Technologies for Safeguarding of Heritage Buildings in Slovenia

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1. Introduction

The introduction of modern technologies in safeguarding of heritage buildings in Slovenia is governed by rich experiences gained from post-earthquake interventions in Slovenia and neighbouring parts of Europe (Italy and former Yugoslav republics). However, the new or so-called "emerging materials" bring new challenges in the development and application of entirely new or modified traditional repair and strengthening technologies. The research in the field of application of emerging materials[1] started in mid-eighties of the last century, mainly in the USA and Japan where the development of earthquake mitigation methods is one of the high priorities. The best known emerging materials that are in use in civil engineering and that can be well applied also for heritage safeguarding are: smart materials suitable for sensing applications (monitoring of heritage), fiber reinforced composites (FRP) suitable for the repair and strengthening of structures, geomaterials for ground improvement, aluminium materials suitable for the construction of protecting structures (shielding) often in combination with glass or transparent plastics, polymer modified mineral materials (mortars, concrete) and masonry modifying materials mostly based on polymers. With the delay of several years, the interest for the application of some of these materials (FRP for instance) entered Europe together with the pressure of commercial interest for wide introduction of these types of materials in heritage safeguarding. However, some of the emerging materials appeared first in Europe and then spread all over the world. The delay in interest for some materials has been positively reflected in learning from the experiences of American and Japanese researchers and engineers. However, the character of European heritage and specific properties of structures and materials makes the intervention more demanding than in the cases of contemporary building systems and materials. The most problematic issues are the compatibility of behavioural mechanisms of heritage buildings after intervention and the long-term compatibility of traditional and emerging materials. These problems should be very seriously taken into consideration in earthquake-endangered areas of Europe, where also Slovenia is located. The "conservatism" that is present in approach to safeguarding of heritage buildings is positive response on uncertainties emerging from lack of experiences with the long-term effect of new technologies introduced to conservation. The Venice Charter (1964)[2] addressed the problem of use of modern techniques in its Article 10:

"Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modem technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience."

In the years to follow, the number of new materials and technologies grew fast and the interest of producers of new materials influenced the wide application of them in the domain of cultural heritage preservation. The challenges for conservators and others involved in safeguarding of

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1 Emerging Materials for Civil Infrastructure, State of the Art, edit. R.A.Lopez-Anido and T.R.Naik, American Society of Civil Engineers, 2000.

2 International Charter for the Conservation and Restoration of Monuments and Sites, Decisions and Resolutions, Document 1, *II. International Congress of the Architects and Technicians of Historic Monuments*, Venice, 1964.(http://www.international.icomos.org/e_charte.htm)

heritage buildings that were faced with the problems and uncertainties arisen from the application of new technologies is reflected in Article 10 of the Krakow Charter (2000)[3]:

"Conservation/preservation techniques should be strictly tied to interdisciplinary scientific research on materials and technologies used for the construction, repair and/or restoration of the built heritage. The chosen intervention should respect the original function and ensure compatibility with existing materials, structures and architectural values. Any new materials and technologies should be rigorously tested, compared and understood before application. Although the in site application of new techniques may be relevant to the continued well being of original fabric, they should be continually monitored in the light of the achieved results, taking into account their behaviour over time and the possibility of eventual reversibility. Particular attention is required to improve our knowledge of traditional materials and techniques, and their appropriate continuation in the context of modern society, being in themselves important components of cultural heritage."

The wide interest for the reuse of heritage buildings for business purposes that is present in Eastern and Central European countries brings new aspects. The need for fast renovation of valuable heritage buildings and large amounts of funds activated for the purpose may cause additional problems where the modern construction technologies are introduced in conservation with sometimes neglecting of buildings characters. The additional demands are to be considered in earthquake prone areas where contemporary knowledge is to be applied. In some cases it can cause exceptional pressure for introduction of modern techniques without real understanding of all potential problems associated with the lack of knowledge about material and the compatibility of behavioural mechanisms.

Slovenia is located in earthquake prone area where heritage buildings were often damaged and repaired or restored after earthquakes. The most significant earthquakes occurred in 792, 1000, 1511, 1895, 1976 and 1998. Most of the existing residential heritage buildings that are still in function are about five centuries old. Apart from them, there are sacral buildings and castles in more or less preserved shape from the early medieval period and many archaeological sites from and before the Roman times. The structure of heritage buildings in Slovenia is of the type that is characteristic for Central European and North Mediterranean countries. They are massive, constructed from limestone, burned clay bricks or mixture of both. Lime mortar was used for the construction of walls and plastering. Floor constructions are constructed in forms of vaults or timber structures. Timber roof structures are mostly covered by burned clay tiles or wooden shingles. The early seventies of the last century were the beginnings of the Slovenian approach to repair and structural strengthening of heritage buildings in earthquake prone areas. It was based on lessons learned from earthquake response of buildings, traditional techniques of construction of masonry buildings and experimental research in laboratories and on site testing. The 1976 Friuli earthquake was an opportunity for wide application and further development of repair and strengthening techniques. The earthquake that hit the same region of Slovenia in 1998 as in 1976 shows that the techniques applied in 1976 were efficient. This increased the confidence in well-established technologies that were in further improved in the last decade. They are following the contemporary relevant codes that are being developed in Europe[4].

