Seismic resistance of stone masonry building and effect of grouting

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Scientific paper - Preliminary note

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Grout injection is one of the most effective and often most appropriate techniques for strengthening of old stone masonry walls. In order to assess the influence of different types of injection grouts on the mechanical properties of masonry, an actual stone masonry building was tested in-situ using various testing methods. The results obtained were used to evaluate seismic resistance of a building using the pushover method, and considering the storey mechanism approach and the global response mechanism. More compatible types of grouts can match cement grouts. The results show that the global response approach provides more realistic results even for low-rise masonry buildings.

Key words:

Stone masonry, strengthening, mechanical properties, grouting, grout type, seismic resistance

Znanstveni rad - Prethodno priopćenje

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Seizmička otpornost zidanih kamenih građevina i utjecaj injektiranja

Injektiranje je jedan od najdjelotvornijih, a često i najprikladnijih postupaka za ojačanje zidova starih zidanih građevina. Da bi se ocijenio utjecaj raznih vrsta injekcijskih smjesa na mehanička svojstva zidanih građevina, obavljeno je ispitivanje in situ postojeće zidane građevine. Dobiveni rezultati korišteni su za ocjenu seizmičke otpornosti građevine pomoću metode postupnog potiska, uz primjenu analize katnog mehanizma i mehanizma globalnog odziva. Prihvatljivije vrste injekcijskih smjesa usporedive su s cementnim injekcijskim smjesama. Dobiveno je da se analizom globalnog odziva postižu realniji rezultati čak i kod niskih zidanih građevina.

Ključne riječi:

zidana kamena građevina, ojačanje, mehanička svojstva, injektiranje, vrsta injekcijske smjese, seizmička otpornost

Wissenschaftliche Arbeit - Vorherige Mitteilung

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Erdbebenwiderstand von Steinmauerwerksbauten und Einflüsse der Injektion

Injektionseingriffe gehören zu den wirksamsten und oftmals angemessensten Verfahren zur Verstärkung bestehender Mauerwerksbauten. Um den Einfluss verschiedener Injektionsmittel auf die mechanischen Eigenschaften des Mauerwerks einzuschätzen, sind in-situ Versuche durchgeführt worden. Die Resultate sind zur Beurteilung des Erdbebenwiderstands mittels Pushover Analysen, unter der Berücksichtigung von Stockwerksmechanismen und globaler Antwortmechanismen, angewandt worden. Angemessene Injektionsmittel sind mit Zementmörteln vergleichbar. Durch die auf globalen Antwortmechanismen beruhenden Berechnungen sind, sogar bei niedrigen Mauerwerksbauten, realistischere Resultate erzielt worden.

Schlüsselwörter:

Steinmauerwerksbauten, Verstärkung, mechanische Eigenschaften, Injektion, Injektionsmittelarten, Erdbebenwiderstand

1. Introduction

In Slovenia, and especially in rural areas, older residential as well as more important public buildings were mostly built out of stone. Depending on the geographical area, stone walls were built using limestone, sandstone or slate. Irrespective of the historical period to which they belong, thinner walls were usually built with two leaves, while thicker walls had three leaves. In general, the low strength lime mortar was used. Because of weak connections between leaves, low strength of mortar used, and voids present in the inner core, the in-plane lateral load bearing capacity of such walls is mostly insufficient [1, 2]. Grout injection is one of the most appropriate strengthening techniques for improving the load bearing capacity of such walls due to its main advantage: the exterior of the wall remains virtually unchanged while the mechanical properties are increased significantly. The method is based on the injection of grout (a fluid mixture made of water, binder, and additives) into the stone wall in order to fill up the voids and establish proper bond between the stones and the leaves of the wall. Injection assisted by gravity has been known since Roman times. More recently, namely in the first half of the 19th century, the injection of grout was initially also gravitational. However, first devices for the injection of grout under pressure were introduced [3] at the end of the 19th century. In fact, mass production of devices for grout injection under pressure [4] begun at about that time in England and Germany. Before World War I, first heritage buildings were strengthened using the cement injection grout [3]. Several phases can be differentiated in the history of grouting: at first, mostly cement-based grouts were used but later on, other grout types, more compatible with the fabric of historical masonry walls, were developed due to strict requirements and limitations for the strengthening of heritage and monumental buildings. Since lime mortar was mostly used for the construction of older masonry buildings, the development of grouts for such applications focused on reducing the share of cement and increasing the share of lime in the mixture. In this context, the question arose about whether the rate of improvement in the mechanical properties of injected wall depends on the type of the injection grout used. Most research focusing on the influence of grout injection on mechanical properties of stone masonry walls was conducted on specimens prepared in laboratory conditions. Most researchers also tried to assess the influence of the type and the properties of injection grout on the rate of improvement of mechanical properties of the tested specimens. Tomaževič and Apih [5] concluded that seismic resistance of stone masonry walls increases significantly after injection of cement grout. Vintzileou and Tassios [6] established that the compressive strength of specimens injected with two types of grout increases significantly (50-200 %), but were unable to make reliable conclusions about the influence of compressive strength of grout on the compressive strength of walls, due

to small number of specimens tested. Test results presented in [7] showed no significant differences between compressive strengths of grouted walls, although two injection grouts with different compressive strengths were used. A more complex research, which also took into account the ability of injection grout to achieve a solid bond with in situ material [8], revealed that the shear adhesive strength between the injected grout and the material used for wall construction is the most important parameter influencing the effectiveness of grouting. Similar findings were presented in [9] where it was determined that the improvement in the mechanical properties of stone masonry walls after grout injection is not proportional to the compressive or flexural strength of the injection grout, but rather that it depends on the bond strength achieved between the grout and the existing materials. According to [10], the development of injection grouts should be oriented towards achieving the main function of the injection grout, which is to connect different layers and parts of the wall, and should therefore aim to improve the bond and tensile strength of injection grouts.

