Vultenability of Romanian Cultural Heritage to Hazards and Prevention Measures

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1. ABSTRACT

The cultural heritage preserved in Carpatho-Danubian-Pontic region, where tectonic earthquakes often occur, consists mainly churches. For centuries they were the most representative creations of ecclesiastic and monumental architecture. Orthodox churches in that region are three-lobed. Originally shaped according to the Greek cross their geometry was slightly changed during centuries being adapted to the seismic hazard of each site. The paper shows that the reason of this paraseismic shaping of three-lobed churches was to reduce their vulnerability to overall torsion. The size and position chosen for steeples were also carefully studied to reduce the damaging effects of shearing forces. Churches correctly designed successfully faced strong earthquakes and are lasting for centuries. The others have been more or less damaged. The paper also presentsts an innovative method for repairing three-lobed churches made of stone and brick masonry. The method consists in reinforcing, coating or confining masonry structural members with the aid of polymer grids of high density and strength. The results obtained by static and dynamic tests on reduced and full scale models show that the method is reliable and worth to be applied.

2. INTRODUCTION

The oldest monumental buildings preserved in the Carpatho-Danubian-Pontic region are churches. For centuries they were the most representative creations of ecclesiastic and monumental architecture. More specifically, they have always represented typical orthodox churches since Romanians are the only Latin nation of orthodox religion, while all the other peoples of Latin origin are catholic. Erected with stone and brick masonry, these Eastern Churches of Balkan-Byzantine style were always an evidence of the level of technical knowledge, cultural receptivity and artistic refinement reached during their époques. As a rule, they followed the Byzantine pattern based on the standard scheme of the Greek Church, the straight cross inscribed in a rectangle and the dome supported on pendentives or on piers. However, they are creatively adapted to the regional traditions of the secular architecture. These Orthodox Churches also reflect the foreign influences on the autochthonous art of building.

Although Orthodoxy as a religious cult is extended over a large part of Central and Eastern Europe the typical churches of three-lobed shape are spread only in the Carpatho-Danubian-Pontic region. The region is well known for its early Christianity. One of the three lobes, namely the front one, is devoted to altar, the other two, equally sided with respect to the symmetry axis, define the nave, while the narthex, with or without porch, is closed by a rectangle. Naturally, there are architectonic and stylistic differences between these three-lobed churches. Their size, number of steeples or decorations depends by the cultural level, economic power of parish, local tradition and specific environment of their sites. However, in all cases the three-lobed shape of Orthodox churches is here always strictly preserved.

Initially built of wood, with fourteen century the three-lobed churches are made of stone and brick masonry. At the beginning these churches were provided with a single steeple, the Pantokrator one. Later two, three or four steeples were added to decorate these ecclesiastic monuments. Sometimes one of the back steeples is used as belfry and/or watchtower. The two geometric characteristics of steeples are the external diameter D and the height H, from basis to the top of masonry cupola, while their slenderness is defined by the aspect ratio

D/H, usually between 1/2 and 1/3.25. The size of three-lobed churches is rather reduced, like that of a building with two or three stories. For churches of greater sizes either buttresses are provided or the narthex is slightly enlarged (Figs. 1, 2).

Figure 1: Church of Hurez Monastery-1692

Figure 2 : Church of Plumbuita Monastery-1647

Strong tectonic earthquakes periodically haunt the region where typical three-lobed churches are located. Only in the former century, between 1901 and 1990, 95 earthquakes, with magnitudes higher than 5, were registered. Most of them had their focus in the vicinity of Carpathian bend, in Vrancea County. Under seismic actions some of these churches were dramatically damaged or even destroyed. The curved walls of apses yielded under the overall torsion, while the slender steeples ceased to the shearing forces. The three-lobed shape is far to be the most appropriate one for facing earthquakes. However, it was faithfully preserved during centuries (Fig. 3).

After each earthquake the damaged churches should be repaired and strengthened. Many of them even several times. To some churches the steeples originally made of brick masonry were shortened in height, to reduce the overall weight, or replaced by wooden ones covered with metallic sheets. Obviously, all works of repairing are long lasting and expensive. Since long ago it was known that it is easier to prevent than to repair and this principle was successfully applied to the three-lobed churches (Fig. 4).

