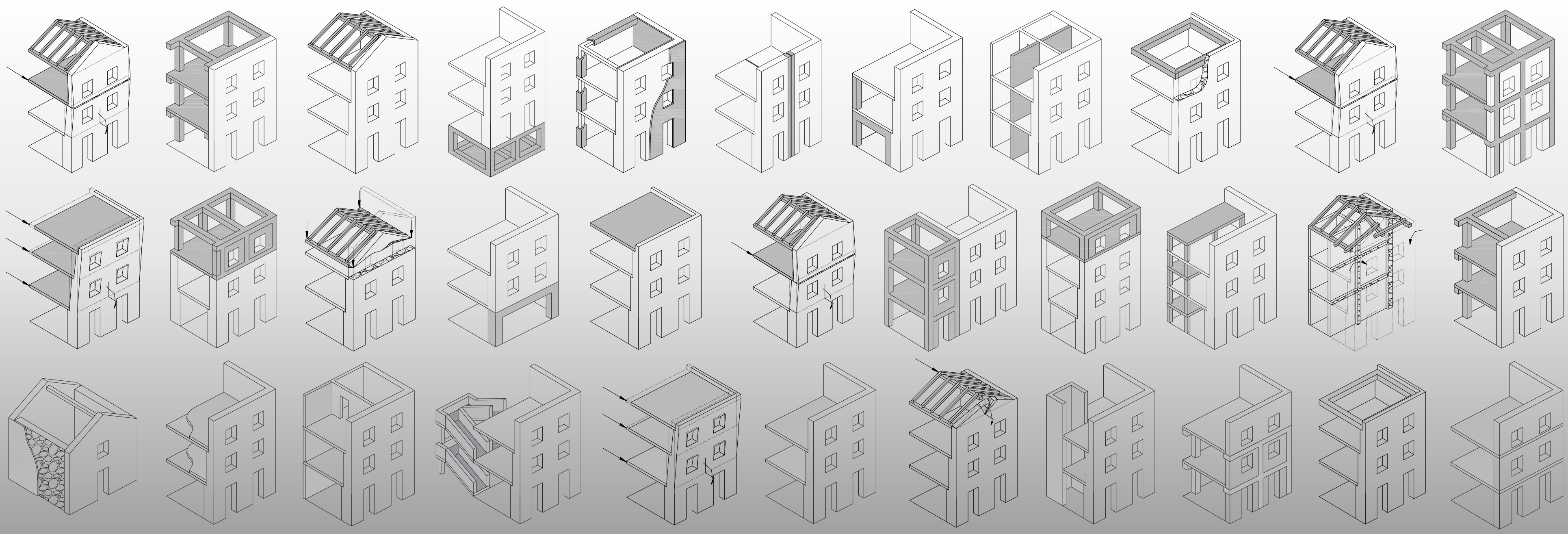
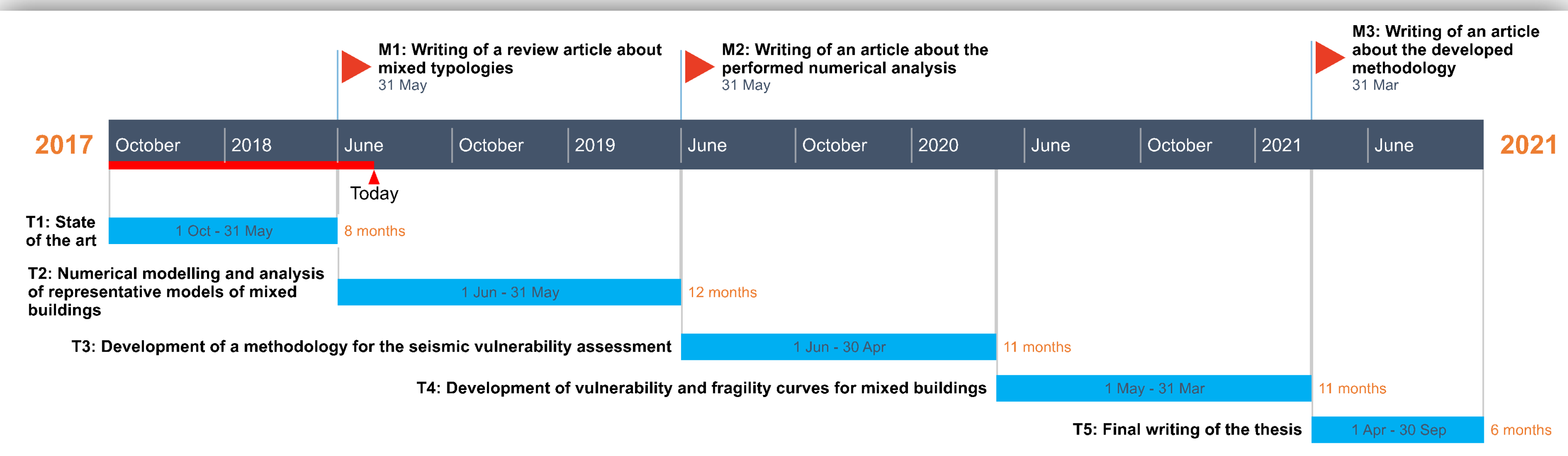


Presentation summary

- Thesis timeline and objectives
- T1: State of the art
    - Highlights
    - Principal stages of the evolution of the RC role in buildings (RC elements shaded in grey)
    - Intervention types for derived URM-RC buildings
    - Structural typologies of derived URM-RC buildings
    - Damages from past earthquakes to mixed URM-RC buildings

- T2: Numerical analysis of representative URM-RC structural strengthening solutions for buildings

Thesis timeline and objectives



T1: State of the art

Comprehensive catalogue of existing Unreinforced Masonry-Reinforced Concrete mixed building typologies (URM-RC) resulting from past retrofitting or strengthening actions;

T2: Numerical analysis of representative URM-RC structural strengthening solutions for buildings

T3: Development of an innovative vulnerability assessment approach suitable for URM-RC structural typologies

T4: Development of vulnerability and fragility curves for the URM- RC building typology

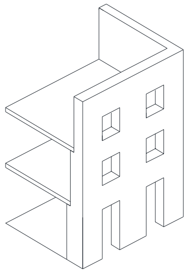
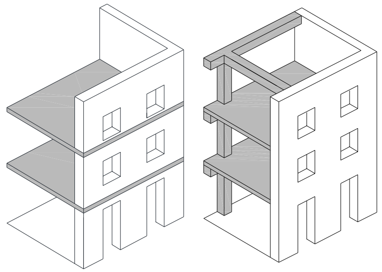
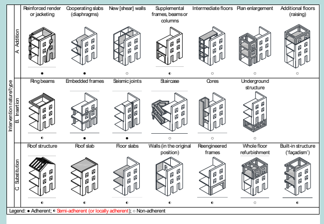
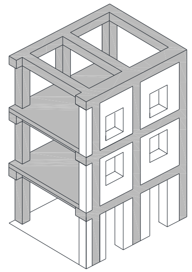
Task 1
State of the art

Highlights:

- State-of-the-art of mixed URM-RC building typologies: regulations, numerical modelling and analysis methods, existing investigations;
- Damages associated with mixed URM-RC buildings;
- Comprehensive understanding and categorization of the existing mixed URM-RC building typologies;
- Existing challenges and research gaps.

URM-RC building typology characterization

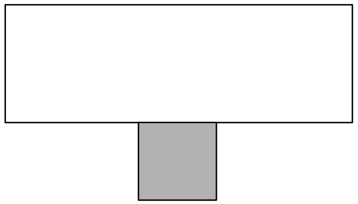
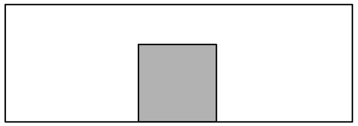
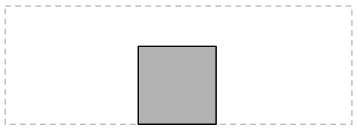
Principal stages of the evolution of the RC role in buildings (RC elements shaded in grey)

Designation	Old URM buildings (no RC)		Mixed URM-RC buildings			RC frame buildings with confined URM infill walls
			Original URM-RC buildings	Derived URM-RC buildings (intervened URM buildings)		
Scheme		Advent of RC			New RC building codes	
Period*	<1930		1930-1960	1940-present		1960-present
Vertical loadbearing elements	Stone or old brick URM walls (and/or wood elements)		Stone or old brick URM walls (sometimes w/ RC frames/walls)	Stone or old brick URM walls (and/or new RC frames/walls)		RC frames
Floor structure	Wood		Wood and/or RC slabs	Wood (and/or new RC slabs)		RC slabs
Roof structure	Wood		Wood	Wood (and/or new RC structure)		RC joists (sometimes wood)

*Period relevant for the Portuguese building stock.

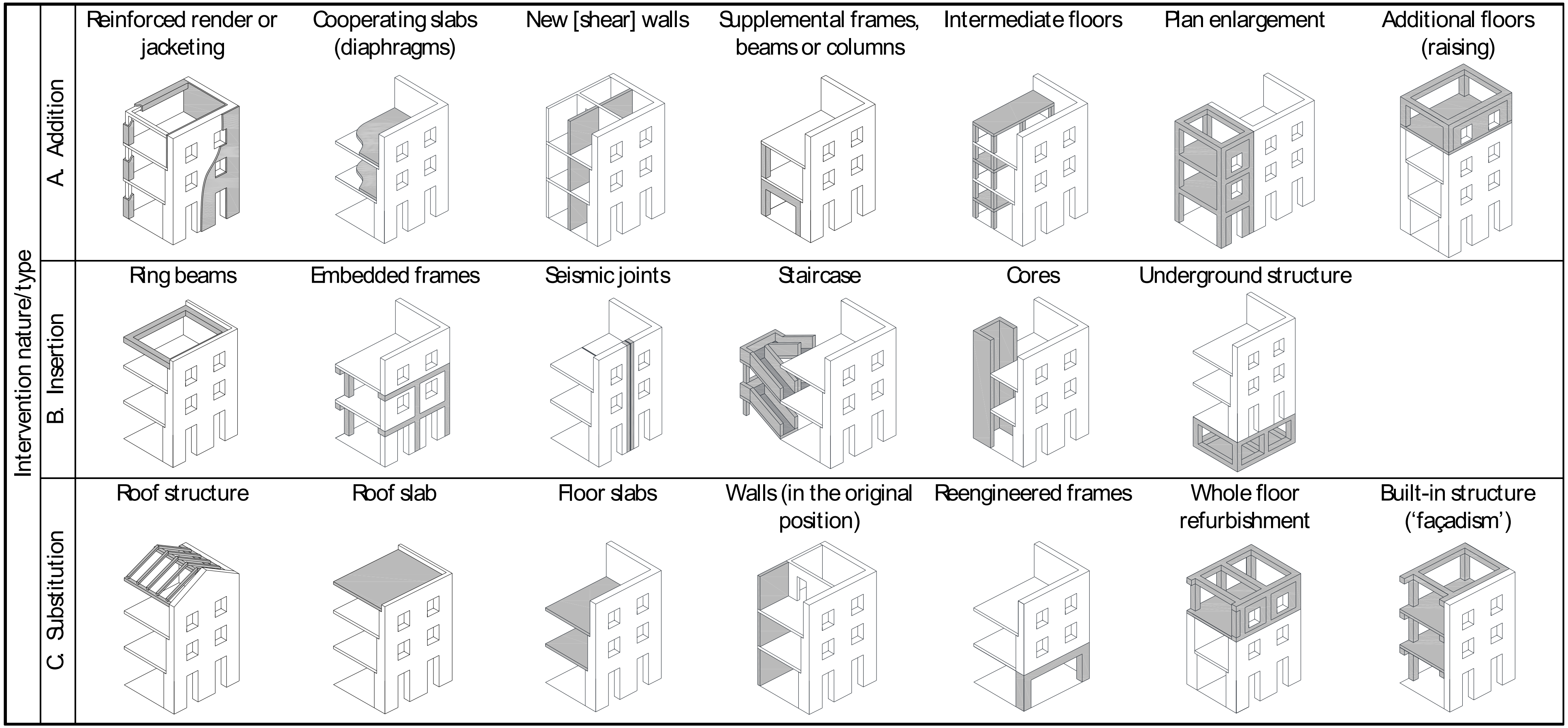
URM-RC building typology characterization

Intervention types for derived URM-RC buildings

Intervention nature/type			
	A. Addition		**Addition** of new RC structural elements to the existing structural system (as well as the solution of increasing the dimensions of the existing elements with RC)
	B. Insertion		**Insertion** of new RC structural elements embedded in the existing structure. This action involves a small up to moderate amount of dismantling of some parts of the existing structure
	C. Substitution		**Substitution** of original elements from the existing structure by new RC structural elements (as well as the solution of changing the position and configuration of the existing URM elements). This action involves a moderate up to high amount of partial demolishment of the structure.

