State of Art of Technologies for Safeguarding Historic Structures in Bulgaria

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1. ABSTRACT

In this paper new and traditional technologies for analysis, restoration, repair, maintenance and strengthening of historic structures in Bulgaria are presented. It is emphasized on the masonry structures as churches, mosques, synagogues, monasteries, tombs, towers, belfries, minarets, etc. A short review of the valuable Bulgarian architectural, historic and cultural is shown. The general peculiarities of these structures are discussed. The models and methods for their analysis are regarded and compared. The seismic response and analysis are drawn. Basic methods and techniques applied for safeguarding and renovation of such structures are described. Important examples of some typical representative historic monuments from different historic epochs are given. Experience, state and problems in this domain are outlined. Conclusions, recommendations and proposals for study, repair, exhibiting, maintenance and strengthening of historic structures are derived.

2. INTRODUCTION

The cultural heritage of Bulgaria is exclusively rich and diverse. It reflects our national history. Some of these monuments have world meaning and they are under the aegis of UNESCO. Our duty is to safeguarding and show this valuable richness.

Basic definitions and classifications in this domain should be taken into account. Following the World Heritage Committee in conformity with the World Heritage Convention it has developed a system of operational guidelines which can be maintained and revised as necessary. The following three categories are specified as world cultural heritage as well:

Monuments. Architectural works and works of monumental sculptures are included in this category. Also, structures that have archeological nature and cave dwellings should be considered in this class. Works that have outstanding value from the viewpoint of the history, art and science are specified to be considered as monuments too.

Particularly for Bulgaria, this class is represented by a number of old churches in Sofia, Svishtov, Veliko Turnovo, Nessebar, Roman theater in Plovdiv, etc.

Groups of buildings. These are groups of separate or connected buildings which, because of their architecture, homogeneity or place in the landscape, are of outstanding universal value from the point of view of history, art or science.

This class is represented by a number of houses typical for the period of the Bulgarian Renaissance in the town in Plovdiv, Koprivshtitza, Veliko Turnovo, Melnik, etc. These houses are related to the Bulgarian traditions and culture.

Sites. These are works of man or the combined works of nature and of man, and areas including archeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological point of view.

From the viewpoint of the civil engineering the first two categories are the most essential for repairing, strengthening and rehabilitation. For the sake of simplicity in the further considerations this two categories will be called shortly “ancient structures” or “historic structures”.

The historic epochs were made their influences by the characteristic religious structures. Peoples of different ethnic were lived at the Bulgarian territory. They were left their effect on the temples and other monuments connected with the religious rituals. The historic processes effect also strong to the church construction. There are magnificent paragons of this imposing group of historic structures dated from different historic periods. Some of these masterpieces were built by genius past masters and they are real sacred monuments. They bring distinguishing marks of their times. First of all they depend on the canonical function of these structures and the state of the nation (scientific knowledge, technological level, financial possibilities, state management, etc.) during the period of their construction. The religious canonical requirements are very strong and therefore all human interventions to the historic structures should be conformable to them. The engineering interventions should be realized only when all reserves of the historic structures are exhausted. These interventions should be minimal and appropriate. Usually these activities must keep the external and internal architecture of the visible parts of the unique historic structures. Strong control on the human activities in this domain is need to safeguarding the valuable cultural heritage. In view of these numerous and strong limitations and requirements the restoration and preservation works including engineering works meet many difficulties.

The multi and inter disciplinary team is need for restoration and preservation works. It should includes investigators, specialists, designers, executors, investors, users, etc. Architects, geologists, civil, heating, electrical, hydraulic engineers, painters, chemists, etc. are members of these group. The activity of this body should be subordinated to the following factors: information for the state of the cultural monuments, methods for the management of information, the process of intervention in the monument, the human resources and the standard base. The second factor is especially important. The responsibility of these professionals is enormous. Their works of high quality and their professionalism are compulsory in the name of all human society. Violations, mistakes and lapses are inadmissible.

Three main subsequent steps should be carried out in the process of safeguarding of the cultural monuments: monitoring, analysis and restoration and preservation. The monitoring is an expensive activity and it is applied rare in Bulgaria. But experts make inspections on these monuments. Each monument should be provided with a “passport” in which all changes, interventions and other data should be recorded. It is established National Institute for the Monuments of the Culture. Its specialists study the state of these structures, manage and inspect their restoration and preservation. There are some national licensed laboratories for testing of construction and soil materials.

3. GENERAL FEATURES OF HISTORIC STRUCRURES AS GUIDELINES FOR REHABILITATION

Stones, bricks, wood and mortar were typical construction materials in old times. Stones and bricks were ordinary made by special technologies. For example the ancient Roman masters were used special clay for producing bricks. The clay were washed out by a large quantity of water. Then the clay were matured for some time. After that the bricks were fired into special furnaces in a high-temperature regime. This production process was continued about one year. The stone blocks were left in natural conditions for a long time and the cracked blocks were not used. The stones were cut out or knocking out very carefully. Often travertine and limestone are used. The mortar was mixed with river felt and brick small pieces. Therefore the joints in ancient and old masonry are about 4-5 cm thick. In the cases where the masonry is not wear-out the up-to-date tests sometimes determine significant higher strengths of these construction materials in comparison with the present-day ones.

Usually the historic structures have shallow embedded stone masonry strip foundations or column footings, large span and high premises, complex geometrical forms, underground basements, massive masonry walls minimum 60 cm thick, internal rows of masonry columns, vaults, domes, arches without or with wooden or wrought iron tension members in one or two rows and in one or two directions, roofs of different levels, wooden balconies, frescos, etc. Often the structure above the cornice level is with equal ceiling on trim joists at one or different levels. Usually one vertical longitudinal plane of symmetry exists. The stone masonry is mostly implemented.

The cultural heritage as churches, historical buildings and monuments have specific features and deserves special attention when their civil engineering parameters are to be improved. In a number of cases conventional methods for repairing and strengthening can not be applied in ancient structures. It is worth mentioning the following **features** that are common for large classes of ancient structures:

The construction technologies used in ancient structures are quite different from the up-to-date technologies.