Recently the set of well-established technologies was included in what is called Integrated approach to preservation of built heritage. It can be defined as a holistic effort to establish the evaluation criteria, data collection and determination of most suitable techniques and relevant criteria for the evaluation of intervention works. The important part of procedure is quality assurance of all intervention and post-intervention works including the long-term maintenance. The procedures should lead to understanding of the past behaviour of a building and the predicting of

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[3] The Charter of Krakow 2000, Principles for conservation and restoration of built heritage, T*he International Conference on Conservation "Krakow 2000",* (http://a1.arch.pk.edu.pl/c2000/en/charter.html)

[4] ENV 1998-1-4:1996 (Eurocode 8: Design provisions for earthquake resistance of structures - Part 1.4: General rules - Strengthening and repair of buildings), *CEN/TC 250*, Brussels, January 1996.

its behaviour after the intervention. The emerging materials and technologies based on their application are entering in practice where traditional techniques reach their limits.

On following pages the method for the assessment of earthquake resistance of masonry heritage buildings will be presented together with some typical techniques for strengthening of foundations, masonry walls and vaults and tying of horizontal and vertical structural elements of masonry buildings.

2. Performance of the earthquake endangered masonry buildings

The contemporary approach to seismic design is based on performance-based engineering that can achieve its objectives through deformation-controlled design with respecting the influence of torsion effects due to plan irregularities. Performance based engineering is defined as the integrated effort to design, construction and maintenance needed to produce engineered facilities of predictable performance for multiple performance objectives[5]. Current seismic codes introduce performance levels that include serviceability and basic safety. These levels are defined in terms of various limit states. The relationship between limit states as now defined and the performance levels currently in use or under development are usually not very well clarified. The performance targets can be related to strength, stiffness and ductility requirements in a manner, which results in an efficient structural system that will ultimately fulfil all specific performance objectives. When collapse based design is used, it should be recognized that structural stability depends on the complete structural system rather than on strength or deformation capacity of individual members

The major dilemma is how strictly should the existing buildings be treated in the process of rehabilitation. The fact is that older masonry and reinforced-concrete structures were not constructed according to any seismic code. The strict respect for the existing codes increases the investments in the rehabilitation or even makes them restricted to the cases of valuable cultural monuments. The main requirements of European Prestandard on design provisions for earthquake resistance of structures (Eurocode 8)[6] are to preserve human lives, to reduce economic impacts and to ensure the post-earthquake safety of important public buildings. However, in practice these aims can be achieved with certain limitations. According to Eurocode 8, the structure should be designed and constructed in the way to prevent its collapse and ensure the required post-earthquake residual resistance. Additionally, the extension of damages should be within certain limits that are defined with post-earthquake use of buildings and with the reasonable cost of repair works in comparison to the value of the entire structure. The most demanding problem is quantification of the basic principles.

The codes require verification of structural system endangered by earthquake regarding its strength and ductility. Both are related to the capacity of structure to dissipate the seismic energy and to withstand the base non-linear deformations without losing its stability. In the verification of seismic resistance, the design resistance of a building is compared with the design base shear coefficient. If it is fulfilled, the global ductility requirement should also be verified. The global ductility of a building can be defined as the ratio between the ultimate story drift and the drift at the elastic limit.

The performance-based approach can be very well applied on masonry buildings and it is referred to in Eurocode 8-1-4 (paragraphs 3.5.3 and K.2.4 (3)) as an approximate static non-linear method. The same approach has been in use in Slovenian construction and building renovation practice for the last twenty-five years[7]. It was developed combining theoretical, analytical and

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[5] Seismic Design Methodologies for the Next Generation of Codes, Edit P. Fajfar and H. Krawinkler, A.A.Balkema, Rotterdam, 1997.

[6] ENV 1998-1-1:1994

[7] M. Tomazevic, Seismic Resistance verification of masonry buildings: Following the new trends, *Seismic*

experimental research with on-site experiences obtained from earthquakes at Friuli (1976), Montenegro (1969), Posočje (1998) and several others. The original method became known after the Friuli earthquake (1967) as "the POR method". Story resistance envelope that determines the relationship between relative story drift and base shear resistance is obtained as superposition of resistance of all walls of story. Assuming the boundary restraints and relevant mechanisms, i.e. cantilever walls, fixed-ended piers, piers coupled with spandrels, walls strengthened by reinforced plaster coatings etc., the resistance of each wall in the story can be calculated. It is usually expressed in the form of bi-linear or tri-linear deformation-strength relationship representing the resistance envelope of each contributing wall. The relationship is obtained by relevant equations for the shear and flexural resistance where five basic mechanical properties of masonry are used: compressive strength, tensile strength, modulus of elasticity, shear modulus and ductility. The story resistance envelope is calculated by stepwise drifting of the story by small values. The masonry walls are deformed equally and internal forces are induced according to the assumed shape of resistance envelope of each particular wall. When torsion effects are induced due to displacing of the story mass centre relatively to the stiffness centre, the displacements of individual walls are modified. The calculation is repeated step-by-step, the particular walls are reaching different levels of deformations, and corresponding loading passing from elastic to inelastic range up to collapse state after assumed ductility is reached. When the first wall of story enters inelastic range the structural system of the story and its stiffness matrix are modified. From this point forward it repeats constantly from step to step of the calculation whenever the next wall reaches the elastic or ultimate limit state. The calculation result is expressed in terms of the story resistance envelope. In each calculation step, the level of reached ductility of walls can be presented graphically to get better insight in the distribution of the damages of walls.

Several basic assumptions are taken into account when the above described calculation method is used. The first basic assumption is the rigid diaphragm action of floors so that story displacements can be evenly distributed to all load-bearing walls in proportion to their stiffness. The next assumption is predominant first vibration mode shape with inverse triangular distribution of displacements over the entire height of the building. The third basic assumption is that the contribution of each wall to story resistance depends on the displacement imposed to this wall and its mechanical properties determined by resistance envelope. Although a wall fails in shear, it is still capable of carrying its share of gravity load acting on the story. The fourth assumption is the separate action of walls although they are connected along the height with perpendicularly positioned walls.