Compared to research performed by other authors, the contribution of the research presented in this paper is the in situ application and investigation of the influence of different types of injection grouts on mechanical properties of wall specimens of an actual building. The rate of improvement in the mechanical properties of test specimens, and in seismic resistance of the building, was assessed after grout injection by cement and combined lime-cement grouts. The influence of grout type on seismic resistance of the building was evaluated by non-linear static analysis using the pushover method. Two modelling approaches were applied: the storey mechanism with SREMB software, which is a relatively common tool for the analysis of URM structures, and a more modern approach featuring a global mechanism response model, where the structure is modelled with the Frame by Macro Elements (FME) method using 3MURI [26]. In order to determine which approach fits better the actual damage suffered by the building exposed to earthquake, the registered crack pattern was compared to failure modes at ultimate limit state obtained by both approaches.

2. Typology and mechanical properties of stone masonry walls

Structural characteristics of stone masonry vary depending on the historical period, importance and location of the building. Some characteristic cross-sections of stone masonry walls in different historical periods are shown in Figure 1. The so-called Roman concrete composed of lime, pozzolana, sand, and crushed brick was used in the Roman period. Roman walls were additionally strengthened with transverse connections between outer leaves. Although hewn stone was also used in the Romanesque period, most of the buildings were built using uncut or irregular stone and lime mortar, occasionally

with the addition of crushed brick. In the Gothic period walls were thinner, built out of partly shaped stones. Hewn stones were used only at corners, intersections, and edges of openings [11].
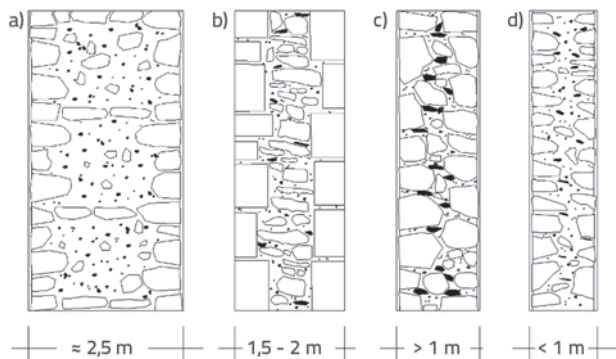

Figure 1. Characteristic cross-sections of stone masonry walls from different historical periods, according to [11]: a) Roman period; b,c) Romanesque period; d) Gothic period

Stone masonry walls can be divided into several types [12] such as the single leaf, two leaves with no connection, two leaves with simple connection made with overlapped stones, two leaves with transversal connection made by long regular stones, three leaves with outer leaves built with hewn stones and rubble inner core, and three leaves with outer leaves out of coarser rubble units and rubble inner core. Most of the above listed cross sections can also be found in Slovenia. Different values of cohesion within the inner core and adhesion between separate leaves, presence or absence of transverse elements and various percentage of voids, result in significant differences in structural characteristics and mechanical behaviour of stone masonry walls with voids [13]. Mechanical properties for different typologies of heritage building walls were proposed in the scope of the Perpetuate project [14]. Reference values provided in Table 1 represent a modification of values given in the Italian standard [15], taking into account also the results of in situ tests performed in Slovenia, Croatia and Montenegro.

Values presented in Table 1 are to be modified using correction coefficients dependent on several parameters such as the quality of mortar, presence of transverse connections, inner core thickness, grout injection strengthening, etc. The correction coefficient that relates to the improvement of mechanical properties after grout injection ranges between 1.2 and 2.0 depending on the type of stone masonry. The presented values predict radical improvement of all mechanical properties of stone masonry walls after grouting, but do not change results depending on the type of the injection grout applied. Walls of a two storeyed stone masonry building from Posočje region were analysed in the scope of our test campaign, as presented below. The analysis of texture and morphology (Figure 2) revealed that the walls were built with lime mortar and roughly shaped limestone and sandstone with some bricks intrusions. Walls were constructed with two leafs without an explicit inner core, but with simple connections through the cross section made by occasionally overlapping stones. The analysis of the cross sections showed that walls consist of 70-75 % of stones, 15-20 % of mortar, and 10 % of voids, which makes them highly injectable (according to [16], the bottom limit of injectability is 4 %).

Figure 2. Texture (left) and morphology (right) of stone masonry walls

Table 1. Reference values of mechanical properties for different typologies of heritage building walls [14]

Type of stone masonry	Compressive strength f_c [MPa]	Tensile strength f_t [MPa]	Modulus of elasticity E [MPa]	Shear modulus G [MPa]	Specific weight γ [kN/m³]
Irregular stone masonry (pebbles. erratic. irregular stone)	1.00-1.80	0.020-0.048	200-1050	130-350	19
Uncut stone masonry with facing walls of limited thickness and infill core	2.00-3.00	0.053-0.080	1020-1440	340-480	20
Cut stone masonry with good bonding	2.60-3.80	0.084-0.111	1500-1980	500-660	21
Soft stone masonry (tuff. limestone....)	1.40-2.40	0.042-0.063	900-1700	300-420	16
Dressed rectangular stone masonry	4.70-8.00	0.135-0.180	740-3200	200-940	22
Full brick masonry with lime mortar	2.00-4.00	0.040-0.140	240-1800	80-600	18

Table 2. Composition of grouts in % by mass

Type of grout	Ordinary Portland cement	Hydrated lime	Limestone powder	Quartz powder	Bentonite	Expansion additive
LC1	54	15	17	14	-	-
LC2	75	25	-	-	3	0,3
C1	100	-	-	-	3	0,3
C2	100	-	-	-	-	0,5

Table 3. Properties of hardened injection grouts at 90 days

Type of grout	Volume change ΔV [%]	Bulk density ρ_m [kg/m³]	Flexural strength f_{fm} [MPa]	Compressive strength f_{cm} [MPa]	Tensile splitting strength f_{ctm} [MPa]
LP1	1.2 (8)	1356 (1.2)	0.4 (24)	12.4 (2)	0.7 (26)
LC1	0.9 (16)	1467 (0.6)	6.3 (10)	23.7 (6)	0.9 (4)
LC2	0.6 (18)	1361 (0.4)	2.8 (7)	21.7 (5)	1.4 (21)
C1	1.2 (26)	1815 (0.4)	4.4 (14)	52.3 (6)	1.4 (14)
C2	0.0 (130)	1683 (1.0)	4.4 (12)	47.0 (2)	1.6 (19)
*Coefficient of variation is indicated in brackets (%)					

Mechanical properties obtained were comparable with reference values for the first two types of masonry presented in Table 1. However, in our case, the values of correction coefficients related to the improvement of mechanical properties after grout injection were higher, and they varied depending on the type and properties of injection grout applied. Since stone masonry walls with similar morphology are relatively common in the region of Posočje, and as grout injection is the most frequently used strengthening method for such walls, the obtained results could also be considered valid for other stone masonry building walls in the area. Furthermore, similar wall morphologies can also be found in other rural parts of Slovenia.

