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Vulnerability Study of Urban and Rural Heritage Masonry in Slovenia Through The Assessment of Local and Global Seismic Response of Buildings

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SUMMARY:

Uncertainties regarding the influence of modelling strategies for the evaluation of seismic vulnerability of masonry buildings in Slovenia were studied on two case studies– damaged buildings from the rural area of NW Slovenia hit by earthquakes in '98 and '04 and the urban buildings from the old city centre of Ljubljana. Two strategies were applied – failure mechanisms analysis by means of FaMIVE methodology and non-linear response analysis by means of storey and global response (SREMB and 3Muri). The accuracy in predicting failure modes by FaMIVE was 50% considering the stock of investigated building in rural area. The most critical failure mechanisms were due to out-of-plane loading. For urban architecture, in-plane failure due to weak spandrels was the predominant one. The mechanism assessment yields more conservative results in respect to non-linear approach and thus may be an efficient tool for the design of strengthening measures for heritage buildings to prevent damage in lower intensity events with higher probability of occurrence.

Keywords: vulnerability, masonry, heritage buildings, local and global response

1. INTRODUCTION

The seismic assessment of old masonry buildings with architectural characteristics in a given earthquake prone area is subjected to many uncertainties that may be attributed not only to the randomness of earthquake motion, but also to their physical variability and to modelling strategies. The main components of a vulnerability analysis are the seismic capacity of the structure expressed in terms of a capacity curve, and the seismic demand expressed in terms of non linear response spectra. The convolution of these two parameters leads to the computation of vulnerability functions, usually expressed as fragility curve with the expected damage as a function of seismic input.

The vulnerability of structures can be evaluated either by statistical studies considering the damage distribution for a number of buildings typologies specific of an earthquake-struck area or by numerical simulation of seismic behavior of representative structures. In the latter case, different modelling strategies can be applied such as Continuum Constitutive Models (CCM), Structural Element Models (SEM), Discrete Interface Models (DIM) or Macro Element Models (MEM) (Calderini et al, 2010). Most common strategies for the seismic assessment of stone masonry structures are either MEM or SEM, which can be conducted for different portions of a structure. The first approach is particularly suitable for the out-of-plane response of walls. This type of seismic response is characteristic for historic stone masonry buildings where connections between orthogonal walls and between walls and floors are not efficient. This analysis is conducted as a limit state approach, and the main uncertainties are urban data, geometric characteristics of the façade and openings, presence of tie rods and intersecting walls, structural characteristics and presence of further vulnerable elements. Depending on the construction details of the building, different failure mechanisms can be identified (Fig.1). The mechanism analysis returns a collapse load multiplier that may trigger critical mechanism of failure. The vulnerability function can be expressed as the product of the collapse load factor, the type of mechanisms and the extent of structure collapsing. A procedure to derive a capacity curve from this assessment and compute performance points for a given shaking response spectra is shown in D'Ayala & Ansal (2011).

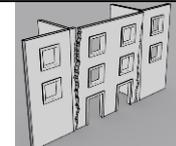
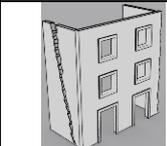
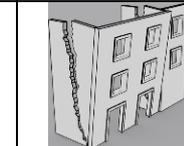
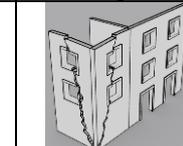
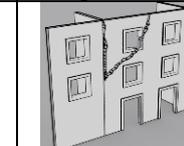
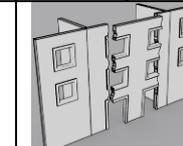
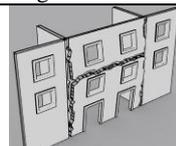
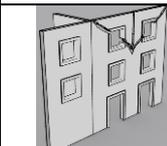
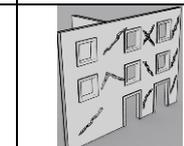
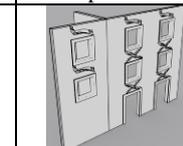
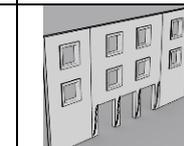
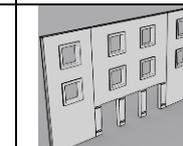
A	B1	B2	C	D	E
overturning with vertical cracks	overturning with one side wall	overturning with two side walls	diagonal cracks involving corners	overturning with diagonal crack	overturning with crack at spandrels
					
F	G	H1	H2	M1	M2
overturning constrained by ring beams or ties	overturning with diagonal cracks	diagonal cracks mainly in piers	diagonal cracks mainly in spandrel	soft storey due to shear	soft storey due to bending
					

Figure 1. Failure mechanism FaMIVE procedure by Novelli & D' Ayala (2011)

