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Strengthening techniques for masonry structures of cultural heritage according to recent Croatian provisions

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Abstract. The buildings of architectural and cultural heritage are mostly built with stone or brick wall elements, which are connected using limestone or limestone cement mortar, without a full knowledge of the mechanical properties of masonry structures. The compatibility of heritage masonry buildings with valid technical specifications and the rules for earthquake resistance implies the need for construction work such as repairs, strengthening or reconstruction. By strengthening the masonry buildings, ductility and bearing capacity are increased to a level, which, in the case of the earthquake design, allows for some damage to happen, however the structure retains sufficient usability and bearing capacity without the possibility of collapse. Comparison between traditional and modern techniques for seismic strengthening of masonry buildings is given according to their effects, benefits and disadvantages. Recent Croatian provisions provided for heritage buildings enabling deviation of technical specifications are discussed.

Keywords: technical provisions for buildings; masonry buildings of architectural heritage; strengthening techniques

1. Introduction

Natural hazards represent danger to many communities around the world. Earthquakes are one of the strongest and most destructive forces in nature (Rodrigues *et al*. 2018). Governments and academia in earthquake prone areas faced with a high concentration of population and urbanization are confronted with the assessment of seismic risk of building stock (Işık and Kutanis 2015, Işık 2016). The natural hazards approach is important for the development of disaster response systems as well as to ensure a state of preparedness and mitigation of disaster risk in accordance with sustainable development.

In recent years, there have been comprehensive researches that deal with earthquake assessment of cultural heritage in areas which are seismically active (Morić 2002, Ademović 2015, Aras and Altay 2015, Lacanna *et al*. 2016, Cakir and Kocyigit 2016 and many others). The main difficulties which may occur with seismic analysis of cultural heritage are as follows: complex geometry, heavy masses of masonry, high heterogeneity and anisotropy. This makes it an area of great interest for researchers (Preciado *et al*. 2015, Souami *et al*. 2016).

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Most buildings of cultural or architectural heritage are masonry buildings constructed mostly of stone or brick elements linked to limestone or limestone mortar without reinforcement. They were built before the existence of seismic provisions (Hadzima-Nyarko *et al*. 2017). During the lifetime of historical buildings, they have gone through various upgrades and suffered from disasters, such as fires, earthquakes or explosions. Existing masonry buildings can withstand the effects of vertical forces (self-weight and imposed loads) as well as horizontal wind forces. However, most of these buildings have not been designed for seismic loads and therefore need to be strengthened (Churilov and Dumova-Jovanoska 2013, Altunışık *et al*. 2016). Importance of historic structures' preservation as representatives of a certain period and their historic significance to the cultural heritage has to be emphasized and cherished. This is something that has to be passed over to new generations and the only way to do so is by preserving, rehabilitation and strengthening.

In the Republic of Croatia, which lies in seismically active Mediterranean-Trans-Asian belt, there is a long-standing experience in the renewal of damaged cultural heritage masonry buildings due to seismic actions (Hadzima-Nyarko and Kalman Šipoš 2017). The city of Dubrovnik, devastated by the 1667 earthquake, is even nowadays exposed to frequent seismic actions.

In many areas of the world, rehabilitation of historical unreinforced masonry buildings (URM) is of great importance. Those buildings serve as examples of human capability and development of the humankind throughout the ages (Pardalopoulos *et al*. 2016).

There are two extreme, diagonally opposite approaches, conservation and structural. On the one hand, the conservative approach assumes that the longevity of old

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buildings has itself been proven and that the intervention in terms of encroaching upon the capacity of the same is not required. On the other hand, the modern structural designers' view is that bearing structures should be secured in accordance with the new applicable regulations. Now it is believed that the right path is a combination of these approaches. All the actors should be involved: conservators, architects, engineers and owners. This is important as the characterization of an existing structure is a very complex task, which requires a specific multidisciplinary evaluation methodology for its assessment, as stated in the ICOMOS Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage (Ademović 2011, Ademović *et al*. 2016). It is advised that an integrated multidisciplinary approach be used for intervention on cultural heritage. This approach encompasses patrimonial, social and technical matters, and would culminate in distinct classes of buildings depending on the level of intervention needed (Ornelas 2016). For this reason, the preservation of historical monuments cannot have survival as its only goal, but rather incorporate multidisciplinary considerations within the approach. Aesthetics, character and architectural value of the monument should be taken into consideration when performing any work (Tzanakis *et al*. 2016).

2. Technical specifications for buildings in Croatia

Cultural heritage buildings are predominantly masonry structures, generally characterized by massiveness, high compressive strength, fire resistance, good acoustic and thermal properties, having various forms of construction, use and aesthetics. These features have ensured the long life of the cultural heritage buildings and their usability to this day. Over time, buildings are exposed to different predictable and unpredictable natural (wind, earthquakes, etc.) and other (chemicals, fires, warfare) actions affecting their durability. In addition to the above-mentioned actions, a significant contribution to the insufficient durability of structures is due to (Radić *et al*. 2008) insufficient attention being given to the durability during design planning, shortcomings during construction and irregular or inadequate maintenance during the construction use.

In addition to the lack of professional and scientific knowledge of builders who built the historic heritage buildings, it is necessary to consider the fact that the building material in time lacks its initial properties. Timely prevention and exclusion of damage that occurs over time, as well as, preventive and protective measures, ensures, through the maintenance process, a sufficient level of safety and usability of the cultural heritage buildings.

The recent Croatian specification (Croatian Technical Specification for Buildings (Official Gazette (OG) 17/2017)) includes the mandatory application of HRN EN 1993-1-3: 2011 regulating how to restore and reinforce all types of buildings. This category also includes cultural monuments (undamaged or damaged due to earthquake). The standard gives a lot of freedom to the designer/constructor for decision making, in agreement with the investor and other participants (architects, conservators), how to proceed with respect to earthquake hazard, residual life, purpose, architectural and conservation restrictions, etc. This is the novelty and a new feature in the earthquake analysis of resistance of cultural monuments.

How to deal with cultural monuments that do not meet today's requirements with regard to building safety and earthquake activity was not resolved until the adoption of the HRN EN 1998-1-3: 2011.

