

Author:

Petra Prašnikar, m.i.a.

Evaluating the applicability of contemporary seismic retrofitting techniques on post-war structures in Slovenia

Supervisor: Asst. Prof. Dr. Simon Petrovčič

Figure: Savsko neighborhood, Ljubljana, Slovenija.

(Reference: The Museum of Contemporary History of Slovenia)



Introduction and Context

- Due to post-WWII immigration to larger cities and immigration from former Yugoslavia, massive construction of multi-unit residential buildings began in Slovenia (Petelin, 2017).
- 22.6% of total area of multi-story buildings in Slovenia were constructed between 1945-1963 (Kilar & Kušar, 2009).
- Focus on buildings predating earthquake safety regulations introduced after 1964 Skopje earthquake.



Reference: Studio Krištof architects

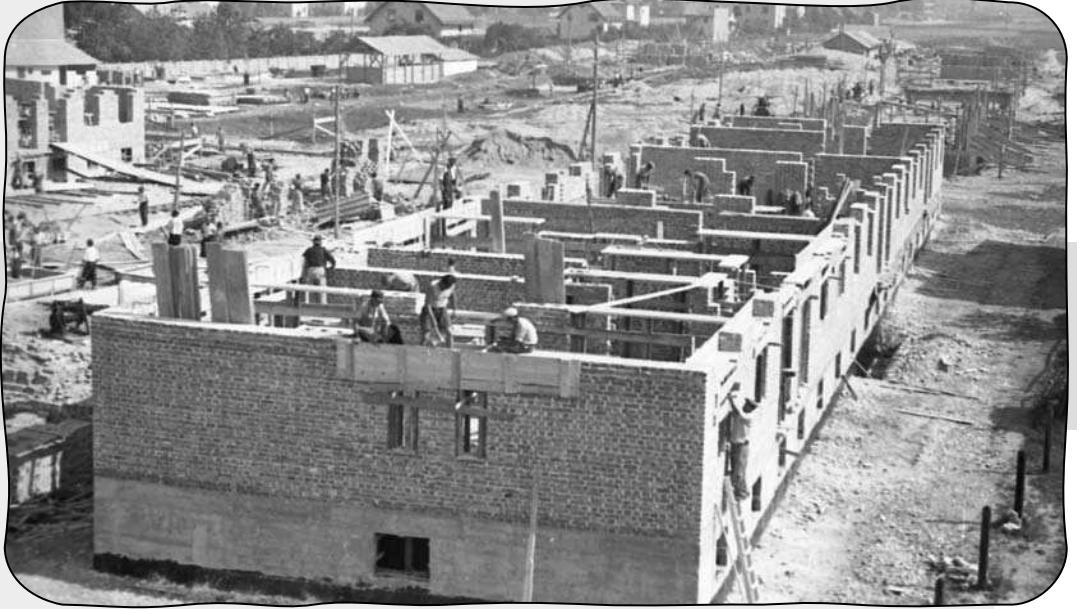


Figure: Building of multi-residential buildings in Ljubljana (Litostroj neighborhood) (Reference: Štajer, 1947)

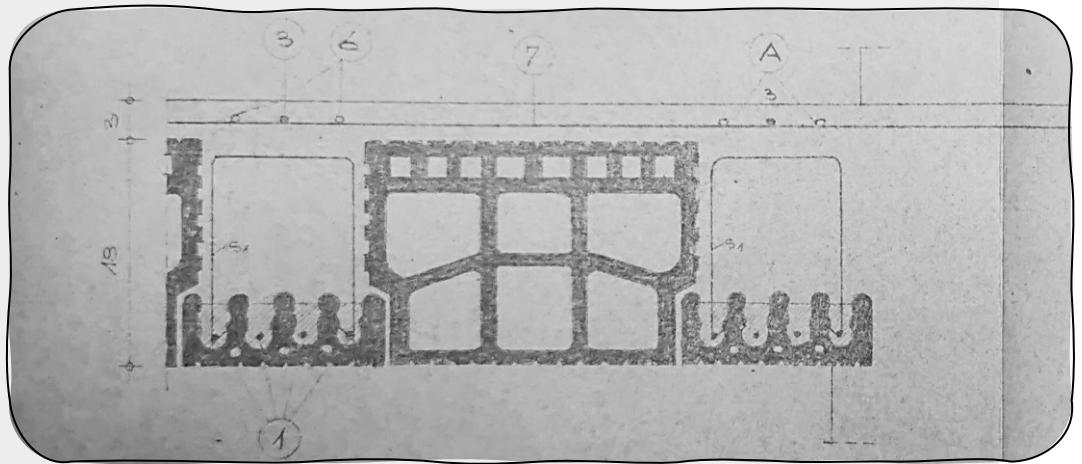


Figure: Ceiling structures made of reinforced concrete joists with hollow clay brick. (Reference: Historical archive of Ljubljana)

Building Characteristics

- Vertical load-bearing walls: various mortar types, lack of wooden or iron ties.
- Ceiling structures: reinforced concrete joists, hollow clay brick, limited connection to walls.
- Such buildings are often situated in high-intensity seismic areas.