In common design practice global analysis of masonry structures is done by SEM approach. SEM approximates the actual structural geometry more accurately by describing individual structural elements such as piers and walls. The SEM models are usually used with static nonlinear analysis. In this case a step-by-step procedure is followed, using decreased stiffness values under increasing lateral loads. Nonlinear element behaviour is prescribed in the form of nonlinear lateral deformation-resistance relationships, depending on the boundary conditions and failure mode of masonry elements. Usually the bi-linear or tri-linear behaviour of SE is considered. The result of analysis is resistance envelope that is calculated by stepwise drifting of the structural point of interest. SEM can be applied either in simplified form by considering Storey Mechanisms Response (SMR) or by considering Global Mechanisms Response (GMR) of the whole structure. With GMR both modal and uniform mass lateral load distribution can be considered, whereas with SMR only uniform mass. In SMR the SE's are deformed equally (assumption of infinite rigidity of floor structure) and internal forces are induced according to the assumed shape of resistance envelope of each SE. On the other hand, GMR is based on the formation of equivalent frame idealization of multi-storey walls where behaviour of masonry piers and lintels with flexural and shear hinges is defined by a bilinear ideally elasto-plastic moment-rotation or force-displacement relationship. The result of SMR analysis is usually presented as the ultimate design Seismic Resistance Coefficient (SRC), which represents the ratio of H_{id}/W , where H_{id} is idealised resistance of analysed storey and W represent the weight of the building. With SMR the seismic performance of the structure can be directly correlated to the seismic demand imposed in the terms of target displacements and accelerations.

On the other hand the nonlinear static procedure considering GMR requires in order to identify the performance point (PP) of the structure (Fig.2): firstly, the conversion of the original multiple degree of freedom structure (MDOF) response, represented by the pushover curve, to an equivalent single degree of freedom structure (SDOF) response; secondly, the comparison between the capacity of the equivalent SDOF system and the demand expected, described by an elastic spectrum appropriately reduced (inelastic or overdamped spectra). This approach focuses in the determination of the target displacements and deformations which are considered to be the more relevant parameters in seismic design. The outcome of GMR analysis is related to the PP of interests and is usually interpreted through ultimate Limit State (LS) Peak Ground Acceleration (PGA) for the PP of interest.

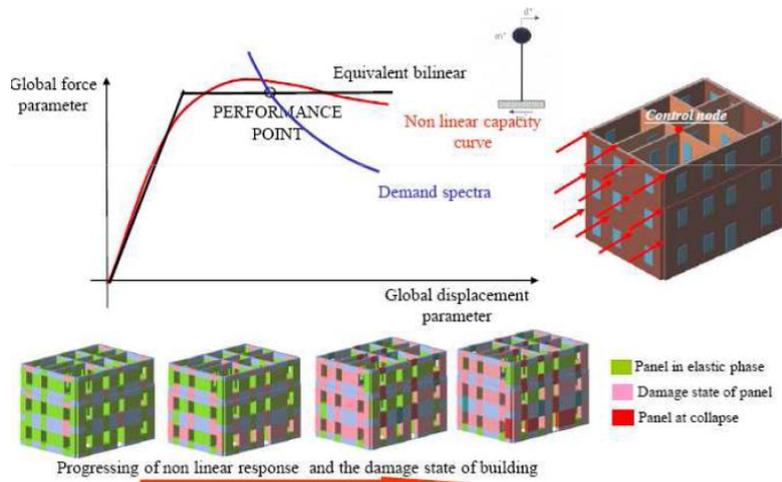


Figure 2. Identifying performance point through GMR considering seismic demand (Lagomarsino et al., 2011)

2. APPLICATION OF MBM THROUGH FAMIVE METHODOLOGY - CASE STUDIES

Within the framework of EU research project PERPETUATE (www.perpetuate.eu), the efficiency of different strategies for the assessment of stone masonry structures was investigated by application to two case studies in Slovenia (Fig. 3), one in a rural area, the other in an historic urban setting. For rural architecture a set of already damaged buildings from Bovec basin (NW Slovenia) that has been recently struck by two strong earthquakes (1998 and 2004) were investigated, while for urban architecture – the historic city center of Ljubljana was chosen (last stronger earthquake in 1895).

For both case studies, MEM was done by FaMIVE methodology. Failure Mechanisms Identification and Vulnerability Evaluation (FaMIVE) methodology was developed by D' Ayala & Speranza (2003) on the basis of expected failure modes for buildings in urban area (buildings closely spaced together). Thus one of the goals was to investigate whether this strategy is efficient also for the architecture of stone masonry houses in typical rural area.