The codes require verification of structural system endangered by earthquake regarding its strength and ductility. Both are related to the capacity of structure to dissipate the seismic energy and to withstand the base non-linear deformations without losing its stability. In the verification of seismic resistance the design resistance of the building (SRC_d) is compared to the design base shear coefficient (BSC_d):

$$SRC_d \geq BSC_d \tag{1}$$

If it is fulfilled, the global ductility requirement should also be verified. The global ductility of building can be defined as ratio between the ultimate story drift and the drift at the elastic limit. Considering the definition of structural behaviour factor q and values given in Eurocode 8, the simple formula for deriving global ductility factor can be used:

$$\mu_u = 0.5\,(q^2 + 1) \tag{2}$$

In the case of unreinforced masonry structures, the values of q and μ_u are 1.5 and 1.6, respectively while in the case of reinforced masonry structures the values of q and μ_u are 2.5 and 3.6, respectively. The seismic resistance of building is sufficient according to Eurocode 8 if both criteria (Equations 1 and 2) are fulfilled. If the second criteria is not fulfilled, the design resistance

Design Methodologies for the Next Generation of Codes, Edit P. Fajfar and H. Krawinkler, A.A.Balkema, Rotterdam, 1997, p.p.323-334.

of building should be lowered until the ductility criteria is fulfilled. The described method is illustrated with the case study of a heritage building located in Ljubljana, Slovenia. The seismic resistance of the presented building was calculated following the above-described method using the latest version of SREMB program[8].

3. Case study

3.1 Description of the building and its strengthening

The last strong earthquake struck Ljubljana in 1895 with the magnitude of 5.8. In the twenty years to follow, many new buildings were built raising Ljubljana from a small provincial town to a regional centre. Buildings were constructed according to the Austrian codes and good building practice rules. Nowadays they still represent high quality masonry buildings, but their seismic resistance does not meet the contemporary demands. Therefore, in the process of their rehabilitation structural strengthening has to be performed. The renowned architect Jože Plečnik contributed to that period of development with his first designed building. Although the building (Figure 2) may not appear today as an attractive one, it represents a valuable heritage of the most important Slovenian architect who contributed to built heritage of Vienna, Prague and Ljubljana in the first half of the 20th century. The building was in university use since its establishing on 1919 and it will serve the same purposes after the current renovation.

The building is divided in two parts connected with entrance hall. The approximate length and width of the southern part's plan are 60 and 10.5m, respectively. The approximate length and width of the northern part's plan are 50 and 10.5m, respectively. The cellars are located only under the parts of the ground floor. The story heights of ground floor, first floor and attic are 4.3m, 4.1m and 4.5m, respectively. The original structural system of the building consists of clay-brick masonry walls and timber floors. The masonry walls are of the same width of 45cm in both ground and first floors. According to laboratory tests the compressive strength of bricks is in the range of 2.5MPa and estimated compressive strength of high quality lime mortar is about 1 MPa.

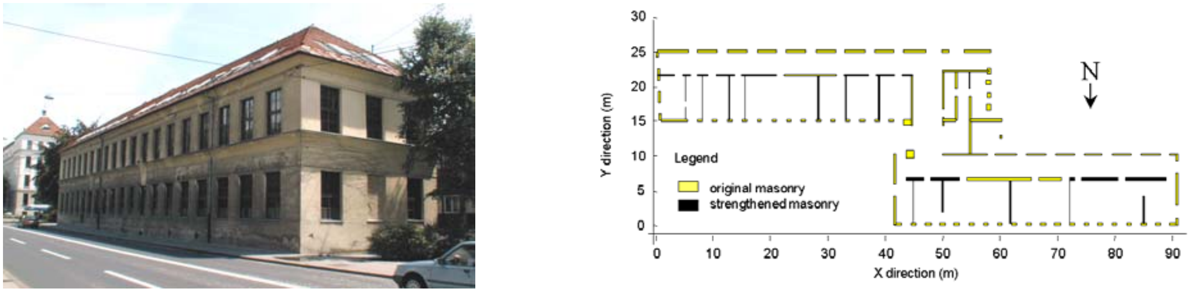

Figure 1: West-east view of building's northern part and layout of ground floor load bearing walls

The layouts of the plan show relatively low shear resistance of stories (Figure 1) judging by contemporary demands. This was proved by the pushover inelastic analysis using the above-described program SREMB. The shear resistance of the masonry building depends mainly on the number and position of the masonry walls and their strength, stiffness and ductility. The main problem of masonry walls is relatively low ductility that can be improved by reinforcing the walls or by coating them. Vertical and horizontal reinforced concrete ties usually confine walls. In the case of the herein-presented building, the horizontal ties will be placed above the load-bearing walls during the replacement of existing floor structures with the reinforced concrete slabs. Altogether

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[8] Building Construction under Seismic Conditions in the Balkan Region, Volumes 3, 5 and 6, UNDP/UNIDO Project RER/79/015, Occidental Press, Vienna, 1984.

four different cases were studied: the original layout of the existing unreinforced masonry walls, the original layout with several existing walls strengthened by both sided reinforced cement plasters, the original layout with several existing walls replaced either by new reinforced clay block masonry walls or reinforced concrete shear walls. The main mechanical properties of the existing unreinforced walls and new reinforced masonry walls are shown in Table 1. The material characteristics were obtained by laboratory cycling tests of masonry walls.