Material

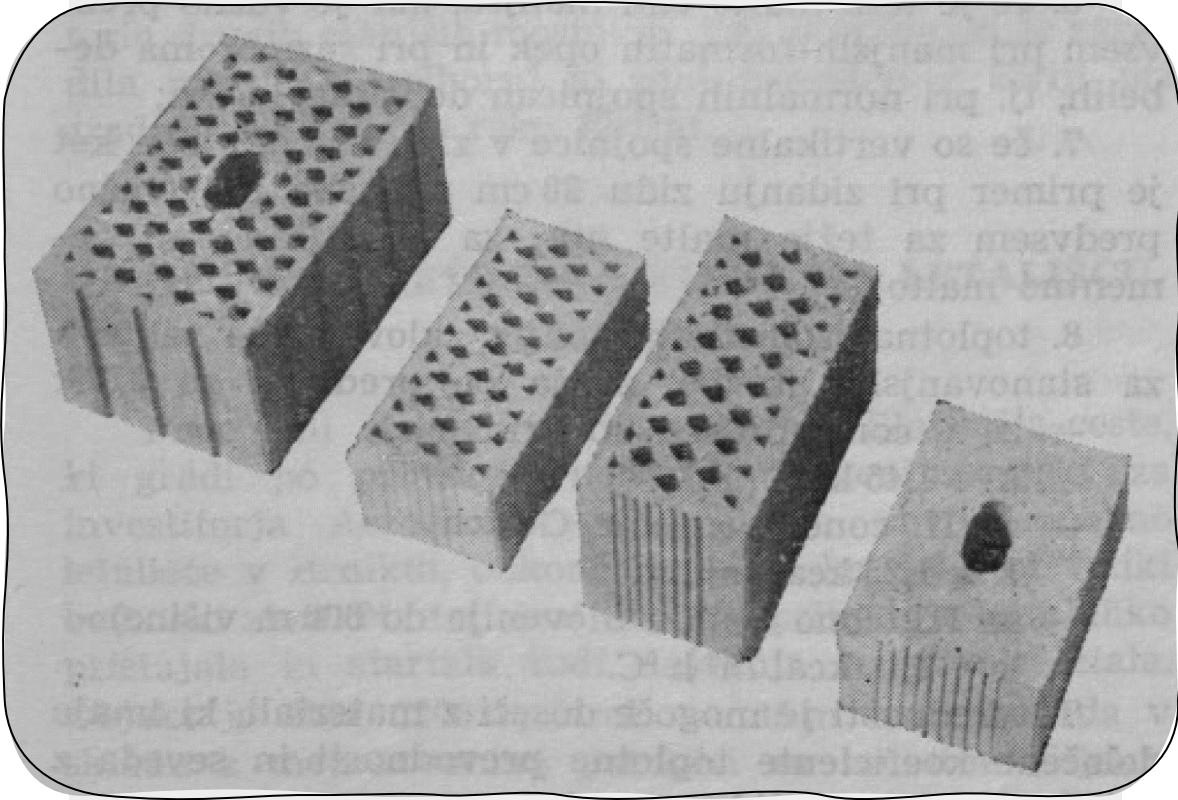


Figure: Hollow brick used in that period of time

(Reference: Gradbeni vestnik no. 11, 1963).

Figure: Full bricks used for construction..

(Reference: The Museum of Contemporary History of Slovenia).



MAP OF SEISMIC HAZARD IN SLOVENIA WITH GROUND MOTION ACCELERATION

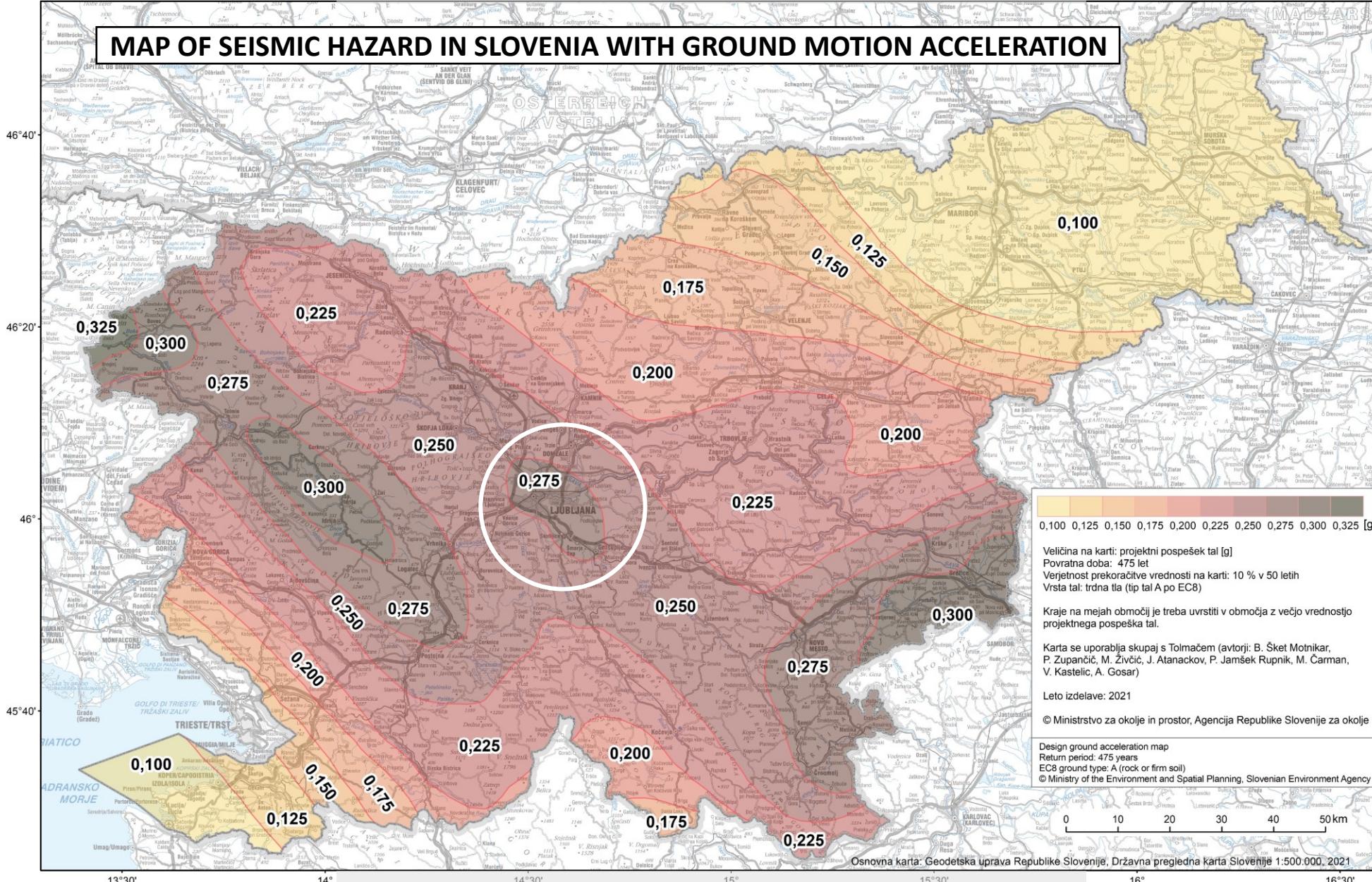
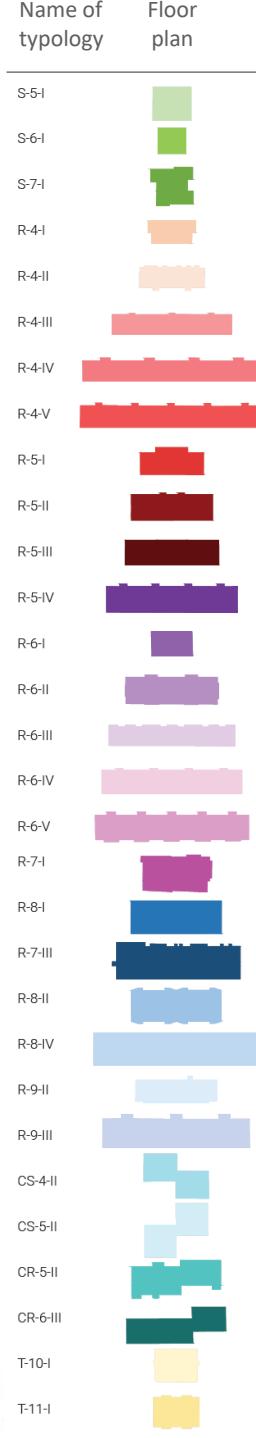
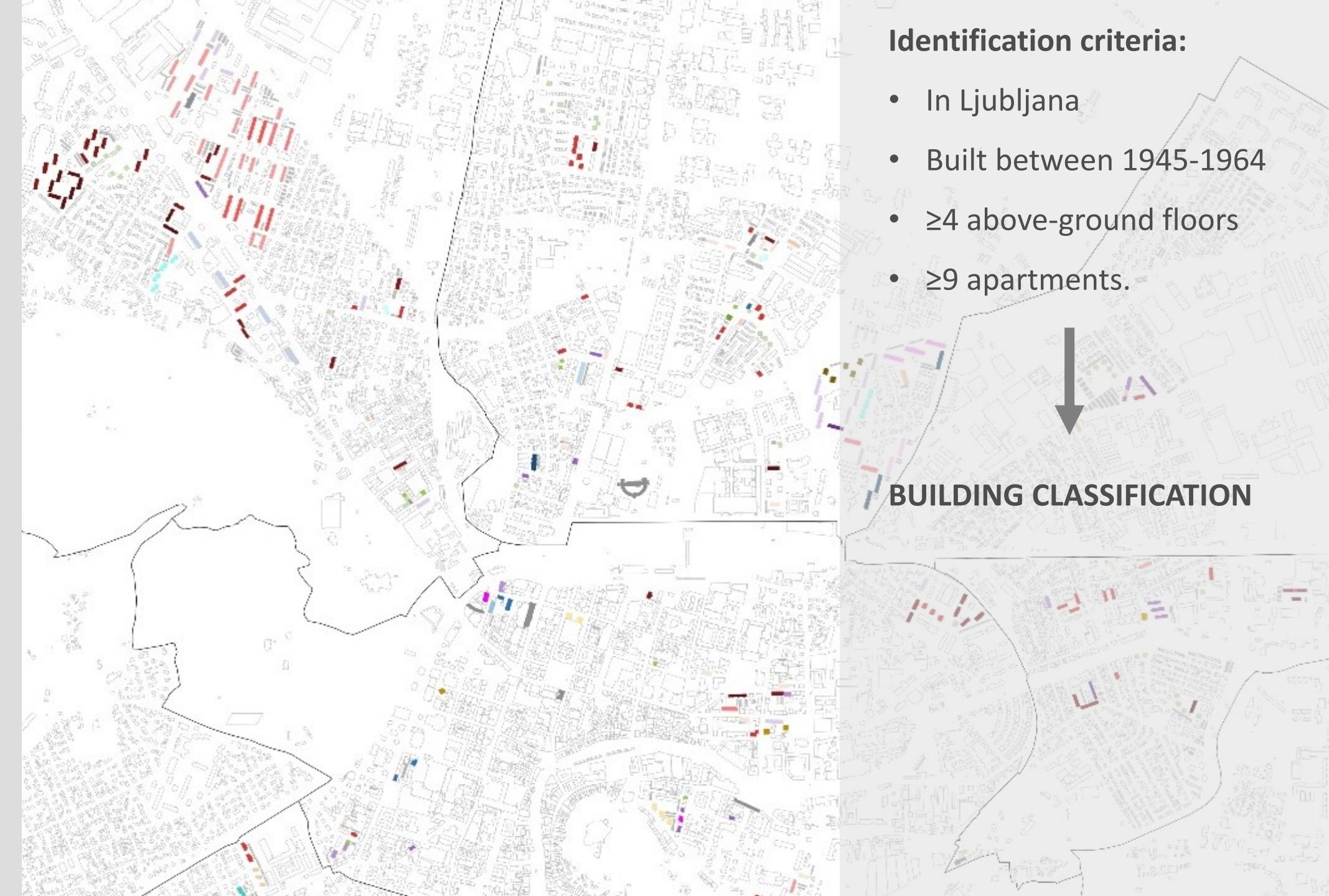