Recent Croatian Technical Specification for Buildings (OG 17/2017) consist of chapters: General Rules, Special Rules for Concrete Structures, Special Rules for Steel Structures, Special Rules for Composite Structures made of Steel and Concrete, Special Rules for Timber Structures, Special Rules for Masonry Structures and Special Rules for Aluminum Structures.

Maintenance of structures is carried out using the rules given in the Croatian standards, and they are listed in Annex II of the Technical Specification.

During the service life of the building, certain technical properties of the building must be preserved. Regular maintenance is a set of preventive measures aimed at ensuring the permanent retention of the building's usability. In the case of accidental events that have a negative impact on the structure, extraordinary maintenance is prescribed.

Regular inspections (basic, main and supplementary) are part of regular maintenance procedures. The general state of the structure is determined by implementation of the basic inspection, by checking the available documentation and by visual inspection of the main structural elements. Main inspections determine the state of the structure and materials. The technical specification stipulates the time interval between inspections: 1 year between basic inspections, 10 years between main inspections for the building and 5 years for bridges, towers and other engineering structures.

Additional inspections are prescribed by special rules for specific types of structures. For structures where during the construction inspection it was noted that it does not satisfy the technical specification, in accordance with which they have been designed and constructed, it is necessary to conduct certain construction works (repairs, rehabilitation, adaptations, reconstruction) to bring them to a required minimum or eventually to the removal of the structure.

European and Croatian standard HRN EN 15989:2012 Preservation of cultural heritage defines the term cultural heritage as: "material or non-material entity of significance to current and future generations ".

The term "cultural heritage", according to UNESCO, may include three components: monuments, groups of buildings and sites (UNESCO 1982). UNESCO World Heritage List has so far 832 protected cultural heritage entities, among which the most numerous are cultural heritage structures.

In Croatia, out of 9 entities from the UNESCO tangible heritage list, 6 are in the category of "building groups": the historical complex of Split and Diocletian's palace, the old city of Dubrovnik, the Euphrasian basilica complex in the historic center of Poreč, the historic town of Trogir, the St. Jacob's Cathedral in Šibenik and the defense systems of the


(a)

(b)

(c)

(d)

(e)

f()

Fig. 1 UNESCO tangible heritage list 6 are in the category of “building groups”: (a) Diocletian’s Palace in Split; (b) Dubrovnik, the historical core; (c) Euphrasian basilica in Poreč; (d) Historic town of Trogir; (e) St. Jacob’s Cathedral in Šibenik; (f) Defense systems in Zadar

Republic of Venice from the 16th and 17th centuries in Zadar and Šibenik (Fig. 1).

Two monuments on the World Heritage List from Bosnia and Herzegovina are: Mehmed-paša Sokolović Bridge in Višegrad and The Old Bridge in Mostar.

All of the above-mentioned buildings have been constructed by traditional masonry techniques made of stone and/or brick elements.

With the aim of preserving what one inherited from the past, and what one is creating today, and what one will give to future generations, the Law on the Protection and Conservation of Cultural Goods, Official Gazette 69/99, lays down provisions on the establishment of protection of cultural goods, protection measures and the preservation of other issues related to the protection and preservation of cultural goods. This Law prescribes that:

- the owners and holders of rights of use are the ones responsible for the protection and preservation of cultural goods

- all physical planning documents must conform to a conservation background that contains a system of general and special protection measures

- the Ministry of Culture is responsible for all administrative, professional and inspection activities for the protection and preservation of cultural goods, which can only give authorization to specialized legal and natural entities for maintenance and renewal purposes.

According to the Construction Law (OG 153/2013) each building must be designed, calculated, constructed and maintained in such a way that it complies with the seven essential requirements according to EU Regulation 305/2011.

Basic requirements are presented in Fig. 2.

Fulfillment of the essential requirements is not always possible during the reconstruction of cultural heritage buildings as they were built prior to the adoption of the Law on Construction. For the reconstruction of buildings registered in the Cultural Property Register, deviations from

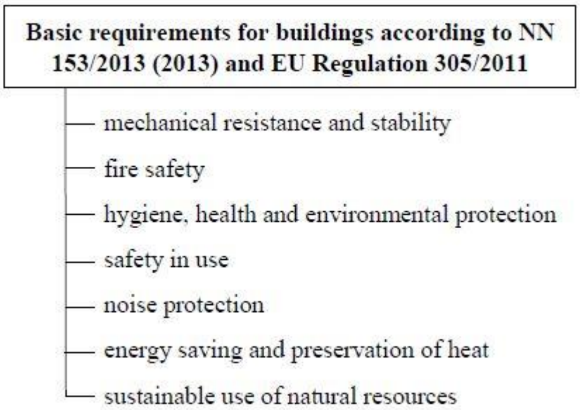

Fig. 2 Basic requirements for buildings

some essential requirements are allowed, with the prior consent of the Ministry of Environmental Protection and Physical Planning.

Aging, deterioration and damage of civil engineering structures is a permanent process, and analogously the need for their maintenance and renewal is mandatory.

The traditional and non-engineering construction of old masonry buildings provokes doubts regarding the assessment of residual capacity, mechanical resistance and stability, building quality and safety in general. Additionally, with the assumption of a possible earthquake effect, one faces a complex problem and a complex decision regarding the selection of measures and actions that should and could be taken in the maintenance and renewal processes.

3. Behaviour assessment of cultural heritage buildings

At the time of the traditional construction of most of the old buildings, the usual actions were considered, however at

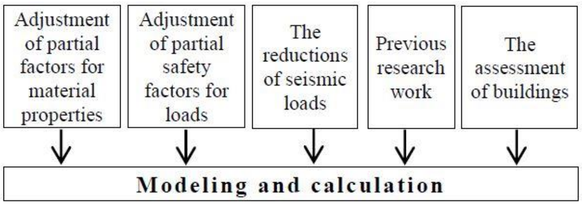

Fig. 3 Behavior assessment of the masonry cultural heritage buildings under seismic actions

Table 1 Levels of earthquake vulnerability according to Sorić (2016)

Level	Vulnerability assessment	Assessment parameters
I	very fast	structure age structure typology
II	longer	structure age structure typology structure geometry
III	long-term	detailed structure geometry mechanical properties of materials

that time there were no building codes, so seismic actions were not taken into account. Numerous earthquakes, due to this fact, but also due to lack of maintenance and/or poor reconstruction, have recently caused inadequate behavior and significant damage to historic masonry buildings. The occurrence of an earthquake in these cases led to situations requiring significant repairs, which could have been avoided or reduced to a minimum if structures had been designed in accordance with the aseismic rules and philosophies.