3. Laboratory and in situ tests

The procedures and results of laboratory tests of materials and in situ tests of wall specimens are already presented and described in detail in [17]. Main results and findings are given in this section in order to complete the data necessary for understanding mechanical behaviour of the test specimens, and for evaluation of seismic resistance of the building in its existing and strengthened state.

3.1. Properties of mortar and stone samples

Samples of lime mortar extracted from the building's wall joints and two types of stones (limestone and sandstone) obtained from the surroundings of the building site were subjected to the laboratory tests. The average compressive strength obtained by testing eight mortar specimens amounted to 1.75 MPa (cov. = coefficient of variation = 17 %). Since mortar specimens presented an irregular prismatic

shape with edge lengths of 3.1-3.6 cm, and heights of 2.1-2.5 cm, the results had to be converted using the shape factor d = 1.5 [18] in order to obtain the compressive strength on 4 cm mortar cubes. Consequently, the mean compressive strength of f_{cm} = 1.17 MPa was obtained for the lime mortar. Compressive strength tests of stone specimens were carried out according to [19]. The mean compressive strength of f_{cl} = 120 MPa (cov 14 %) was obtained for limestone and f_{cs} = 209 MPa (cov 7 %) for the sandstone specimens.

3.2. Injection grouts

Five types of injection grouts were tested in the laboratory: hydraulic lime-pozzolan grout LP1, two combined cement-lime grouts designated LC1 and LC2, and two cement grouts designated C1 and C2. The composition of the tested injection grout, with the exception of LP1, is given in Table 2. The composition of the latter was not known in detail, i.e. according to available information, it was composed of hydraulic lime, filler, and eco-pozzolan.

Mean values of injection grout properties in hardened state are presented in Table 3. The volume change of grouts was measured according to the test method described in [20], and the bulk density was determined according to [21]. The flexural and compressive strength was defined in accordance with [22], and the tensile splitting strength according to the procedure described in [23]. Three specimens were used for each test and injection grout type.

As expected, the highest values of bulk density, compressive strength, flexural strength, and tensile splitting strength were achieved in the case of cement grouts C1 and C2, with the exception of the flexural strength of lime-cement grout LC1 where the highest value was obtained. The latter may

be attributed to the incorporation of limestone and quartz powder into the composition, which acted as filler. The volume change of all tested grouts was relatively small since the maximum value of 1.2 % was reached.

3.3. Cylindrical specimens

In order to simulate the inner core of the strengthened multiple leaf stone masonry wall, cylinders measuring 15 cm in diameter and 30 cm in height were prepared and injected with the grouts LP1, LC1, LC2, C1 and C2. The cylinders were gradually filled with limestone and sandstone, i.e. 37 % (by mass) of the fractions 45/63 mm and 32/45 mm, 25 % of the fraction 16/32 mm, and 1 % of the fraction 8/16 mm. The cylindrical specimens were injected with the grouts LP1, LC1, LC2, C1, and C2. Cylindrical specimens during grout injection are presented in Figure 3.

Figure 3. Cylindrical specimens during grout injection

At 90 days, the injected cylinders were subjected to compressive strength testing (3 per each grout type) according to [24], whereas the tensile splitting strength tests (3 per each grout type) were conducted according to [23]. The secant modulus of elasticity $E_{c(30-60\,\%)}$, Poisson`s ratio $\nu_{c(30-60\,\%)}$ and shear modulus $G_{c(30-60\,\%)}$, were determined from the stress-strain diagrams obtained at the compressive strength testing. As indicated by the index, all quantities were calculated in the range between 30 and 60 % of the achieved compressive strength, where a linear behaviour could be assumed. Test results are presented in Table 4.

As expected, the highest values were obtained in case of cylinders injected with cement grouts C1 and C2. Somewhat lower values were obtained by cylinders injected with lime-cement grouts LC1 and LC2, while the smallest values were obtained for cylinders injected with the hydraulic lime-pozzolan grout LP1. The greatest differences between different grout types were observed in the results of the modulus of elasticity and shear modulus.

3.4. Assessment of mechanical properties of walls by in situ shear and double flat jack tests

Mechanical properties of wall specimens injected with injection grouts LC1, LC2, C1, and C2 were assessed 180 days after grout injection, while one wall specimen was tested in an un-grouted state. The shear tests, along with flat jack test, enabled us to evaluate mechanical properties of the walls and also the effectiveness of the grout injection technique. The earthquake response of wall specimens was simulated with an in situ shear test by which the in-plane lateral resistance, effective stiffness, and tensile (shear) strength of tested wall specimens was determined. Fixed-ended wall specimens measuring 250 cm in height, 100 cm in width, and 40 cm (2-LC1, 3-LC2) and 50 cm (1-C1, 4-C2, 6) in thickness were obtained using the diamond circular saw, and the preparation included realization of vertical grooves (Figure 4).

The lateral load was applied by hydraulic actuator, and displacements were increased in 0.25 mm increments up to the limit state. Although the goal was to achieve the NC (near collapse) limit state, the tests were ended, due to safety issues, once the SD (significant damage) limit state was exceeded.