1. Considering stone and brick masonry structures, their lateral stiffness is mainly influenced by the gravity effects and adhesion between separate blocks/bricks.
2. The loads that are considered within the analysis are mainly vertical (dead and live loads). However for seismic active areas like Bulgaria where seismic risk is potentially large, seismic type of loading appears to be quite unfavorable.
3. Dynamic parameters of ancient structures are not favorable from the viewpoint of the aseismic design. For example the fundamental period of such type of structures ranges between 0.10 – 0.30 s, i.e. they are very rigid. The consequence is that such structures are much sensitive to pulse type of loading. Stone and brick masonry both have large specific mass.
4. Ancient structures are not ductile and their failure modes show tendencies of brittle fracture. Current design philosophy based on the reduction of seismic forces as because of inelastic behavior can not be applied.
5. Repairing and strengthening of the ancient structures should be so performed as to keep architectural style and some other requirements that are to be satisfied from canonical point of view.
6. Traditional methods for modeling, calculation and design are not directly applicable to the analysis. For example, the well known finite element method needs additional upgrade in order to obtain more adequate solutions. The idea for development of problem-oriented software is very fruitful for the purposes of ancient structures analysis.
7. In contrast with the conventional buildings in ancient structures no damages are allowed. The prevention from earthquakes implies lack of damages.

These structures were well predicted to sustain only or predominantly basic vertical loads as self weight, useful and snow loads. Possible damages caused by these loads are the following [14]: wear-out of the stones and mortar, putrefaction and decrease the bearing capacity of the wooden material. As a result deflections, geometrical changes, shear of the cross section, crease of the supporting parts occur and can be attended with carrying away of the above structure.

But the historic structures are also subjected to horizontal reversal loads caused first of all by earthquakes and wind loads too. The wind loads influence slightly on religious buildings but strong on some high-rise structures as minarets, towers, belfries. In almost all cases the historic religious structures are not ensured to withstand the special horizontal loads originated from strong earthquakes. Almost all Bulgarian territory fall into a seismic active zone. A large part of the rich Bulgarian culture and historic heritage was effected by the numerous past strong earthquakes. Many historic monuments were endured significant damages and failures caused first of all by catastrophic earthquakes and climatic effects. They have no half-storey plates to redistributed the horizontal loads. Their horizontal strength and the spatial interaction of the structural elements are insufficient or absent. They resist mainly by their self weight and work by shear predominantly. (Fig. 1). Their shear base coefficient at some level, i.e. above structure weight to a horizontal force ratio is up to 0,10, while for the usual buildings this ratio is between 0,20-0,40. That is mean the ancient masonry structures withstand horizontal loads up to 10 % large versus vertical loads. The masonry tensile strength is very little. They can not dissipate energy. Therefore they are quite sensitive to horizontal loads, tensile stresses in structural elements and non-uniform settlements of the subsoil. They are in danger to a brittle demolition, if their bearing capacity is exceeded (Fig. 2).

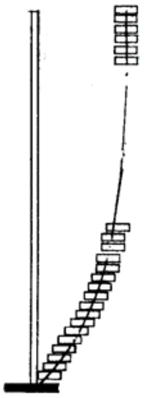


Fig. 1. Simplest model for church seismic response

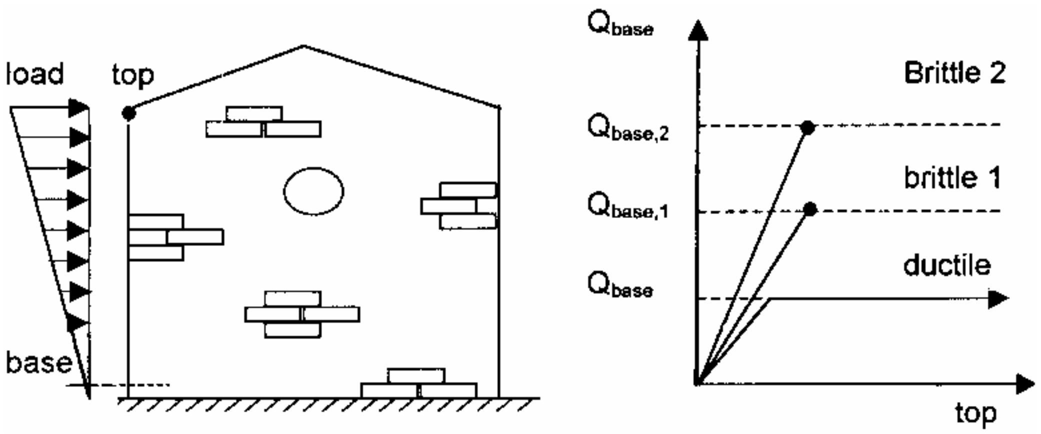


Fig. 2. Base shear - top displacement relationship for ductile and brittle structures subjected to lateral monotonically increased static load

In addition during earthquakes specific crack meshes propagate (Figs. 3, 4), the available tension members get loose or they are pulled out, the internal columns are inclined, the supporting nodes of the trim joists and beams of the roof structure are damaged. Strains, crack propagation, deplanation and disemboweling of the masonry, failures, non-uniform subsoil settlements are the most spread damages in these structures. This insufficient horizontal loading capacity of the historic religious structures is always limiting for their state. Significant construction interventions are need to safeguarding them according to current design codes and standards.

During the catastrophic earthquake in 1858 in Sofia there were 24 mosques and 7 churches. But the minarets of 19 mosques were destroyed and large cracks were arisen. Only 2 churches were stayed fitted for use too.

Capillary humidity, aggressive effect of the candle smoke, the human temperature and humidity arising by the congregation and visitors are other external actions on these structures. These actions and especially the humidity effect also on such structures.

4. IMPROVING THE SEISMIC RESISTANCE OF HISTORIC STRUCTURES

As it is mentioned above, ancient structures are not ductile and are unable to dissipate energy. In contrast with the newly designed buildings their failure mechanisms are in a large extent related to brittle failure. The amount of inelastic strains that is expected in ancient structures is considerably small to ensure seismic loading reduction and seismic protection. Thus, it is implied that linear elastic behavior is still valid. After exceeding the elastic limits the capacity of the structure is soon reached and then the structure is collapsed.

Figure 2 illustrates the principle of strengthening that is used as basic philosophy. A single wall structure is considered being subjected to monotonically increased lateral load. This type of analysis is often used to predict some of the properties of the system.