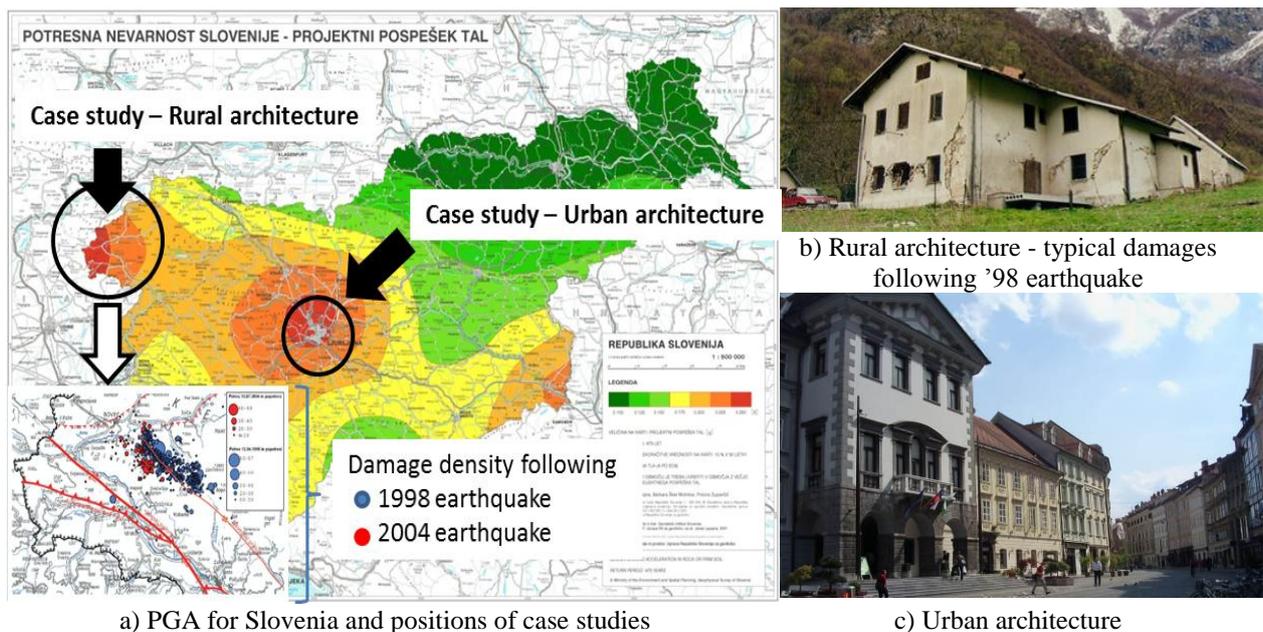


Figure 3. Case studies for MEM approach

2.1. Results of vulnerability study for rural architecture – NW Slovenia

Following '98 earthquake (VII-VIII EMS-98) 3,395 buildings were inspected and 2,298 of them were damaged, while following '04 earthquake with the magnitude of 4.9 and slightly lower intensity VI-VII EMS, 1,860 buildings were investigated and 1,764 were damaged. Although '04 earthquake had 10 times less energy, some of the buildings that were already retrofitted after '98 earthquake suffered major structural damage again during '04 earthquake.

Following the analysis of 33 already damaged buildings, critical failure mechanisms evaluated through FaMIVE methodology were compared with observed one (Fig. 4) following earthquake events.

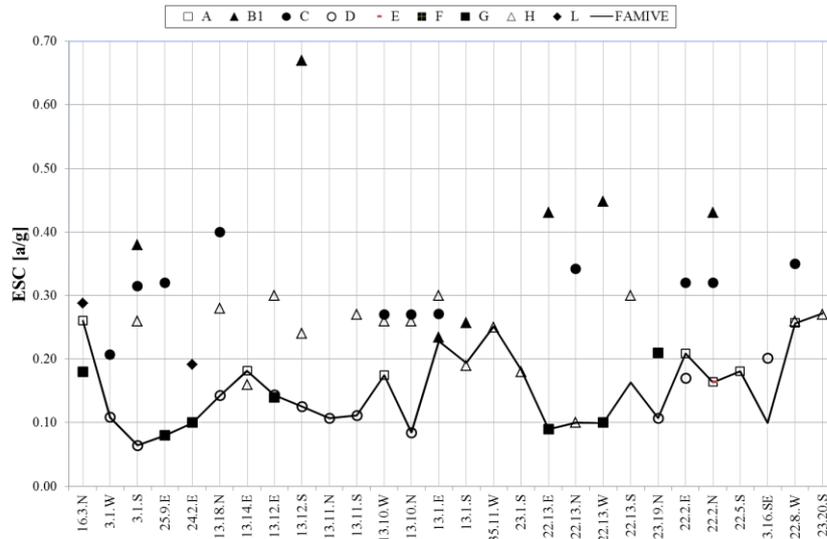
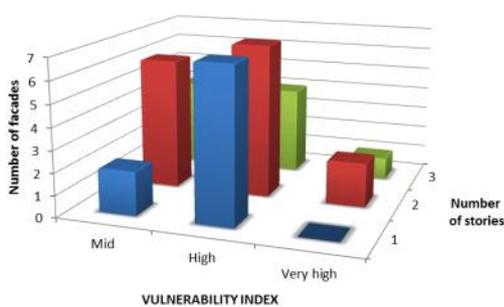
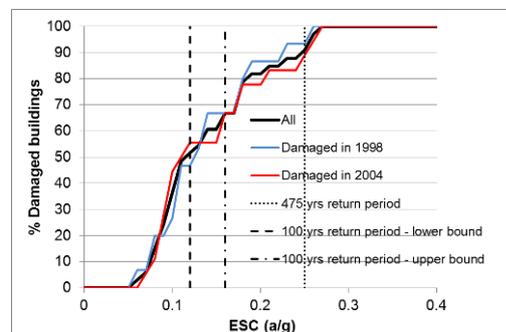


Figure 4. Evaluated Equivalent Shear Capacity (ESC) for 33 case studies and comparison between observed and calculated critical mechanisms

