Progetto DPC-ReLUIS 2022-2024 WP3-Task 2

PROTEZIONE CIVILE
Presidenza del Consiglio dei Ministri
Dipartimento della Protezione Civile

Seismic risk of retrofitted existing buildings

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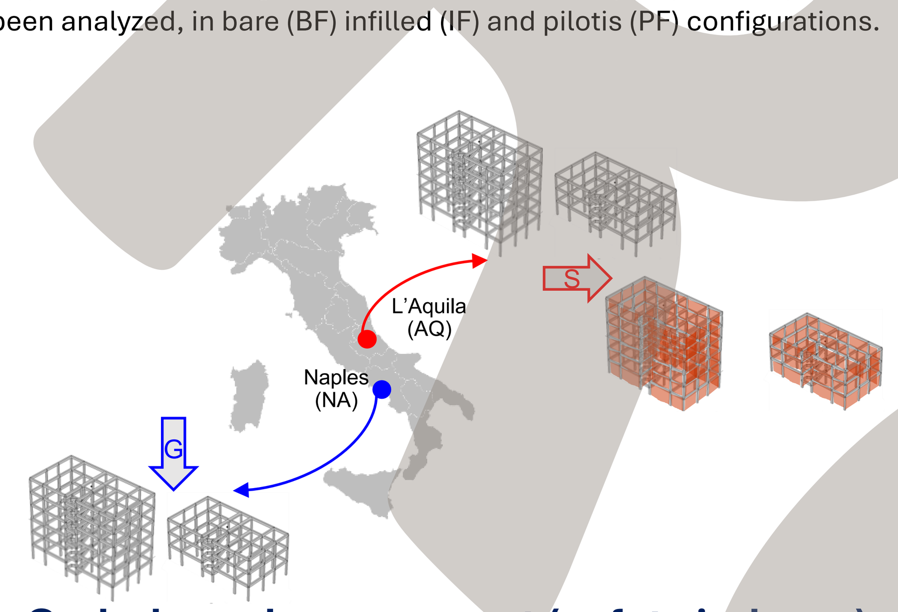
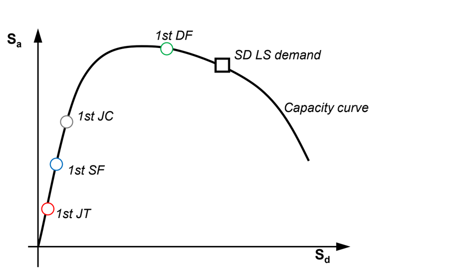
REINFORCED CONCRETE BUILDINGS

1. Case study buildings

3- and 6-storey RC buildings, designed for gravity loads only (GLD) – in Naples – or according to obsolete seismic code (SLD) – in L'Aquila – have been analyzed, in bare (BF) infilled (IF) and pilotis (PF) configurations.



2. Code-based assessment (safety indexes)



Building (BF)	SI (SD LS)					SI (DL LS)
	DF	SF	JT	JC	min	
3-SLD	1.01	0.34	0.34	0.34	0.34	0.84
3-GLD	1.06	0.28	0.28	-	0.28	1.25
6-SLD	0.59	0.34	0.34	0.34	0.34	0.77
6-GLD	0.73	0.28	0.28	0.28	0.28	1.01

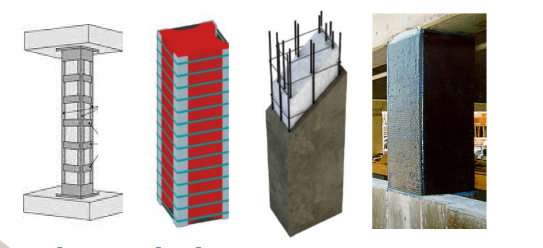
N.B. *SI = safety index; SD LS = Severe Damage Limit State; DL LS = Damage Limitation Limit State; DF = 1st ductile failures; SF = 1st shear failures; JT = 1st joint tensile failures; JC = 1st joint compressive failures.*

3. Intervention Strategies

STRATEGY "A" – local strengthening

Pre-stressed steel strips and local integrative jacketing for JT and JC, respectively.

