Seismic strengthening of historical stone masonry structures in Bosnia Herzegovina

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SUMMARY:
Bosnia Herzegovina is situated in a seismically active region of south-eastern Europe where peak ground accelerations could reach 0.30-0.35 g. Robust and durable stone masonry buildings, which constitute an important part of cultural heritage, can be very vulnerable to earthquake motion. Design and construction procedures for rehabilitation and strengthening of two mosques dating from the Ottoman period are presented. The analyzed structures were heavily damaged in the 1969 earthquake, renovated afterwards and then completely blasted in 1993 during war time. Traditional and contemporary materials were used for retrofit of all bearing elements comprising domes, drums, squinches, pendentives, arches, walls, minarets and foundations. In the course of reconstruction, special attention was paid to seismic requirements of slender minarets susceptible to lateral loads. Static and response spectrum analysis were performed using beam, solid and shell finite elements. The challenge for structural engineer was to find equilibrium between aesthetical and structural demands. .

Keywords: stone masonry, seismic strengthening, historical buildings

1. INTRODUCTION

Earthquakes can be considered to be some of the most dangerous phenomena occurring in nature. The risk of destroying life and material assets in some parts of the world is very high, and special care has to be paid to adequate earthquake resistant design. In this paper we focus on historical buildings belonging to national cultural heritage of Bosnia and Herzegovina made of robust and durable stone masonry. The country is situated in a seismically active region of South-East Europe and it is divided in seismic zones with peak ground acceleration PGA ranging from 0.1–0.2 g for 475 years return period (zone VII – VIII according to MCS or EMS-98 scale) in the most parts of the country to PGA of 0.30-0.35 g (approx. zone IX according to the seismic intensity scales) in some parts (see Fig. 1). Masonry buildings with their massive and enduring structure could suffer substantial or heavy damages in the case of stronger earthquake motion (Hrasnica, 2009).

Stone masonry buildings are very vulnerable when exposed to the stronger earthquakes. Within European Macroseismic Scale EMS-98 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. Stone masonry buildings could be roughly classified into vulnerability class B. The classification of damage degrees for buildings is given within the same EMS-98 scale as well. The class of building vulnerability, which depends on the structural type, can be related to damage grades, which can be expected for different seismic intensities. The stone masonry structures, which also comprise most of the historical buildings in Bosnia and Herzegovina, could suffer serious damages, related to the grades from 3 to 5 in the case of stronger earthquake. It means heavy damages and even partial collapse of the structure. These facts confirm the necessity of seismic evaluation of existing historical buildings in order to prevent the destruction of the building. The previous classification refers to some averagely designed and constructed masonry buildings. In cases of worse construction quality heavier damages than those described must be taken in consideration.

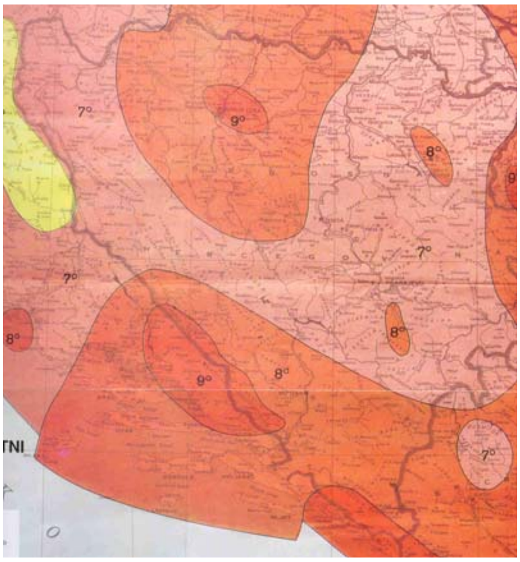

Figure 1. Seismic intensity map of B&H according to MCS scale.

Assessment of historical buildings presents specific problem considering the ways they were built and the materials, which were used. Capacity of different structures regarding their earthquake resistance is shown in Fig.2, where we can see that older historical buildings are characterized by relatively high resistance and stiffness, but low ductility. Some structural elements of historical buildings, as domes and arches, crack already by moderate earthquake but without loss of stability. The damages are sometimes accumulated through many years due to different causes, e.g. few moderate or stronger earthquakes, foundation settlement etc. (Hrasnica et al., 2010).