Table 4. Mechanical properties of grouted cylindrical specimens at 90 days

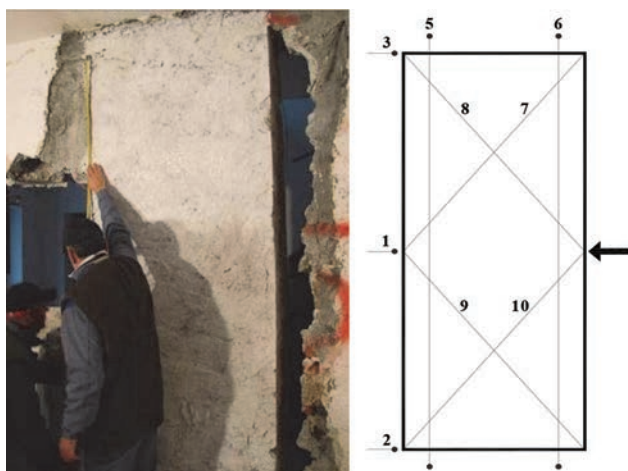| Cylindrical specimen	Compressive strength f_{cc} [MPa]	Tensile splitting strength f_{tsc} [MPa]	Modulus of elasticity $E_{c(30-60\%)}$ [GPa]	Shear modulus $G_{c(30-60\%)}$ [GPa]
LP1	7.21 (2)	0.84 (15)	3.17 (17)	1.11 (21)
LC1	9.99 (8)	1.08 (11)	7.04 (15)	2.57 (21)
LC2	9.32 (10)	1.15 (5)	7.41 (48)	2.86 (29)
C1	15.62 (4)	1.83 (13)	13.28 (22)	5.03 (29)
C2	13.61 (28)	1.72 (12)	13.54 (23)	4.79 (32)
*The coefficient of variation is indicated in brackets (%)				

Figure 4. Cutting, measurements and shear test setup of wall specimen

During the testing, the displacements at the lower, middle and upper spans of the wall specimen were measured. Diagonal deformations and possible vertical displacements were also measured. The relationship between the lateral load and drift (the ratio between the relative lateral displacement d and the height of specimen h in %), along with the stiffness degradation of the wall specimens, is presented in Figure 5.

The experimentally obtained hysteresis envelopes were idealized with bilinear envelopes which were defined by the effective stiffness and displacement at the completion of the test. The effective stiffness of the injected wall specimens was calculated at the lateral load level at which first significant cracks were formed. The average crack-formation level for the injected specimens was at $H_{cr} = 0.80 H_{max}$ at the drift of 0.10 %. In case of un-grouted specimen, the formation of significant cracks began at a lower lateral force level $H_{cr} = 0.61 H_{max}$ and a higher drift of 0.14 %. The effective stiffness K_e was defined as the ratio between the lateral resistance H_{cr} and the wall displacement d_{cr} at the crack limit:

$$K_e = \frac{H_{cr}}{d_{cr}} \tag{1}$$

As can be seen from Figure 5, the stiffness degradation of injected wall specimens by the increasing displacement was very similar. After the formation of first significant cracks, a significant reduction of stiffness, with a sharp decline of curve slopes, was registered. For the un-grouted wall specimen, the decline of the curve showing stiffness degradation was much smaller. Athough the stifness of the wall specimens increased substantially after grouting, the imposed displacements beyond the achieved effective stiffness resulted in faster propagation of damage, and faster reduction in stiffness, compared to the un-grouted wall specimen. The ultimate resistance of wall specimens was calculated using Eq. 2:

$$H_u = K_e \left(d_{max} - \sqrt{d^2_{max} - \frac{2A_{env}}{K_e}} \right) \tag{2}$$

where d_{max} is the maximum relative lateral displacement attained during the test, and A_{env} is the area beneath the experimental resistance envelopes. According to [24], the tensile strength f_{tw} can be obtained from Eq. 3:

$$f_{tw} = -\frac{\sigma_0}{2} + \sqrt{\frac{\sigma_0^2}{4} + \left(\frac{H_u b}{A_w} \right)^2} \tag{3}$$

where σ_0 stands for the level of vertical load, A_w for the horizontal cross-section of the wall specimen, and b is the variable representing the height-to-width ratio of the wall specimen. By definition, the ductility factor represents the ratio between the ultimate displacement d_u at which the force decreases to 80 % of the maximum attained force level, and the displacement d_e at the idealized limit of elasticity. Due to safety issues, the tests had to be ended before the force dropped to 80 % of the maximum value. Consequently, the ductility was evaluated as the ratio of the maximum attained displacement d_{max} to the displacement d_e (Eq. 4).
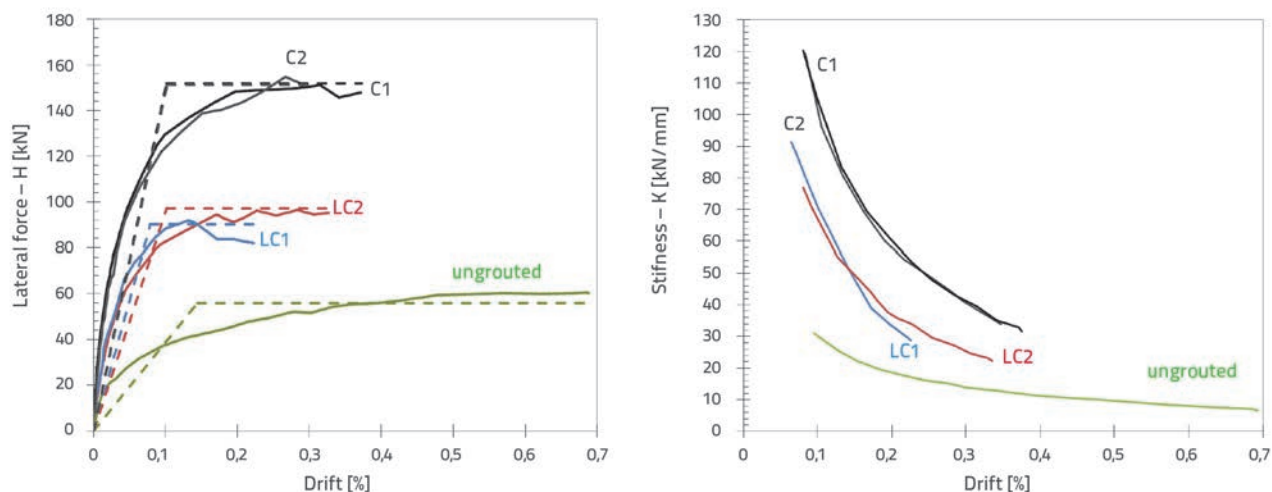