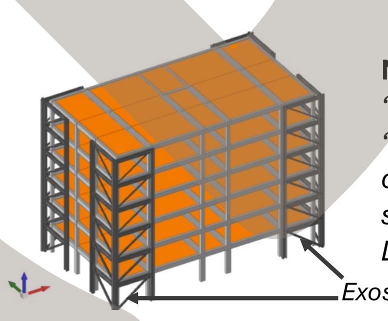
Investigated alternativ columns SFs and DFs.



STRATEGY "B" – steel exoskeletons

In **Scenario 1**, exoskeletons are designed as the sole structural system resisting seismic forces.

In **Scenario 2**, the intensity of the design base shear force is the half of the one corresponding to Scenario 1 to modulate the stiffness and resistance of the new steel structure relative to the existing RC frame structure.

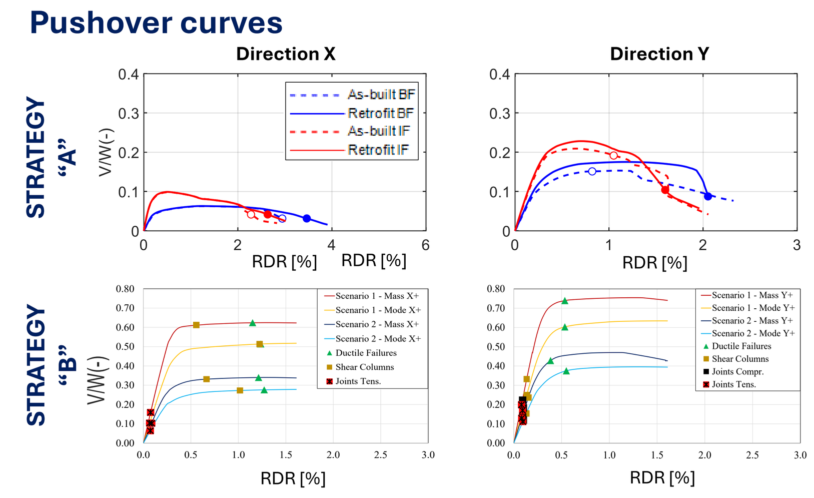


N.B. *The application of Strategy "B" is required especially by the "6-SLD" structure, as it is characterized by the lowest safety indexes both for DF at SD LS and at DL LS.*

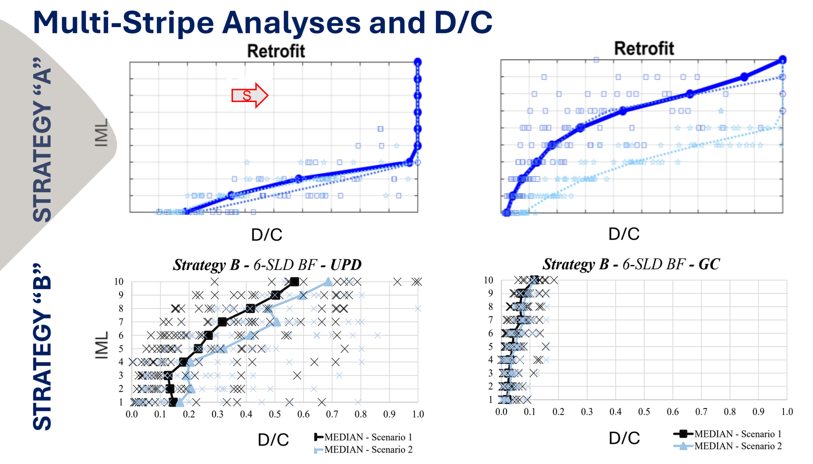
4. Analysis of retrofitted buildings

Example: 6-storey SLD building. Pushover results, used to obtained Capacity (C) at Usability Prevention Damage (UPD) and Global Collapse (GC), and Multi-Stripe Analysis to obtain Demand (D)