For each building several possible failure mechanisms were observed on-site (Fig. 3-b) and the matching with FaMIVE outcome was almost 50%. In respect to the investigated stock of buildings, identified critical failure mechanisms were A, B2, D, G and H2 (Fig. 1), where the out-of-plane failure (D and G mechanisms) were the most critical. Results of vulnerability analysis show that the major stock of buildings of one and two stories are highly vulnerable (Fig. 5-a). Fragility curve (Fig. 5-b) reveals that 87% of damaged investigated buildings were exposed to maximum expected PGA for 475 yrs. return period earthquake for Bovec region (0.225 – 0.25 g – for soil class A). Considering more probable seismic event with 100 yrs. period of return, 51-67% of buildings would be damaged.



a) Calculated vulnerability index according to FaMIVE criteria



b) Fragility curve for the set of investigated buildings

Figure 5. Seismic vulnerability of investigated stone masonry houses in Bovec (NW Slovenia)

2.2. Results of vulnerability study for urban architecture – Old city centre of Ljubljana

Buildings investigated in Ljubljana (Fig. 6-a) represent the historic part of the city and may be related to the urban architecture of Ljubljana characteristic for the period between XIV and XIX century. The older buildings are rubble stone masonry, while others more recently built can be classified as brickwork masonry. Number of floors also varies depending on the time of construction, so the characteristic buildings are 2 to 4 storey high structures with wooden floor structures and a few or no ties visible on the façade. Most of the buildings are closely packed together and leaning on each other (Figures 3-c and 6-a), thus effective seismic assessment cannot be provided with SEM approach.

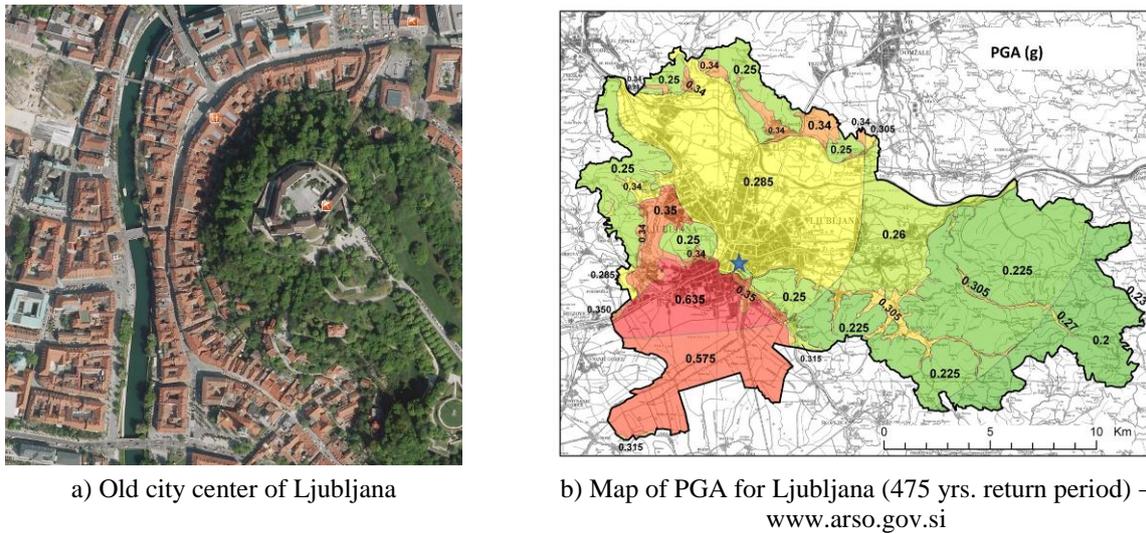


Figure 6. Case study - Old city center of Ljubljana

Results of FaMIVE analysis of 34 buildings (Fig. 7) revealed that the critical mechanisms of failure are D, G and H2, with the predominant number of buildings that would fail due to in-plane shear mechanisms due to presence of large openings in ground floors, numerous openings in upper floors and weak spandrels (H2). Damage index is also very high and thus final vulnerability of the investigated stock of buildings can be classified as high or very high according to FaMIVE criteria.