Table 1 Mechanical properties of clay brick/block masonry

Mechanical properties of masonry	Existing unreinforced wall solid clay brick	New reinforced wall hollow clay block
Compressive strength f_k [MPa]	2.00	5.00
Tensile strength f_t [MPa]	0.08	0.2
Modulus of elasticity E_w [MPa]	750	4500
Shear modulus G_w [MPa]	60	500
Ductility d_u	1.5	4.0

The layout of the ground floor and the position of new and strengthened walls is shown in Figure 1. The cement plaster of coated walls is planned to be 3cm thick on each side and reinforced with steel mesh fabric of 3.35 cm^2/m^2. The new reinforced clay block masonry walls were assumed 25cm thick and reinforced with two steel rods of 6mm in diameter. The reinforced concrete shear walls of cross section dimensions 20/250-cm were assumed, made of concrete with compressive strength of 40MPa. They will be reinforced with steel mesh fabric of 3.35 cm^2/m^2 with boundary columns reinforced with 20ϕ12mm (steel f_y=400MPa). The easiest method of strengthening is applying coatings to the existing walls. In the case of the presented building, this method gives sufficient results in terms of both strength and ductility demands according to Eurocode 8 and the old Slovenian codes (Figure 3). If the building was located in an area with expected higher earthquake intensity, methods that are more radical would be necessary. Therefore, the results of seismic resistance analysis for the existing building and the building with coated walls are discussed, and briefly compared with the results of the analysis of the building strengthened with two other methods.

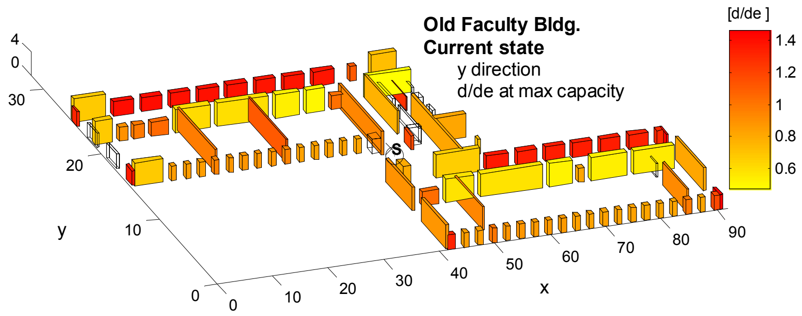

Figure 2: The distribution of deformation level of walls (building in current state)

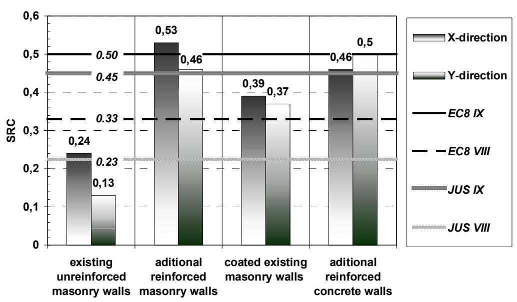

Figure 3: Comparison of base shear capacity of building strengthened with different methods

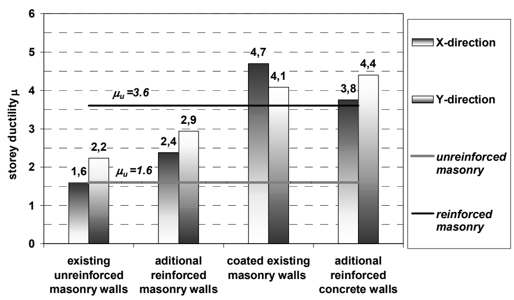

Figure 4: Comparison of base story ductility of building strengthened with different methods

4. Examples of safeguarding techniques

The concept of masonry rehabilitation includes a set of measures that establish stiff-box type response of building response on earthquake excitation. In most cases, the following technical measures are necessary to establish stability and earthquake resistance of masonry heritage building:

- Consolidation of foundations,
- Tying together the walls and floor structures,
- Strengthening of walls by grouting and/or cracks with injections,
- Strengthening of masonry vaults,
- Systematic renovation of the existing floor structures or replacing them with new, in-plane stiff diaphragms,
- Renewal of wooden roof structure, and
- Repair and strengthening of non-structural elements.

The different varieties of methods are present in safeguarding practice, from those that strictly follow the traditional crafts and techniques to those that fully introduce new, emerging materials. Recently, more attention has been paid also to the methods that slow down the progresses of building fabric deterioration by protecting them from decay or from the influences of moisture and other deteriorating agents. During last decades in Slovenia there have been different technologies developed or modified and improved using the results of on-site and laboratory experimental research supported by analytical research. One of the most significant contributions of Slovenian researchers is the development of the above presented performance-based method for the calculation of seismic resistance of masonry building.

4.1 Stabilisation of shallow foundations

Recently, the new combined technique for the consolidation of shallow foundations of heritage buildings and the prevention of masonry walls from raising damp has been developed[9]. The author of the method, Ivan Klaneček, was awarded gold medal of INPEX ® (Invention/New Product Exposition) in 2001 for bringing new product to the construction market.

There are many known solutions for the placement of moisture barriers in the level of wall to foundation contact. Some of them are based on the construction of horizontal diaphragm, which prevents capillary moistening of the walls from the ground. There exist some varieties, particularly in various technological solutions, for constructing a hydro-impermeable layer. Hover, the unsolved problem is how to stabilize an already greatly dilapidated lower wall without a real foundation, how to consolidate and then hydrophobias an existing building material to a suitable static result. The most common stabilization of walls without foundations has been the construction of the missing foundation in the ground. In case of poor, over moistened foundations, acting as conduit for moisture from the ground into the walls, the known technological procedures have been carried out by sawing and knocking out the walls and inserting hydro insulating tampons as the horizontal hydro insulation. These kinds of interventions are unfavourable in earthquake prone areas because they may influence the lowering of earthquake resistance of the entire masonry building. Therefore, the non-destructive methods of here-described type are more suitable.