Pushover curves

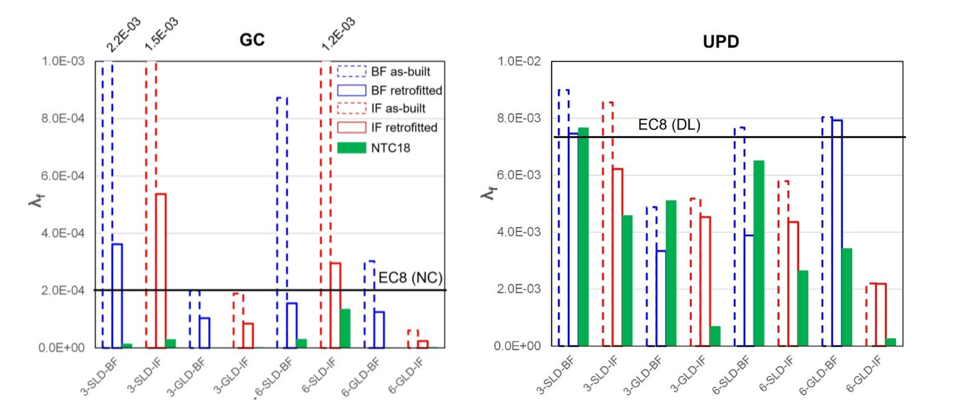


Multi-Stripe Analyses and D/C



5. Failure rates

Lastly, failure rates have been obtained by R2R software, based on D/C ratios previously obtained.



STRATEGY "B"

Failure rates - Strategy "B"		
Structural model	λ_F at UPD	λ_F at GC
6-SLD Scenario 1 - BF	$2.2 \cdot 10^{-6}$	-
6-SLD Scenario 2 - BF	$1.7 \cdot 10^{-4}$	-

N.B. *in the case of "Strategy B" scenarios, it was possible to evaluate a failure rate only at UPD, due to their very modest D/C values at GC.*

6. Conclusive remarks

- Retrofitting mitigates the fragility compared to the as-built condition, especially in SLD buildings and BF configurations.
- For GLD buildings, λ_f reduction falls within 48-60% while SLD cases show a higher range (66-84%);
- Retrofitted buildings still exhibit lower seismic performance at GC compared to newly designed buildings.
- Failure rates of retrofitted SLD buildings may exceed Eurocode 8 threshold, while GLD buildings generally meet this target.

MASONRY BUILDINGS

Without soil-foundation-structure interaction (SFSI)

Case-studies

Sites: L'Aquila (Aq)/ Naples (Na), soil A/C

Design of retrofit interventions

Building 1 interventions:
- RC tie beams at upper level, stiffening of diaphragms with RC slab (retr. 1 Na C)
- Retr. 1 Na C + plastering of piers with FRCM (retr. 1 Aq C)

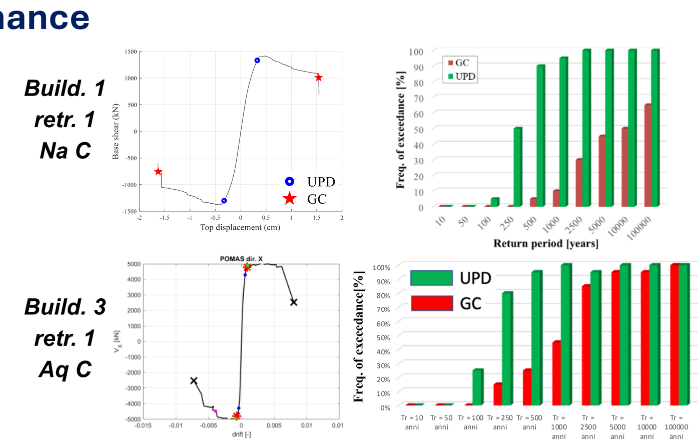
Building 2 interventions:
- RC tie beams at upper level, stiffening of diaphragms with RC slab, mortar injections, plastering of selected piers with FRCM (retr. 1 Na C)
- retr. 1 Na C + plastering of all piers with FRCM, steel framing of openings (retr. 1 Aq C)
- RC tie beams at upper level, stiffening of diaphragms with RC slab (retr. 0.8 Na C)
- retr. 0.8 Na C + mortar injections (retr. 0.8 Aq A)
- retr. 0.8 Aq A + plastering of all piers with FRCM (retr. 0.8 Aq C)