Figure 5. Horizontal resistance and stiffness degradation of wall specimens obtained by in situ shear testing

Table 5. Mechanical properties of wall specimens obtained by in situ shear testing [17]

Designation of wall specimen	Vertical load σ_o [MPa]	Lateral resistance H_u [kN]	Effective stiffness K_e [kN/mm]	Ductility μ [-]	Tensile strength f_{tw} [MPa]
un-grouted	0.14	56	31	4.84	0.07
LC1	0.17	90	91	2.85	0.21
LC2	0.19	97	77	3.32	0.21
C1	0.21	152	120	4.21	0.29
C2	0.15	151	119	2.99	0.30

Table 6. Mechanical properties of wall specimens obtained during the double flat jack test [17]

Designation of wall specimen	Compressive strength f_{cw} [MPa]	Modulus of elasticity E_w [MPa]	Shear modulus G_w [MPa]
un-grouted	1.65	785	113
LC1	2.00	1347	476
LC2	2.00	1164	411
C1	2.50	1520	537
C2	2.50	1507	532

$$\mu = \frac{d_{max}}{d_e} \tag{4}$$

In situ shear test results are presented in Table 5. The comparison of tensile strength results for the un-grouted wall specimen with the tensile strength results obtained through in-situ shear tests on the same type of masonry and in the same region of Slovenia [26] shows comparable values. After grouting by cement injection grouts, the increase of tensile strength by a factor of 1.8-2.5 was achieved, which is somewhat smaller compared to the improvement achieved in our case (increase by the factor of 3 for LC1 and LC2, and the factor of 4 for C1 and C2). The factor of increase in the mechanical parameters proposed in [14] for the similar type of masonry after grout injection ranges between 1.7 and 2, which is also considerably lower compared to the increase obtained during our test campaign. This could be due to better quality of the initial wall structure tested in [14] and [26] (presence of transversal stones, thinner mortar joints, smaller quantity of voids, and better mechanical properties of constitutive materials), which limited the effectiveness of injection grouting. The ductility factor for the un-grouted wall specimen reached the value of 4.84 and was reduced after grouting, regardless of the type of grout. With exception of the wall specimen C1, ductility factors obtained for grouted specimens show comparable values, although a more ductile behaviour was expected for wall specimens injected by lime-cement grouts LC1 and LC2. A double flat jack test was performed in order to assess the elastic modulus, shear modulus, and compressive strength. Two horizontal cuts, made at the vertical distance of 50cm, were used for placing the double flat jack (Figure 6).
By the test which was performed before and 180 days after injection of grout C2, the oil pressure in both flat-jacks was gradually increased. The mechanical behaviour of masonry portion before and after grout injection was monitored by placing four vertical and one horizontal LVDT between the two cuts. Double flat jack test results are presented in Table 6.
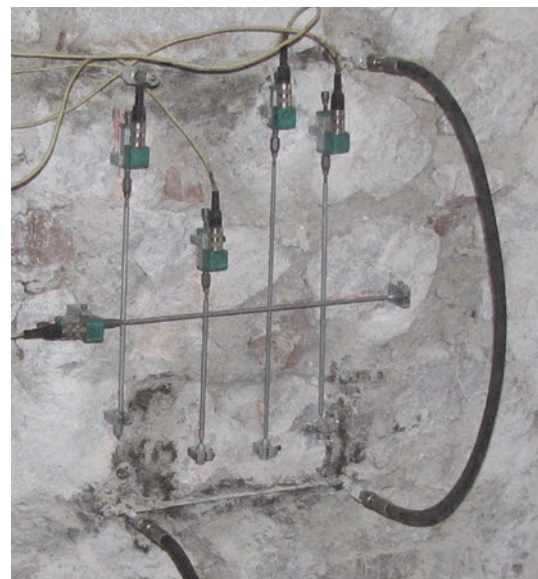
Figure 6. Set up of the double flat jack test

4. Influence of injection grout type on mechanical properties of tested specimens

An obvious distinction between related types of grouts (cement/cement-lime grouts) was revealed both in the case of compressive and splitting tensile strength tests of injected cylinders, and in the case of shear tests performed on walls. The analysis of split surfaces, which was performed on cylinders after the splitting tensile tests (Figure 7), showed

that the prevailing mode of failure was that of the bond between the stones and the grout, and that better bonding was achieved in the case of cement grouts, compared to the cement-lime and lime-pozzolan grouts.

Figure 7. Average splitting tensile strengths of cylinders and grouts, and percentage of stone and bond failure at tensile splitting strength test of cylinders

Main reasons for considerable improvement of mechanical properties of walls after grout injection, and different levels of improvement (depending on the type of grout used), are poor mechanical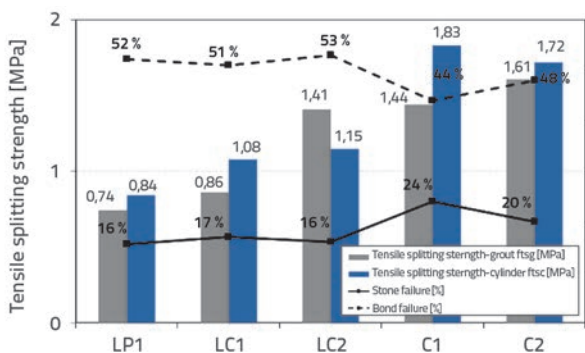 properties of the walls in their existing, un-grouted state, and a relatively high percentage of voids (around 10 %). After grout injection, the behaviour of the walls was significantly dependent on the strength of the bond established between the stones and leaves that enhanced their mechanical properties. It is obvious that in the case of walls with low initial mechanical properties and high percentage of voids, mechanical properties of the walls depend significantly on the type and properties of grout used (i.e. on its ability to achieve a solid bond between the stones and the leaves). Most researchers, with the exception of two [7] and [8], have not registered major differences in the mechanical properties of the walls injected with different types of injection grouts. This can be attributed to the method of construction of test specimens. All test specimens were built in laboratory conditions using the lime-cement, lime-pozzolan, or hydraulic lime mortar with relatively good mechanical properties. Such mortars were used either to illustrate actual on-site conditions or, more often, because of time limitations related to the research projects, and problems

related to maturing the specimens with lime binders. Therefore, researchers used mortars that gained strength faster compared to lime mortars, but also those that demonstrated higher final strengths. Although the injection grout was able to fill up the voids, the behaviour of test specimens was predominantly dependent on the basic mortar with relatively high strength characteristics.