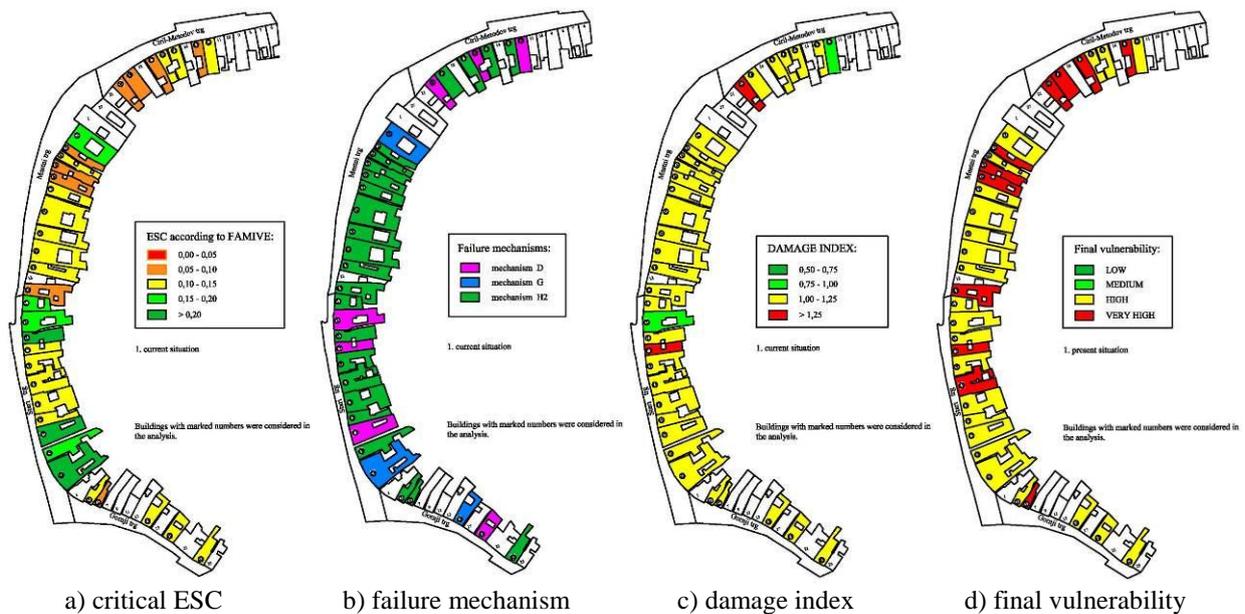
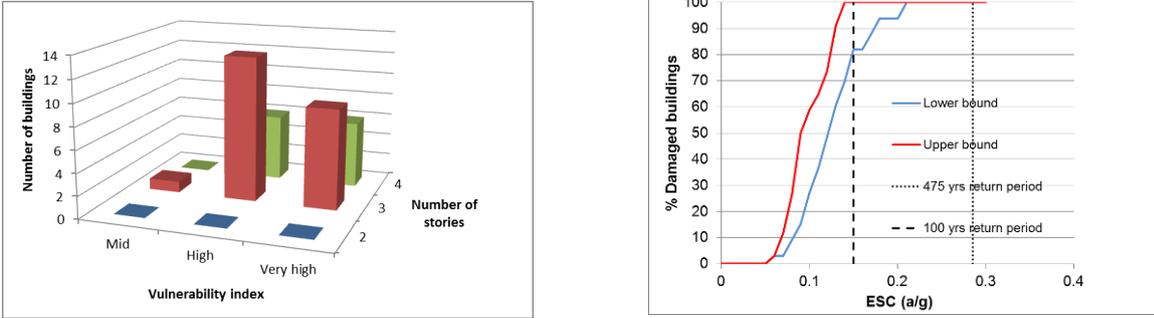


Figure 7. Seismic vulnerability of old city center of Ljubljana

Considering also other uncertainties such as connections between buildings, position of ties in the building and material parameters considered in the evaluation, upper and lower bound for vulnerability curves for the stock of buildings from the old city center in Ljubljana (Fig. 8-b) revealed that for the 100 yrs. return period at least 80% of buildings would be damaged. None of the investigated building would sustain maximum expected PGA for 475 return period for Ljubljana (Fig. 8-b).



a) Calculated vulnerability index according to FaMIVE criteria

b) Fragility curve for the set of investigated buildings

Figure 8. Seismic vulnerability of old city center of Ljubljana

3. APPLICATION OF SEM THROUGH SMR AND GMR ANALYSIS

The economic impact of extension of damages following the '04 earthquake in NW Slovenia raised the question of effectiveness of the applied methodologies for the evaluation of the seismic resistance of existing masonry buildings. In order to clarify uncertainties that may influence the outcome of the assessment of the structures (PERPETUATE methodology) we have focused on two potential problems: efficiency of applied strategy for the assessment of seismic resistance of buildings and possibility of site amplification due to soil-structure interaction. This was done through the study of efficiency of three models: MEM approach by application of FaMIVE model and SEM approach by using two models – SMR (SREMB – Tomažević et al. 1982) and GMR (3Muri – Galasco et al. 2009). Following comprehensive in-situ campaign on the case study of stone masonry building (Uranjek et al. 2012) a reliable set of mechanical properties was gained for this study. This building (Fig. 9) represents a typical building for this area and since it was already damaged following '04 earthquake and it was foreseen for demolishing, it represented ideal case for extensive testing and for the study of the efficiency of different modelling strategies.

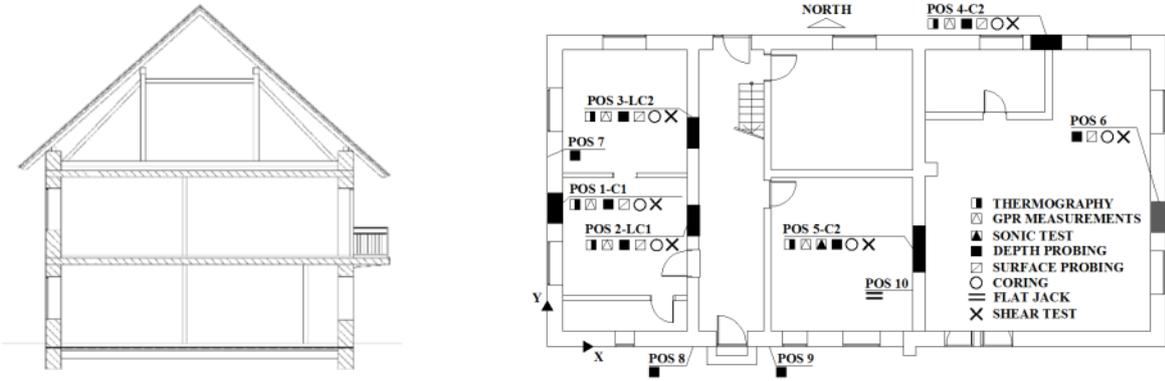


Figure 9. Cross-section of typical stone masonry building and in-situ testing positions