However, without seismic design, most of the time structural components of masonry structures, which were exposed to earthquake actions were mechanically damaged. Due to the separation of the links between the loadbearing elements, permanent deformations and displacements occur, the advancement of which initially destroys the weakest parts, and this ultimately can lead even to the demolition of the whole building. The avoidance of this scenario in order to protect human lives and tangible assets in cultural heritage buildings depends on the preservation of constructional, architectural and cultural values.

Standard EN 1998-3:2005, accepted as the Croatian standard HRN EN 1998-3:2011, Design of structures for earthquake resistance, Part 3: Assessment and retrofitting of buildings, provides criteria for assessment of the behavior of existing buildings during an earthquake and sets criteria for designing repair measures and gives guidelines for the selection of necessary correctional measures and strengthening procedures. The value of the chosen solutions, methods and procedures for cultural heritage buildings must not exceed the value of the building as a cultural property. According to this standard, and according to Aničić (2000), the procedures preceding the modeling of old buildings and the assessment of their behavior under seismic actions are shown graphically in Fig. 3.

Previous research works include collecting the data about such a building: the year of construction, the applied regulations, the quality of materials from the construction time, the estimation of the remaining economic value, the data of recorded old damages, previous repairs and/or strengthening, data on the building behavior in previous earthquakes or other extraordinary circumstances etc. The engineer can get a complete picture of the building's condition by conducting visual inspection, and, if necessary, carrying out or commissioning investigations works.

The assessment of the building's condition may be done with the aim to conduct strengthening and/or repairing of the building's structural system or assessing the vulnerability of a group of buildings in the event of a possible occurrence of an earthquake. Determining the state of the loadbearing structure of a building implies, for an intended lifetime, an estimate of the resistance capacity of an existing damaged or undamaged structure exposed to the usual and expected possible seismic actions. Due to the shorter remaining life of the building and higher insecurity, it is permissible to change the value of the actions and the safety coefficient in relation to those that are valid for new buildings.

Vulnerability assessment of a group of buildings is based on an assessment of the seismic risk. Seismic risk is often, when it comes to old buildings, more a result of high vulnerability of buildings than a result of high seismic hazard. The consequence of the earthquake is the damage that depends on the magnitude and frequency of an earthquake, vulnerability of a building and its exposure. Estimated damage is expressed in terms of expected economic loss, possible consequences on people (wounding, death) or physical damage to property.

According to Sorić (2016), there are three levels of vulnerability assessment (Table 1).

In determining the permissible vulnerability of cultural heritage buildings, besides the safety of structural elements, the safety of elements and parts of a building having a cultural and historical value (capitals, frescoes, vitreys, etc.) must also be included.

The reduction of seismic actions, in relation to the prescribed one, is permitted for some old buildings, in cases (Aničić 2000):

a) when the residual lifetime of the building is determined to be shorter than the mean return period of the strong earthquake

b) when strengthening is needed for future seismic action effects or renewal after earthquake damage in a large number of buildings of an urban entity, and the state cannot economically support the required level, although this level is below the prescribed (European) standard

c) when the application of the prescribed design ground acceleration on the building-monument would cause such structural construction works which, from the point of view of protection of the monumental properties, is unacceptable.

The assessment of the capacity of traditionally constructed masonry structures requires the adjustment of partial factors for material properties. According to HRN EN 1998-1:2011, for assessment of the earthquake resistance the characteristic strength values of materials are used and reduced by the partial factors for materials of the masonry γ_M.

The values of partial factors of safety for masonry are determined based on the category of performance control and execution control. For the existing buildings, it is permissible to use the nominal value of the material's strength as the design value if it is based on previous experience or experiments conducted regarding the strength of the masonry structure. The use of the design values for the strength of materials on the already constructed building is permitted if an original design and execution documentation exists, if there are no changes in the strength of materials or signs of inadequacy, and if the results of *in-situ* test confirm the previous assumptions (HRN EN 1998-3:2011).

In case of non-fulfillment of all three conditions, an assessment of material's strength is carried out by conducting experiments or comparing with the standards that were in force at the time of construction.

Tomaževič (2000) recommends, in calculating the seismic resistance of old masonry buildings, the following experimentally obtained values of partial safety factors for materials γ_M:

- γ_M = 1.0 when in a given area and for a given type of masonry mechanical properties are determined by *in-situ* or laboratory testing on samples taken from the existing masonry structure
- γ_M = 1.2 when the characteristic values are obtained based on literature data, and when the masonry type identification is performed by removal of the plaster and opening of the walls
- γ_M = 1.7 when characteristic values are determined on the basis of literature data, but without performing identification tests.

For the calculation of the limit states, the values of partial safety factors for action, γ_F, according to HRN EN 1998-1:2011 are selected with respect to the action (favorable/unfavorable). When calculating seismic actions for existing buildings, higher values of partial safety factors are used. In this way, account is taken of the inadequacy or uncertainty of the calculation model, and in the case of damaged structures, the inadequacy of the model.

During the modeling procedure of old structures, it is necessary to take into account the possibility of stiffness change of the structural elements and floors (in their own plane) with respect to the original ones. Ductility can also be changed due to occurred earthquakes or permanent degradation of the structure, as well as change of the load bearing system due to damage and executed works. For the needs of the model, it is necessary to carry out the measurements of the structure according to its actual state.

Calculation of seismic resistance of masonry structures can be carried out on the appropriate model. Linear static and multimodal analysis are used, as well as non-linear static analyzes, of which the most common one is Pushover Analysis.

4. Principles of aseismic protection of cultural heritage buildings

Any serious approach for the maintenance and restoration of masonry cultural heritage buildings, apart from knowing the structural behavior, should respect and understand their historical and cultural characteristics and values. Such an approach requires a methodology that implies a series of gradual and interconnected actions aimed at ensuring sufficient load capacity and extending the service life of such masonry buildings.