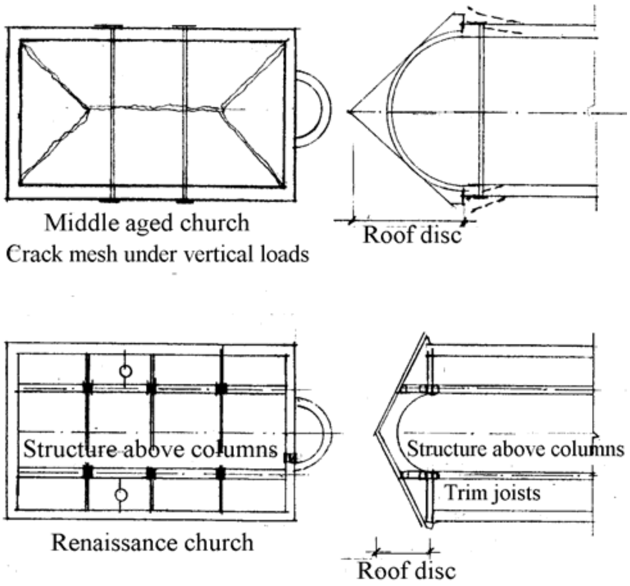


Fig. 3. Simplifies schemes of churches and typical crack mesh under vertical loads

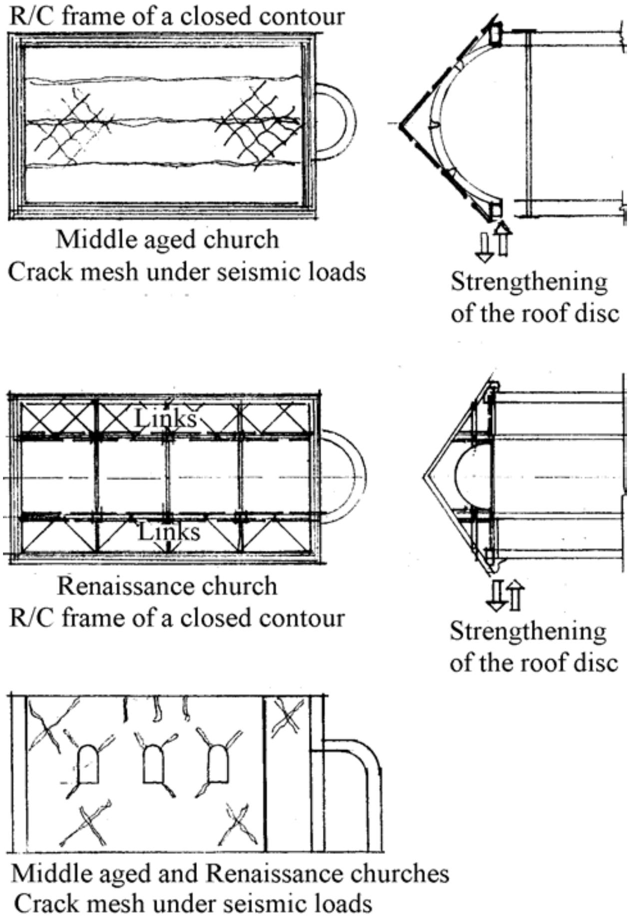


Fig. 4. Simplified schemes of churches, typical crack mesh under seismic actions and roof strengthening

The relationship base shear Q_{base} – top displacement, v_{top} , is selected as representative for structural behavior. Current design philosophy enables the structure to dissipate energy by making it ductile (see the plot of the line denoted by *"ductile")*. The elastic limit is slightly exceeded and inelastic behavior is initiated.

The plot of the next two curves in Fig. 2 is given for better understanding the difference that exists between ductile and brittle structures. The line denoted by *“brittle 1”* is representative for structure, whose capacity in shear is $Q_{base.1}$. Before reaching this limit structure will remain elastic. For a value of $Q_{base,2}$ slightly greater than $Q_{base,1}$ structure will be fractured. If this structure is to be improved, its strength should be increased rather its stiffness (see the curve, denoted by *“brittle 2”*). It means that the strength is increased reaching the value $Q_{base,2}$. The idea of strengthening is to increase structure strength using structural engineering approaches.

The reasons for important structural defects in the historic structures can be summarizes and generalized in three groups as follows:

- Mistakes during the construction, operation and repair because of insufficient knowledge of the construction science;
- Deformations, crack propagation and damages caused by the basic loads;
- Deformations, cracks and damages due to seismic actions;
- Environmental conditions as sun radiation, water, rain, humidity, frost, temperature changes, air pollution, etc.

5. ANALYSIS OF HISTORIC STRUCTURES

The antiseismic insurance of the historic religious structures is more difficult. Many problems arise. First of all the real available carrying capacity of the structure is to be carefully studied and evaluated. The physical-mechanical characteristics of the original construction materials (stones, bricks, mortar, wood) of the bearing elements, the soil and the properties of the whole examined structure should be studied carefully by field and laboratory tests using the experimental and analytical methods of the structural physics, soil mechanics and construction materials. Especially shear test of the masonry is need. The tangential (shear) strength in horizontal direction versus the normal tensile and compressive stresses in vertical direction in conditions of different normal and tangential horizontal stresses are the most important characteristic diagrams of the masonry. Non-destructive or destructive experimental methods can be implemented. Full-scale dynamic and static experiments of the structure are need to determine the free vibration periods, distortions, displacements, inclinations, settlements. This test can be accomplished by special dynamic equipment. The displacements are measured by transducers located at appropriate places of the structure in plan and in height. The crack mesh propagation should be studied too.

The current seismic design codes are not treated this type of special and complex structures. Adequate mechanical-mathematical models of the structure should be used in research. The effective up-to-date methods should be applied in dynamic and seismic analysis. First of all the finite element method (FEM) is most appropriate for structural analysis. Thick shell or 3D brick elements of higher order are adequate for modeling of walls, vaults and domes. Thick beam-column or 3D brick elements of higher order are suitable for idealization of the columns, foundations and arches. Special masonry models and elements can be utilized also. The shear are to be taken into account. The cracks in masonry can be modeled in some ways: by finite elements with double unconnected nodes at the two sides of the crack, with orthotropic elements of different properties in parallel and orthogonal directions to the crack, using special finite elements provided with special properties as gap elements, etc. In the first case large stress concentration is obtained. In the second case the value of Young’s modulus in the crack orthogonal direction can be assumed 5-10 times less than in parallel direction. In this case stress concentration is slightly expressed. All finite elements should be orthotropic since the value of Young’s modulus in horizontal direction, i.e. parallel to the horizontal joints between the masonry rows is less than in vertical direction, i.e. orthogonal to these joints. The old thin shell elements of lower order and plane initial geometry are too inaccurate. They are provided with 5 DOF - 3 displacements and 2 rotations - in each corner node. These elements lead to non-smooth diagrams of the internal moments at the nodes since the curvatures expressed by the second derivatives of the displacements are not included as basic unknowns (DOF) and there are no internal nodes at the element sides. Therefore fine meshes should be implemented. The new thick and thin shell finite elements of higher order with curved initial geometry and including shear are significantly more precise. They are assumed to provide with 6-9 DOF - 3 displacements, 2-3 rotations and 2-3 curvatures - in each node and have internal nodes on the element sides and in the shell thickness. As a result smooth diagrams of the internal moments at the nodes are obtained. Then rough meshes can be used. Results obtained by some models and methods should be compared.