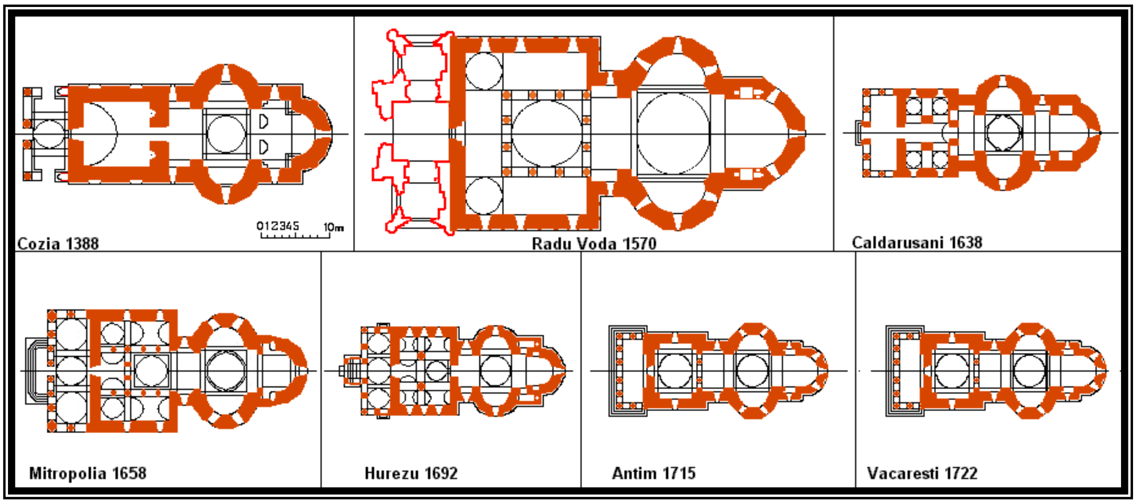

Figure 3: Typical three-lobed churches

3. THE ART OF BUILDING IN MASONRY

Masonry is one of the oldest construction materials. There are sources stating that in Palestine, wherever stone was scarce, about 9,000 years ago the inhabitants were building in brick. Since then masonry was called artificial stone. However it essentially differs by the natural stone by nothing else but ***ductility***. Indeed, natural stone is elastic and brittle while elastic clay brick and plastic lime mortar compose the ductile masonry. Therefore even by construction the masonry get strong properties of ductility. Without ductility masonry is no longer genuine. It is the case of masonry with cement mortar when brittle bricks are bound with brittle mortar. When natural stone and masonry are equally loaded in both materials mechanical work of deformation is developing. In the case of natural stone all the mechanical work passes into potential elastic energy. When unloaded this energy is restored by a reverse mechanical work and all the former deformations disappear as nothing happened before. However, when elastic energy is accumulated in large quantities it might become dangerous. The stresses developed around hidden structural faults might cause without warning brittle failure of the stone. On the contrary in the case of masonry only a part of mechanical work is preserved as a potential energy. The level of stresses developed by elastic deformations remains limited and low. The rest of mechanical work is converted by friction or shearing in heat or noise and dissipated. Similar phenomena occur during climate change. In cold regions e.g., when temperature is much lowering, the stone hardly resists not cracking while in the same severe conditions the masonry perfectly behaves. By ductility the masonry is endowed with a self-protection capacity against any concentrations of stresses caused by unequal settlements, natural hazards or technological aggression. Due to the remaining deformations masonry appears as a material with memory. The memory of masonry buildings contains the self-defending mechanisms spontaneously developed during their service (Fig. 5).

Figure 4: Church of Arges Monastery – 1512

Figure 5: Church of Snagov Monastery - 1514

Masonry has been used to Romanian orthodox churches beginning with the fourteenth century. The most representative church of that time is the Church of Cozia Monastery built in 1388 and still in service. Before that date they were built by wood and stone masonry on carefully chosen places according to strictly sacred compulsions. Along with Cappadocia and Mount Athos the monastery and parish churches spread in Carpathian-Danube-Pontic region have been for over one millennium the most representative centres of orthodoxy. Unlike Catholic stately cathedrals Romanian churches are relatively small in size. Their apparently modest dimensions actually testify to a spiritual and pragmatic attitude. Those sanctuaries were meant to serve the devoted communion of human beings with the infinite of divine order, and their proportions were miraculously preserved from the restlessness and confusion of the contemporary world. Typical for Romanian orthodox churches is the three-lobed plan. It played a crucial role in preserving the ecclesiastic architecture of the region where periodically severe earthquake occur.

4. THE Myth of Immolation

One of the most representative three-lobed churches in Romania is that of Argesh Monastery. It was built up in six years, between 1512 and 1518, under the reign of Prince Neagoe Basarab, being conceived as a Mausoleum-Church where the Prince and his family to be buried. Later around the church a monastery was raised up. Due to its outstanding beauty and fame many other churches have been similarly shaped. Today it is a Bishop Church and quoted as a patrimonial monument (Fig. 6).

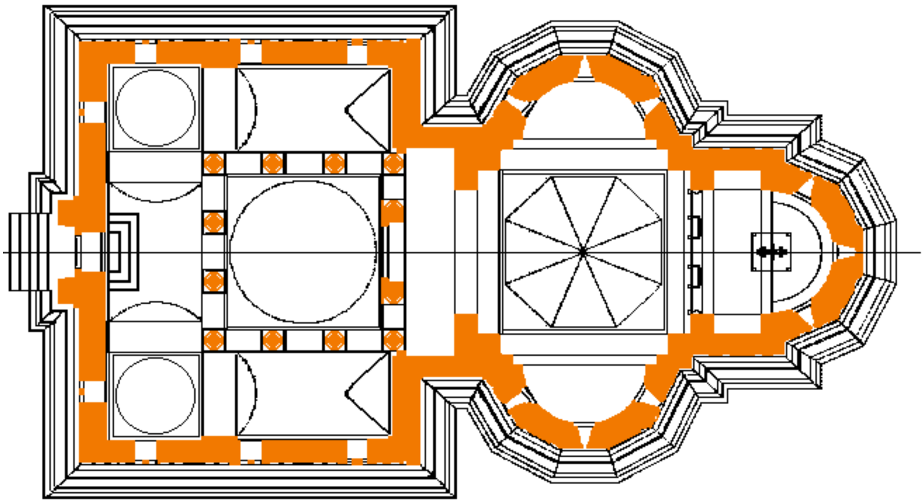

Figure 6: The three-lobed plan of Argesh Church - 1512

Since long ago the fame of Argesh Church has been spread through a famous legend. According to the legend Negru Voda, a Romanian Prince ordered to a team of masons to erect an outstanding church on the upper course of the River Argesh, at the foot of Carpathians. The work was carefully organized and well conducted until the walls started to rise up. Then surprisingly all what they raised up during the day next night fell down. Only after the Master immolated his wife the church could be completed. The beauty of his church enchanted the Prince. To prevent the masons rising up another monument of the same beauty he decided to sacrifice the Master together with his team.

Mircea Eliade, as a historian of religions, explains that such a legend is typical for Balkan region. Although some versions are spread far away, towards India and Scandinavia e.g., only here, in Romania, one finds its richest philosophical content. Since 55 years ago in Lisbon Mircea Eliade concluded his Comments to the Legend of Master Manole from a metaphysical perspective. Three ideas are of special interest for this paper, namely:

1. He showed that the place where the future church will be located should be carefully chosen. Special care is devoted to avoid the chaos. The time of beginning the work is also significant. Mircea Eliade speaks of a mythical time essentially different by the real one. One finds here the same time like the original one about Stephen Hawking scientifically wrote. For both authors time and space become *consubstantial.*

2. The next step is to choose the church centre. In this very point or a certain limited area is concentrated the whole act of creation and this is why it should be located on the so-called *axis mundi.* Around the chosen centre the shape of church is further developed. The future church will last forever only if it is shaped as an *imago mundi.*

3. In order to be protected against disasters church geometry should remind of the original or archetypal act of creation. This is why some symbols of genesis were adopted. Finally, the act of immolation according to a magic rite is consummate. It aims to transfer ceremoniously the life from a human body to church building, by sacrifice and violence, like in the explosive creation of universe. By this imitation of divine act of beginning the new building receives personality and protection.