Figure: Map of Seismic Hazard in Slovenia - Ground Motion Acceleration.

(Reference: ARSO, 2021)

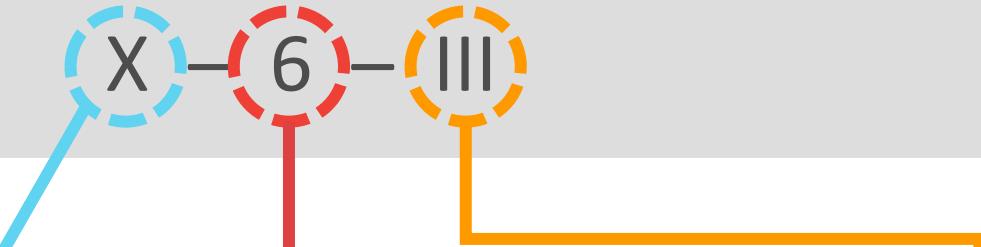


Building Identification



Building Classification

- The X represents the shape of the building, which is divided in to three separate groups:
 - ❖ S - buildings with floor plans approximately square in shape, with a width-to-length ratio between 1.0 and 1.2
 - ❖ R - buildings with floor plans that are rectangular, having a width-to-length ratio greater than 1.2
 - ❖ T - buildings shaped like towers, with a floor plan aspect ratio less than 2.0 and a height-to-width ratio greater than 2.0.



Arabic number in the proposed name represents the total number of floors above ground.

Roman numeral indicates the number of building cores present in the building.

Name of typology	Floor plan	No. of buildings	Specific data aquired	Ratio x vs y direction	Ratio height vs y direction	Proportion of walls in x direction [%]	Proportion of walls in y direction [%]	Material of vertical structure	Floor material	LEGEND	MATERIAL OF VERTICAL CONSTRUCTION:	INTER-FLOOR SLAB COMPOSITION:
											OPE - unreinforced brick masonry	BET - unreinforced concrete block masonry
S-5-I		70	14	1.00-1.20	0.90-1.55	5.44-6.40	2.45-8.00	OPE, BET	MSS			
S-6-I		9	1	0.99-1.20	1.13-1.62	1.94	7.03	OPE	MSS			
S-7-I		1	0	1.08	1.15	/	/	/	/			
R-4-I		10	0	1.33-3.49	0.87-1.58	/	/	/	/			
R-4-II		19	3	2.4-4.35	0.92-1.92	6.30	5.50	OPE	MSS, AB			
R-4-III		27	6	2.91-6.27	0.97-1.91	3.06	6.57	OPE	MSS			
R-4-IV		5	2	3.93-7.75	1.10-1.61	6.80	6.00	OPE	AB			
R-4-V		6	0	7.06-7.78	1.16-1.32	/	/	/	/			
R-5-I		66	9	1.21-3.27	0.79-1.82	5.51-6.00	3.44	OPE	MSS			
R-5-II		46	7	1.84-4.71	0.93-1.82	6.00	3.70	OPE, BET	MSS			
R-5-III		18	8	3.44-7.45	1.20-1.90	2.68-5.60	3.54-4.75	OPE, BET	MSS			
R-5-IV		6	3	4.35-7.5	0.85-1.61	3.12	6.70	OPE	MSS			
R-6-I		26	2	1.25-2.21	1.18-1.95	5.55	3.28	OPE	MSS			
R-6-II		6	1	1.73-3.48	0.93-1.63	5.20	2.84	OPE	AB			
R-6-III		22	4	3.35-6.16	1.13-4.75	6.80	6.00	OPE	MSS			
R-6-IV		1	1	5.91	1.96	6.80	6.00	OPE	AB			
R-6-V		3	0	3.73-5.90	1.17-1.60	/	/	/	/			