During strong earthquakes the historic structures should be kept in view of their importance. The modal superposition method and the response spectrum method can be used in linear seismic analysis. Two equal or correlated horizontal simultaneous spectra in parallel and orthogonal directions to the church main entrance can be used. Then the results will be on the safety side. A preliminary solution to a vertical seismic spectrum usually establish that for this type of structures the internal forces caused by a vertical seismic spectrum are usually less than 30 % to the internal forces originated by dead vertical loads. In these cases a vertical spectrum is not need according the design codes for masonry structures. Non-linear time history seismic analysis is recommended and rational for such unique and important structures. In such cases real characteristics of the construction materials including non-homogeneous or orthotropic masonry and adequate real or artificial accelerogramms of the region and the site should be taken into account. As a rule two criteria for masonry failure can be applied. They cover displacement and force requirements respectively. Powerful and multi-purpose computer programs as ANSYS, COSMOS, NASTRAN, ABACUS, SAP, TOWER, ALGOR, STAAD, etc. are desirable (need). The complex geometry can be previously idealized by the AUTOCAD, SOLID EDGE, COREL DRAW, PRO-ENGINEER, etc. programs.

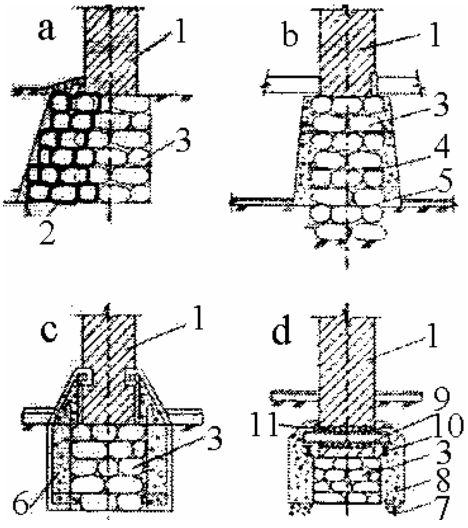
The structure are to be investigated numerically and/or experimentally before and after the strengthening. Comparisons and assessments are need. Moreover the structure must be ensured in all periods of its structural renovation.

6. METHODS AND TECHNOLOGIES FOR STRENGTHENING OF HISTORIC STRUCTURES

The restoration and preservation of historic structures is difficult, important and responsible problem. New effective and adequate methods, materials and technologies should be used to ensure their reliability. Experienced experts should be engaged. Restoration works are expensive too. They need to be executed of high quality. The strengthening can not increase the ductility of these structures but it can enlarge their bearing capacity (limit for brittle failure). Seismic isolation or vibration dampers are almost impossible in such structures. The research results and estimation serve to make a precise diagnostics and to accept right and optimal approach for the strengthening.

Some methods for strengthening of the masonry foundations are shown in Fig. 5 [11]. The aim of this approach is to reach strong soil at deeper level and to decrease the stresses in the soil-foundation contact surface by enlargement of the foundations. In the case a) the dimensions of the foundation basic plane are spread by new stone masonry built-in in the old masonry making bond between them. To improve this connection steel anchors of diameters 12 to 16 mm and class A-III can be anchored in the horizontal joints at a distance 50-60 cm and cement-lime mortar can be used as a connection. In the case b) the strengthening of the existing masonry foundations is realized by execution of the concrete enclosures. Steel anchors can be driven in the horizontal joints of the masonry to withstand the horizontal forces arising in the vertical joints between the masonry and the concrete enclosure. In the case c) the strengthening is analogous to the case b) but the concrete enclosure is reinforced by transverse and longitudinal reinforcement. In the case d) for stronger overloading of the existing masonry foundations the strengthening is carried out using the concrete enclosures united by horizontal bearing steel beams of spacing 1,5-2,0 m. They distribute the concentrated loads in longitudinal direction between longitudinal beams built-in into the concrete enclosure. The transverse beams cross via holes bored through the existing foundations. The holes are about 50 cm in dimensions and after the mounting of the cross beams they are filled up by concrete. The simplified diagram of the stresses at the subsoil before and after application of the additional loading is drawn in Fig. 6.

In the case of the cohesionless soils, If the masonry foundations are in a good state, their load capacity can be increased by their silicatization, i.e. by injection of cement mortar and water glass. If the soils are cohesive, it can be implemented an electrical-chemical method to enhance their carrying capacity (Fig. 7).



a - Enlarging of the masonry base by stone masonry

b, d - Enlarging by a concrete enclosure

c - Enlarging by a reinforced concrete enclosure

1 - Masonry

2 - New masonry, connected with the existing ones

3 - Old masonry

Anchors

5 - Concrete enclosure

6 - Reinforced concrete enclosure

7 - Sand bed

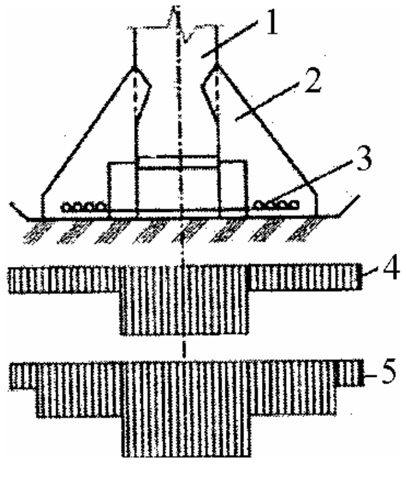
8 - Concrete add

9 - Bearing beam

10 - Distributing beam

11 - Thickening concrete

Fig. 5. Methods for strengthening the bases



1 - Existing foundation

2 - Enlargement of the base

3 - Reinforcement

4 - Simple diagram of the compression loads before the enlargement

5 - Simple diagram of the compression loads after the enlargement and additional loading on the foundation