5. Ancient concept of SEISMIC PROTECTION

Saint Peter's Basilica in Rome begun by Pope Julius II in 1506 and completed in 1615 under Paul V. It was designed as a three-aisled Latin cross with a dome at the crossing, directly above the high altar, which covers the shrine of St. Peter the Apostle. In 1546 Michelangelo was commissioned as chief architect. He designed St. Peter's Dome and erected its drum. The dome, modified from Michelangelo's design, was completed under Sixtus V (1585-90), and Gregory XIV (1590-91) ordered the lantern above it. Since then similar domes of different sizes, devoted to the All-Ruler, were erected around the world.

By coincidence during the early years of construction St. Peter's Basilica in Rome the Argesh Church in Wallachia was completed as a three-lobed Greek cross. In this way legend's hero Master Manole was Michelangelo Buonaroti's contemporary. By carefully keeping the proportions both churches are masterpieces of art and architecture. Before consecration both have had technical problems, St. Peter's with gravity, while Argesh Church with those mysterious forces occurring only during nights. In the first case, that of St.Peter’s Basilica, the problem was scientifically solved. By applying the most advanced theories of those époques, after more than two centuries Dome's cracks were definitely repaired. In the second case it is known that only by the symbolic act immolation any subsequent damaging was prevented. Indeed, Argesh Church safely behaved during its almost five centuries of existence. It is a proof of what it is called today *seismic protection.*

At the end of his *Comments* to the Legend of Master Manole, Mircea Eliade mentions that in ancient times it was a tradition that some professional rules to be secretly kept. This is why he admits that the myth of immolation has an esoteric character. The legend aims to transmit some professional *golden rules* but only the few and well-initiated persons could understand their true meaning. Indeed, if the three above presented ideas are attentively analysed the ancient concept of durability comes out as follows:

1. The mysterious forces destroying over nights the church walls can't be but only earthquakes. Therefore in seismic areas the construction site should be carefully chosen. It mainly depends on seismic hazard of the site and of its seismic risk as well. The most important source of information comes from the history of site. In this way the two factors, space and time, should appear as *consubstantial*. It is a long tradition to locate churches and monuments on hills or local heights where seismic intensity is somewhat lower. The rule was recently applied in Bucharest where for the House of Parliament such a place with lower seismic intensity was chosen.
2. The idea of centering the church from the very beginning is basically connected with the need of balancing. Each church has two intrinsic centres, one of mass or gravity and another one of rotation or stiffness. Both centres, *CG* and *CR*, are located on the longitudinal axis of symmetry. The inertial forces induced by earthquakes are applied in *CG* and with respect of *CR* the overall torsion is developed. Progressing upwardly the seismic excitation reach the steeples and their own inertial forces submit them to shearing. Seismic vulnerability of churches depends on the relative position of the two centres. According to Eurocode 8, ENV 1998-1-2 Part 1-2, for seismic protection the distance between the two centres, which is in fact the eccentricity of seismic forces, should be reduced fewer than 10% of church length.
3. The shaping means to put in value church geometry versus construction material. Geometry means not only proportioning for balance needs, but it has an essential role in preventing rotation. It is also a measure of the induced intelligence. In the specific case of

Argesh Church the myth of immolation have had geometric consequences. Indeed, in order to create the space for victim body the Master was obliged to modify the original shape of church by enlarging the narthex. For the sake of symmetry both sides of church were displaced. In this way the relative position of the two centres has changed. The phenomenon of overall torsion was accordingly modified. Since that old times in three-lobed churches the place of graves remained in narthex.

6. THE three-lobed PLAN

Eastern Churches shaped according to the three-lobed plan have been consecrated during the sixteen and seventeen centuries when religion played a leading role in all European societies. This typical shape was developed from structural and plastic reasons by using as construction material brick masonry. The shape allows natural connections between curved and straight surfaces, from horizontal to vertical plans. Three-lobed

churches are spatially balanced structures in accordance with the specific actions of their sites. They are able to safely face gravitational and lateral actions in accordance with durability requirements. Equilibrium is the main condition of aesthetics and means beauty. With this outstanding quality the three-lobed churches are continuing even nowadays to integrate themselves in their environment. There is little difference in shaping between urban and rural three-lobed churches.

Original three-lobed plan is shown in figure 7. The two intrinsic centres *CG* and *CR* are located behind the central axis, and for the given dimensions the distance between them is only 1.71% of the total length of church. It is smaller even than the accidental eccentricity that according to the same provision of Eurocode 8 is 5% of the total length. The two centres are almost superposed. However, the result is far to be as favourable as it appears.

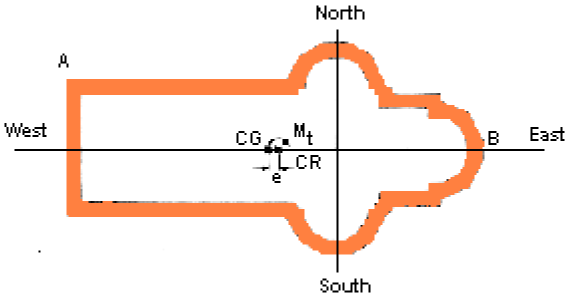

Figure 7: Original three-lobed plan

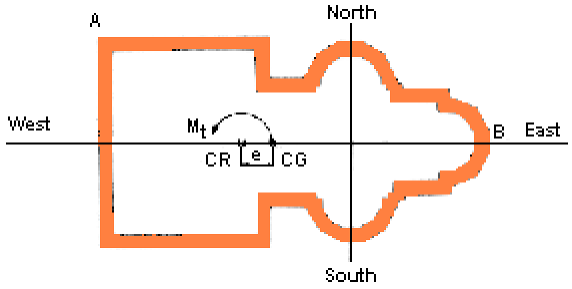

Figure 8: Enlarged three-lobed plan

Indeed, for the same moment of torsion the shearing forces are inversely proportional with the distances from *CR* to the extreme points. Since in this case the distance from *CR* to *B* is lower than that to *A* the curved walls would be more exposed to seismic actions. This explains why so many three-lobed churches present crack on theirs apses and should be strongly restored.