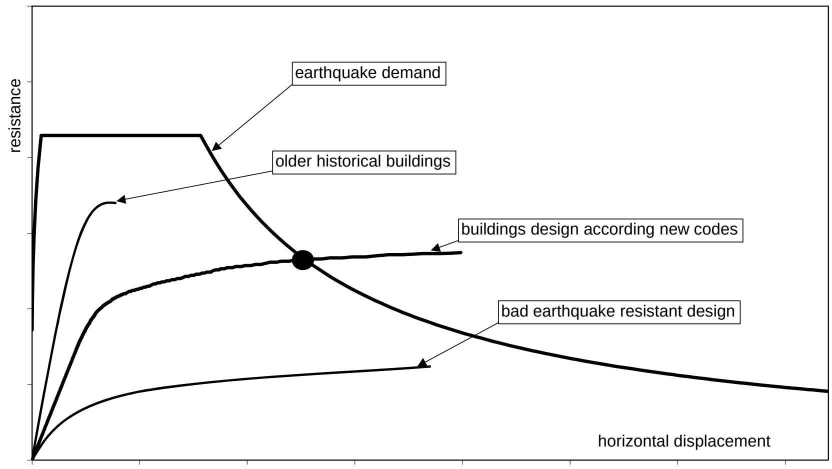

Figure 2. Capacity of different structures regarding their earthquake resistance.

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. As an example we show two lately retrofitted domes in Bosnia Herzegovina where injection of cracks and placing of carbons strips was implemented (see Fig.3). Many important principles for the assessment of historical buildings and monuments are summarized in the Venice Charter.

Figure 3. Injection of cracks and built in carbon strips.

The principles of renovation and strengthening of two distinguished buildings destroyed during 1992-95 war in the city of Banja Luka, Bosnia and Herzegovina are presented, namely historical stone-masonry mosques Ferhadija and Arnaudija Mosque dating from the Ottoman period. Adequate restoration is a complex task for structural engineers challenging them to find equilibrium between aesthetical and structural demands, especially considering modern seismic codes. We briefly describe the aesthetical and structural concepts pertinent to the mosques, thereafter analytical procedures used for assessing structural integrity and some strengthening techniques are discussed.

2. AESTHETICAL AND STRUCTURAL ASPECTS

The mosques in Bosnia-Herzegovina, dating from 16th-17th century, were mostly designed and built by apprentices of famous Ottoman architect Mimar Sinan (Günay,1998). The structural system consists of domes, semi-domes and squinches which usually cover the interior space, pendentives, arches, walls, buttresses, columns and minarets (see Fig.4). Typically, the dome is a semi–sphere usually sitting on a cylindrical drum. The stresses in the dome are compressive in the upper part and tensile in the lower part (measuring ca. 40° from the horizontal) what could induce radial crack. To counteract the spreading out, the old master builders wrapped the dome by iron belts. The load transfer from the dome to polygonal base is provided by transitional elements consisting of squinches (corner arches) as in Arnaudija Mosque or pendentives (spherical triangles) as in Ferhadija Mosque. Arches can stand alone or can be incorporated in the walls which are usually braced by timber beams acting as tie–beams.

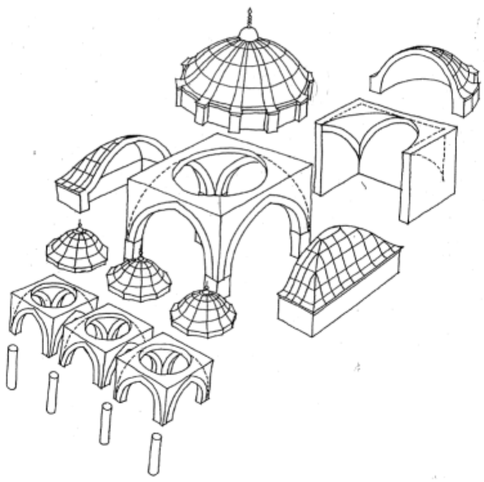

Figure 4. Structural composition of Ferhadija Mosque.