Compliance to the code-based design criteria

Design criteria and/or construction rule	Compliance
Masonry buildings shall be composed of floors and walls, which are connected in two orthogonal horizontal directions.	No
The connection between ceilings and walls must be ensured by steel or reinforced concrete ties.	No
If it provides general requirements for continuity and effective functioning as a diaphragm, any type of ceiling may be used.	Partial
Shear walls must be provided in at least two orthogonal directions.	Yes
The effective thickness of URM shear walls may not be less than 240 mm.	Yes
The ratio of the effective height of the shear wall (based on EN 1996-1-1) to its effective thickness may not exceed a maximum value of 12 for URM.	Partial
The ratio of the length of the shear wall to the greater clear height of the opening adjacent to the wall may not be less than 0.35 for URM.	Partial

Table: Design criteria and construction rules for the seismic design of masonry structures in accordance with Eurocode 8 and the compliance of examined building typologies (Reference: Petrovčič et al., 2023).

Case study R-6-III



Figure: Case study building, type R-6-III

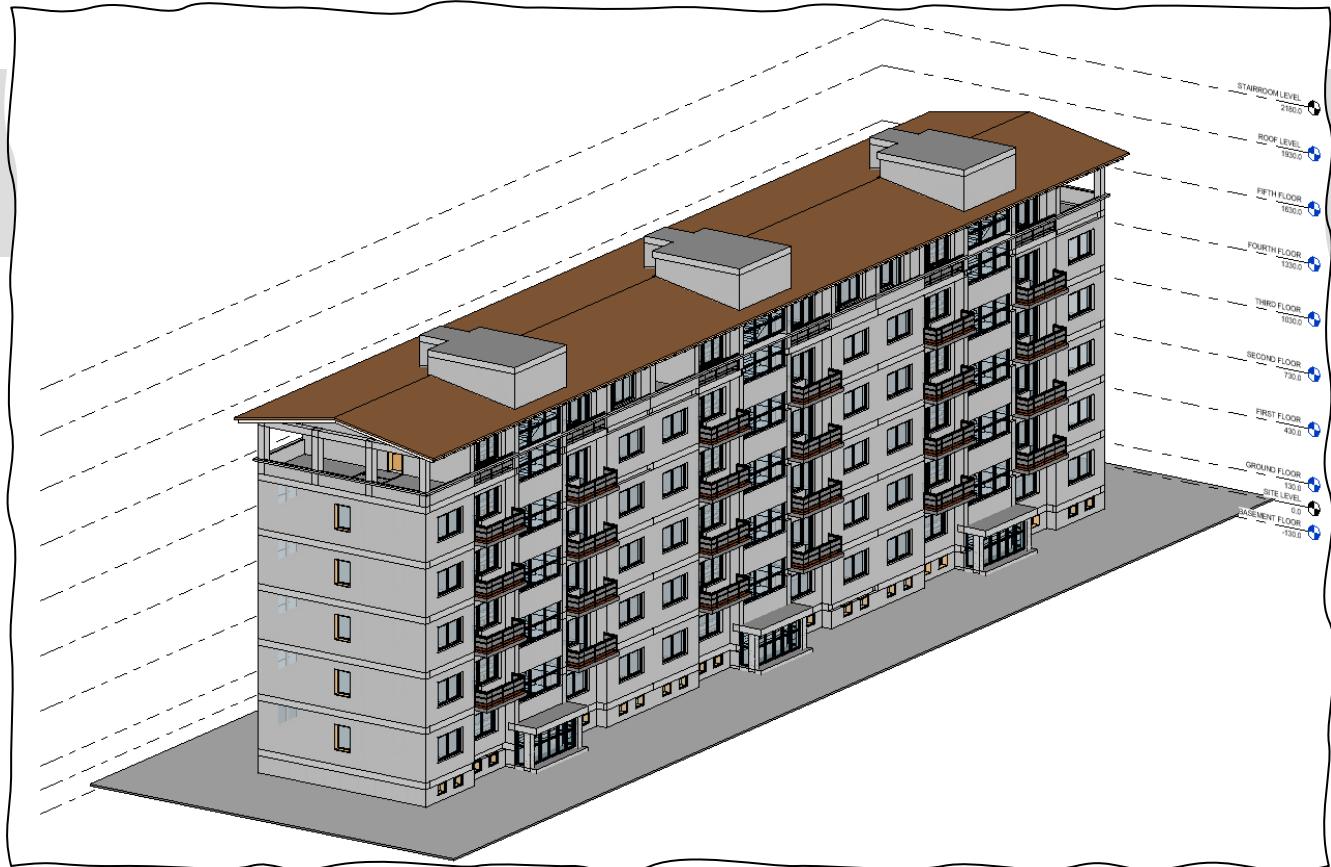


Figure: BIM model of a case study building, type R-6-III (Reference: Student project ARRS, University of Ljubljana, Faculty of Architecture)