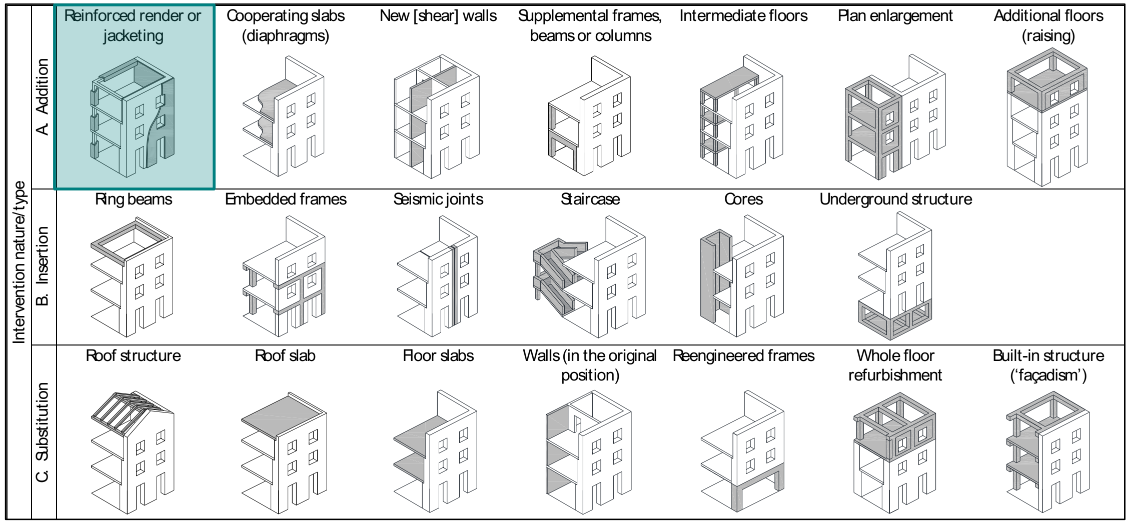
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings (RC elements shaded in grey)



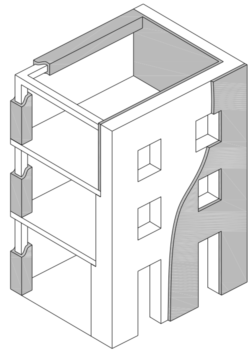
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



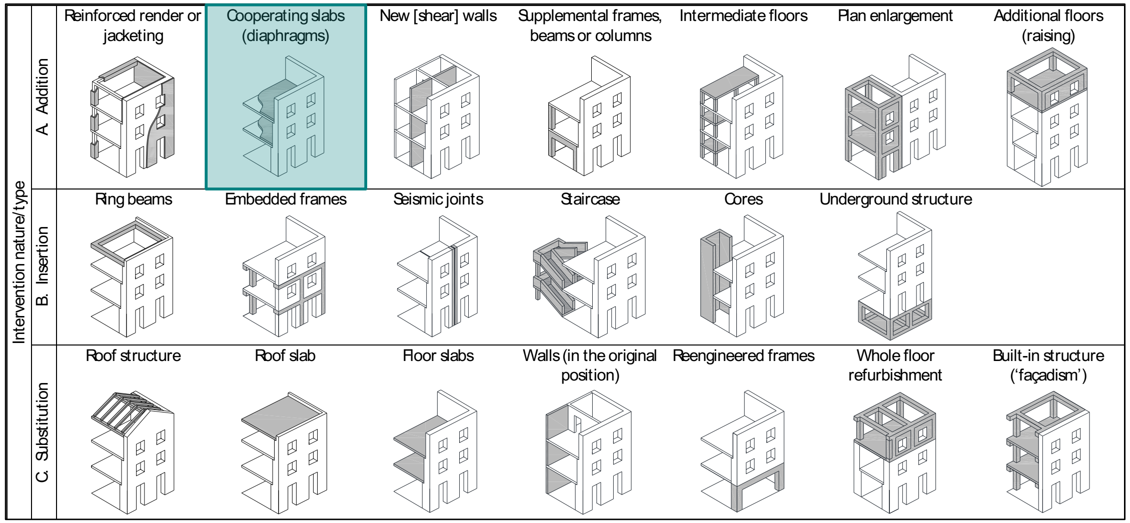
A: Addition

Reinforced render or jacketing



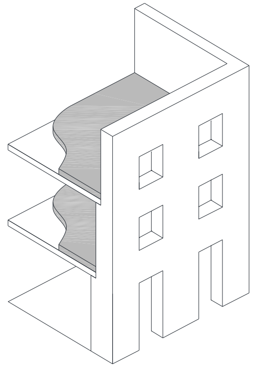
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



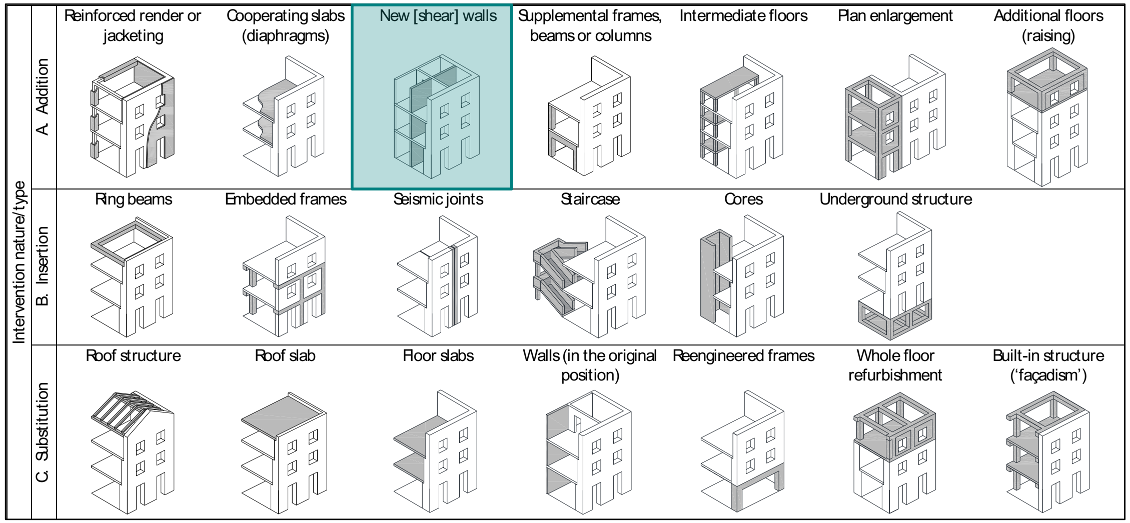
A: Addition

Cooperating slabs (diaphragms)



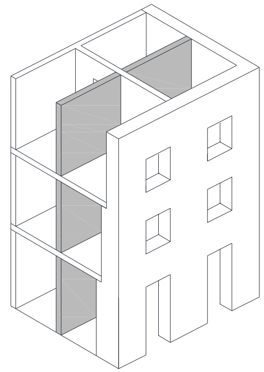
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



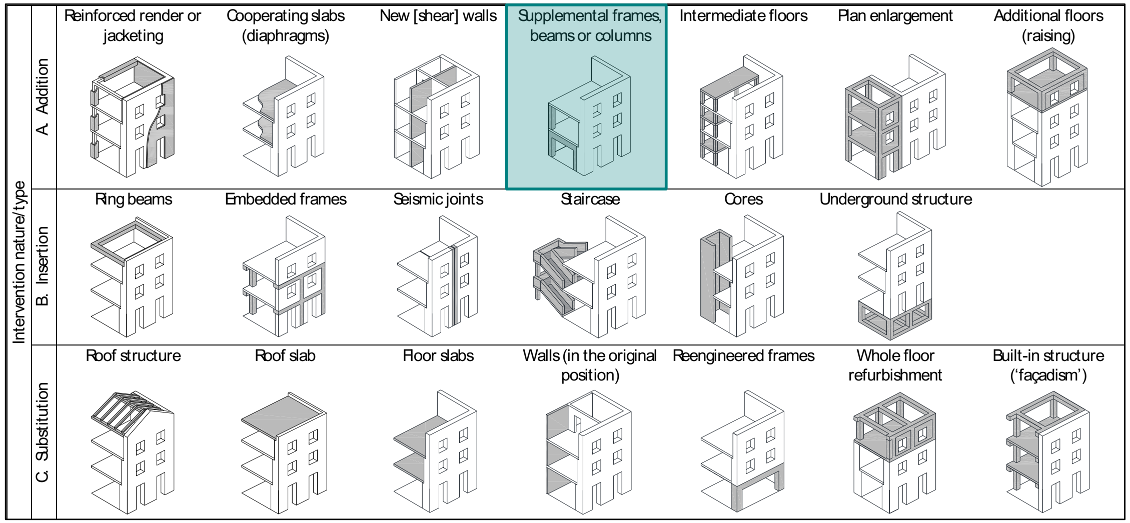
A: Addition

New [shear] walls



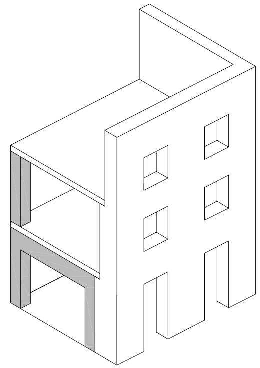
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



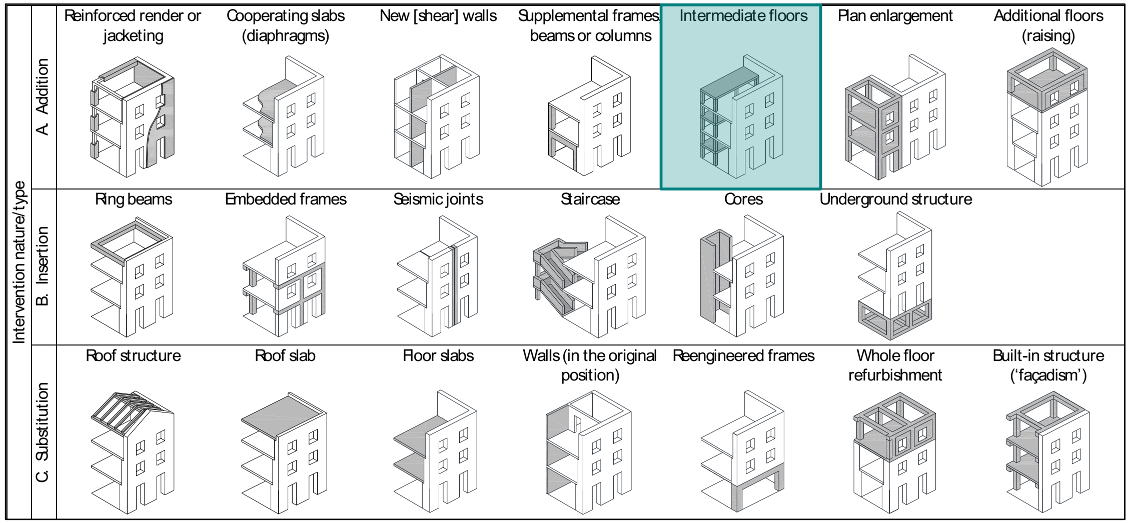
A: Addition

Supplemental frames, beams or columns



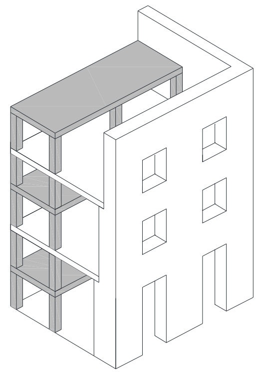
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