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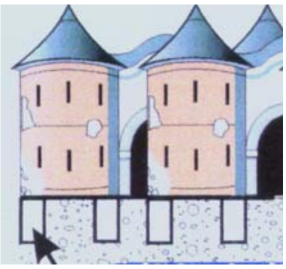
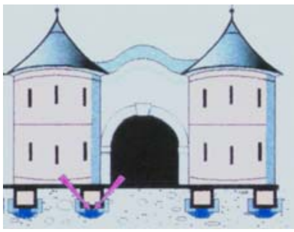
[9] Klaneček I., "Stabilisation and hydro-isolation of wall foundation", *The future of the city, new quality for life: abstracts*. Žarnić, R. (edit.), Ljubljana: UL FGG, 2001, p. 132-133.



Traditional stabilization



New approach to stabilization

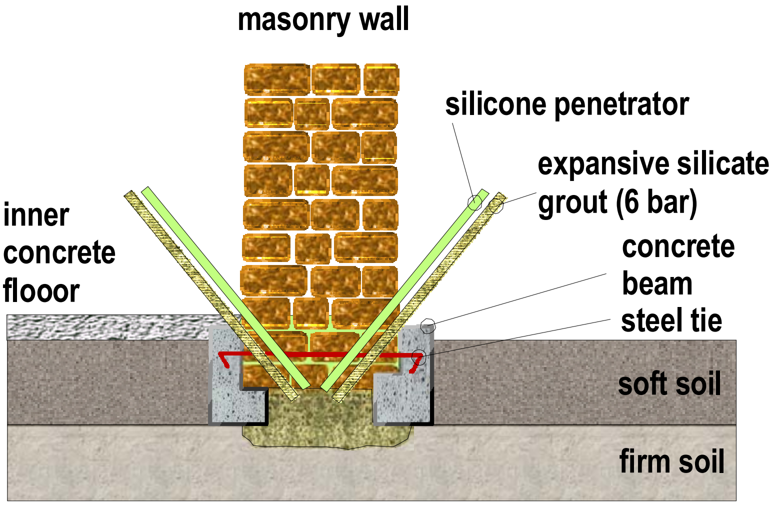


Figure 5: The scheme of the new method for the stabilization of shallow masonry foundations

Shallow foundation of heritage buildings constructed on locations with relatively good soil conditions are traditionally strengthened with additional reinforced concrete foundations constructed under the existing masonry foundations. The new method combines this traditional technique with grouting technique as can be seen from Figure 5. After the construction of reinforced concrete foundation jackets along the masonry foundation and aconnecting them by steel tie through it, the contact to the supporting soil is grouted. Grout is composed of mineral, expansive silicate mortar that is injected under pressure of 6 bars. The effectiveness of grouting is controlled by pressure measuring and control of tilt of the injected wall. The pressure achieved should be of the magnitude of stresses induced in soil due to vertical loading of the treated walls. The expansive grout fills up all the softened places in the wall as those under the foundation up to the hard-finish layer. After the first round of grouting that aims structural stabilisation of foundations, the second round is carried out to form the raising damp prevention barrier. Smaller pores or cavities may be completely filled up by silicon penetrators, which are permeable and water-repulsive.

4.2 Grouting of stone masonry

The most effective and economic strengthening of voided stone and mixed stone-clay brick masonry can be achieved by pressurised grouting. The grout material composition is often an issue of discussion between constructors and conservators. The main dilemma is related to the influence of chemical substances that are present in cement by its nature or because of the modification of cement grout modification. Well-known concern of conservators is related to sulphurous and alkali compounds and their influences on painted surfaces of heritage walls. Therefore, the grout producers are together with researchers trying to develop grouts that would meet the requirements of conservators. An example of the development of what are called “masonry friendly grouts” is described by Apih[10]. The composition of grout mix can be designed according to the specific problems to be solved by grouting. The stone masonry needs not to be injected by pure cement grout. Regarding strength demands, 60% of cement can be substituted by

[10] Apih V., Masonry friendly strengthening of the walls, International workshop CNR-GNDT (National Group for Earthquake Loss Reduction of Italian Science Foundation) on effectiveness of injection techniques for retrofitting of stone and brick masonry walls in seismic areas, Binda, L. (edit): Politecnico di Milano, March 30, 31 1992. [Milan: Department of Structural Engineering, 1992], p. 81-93.

fine sand aggregates of different origins. Reducing the quantity of cement, less stone masonry foreign material is introduced in walls. Hydrophobic additives that are added to the grout hinder the transport of water and water dissolved salts through porous structure of the grouted wall and help in drying out of walls.

The main purpose of grouting is to fill as much voids as possible. This makes stone masonry more homogenous and prevents movement of stone blocks and rubble during earthquake action. The needed strength of hardened grout is not too high because internal stresses induced in stone-to-grout interfacial surfaces are not high. That was proved by laboratory experimental research[11]. Stone masonry walls grouted with four different grouts were tested by cyclic horizontal load and constant vertical load (Figure 7). Although the mechanical properties of grout expressed in terms of bending and compressive strengths (Figure 8), the shear strength and stiffness of grouted wall did not differ significantly (Figure 9). The composition of four types of grouts is presented in Table 2 below.