5. Seismic response of the building in the existing-unstrengthened state

Seismic response of the building in its existing-unstrengthened state was analyzed by two numerical tools, both based on the non-linear static analysis using pushover method. Firstly, the structure was analysed by considering the so-called storey mechanism approach with the SREMB software [29]. Secondly, the analysis was carried out using the software package 3MURI [27] that considers global response by modelling the structure with the Frame by Macro Elements (FME) method. Results obtained for the existing-unstrengthened state of the building were compared with actual registered damage following the cracking pattern investigation of the building after it suffered earthquake damage in 2004. The facades of the building are presented in Figure 8, and the models used for seismic analysis are shown in Figure 9.

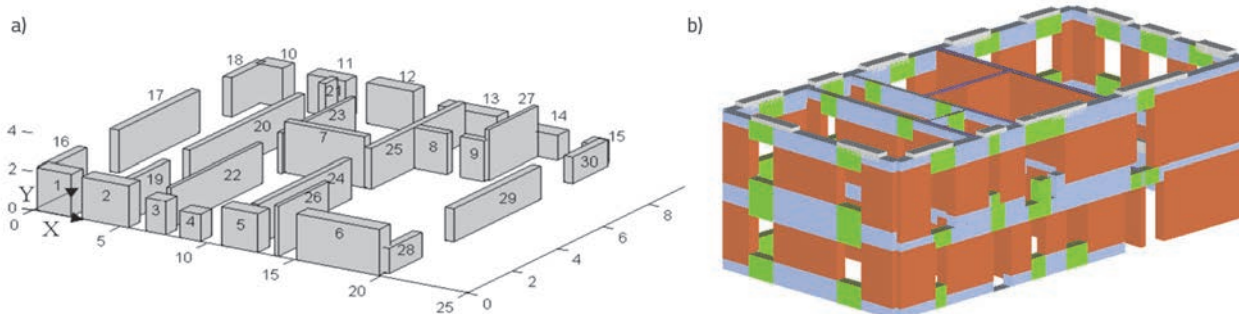**Figure 8. Northern and western facade of the building**

Figure 9. Models used for non-linear seismic analysis: a) SREMB; b) 3MURI

The seismic demand was calculated according to requirements given in EC8-1 [28]. The following input parameters were used in seismic analysis: the importance factor of $\gamma_1 = 1.0$, the design ground acceleration of $a_g = 0.225g$, the soil factor of $S = 1.2$, and the lower limit of the structural behaviour factor of $q = 1.5$. If the actual ductility factor of $\mu = 4.84$ obtained through in situ shear tests were taken into account, the structural behaviour factor considering the Eq. 5 proposed in [29] would amount to $q = 2.95$, which would result in a higher level of seismic resistance.

$$q = \sqrt{2\mu - 1} \qquad (5)$$

Our analysis took into account mechanical properties obtained through in situ shear and double flat-jack tests (with the exception of actual ductilities). The full knowledge level (KL3) of the building, and the confidence factor of CF = 1.0 according to EC8-3 [30], were assumed. Consequently, the actually obtained values were considered in the numerical analysis. In order to compare the results of both programs, the results obtained by SREMB were converted into the form of ULSPGA (ultimate limit state peak ground acceleration) taking into account the relations defined in the N2 method [31]. The results obtained are presented in Figure 10. The expected peak ground acceleration on the micro location of the building considering the soil factor of $S = 1.2$ amounts to 0.27g, and is marked with a dashed line. As can be seen, the seismic demand in the existing un-grouted state is not achieved by either of the programs used.
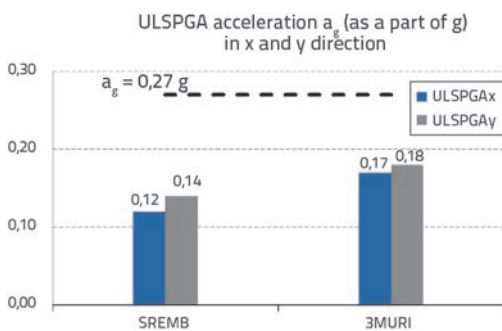

Figure 10. Seismic resistance of the building in the existing state, calculated using SREMB and 3MURI

The crack pattern registered at the south façade wall is compared to the failure mode at the ultimate state obtained by SREMB and 3MURI for the existing un-grouted state (cf. Figure 11). As can be seen, the shear failure prevails in both models at the ground storey, which is in accordance with registered crack pattern. A somewhat better interpretation of the actual damage state of the ground storey is obtained by the 3MURI model. In the upper storey, the 3MURI model foresees primarily flexural cracks in the middle portion and an undamaged state at the left and right parts of the storey walls. In the actual state, the flexural cracks are also present,