The loads are further transmitted to the foundation structure which comprises upper layers of fine stones and detritus beneath, forming foundation strips. The traditional foundation structure is strengthened with oak piles which act as micro–reinforcement (see Fig.5). Finally, the most elegant element of the mosque is slender minaret (tower) which is usually connected with the thick mosque wall at its bottom part. This affects positively the lateral behavior of the high minaret exposed to horizontal forces like wind and earthquake.

Figure 5. Detail of existing foundations with emphasis on oak micro-piles.

The Ferhad-Pasha Mosque (Hamidovic, 2004) has an elaborate multi-domed roof system over a central prayer hall (ca. 8.0 x 8.0 m), flanked by vaulted galleries to the east and west (ca. 3.5 x 10.5 m) and with a semi-domed qibla iwan (ca. 9.0 x 4.5 m) pointing towards southeast (see Fig.6). The main dome spans ca.7.5 m in diameter and the crown of the dome lies at ca.+18.0 m above the ground. The loads are transferred over the octagonal drum to the free-standing arches (span ca. 7.7 m, thickness of 0.7 m) via pendentive and further to the walls (ca. 1.0 m thick). The lateral protruding parts of the side–rooms have rectangular plans covered by segmental composite vaults. The porch of the mosque – so called sofa – is vaulted by three small cupolas laying on four arched stone structures with pointed crowns. The prominent part of the mosque is its 'tower' – minaret (ca. 35.0 m height) which consists of base, waist, minaret-body, veranda, vat and roof. All elements of the minaret are made of cut stone masonry, calcareous cement and horizontal iron clamps cast in place with lead. The structure is made of local stone materials (crystallized white tuff), thin brick ("tugla") and good-quality scrap detritus as wall infill material without organic ingredients. High quality semidry and moist lime mortar was used as plaster which was traditionally reinforced with sheep hair. The structural composition of Arnaudija mosque is similar wherefore the detailed description of its structural properties will be omitted here.

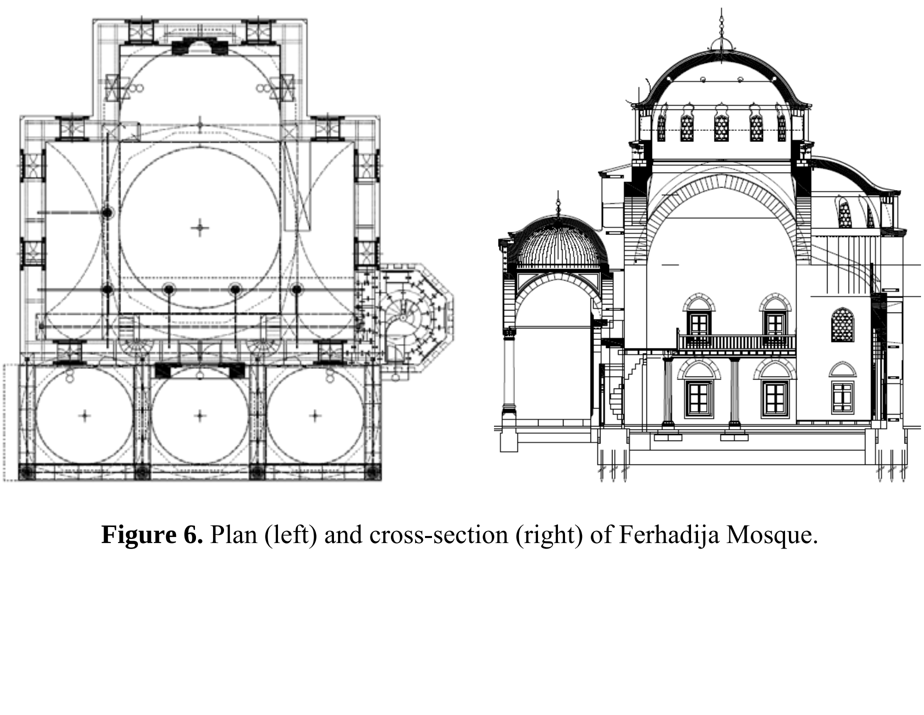

Figure 6. Plan (left) and cross-section (right) of Ferhadija Mosque.