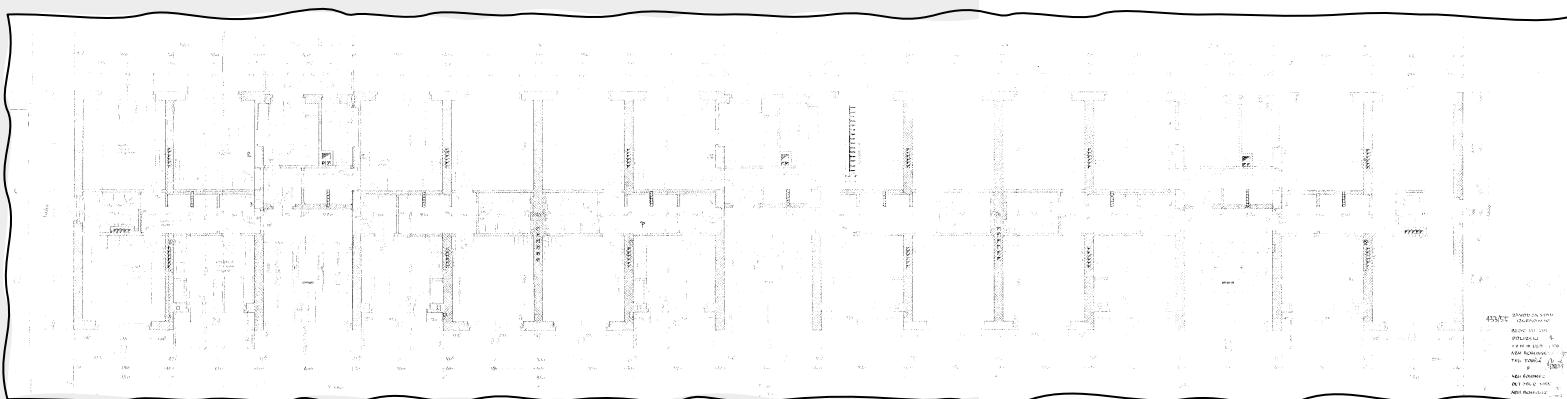
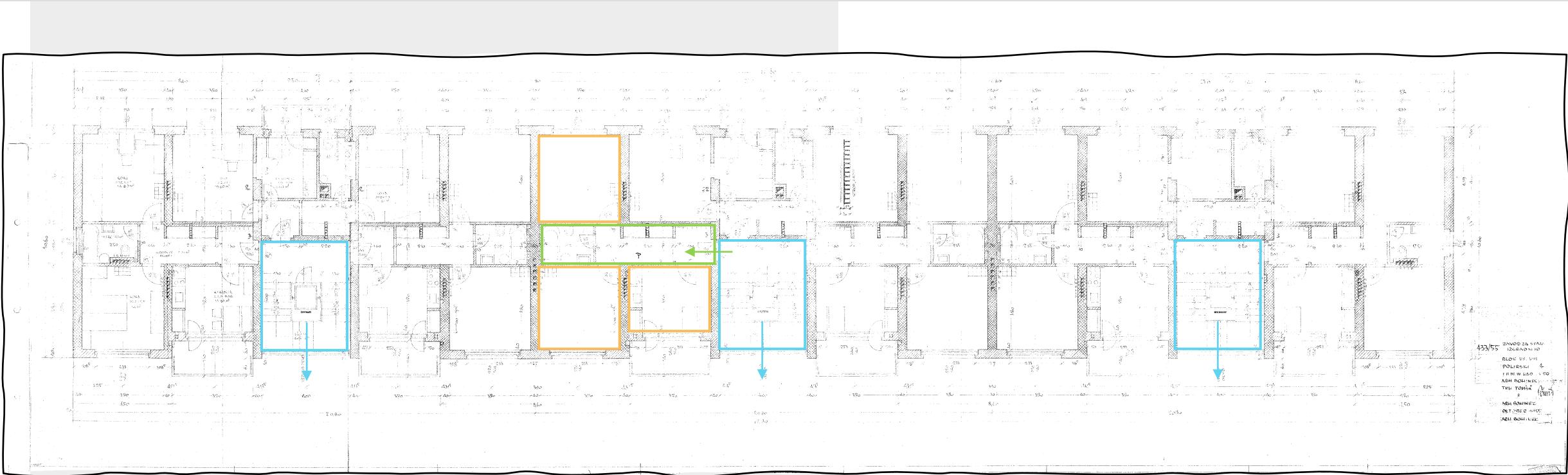


Figure: Case study building floor plan (original plan)

Floor plan and properties



- Bigger openings in the longitudinal wall
- The staircases are in the front longitudinal facade and contribute to irregular wall openings

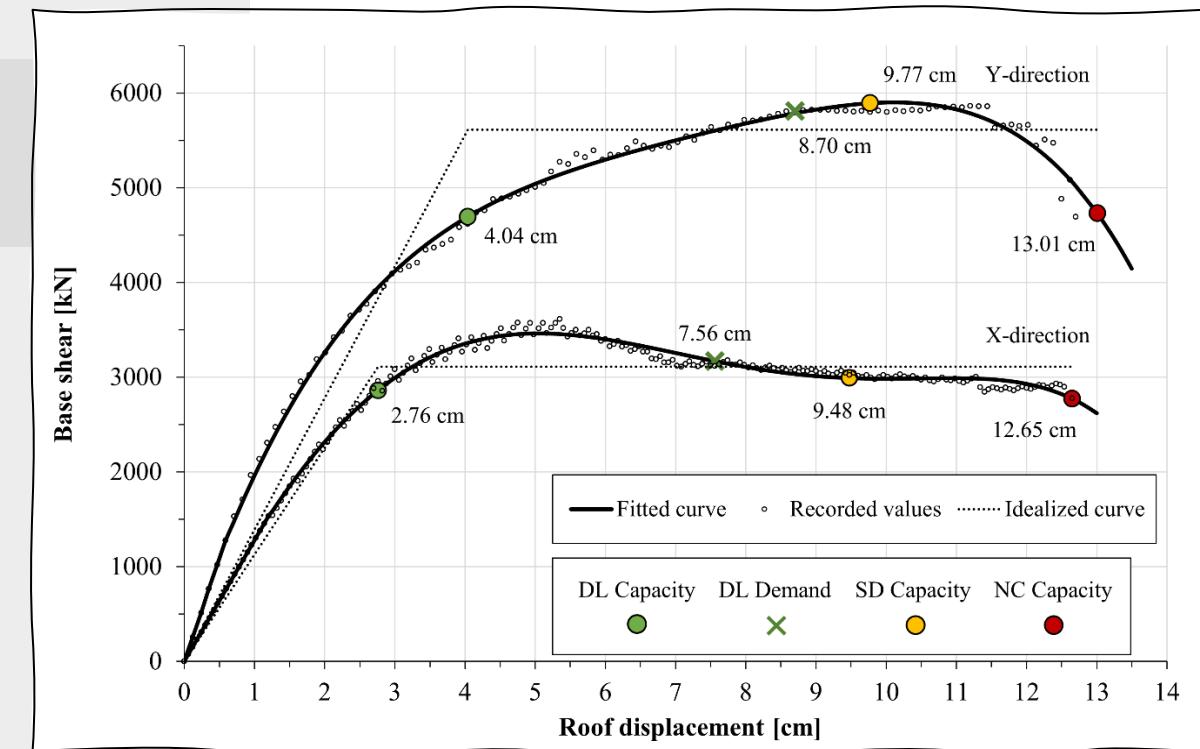
Percentage of walls:

- In longitudinal direction: **2,52 %**
- In transversal direction: **7,10 %**

R-6-III type – analysis

- 3Muri Software
- Pushover analysis
- Protection levels:
DL, SD, and NC

Maximum base shear force:
 • X direction: **7,1%**
 • Y Direction: **12,1%**
 Of the weight of the
 structure.