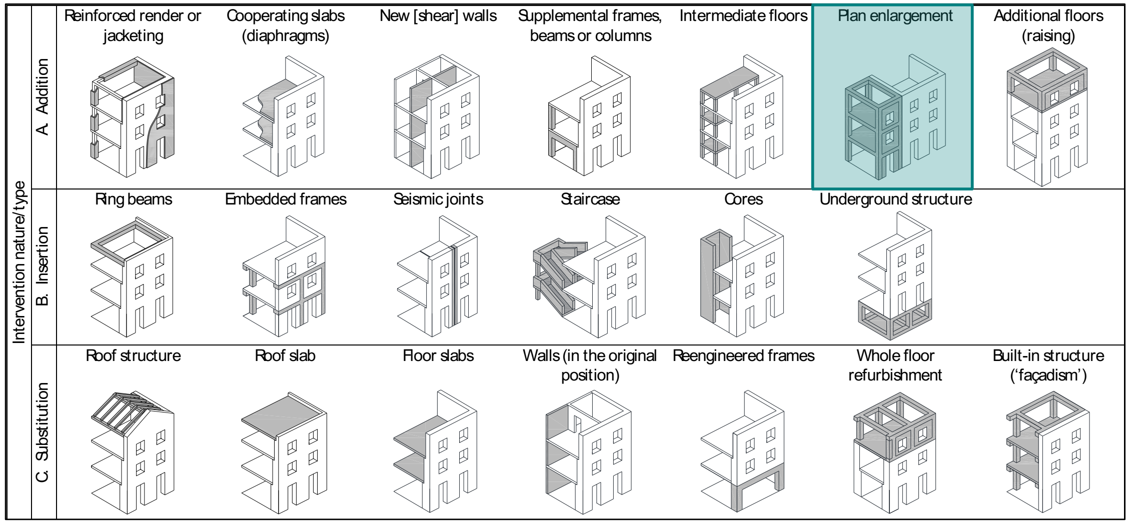
A: Addition

Intermediate floors (mezzanines)



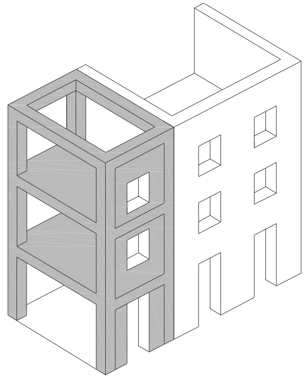
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



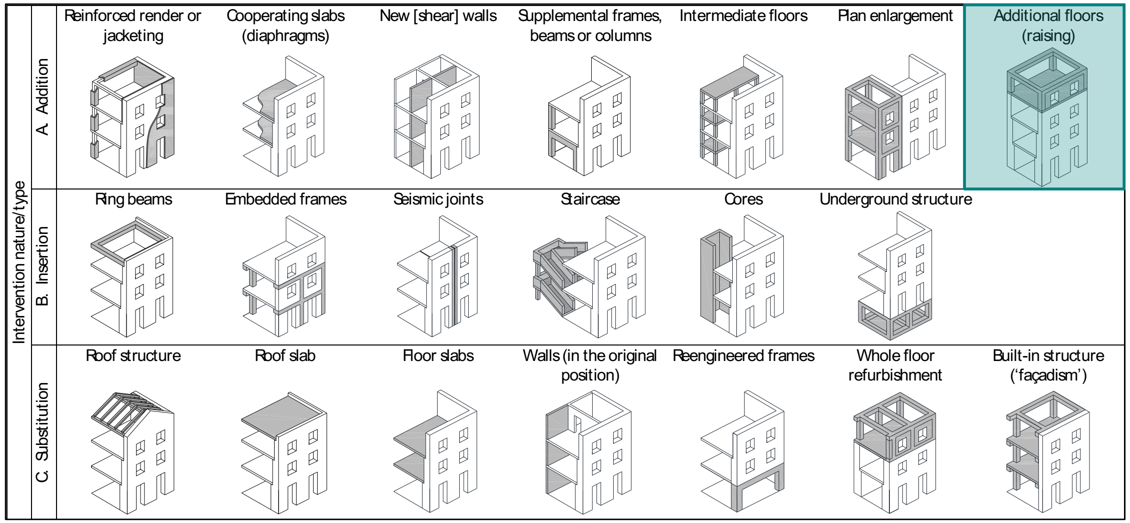
A: Addition

Plan enlargement



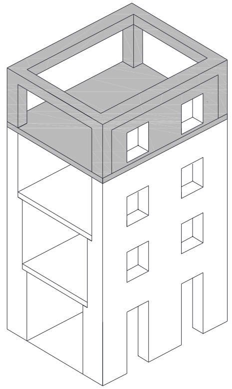
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



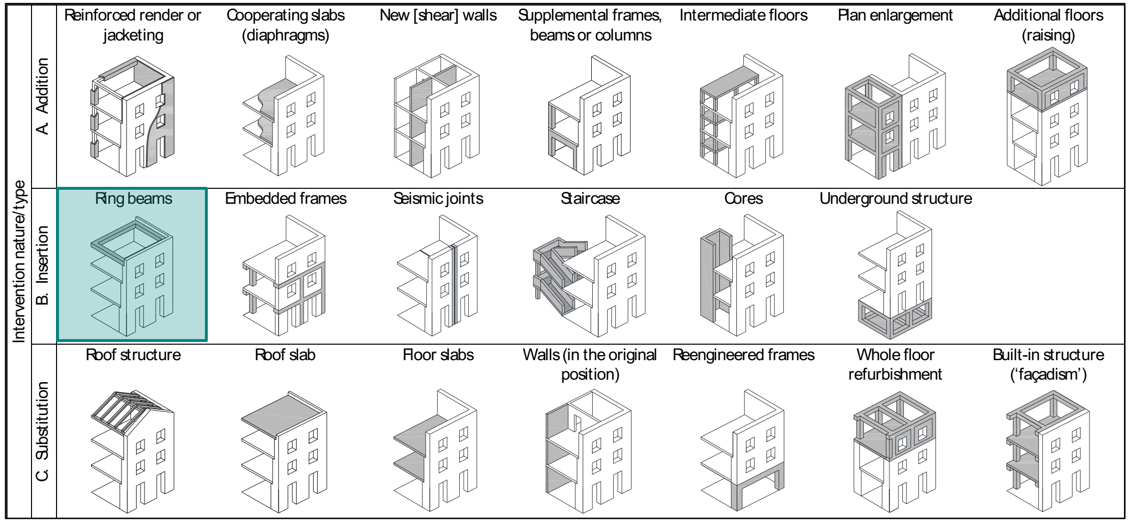
A: Addition

Additional floors (raising)



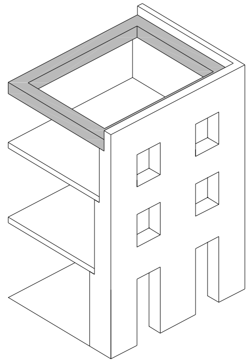
URM-RC building typology characterization

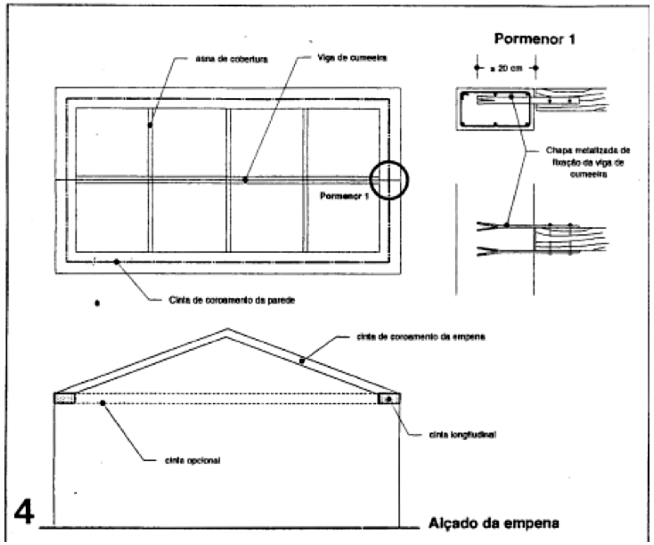
Structural typologies of derived URM-RC buildings



B: Insertion

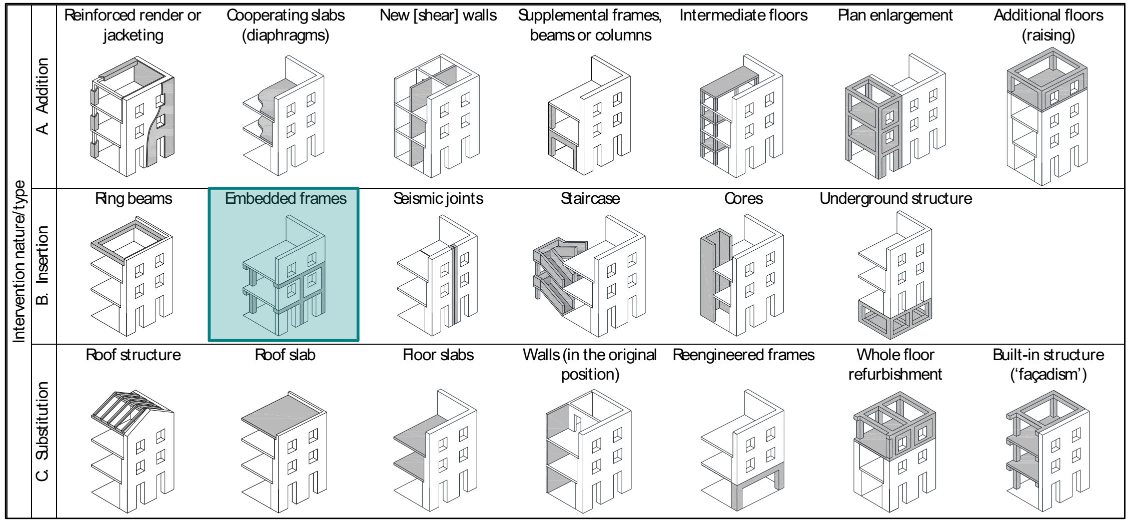
RC ring beams





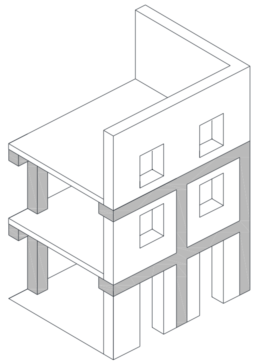
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