In the numerical analysis different sets of mechanical parameters were considered on the basis of the results from in-situ tests on the masonry in ungrouted and grouted state (Table 3.1).

Table 3.1. Mechanical parameters derived through in-situ tests

	Compr. str. f_c (MPa)	Tensile str. f_t (MPa)	Shear modulus G (MPa)	Elastic modulus E (MPa)
UngROUTED – in situ	1.65	0.07	113	785
Grouted by cement grout – in situ	2.50	0.29	537	1520

Results of crack pattern investigation revealed that the structure did not have SRM response (Fig. 10) during '04 earthquake. Thus the results of SREMB analysis of building in existing (ungROUTED) state might be less relevant.

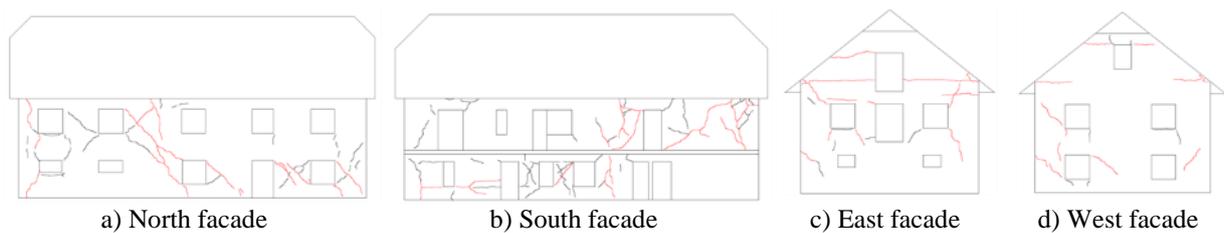


Figure 10. Results of crack pattern investigation

In Fig. 11, some of the results from SREMB analysis are presented. Since SREMB in its analysis considers both in-plane and out-of plane response of SE, for different direction of loading, different mechanisms of failure are critical. In Fig.11-c&d, SE's colored in yellow failed in shear, while those in red failed in flexure.

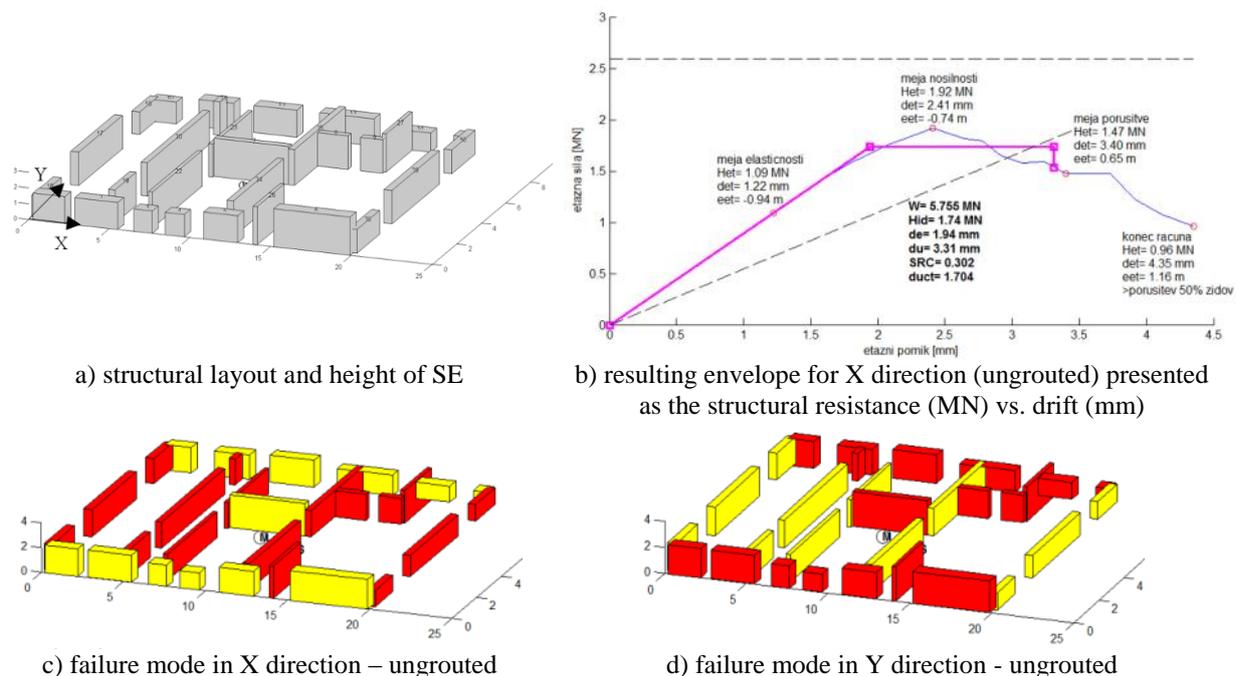


Figure 11. Graphical presentation of results from SREMB

Unlike SREMB, program 3MURI considers only in-plane response of the structure and the global response of the structure is considered by introducing frame modelling also spandrels and diaphragms. Thus obtained failure modes correspond better to observed ones following the earthquake (Fig. 12).