Table 2 Composition of four types of grout (in % of mass) (a) and (b) are types of hydrophobic additives based on the salts of stearic acids

Grout mix	Cement	Pozzolana	Water	Quartz dust	Additive
A	52,9%	5,9%	41,2%	0,0%	0,0%
B	50,0%	5,6%	38,9%	0,0%	5,6 (a)%
C	38,9%	5,6%	33,3%	16,7%	5,6 (a)%
D	38,9%	5,6%	33,3%	16,7%	5,6 (b)%

Figure 6: Grouting of stone masonry

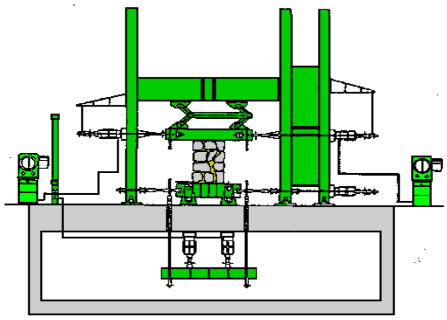


Figure 7: Cyclic testing of grouted stone wall

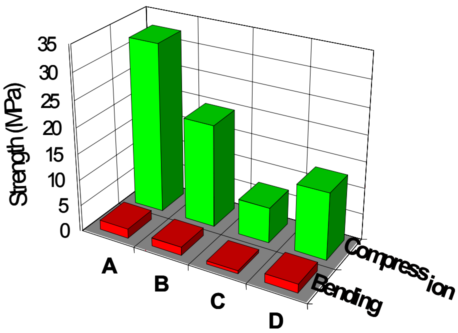


Figure 8: Compressive and bending strength of four types of grout material

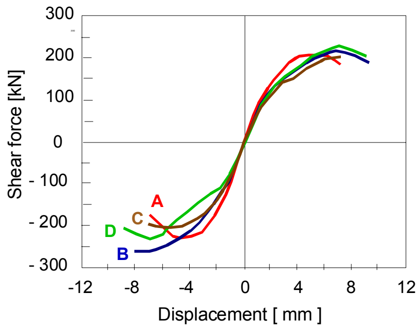


Figure 9: Shear strength - displacement relations obtained by cyclic testing of stone masonry walls grouted by four different grouts

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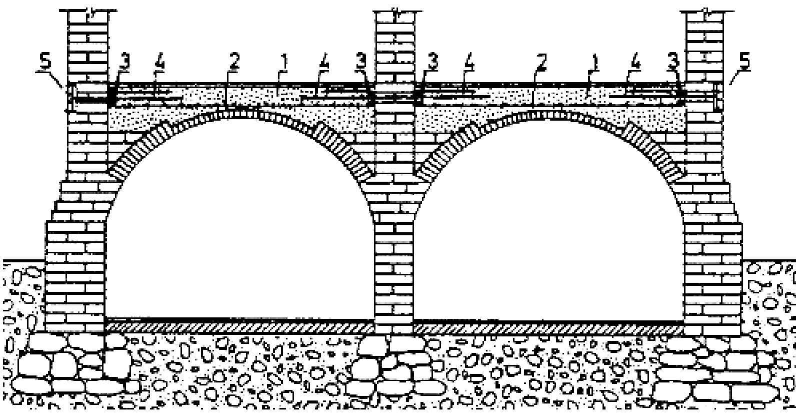
11 Tomaževič, M. "Laboratory and in site tests of the efficacy of grouting and tying of stone masonry walls". International workshop CNR-GNDT (National Group for Earthquake Loss Reduction of Italian Science Foundation) on effectiveness of injection techniques for retrofitting of stone and brick masonry walls in seismic areas, Binda, L. (edit): Politecnico di Milano, March 30, 31 1992. [Milan: Department of Structural Engineering, 1992], p. 95-116

4.3 Strengthening of masonry vaults

Masonry vaults are earthquake vulnerable parts of heritage buildings because of their slenderness and high masses added atop of them. Properly designed heavy gravel topping provides the regular distribution of compressive stresses along the central part of vault when they are loaded only with static actions. The additional horizontal action of earthquake disturbs the balance of stresses and even causes tensile stresses in different parts of vaults, which leads to cracking and further development of damages during the dynamic action of earthquake. Similar but slowlier developed damages can appear due to uneven settlement of foundations. Faced with the problem of earthquake strengthening of masonry vaults a simple method was developed combining laboratory experiments[12] and on site trials. Figure 10 shows a scheme of strengthened vault.

The gravel topping is replaced by lightweight foam concrete that can be produced at the construction site by mixing organic foam with standard concrete. The mechanical characteristics of foam concrete depend on the quantity of foam added to the concrete. For use on masonry vaults, the average density of foam concrete is about 1600 kg/m^3, with a compressive strength of 20 MPa. The recommended density of foam concrete is about the same as that of masonry walls, and no higher than density of gravel usually used for topping the vaults. The advantages of this material are workability, relatively low density with sufficient strength, and a low modulus of elasticity (3 to 4 times less than that of standard concrete)

Before the foam concrete is applied, the gravel topping has to be removed, the upper surface of the vault cleaned, and cracks and other defects repaired by the usual techniques. The foam concrete top ping should be reinforced by wire mesh. Minimal reinforcement is sufficient. The thickness of the topping above the highest point of vault may vary from the thickness of the vault to the thickness of the removed gravel topping. The wire mesh has to be placed about 30 mm above the vault, and fixed to the surrounding walls by steel anchors. It is recommended to use steel bars of diameter 16 mm to 20 mm on each 1.5 m to 2.0 m of surrounding walls lengths, anchored to the wall by means of rectangular steel plates and nuts. The usual length of the anchor steel bars in the foam-concrete topping is about 1.0 m. It is recommended to add the polypropylene or steel fibres to reduce the amount of cracks induced by shrinkage of foam concrete.



1 - foam concrete topping

2 - wire-mesh fabric

3 - longitudinal steel ties

4 - transverse steel ties

5 - anchor-plate

Figure 10: Strengthening of masonry vaults with foam-concrete topping

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[12] Žarnić, R.: "Strengthening of Masonry Vaults by Foam Concrete Application", Proceedings of the 1st International Seminar on Modern Principles in Conservation and Restoration of Urban and Rural Cultural Heritage in Seismic-Prone Regions, Skopje, 1988, pp. 375-381.