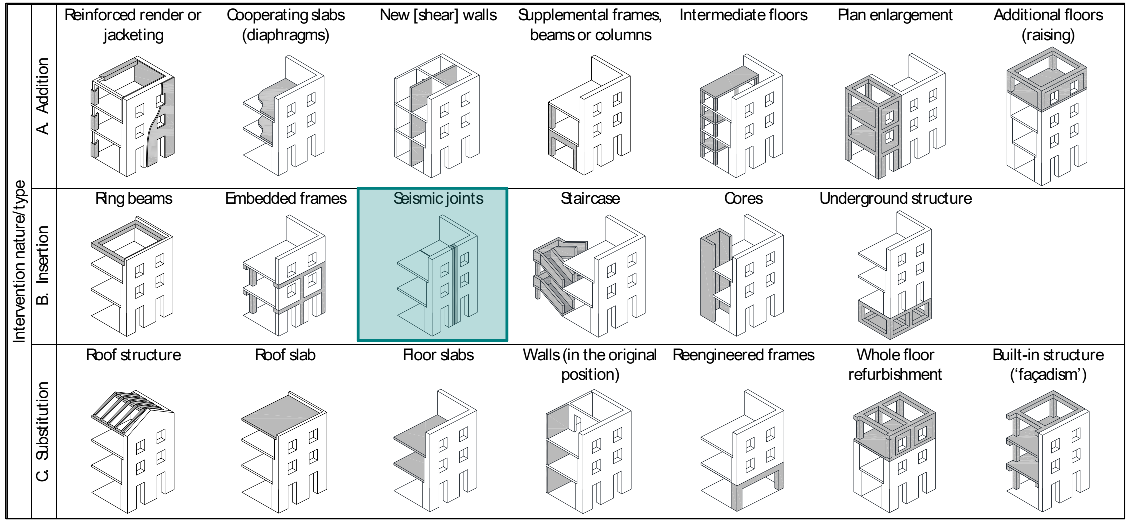
B: Insertion

Embedded frames



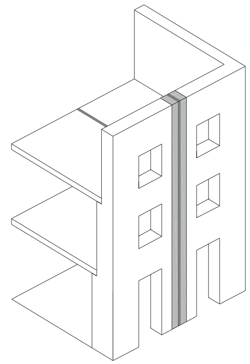
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



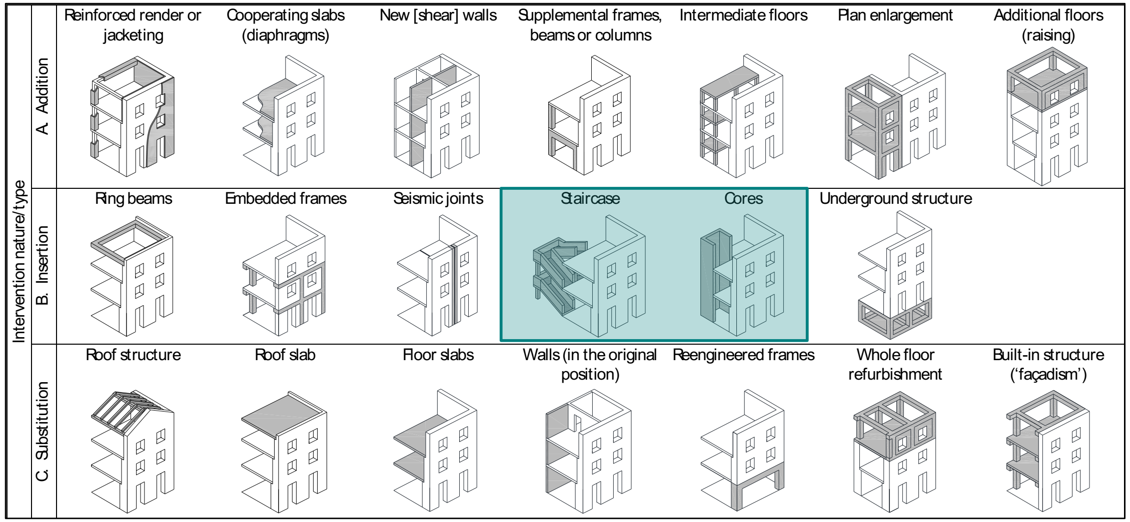
B: Insertion

Seismic joints



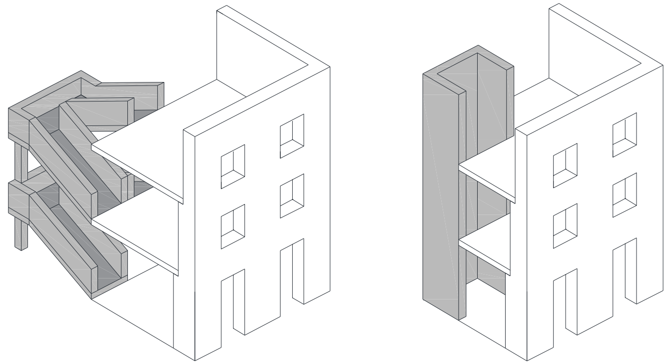
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



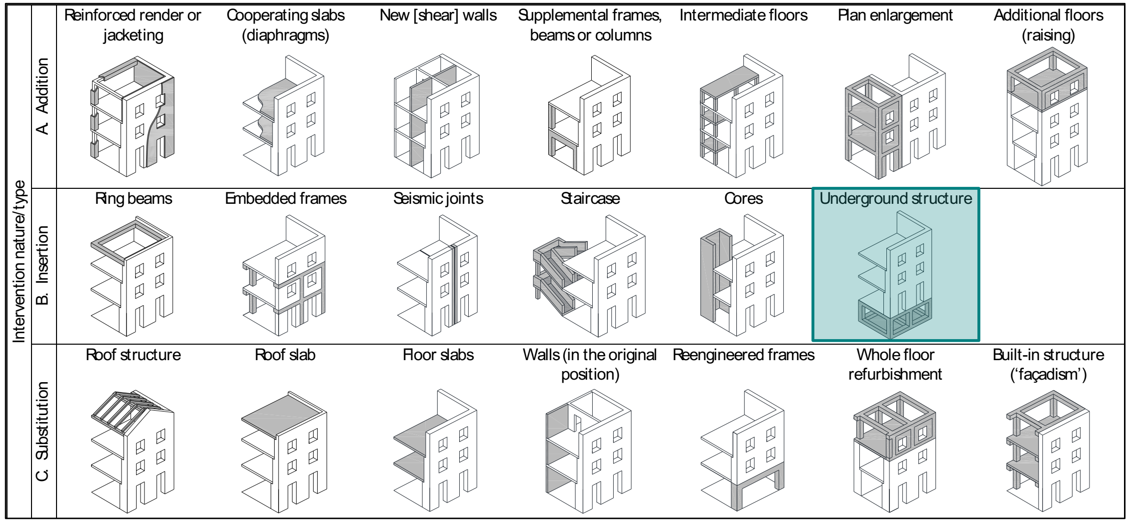
B: Insertion

Staircases and cores



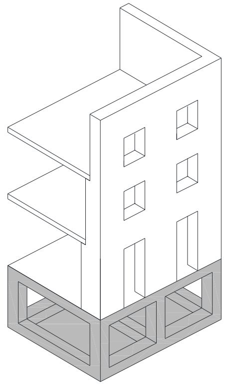
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



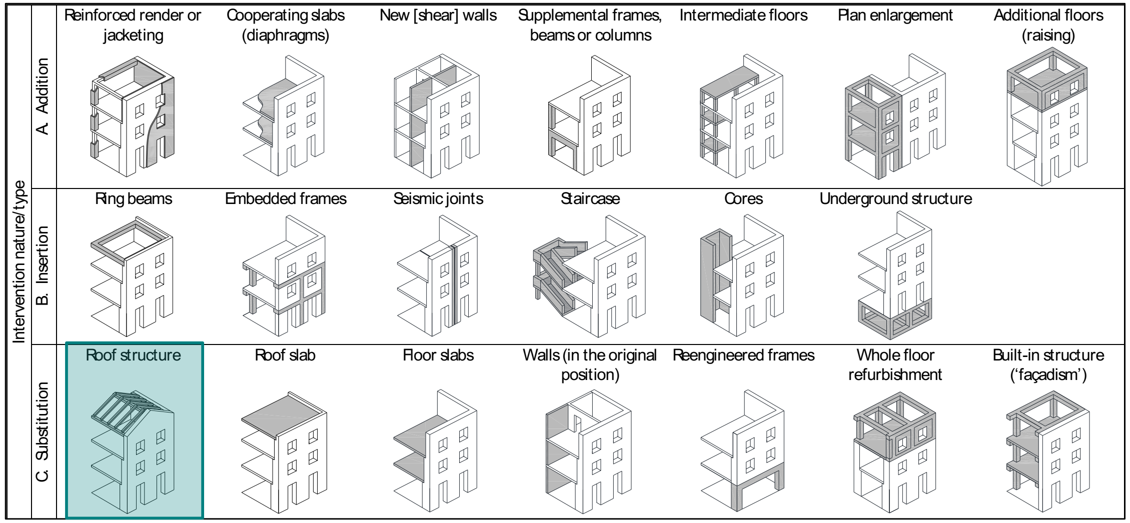
B: Insertion

Underground structure



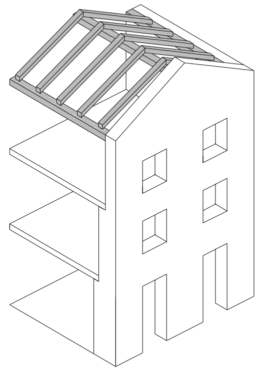
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



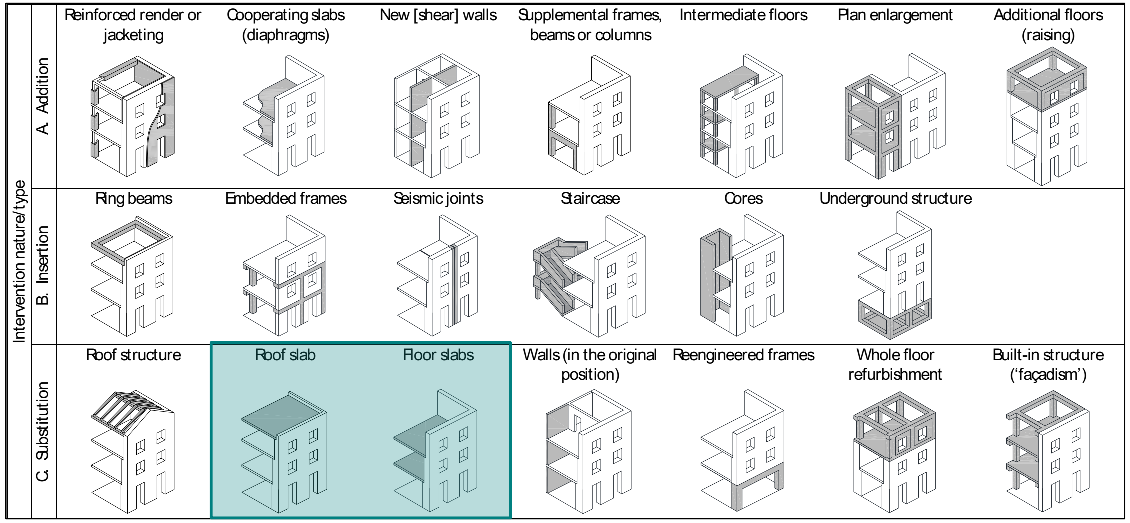
C: Substitution

Roof structure



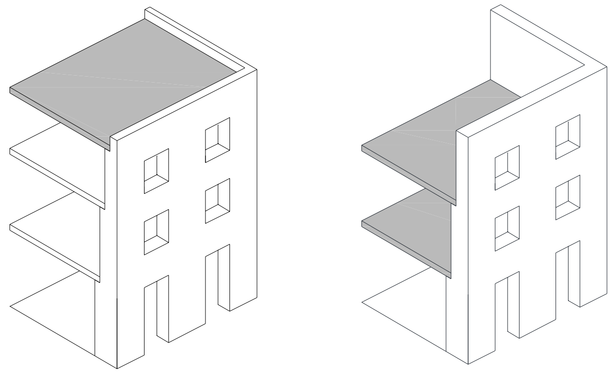
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