3. EARTHQUAKE DAMAGES AND DESTRUCTION OF MOSQUES

Three strong earthquakes consecutively hit the city of Banja Luka on 26th, 27th and 31st Oct , 1969, whose intensities were 7.5 MCS, 8.5 MCS and 6.5 MCS respectively. Numerous buildings were destroyed, 15 people lost their lives and 1300 were injured. Two mosques were heavily damaged. Still, from the structural point of view, the damages occurred at the expected places. The minaret of Ferhad-Pasha's mosque cracked above the balcony, where the significant change of stiffness exists (see Fig.7). As usual, the minaret's cross-section is thinner above the balcony and exactly at that level the minaret was cut by the earthquake. The walls of Arnaudija mosque suffered from large inclined cracks over the window (see Fig.8). The windows in the mosque's walls and domes represent the weak places in the rather stiff and brittle structure. It cracks already due to moderate earthquake motions. It is to notice that damages can be accumulated through history as the consequences of different seismic activities.

Figure 7. 1969 Earthquake damages on Ferhadija's minaret that cracked above balcony.

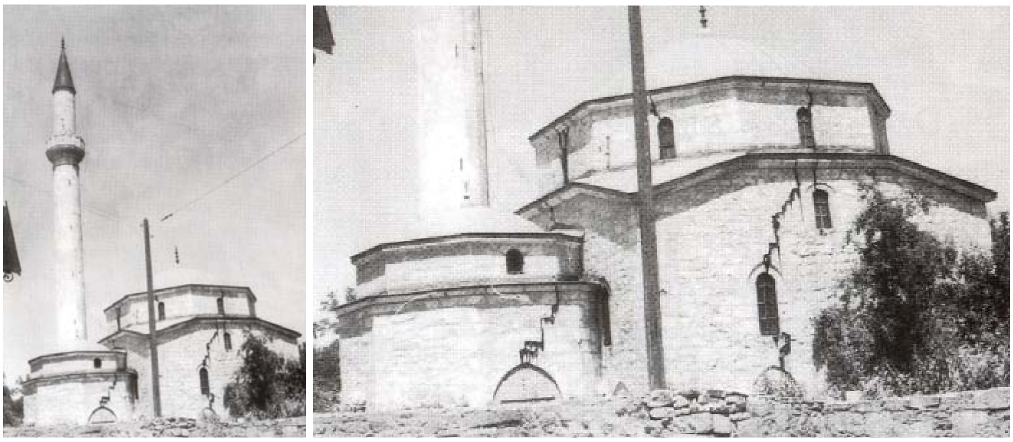

Figure 8. 1969 Earthquake damages on Arnaudija's walls.

After 1969 earthquake the mosques were reconstructed, however this was done inadequately. All mistakes came to surface when a weaker 6.5 MCS quake hit the city in 1981.

In 1993 during aggression on Bosnia and Herzegovina, the mosques were completely destroyed by blasting and the remains were thrown to garbage (see Fig.9).

Figure 9. Remains of Ferhad Pasha's mosque after blasting in 1993.

4. ANALYSIS, REBUILD AND STRENGTHENING

Simple models of the dome, drum, arches, minaret etc. as well as the global FE models with beam, solid and shell elements (see Fig.10) encompassing also the sub-soil influence were used. Geometry generation was quite demanding because no easy input from the drawing file was possible. The differences in the precision and interpolation type of CAD (splines) and FE (polynomials) program caused major problems especially for intersections of different elements. With the help of program Mathematica , this problem was overcome.

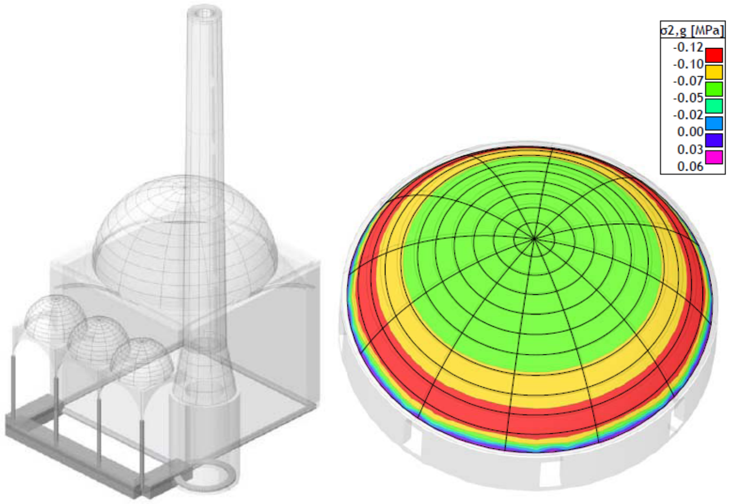

Figure 10. Global FE model (left) and detail with equatorial stresses in dome (right).