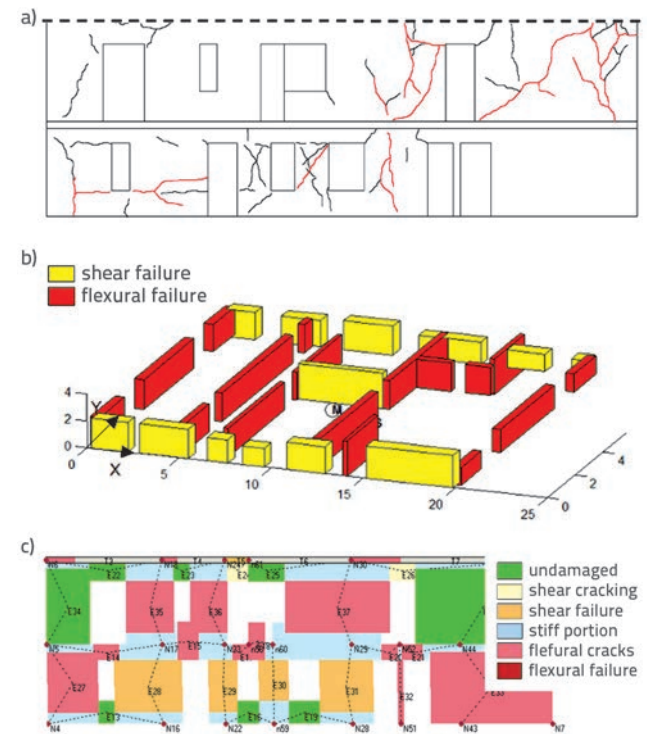but a substantial shear cracking is also present mainly in rightmost and leftmost parts of the storey walls.

Figure 11. Cracking pattern registered at the south façade: a) compared to the failure mode at ultimate state obtained by SREMB; b) and 3MURI; c) for un-grouted state

The results of the crack pattern investigation revealed that the damage was not concentrated only in the ground storey wall piers as predicted by the SREMB model, but that the cracks also formed in the upper storey, and in lintel area of the lower storey. Although the 3MURI model was not able to provide the exact interpretation of the actual state of damage, it seems that in the case of the analysed building it enabled better approximation of the actual state compared to the SREMB model.

6. Influence of injection grout type on seismic resistance of the building

In order to assess the reflection of obtained in-situ test results on the seismic resistance of the building prior to and after grouting with the C1, C2, LC1 and LC2 grouts, the seismic analysis was repeated using both programs, i.e. SREMB and 3MURI. Just like for the unstrengthened state, an equal behaviour factor of $q = 1.5$ was considered in the analysis after grout injection. Also in this case, if actual ductilities were taken into account, this would result in higher levels of seismic resistance (especially in case of the grout C1 where the highest value of ductility factor $\mu = 4.21$ was achieved). The comparison of failure modes in the x direction before and
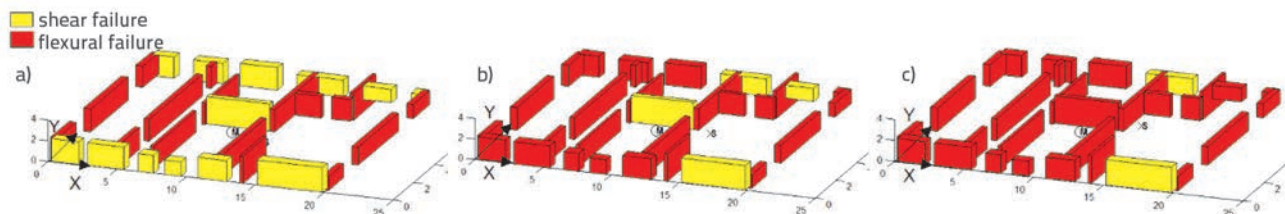
Figure 12. Failure modes at ultimate state in x direction obtained by SREMB: a) before grouting; b) after grouting with LC1; c) after grouting with C1
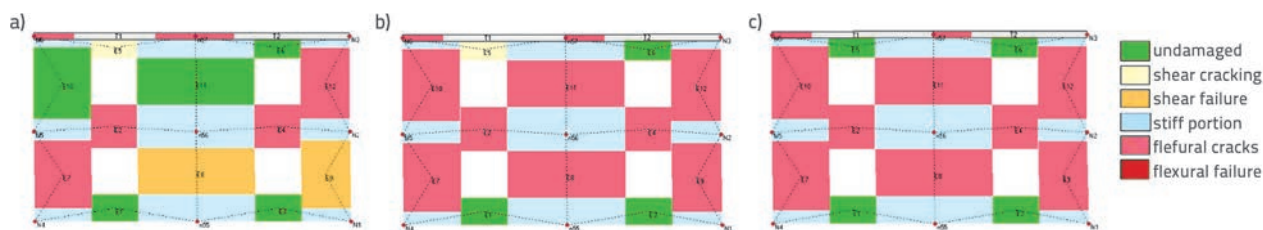

Figure 13. Failure modes at ultimate state in y direction (west façade wall) obtained by 3MURI: a) before grouting; b) after grouting with LC1; c) after grouting with C1
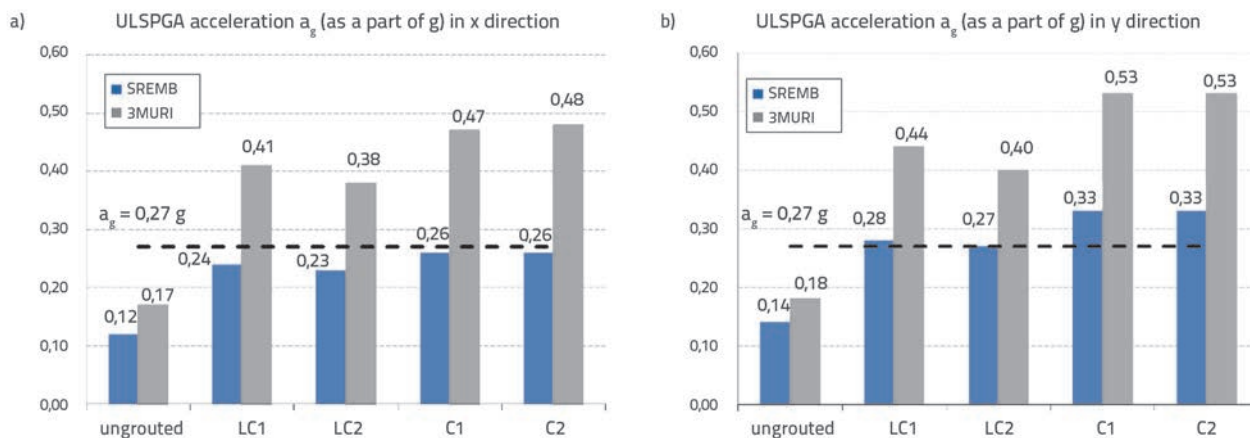