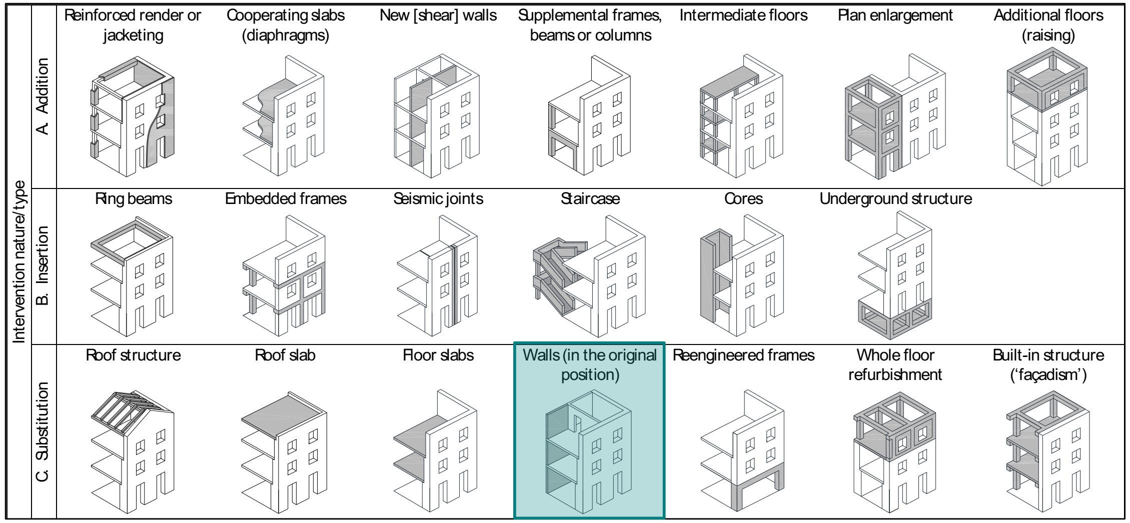
C: Substitution

RC roof slab and/or floor slabs



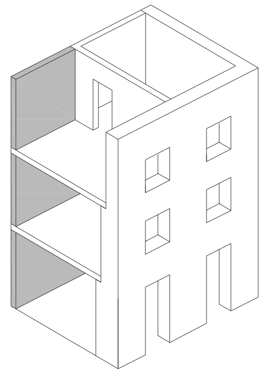
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



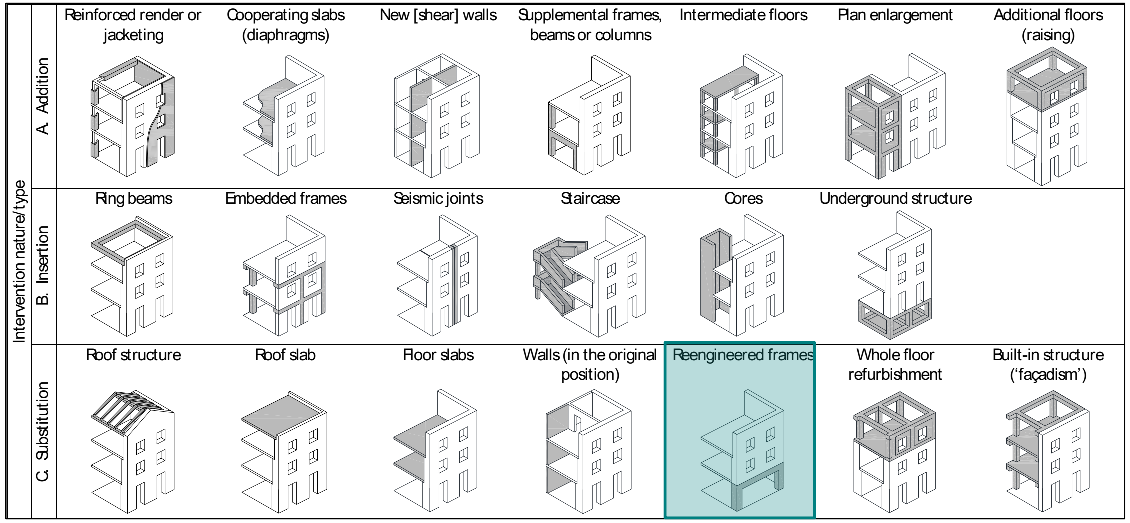
C: Substitution

RC walls



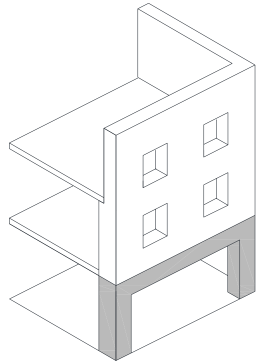
URM-RC building typology characterization

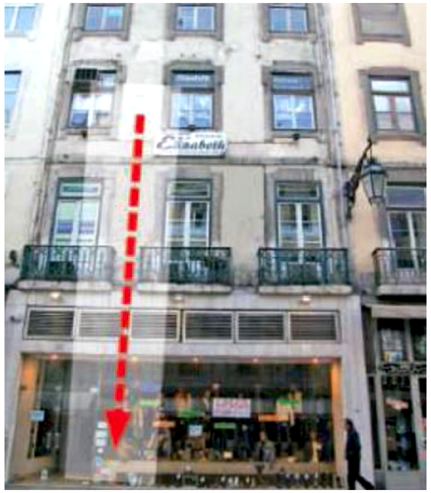
Structural typologies of derived URM-RC buildings



C: Substitution

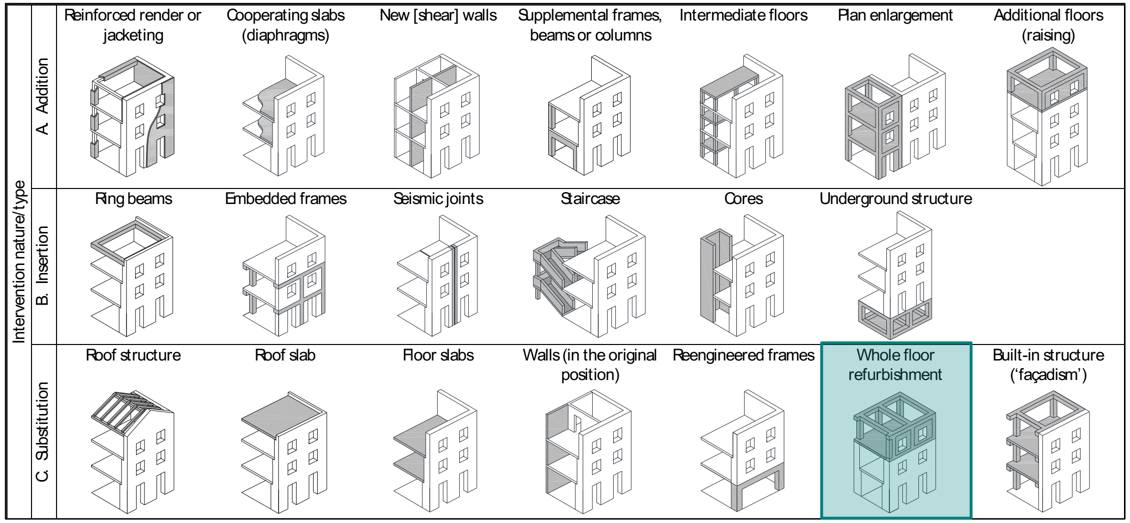
Reengineered frames





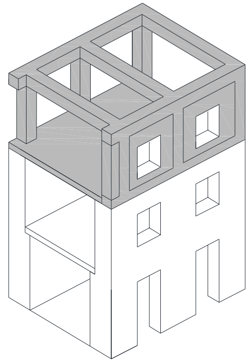
URM-RC building typology characterization

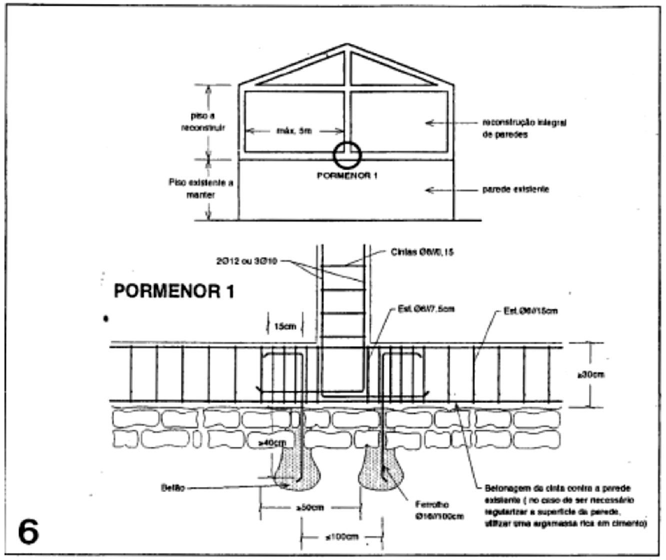
Structural typologies of derived URM-RC buildings



C: Substitution

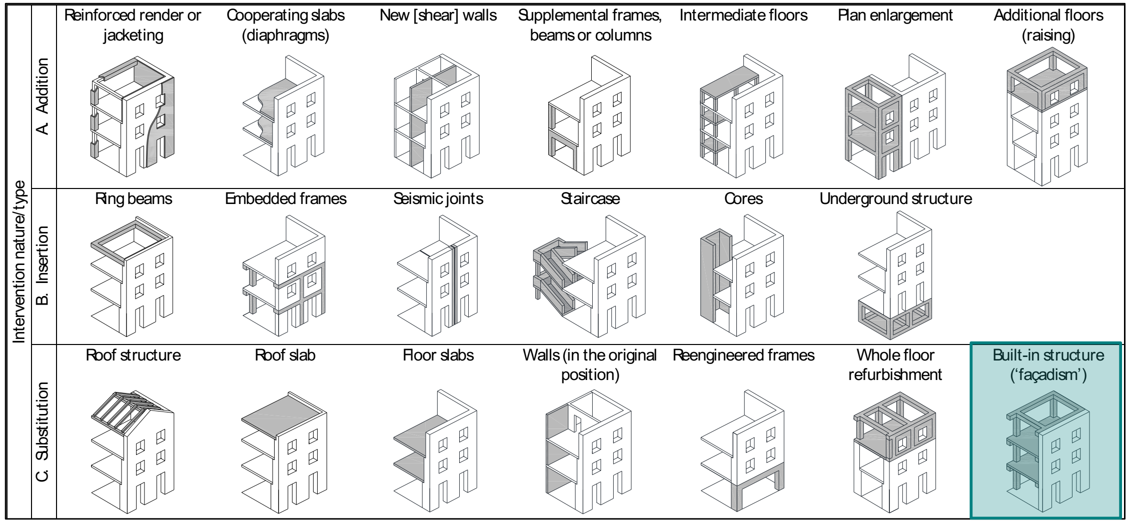
Whole floor refurbishment





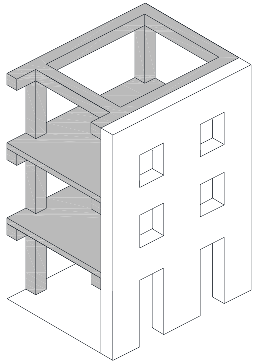
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



