Seismic strengthening and repair of typical stone masonry historical buildings in Bosnia and Herzegovina

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ABSTRACT:

Bosnia and Herzegovina is situated in seismic active region of South-East Europe, divided in seismic zones with peak ground acceleration of 0.1–0.2 g for 500 years return period, even PGA of 0.30-0.35 g in some parts. Traditional art of building comprises masonry structures. Most historical buildings belonging to the national cultural heritage were made of stone-masonry with robust and enduring structure. In the case of stronger earthquake motion such buildings could suffer substantial or heavy damages. Some structural elements of historical buildings, as domes and arches, crack already by moderate earthquake but without the loss of stability. Stone-masonry buildings in Bosnia and Herzegovina can be classified in vulnerability classes B and C according to European Macro-seismic Scale, where A stands for the weakest seismic structures and F for those expected to have best seismic performance. Design and construction procedures for rehabilitation are presented here on examples of repair and strengthening of mosques situated in three different seismic regions. These mosques are historical stone masonry structures dating from the Ottoman period in Bosnia and Herzegovina. Traditional and contemporary materials were used for their rehabilitation. The challenge for structural engineers was to find equilibrium between aesthetical and structural demands considering seismic codes as well.

Keywords: *S*tone masonry, historical buildings, seismic strengthening

1 INTRODUCTION

The existing buildings in Bosnia and Herzegovina are traditionally built as masonry buildings, which includes most of historical buildings. After the World War II reinforced concrete structures prevail in the new erected buildings, but masonry structures are further built with apply of new materials. If one wants to assess possible damages, especially those caused by an earthquake, the existing older buildings are more vulnerable compared to the buildings constructed according modern technical codes. Many historical building, which belong to national cultural heritage, were made of stone-

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masonry. Generally they have robust and enduring structure and in the case of stronger earthquakes could suffer substantial or heavy damages.

The territory of Bosnia and Herzegovina is situated in active seismic region of South-East Europe. Shown on the seismic intensity map of Bosnia and Herzegovina for the reference return period of 500 years (Figure 1) the greatest part of the country lies in the zones of 7th and 8th intensity degrees according to MCS-scale or the new European Macroseismic Scale [1]. Relatively small part of the territory is situated in the seismic intensity zone 9. Referred to peak ground acceleration (PGA), PGA between 0.10 and 0.20 g corresponds to the greatest part of the territory and even PGA of 0.30-0.35 g in smaller part of the country.