Fig. 4 Arena in Pula, today

Earthquake resistance of existing buildings is the basis for deciding on their rehabilitation or strengthening. Seismic resistance calculation of historical buildings is carried out in the case of the largest expected earthquake, causing only reparable damage but not large artistic damage. The expected service life in the calculation of seismic resistance of historic buildings is significantly longer than for ordinary buildings.

Provisions applicable to ordinary buildings apply to historic buildings only if their application has no negative effects on the preservation of cultural and historical value of the building. Conservation requirements are achieved by the proposed intervention techniques that must meet the following criteria (Aničić 2000):

a) efficiency - which must be proven by quality and quantity,

b) consistency - with the original structure and materials from chemical, mechanical, technological and architectural standpoint,

c) durability - which must be ensured by the use of materials and techniques that are durability comparable to those built in the building. If an occasional replacement is foreseen, the shorter duration is acceptable,

d) reversibility of the procedure - if in the future there is another better decision, the previous technique can be removed.

Depending on the significance of the building, the quality of the construction material and its general condition, it is necessary to take into account the feasibility of the operation and the availability of the appropriate technology and qualified labor.

Safety, usability and vulnerability of the building depends on the actual earthquake resistance of the structural system. However, often in cultural heritage buildings, there are doubts about the decision of giving priority to structure safety or the architectural and artistic integrity of the building.

The dilemma can be solved by cost-benefit analysis, whereby the gain increases the safety of the building, and the cost of architectural integrity. Reasonable and realistic consideration of the problem leads to a decision that will ensure a good seismic behavior of the entire structural system and satisfy the cultural and historical criteria.

An example of unreasonable consideration and solution of the problems of cultural heritage buildings is indisputably the architectural and cultural treasure, Arena in Pula (Fig. 4). Due to inadequate repairs and concreting in the basement, Arena lost the necessary conditions to be listed on the UNESCO World Heritage List. Considerable resources for reconstruction and maintenance were used, and today the state of the structure is such that certain parts are threatened to collapse.

5. Reconstruction and strengthening techniques

A good seismic behavior of the entire structure is the basic aim of strengthening and/or renovating of the existing masonry buildings. This is achieved by operations that increase the resistance and ductility and ensures adequate dissipation of energy. Based on the observed damage, the basic structural defects are defined, and the procedures and techniques will be determined, with the goal to (Čaušević and Rustempašić 2014):

- reduce the seismic effects by limiting the transmission of energy to the foundations or only to individual, sensitive parts of the building, through the control of the percentage of dissipated energy, so that the structure absorbs only a part of the energy, in accordance with its resistance
- reduce induced forces, by reducing the mass, especially at the highest level
- increase the bending strength of masonry by vertical and horizontal connections
- improve the loadbearing capacity of the foundation by expanding the foundation or enabling some kind of support
- strengthen the existing structure by selecting appropriate materials and/or adding new structural elements
- eliminate unaccepted changes in certain elements (cracks, weak mortar).

The size and type of the procedure and the technique to be applied to the building depends on the actual earthquake resistance, significance, type and purpose of the building. The process of reconstruction and/or strengthening should be directed in such a way that the principles of selectivity and consistency in the selection of priorities and the comprehensiveness of respecting historical values and scientifically based interventions are comprehended.

Methods for strengthening and/or restoration of historic masonry structures can be grouped as (Tomaževič 2000):

- those that renew and/or strengthen the walls in order to increase the resistance of the existing wall (glueing, injection, shot concrete, prestressing, wrapping, complete replacement of elements):
- those that increase the resistance of the entire structure (addition of new walls in the weak direction, shrinkage-connection of walls, ties, clamps)
- those that establish the spatial stiffness of the entire structure, i.e., it prevents the movement perpendicular to the plane (interconnection of the walls, interconnection of the walls and floors - tie beams, reinforced concrete frames, prestressed steel frames).

The renovation and/or strengthening of the cultural heritage buildings can be carried out using traditional and/or modern strengthening techniques or by combining them. There is a large selection of both techniques, as well as attitudes about what would be, in terms of the type of structure or damage, more suitable for use.

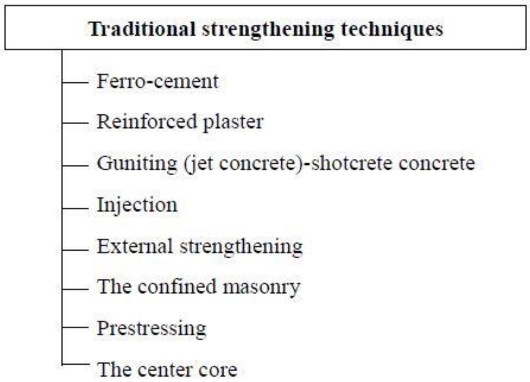

Fig. 5 Traditional strengthening techniques of masonry structures according to El Gawady and Lestuzzi (2004)

6. Traditional strengthening techniques

Traditional strengthening techniques (El Gawady and Lestuzzi 2004) of cultural heritage masonry buildings are shown in Fig. 5.

The strengthening of masonry surface is most often performed with ferro-cement, reinforced plaster and guniting or shotcrete.

Ferro-cement is characterized by high elasticity and resistance to crack occurrence. Its tension resistance is equal to the carrying capacity of the reinforcement itself. In the case of compression load, the carrying capacity of this technique depends on the ratio of reinforcement and mortar in the cross-section, and on the cross-section orientation. The mesh helps to limit the movements of wall elements after cracking and increases the capacity of non-elastic deformations in-plane of the wall. Static cyclic experiments on the walls reinforced by this technique showed significant lateral in-plane resistance of the masonry (Abrams and Lynch 2001). This technique increases the ratio of height and thickness of the masonry, which improves the out-of-plane stability of the masonry.

Reinforced mortars increases the ductility and shear resistance of masonry, reduces stresses and ensures better control of cracking. Mechanically, the most resistant mortars are cement-based, reinforced with nets or fibers. The improvement in the strength of the masonry depends on the thickness of the cement mortar layer, the amount of reinforcement and the means for its binding to the wall, which is being rehabilitated, and the degree of damage to the walls. Compatibility with original materials of the wall increases the durability of the wall, and a more efficient response of the wall strengthened by this technique to the earthquake-induced seismic actions is achieved (Marques *et al*. 2014).