C: Substitution

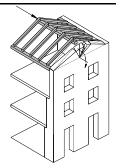
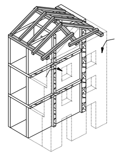
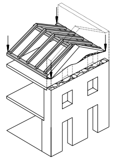
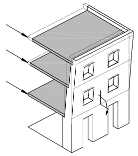
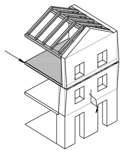
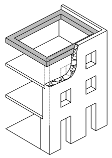
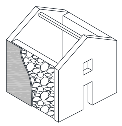
Built-in structure ('façadism')







Damages from past earthquakes to mixed URM-RC buildings

Observed damages	Scheme	Description			
		Interventions	Observed damages	Probable mechanisms	Probable structural causes
		Substitution of roof structure.	Local collapse in the top of the walls of the tympanum.	Out-of-plane overturning due to the hammering of the RC ridge beam.	Roof not effectively connected to the masonry; High inertial forces due to the increased weight of RC.
		Substitution of roof structure; Insertion of ring beam at roof level.	Total collapse of the end-part of a building.	1st: overturning and out-of-plane collapse of lateral supporting walls at one or more floors due to the eccentricity of the vertical load from the roof; 2nd: collapse of the roof structure above.	High out-of-plane inertial forces due to the increased weight of RC. Horizontal pushing force coming from the heavy roof; Lack of or poor vertical and horizontal connections to restrain the movement; Poor quality of loadbearing masonry walls.
		Substitution of roof structure; Insertion of ring beam at roof level.	Collapse of upper floor of a building.		
		Substitution of roof structure; Substitution of floor slabs; Insertion of ring beams.	Total collapse building.	1st: horizontal displacement of floor slabs; 2nd: overturning and out-of-plane collapse of the walls bellow.	Higher values of inertia forces caused by the rigid floors; Insufficient resistance capacity of deformation of the walls for the actions perpendicular to their plane; Poor vertical connections;
		Substitution of floor slab; Insertion of ring beam at intermediate floor.	Partial overturn of a large section of a façade.	1st: horizontal displacement of the floor slab; 2nd: out-of-plane collapse of the walls above and below.	Higher values of inertia forces caused by the rigid floor; Lengthy wall with poor or none vertical connections to restrain the movement; Heavy RC floor slab supported only on the inner layer of poor quality double leaf masonry wall.
		Insertion of ring beam at roof level.	Partial collapse of a large section of a façade.	Out-of-plane collapse of the masonry walls bellow a ring beam.	Poor connection between the RC ring beam and the underlying masonry.
		Addition of reinforced renders and/or jacketing.	Detachment and deterioration of the renders.	Collapse of the render layer due to chemical and mechanical incompatibilities.	Incorrect design and execution of consolidation techniques; Lack of validation by proper studies; Poor connection or insufficient steel net/rebar; Low durability and corrosion.

Damages from past earthquakes to mixed URM-RC buildings

The observed partial and total collapses of mixed URM-RC buildings are generally due to:

1. **Increased horizontal seismically induced inertial forces**, owing to the **greater weight of RC elements**, resulting in larger horizontal displacements (most severe at upper floors) and higher shear forces and bending moments (most severe at lower floors);
2. **Destabilizing out-of-plane moments**, owing to the **increased vertical load** at the top of the walls combined with eccentricities and horizontal displacements (p-delta effect);
3. **Incompatibility between existing and new technologies**: incompatible deformations of RC elements (more ductile) with the existing URM walls (more brittle), owing to the different stiffness-to-weight ratios (EI/m);
4. Poor understanding of the seismic response of the structure owing to **questionable technical choices, inaccurate design and incorrect execution of the retrofitting interventions** themselves;
5. **Lack of accurate analysis** of the static/dynamic behaviour of the building before and after the interventions;
6. **Insufficient in-plane stiffness of the floors** and **inadequate structural connections** between perpendicular walls (vertical connections) and between walls and floors, ring-beams and roof structure (horizontal connections).

Task 2

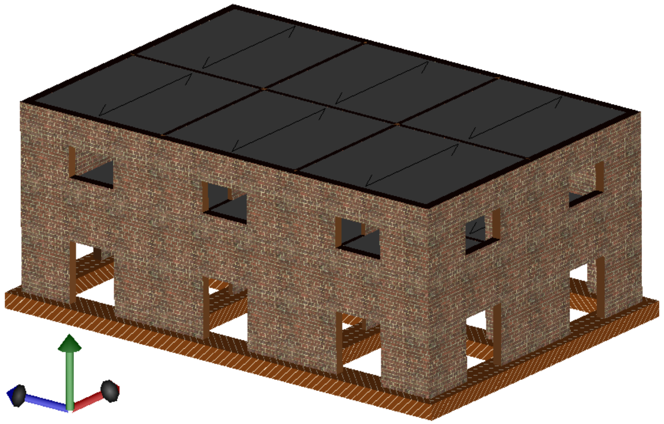
Numerical analysis of representative URM-RC structural strengthening solutions for buildings

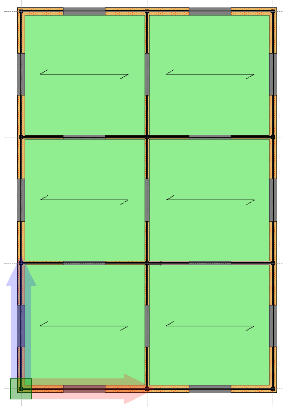
Goal:

- Study of which type of interventions and structural systems are more likely to cause/prevent damage and collapse mechanisms, thus increasing/decreasing the vulnerability of such structures
    - First part (ongoing): pushover analyses using nonlinear macro-element models implemented in the equivalent-frame software 3DMacro;
    - Second part (future): analysis of shell-element models using the simplified micro-modelling approach using the software DIANA/ANSYS.

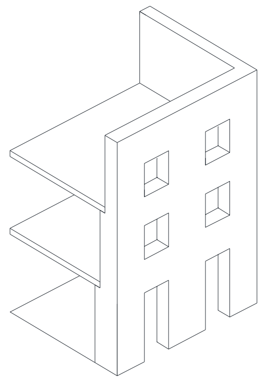
Numerical analysis of representative derived URM-RC buildings

Case study: original URM building



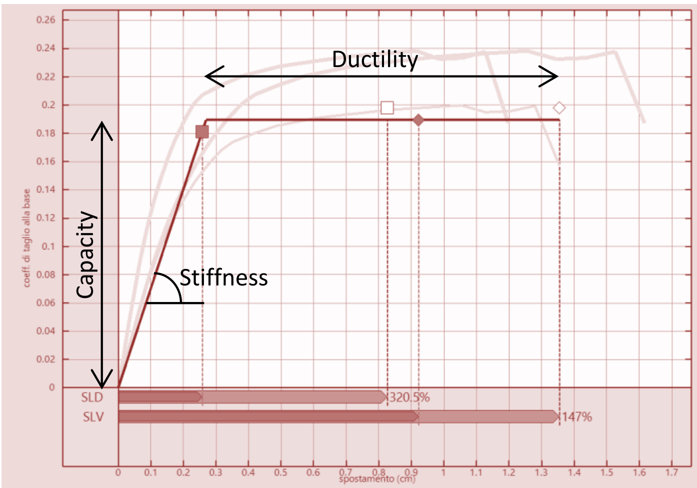


Old URM building (no RC)



- Wooden floors
- URM walls

- dimensions:
- 10 m x 15 m x 6 m (2 floors)
- PGA = 0.2593 g



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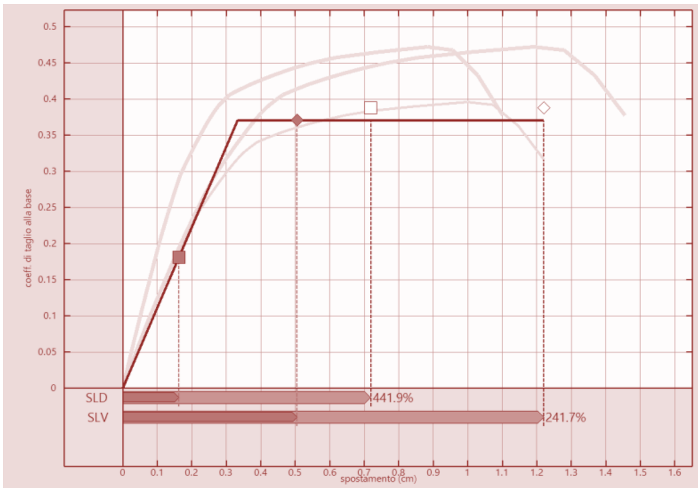

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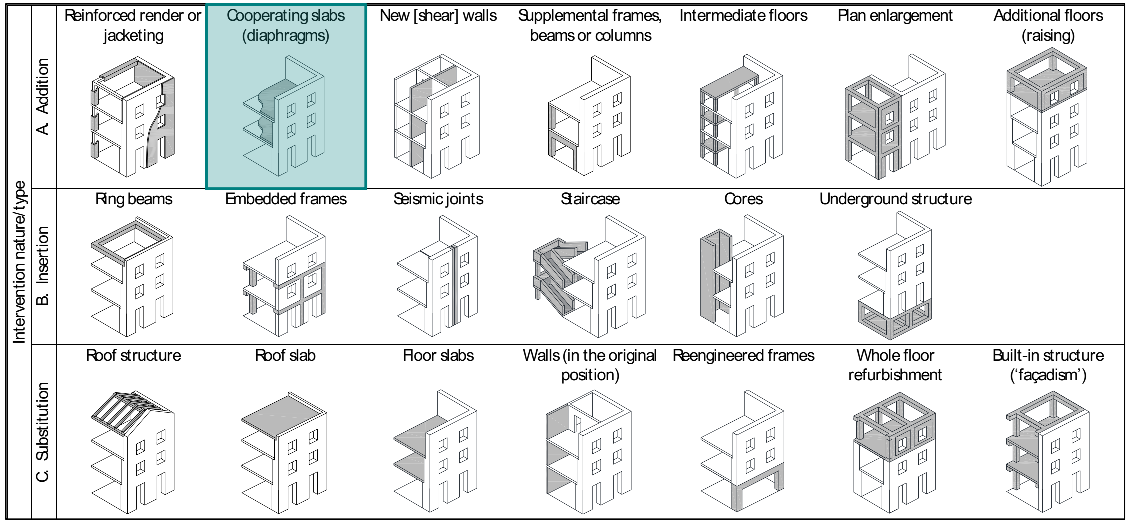
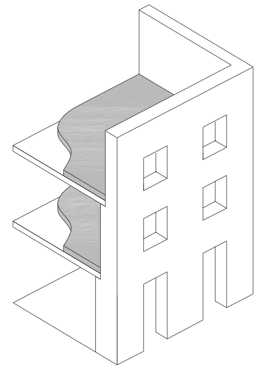
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



A: Addition

Cooperating slabs (diaphragms)



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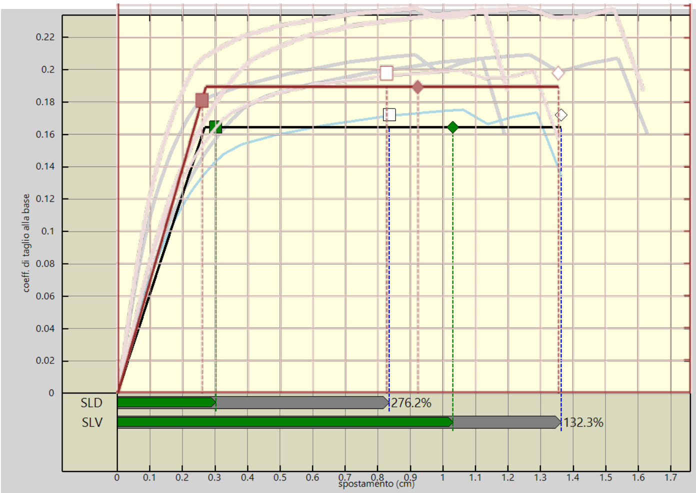