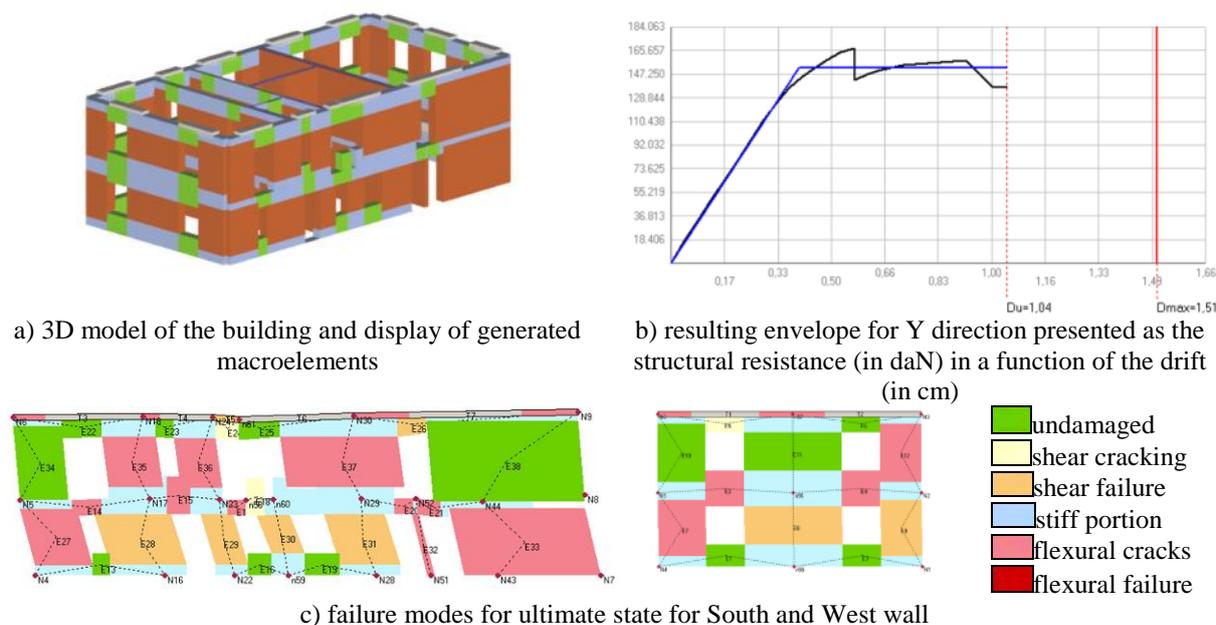


Figure 12. Graphical presentation of results from 3MURI

While the results of SREMB analysis relate to the PP which is center of mass, the results of 3MURI analysis may be related depending from the point of interests (usually most critical element). For the purpose of comparison of results of SREMB and 3MURI, the results of this analysis are related to the center of mass of the building (Table 3.2). Here H_{id} is idealized seismic resistance, $SRC = H_{id}/W$, where W is the weight of building, D_e – max. elastic displacement, D_u – ultimate displacement, μ – ductility, f – frequency, SLSPGA – peak ground acceleration at attainment of serviceability limit state, ULSPGA – peak ground acceleration for ultimate limit state. The results of analysis are presented for ungrouted state (state of masonry before the earthquake) and strengthened (as if it would be grouted) state of masonry.

Table 3.2. Mechanical parameters according to design practice and derived in-situ

Direction	H_{id} (kN)	SRC (-)	D_e (mm)	D_u (mm)	μ (-)	f (Hz)	SLSPGA (g)	ULSPGA (g)
SREMB								
X	1.740	0.30	1.9	3.3	1.70	6.3	0.10	0.12
Y	2.140	0.37	2.3	3.2	1.41	6.3	0.12	0.14
3MURI								
X	1.509	0.23	4.3	10.4	2.41	4.8	0.13	0.17
Y	1.506	0.23	3.9	10.4	2.64	5.0	0.12	0.18
Grouted with cement grout - SREMB								
X	2.983	0.52	0.9	1.5	1.68	12.5	0.24	0.26
Y	3.553	0.62	1.0	1.8	1.90	12.5	0.29	0.33
Grouted with cement grout – 3MURI								
X	1.892	0.29	1.6	19.2	12.11	9.1	0.34	0.47
Y	2.455	0.37	1.8	15.0	8.16	9.1	0.40	0.53

From the results of analysis it may be concluded, that SREMB provides more stiff response of the structure, which was expected (storey vs. global response). Higher SRC may be attributed to the contribution to the resistance of the out-of plane walls, which 3MURI does not consider (in accordance to EC8-3, 1998). Regarding seismic demand, it may be concluded that building in its current state does not fulfill seismic demand for Bovec region. From the results of analysis of building in strengthened state it may be concluded that both strategies provide resistance that is higher than seismic demand.

