Influence of Ageing and Deterioration of Masonry on Load Bearing Capacity of Historical Building

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SUMMARY:
Numerous heritage buildings in the former Eastern Europe that were neglected in the past are severely deteriorated due to ageing and moisture problems. The paper summarizes experimental and numerical work carried out on 150 yrs. old Kolizej Palace in Ljubljana (Slovenia) which has recently been demolished, despite the overall opinion among conservators that it should be preserved. Experimental tests proved almost completely saturated conditions in the ground level of the building, while all the stories above were in almost dry condition. The results of tests on masonry revealed that moisture content and state of deterioration affected both strength and stiffness properties of built masonry in that extend so that the previous estimations and calculations regarding the state of the structure and its static load bearing capacity were too optimistic. Both storey and global response non-linear seismic analysis have proved that building in its current condition is far below the current seismic code requirements.

Keywords: masonry, historical structure, deterioration, moisture, in-situ tests

1. INTRODUCTION

Primary scope in evaluation of the static and dynamic resistance of existing structures is determination of the mechanical characteristics of built in material and its components. Despite numerous laboratory test results on masonry and its constituents (mortar and bond), global definition of the state of the built in material is rather hard to define. General definition of the masonry solely by the type of the unit and mortar may be misleading due to ageing and deterioration processes. According to the current code requirements in Slovenia (SIST EN 1998-3: 2005), depending from the knowledge level (KL) of the investigated structure its mechanical characteristics adopted for the modeling should be adjusted considering confidence factors CF. Within this prospect, properties of constituent materials, physical condition of masonry and presence of degradation should be somehow assessed as well. For this task for historic masonry buildings apart from in-situ tests at the moment there are no alternative solutions.

Within the scope of EU funded PERPETUATE project (www.perpetuate.eu), one of the case study for the evaluation of the efficiency of adopted PERPETUATE methodology was The Kolizej Palace in Ljubljana, Slovenia. Prior the start of the project, building was already set to be demolished since the owner’s vision of the future buildings function was far above the current state of the building and load bearing capacity (Bosiljkov et al. 2008). Before the demolition of the structure two more independent analyses based on limited knowledge of the structure were prepared (Bergant et al. 1995; Lutman et al. 2004). None of them proved that the building could be saved without jeopardizing its heritage values and keeping in mind economic feasibility of strengthening measures. Thus, the aim of this study was to assess some of the uncertainties that may significantly influence the outcome of the seismic analysis of the historical buildings and to get better insight in the behaviour of decayed building under seismic loading.

2. CASE STUDY – KOLIZEJ PALACE IN LJUBLJANA

Kolizej in Ljubljana was built after the plans of architect Josef Benedict Withalm in 1847 as a multipurpose building for soldiers of the former Habsburg Monarchy. Before its demolition, it was the last of three buildings of such kind in the monarchy, so the overall opinion among the conservators upon its preservation was to be understood. It was proclaimed as a Slovenian national natural and cultural heritage monument in 1993. The building was erected very quickly within only two years and ever since it remained almost unchanged. In 1895 Ljubljana was struck by a strong earthquake but the records regarding the damage on Kolizej are unknown. From 1918, the building was turned into social apartments and its state went into worse. More recently, after local, unsupervised structural changes of the building, small part of it collapsed in 1995.

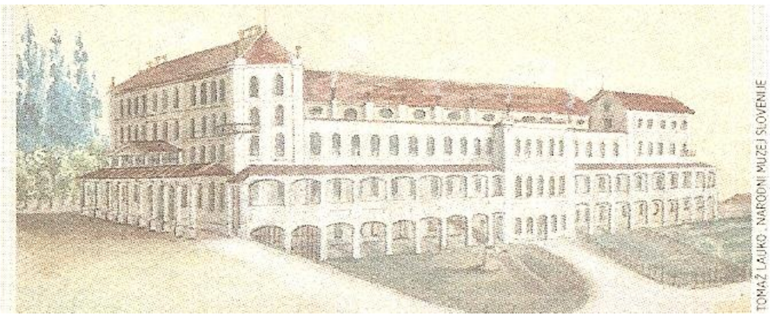


Figure 1. Kolizej Palace in its former appearance (photo: Tomaž Lauko)