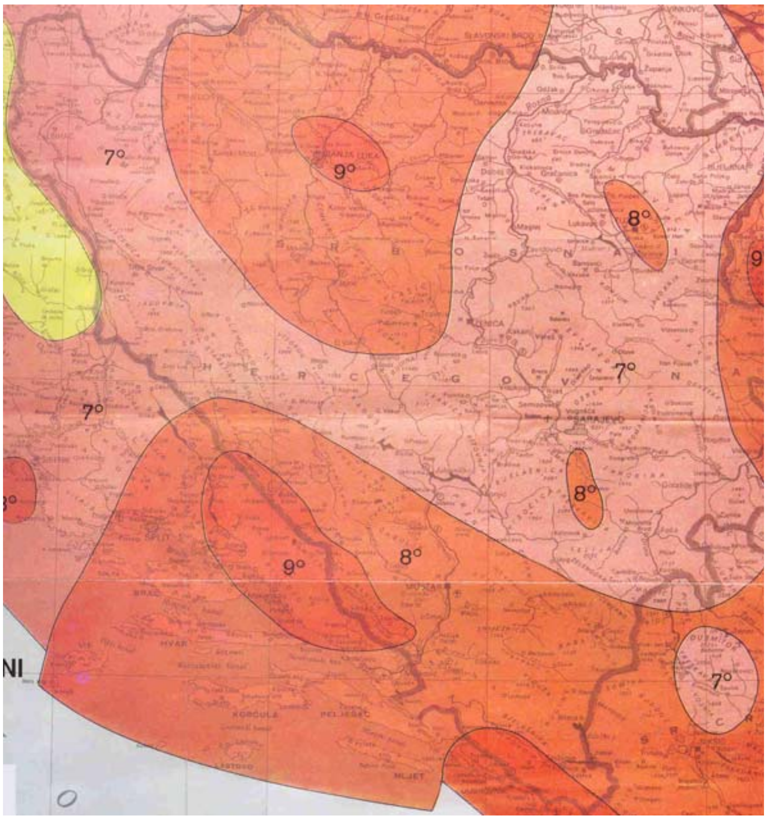


Figure 1. Seismic intensity zones in Bosnia and Herzegovina

Several strong earthquakes that happened during few last decades underlined the importance of seismic vulnerability assessment including evaluation of strengthening and retrofit measures. They caused loss of human lives, a lot of injured inhabitants of the hit areas and substantial damages to the building structures. Some of the recent earthquakes, which caused damages of the buildings, also influenced development of seismic codes for the whole Europe (Earthquake in Skopje, Macedonia in 1963, Banja Luka, Bosnia and Herzegovina in 1969, Friuli, North-East Italy in 1976, Montenegro Coast in 1979).

Within European Macroseismic Scale [1] structural systems of buildings are classified according to vulnerability classes depending on structural type. Vulnerability classes are A – F, where class A is for the weakest seismic structures and class F for those that are expected to have very good seismic performance. The classification of damage degrees for buildings is given within European Macroseismic Scale as well. Damage degrees are from 1 to 5 that means from irrelevant damages or only damages of nonstructural elements that correspond to damage 1, to destruction or even building collapse that corresponds to damage degree 5.

Classification of damage to masonry buildings is made generally for masonry buildings as follows:

- Grade 1: Negligible to slight damage (no structural damage). Hair-line cracks in very few walls. Fall of small pieces of plaster.
- Grade 2: Moderate damage (slight structural damage). Cracks in many walls. Fall of fairly large pieces of plaster.
- Grade 3: Substantial to heavy damage (moderate structural damage). Large and extensive cracks in most walls, roof tiles detach.
- Grade 4: Very heavy damage (heavy structural damage). Serious failure of walls, partial structural failure of roofs and floors.
- Grade 5: Destruction (very heavy structural damage). Total or near total collapse.

Damage degrees depend also on earthquake intensity. The class of building vulnerability, which depends on the structural type, can be related to damage degrees [2], which can be expected for different seismic intensities (Table 1). Within the European Macroseismic Scale there are short descriptions of effects that could be expected for the specific degree of seismic intensity.

Table 1. Damage grades of typical masonry buildings in Bosnia and Herzegovina

Type of masonry and R.C: wall buildings	Zone VII	Zone VIII	Zone IX
Masonry buildings made of earth brick or field stone	3 - 4	4 - 5	5
Unconfined masonry, older than approx. 60 years, mostly with timber floor structure	2 - 3	3 - 4	4- 5
Unconfined masonry, younger than approx. 60 years with reinforced concrete floors	2	2 - 3	3 - 4
Confined masonry with R.C. floors, mostly newer masonry buildings	1	2	2 - 3

Masonry buildings made of rubble stone or earth brick generally belong to vulnerability class A and already for 7th degree of seismic intensity serious damages can be expected, including instability of walls or falling down of ceiling. Such buildings have no many floors, usually ground floor and a story; they are situated in village, often in inaccessible environment. There are masonry buildings constructed with bricks produced in factory, but without vertical confining elements. We speak about unreinforced masonry (URM) without confinement [3]. Older buildings have usually wooden floors, while buildings built after World War II generally have R.C. floors. The first belong mostly to vulnerability class B where very heavy damages can be expected for the earthquakes whose intensity corresponds to the seismic zone 8. Masonry buildings with R.C. floors according to EMS classification could stand heavy damages of the structure including falling down of some walls for the intensity degree 9 and they belong mostly to vulnerability class C.

Most of the historical buildings, especially public and religious buildings, are built of stone masonry. The conclusions made from previous table could be used to estimate roughly seismic vulnerability of historical buildings as well. But, some of them have rather specific structure, especially monumental buildings and they can not be directly ordered into the table above. Also, it has to be mentioned that previous classifications refer to some average design and constructed masonry buildings. In the cases of worse construction heavier damages than those described must be taken in consideration. Presented vulnerability classification of masonry buildings corresponds to relatively regular structures, which should be noted as well.

Assessment of historical buildings presents specific problem considering the ways they were built and the materials, which were used. The damages are sometimes cumulated through many years and many causes, e.g. few moderate or stronger earthquakes.