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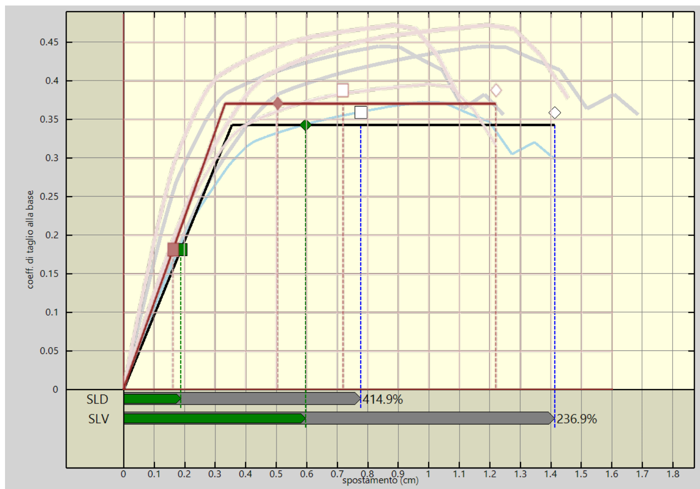

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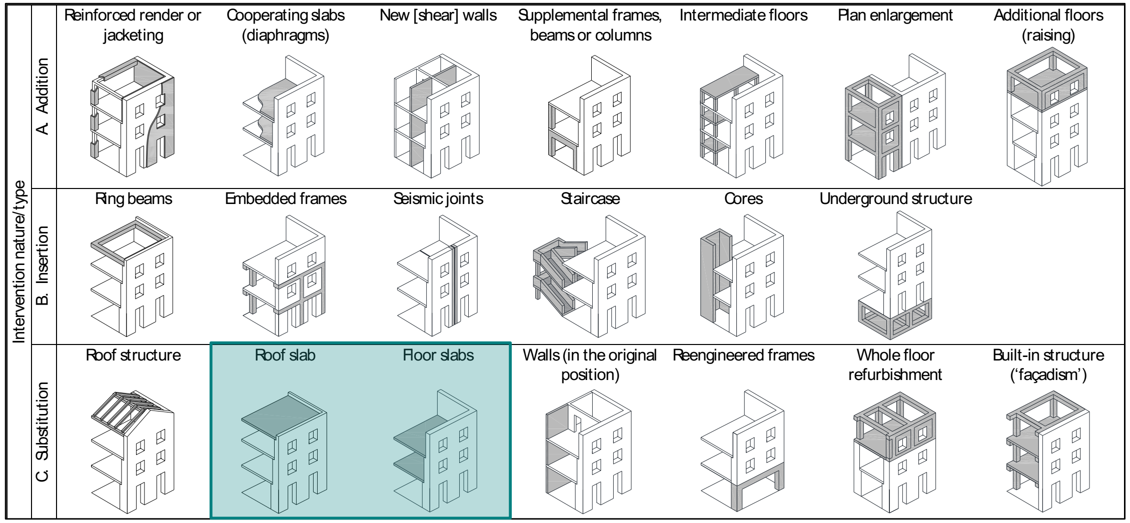
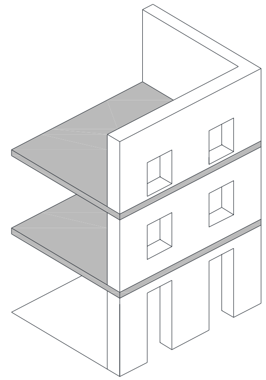
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



C: Substitution

RC roof slab and/or floor slabs



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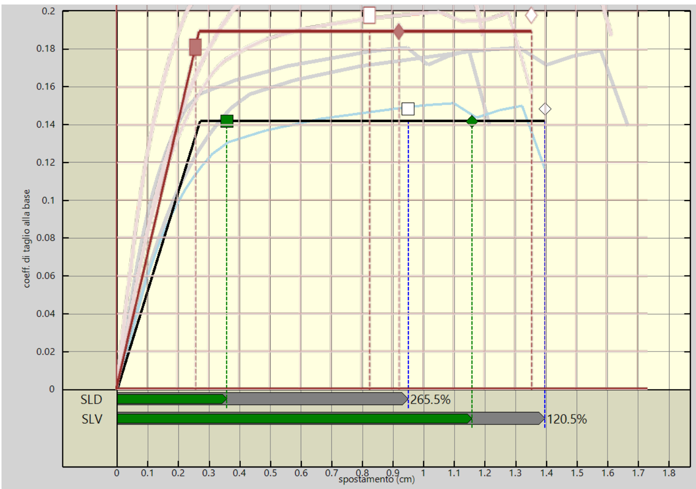

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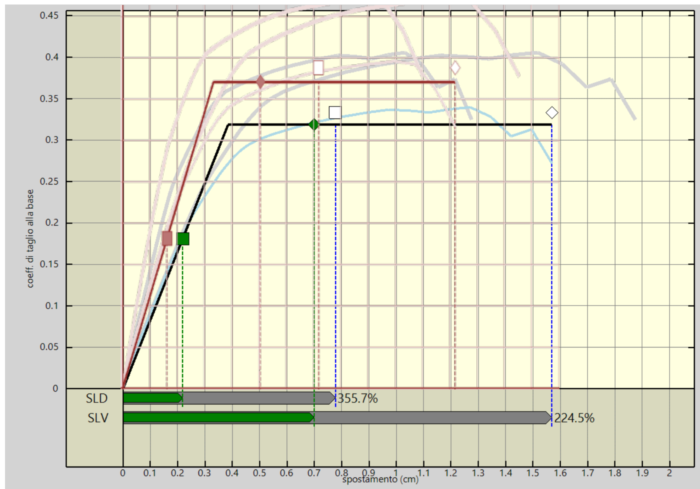

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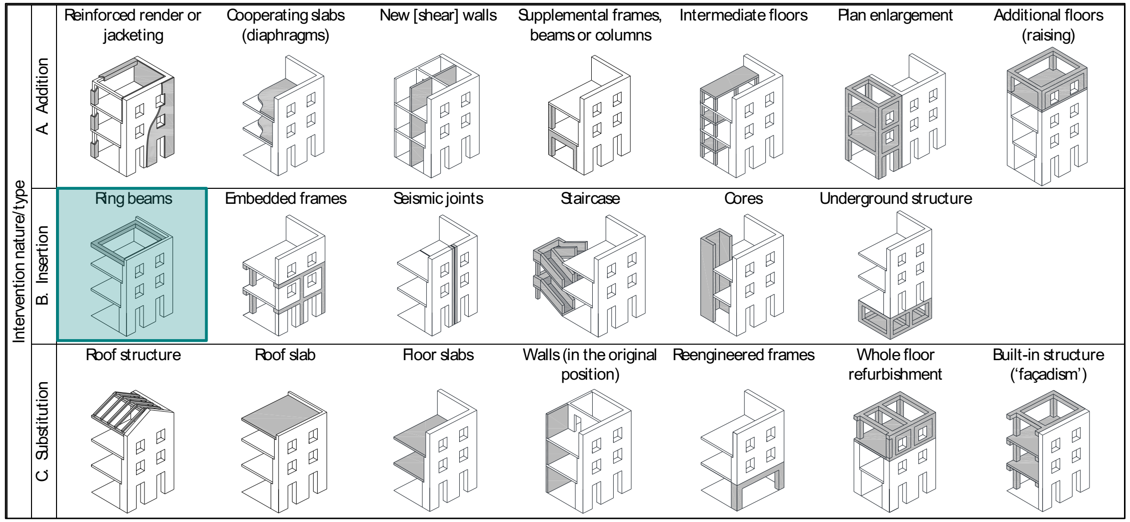
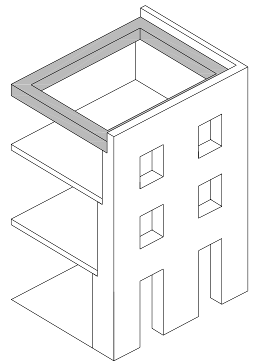
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



B: Insertion

RC ring beam



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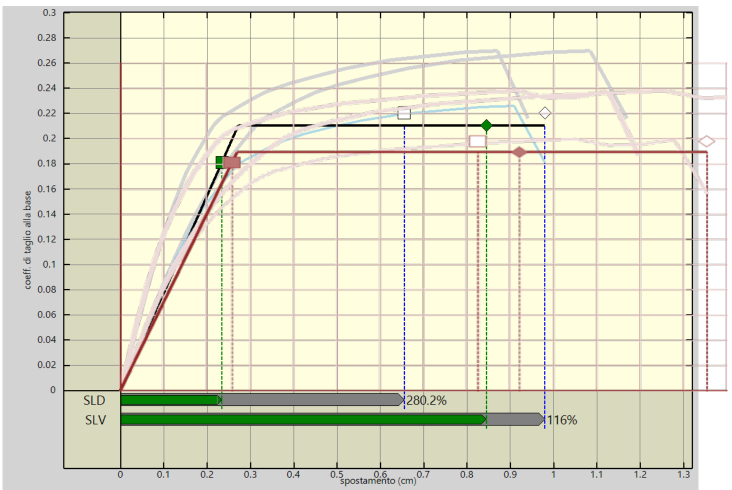

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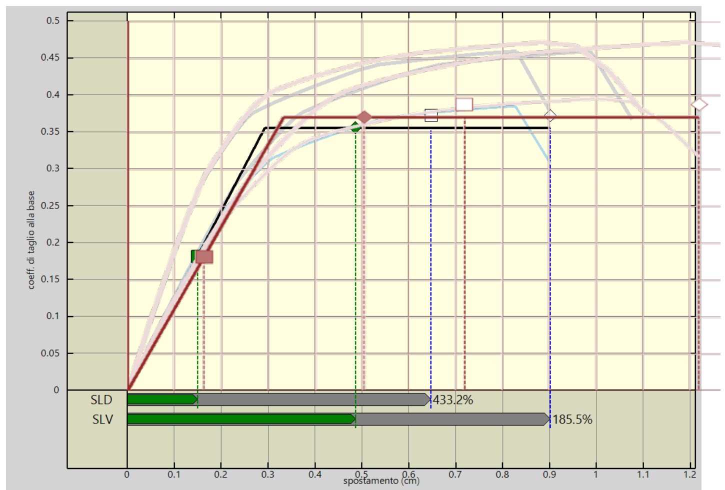

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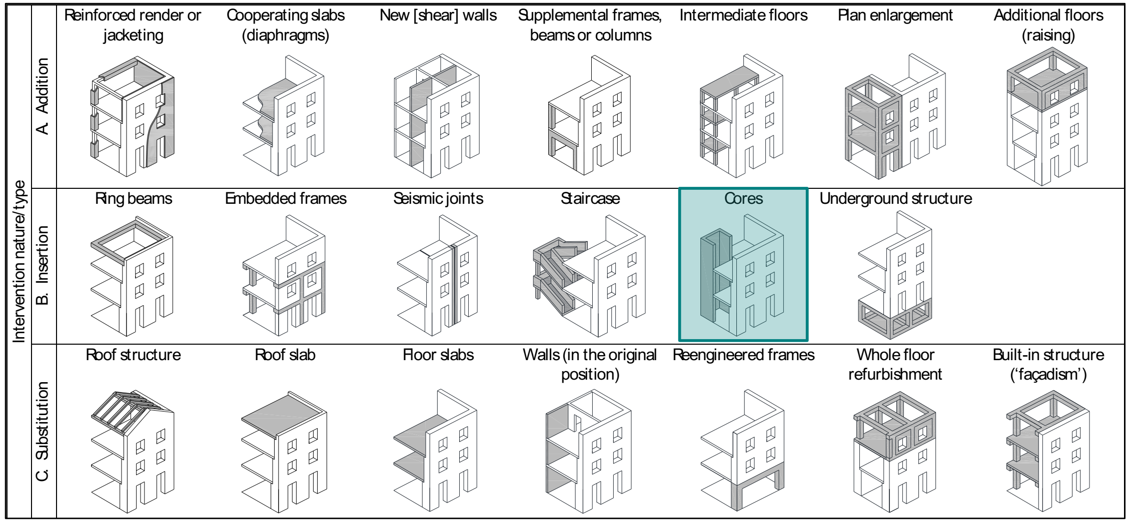
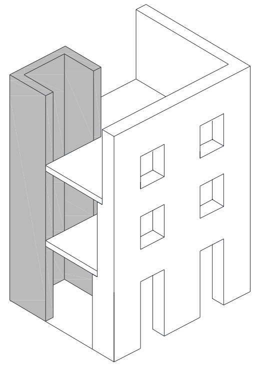
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