Guniting (jet concrete)-shotcrete significantly contributes to the improvement of dissipation of seismic energy due to the successive extension and relaxing of reinforcement and lateral resistance of masonry. The thickness of the concrete layer can be adapted to the seismic requirement, i.e., the required lateral resistance. According to Abrams and Lynch

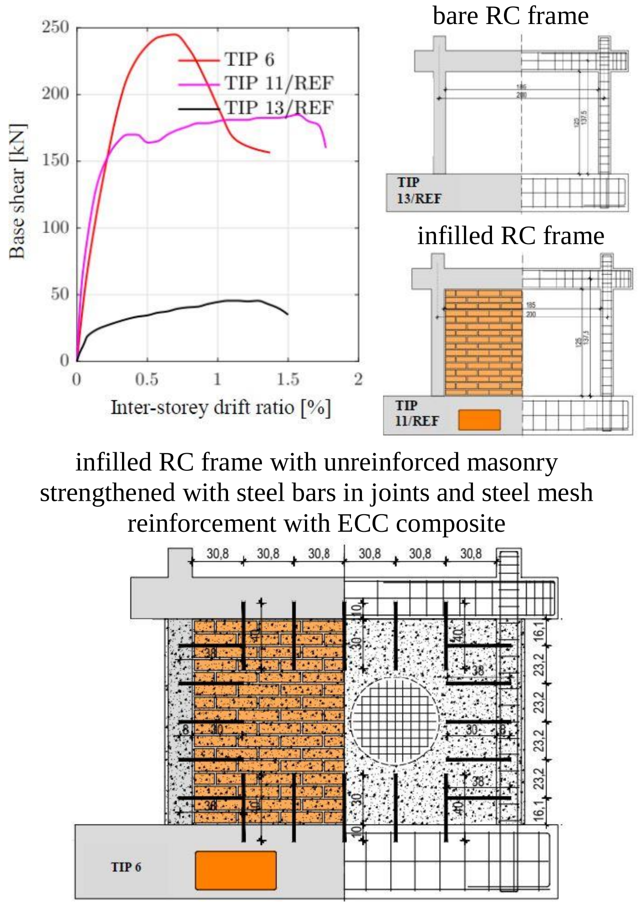

Fig. 6 Comparison of strengthening of infilled frames (Grubišić 2016)

(2001), the smallest layer thickness is 60 mm. The transfer of the shear stresses to the surface of masonry is ensured through the connections embedded in the walls.

This strengthening technique affects the physical properties of masonry, substantially limiting the vapor permeability, which should especially be taken into account in the old damp buildings.

Injection is generally effective as a strengthening technique in increasing the initial stiffness and masonry strength. By filling the cavities and cracks, masonry restores its integrity, equalizes its stiffness, and increases bending and shear strength. Masonry strengthened by injection has significant lateral deformability and better ability to dissipate seismic energy.

Injection efficiency in terms of improving the mechanical properties of masonry depends on physical and chemical compatibility of the mixture that is being injected with the existing masonry.

A cementitious injection mixture is suitable for filling larger voids and cracks, while for relatively small cracks (less than 2 mm wide) more efficient injection is with epoxy resins (Calvi and Magenes 1994, Schuller *et al*. 1994).

External strengthening with steel plates and/or bars/pipes provides relative stiffness to the structure and ensures seismic cooperation between the structural elements (Fig. 6). Increasing of masonry's lateral resistance is limited at the ends due to the resistance of the perpendicular wall, followed by vertical wrapping. Vertical and diagonal support improves the lateral plane resistance and significantly reduces bucking (Taghdi 2000). In the case of an earthquake, on such a supported and reinforced structure, cracks are expected, but the system of masonry and steel reinforcement, will remain effective and sufficiently rigid. Steel reinforcements ensure a satisfactory mechanism of energy dissipation and good control of lateral displacement (Fig. 6).

The confined masonry is performed with the aim to increase the deformability, that is, to improve the bending and shear strength in-plane of the wall. The efficiency of the confined masonry on the old wall depends, largely, on the relative stiffness between the existing walls and the frames, and less on the material properties. Prior to cracking of the wall, contribution of the confinement can be neglected, but the lateral deformability is improved. In addition to preventing the disturbance of the whole masonry wall and improving ductility, this technique also increases the ability of seismic energy dissipation, but its effect is limited when it comes to increasing the total resistance of the building (Zezhen *et al*. 1984, Chuxian *et al*. 1997). After a devastating 1969 earthquake in Banja Luka, Bosnia and Herzegovina, only masonry structures constructed as confined masonry retained its stability and integrity.

Prestressing improves the final behavior of the walls in-plane and out-of-the plane. It ensures a significant increase in strength and ductility of the walls and an even distribution of loads and cracks. Prestressing has three positive effects: a) decreases the eccentricity of the resulting force in the cross-section which is a result of horizontal forces; b) ensures a ductile behavior of the bending of the exposed cross-section due to the presence of reinforcement in the tensile zone and allows for longitudinal forces of high eccentricity in complex, stone-reinforced, cross section; c) increases the resistance of the wall to the effects of horizontal forces.

Vertical prestressing, which is explained in detail in the works done by Aničić (1982, 1983, 1988, 1992, 1994), was applied as a successful strengthening technique of cultural heritage, especially for Croatian belfries damaged during the earthquakes in Dubrovnik.

In the past, three belfries were built in the city center of Dubrovnik (Fig. 7): The Town Belfry (right) measuring

Fig. 7 Three belfries in Dubrovnik which were reinforced using vertical prestressing

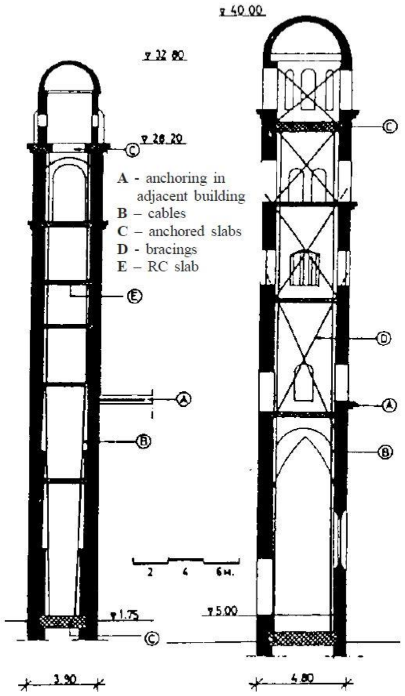

Fig. 8 Vertical cross-section with a scheme of the strengthening of the Town Belfry and the Franciscan belfry in Dubrovnik (Aničić 1988)

3.8×3.8×31.3 m, Belfry of the Franciscan Monastery measuring (middle) 4.8×6.4×36.5 m, and Dominican Monastery Belfry (left) measuring 4.5×4.5×37 m. In previous catastrophic earthquakes, the belfries had experienced partial demolitions in their upper parts and were later remodeled. They were again lightly damaged during the earthquake of 1979.