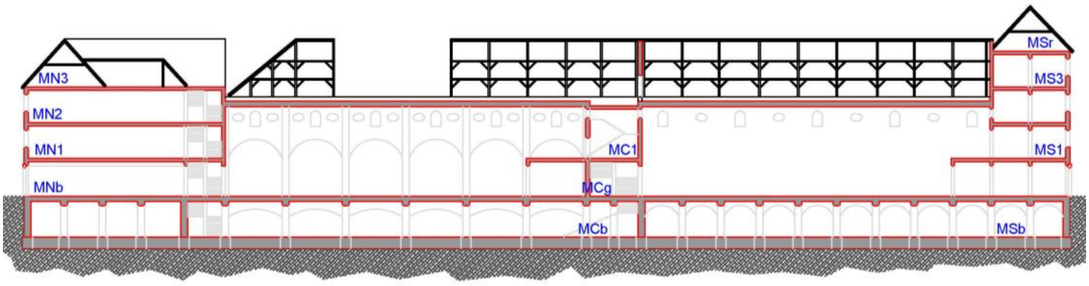
The building of Kolizej was 122 m long and from 29 to 32 m wide. Central part of the building had four stories, while the South part had five stories and was called "The South Tower". The lowest level, to which we refer in our analysis as basement, was from two sides below the street level. The building's walls and columns were made of brick and lime mortar and stood on brick masonry foundations. Vertical load bearing elements in the basement were outer walls and inner columns with a few partition walls. Above the basement horizontal bearing elements were masonry cap and barrel vaults. Upper storeys consisted of outer and inner brick walls and timber floors.

3. IN-SITU INVESTIGATION AND EXPERIMENTAL ANALYSIS

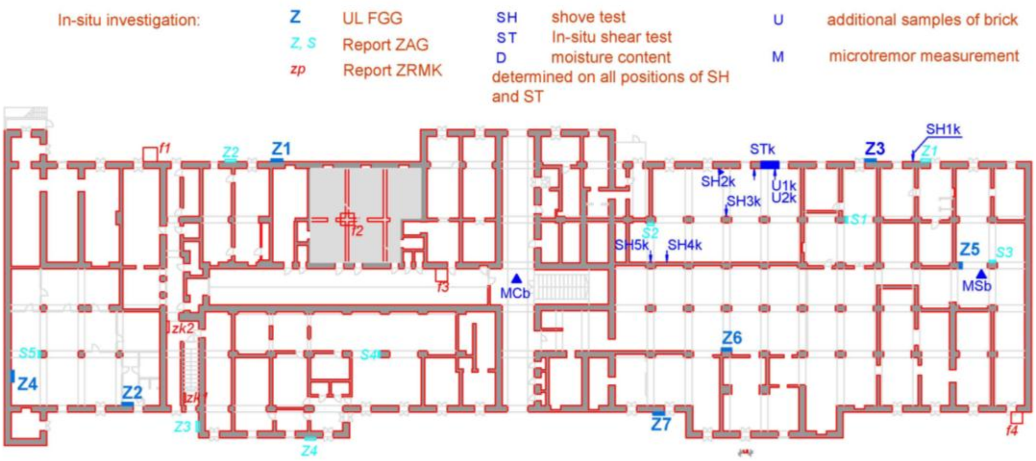
In-situ inspections in 2008 (Bosiljkov et al., 2008) revealed that the load bearing walls and columns were in some parts in very bad condition. Consequences of moisture due to capillary rise, unsuitable introduction of hydro isolation, damaged downpipes and damage due to overloading were obvious (Fig.2). Deterioration due to moisture was extensive throughout the basement and partially in the ground floor, while in the upper floors along drainage at some positions on outer walls. The building was abandoned for at least a decade; therefore neither structural repairs nor proper maintenance have been done recently.

Figure 2. Deterioration due to capillary rise, inadequate drainage, freezing-thawing and overloading

In 2011, as the Kolizej was consented to be demolished, a permission from the owner and conservators was obtained for extensive in-situ testing campaign. It represented ideal opportunity to assess physical and mechanical characteristics of deteriorated brick masonry, which is impossible to simulate in laboratory conditions. Microtremor measurements (Fig.3-a), in-situ shear and compressive tests, shove tests, moisture measurements as well as numerous laboratory tests on masonry components and assemblages were carried out. For the basement layout of testing and sampling position is presented in Fig.3-b.



a) cross-section of Kolizej Palace and position of microtremor measurements



b) layout of the basement, testing positions and positions of masonry constituents sampling

Figure 3. Map of in-situ tests and specimen samplings.