Another specific problem arises by reparation and necessary strengthening or retrofit, for example to achieve earthquake resistance demanded by modern seismic codes. Speaking about historical buildings and monuments the aim is to preserve and reveal their aesthetic and historical values and to use original materials and original way of construction, if possible. But, where traditional techniques prove inadequate some modern construction and conservation techniques must be implemented. The same problems occur with traditional construction materials. In order to provide necessary resistance and ductility and fulfill the demands of new building codes the contemporary building materials have to be carefully implemented in the structures of those buildings. Many important principles for the assessment of historical buildings and monuments are summarized in the Venice Charter.

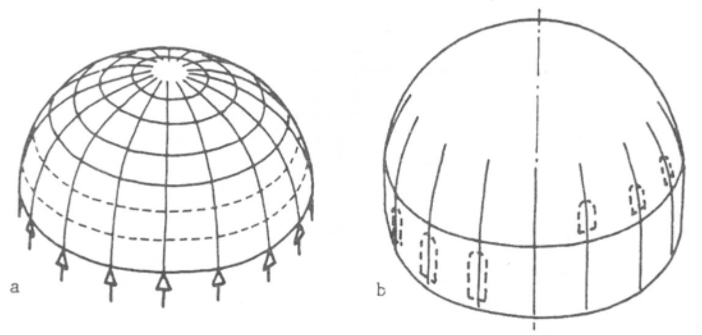


Figure 2. Structural system and cracks in the dome masonry structure

The large majority of all historical buildings are built as masonry structures, a lot of stone masonry, but in some regions bricks masonry as well. They are traditionally built as unreinforced masonry without confining elements. In some regions timber confinement was used. Typical curved structural forms as domes, arches and vaults are often part of historical buildings especially the religious ones. As they are built as unreinforced masonry structures, the historical buildings are relatively stiff and show generally brittle behavior. So, the first damages in form of cracks appear already by moderate earthquakes on softer structural elements as domes and arches [4], or ceilings attached to wooden floors and on partition walls, if there are any. At the same time the main structure, as dick walls and abutments, is in linear range of the behavior, with no or almost no cracks. But, it's generally not the case for very strong earthquake motion.

During the last war in Bosnia and Herzegovina many historical buildings, valuable as important cultural heritage, were damaged and even barbarically destroyed. Examples of the three historic stone masonry buildings from Ottoman period in Bosnia and Herzegovina are described and discussed in the three following chapters.

2 ŠIŠMAN IBRAHIM-PAŠA'S OR HADŽI ALIJA'S MOSQUE IN POČITELJ

The mosque was built in 1562-63, the early period of Ottoman ruling in Bosnia and Herzegovina. During the recent war in 1993 the minaret and the dome were completely destroyed and the rest of the building badly damaged by explosion. Guidelines for rehabilitation and protection of historical urban site of Počitelj were set in 2001 by the expert group and led to reconstruction design [5] for the mosque in 2002 and further to reconstruction works in 2003 (Figure 3).

The stone masonry building of the mosque comprises the closed room of 12x12m size covered by a hemispherical dome with inner radius of 4.84m, entrance area of 12x4m size covered by three smaller hemispherical domes and the minaret of 32.36m height. The transition between the rectangular basis and circular dome shape above the closed room is done with pendentives and octagonal drum and above the entrance porch with pointed arches, pendentives and shallow drums all supported by circular columns. The top of the dome is at 15m above the floor level. Building walls of 1.10m thicknesses are done as three-leaf stone masonry consisting of outer ashlars and inner core filled with rubble stone in mortar. Facade blocks are of a very fine shape with thin layer mortar joints and of a better quality limestone then the blocks used for the outer leaf at inside.

Figure 3. Destructed and reconstructed mosque building in Počitelj

Four types of limestone were used for the construction. The most resistant one locally called *krečnjak,* was used for façade blocks. At the inside and for inner core two other types may be found: *tenelija* and *miljevina*. These types are less hard and easier for shaping. The fourth type is soft and extremely porous tufa limestone used for the great central dome and for the three small domes above the porch. Existing mortars were found to be hydrated lime mortars. Roof cladding for domes and minaret cone is done with lead sheets.

Minaret (mosque tower), central great dome, one small dome close to the minaret and two porch columns were completely destroyed. The middle small dome was partly destroyed and the third dome damaged. Cracking and local damages were significant at the rest of the building structure visibly increasing towards the top and the minaret side. An additional stone foundation layer laid on a rocky substructure was identified by excavating two pits. Material characteristics, used for analysis, such as volume weight and compressive strength were taken from the literature or from previous testing results. Detailed testing was performed only for tufa stone due to known significant differences among samples from different quarries.