In each corner of the belfry, a single cable is placed symmetrically in relation to the vertical axis; amounting to a total of four, due to which the belfry is vertically overlaid (Fig. 8). The cables end up on the bottom and the top of the anchor plate (reinforced concrete slab with a thickness of 40 to 60 cm) over which compressive load is transferred to the walls. The cables bring axial force into the belfry; this force equals the weight of the belfry at the bottom. In Dubrovnik belfries, the total prestressing force in the belfry was 4000 kN. This process minimizes the interference on the existing structure as well as meets the aesthetic and safety requirements (Aničić 1982, 1983, 1988, 1992, 1994).

Vertical prestressing is more suitable for increasing the strength and ductility of slender old masonry structures than horizontal prestressing, and the level of strengthening depends on the level of the prestressing force. Greater initial prestressing force ensures greater lateral resistance and increases ductility. For slender old masonry structures Preciado *et al*. (2016, 2017, 2018) suggest a medium prestressing level which increases the bending and shear resistance without reducing ductility.

Besides prestressing being performed with steel tendons, masonry heritage buildings are now being prestressed with tendons made of Shape memory materials, NiTinol (Nickel-Titanium) and other modern materials. The super elastic behavior of the NiTinol material is used in the earthquake retrofitting of cultural heritage buildings. This material can be subjected to large deformations in loading and unloading cycles without permanent deformations forming a loop representing the dissipation of energy (Preciado *et al*. 2017).

The center core technique with its homogeneity and central position in the existing wall provides a strength capacity that is sufficient to withstand loads acting in-plane and out-of-plane of the masonry wall. Masonry wall strengthened by the center core, exposed to cyclic stresses according to Abrams and Lynch (2001), has a two times higher seismic resistance than the unstrengthened one.

The disadvantage of this technique is the tendency of creating a zone with very different and variable stiffness and strength.

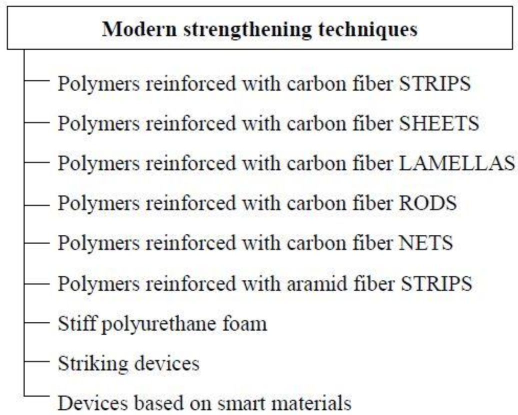

Fig. 9 Modern strengthening techniques

7. Modern strengthening techniques

Modern techniques to strengthen the historic heritage buildings represent different types of composite polymers and devices of specific use and function (Fig. 9).

Fiber reinforced polymers (FRP) are composites of at least two layers of fine continuous fibers and a polymeric substrate that connects them (epoxy resin, polyester, vinylester). Most commonly used fibers are: carbon fiber reinforced plastic (CFRP), aramid fiber reinforced polymer (AFRP), glass-fiber reinforced polymer (GFRP), and natural fibers of cellulose and agave. Composite fibers take over the load (they are the carriers of strength), while the substrate ensures the load distribution between the fibers and protects them against adverse environmental and mechanical damage. In addition to the material characteristics, the composite efficiency is directly influenced by the matrix system, interlayer area and fiber orientation.

Depending on the purpose, composite polymers may be thin, in the form of strips, lamellas, sheets and nets, or rods and strips of square or round cross-section.

Methods of strengthening and/or restoration of old buildings, especially seismic strengthening, require the use of high-quality materials, which, with their mechanical characteristics, strength and rigidity, besides rehabilitation need to ensure stability and durability of masonry. The main

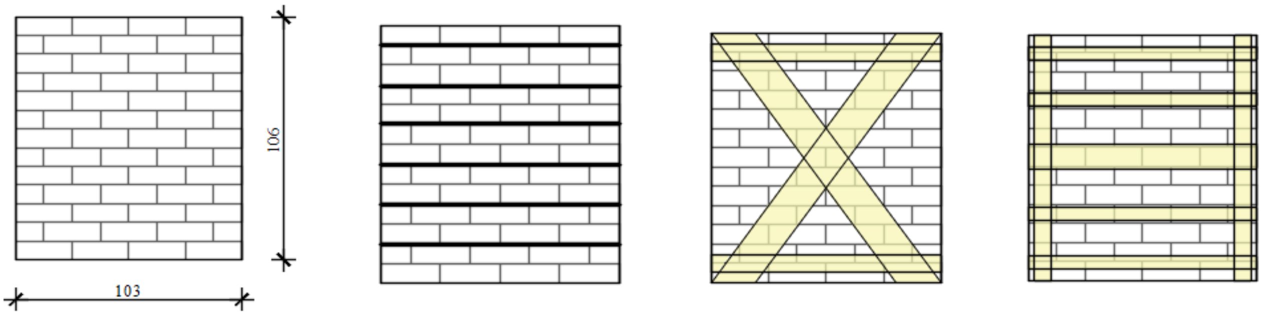

Fig. 10 Type of strengthen masonry walls (Galić and Sorić 2007)

characteristics of composite polymers are easy handling and transportation, good properties in terms of material fatigue, high tensile strength in the direction of fibers, suitability for processing, extraordinary corrosion resistance (corrosion insensitivity), good behavior under dynamic load, small specific weight, non - conductivity of electric current and neutrality of magnetism and good ratio of stiffness and self-weight compared to conventional materials (Čaušević and Rustempašić 2014).