3.1. Tests on masonry constituents

Sampling of brick and mortar samples for the laboratory tests were done systematically all through the building with 10 samples in average per storey. Two different classes of bricks were identified. Bricks, which have a non-homogene structure and prevail in the walls (90%), are of lower strength class (7.9 - 14.7 MPa), while other bricks coincide with higher strength class (21.0 - 33.9 MPa). Splitting tensile strength for two classes of bricks were 0.8 and 2.0 MPa respectively. Water absorption of the bricks of better quality was 9 - 14%, while for the bricks of lower quality 21 - 32%. Compression strength of mortar was determined on the size of the specimens of tablets. Minimal strength in the basement (where it was possible to take intact samples) was 0.8 - 3.6 MPa, while in the upper floors the values were between 1.3 – 9.9 MPa.

3.2. Moisture content measurements

Moisture content of bricks was determined on the basis of drilled brick powder and brick specimens taken from the walls and drying them till constant mass. Moisture content of powder from the basement was 18.9 -29.6% for exterior walls, and 1.4 – 14.3% for interior columns. In the upper floors the moisture was noticeable lower; 1.3 - 3.3%. Comparison of moisture and water absorption for different classes of bricks confirms, that in the basement the bricks were in almost completely saturated state.

On site damp investigation was also done with surface electronic moisture meter. Moisture content was measured in the basement, ground level and the 1st floor. Along the height of the building where in-situ shear tests were done, across the entire basement floor wall and approximately half of the height of the ground floor the masonry was damp, but then in relatively short transition it became very dry as seen in Fig. 4-a. The reason for high level of moisture in the ground level was due to improper introduction of bitumen coating for almost all elements of the basement level (Fig.4-b).

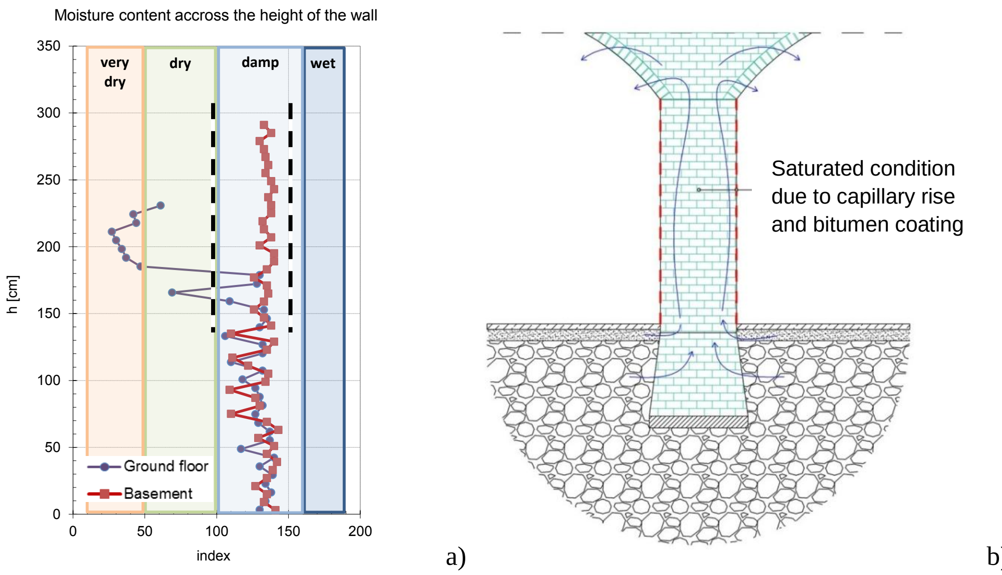


Figure 4. Cross-section of basement column and moisture content measurements across the height of the walls

3.3. Test of brick – mortar junction by shove test

Shove tests were executed at five different positions in three different floors. From obtained in-plane horizontal sliding resistance along a mortar bed joint τ_b, initial shear strength of the masonry τ_0 can be calculated, if coefficient of friction is presumed and vertical load σ_0 is known.

$$\tau_0 = \tau_b - 0.4\,\sigma_0 \qquad (3.1)$$

Test setup and calculated initial shear strength in correlation with vertical load are presented below.