Building 3 interventions:
- Type A: mortar injections, tie-rods in perimeter walls (retr. 0.8 Aq A)
- Type B: Type A + stiffening of diaphragms, re-pointing of mortar joints, FRCM on internal walls (retr. 1 Aq A, 0.8 Aq C)
- Type C: Type B + FRCM on all walls (retr. 1 Aq C)

Building 4 interventions:
- Type A: mortar injections in piers (retr. 1 Aq A)
- Type B: mortar injections in piers and spandrels, FRCM on selected piers in X and Y dir. (retr. 0.8 Aq C)
- Type C: mortar injections in piers and spandrels, FRCM on piers in X dir., steel exoskeletons in Y dir. (retr. 1 Aq C)

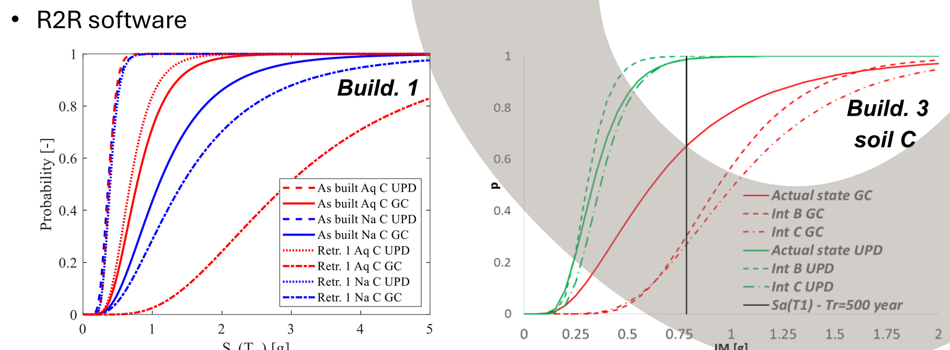
Assessment of seismic performance

- Equivalent-frame strategy (TREMURI software)
- Advanced constitutive models
- Specific modelling strategy for each intervention
- Capacity from NLSA
- Demand from multi-stripe NLDA
- Performance states: usability preventing damage (UPD), global collapse (GC)



Failure rates and fragility curves

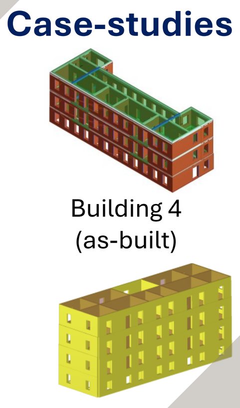
- R2R software



Perf. state	Building 1				Building 3					
	As-b. Na C	As-b. Aq C	Rtr. 1 Na C	Rtr. 1 Aq C	As-b. Aq A	As-b. Aq C	Rtr. 0.8 Aq A	Rtr. 1 Aq A	Rtr. 0.8 Aq C	Rtr. 1 Aq C
UPD	6.5×10^{-3}	1.6×10^{-2}	5.3×10^{-3}	5.2×10^{-3}	2.2×10^{-2}	2.7×10^{-2}	2.6×10^{-2}	2.9×10^{-2}	2.9×10^{-2}	2.0×10^{-2}
GC	8.8×10^{-4}	4.2×10^{-3}	5.9×10^{-4}	2.3×10^{-4}	5.2×10^{-3}	1.1×10^{-2}	4.7×10^{-3}	1.6×10^{-3}	2.1×10^{-3}	2.1×10^{-3}