Graph: Results of the Pushover Analysis of the Existing Condition of the Building (Reference: Petrovčič et al., 2023).

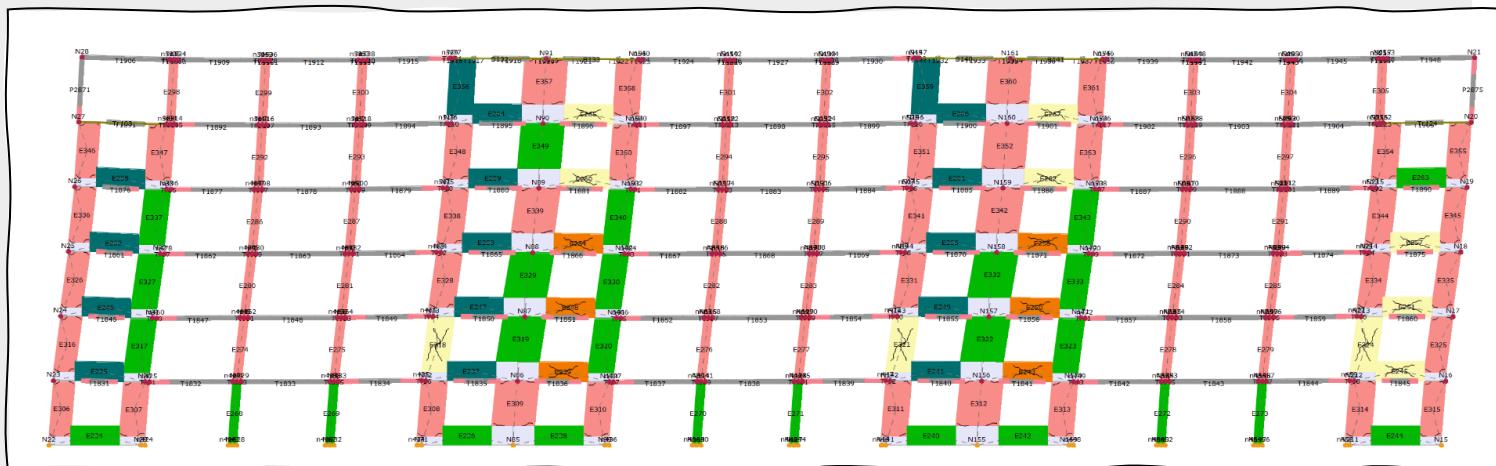


Figure: Results of the Analysis of the Existing Condition of the Building - Front Facade (Reference: Petrovčič et al., 2023).

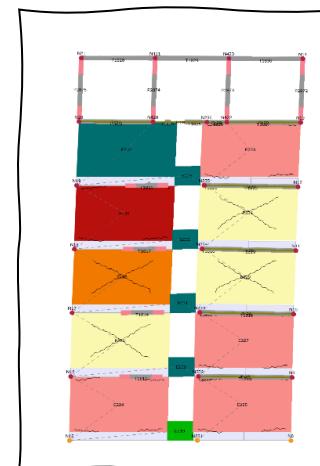


Figure: Analysis Results - Side Facade (Reference: Petrovčič et al., 2023).

LEGEND	
Undamaged	Green
Shear damage	Yellow
Shear failure	Orange
Bending damage	Red
Bending failure	Dark Red
Compression failure	Purple
Tension failure	Blue
Failure during elastic phase	Dark Teal

Seismic strengthening

FRCM

- Used for strengthening URM walls.
- It is a composite material with fibers embedded in a cementitious matrix.
- Easy installation, thinner layers, and minimal mass increase.
- Suitable for inhabited buildings with mixed ownership, practical application, and avoiding major downtimes.



Figure: FRCM application to masonry wall

Seismic strengthening

Four different retrofitting cases:

- Building core (BC)
- Building core, outer piers and outer walls (BC—OP—OW)
- Building core, inner piers and outer walls (BC—IP—OW)
- All positions (BC—OP—IP—OW—IW)