By enlarging the narthex like in the case of Argesh Church the things are essentially changing (Fig. 8). The *CR* passes on the other side of *CG* on the axis of symmetry. It happens in this case that the eccentricity to increase to 8.29% of the total length of church but it remains fewer than 10% as EC8 recommends. In the same time the distances from *CR* to apse walls substantially increase while the shearing forces are diminishing. In the particular case of Argesh Church the magnitude of shearing forces is reduced with 32%. This explains why the apses of three-lobed churches correctly designed have been without any exception so well preserved. One can't say the same thing about their steeples. Most of them are circumferentially cracked, always in the same place namely at the level of arch springers that upwardly close steeple openings. The specific problem of steeples will be separately presented.

The above comparative example emphasizes the role of geometry in preventing seismic damages. The message assigned by the myth of immolation seems to consist in the idea that by enlarging the three-lobed churches they become paraseismically shaped and accordingly protected against earthquakes. Definitely, it is a firm message of seismic protection.

7. ADVANCED CONCEPTS OF SEISMIC PROTECTION

Seismic design of masonry buildings and monuments is a high priority at the start of the new millennium. Human lives, cultural assets and the outstanding achievements of advanced technologies should be carefully preserved. Site collected data, test results and numerical models are being used to develop accurate and realistic methods for assessing structural performance during earthquakes. Presently, seismic design codes recommend either confining masonry with RC tie beams and tie-columns or reinforcing masonry with steel reinforcement. Both are currently applied and there is a long, rich experience with the two techniques.

The incorporation of RC members in masonry produces mixed or composite building structures and may dramatically affect building dynamic behaviour. Any interventions with RC or steel structural members, jacketing with reinforced cement plaster or providing stiffening ties, braces or diaphragms modify the initial design and the seismic response becomes less predictable. Non-regular buildings with asymmetries and setbacks are mostly affected by mechanical and physical non-homogeneity. Differences in both the unit mass and elastic modulus of the two materials, masonry and RC, influence the spatial locations of the centers of gravity and stiffness, as well as the relative distance between them. The differences in elastic modulus also inhibit true composite action in resisting forces. Moreover, RC structural members tend to concentrate the induced forces, which is particularly detrimental for brittle masonry.

Masonry performs better when it is reinforced with steel reinforcement and the induced forces by earthquakes are distributed. Only cement mortar is allowed in this case. Through the shrinkage of mortar the circular bars of steel are gripped and a phenomenon of strong adherence develops, allowing direct transfer of stresses from mortar to the reinforcement. However, due to high energy use during production, steel reinforcement is expensive. Additional expenses are often needed to provide anti-corrosion protection. These costs have promoted advanced technologies for the extensive production of non-metallic reinforcements. At a lower cost than steel reinforcement, they provide both strength and ductility. Some forms of non-metallic reinforcement, including fibers, are successfully replacing steel reinforcement. Most of the others are only alternative solutions. Polymer grids belong to this latter group. They are of special interest due to the simplicity of their use.

8. NATURAL DISASTERS AND ECONOMIC LOSES

According to the data published by **©Munich Re, REF/Geo–April 2001** the number of great natural disasters is exponentially increasing. Between 1950 and 1999 occurred 243 natural disasters of which 20 in the first decade 1950-1959 and 86 in the fifth decade 1980-1999, the factor 90s: 50s = 4.3 (Fig. 9).

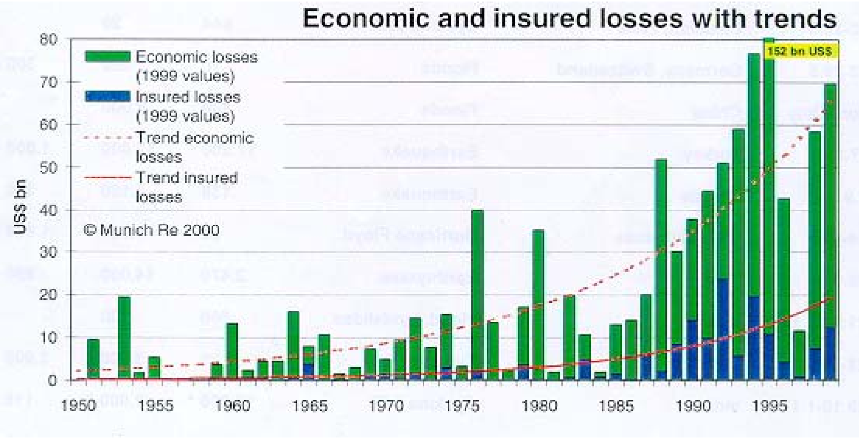

Figure 9: Economic and insured losses in US$ during the second half of last century

Total economic losses in fifty years reached US$1045.1 billion of which 39.6 in the first decade 1950-1959 and 607.0 in the fifth decade 1980-1999, the factor 90s: 50s = 15.3. During the year 2000 worldwide occurred 851 events with 9,267 fatalities and US$ 31,064 million losses. In the same year 2000 in Europe occurred 178 great disasters concluded with 411 fatalities and US$ 13,163 million losses. Floods, earthquakes and landslides are typical disasters for Europe. However, the funds spent for prevention of such natural phenomena are still far too little. What are worse the remarkable advances made by technology are not properly applied. Few regions benefit by the twenty-century technological discoveries. Although the performances of composite materials and structures are well known they are still little used for prevention of natural disasters.