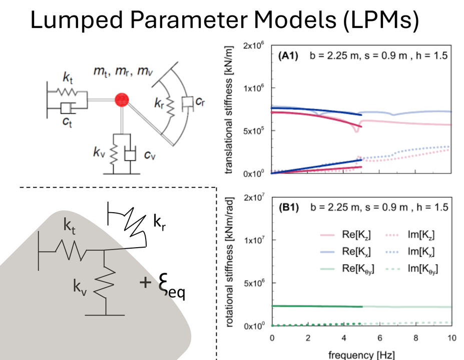
With soil-foundation-structure interaction (SFSI)

Case-studies

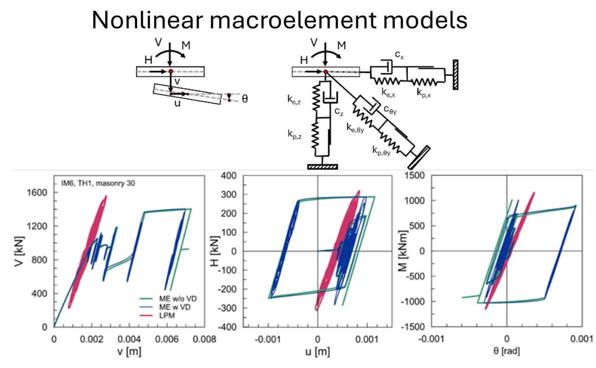


Modelling strategies for SFSI

Lumped Parameter Models (LPMs)