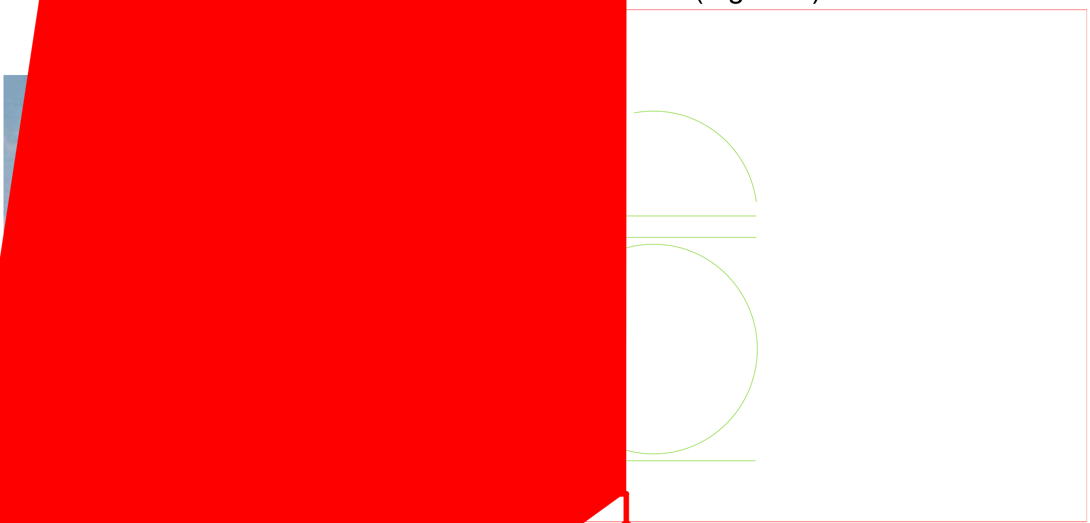
Figure 4. Strengthening solutions for minaret and dome, mosque in Počitelj

The minaret was modelled as cantilever tube with discrete masses spread uniformly over its height. The inner diameter of 1470mm is constant up to the cone, while the outer diameter varies from 2670mm up to the level +7.37m, over 1999mm from +9.75 to +20.74m ending with 1790mm up to the level +27.00m (the beginning of the cone). Thus the tube thickness is of 600, 260 and 160mm over the same heig[...] minaret is 1300kN. The section area at the bottom is 3.90m2 leadi[...]/mm2 due to self weight. This is approximately one order of mag[...]pressive stress of 2.50N/mm2 according to DIN 1053 and the dete[...] time for this analysis. The influence of the horizontal load, either [...] to increase in compressive stress up to 1.33N/mm2. Typically th[...]one at the end of transition from 600mm to 260mm thickness, w[...] Most of the joints are opened and at the critical zone the opened[...] cross-section, which led to decision on reinforcing measures [...]one was identified to be between levels +8.55m and +17.85m.

Local cr[...]n accordance with partial safety factor concept, where masonry [...]carbon fiber strips (CFRP) spread uniformly along the inner cyli[...]ive strength of masonry is 4N/mm2 with safety factor for mater[...]of CFRP strips is 1236N/mm2 with safety factor of 1,1. Stress-s[...]nd for masonry in accordance with EC6. Partial safety factors f[...]1.5 for wind load. Sika CarboDur S812 strips of 12m length [...] and later on chosen for the construction. Technical problem[...]taircase was solved by leaving voids in stair masonry blocks. [...]rcing the bottom part on the outer side of the main mason[...]ng and fixing with a bolted steel plates (Figure 4).

3 F[...]LUKA

The [...]n period in Bosnia and Herzegovina (Figure 5). It was built [...]t was for the centuries the real distinctive mark of the town [...]conducted by an unknown apprentice of Mimar Sinan. Mos[...]ent mausoleums containing the tombs and a central fou[...] mosque was completely destroyed in barbaric way, usi[...]hind (Figure 6).



Rehabilitation project [6] started in 2001. During design phase a lot of discussions were conducted regarding construction method and appropriate structural analysis. A special topic was seismic design due to the fact that the mosque is situated in the highest seismic zone in Bosnia and Herzegovina.