9. SEISMIC RISK

Seismic hazard is defined by the probability of occurrence, within a specified period of time and in a given area, of a potentially damaging earthquake. There are three parameters considered typical for the peak ground motion: displacement, velocity and acceleration. The last parameter called *design ground acceleration* is abbreviated with DGA and defines the intensity of a predicted earthquake. They are expressed in the frequency ranges relevant to seismic engineering. Any other parameters obtained from site observations or simulated through theoretical signals can also be considered for defining the level of seismic hazard. Over the last two centuries in Romania, six earthquakes with magnitudes higher than 7.0 occurred as follows: October 26, 1802 – $M_w = 7.9$, November 26, 1829 - $M_w = 7.3$, January 11, 1838 - $M_w = 7.5$, November 10, 1940 - $M_w = 7.7$, March 4, 1977 - $M_w = 7.4$ and August 30, 1986 - $M_w = 7.1$, where the subscript *w* comes from Wood. In 1993, the seismic hazard map of Romanian territory was updated through the code SR 11100/1. For the Vrancea area, two typical sources of earthquakes have been identified: one located at the upper part of the slab at 90 km depth and another one at its lower part at 150 km. The corresponding peak ground motion parameters for Bucharest are 0.23*g*, 27 cm/s and 18 cm generated by the first source and 0.52*g*, 105 cm/s and 42 cm generated by the second one, where *g* is the acceleration due to gravity. Obviously, these values are rather large.

Seismic vulnerability of buildings and structures is the probability of occurrence in damage and losses corresponding to a specific level of seismic hazard. The observed vulnerability is related to the histograms as derived from post-earthquake surveys, while the predicted vulnerability consist in families of damage and loss distributions in terms of seismic intensity. The quantification of vulnerability is based on an adopted scale of damage degree, abbreviated by DD. There are five such degrees: 0 or None, 1 or Light, 2 or Moderate, 3 or Heavy, 4 or Total and 5 or Collapse. In Romania, for bearing masonry the following degrees are considered: not affected 0, slightly affected 1, cracked 1.75, highly cracked 2.50, out of vertical plan 4 and collapse 5, while for non-bearing masonry: not affected 0, cracked 1, partially collapsed 2, totally collapsed 3. For infill masonry the following

DD are considered: not affected 0, boundary cracks 1, extended cracks 1.5, strong cracking 2, dislocation 2.5 and collapse 3. The expected losses are also expressed in terms of DD. Finally, the assumed vulnerability characteristics are expressed in percentages.

By convolutions of hazard and vulnerability characteristics the seismic risk of buildings and structures is obtained. Seismic risk evaluations require appropriate quantification of elements at risk, namely the time or degree of exposure to seismic hazards and their importance or sensitivity in terms of expected losses and damage degrees. Such probabilistic analyses are affected by considerable uncertainties resulting from all categories of input data like hazard and vulnerability characteristics, expected conditional losses and cost-benefit balances. However, they are extremely useful for an efficient and objective structural design.

10. SYNTHETIC REINFORCEMENT

The proposed masonry reinforcement. is produced by extruding high-density polypropylene under controlled heating. During stretching, the randomly oriented long-chain polymer molecules are drawn to an ordered and aligned state that dramatically increases the tensile strength and stiffness of the grids. The orientation is maintained through both the ribs and junctions. From this technique, structural performance is enhanced in three ways. Firstly, a high modulus ensures mobilization of the high tensile strength at low strains. Secondly, the tendency for polymers to deform under long-term sustained loading is substantially reduced as confirmed by long-term testing. Thirdly, since the favorable molecular orientation is maintained through the junctions, it creates integral biaxial grids unlike the other types with woven or welded joints (Fig. 10).

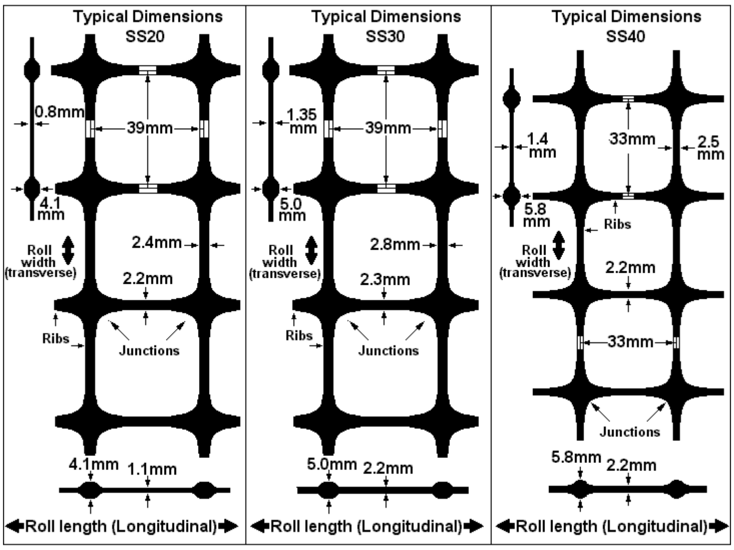

Figure 10: Geometric characteristics of polymer grids

When placed in a continuous medium such as mortar, the ribs that are transverse to the direction of primary loading act as a series of bearing surfaces or anchors. This is a highly efficient mechanism for transferring stress that mobilises the maximum benefit from the grid reinforcement and minimises anchorage lengths. According to tests performed at Drexel University, USA, junction strength is 91% to 100% of the tensile strength of a single rib for integral biaxial grids. This strength ratio is less than 10% for non-integral grids with melt bonded joints and 3% to 13% for non-integral biaxial grids with woven joints.