Fig. 6. Simple scheme of the increased loading under the foundations

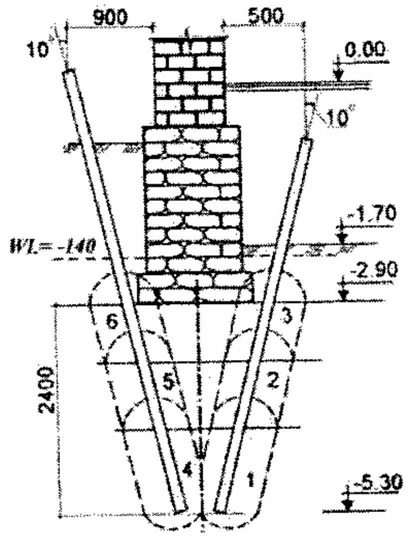


Fig. 7. Electrical-chemical strengthening of the soil under the foundations

Some of these historic structures were built at sloping land. The rain and surface water were caused common wetting and erosion of the masonry. Therefore on the side of water moistening dry channels were built to collect and lead away water and the walls to remain dry.

There are not serious problems about the strengthening of the historic structure to vertical loads. The main ideas and principles are presented here. The old and rotten bearing elements are replaced or strengthened. The damaged masonry can be rebuilt. The damaged tension members are also substituted by the new steel ones including the anchor places. Different types of braces are used: steel (bars, shaped iron), wooden (circular, rectangular), steel with wooden cover, etc. The braces can be anchored by epoxide resin directly in the holes bored in the masonry. They can be anchored outside of the reinforced concrete legs (footings) hidden into the masonry wall. The holes can be drilled through the whole wall thickness and the anchorage can be made outside of the wall. Sometimes the tension members are provided with pipe thread to be tightened, if it is need. The damaged internal columns are replaced or strengthening in their lower footing. The cracks are filled up by appropriate structural mortar neutral to the masonry. All these activities require permanent and continuous contact between the structural engineer, architect, painter hydroengineer, heating engineer and engineer-geologist to control the results from the intervention. The capillary humidity is removed by adequate in disposition and in type isolations, air channels and floors, electrical heating, injection of masonry and subsoil for their hydrophobization. The insufficient foundation in depth, type and dimensions can be improved by spreading and tamping. In special cases the appropriate foundation pile system can be applied.

The seismic vulnerability of these structures can be decreased by hardening of the roof disk (Figs. 4, 8) [14], i.e. by maximal diminishing of its strains and the seismic internal forces to be transfered onto the existing outer masonry wall. To achieve this aim at the top of the walls at the cornice level a hidden horizontal closed reinforced concrete frame (ring) can be built and connected by dowels with the underlain existing masonry (Fig. 9). It is very important to ensure the reliable anchorage of the hardened roof disc into the r/c frame. This frame can be provided with vertical r/c legs with or without footings hidden in the masonry walls too (Fig. 10). In this way better connection between the frame and the walls is achieved and the braces can be anchored more reliable through the r/c legs or footings. If the roof is located at different levels, this frame can be built at the top of the largest and higher main structural body. Besides, if the limitations admit, vertical r/c columns hidden in masonry or as external wall pilasters can be also built and connected with the roof frame forming a space r/c system. But usually the canons of the East Orthodox Church do not permit the pilasters.

Another way to strengthening the historic religious structure is to build a new r/c roof (vaults, domes, etc.) located above the existing damaged masonry roof (Figs. 8-10). The new roof is structurally connected with the r/c roof supporting frame (ring) mentioned above. This roof can cover directly the old one or by an air interlayer to ensure the “breathing” of the existing roof. This is need in order to keep the climatic conditions in the temple. In this way the frescos can be preserved more successfully. The connection between the two roofs is realized by steel anchors (dowels) built-in them. In this way the old roof is hanged to the new one. This method is especially suitable in the case of very damaged existing roof. The new roof can be cast-in-situ or be built by light concrete blocks. In the second case thin steel meshes are used in the joints between the adjacent blocks. Ordinary it is assumed the new roof will sustain the old one. Besides the new roof prevents the old one from outside to the surrounding environment effects and can improve its isolations too.

In another version of this idea the new roof can be built directly on the old one as a thin cover constructed by structural polymer mortar reinforced by thin steel meshes and strips of geotextile (geo-nets). The holes were remained in the cover to breath the old roof. This approach is implemented in the church “St. Iliia” in Iliiamtzi [14].

Such idea can be extended if the old damaged masonry roof is hanged on steel roof frames anchored in the r/c roof horizontal frame hidden in the walls (Fig. 11). To ease the hanging a central r/c beam built-in the old roof can be used. This technique was applied to the church “St. George” in Kremikovtzi [14].

In other cases the pretension of cracked walls in one or in two directions (horizontal and/or vertical) will increase the load capacity of the structure.

If there are no other possibilities or they are insufficient, some monuments can be visibly strengthened from inside and/or outside. For example the structure can be girded with external horizontal closed steel or r/c frames which tighten the masonry walls. Horizontal ray-type beams can connect these frames with steel or r/c columns erected at a certain distance to the old building. All monument can be put on by transparent plastic to keep the visibility. The polymer can contents built-in special fibers for heating and thaw the snow by electricity.