Compared to steel, FRP has a higher strength of 10 times and it is 15 times lighter, while compared to aluminum it is 8 times stronger, 2 times stiffer and 1,5 times lighter (Čaušević and Rustempašić 2014).

An increase of overall masonry capacity is established by placing vertical, horizontal and diagonal fiber-reinforced polymers on an existing masonry wall and by glueing and/or anchoring,.

Testing of masonry walls (built using old wall elements consisting of solid brick, dimensions 12/6.5/25 cm, which were obtained from the demolition of an old building built in 1941) reinforced with FRP that were performed in the work of Galić *et al*. (2007) showed a significant increase of bending bearing capacity in-plane and out-of-plane of masonry wall, as well as an increase in shear load capacity.
For the reinforcement of samples, ribbed steel bars of diameter Ø 6, with a declared yield limit of f_y=500 N/mm^2, and GFRP #2 bars were used. Fiberglass strips and fabrics were used to reinforce the samples. The types of tested wall samples are (Fig. 10):

a) Unreinforced wall - a masonry wall made of solid bricks in the mortar (Fig. 10(a))

b) Wall reinforced with steel rods - Ø 6 reinforcing bar placed into alternate mortar layers (Fig. 10(b))

c) Wall reinforced with diagonal and horizontal fiberglass strips (Fig. 10(d))

d) Wall reinforced with horizontal and vertical fiberglass strips (Fig. 10(e)).

The largest increase in bearing capacity was achieved in reinforced walls with horizontally placed strips. This type of reinforcement with straps contributed to the following: the non-ductile mechanism of cracking with fracture has not been formed along the pressure diagonal, the wall did not collapse, and the bearing capacity was significantly increased. When comparing to the force of the unreinforced wall, the increase in the horizontal force of the wall reinforced using horizontal strips was about 86% (Fig. 11).

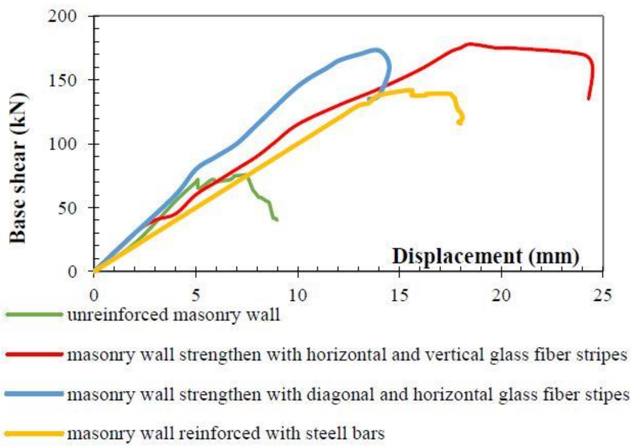

Fig. 11 Comparison of behavior of experimental samples (Galić and Sorić 2007)

In addition to the strengthening, composite polymers on the cultural heritage buildings serve to prevent problems and reduce overload effects from the action of possible tension and shear seismic forces.

Large difference in the mechanical characteristics in longitudinal and perpendicular direction of the fibers, linear elastic behavior to fracture and absence of material relaxation (not ductile), represent deficiencies of fiber-reinforced polymers (Španić *et al*. 2012).

Shock transmission units (Fig. 12) link the structural elements whose behavior depends on the speed of relative displacement. With their installation in the building, low speed displacements (temperature changes, creep and shrinkage of material) are ensured and the displacements due to different impacts (earthquake, wind, and explosion) are prevented.

Their rigidity prevents significant displacements between the elements, transmit the designed force onto them, and control the dissipation of the input energy. In the serviceability conditions of buildings, these devices do not cause undesirable forces (Bonci *et al*. 2001).

Most commonly used composite polymers and devices for restoration and strengthening of historic cultural heritage buildings (Čaušević and Rustempašić 2014), their effects, advantages and disadvantages are shown in Table 2.

Devices based on smart materials (shape memory alloys) are devices made of materials that have the ability to recover from large deformations during the loading/

Table 2 The most commonly used modern techniques for seismic strengthening of cultural heritage buildings

Modern strengthening techniques	Effects	Advantages	Disadvantages
Polymers reinforced with carbon fiber STRIPS	increase of the bending resistance from actions acting perpendicular to the plane of the masonry and increase of shear resistance in-plane of masonry	good behavior and endurance under dynamic loads, high tensile strength in the direction of fibers, easier adoption to the surface of the wall	linear elastic behavior to failure, small total elongation
Polymers reinforced with carbon fiber SHEETS	static strengthening and renewal	good behavior and endurance under dynamic load, high tensile strength in the direction of fibers, easier adoption to the surface of the wall	humidity and air impermeability through the wall, different tensile resistance along and perpendicular to the direction of the fiber
Polymers reinforced with carbon fiber LAMELLAS	increase of bending resistance against actions acting out-of-plane and increase of shear resistance	increase of shear resistance up to 80%	problems of anchoring in the joints and at the ends, the abrupt release due to long-term stresses close to the strength
Polymers reinforced with carbon fiber RODS	increase of bending and shear resistance	no mechanical damage and negative environmental impact on fibers in the rod	problems of anchoring, the abrupt release due to long-term stresses close to the strength
Polymers reinforced with carbon fiber NETS	increase of structure ductility and ability to dissipate energy	prevention of partial or total collapse of the building	ultraviolet radiation nonresistance, plaster-dependent performance
Polymers reinforced with aramid fiber STRIPS	the connection of structural elements whose behavior depends on the speed of relative displacements	higher final strength, alkaline chemical resistance of connections, waterproofness, good reversibility, low thermal and electrical conductivity	humidity and air impermeability through the wall
Stiff polyurethane foam	filling cavities and cracks, insulation properties	connecting the elements of the masonry, higher strength and reduction of earthquake vibrations among the elements	ultraviolet radiation nonresistance
Striking devices	preventing momentary displacements (earthquakes), possible small displacement (temperature elongation)	securing seismic stiffness without causing undesirable forces under the conditions of use	maintenance and replacement
Devices based on smart materials - Shape memory alloys	displacement control and force limitation to the design value	reducing the risk of collapse of the wall out-of-plane	the influence of temperature change on smart materials (Preciado *et al*. 2018) maintenance, financial aspects

Fig. 12 Set of the device of 220 kN for strike (Bonci *et al*. 2001)

Fig. 13 Shape memory alloy device insertion for the San Feliciano Cathedral façade (Indirli and Castellano 2008)

unloading cycle (Bonci *et al*. 2001). They are developed as a substitute for the conventional rigid, horizontal connections of structural elements (masonry wall-floor/roof) with the aim of reducing the risk of out-of-plane masonry walls collapse. The wired (nickel, titanium) flexible connection controls the displacements and limits the forces to the design value by changing the crystal structure due to heating/cooling or physical stress. As an effective means of improving the dynamic response of the structure, this technique is used to protect the historic cultural heritage buildings (Fig. 13).