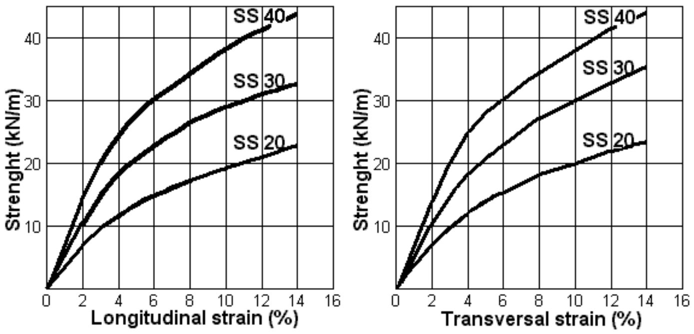

Figure 11: Characteristic strength-strain diagrams for polymer grids

The ribs of the integral biaxial grids are manufactured with near vertical faces, which provide an excellent bearing surface for interlocking with aggregate particles of the mortar. The interlocking mechanism between grid reinforcement and different matrices has been demonstrated in both laboratory and on site pull out testing. Polarised light has been used to view the rupture patterns during pull out testing of a grid in a bath containing sintered glass and glycerine. This effective interlock mechanism combined with high junction strength, sufficient constraining hoop bursting stress and high tensile stiffness at low strains, accounts for the efficiency of the biaxial grids in strengthening mortar and confining masonry. The reinforcing approach with synthetic grids essentially differs from that used for steel bars. Polymer grids are firmly fixed in mortar by interlocking of their joints. The mechanism of stress transfer from mortar to grids is discontinuous and produces only in the solid joints through normal stresses, without any contribution of the tangential ones. Only tensile forces are transferred from mortar to grids.

At present time there are available three qualities of polymeric grids with square apertures: *SS20, SS30* and *SS40* (Fig. 11). These figures indicate their controlled strength in *kN/m,* equal in both the transverse and longitudinal directions. Inserting such grids in bed joints prevents lateral expansion of the mortar through tensile forces in the grid. In addition, the tensile forces in grids together with shearing stresses at the two interfaces prevent the development of lateral strains in the horizontal plane. In this way the mortar is subjected to a triaxial state of compression, which substantially increases its bearing capacity. Since the strengths of grids are much higher than the loads transmitted by bricks, it is practically unnecessary to reinforce each bed joint. In most cases, reinforcing each fifth layer, or 2-3 layers per meter run, would be sufficient.

11. REINFORCING TECHNIQUES

For seismic protection of buildings and monuments, reinforcing the masonry structural members with polymer grids shows great potential. This work involves three specific techniques for reinforcing masonry with polymer grids: 1) inserting them in the horizontal layers of mortar between bricks; 2) coating the outer surfaces of masonry with reinforced plaster; and 3) confining the structural members with the same reinforced plaster. In all cases, synthetic reinforcement compensates for masonry’s lack of ductility and enhances its natural strength capacity.

The first technique improves load transfer capacity between the masonry units, since the reinforcement prevents horizontal expansion of mortar. As already mentioned, it is not necessary to lay the grids in all mortar beds, but only in some of them at vertical distances between 20 cm and 40 cm. The joints are obtained by superposition without any joining devices. Coating the masonry with reinforced plaster improves the shear resistance of the masonry wall, whether or not the horizontal reinforcement is present. This technique is efficient only when the reinforced plaster adheres well to the masonry surface. The effect of this type of reinforcement is bi-directional, in the plane of the wall. Finally, confinement with reinforced plaster improves both compression and shears resistance and is most efficient when combined with the reinforcement in horizontal layers. This type of reinforcement acts in a three-dimensional sense and can be used to increase the bearing capacity of structural members several times.

The polymer grids can be used as reinforcement for both engineered and non-engineered masonry within either new or old buildings. Each case should be analysed separately according to the characteristics of the masonry units and the mortar, as well as the type of construction. The importance of workmanship in this context cannot be overstated. Typical masonry configurations are commonly laid in “running” bond, with the units overlapped on half their length. Single-wythe, or barrier walls are most common. Multiple-wythe walls are also constructed and can consist of composite brick-block walls. However, cavity walls are not allowed in seismic areas.

All the available masonry units, such as bricks and blocks, can be associated with polymer grids. Clay units, dense or lightweight aggregate concrete units, autoclaved aerated concrete units, calcium silicate units and natural stones can be used in reinforced structural members. Solid clay bricks are the most efficient for use with reinforcing, since they produce a rather uniform pressure on the polymer grids. Vertically perforated bricks are also useful in reinforced masonry. In seismic areas vertically hollowed bricks are not recommended, while horizontally hollowed ones are prohibited. Three types of mortar are commonly used for masonry: cement, cement–lime and lime mortar. When masonry is reinforced with steel bars, lime is not allowed for corrosion reasons and only cement mortar should be used. On the contrary, for synthetic reinforcement there are no restrictions on mortar composition. Of course, the most common cement-lime mortar, in all code-specified proportions, can be freely used. In some cases, lime mortar may be preferred for special convenience. There is also no limitation on characteristic compressive strength of the mortar. The additives like plasticizer, air-entraining, water-retention and set-retarding agents can be freely associated with the polymer grids.

12. NEW MASONRY BUILDINGS

For reinforcing masonry in new buildings, the polymer grids are simply laid down in the bed joints and well covered with mortar. It is not necessary to insert grids into each bed joint. The tests on masonry models made of 240x120x60 mm solid bricks have shown that the influence of a single grid extends over five layers. When the vertical faces of a wall remain unplastered, then the width of grids should be within 20 mm less than the wall’s width. On the other hand, when the wall will be plastered the width of grid should be within 30 mm larger than the wall’s width (Fig. 12).

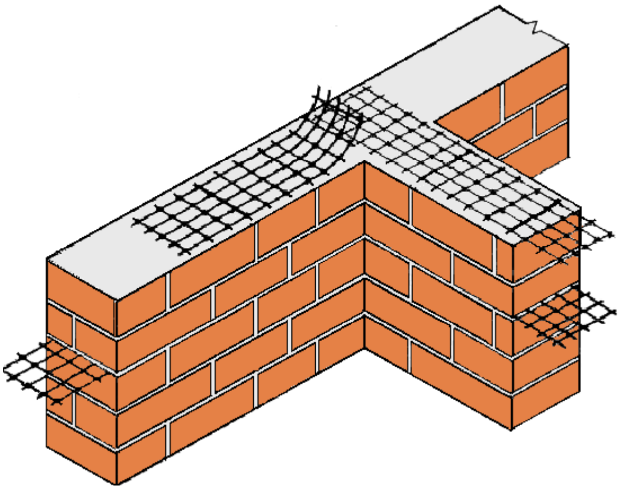

Figure 12: Isometric view of reinforced masonry

Masonry walls reinforced with such horizontal layers and submitted to seismic type loading, no longer exhibit diagonal cracking in an X-shaped pattern. This outstanding performance is obtained using 200-300 g of polymer grid per cubic meter of masonry, which corresponds to a supplementary cost of only 0.4 - 0.6%.