A few important mechanical parameters of stone used for the analysis are listed in Table 4.1. Globally we have assumed linear elastic behavior for calculations performed with SAP2000. However, for cross sectional analysis with XTRACT we adopted nonlinear properties.

Table 4.1. Mechanical parameters of stone used for the analysis.

Specific Weight γ [kN/m^3]	Elastic Modulus E [MPa]	Uniaxial Compressive Strength f_{ck} [MPa]	Uniaxial Tensile Strength F_{tk} [MPa]	Yield Strain/Crushing Strain ε_y/ ε_u [/]
20	$3\text{-}5\cdot10^3$	5	0	$2\cdot10^{-3}/3\cdot10^{-3}$

The structural system of typical historical mosque consists of relatively stiffer main mosque building and slender minaret. Assuming that the builders of the 16^{th} century mosques considered almost exclusively gravity loads in their analysis, special attention was paid to fulfill the requirement of earthquake resistant design. Both historical buildings are located in the seismic intensity zone IX according to EMS-98 or MCS, which means PGA of up to 0.35 g. The analyses performed were the crude equivalent static force method and the response spectrum analysis. The spectrum was defined according to Bosnian national standard which is equivalent to ex-Yugoslav seismic code. In a 3D model we obtain the basic vibration period of minaret as cantilever tube is around 1.0 second (see Fig. 11). Due to axial symmetry, the problem can also be analyzed in 2D, for which we have used beam elements. First five periods (determined by modal analysis) and the modal participation factors are listed in Table 4.2. We notice that the first three periods total 92 % of the modal mass, which is practically sufficient for seismic analysis. The calculated drift of the top node was around 8 cm, which yields the displacement index (δ/h) equal to 0.004. This value is well enough below the critical 0.01. However, this should be taken with reserve since the stone blocks can resist only negligible tensile stresses.

Table 4.2. First five modes and modal participation factors.

Mode	1	2	3	4	5
Period [sec]	0.81	0.18	0.08	0.06	0.05
Factor	0.58	0.24	0.10	0.0	0.05

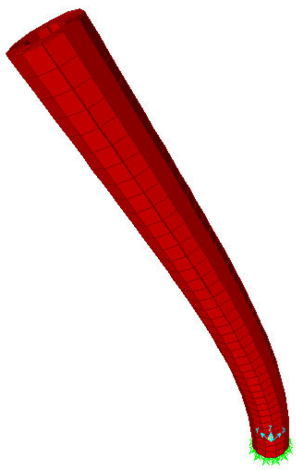

Figure 11. First eigen mode of Arnaudija mosque with period $T_1 = 0.82$ s.

According to the performed structural analysis different strengthening measures are necessary in order to fulfill the demands of modern structural codes. An interesting result is that the geometry of some stone arches did not follow the thrust line, as expected. However, the arches stood there for centuries without damages, apart from few hair-like cracks. The strengthening measures range from foundation to the dome. Existing shallow foundation structure is tightened and strengthened by reinforced concrete jacketing on micro-piles with the diameter of 20 cm. The lower part of the brick masonry dome should be strengthened in the direction of ring forces, where reinforcement bars are built in mortar layers. According to the performed structural analysis minaret cannot withstand the earthquake of intensity grade IX. Two solutions were discussed, with traditional and modern materials. The first one with vertical reinforcement built in masonry stones around the inner perimeter. We have assumed linear elastic – plastic diagram (without hardening) for reinforcement S500 (yield strength 500 MPa, yield strain $2.5\cdot10^{-3}$, ultimate strain $20\cdot10^{-3}$). The constitutive law for stone blocks and the resulting moment-curvature capacity obtained with XTRACT are displayed in Fig.12. Strengthened in this manner, the slender minaret is capable of resisting the seismic influences.