Response of the shape memory alloys devices depends on the type of load, as stated in Čaušević and Rustempašić (2014):

a) horizontal effects of lower intensity, they remain stiff and do not allow for significant displacements

b) significant horizontal effects, they reduce the force, microcracks are permissible

c) exceptional horizontal action, increases the stiffness with the aim of preventing large movements and instability.

Numerical analyzes and experimental results have shown that devices based on smart materials reduce the effects of ground acceleration, and prevent in-plane collapse of the masonry. According to Castellanno (2000), the masonry wall, which was connected with this technique did not suffer any visible damage, even when subjected to an earthquake characterized by a PGA almost 50% higher than the earthquake causing the first collapse in the wall connected by traditional steel ties.

Shape memory alloy are sensitive to temperature changes. A constant prestressing applied force should be ensured by prestressing with the shape memory alloy tendons in static conditions with the aim of achieving the transformation phase. Due to temperature influence, it is difficult to precisely determine and control the prestressing force and if the possibility of complex earthquake effects is added, significant displacement of the top of the structure may occur (Preciado *et al*. 2018).

8. Conclusions

The historical cultural heritage buildings carry the features of past times, but also the answers to the cultural identity of a society and events over time in a certain area. Preserving what one is creating today and has inherited from the past, is the heritage that needs to be preserved and passed to future generations. By maintaining and strengthening masonry buildings, their service life is extended and their value is promoted.

The recent Croatian Law on the Protection and Conservation of Cultural Property stipulates the obligation to protect and preserve cultural goods and this is a joint obligation of the owners and the state. In accordance with the principles of the European Union, the recent Croatian Construction Law regulates the design, construction, use and maintenance of buildings, so that each building in its intended service life, with regular use and maintenance, must have sufficient bearing capacity and safety.

Failure to comply with all the requirements is allowed in the rehabilitation and reconstruction of buildings listed in the Registry of Immovable Cultural Property. The Ministry of Environmental Protection and Physical Planning, with prior consent of the Ministry of Culture, gives out a permit regarding the level of tolerance and admissibility of the deviation. Determining and enacting legal regulations does not guarantee their consistent implementation, so it is imperative, during each reconstruction, renewal or maintenance process, to have good supervision measures in order to enforce them.

There are numerous reasons why maintenance and restoration of historic masonry buildings have so far shown insufficient results. However this does not mean that, by applying scientific knowledge and modern techniques, maintenance and renovation of masonry buildings, the situation cannot be improved.

Decision on the strengthening or restoration of an existing building is based on the assessment of seismic resistance. Croatia and Bosnia and Herzegovina are areas of moderate to high seismic activity. Using the results of analysis and research of the elements of structures under cyclic loading, with regular maintenance and the use of traditional and modern techniques and strengthening devices, the consequences of seismic actions can be reduced or lowered to an acceptable level and the service life of the building is to be extended.

That is why, in the first place, it is necessary to develop a methodology for assessing the behavior of masonry buildings, and then adopting the principles of seismic protection of masonry buildings of cultural heritage.

The success of building maintenance and renovation is based on understanding the structures' behavior and respecting the historical uniqueness and cultural value of the building. These principles should be taken when deciding on the choice between traditional or modern reinforcement techniques. The criterion to be taken when selecting strengthening techniques can be the material properties that can be applied, the appropriateness and availability of procedures and technologies, and the required degree of improvement of the building's resistance.

Improvement of resistance can be directed to improving mechanical properties of masonry and/or rectifying structural defects in the behavior of the structure as a whole.

Selected techniques and materials have to have mechanical and structural compatibility with the behavior of the original structure and physical and chemical compatibility with the existing materials in order to prevent the creation of new damage, and to extend the durability of the building.

The most important reason for selecting between traditional and modern strengthening techniques is the need to increase the masonry strength, which can only be achieved by using much more efficient materials than the original ones.

Traditional strengthening techniques often do not provide the structure sufficient resistance to the maximum expected earthquake action and cause changes in the original constructive shape that is not acceptable from the cultural standpoint. Strengthening with these techniques can often be complex, resulting in disruption of use, higher financial costs, and in some cases these kinds of strengthening procedures are even unmanageable.

Recently, therefore, the advantage is increasingly given to techniques that meet criteria such as minimal intervention, compatibility, durability, reversibility or substitutability.

Modern strengthening techniques with composite polymers, due to small or no additional weight, increased tensile and shear strength of the masonry, and rapid and non-invasive applications, have become the primary technique for strengthening of masonry buildings of cultural heritage. The passive control devices affect the parameters of the dynamic response of the structure (attenuation, frequency or mass arrangement) with the aim to reduce the structural response to the earthquake action. The use of these modern strengthening techniques is unavoidable in strengthening and preserving the buildings of historic cultural heritage.

The problem of maintenance, strengthening and preserving of masonry buildings of historic cultural heritage is a complex multidisciplinary process. It is based on respecting the safety assessment methodology and the choice of the correct and effective strengthening techniques that best meets the requirements of a specific building with respect to its original structure and architectural-historical value. Extending the life and service life of cultural heritage buildings for future generations is not possible without a thorough understanding of the mechanisms and causes of their decline, in terms of sustained maintenance and effective reinforcement and renewal. Consideration and implementation of these attitudes is not simple and requires qualified people able to combine advanced knowledge and technology in the field with engineering conclusions, as well as, a long-lasting and accurate approach to the problem.

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