The behaviour of strengthened vaults was experimentally verified, by tests on two half-scale, one-bay masonry vaults, constructed using materials with prototype properties, and having a gravel topping. One was loaded gradually by a distributed vertical load and the other by a cyclic horizontal load (specimens O-1 and O-2 of Fig. 6). After severe cracks had occurred, the specimens were repaired by cement grouting of cracks and strengthened by reinforced foam-concrete topping, which replaced the gravel topping.

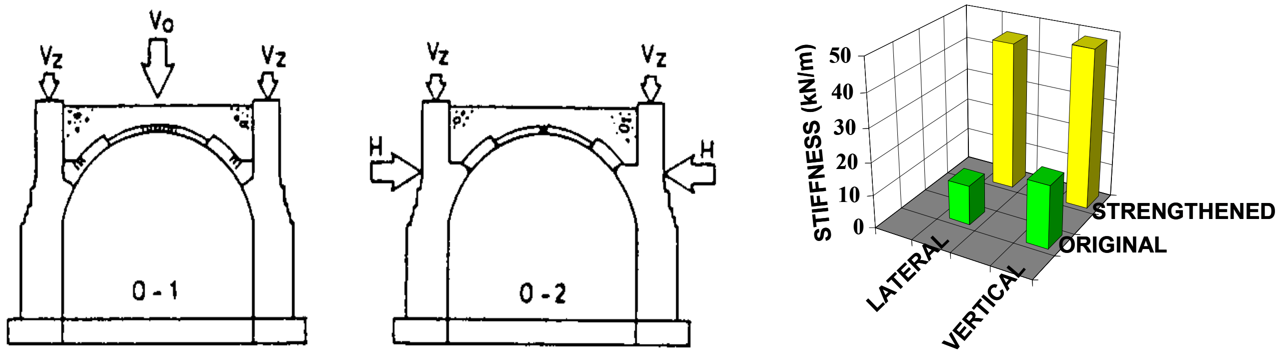


Figure 11: Crack pattern of original vaults tested with vertical and cyclic horizontal load at attained ultimate load and comparison of the attained stiffness of original and strengthened vaults

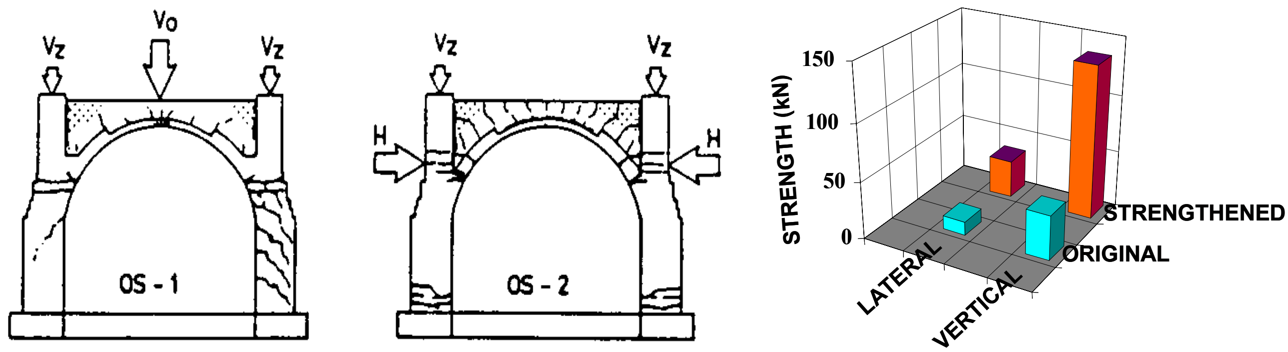


Figure 12: Crack pattern of strengthened vaults tested with vertical and cyclic horizontal load at attained ultimate load and the comparison of attained strength of original and strengthened vaults

By examining the relationship between the applied loads and the deformation and strains of masonry and reinforcement of the tested specimens, the failure mechanisms of the original and strengthened vaults were analysed. It was found out that the foam concrete topping has a great influence on the load-carrying capacity and stiffness of vaults, as well as on the entire behaviour of these structures, as outlined in Figures 11 and 12. In this particular case, the load-bearing capacity of the strengthened and vertically loaded specimen increased by a factor of 3.4; and in the case of the horizontally loaded specimen, by a factor of 2.3. The initial stiffness of the vertically loaded vault increased by a factor of 1.3; the initial stiffness of the entire laterally loaded structure was increased by a factor of 3.8.

The behaviour mechanism of the strengthened vaults was entirely different from that of the virgin vaults with gravel topping. Under vertical load, the first cracks in the vault with gravel topping developed at the top of the vault. By increasing load, additional cracks developed at the quarter-span, points where the cross-section of the vault changes, and at the supports of the vault (O-1, Fig. 11). No cracks or damage occurred in the supporting walls. In the case of the repaired and strengthened specimen, a different pattern of cracks formed. The foam-concrete topping behaved as a slab with a variable cross-section, fixed to the supporting walls. The first cracks developed at the mid-span of the vault due to bending, as seen from the measured strains of the wire mesh.

Internal forces at the fixed supports of the foam concrete slab were partly resisted by the steel anchors. Near the ultimate load, horizontal cracks developed in the supporting walls due to the action of bending moments. At ultimate load, shear cracks caused by the reaction forces developed in one of the supporting walls (OS-1, Figure 12). In the case of the virgin vault, the load-bearing capacity of the structure depended on the load capacity of the vault, whereas the shear strength of the supporting wall was the critical parameter of load bearing capacity in the case of the repaired and strengthened structure.