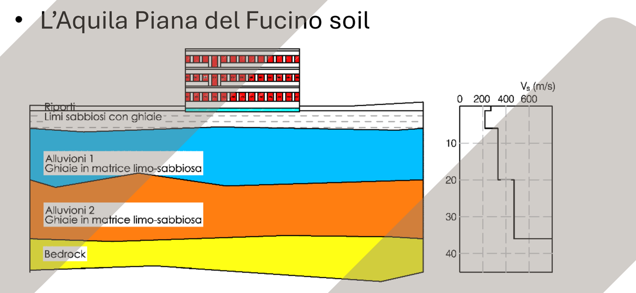
Nonlinear macroelement models



→ Implementation in TREMURI

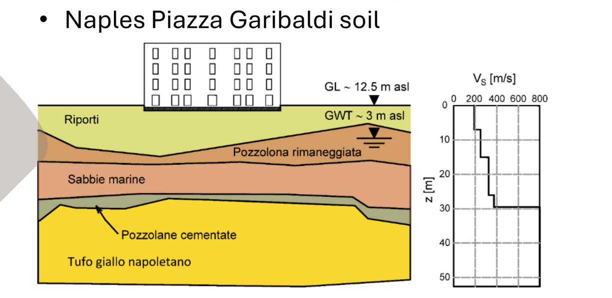
Analysis of Building 4

- L'Aquila Piana del Fucino soil

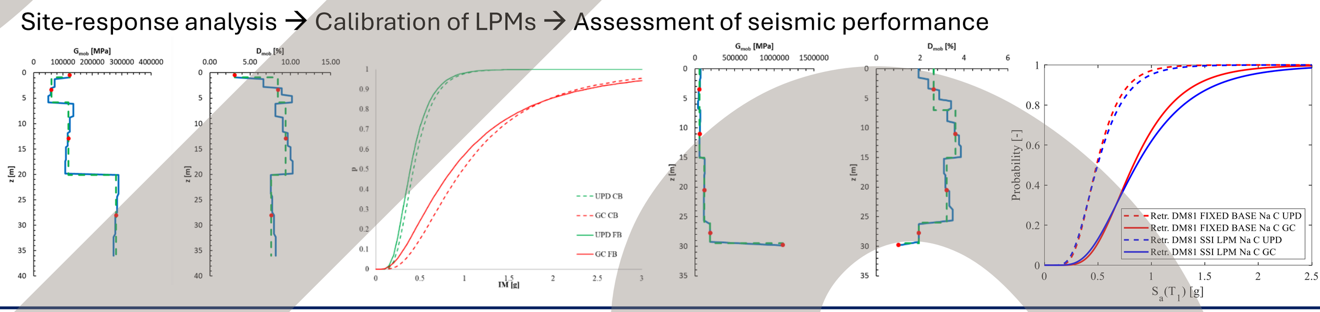


Analysis of Building 5

- Naples Piazza Garibaldi soil



Site-response analysis → Calibration of LPMs → Assessment of seismic performance

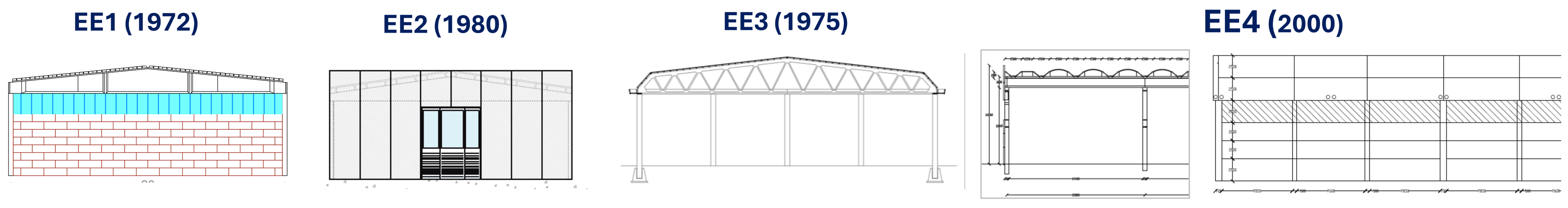


PRECAST REINFORCED CONCRETE BUILDINGS

Objective: The study aims to assess the seismic risk of single-story existing RC industrial buildings, both in their non-retrofitted and retrofitted states. The research is conducted by four units: EUCENTRE (Building EE1), UNIBG (Building EE2), UNINA (Building EE3), and UNINSUBRIA (Building EE4).

Case study buildings: single-storey precast buildings derived from RINTC-Project

EE1 (1972) | EE2 (1980) | EE3 (1975) | EE4 (2000)



EE1 (1972)	EE2 (1980)	EE3 (1975)	EE4 (2000)
$\zeta_{E,min}(MI) = 14\%$	$\zeta_{E,min}(MI) = 26\%$	$\zeta_{E,min}(MI) = 9\%$	$\zeta_{E,min}(MI) = 16\%$
$\zeta_{E,min}(AQ) = 6\%$	$\zeta_{E,min}(AQ) = 16\%$	$\zeta_{E,min}(AQ) = 2\%$	$\zeta_{E,min}(NA) = 20\%$

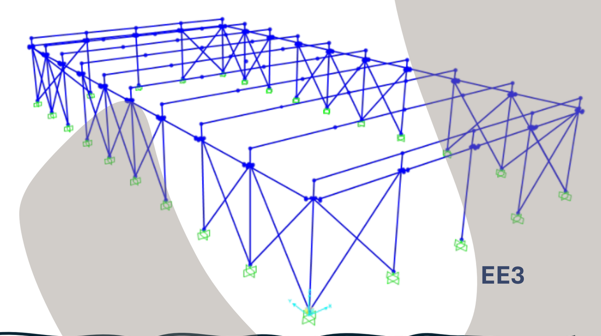
Approach to the retrofit design

- ❑ Response spectrum analysis (behavior factor equal to 1.5). Safety determined from demand/capacity ratio (ζ_E)
- ❑ Design of the interventions:
- Roof connections: design load equal to 1.3 times the demand from analysis.
- Connections between cladding elements and main structure
  - Out-of-plane design load evaluated as for secondary elements [§7.2.3 NTC18]
  - In-plane displacement demand derived from elastic spectrum analysis.
- Capacity design of the connections, etc., based on the capacity of the columns.