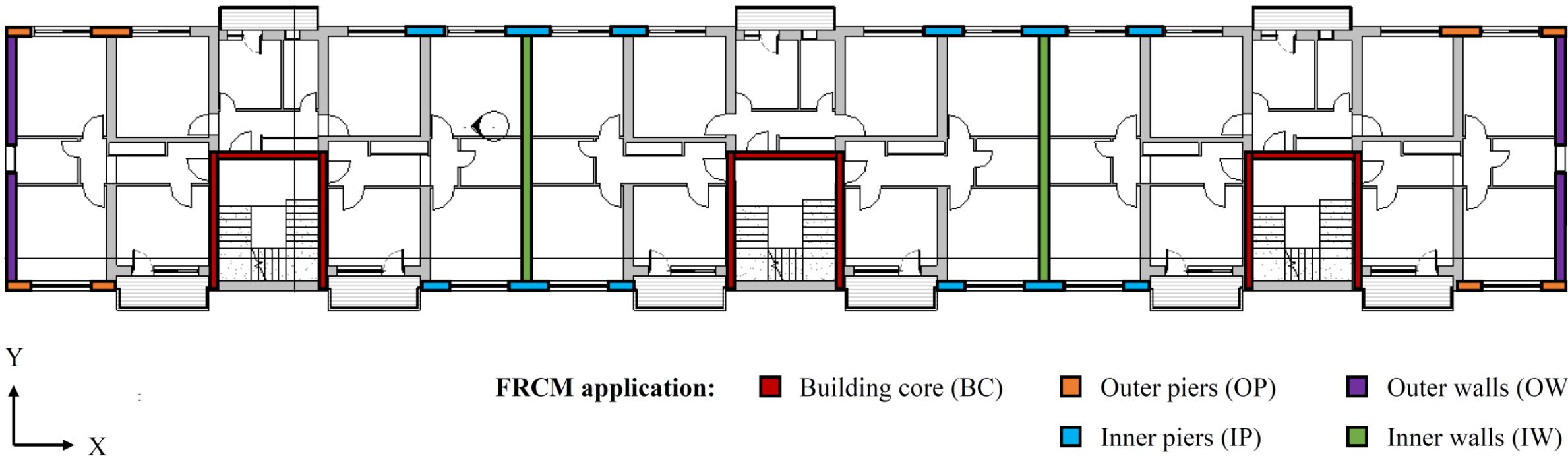
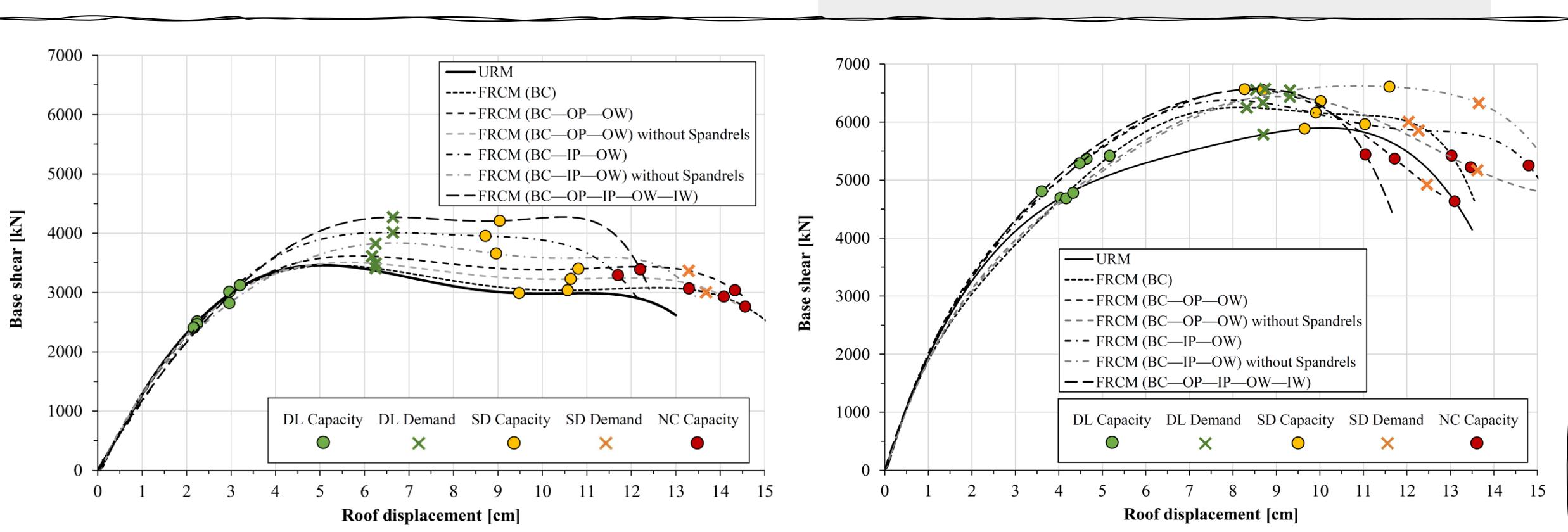


Figure: Retrofit positions (Reference: Petrovčič et al., 2023).

Comparison of results



Graph: Capacity curves of the retrofitted variants in X and Y direction (Reference: Petrovčič et al., 2023).

Conclusion

- URM building from studied period showed inadequate seismic resistance in both directions.
- Seismic retrofitting measures are necessary.
- Sole use of FRCM is insufficient for prescribed seismic resistance.
- Retrofitting plan should consider additional actions, e.g., external RC walls or reinforced plasters.
- A possibility: alternative construction, built to modern standards.
- We need future studies to be based on stochastic data, larger typological sample and systematization.



Figure: A typical multi-residential building in Ljubljana.

(Reference: Historical archive of Ljubljana godovinski arhiv Ljubljana)

References and literature:

- ANĐELOVIĆ, G.V., 2018. Specifičnosti in pomen tlorisne zasnove večstanovanjske arhitekture modernizma v obdobju 1950-1973 v Beogradu, Ljubljani in Zagrebu: doktorska disertacija = The specifics and significance of plans in modernist housing 1950-1973 in Belgrade, Ljubljana and Zagreb.
- ARSO, 2011. Karta potresne intenzitete Slovenije. Pridobljeno 5. 1. 2023.
https://potresi.arso.gov.si/doc/dokumenti/potresna_nevarnost/intenziteta_resevanje.jpg
- BABIČ, A., ŽIŽMOND, J. & DOLŠEK, M., 2022. Potresno tveganje stavbnega fonda v Sloveniji = Seismic risk of the building stock in Slovenia. Gradbeni vestnik, [online] (71), pp.34–47. Available at: <http://www.dlib.si/details/URN:NBN:SI:doc-R5IVLJAN>.
- CARDINALI, V., TANGANELLI, M., & BENTO, R. (2022). A hybrid approach for the seismic vulnerability assessment of the modern residential masonry buildings. International Journal of Disaster Risk Reduction, 79, 103193.
- FAJFAR, P. 2017. Razvoj predpisov za potresno odporno gradnji v Sloveniji-Development of seismic codes in Slovenia. Gradbeni vestnik, 66.
- GAL, J. 1959. Savsko naselje v Ljubljani 1959. Wikipedia, pridobljeno 6. 1. 2023,
https://sl.wikipedia.org/wiki/Savsko_naselje
- GRÜNTHAL, G. 1998. European macroseismic scale 1998. European Seismological Commission (ESC).
- JAKOŠ, A. 2006. Ljubljana-faze urbanega razvoja. Urbani izviv, 17, 12-17.
- KILAR, V. & KUSAR, D. 2009. Assessment of the earthquake vulnerability of multiresidential buildings in Slovenia. Acta Geographica Slovenica-Geografski Zbornik, 49, 89-106.
- KILAR, V. & PETROVČIČ, S., 2017. Seismic rehabilitation of masonry heritage structures with base-isolation and with selected contemporary strengthening measures. International journal of safety and security engineering. (Vol. 7, iss. 4, str. 475-485)
- KILAR, V., PETROVČIČ, S., KOREN, D., ŠILIH, S., 2011. Seismic analysis of an asymmetric fixed base and base-isolated high-rack steel structure. Engineering structures. (Vol. 33, iss. 12, str. 3471-3482)
- MAHOVIČ, Z., 1950. Titovi zavodi Litostroj kot simbol povojne industrializacije Ljubljane ter litostrojski bloki in bloki Mestnega ljudskega odbora. Muzej novejše zgodovine Slovenije.
- NIKŠIČ, M., GORŠIČ, N., MIHELIČ, B., MUJKIČ, S. & TOMINC, B. 2013a. Smernice za vzdrževanje in prenovo karakterističnih območij mesta Ljubljane, Litostrojsko naselje. Mestna občina Ljubljana.
- NIKŠIČ M., G. N., MIHELIČ B., MUJKIČ S., TOMINC B. 2013b. Smernice za vzdrževanje in prenovo karakterističnih območij mesta Ljubljane, Savsko naselje. Mestna občina Ljubljana, Mestni trg 1, 1000 Ljubljana.