Horizontal cyclic loads caused cracks in the virgin vault O-2 nearly at the same places as in the case specimen O-1 (Fig. 10). The repaired vault with foam-concrete topping behaved as a frame with a stiff beam, with joints at the bottom of the supporting walls and at the supports of the vault. Cracks and damage occurred in the joints due to the action of bending moments. The reinforcement of the topping and the steel anchors prevented the collapse of the entire structure in the large deformation range. The reinforcement of topping significantly lowered the residual deformations of the strengthened specimen compared to those of the virgin specimen. While the load-carrying capacity of the horizontally loaded virgin structure depended on the strength of the vault, the capacity of the strengthened structure depended on the flexural strength of the supporting masonry walls. The mechanisms of crack and further damage developments were entirely different in cases of strengthened vaults in comparison to the original ones. The development of cracks in thin vault may result in collapse of entire vault during an earthquake, which is known from post earthquake observations of real buildings. The advantage of strengthening is development of cracks and damages in supporting walls what does not endanger the stability of vault itself and makes post earthquake repairing easier and less dangerous.

4.4 Microclimate control with wall heating

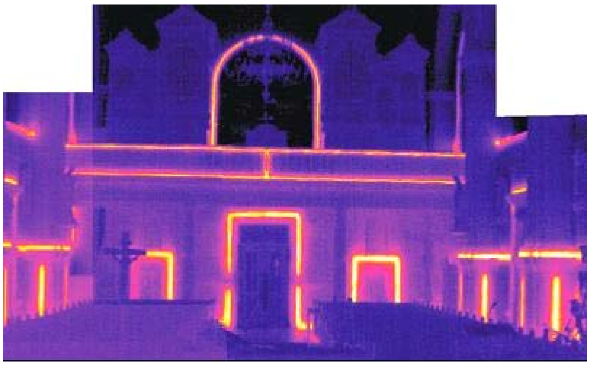
The structural strengthening of heritage buildings prevents them from suffering from exceptional load actions while another set of techniques is oriented to the prevention of building fabric from decay. The major concern is in diminishing of deteriorating influence of water in all its agregations. The contemporary techniques also aim at the improvement of thermal comfort in heritage buildings to make them more suitable for use. One of promissing methods that appeared in conservation about ten years ago is based on solving problems of thermal confort and moisture prevention by wall heating[13].

Wall heating (tempering) is an alternative approach to preventive conservation of masonry buildings built in cold climate. The heating pipes or electric wires installed below the inner wall surface offer many benefits: moderate heating of the building, good level of thermal comfort for occasional visitors, efficient use of energy, stabile indoor microclimate, warmer walls and prevention of damp raising in the walls. Wall heating reduces the need of restoration works due to less particles deposition on walls and exhibits. In addition, the system does not influence the earthquake resistance of the structure in comparison to the systems based on wall cutting. Engineering design of wall tempering system in massive buildings is based on slightly modified methods for space heating. The goal of these methods is to determinate energy demand and heating sources. However, when planning the wall tempering system, the task is more specific and focused also on solving local heat transfer and building physics problems.

The first goal is to determinate/plan the inner surface temperature (mean radiant temperature) of the heated walls. It contributes to the thermal comfort level and together with indoor air temperature determines the effective temperature perceived by the person standing in the space. For example, in large halls (churches, castles) the idea is to provide a thermal comfort for the users by a combination of moderate indoor temperature and a warm lower part of the walls along the

[13] Šijanec Zavrl, M. and Žarnić, R. “Wall heating for thermal comfort in building heritage. 18th International conference on passive and low energy architecture”, November 07-09, 2001, Florianópolis - Brazil. *Renewable energy for a sustainable development of the built environment: proceedings. Vol. 2*. V: PEREIRA, F. O. R. (edit.).Brazil: Organizing Committee of PLEA'2001, 2001, p. 781-785

height of a person. The second goal that can be met by detailed analysis of the temperature field within the building element is the mitigation of the cold wall effect and surface condensation risk. This risk is much more serious where the massive building is occasionally used, intermittently heated and where the users produce additional moisture. This happens most often in churches during the services.



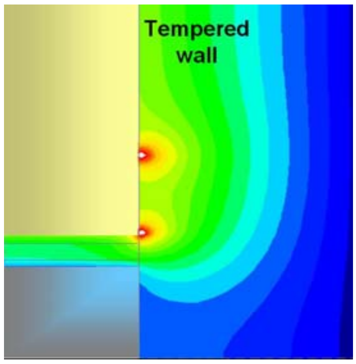


Figure 13 Thermo graphic picture of interior of parish church of St. Martin in Teharje, Slovenia after the installation of wall heating system (left) and the result of mathematical simulation of heat distribution in a wall tempered with two layers of ducts

The wall heating has been recently installed in three heritage buildings in Slovenia as reported by Šijanec Zavrl[14]. Slovenian researchers contributed to the development of the method with extensive on site monitoring of effects of wall heating and the development of mathematical simulation based on commercial software PHYSIBEL[15]

5. Conclusion

The presented examples of assessment approach and safeguarding techniques are not the only ones present in Slovenian practice, but they are most characteristic. All of them were either developed by Slovenian researchers or significantly upgraded and modified from original. The new techniques based on the use of emerging materials have not yet entered the Slovenian practice. The general opinion of experts involved in safeguarding of heritage buildings is in favour of developing new techniques based on traditional materials, the long term behaviour of which is more predictable, than to hurry with the application of not yet enough understood materials. The development of safeguarding techniques is supported with experimental research and development of mathematical models suitable for the simulation of interventions in heritage buildings.

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[14] Šijanec Zavrl M., Analysing indoor climate in building heritage in Slovenia, ARIADNE 7 Workshop, Indoor Climate and Tourism Effects, Prague, November 12-16, 2001

[15] PHYSIBEL, *Users Manual*, Maldegem, Belgium, 1999