MSA ➡ D/C (elements/connections; UPD and GC) ➡ Fragility curves and Failure rates

Nonlinear modelling + Multi Stripe Analyses

Both the structural and non-structural elements were explicitly modelled
- **Column Base (plastic hinge)**
- **Connections**
  - Roof element-to-beam
  - Panel-column
  - Panel-beam
  - Panel-column

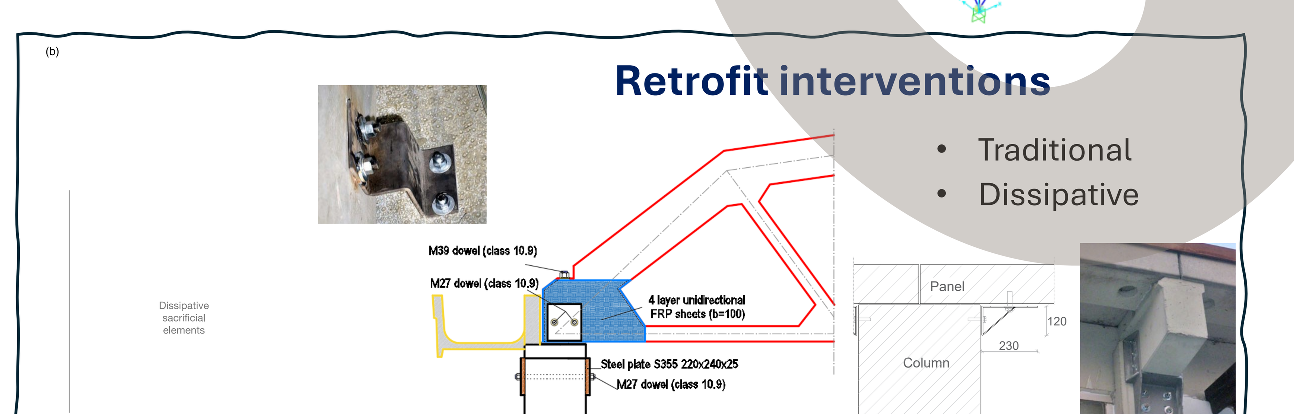


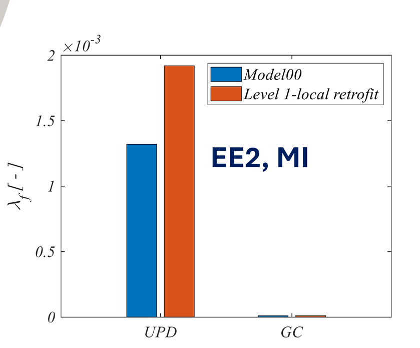
Hysteretic models

- Columns and dowels: Modified Ibarra-Medina-Krawinkler
- Friction connection: Coulomb Friction
- New connections: Elastoplastic

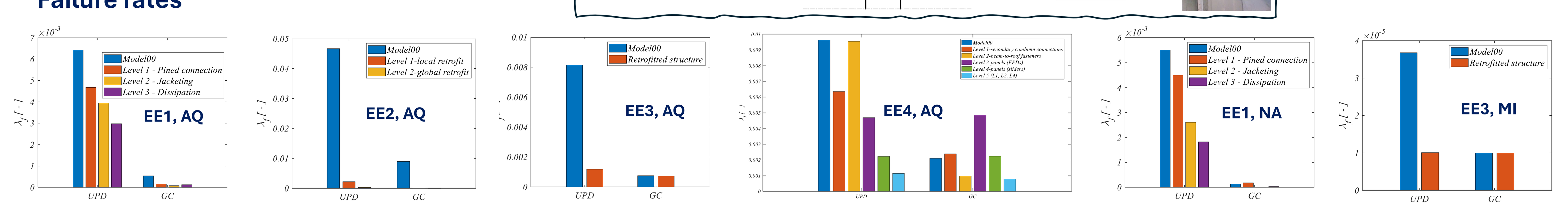
Retrofit interventions

- Traditional
- Dissipative





Failure rates



Conclusions: The study suggests that local retrofitting, especially at the roof level, can improve seismic resistance in existing buildings. However, retrofitting strategies should be tailored to structural and structural features.

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