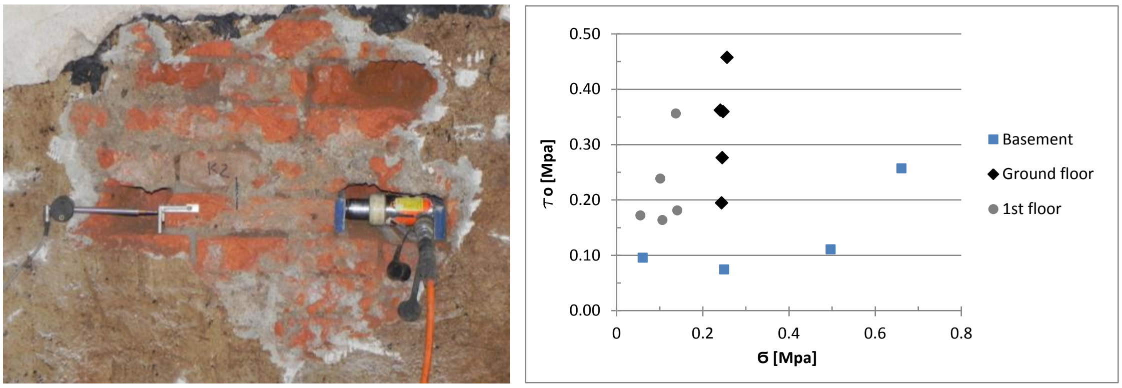


Figure 5. In-situ test setup for shove test and calculated initial shear strengths

Shove tests confirm the presumptions of strength decrease in the basement due to amplified deterioration because of moisture. Ground and the 1st floor had substantially higher initial shear strength τ_0. Average values were 0.33 MPa with coressponding average moisture content of 9.7% in ground floor and 0.22 MPa and 5.7% in the 1st floor, while the basement average initial shear strength reached only 0.16 MPa. Initial shear strength τ_0 was lower in the 1st floor probably due to lower vertical load and the change of coefficient of friction in dependence of vertical load and moisture content. The moisture content (measured at testing positions) was not significanty higher in the basement in comparison to other floors, which may imply that not moisture content itself but the long term exposure to moisture with freezing and thawing cycles contributes to amplified deterioration of the bond and mortar.

3.4. In-situ shear tests

Two in-situ shear tests were performed; one in the basement representative for due to moisture more deteriorated masonry walls (in the following referred as more deteriorated) and one in the ground floor, representative for less deteriorated masonry walls in the upper floors (in the following referred as normal condition). Because of the test setup, each test actually presents two walls. In Fig. 6. test setup and the response of upper parts of the walls in the basement and ground floor are presented. Hysteretic envelope was idealized with bilinear curve; stiffness was calculated at first diagonal crack and maximum displacement considered when decrease of 20% of maximum obtained force is reached.

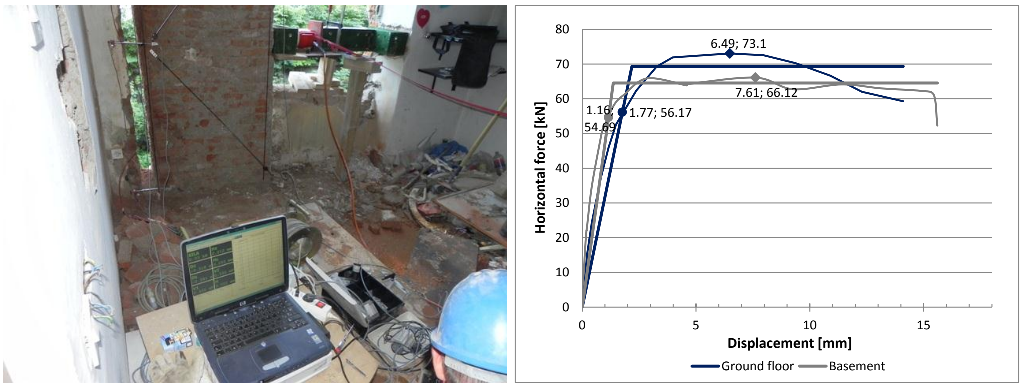


Figure 6. Shear test setup and hysteretic envelopes and idealized bilinear curves for both floors

Reference tensile strength f_t of both walls, calculated considering bilinear idealized curve, clearly shows better state of masonry in normal condition. For the ground level wall f_t was in average 0,072 MPa, while for more deteriorated wall in the basement it was 0.046 MPa, which is 36% less. Ductility and maximum displacements were higher for the specimens in the basement level.