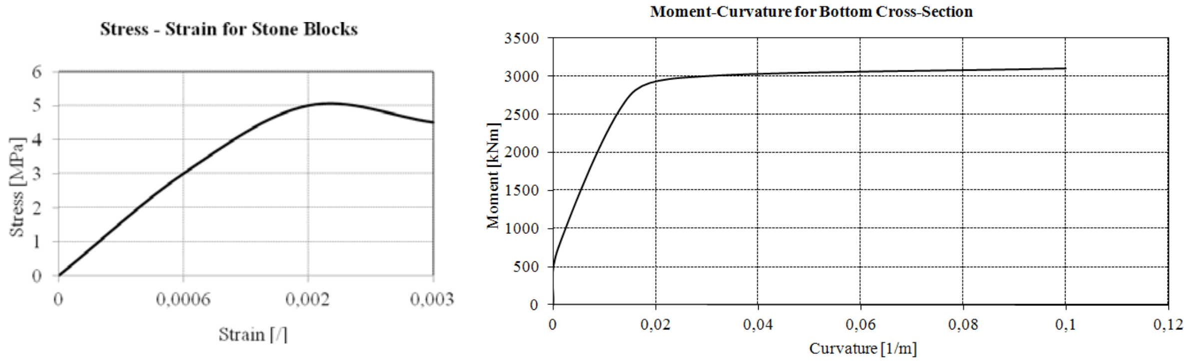

Figure 12. Stress-Strain diagram for stone masonry and moment – curvature for bottom cross-section.

Second solution was built in of CFK-strips on the outer face of minaret cross-section. Disadvantage of this solution is of aesthetical nature because the carbon strips disturb the original appearance of minaret. Also, the impermeability of FRP sheets can induce moisture in walls. The first one was chosen, but the reconstruction work has not been completed until now.

5. CONCLUSION

Reconstruction or rebuild of historical buildings belonging to national cultural heritage represents a special task for structural engineers, because he has to find equilibrium between aesthetical and structural demands considering modern seismic codes as well. This is presented on the examples of two mosques, dating from 16th century, built as stone masonry buildings and located in a high seismic zone with PGA of up to 0.35 g. Due to the fact that the mosques were barbarically destroyed, the reconstruction work means rebuild with respect to very precious geometrical data, using original materials as much as possible. The buildings have specific structural system consisting of load bearing elements such as pendentives, squinches and drums, typical for buildings from that époque. Structural analyses were done using sophisticated 3D finite element programs and relatively simple analysis methods as well. The analysis yields the necessity to strengthen the traditional stone masonry structure. It was performed using modern materials such as carbon strips and traditionally with reinforced confining elements.

REFERENCES

Hrasnica, M. (2009). Damage Assessment of Masonry and Historical Buildings in Bosnia and Herzegovina, Chapter in: *Damage assessment and reconstruction after war or natural disasters*, eds: Ibrahimbegović and Zlatar, Springer Verlag

Hrasnica, M.; Zlatar M.; Kulukčija S. Humo M.; Madzarević M. (2010). - Seismic strengthening and repair of typical stone masonry historical buildings in Bosnia and Herzegovina, "*8th International Masonry Conference*", Dresden

R. Günay (1998). Sinan – The architect and his works, YEM Publications, 6th Ed., Istanbul

M. Hamidovic (2004). Principles and methodological procedure for the renovation of Ferhad – Pasha mosque in Banja Luka, *Acta Architectonica et Urbanistica*, p. 7-72. , Architectural Faculty in Sarajevo – Center for Research and Design

S. Husedzinovic (2005). Dokumenti opstanka, Muzej grada Zenice, Zenica (in Bosnian)

Mathematica 5, www.wolfram.com

Hrasnica, M. (2002). Rehabilitation of Ferhad-paša Mosque in Banja Luka, Institute for Materials and Structures, Faculty of Civil Engineering, Sarajevo

Medic,S., Medic, I. (2010). Rehabilitation of Arnaudija Mosque in Banja Luka, Calypso, Sarajevo

SAP2000 (2009). Integrated Software for Structural Analysis and Design, Computers and Structures Inc., California

XTRACT V3.0.1 (2004). Cross Sectional Analysis of Components, IMBSEN Software Systems