The mosque was built as stone masonry building. The non-regular shape of the mosque (Figure 5) in a plan comprises the central part of 9x9m size covered by a hemispherical dome, two side-rooms of 3×9m and front part of 4.5×9m, all three covered by one half of hemispherical dome. Entrance area of aprox. 15×5m is covered by three smaller hemispherical domes. The top of the domes is 18 m above the ground level. The total height of the minaret (mosque tower) is 43 m.

The mosque structural elements are typical for masonry stone mosque buildings built in Bosnia and Herzegovina from 16th to mid 19th century. The dome is supported by octagonal drum and pendentives. The loads are then transferred to four arches, which closed the central part of the mosque. This was an exception, because of its non-regular shape in a plan. The typical structural solution comprises the walls instead of the arches. This detail contributes to the overall slenderness of the Ferhad-paša mosque. The minaret was built in with the main part of the mosque building up to the height of 9.5m. The walls thickness is 105 cm, they consist of outer very fine shaped blocks and inner core filled with rubble stone in mortar. The main stone material used for the erection of the mosque was tuff (*sedra*). Hydraulic mortar was used for brickworks. The thickness of minaret tube was 53 cm under the balcony (*šerefet*) and 31 cm above it. The basic vibration period of minaret as cantilever tube is around 1 second. The dome was built as brick masonry with minimum thickness of 35 cm. Specific type of brick, named *tugla* was applied.

The foundation structure comprises the stone strips with two layers of rather fine shaped stones. Under the stone stripes slender timber piles were built in. The mosque was completely destroyed, only original foundation structure was left behind (Figure 6). The rehabilitation project comprises rebuilding with completely identical geometrical dimensions and as far as possible the use of the same materials. Due to the fact that the mosque building was completely destroyed, rebuild means in reality erection of the new building, which should include the implementation of modern structural codes. This leads to conflicts between demands of new codes and old historical stone structures, which don't fulfill them. It is especially expressed in the case of seismic codes. The city of Banja Luka is situated in a high seismic intensity zone (zone IX according to MKS-scale), which simply means relatively high horizontal forces acting on the mosque structure. The structural analysis was done already in 2002 using SAP2000 program. The mosque building structure is relatively stiff, but the free part of the minaret has first vibration period of roughly one second. The stone weight was calculated with 20 KN/m^3, elasticity module with 3000-5000 MN/m^2.

Figure 6. Only foundation left after severe destruction, investigation of foundation structure

The rehabilitation work has not been finished yet and the mosque is under construction. The main reason, beside finances, is the intention of all project participants to build the mosque in a way as it was built before. But, in spite of all efforts, some structural parts need strengthening in order to fulfill or almost to fulfill the structural code demands.

The first problem of rehabilitation works was very shallow existing foundation structure. It was tightened and strengthened by reinforced concrete jacketing on micro-piles with the diameter of 20cm. Another strengthening is previewed in a lower part of the dome in the direction of ring forces. A sort of reinforced concrete ring should be built in. According to the performed structural analysis minaret cannot withstand the earthquake of intensity grade IX. Two solutions were discussed. The first one with vertical reinforcement built in masonry stones. Second solution was built in of CFK-strips on the outer face of minaret cross-section. Disadvantage of this solution is of esthetical nature, while the carbon strips disturb the original appearance of minaret. The rehabilitation work has not been finished yet and the mosque is still under construction.

4 ČEKREKČIJA MOSQUE IN SARAJEVO

The mosque was built in 1526 in the old city of Sarajevo, one of the first mosques with the dome constructed during Ottoman period in Bosnia and Herzegovina (Figure 7). The mosque is situated in the heart of the old city and was very popular among the inhabitants. The small oriental stores are directly leaned to the mosques walls. This mosque was not destroyed during the last war 1992-95. There were some smaller damages due to bomb splitting during shelling of the city of Sarajevo from the surrounding hills. The most recognized damages can refer to the durability problems of masonry structure, especially due to the relatively bad hydraulic mortar. First rehabilitation works were done in 1969 and the last in 2000 [7].