3.5. Laboratory compression tests of masonry

Two uni-axial compression tests were performed. Both on the specimens taken from the ground floor level and tested in laboratory. For the first one moisture content was similar as for the specimens from basement therefore it was classified as more deteriorated, the other one was in normal condition. Obtained compressive strength f_c was 2.52 MPa for normal condition and 1.78 MPa for more deteriorated wall. The results for elastic properties were surprisingly low. For E modules – 132 MPa and 236 MPa for deteriorated and normal condition of masonry were evaluated respectively.

3.6. Microtremor measurements

Microtremor measurements were done in order to obtain fundamental frequencies of the building and for the future study of soil-structure interaction (Zupančič, 2011). Measurements were performed in the mass centre and in the both towers. The microtremor horizontal to vertical spectral ratio (HVSR) analysis in the mass centre (1st floor) produced curves with peaks at four different frequencies in the longitudinal, NS direction and three peaks in the transversal, EW direction of the building. This was expected due to geometrical characteristics of the building (irregular plan) and the effect of torsion. Floor spectral ratio (FSR) showed two peaks for NS and three for EW. In the South tower, two (NS) and one (EW) peaks were obtained and one in both directions in the north part of the building (Table 3.1 and Fig.7).

Table 3.1. Estimated fundamental frequencies of the building

	NS	EW
Mass centre	4.8 (2.9) Hz	3.1; 3.9; (4.6) Hz
South tower	3.0 (2.8) Hz	3.3 Hz
North part	4.0 Hz	3.3 Hz

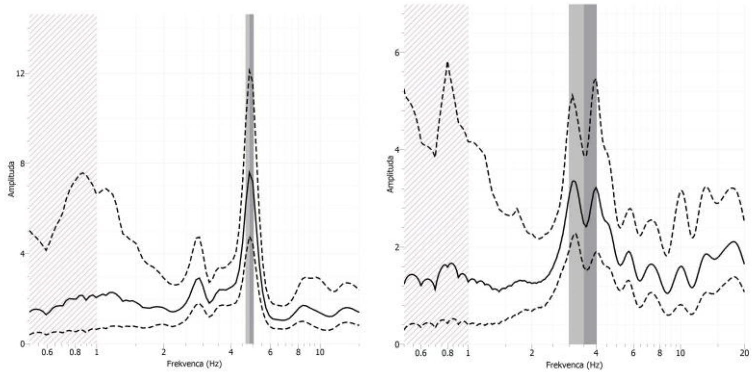


Figure 7. Microtemor measurements (FSR - 1st floor to basement) a) N-S direction, b) E-W direction

Soil frequency measured nearby in previous free-field measurements was 3.3 Hz. Compared with the building's fundamental frequencies; the soil-structure resonance in transversal direction is not excluded.

3.7. Estimated material characteristics for further seismic analysis

From all the experimental tests values in Table 3.2. were determined as characteristic for walls in normal and deteriorated condition of Kolizej. In the table also the ratio between both is presented.

Table 3.2. Experimentally determined mechanical characteristics of less and more deteriorated brick masonry

Mechanical characteristics	f_c [MPa]	f_t [MPa]	τ_0 [MPa]	E [MPa]	G [MPa]
Deteriorated walls	1.78	0.046	0.160	132	82.9
Normal condition	2.52	0.072	0.330	236	66.9
Ratio normal cond./deteriorated	1.42	1.57	1.72	1.79	0.75

In the seismic analysis deteriorated masonry material characteristics were assumed in the basement, while for all upper floors normal condition material characteristics were assumed. Also for the purpose of comparison, two other combinations of material characteristics from literature were used i.e. minimum values according to Italian code NTC08 (NTC 2008, 2008) and experimentally determined values for full brick with lime mortar in Slovenia (Tomaževič, 1987) which are common design values in Slovenia.

Table 3. Material characteristics from literature for full brick masonry wall with lime mortar

Material characteristics	f_c [MPa]	f_t [MPa]	E [MPa]	G [MPa]
Common design practice in Slo.	2.40	0.04	400	250
NTC08, min	2.40	0.09	1200	400

4. SEISMIC RESISTANCE ANALYSIS AND EFFECT OF DETERIORATION

When assessing an existing building according to Eurocode 8 – Part 3: Assessment and retrofitting of buildings (EN 1998-3: 2005), confidence factors which take into account the knowledge level of the building, have to be considered. The knowledge level achieved also determines the allowable methods of analysis. However there are no instructions for how to take into account the influence of deterioration of the material or the fact that moisture is present.