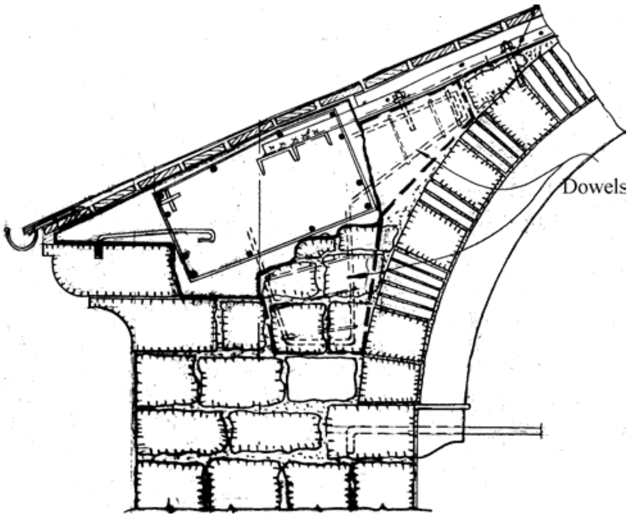


Fig. 8. Strengthening of the damaged masonry vault (dome) by hanging it on the new r/c one located above

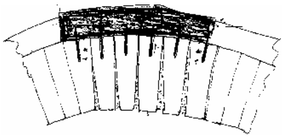


Fig. 9. Dowels between the new and old roofs

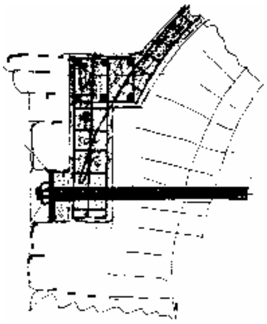


Fig. 10. Legs, footings and brace anchorage

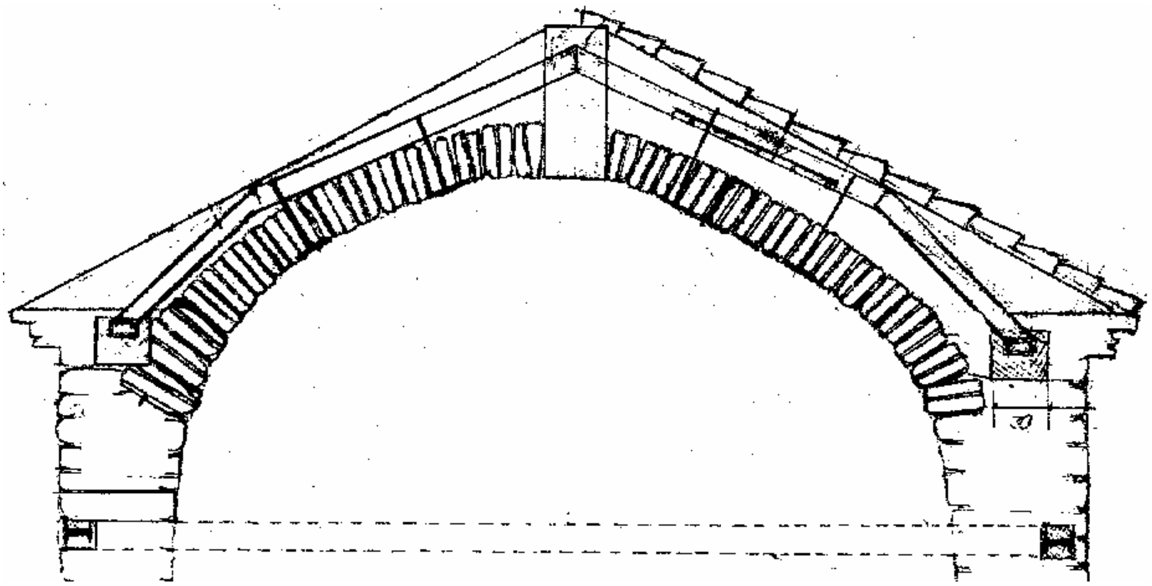


Fig. 11. Strengthening of the damaged masonry vault by hanging it on the steel frame above

It is admissible for some monuments as minarets, towers, belfries, etc. to change them from inside. In these case the strengthening can be executed by construction of an internal thin r/c enclosure connected with the old masonry walls by steel dowels. The reinforcement consists of thin straight and curved bars. The role of dowels can be performed also preliminary cleaned joints of the existing masonry removing their visible mortar and then gunite is injected.

If the limitations admit, r/c columns and beams can be constructed outside and structurally connected directly with the external walls. This new r/c space structure can be hidden by stone facing or brickwork casing from outside. This technology was applied in the church in Eleshnitza.

Besides in these easy cases the cracked walls can be restored as the following (Fig. 12) [11]. The old plaster is removed. On the two sides of the masonry steel meshes are mounted. They are united by steel anchors, crossing through the entire wall thickness at spacing 50-60 cm. The mesh covers the cracked surface and exceeds its bounds of 50-60 cm. Then the masonry and meshes are injected by the gunite 2,5-3,0 cm thick. If the crack reaches to the wall corner, the strengthening meshes continue minimum 100 cm in the opposite side (Fig. 13). If the wall masonry cracks are strong, an more essential intervention is need (Fig. 14). On the two ends of the crack vertical columns passing through the whole masonry thickness are executed. The crack is crossed by intermediate horizontal and vertical belt courses located chess on the external and internal masonry sides. The pilaster thickness is from 10 to 15 cm. The brick masonry between them is reinforced with a mesh and then it is injected by gunite 1,5-3,0 cm thick. The masonry top end should be finished with a r/c belt course which to catch the roof wooden structure (Fig. 15).