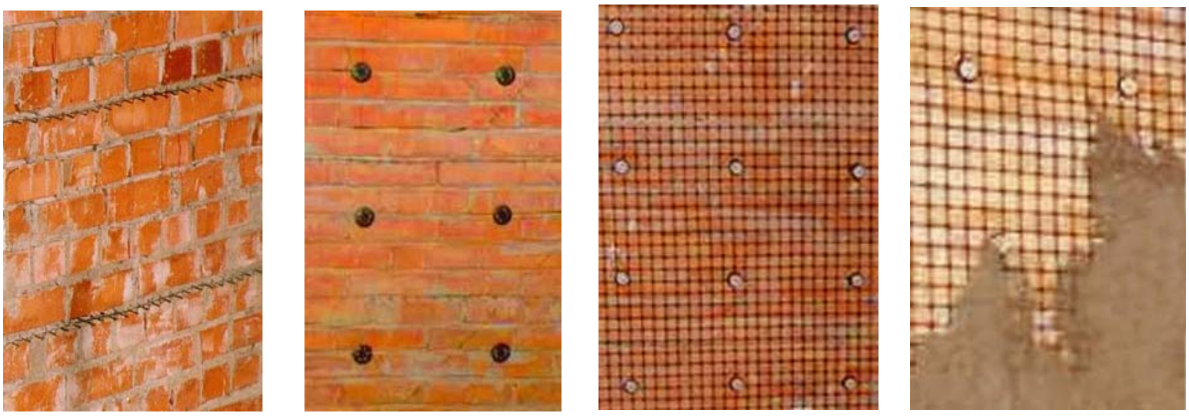

Figure 13: Horizontal reinforcing; Inserts for fixing devices; Fixing the polymer grids; Plastering

Coating or confining can further strengthen masonry structural members whether or not they are already reinforced in horizontal layers. For this purpose the following steps are usually recommended: cleaning the masonry surface, deepening the mortar between bricks a minimum of 10 mm, drilling the holes for fixing devices at a rate of at least four per square meter, inserting the plastic supports for the fixing nails (Fig. 13), applying and fixing the polymer grids and plastering. The fixing devices are provided to ensure good contact between the grids and masonry surface as well as a uniform thickness (15 to 20 mm) of plaster. After the plaster has hardened, the fixing devices do not contribute to any mechanism of stress transfer. Grid supplementary cost in this case increases up to 6% from the masonry value, but the marked improvements in strength and ductility fully justify the increase of cost.

13. DAMAGED BUILDINGS AND MONUMENTS

The most frequent causes of damage in masonry buildings are earthquakes, settlements and bad functional or technological use. To discover and locate the hidden faults, nondestructive methods like Impact-Echo are commonly used. All damages should be mapped in such a way to help the decision for retrofitting. For existing structures, the insertion of polymer grids in bed joints is no longer feasible. The most effective solution in this case is to confine the masonry structural members by wrapping them around with polymer grids and plastering. The confinement can be applied either locally, to isolated structural members like beams, columns, lintels, walls, as well as around openings for windows and doors, or globally, around the bodies of buildings. Note that in most cases, local faults and cracks need not be specially treated with the aid of resins or injections with binding solutions. Through confining actions, all concentrations of stresses are redistributed to the resistant zones of masonry structural members. For the sake of safety and quality control, a post strengthening nondestructive investigation is highly recommended.

14. TESTING VALIDATION

The method of reinforcing masonry with polymer grids was patented in 1995. The first static tests have been comparatively carried out on 12 short columns subjected to axial compression and on 18 wall panels subjected to both axial compression and diagonal tension. Then two three-dimensional models, one for masonry buildings and another for RC frames with masonry infills, have been successively tested on ISMES' shaking table in

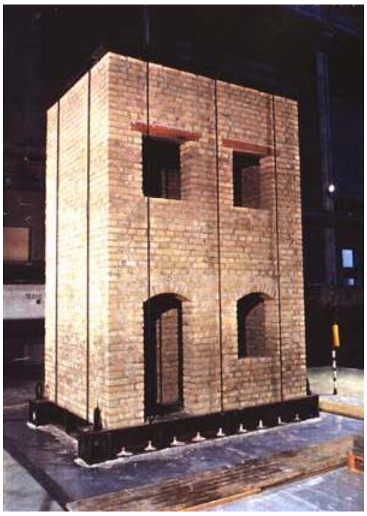

Figure 14: Plain masonry model

Figure 15: RC frame with masonry infills

Bergamo (Fig.14, 15). Further, some masonry infills reinforced with polymer grids have been included among other infill models comparatively tested to lateral actions at LNEC in Lisbon. The behaviour of masonry infills reinforced with polymer grids under lateral loads has been recently tested at the European Laboratory for Structural Assessment of the EC in Ispra. Two typical infills were chosen for testing at full scale: one full panel without openings for doors or windows and another one with two non-symmetric openings. The scope of the testing programme was to obtain basic data on the response of such infills when the surrounding frame is subjected to prescribed alternating lateral displacements of increasing amplitudes, in a manner that simulates earthquakes (Fig. 16).