Regarding all the in-situ investigations and laboratory tests performed, full knowledge level (KL3) was assumed, even though if the size of the building was considered, a more extensive structural details survey could have been done. In analysis, therefore, confidence factor CF_{KL3}=1,0 corresponding to KL3 was considered. With KL3 all types of methods for analysis are allowed. Seismic capacity of Kolizej was obtained with pushover analysis (nonlinear static analysis) with two different modelling approaches; global mechanism response model and storey response. For the first method software 3Muri (S.T.A. Data, 2009) was used and for the second software SREMB, based on the POR method (Tomaževič, 1987).

For both approaches 3D model of the building was prepared (Fig.8). Main difference for two approaches is that 3Muri allows global mechanisms response of the whole structure while SREMB consider only critical storey mechanisms response. For 3Muri the floors were modelled as they were in reality; over the basement masonry vaults and over the upper storeys wooden floors. Presumed eccentricity was 0.5%. In analysis two possible lateral load patterns were considered, modal and mass. SREMB model allows only the capacity of one (critical) storey to be calculated separately (mass lateral load pattern). In our case we considered the basement floor. Floor was considered to be a stiff diaphragm.

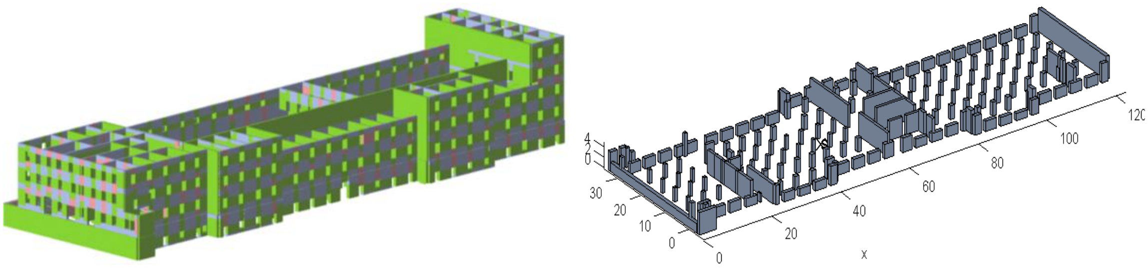
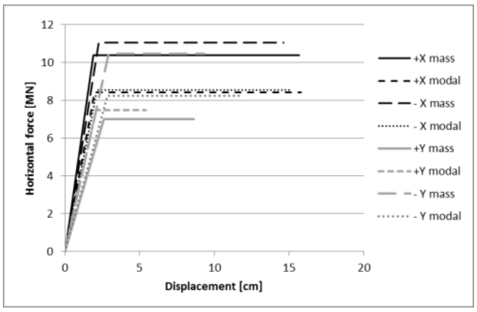


Figure 8. 3-D model in 3Muri and critical storey model in Sremb

Seismic resistance of Kolizej should be greater than the one prescribed through EC8-1 (EN 1998-1: 2004). Design ground acceleration for 475 years return period for this region of Ljubljana is 0.25 g. Considering soil factor for ground type C (S = 1.15), the peak ground acceleration amounts to PGA=0.288 g. For seismic capacity evaluation at this stage of analysis, only half of the prescribed imposed variable load (0,75 kN/m^2) was assigned, mechanical characteristics determined with experimental tests were assumed and maximum drifts for shear and bending were determined according to EC8-3 (EN 1998-3: 2005) provisions.

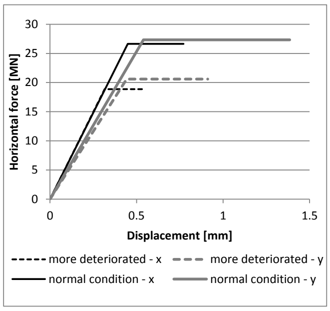
4.1 Analysis with 3Muri

Results with 3Muri show, that in any of the supposed combination of parameters, the Kolizej does not withstand the code demands. Seismic resistance capacity curves for Kolizej with experimentally determined material characteristics for various direction and lateral load pattern combinations are presented in Fig. 9-a. Longitudinal direction is referred as *X* direction and transversal as *Y*. As it can be seen from Fig.9-a, the resistance is the lowest in *Y* direction of the building, furthermore critical is combination with modal lateral load pattern. Hence in all directions modal load pattern is more critical than mass. This indicates that in case of Kolizej the critical storey mechanism model is not the best solution for the assessment of the seismic resistance.