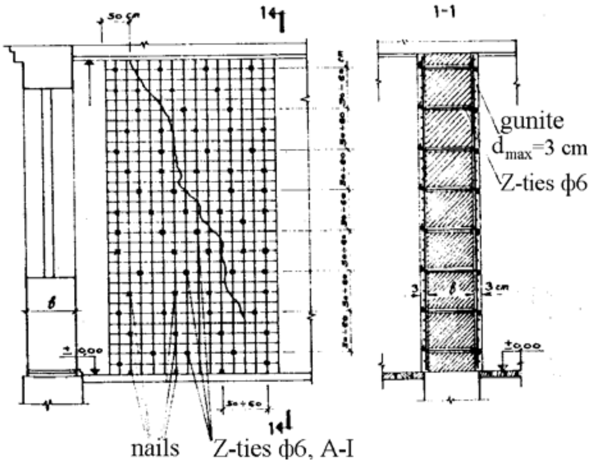


Fig. 12. Strengthening of the cracked masonry

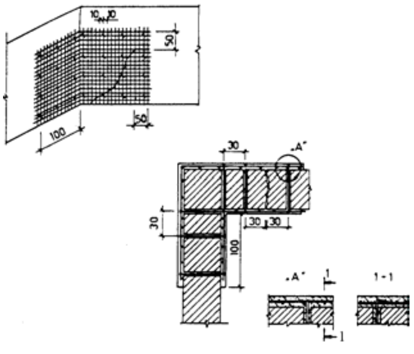


Fig. 13. Strengthening of the cracked masonry in the corner zone

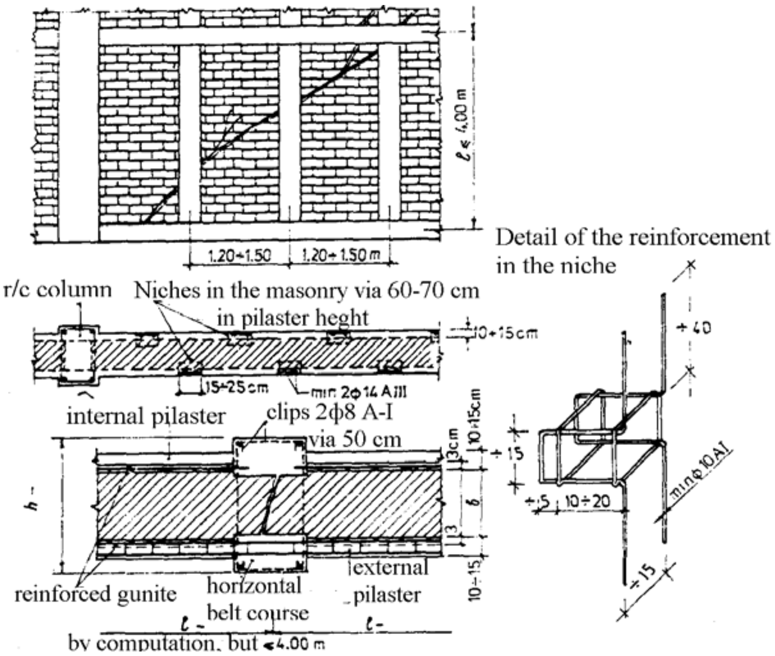


Fig. 14. Strengthening of the masonry with strong cracks

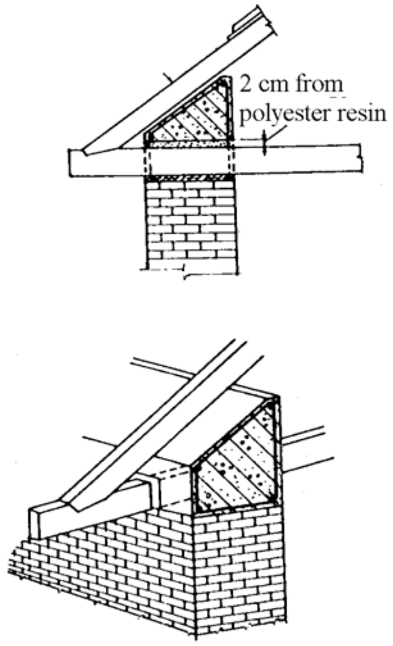


Fig. 15. Connection between the masonry and the wooden roof

If openings in the brick masonry are need, the two-side of the masonry can be covered with meshes anchored at intervals of 50-60 cm (Fig. 16) [11]. Moreover strengthening by the vertical and horizontal bars (above the opening) minimum 4N14 anchored at least 50-60 cm after and on the two masonry sides is need. To prevent the shear strains in the masonry around the opening, it is reinforced by horizontal and vertical stirrups on the opening contour. In the case of wall up the existing openings, they are reinforced by horizontal meshes via 3-4 brick rows (Fig.17). The strengthening of the strip between two walls located in one plane, can be made by cold formed shaped steel in the corners of the strip and its reinforcing by transverse and longitudinal bars continuing out of the strip minimum 50-60 cm still.

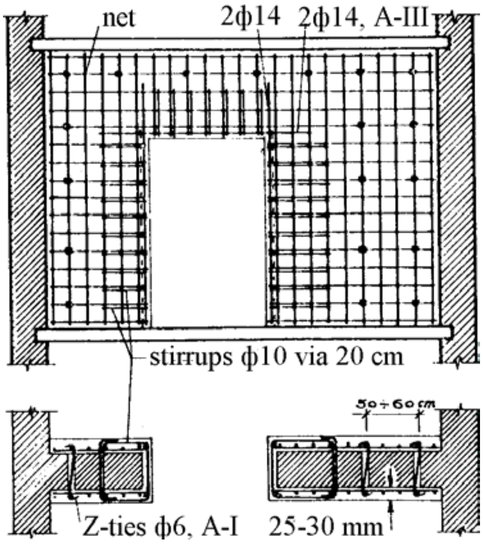


Fig. 16. Strengthening of masonry with an opening

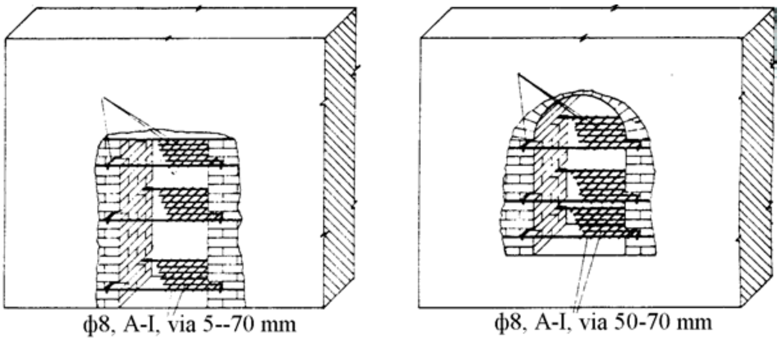


Fig. 17. Block up the existing openings

The deformed vault or arch can be contemporary supported by wooden (from the oak core) or steel curve-pieces. If steel pipe will be used, preliminary a sample is made by a steel bar 6,5 mm in diameter, bent on the real curvature. Then the steel pipe is bent using the thin sample bar.

The cracks can be filled up by mix prepared by epoxide resin, stone, marble sand and brick powder and hardener. Large cracks can be enlarged and excavated to 8-10 cm in depth and then to be injected. Another way is to plaster up slightly the cracks by a thin layer of mix prepared by gypsum and stone or brick powder and then the internal cavities of the cracks to be filled up gravitationally by epoxide resin poured out carefully from above. In such cases good thickening of the cracks can be achieved.

First of all in the beginning of the restoration and preservation process the monument is covered by contemporary steel cover till the necessary amount for safeguarding works is available. This cover is used also during the construction works. It is made by steel frames (columns and beams) and corrugated iron for roof and walls.