Figure 7. Čekrekčija mosque in Sarajevo under reconstruction

The mosque was built as stone masonry building. The total dimensions in a plan are 13×17m, whereby the central part has diameter of 10m (Figure 7). The top of the dome is approx. 13m above the ground level. The total height of the slender minaret is 33m. One could have the impression that minaret is built in with the dome. But, during the investigation for the rehabilitation project it was found out that a joint (gap) exists between dome and minaret structure. Already the ancient engineer was aware of the different stiffness of the relatively rigid mosque building and the slender minaret. The thickness of the stone mosque walls is 115-120 cm. The hemispherical dome (cupola) is also built as stone masonry with the thickness of 40 cm. The stone material is tuff (*sedra*) and the hydraulic mortar was applied. Main structural system is the same as in other mosques from that historical period, dome, octagonal drum, pendantives and 4 robust walls.

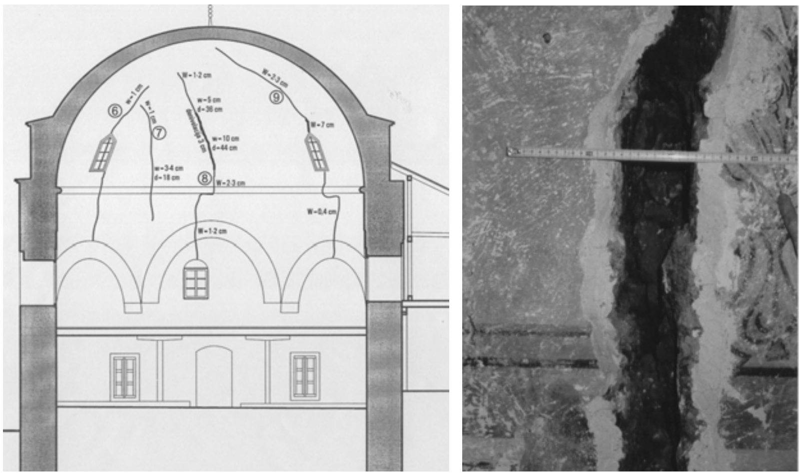


Figure 8. Schema of the observed cracks and crack detail

The observed damages were cumulated through the centuries. Probably first hair cracks had opened during some earthquake motion in the history and during the time they became larger. The most of the damages were concentrated in the mosque dome, and partially in the walls. The cracks were typical for this type of the masonry structures, going in meridian direction (Figure 8). The cracks width was mostly in the range from 1 to 10 cm. They can be estimated as very large cracks. Even, few displacements perpendicular to the dome surface between two portions of the dome divided by the crack were observed. They were in the range from 3 to 12cm. Obviously, the mosque dome was substantially damaged. At the same time there were no damages registered on minaret. One can conclude that instead of original space type of the dome structure few plane arch structures were formed, which provided the roof stability, but not the functionality.

Figure 9. Injection of cracks and built in of carbon strips

However, it was recommended to rehabilitate the structure, which was done. All cracks were injected with special mortar mixture (Figure 9). After the first structural analysis the strengthening with carbon strips was recommended. But during reconstruction works, because of evidently large cracks and shear displacement, the dome was degraded and then rebuilt again. So the strengthening with carbon strips (Figure) has not been even necessary.

5 CONCLUSIONS

Seismic strengthening and repair of three typical historical buildings from Ottoman period in Bosnia and Herzegovina were presented. Due to the fact that Bosnia and Herzegovina is situated in active seismic region of South-East Europe seismic assessment plays important role in their rehabilitation projects. All three mosques were built as masonry stone structures and can be classified as relatively vulnerable when exposed to moderate or strong earthquakes.

The mosques were built in 16th century having typical structure for that period, consisting of masonry dome above central part of the relatively robust and stiff building and slender minaret. Some typical damages caused by past earthquakes could be observed, but two of them were heavily damaged, even destroyed, during last war 1992-95. All three example buildings belong to national cultural heritage of Bosnia and Herzegovina. Reconstruction and strengthening of the building structures had to be performed with additional effort in order to preserve their aesthetical and historical values.

Structural analyses were done using sophisticated 3D finite element programs and relatively simple analyzing methods as well. The investigations of stone material mechanical and chemical properties were conducted too. Seismic strengthening were performed using modern materials as carbon strips and traditional ways as reinforced confining elements. The domes of mosques in Počitelj near Mostar and in Sarajevo were strengthened with radial CFRP-strips and the minaret of the Počitelj mosque with vertical CFRP-strips built in the special openings in the stair structure on the inner side of the minaret tube. Vertical reinforcement is previewed for the minaret of the mosque in Banja Luka, where the stone foundation strips were strengthened and tightened as well. The effects of strengthening, especially using new materials, are now to be observed.

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