Direction and lateral load pattern	ULSPGA [g]
+ X mass	0.152
+ X modal	0.117
- X mass	0.147
- X modal	0.139
+ Y mass	0.155
+ Y modal	0.059
- Y mass	
- Y modal	0.147

a)



b)

Figure 9. Pushover curves for transversal and longitudinal direction from 3Muri – a) and capacity curves resistance obtained considering normal condition and more deteriorated material with SREMB – b)

Furthermore, in Table 4.1. the critical results in terms of characteristic displacement points and ultimate limit state peak ground accelerations (ULSPGA) for the weakest combination for each direction considering mechanical parameters according to experimental results and literature references are presented; in all cases modal horizontal load pattern proved to be the most critical. In Table 4.1 D_y is the yield displacement, D_u ultimate displacement, K_e effective stiffness, F_y yield force, SRC seismic resistance coefficient (yield force divided by the weight of the building). It has to be stressed, that when literature characteristics were considered, the knowledge level should actually be lower. For KL2 Confidence factor CF_{KL2}=1,20 should have been used, but for the purpose of comparison with gained experimental values, this further reduction of characteristics was not made.

Table 4.1. Seismic capacity of Kolizej obtained with 3Muri for different material characteristics combinations

Material characteristics	Direction	D_y [cm]	D_u [cm]	ductility	K_e [kN/cm]	F_y [kN]	SRC	ULSPGA [g]
Experimental tests	+ *X*	2.06	19.74	9.56	3.35	6.91	0.049	0.117
	+*Y*	2.44	3.22	1.32	3.44	8.38	0.060	0.059
NTC08	+ *X*	1.24	5.50	4.45	12.56	15.53	0.111	0.166
	+*Y*	1.32	3.13	2.37	14.41	19.03	0.135	0.104
Common design values in Slo.	+ *X*	2.11	14.71	6.97	3.45	7.28	0.052	0.119
	+*Y*	2.67	4.06	1.52	2.48	6.63	0.047	0.052

With all characteristics combinations, *Y* is the more critical direction. The results for strength characteristics obtained by experimental tests on Kolizej are very close to common design values in Slovenia, while the elastic properties are not. The NTC08 produces higher ULSPGA that is mainly due to at least two times higher yield force. If all the three variants are compared, the stiffness of the NTC08 is almost four times higher as actual characteristics and for common design values in *X* direction and more than four times in *Y* direction.

4.2. Analysis with SREMB

For SREMB analysis two sets of experimental values for masonry were prepared, which shows the influence of deterioration due to moisture on seismic capacity. In one case, the assumed characteristics of the basement were presumed as for more deteriorated and in the other case as for normal condition of masonry walls. The results are compared to results obtained with literature material characteristics (Table 4.2). Yet again the results show, that the palace was far from satisfying current seismic demands. It is clear that deterioration has a great influence on calculated seismic capacity (Fig.9-b). The resistance in terms of maximum force decreases for 28.8% in *X* direction and for 24.8% in *Y* direction and for 28.6% and 36.6% in *X* and *Y* direction in terms of ULSPGA, respectively. It was mentioned before, that storey mechanism is not the best choice for the analysis of Kolizej palace, but considering the results presented in Table 4.2, the results for ULSPGA are more conservative than the results derived with 3Muri despite the fact that mass pattern is less critical. The reason for this lies in characteristics of both models (Kržan, 2010).