B: Insertion

RC core



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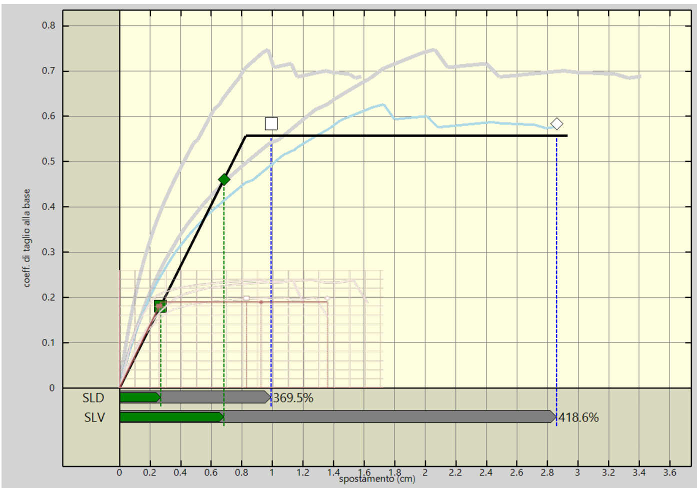

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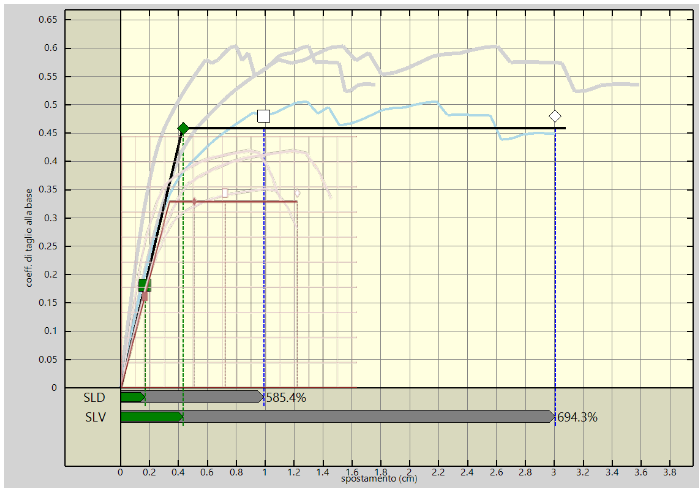

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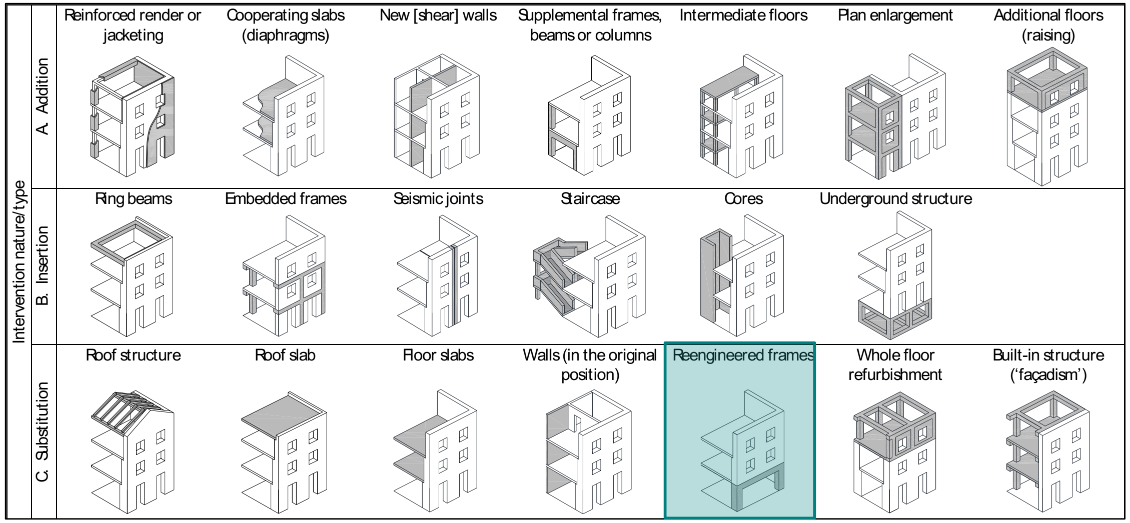
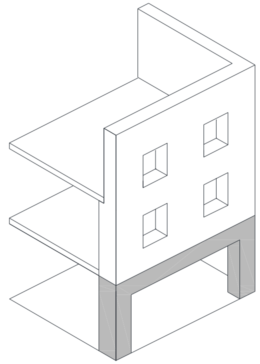
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



C: Substitution

Reengineered frame



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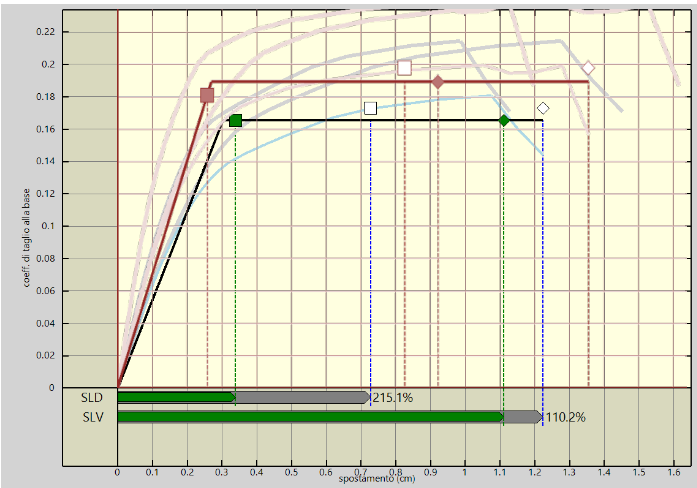

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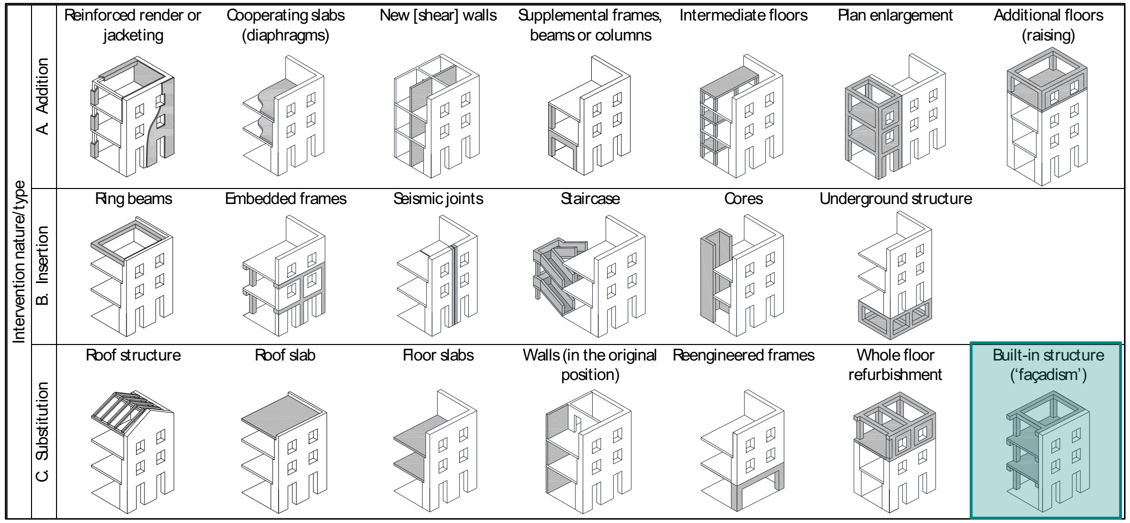
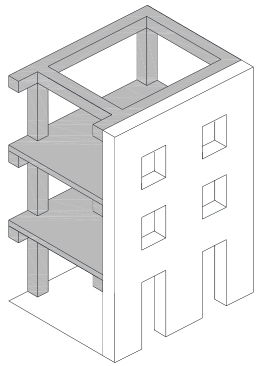
URM-RC building typology characterization

Structural typologies of derived URM-RC buildings



C: Substitution

Built-in structure: frames (on XX direction) and slabs



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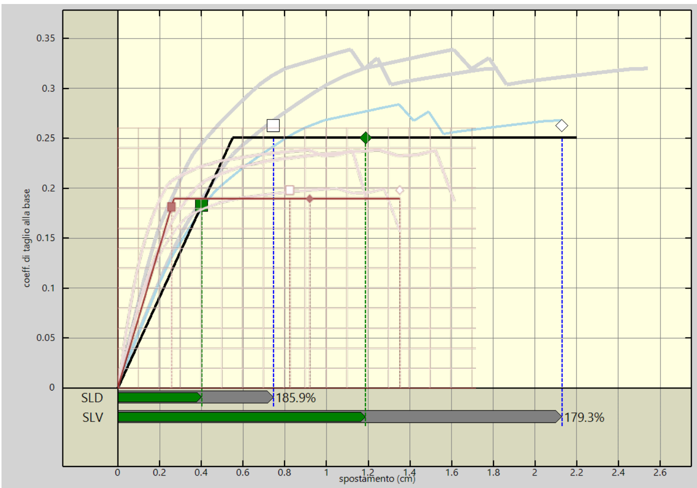

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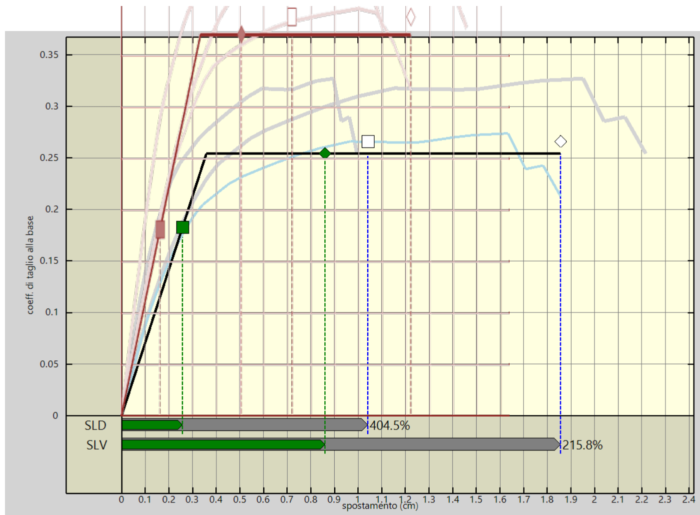

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Challenges

Among the many open issues which need to be addressed are:

1. Lack or inadequacy of experimental data;
2. Difficulties of numerical modelling;
3. Scarcity or technical difficulties of numerical analyses;
4. Insufficient standards and code indications;
5. Lack of an accurate seismic vulnerability assessment methodologies;
6. Influence of strengthening/retrofitting interventions;
7. Lack of practical inspection, diagnosis and appraisal tools.