References and literature:

- PAHOR, M., 2014. Model trajnostne prenove večstanovanjskih objektov, zgrajenih med letoma 1946 in 1990 v Sloveniji = Sustainable renovation model for multi-apartment buildings, built during the years 1946 and 1990 in Slovenia.
- PETELIN, D. 2017. Stanovanske razmere v Ljubljani v letih 1945–1965. Kronika, 1-18.
- PETROVČIČ, S. & KILAR, V., 2018. Arhitekturno-tehnični vidik varovanja arhitekturne dediščine na potresno ogroženih območjih. *Annales: anali za istrske in mediteranske študije. Series histroia et sociologia.* (Letn. 28, št. 3, str. 589-610)
- PETROVČIČ, S., & KILAR, V., 2022. Design considerations for retrofitting of historic masonry structures with externally bonded FRP systems. *International Journal of Architectural Heritage*, 16(7), 957-976.
- PETROVČIČ, S. & KILAR, V., 2017a. Ocena potresne ranljivosti objektov arhitekturne dediščine na območju Slovenije. *Annales: anali za istrske in mediteranske študije. Series histroia et sociologia.* (Letn. 28, št. 2, str. 277-294)
- PETROVČIČ, S. & KILAR, V., 2013. Seismic failure mode interaction for equivalent frame modeling of unreinforced masonry structures. *Engineering structures.* (Vol. 54, str. 9-22)
- PETROVČIČ, S. & KILAR, V., 2017b. Seismic retrofitting of historic masonry structures with the use of base isolation – modeling and analysis aspects. *International journal of architectural heritage: conservation, analysis and restoration.* (Vol. 11, iss. 2, str. 229-246)
- PETROVČIČ, S., PRAŠNIKAR, P., KILAR, V., 2023. Seismic Performance and Retrofit of a Mid-Rise Post-Second World War Residential Building Made of Unreinforced Masonry
- SIST EN 1998-1. 2005. Evrokod 8: Projektiranje potresnoodpornih konstrukcij. Del 1: Splošna pravila, potresni vplivi in vplivi na stavbe.
- SITAR, M. in SKALICKY KLEMENČIČ, V. (2010). Assessment of quality of suburban building stock. Case study: Savsko naselje, Ljubljana, Slovenia.
- SLAK, T. & KILAR, V. 2005. Potresno odporna gradnja in zasnova konstrukcij v arhitekturi. Ljubljana. Univerza v Ljubljani, Fakulteta za arhitekturo.
- SENDI, R. in KOS, D., 2004. Rehabilitacija stanovanske soseske: primer Savsko naselje: povzetek. Ljubljana.
- Stavbinski red za mesto Ljubljana. 1896. Pridobljeno 29.11.2022.
<http://www.dlib.si/?URN=URN:NBN:SI:DOC-SWFPDKPP>
- ŠTAJER, B. 1947. Gradnja litostrojskih blokov in blokov MLO z udarniškim delom. Muzej novejše zgodovine Slovenije.
- TOMAŽEVIČ, M. 2009. Potresno odporne zidane stavbe. Ljubljana, Slo: Narodna in univerzitetna knjižnica, 301.
- ZUPANČIČ STROJAN T., ZBAŠNIK-SENEGAČNIK, M., NOVLJAN T., FIKFAK A. 2002. Degradirana območja organizirane večstanovanjske gradnje med letoma 1945 in 1965 v Sloveniji - metodologija vrednotenja in prenove. *Urbani Izziv*, 13, 82-89.
- ŽIŽMOND, J. & DOLŠEK, M. 2015. Projektni pospešek tal z upoštevanjem ciljne verjetnosti porušitve. *Gradbeni vestnik*.



Figure: Multi-residential buildings in Litostroj neighbourhood, Ljubljana

(Reference: The Museum of Contemporary History of Slovenia).

Thank you for your attention!

Table 2. Considered mechanical parameters of masonry.

Parameter		Value	Parameter		Value
Masonry density	(γ)	1600 kg/m ³	Young's modulus	(E)	1800 MPa
Compressive strength	(f_c)	4.00 MPa	Shear modulus	(G)	360 MPa
Tensile strength	(f_t)	0.14 MPa	Confidence factor	(CF)	1.20

Table 3. Performance requirements based on EC8-3, indicating the corresponding return periods and peak ground accelerations of the examined building.

EC8-3 Limit state	Return period	PGA (subsoil class C)
Damage limitation (DL)	95 years	0.190g
Significant damage (SD)	475 years	0.316g
Near collapse (NC)	2475 years	0.538g

Table 4. Considered mechanical parameters of FRCM.

Parameter		Value	Parameter		Value
Equivalent thickness of FRCM	(t_f)	0.035 mm	Young's modulus of dry fibre	(E_f)	71000 MPa
Number of layers per side	(-)	3 (double sided)	Characteristic strain of FRCM	(ε_{fk})	1.45 %
Environmental conversion factor	(η_a)	0.80 (external) 0.90 (internal)	Design strain of FRCM	(ε_{fd})	0.24 %
			Design debonding strength	(f_{fdd})	113.17 MPa

Table 6. Control displacements.

Case	X-direction							Y-direction						
	$d_{c,DL}$ [cm]	$d_{c,SD}$ [cm]	$d_{c,NC}$ [cm]	$d_{d,DL}$ [cm]	$d_{d,SD}$ [cm]	α_{DL} [-]	α_{SD} [-]	$d_{c,DL}$ [cm]	$d_{c,SD}$ [cm]	$d_{c,NC}$ [cm]	$d_{d,DL}$ [cm]	$d_{d,SD}$ [cm]	α_{DL} [-]	α_{SD} [-]
URM	2.76	9.48	12.65	7.56	/	0.37	/	4.04	9.77	13.01	8.70	/	0.46	/
FRCM (BC)	2.24	10.65	14.56	6.26	13.66	0.36	0.78	5.17	9.91	13.1	8.24	12.39	0.63	0.80
FRCM (BC—OP—OW)	2.24	10.81	14.41	6.13	13.27	0.37	0.81	4.63	8.77	11.72	8.76	12.42	0.53	0.71
FRCM (BC—OP—OW) without Spandrels	2.16	10.64	14.08	6.32	15.82	0.34	0.67	4.25	10.10	13.47	9.37	13.62	0.45	0.74
FRCM (BC—IP—OW)	2.96	8.72	11.70	6.60	14.28	0.45	0.61	4.45	11.12	14.8	8.73	12.38	0.51	0.90
FRCM (BC—IP—OW) without Spandrels	2.96	8.96	13.3	6.32	15.82	0.47	0.57	4.17	11.60	15.5	9.37	13.62	0.45	0.85
FRCM (BC—OP—IP— OW—IW)	3.20	9.12	12.2	6.66	14.45	0.48	0.63	3.61	8.27	11.05	8.69	12.32	0.42	0.67