The results of FaMIVE analysis of this building revealed (Table 3.3), that out of plane failure mechanisms may be triggered before the global resistance of the structure is achieved. This implies that prior effective global analysis of stone masonry structures, tying of walls and improving intersections of walls according to the results of MEM analysis should be done. This strategy may be also effective in preventing major economic losses due to earthquakes with lower intensity but higher probability of occurrence.

Table 3.3. Seismic demand and outcome of modelling for building in ungrouted state.

	Seismic demand		Seismic resistance		
	100 yrs. return period	475 yrs. return period	FaMIVE (MEM)	SREMB (SRM)	3MURI (GMR)
X direction	0.12-0.16 g	0.225 g	0.09 g	0.12 g	0.17 g
Y direction	0.12-0.16 g	0.225 g	0.10 g	0.14 g	0.18 g

4. SITE AMPLIFICATION DUE TO SOIL-STRUCTURE RESONANCE

Though the results of analysis revealed that building in strengthened state would stand seismic demands for Bovec basin, many of buildings that had been strengthened following '98 earthquake were again severely damaged in '04 earthquake. In order to clarify this, microtremor horizontal-to-vertical spectral ratio (HVCR) measurements were applied to a 200 m dense grid of free-field measurements to assess the fundamental frequency of the sediments (Gosar, 2007). As it can be seen (Fig. 13), large variations in the frequencies (3-22 Hz) were obtained. From the map, for our case study value of 6-7 Hz seems to be realistic. This range is close to our calculated frequencies according to both SEM approaches, implying that some of the damage might be amplified due to resonance effect. In respect to analysis of building in strengthened state (grouted) it may be concluded that this effect would be avoided if the structure were strengthened before the earthquake. However, the range of calculated frequencies in strengthened state (9.1-12.5 Hz) imply that for some area of Bovec region even the strengthening by means of grout injection would not be effective enough to prevent damages due to effect of soil-structure interaction.

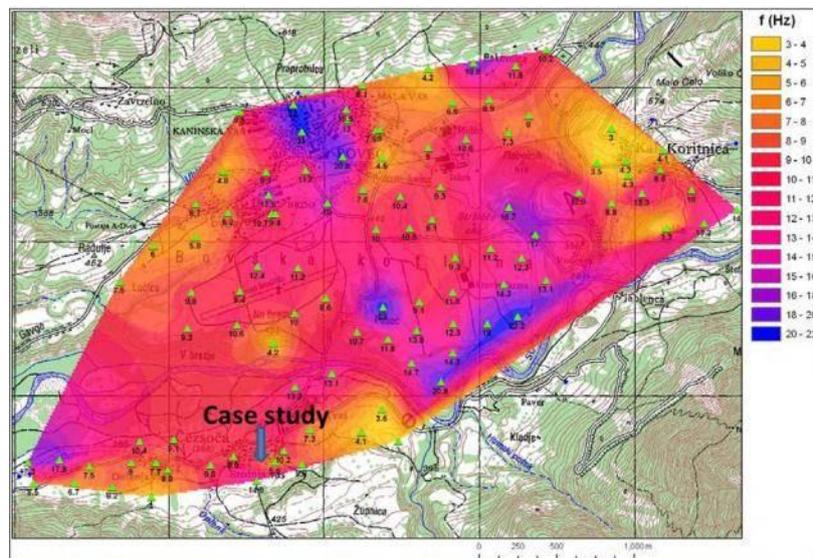


Figure 13. Map for Bovec basin of the fundamental frequency peaks derived through microtremor measurements (Gosar, 2007)

5. CONCLUSIONS

Following the outcomes from this analysis, some of the major conclusions may be drawn as:

- Out-of-plane (MEM) analysis of masonry buildings by means of FaMIVE approach can be effective for the evaluation of most critical mechanisms of failure characteristic for the architecture of the buildings from Bovec basin,
- results of MEM analysis for the historic city center of Ljubljana reveals that it is highly vulnerable. However, it should be stated that the outcome of MEM analysis may be strongly affected by numerous uncertainties. Regarding to this the study of the influence of knowledge level on the results of MEM approach is under way,
- results of non-linear seismic analysis (SEM) of case study revealed that investigated building in unstrengthened state would not stand seismic demand according to current code provisions. Results are consistent with the results from MEM analysis,
- the results of MEM analysis revealed that local mechanisms of failure may be triggered before the global response of the structure is achieved. This imply that prior effective global analysis of stone masonry structure MEM analysis should be performed and the tying of walls and improvement of walls intersection should be done according to identified most critical mechanisms,
- regarding different SEM approaches - the results obtained considering GMR seems to be more realistic (considering crack-pattern survey) in comparison to SMR,
- prior effective global analysis of structure information regarding fundamental frequencies of soil should be obtained, otherwise some of the methods for strengthening buildings may not be effective due to soil-structure interaction.

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