Table 4.2. Seismic capacity of Kolizej obtained with SREMB for different material characteristics combinations

Material charateristics	Direction	D_y [cm]	D_u [cm]	ductility	K_e [kN/cm]	F_y [kN]	SRC	ULSPGA [g]
Kolizej – more deteriorated	+ *X*	0.316	0.552	1.75	59.7	18.86	0.089	0.045
	+ *Y*	0.443	0.911	2.06	46.5	20.61	0.097	0.059
Kolizej – normal condition	+ *X*	0.449	0.771	1.72	59.3	26.64	0.125	0.063
	+ *Y*	0.54	1.385	2.57	50.6	27.33	0.129	0.093
NTC08, min	+ *X*	0.089	0.152	1.71	340.4	30.3	0.143	0.067
	+ *Y*	0.112	0.238	2.13	285.5	31.98	0.150	0.075
Common design values in Slo.	+ *X*	0.072	0.131	1.81	210.7	15.17	0.071	0.032
	+ *Y*	0.094	0.462	4.92	155.7	14.64	0.069	0.061

4.3. Modal analysis

Modal analysis of the building was done with 3Muri for the purpose of the comparison of calculated and measured modal frequencies. Experimentally obtained elastic properties produced unrealistically low fundamental frequencies. Additional analysis with the material characteristics from the literature was also done. Better material characteristics produce higher frequencies and match better with microtremor measurements estimated ones. In Table 4.3 a comparison of the first three modal shapes for various material combinations is presented.

Table 4.3. Calculated modal times considering various material characteristics

Material characteristis	Mode	f [Hz]	M_x [%]	M_y [%]	M_z [%]
Kolizej	1	1.29	0.2	60.8	0
	2	1.37	65.0	0.9	0
	3	1.43	0.1	23.6	0
NTC08	1	2.63	0.1	49.8	0
	2	2.92	2.0	32.6	0
	3	2.95	56.0	1.3	0
Common design values in Slo.	1	1.20	0.4	71.1	0
	2	1.24	76.5	1.2	0
	3	1.30	0.7	15.1	0

As it was mentioned before, calculated frequencies considering experimentally determined material characteristics are much lower than frequencies obtained with microtremor measurements. The results considering elastic parameters from NTC08, however, is not so far off, which imply, that maybe the overall state (related to elastic properties) of the building was not in such a bad shape and with so low characteristics as it was considered in calculation by considering in-situ results. For the purpose of investigation of the influence of deterioration of the material on the mechanical properties of masonry, in-situ tests were performed on the positions where there state of masonry was the worst.

CONCLUSION

Following the results of this analysis it may be concluded, that first major steps for the preservation of the state of built masonry are proper maintenance, preventive measures and monitoring. With this approach (in the long term) the influence of deterioration and ageing of masonry on the load bearing capacity of the structure might be significantly decreased. Following the results of comprehensive in-situ investigation of the Kolizej Palace in Ljubljana, main conclusions regarding mechanical parameters are:

- Influence of deterioration and ageing of brickwork masonry has significant effects on mechanical properties of both masonry constituents and masonry as a composite material. For Kolizej Palace moistening, capillary rise and freezing-thawing cycling were probably the most powerful parameters that accelerated deterioration of the masonry.

- Prior application of more invasive techniques for the evaluation of mechanical properties, detail survey regarding built-in masonry constituents should be done. Evaluation of moisture content of the masonry should be done in respect to the water absorption of particular type of brick built in the masonry.
- Due to moistening and capillary rise, the infiltrating water leads to the mobilization and generation of salts. Salts are powerful damaging agents and can act in porous building material in several ways: by crystallization, hydration, differential thermal expansion and osmosis. All of these processes may significantly influence properties of the mortar and masonry bond. In this respect results of compressive tests on mortar tablets and the results of shove tests revealed reduction in strength of 40-60% for the mortar samples and 50% for initial shear strength.
- Reduction of strength properties due to decay of material may be up to 30% for compressive strength and 36% for reference tensile strength of the masonry. Due to mortar degradation, the modulus of elasticity of the masonry in wet condition is very low and it corresponds to the modulus of elasticity of saturated sand.

Study of the uncertainties regarding adopted modelling strategies and mechanical parameters on the seismic resistance or the building revealed that regardless to adopted modelling strategies and mechanical parameters for the analysis, the resistance of Kolizej Palace was far below seismic demand. Following the results of SREMB analysis by means of storey mechanisms response, the influence of decay of material may be estimated between 28.6 and 36.6% for X and Y direction respectively. Following 3Muri analysis it may be concluded that the modal load pattern in all cases of analysis is more critical one. Comparison of main frequencies derived through microtremor measurements and 3Muri results, revealed that elastic properties of the masonry derived through compressive tests were not predominant in the building. By introducing minimum values for elastic modulus for masonry according to NTC08, better matching with microtremor measurements was obtained in respect to frequencies.

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