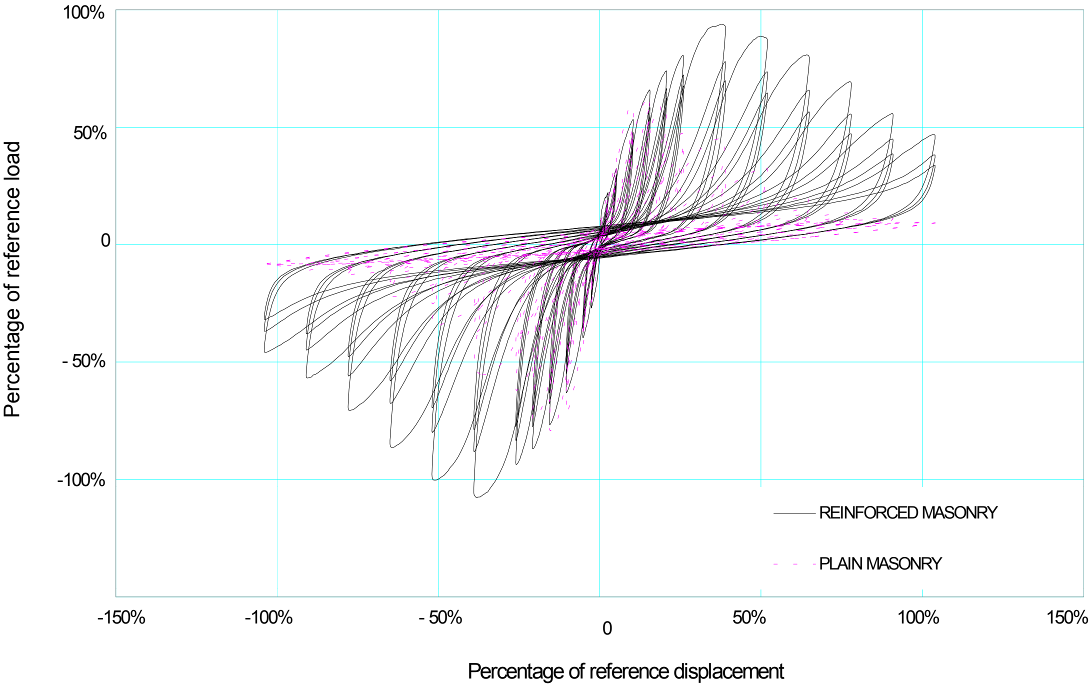

Figure 16: Comparative hysteresis diagrams of plain and reinforced masonry infills

Last testing program was devoted to seismic behaviour of masonry buildings reinforced with polymer grids and without RC structural members.. The aim of reinforcing was not only increasing the strength of masonry but also enhancing its ductility and capacity of energy dissipation as well as structural homogenization. Two 3D physical models of masonry buildings at full scale reinforced with polymer grids have been built up. One was made of cored bricks while another of solid bricks. The synthetic reinforcement was inserted only in horizontal bed joints and no RC structural members were provided. Both one-floor models have had a single axis of symmetry and were tested on the shaking table to the Vrancea'77 earthquake inputs. First model was submitted to 10 increasing shakes, beginning with an intensity of *0.025g* up to *0.7g,* while the second one to 11 shakes, from *0.0025g* to *0.8g*. The seismic responses of the two models were recorded by accelerometers fixed on the upper parts of the walls. The acquired data of testing were used for numerical modeling and validation. The concept of reinforcing masonry with polymer grids is based on Prandtl's mathematical model dated 1923. It was shown why the grids and not fibbers are the most appropriate materials for reinforcing masonry either in bed joints or by confining. Then, there has been checked the influence of the two intrinsic centers of gravity and stiffness on seismic behaviour of both models. Certainly, they are located on the symmetry axes. On the levels outside the openings for doors the two centers are superposed or almost superposed. On the contrary on the heights of openings for doors the centers of stiffness are located outside the bases of models. The eccentricities between the two centers are much higher than that provided by EC8 for seismic protection. The predicted moments of torsion developed at those levels have been confirmed on the shaking table. They are originating the most of damages in such masonry buildings. Finally, the structural control of reinforced masonry in the two models is successively expressed in term of stresses, strains and energetically. The energetic approach is the most advanced because has a holistic character and expresses the real costs of buildings (Figs. 17, 18).

Figure 17: Solid brick masonry

Figure 18: Cored brick masonry

15. CONCLUSION

Romanian cultural heritage is rich in castles, like those of Dracula's and churches, mostly of three-lobed plan. All are made of masonry. Stone or brick masonry with lime mortars. Masonry is not only the oldest construction material but also the most fascinating one. Indeed, it is a wonder how the elastic qualities of brittle units of natural stone or burned clay have been geometrically and mechanically combined with the ductile lime mortars in so long lasting artificial stone. Due to its self-protection quality of avoiding stress concentrations masonry embodies the concept of durability under its genuine form. This is also the chance of our cultural heritage. Unfortunately, the effects of natural and technologic hazards are almost exponentially cumulating. Some of the advanced technologies used for the maintenance or repair cultural heritage are either not quite proper or could alter the original concept on which masonry was based. For example in 1931 the International Charter of Restorations endorsed in Athens accepted *any advanced technique* for saving monuments but in 1964 the same forum expressed some reserves regarding the use of concrete and reinforced concrete. Nowadays there are the Recommendations of ICOMOS/ISCARSAH that recently were defined in Istanbul and will be published and distributed during the International Millennium Congress to be held on 10-12 September 2001 in Paris.

Polymer grids have proven to be one of the most appropriate reinforcements for repair and strengthening of masonry buildings of cultural heritage. They are cost effective, easily applied and long lasting construction materials. Neither additional qualification of labour nor extra devices is required. By using polymer grids, it became possible to eliminate massive RC members or expensive steel reinforcement and create more homogeneous masonry structures accordingly shaped. The existing theoretical background and validated testing data allow developing any conceptual design. The required degrees of safety are achieved on the basis of a *fail-safe* principle. Reinforcing techniques are applied either to existing damaged buildings for repair and retrofitting or to new buildings for strengthening and preventing damages. Polymer grids also solve the problem of compatibility between the old, possibly ancient, and new construction materials for preserving or restoring historical buildings and monuments of cultural heritage. Indeed, one of the most important advantages of polymer grids as reinforcement consists in the fact that cement can be eliminated from the mortar composition and, if necessary, only lime mortar or other binding materials compatible with the polymer can be used. Romanian authorities already delivered the technical agreement for use of polymer grids for repairing masonry buildings in seismic areas.

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