Figure 14. ULSPGA acceleration a_g (as a part of g) calculated with SREMB and 3MURI in: a) x direction; b) y direction - for all analysed cases

after grouting, as obtained by SREMB, is presented in Figure 12. As can be seen in this figure, the shear failure prevails in the existing un-grouted state. As the tensile strength of the walls increases substantially after grouting, the failure mechanism changes from shear to flexural for most of the walls in the x direction. Since the increase in tensile strength is higher if cement grouts are used, the share of walls that exhibit flexural failure is somewhat higher after injection with cement grouts C1 and C2, compared to injection with lime-cement grouts LC1 and LC2. In the y direction, the walls are mostly longer (lower height/length ratio), and so shear is the predominant mode of failure even after grouting.

The comparison of failure modes at ultimate state in the y direction before and after grouting, as obtained by 3MURI, is presented in Figure 13. In the existing un-grouted state, the shear failure prevails in the wall piers with flexural cracks in the lintels of the lower storey. The upper storey walls remain mostly undamaged, with the exception of the shear cracking at

the left lintel, and flexural cracking at the right-side pier. After grouting, flexural cracks form in most of the wall elements, regardless of the type of injection grout used (LC1, C1). In terms of ductile behaviour and energy dissipation during seismic loading, the flexural mechanism that prevails after grouting is more favourable than the shear mechanism.

The seismic resistance of the structure in terms of the ULSPGA, calculated with SREMB and 3MURI before and after grout injection, is presented in Figure 14. After grout injection, the seismic resistance calculated with both programs increases significantly, with a slightly higher increase in the case of cement injection grouts C1 and C2, compared to lime-cement grouts LC1 and LC2. As can be seen, the values obtained by 3MURI are considerably higher compared to those obtained by SREMB. 3MURI takes into account the entire structure allowing the failure mechanisms to be formed in piers and lintels with an even distribution throughout the height of the structure. Consequently, the deformation capacity of such structure

is much higher compared to the single storey mechanism approach considered by SREMB, resulting in higher ULSPGA values. In the un-grouted state, the ULSPGA is higher by 41.7 % in the x direction, and by 28.6 % in the y direction, according to the global mechanism response model, compared to the storey mechanism response. After grouting, the comparison between different models reveals the increase by 70.8 % in the x direction and by 57.1 % in the y direction using the injection grout LC1, and by 80.8 % and 60.6 % in the x and y directions, respectively, by using the injection grout C1, all in favour of the global mechanism response.

The increase in seismic resistance of the building is not directly proportional to the improvement of mechanical properties of the walls as obtained through in situ tests. This was expected since the seismic resistance of the building is also dependent on several other parameters such as the geometry and layout of walls, level of vertical loading, type of connection between walls and slabs, and numerical model selected for the structure. The comparison of calculated periods (for the idealised SDOF system) shows that the stiffness of the structure increases considerably after grouting. For the x direction, the fundamental period of the building in its existing un-grouted state amounts to 0.21 s (3MURI) or 0.16 s (SREMB), and is reduced to 0.11 s (3MURI) or 0.08 s (SREMB) after grouting by cement injection grouts C1 or C2. By using lime-cement grouts LC1 and LC2, the calculated periods amount to 0.12 s and 0.09 s, respectively.

7. Conclusions

The main aim of the presented research was to evaluate the effectiveness of different types of injection grouts in improving the load bearing capacity of stone masonry walls and, consequently, the seismic resistance of the building as a whole. Mechanical properties of cylinders representing the inner core of the strengthened stone masonry wall were higher in case of the cement grouted cylinders compared to the cylinders grouted with the lime-cement or lime-pozzolan injection grout. The analysis of cross-sections after the tensile splitting test revealed that the bond failure was the prevailing mode of failure, regardless of the type of grout used for grouting. This points to the importance of the adhesive strength achieved between stones and injection grout, and is in agreement with findings of some other researchers [7, 8]. Tests performed on cylinders, as well as in situ shear tests of wall specimens, showed that mechanical properties of tested specimens depended significantly on the type and properties of injection grout used for grouting. The results obtained suggest that the type and properties of injection grout applied should also be taken into account when assessing the effectiveness of grout injection techniques by certain stone masonry typologies (high amount of voids, thick mortar joints, low mechanical properties of constitutive materials, absence of transverse stones). Furthermore, correction coefficients for mechanical properties of stone masonry walls after grouting should in such cases be higher, as also proposed in some references [14, 26]. Different rates of improvement of mechanical properties of wall specimens also reflected in different rates of increase in the seismic resistance of a building. Comparison of failure modes at ultimate limit state before grouting and the registered earthquake-induced building damage showed that better approximation of the actual damage can be obtained using the global response mechanism (3MURI) instead of the storey mechanism approach (SREMB). This most likely also applies to the situation after grouting. Using the global response mechanism, the ULSPGA values become considerably higher, compared to those obtained by the storey mechanism approach. Obviously, the storey mechanism approach can underestimate the seismic resistance of the building. In case of existing buildings, this can result in excessively invasive and inappropriate strengthening measures, which can be particularly harmful to heritage buildings with architectural and cultural assets and values such as fresco or stucco work. On the other hand, it seems that an adequate level of seismic resistance would be achieved even with the hydraulic lime based grout in case the global response mechanism approach is applied. Regardless of the numerical method used, a higher seismic resistance of the building was achieved after grouting by cement grouts compared to lime-cement ones. After grouting by either of the injection grouts, the failure mechanism for walls with higher height/length ratio mostly changed from shear to flexural, which is more favourable in terms of ductile behaviour and energy dissipation during seismic loading.

Acknowledgements

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