The engineering systems (heating, ventilation and electrical systems, a water supply and sewerage system) should be put in order also. In view of the features of the liturgy the heating system should be appropriate also to keep the interior and micro climate and to be economic. The heating systems used are by electrical heaters under the floor, by channels in which hot air circulates, by radiators, etc. In some cases special computer programs are implemented to find the optimal decision. Ventilation systems are only utilized in limited cases due to the interior, heating and climate.

7. PRESERVED AND RESTORED HISTORIC STRUCTURES

7.1 Strengthening of the tomb in Sveshtary

This tomb (Figs. 18-20) was built in 4th-3rd century B. C. for a Thracian eminent ruler [2]. It is situated at an archeological reserve “Sborianovo” which comprises the territory of one of the most remarkable centers of the religious and political life in ancient Trace. The tomb illustrates the perfect construction technology, impressiveness, rich sculptor and painting decoration, high creation and talent of the genius ancient master. Therefore the tomb is included in the list of the world cultural heritage. It was discovered in 1982 excavating a tumulus. The tomb consists of a corridor (4,06 m long, 1,85 m wide and 2,15 m high) and 3 almost square cameras of different heights (4,55 m of the tomb camera and 3,25 m of the side camera). They were built by well trimmed stone blocks from white limestone and they were covered by semi-cylindrical vaults. The total dimensions of the tomb are 7,52 m long and 6,23 m wide at the facade. This unique monument of exclusive significance is a part of an unified architectural complex.

Fig. 18. Thracian tomb

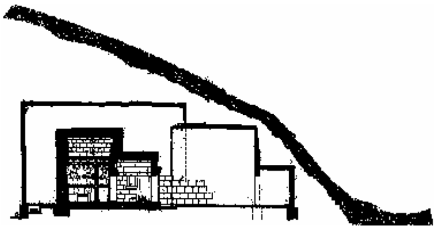


Fig. 19. Vertical section

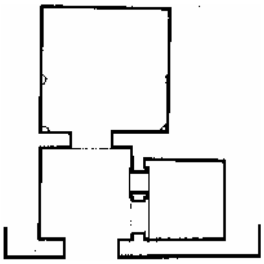


Fig. 20. Plan of the tomb

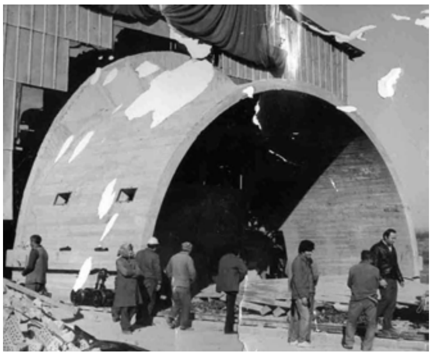


Fig. 21. Covering shell structure at the site

The structural and technological preservation, restoration and presentation of the tomb was a complex problem due to the following severe limitations: prohibition to the wet processes near the tomb, to keep the climatic conditions in the tomb, highest biological sterility of the used materials, maximal consideration and utilization of the soil properties (collapsible loess of second group), minimal risk, etc. Two temporary protection metal covering were mounted (Figs. 18, 19. 21) [17]. First one was also climatic and nearest to the tomb. It was assembled by the steel sheets simultaneously with the careful excavation around the tomb. A soil layer 60-70 cm thick was remained on the tomb to keep the internal climate. The second one was erected later on the tumulus part above the tomb and it was a tubular scaffold of large dimensions (about 18 m span) and far from the tomb.

The constant covering is composed from two r/c cylindrical shells of equal span and 20 cm thick but of different radii of curvature (Fig. 21) [17]. The higher shell was designed with a variable radius in two steps but the shallower shell has a constant radius. They were cast-in-situ at a site situated about of 35 m to the external temporary covering. The shells were provided with two external longitudinal supporting ribs near the ends. The vaults were lifted by 10 hydraulic jacks of 50 t every one and jacked dawn on 6 special transport double rail cars supporting the shell ribs. The back r/c retaining wall was constructed behind the tomb against the tumulus embankment. Then the higher shell was transported by pushing the rail cars between the two temporary coverings and to the back wall. Then the shell was slightly lifted by the jacks and jacked down on the lead thrust bearings placed at the preliminary constructed r/c strip foundations. The shallower shell was transported by thrusting the cars to the first shell, jacked dawn on its bases and the two shells were connected. The fore r/c wall was built. The internal temporary covering was disassembled. The soil layer on the tomb was removed. The external temporary covering was dismounted and the shell vaults were mutually and uniformly filled back. All technological process were realized by a strong time control. The shells were computed by the FEM applying the STRUDL program. This unique technology is also very effective. The technology and the transporting cars were technical innovations. The tomb was presented in 1985.

7.2 Research and strengthening of the basilica “St. Sofia” in Sofia

This church is a unique monument from the early Byzantine construction. It dates from the second half of the 5th century [1], [2], [3]. It is a three auditorium construction with total length 46,50 m and width 23,00 m (Figs. 22, 23, 24). The central part of the structure is divided into three auditoriums by massive masonry columns with a cross-type cross-section. They are connected one another by arches without capitals. The main auditorium after crossing with the transverse auditorium continues with a same height in the altar space and forms a Latin cross. On the crossing place of the two auditorium a square is formed marked by 4 columns that sustains the main cupola by means of 4 triangular spherical surfaces. The cupola is hidden from outside by tetrahedron. In 1878 the main architect of Sofia the Czech L. Bayer and engineer Prosech pay attention to the church keeping and restoration.

The basilica ‘Saint Sofia’ has almost 15 century history. It had been constructed for a long time. The structure has endured some strong earthquakes. The last reconstruction of the church has been made in 1930. Two investigations were made to evaluate the seismic vulnerability of the church. The first one is accomplished for the unstrengthened structure in 1989 by the computer programs COSMOS [8] and IES using 3D brick finite elements [5].

The second analysis is performed in 1998. In this study the spatial model is composed from existing structural elements from one side and some new strengthening elements (two reinforced concrete shells above the existing masonry domes and six tension bars of the roof arches and vaults) on the other hand [6]. The analysis is made by the finite element method (FEM) using also the COSMOS computer program [8]. The model contains 2475 finite elements and 2283 nodes with 6 DOF (3 displacements and 3 rotations) in each one (Fig. 24). The total number of equation is 12666. The following types of finite elements are used:

- type 1: 3-node linear triangular thick shell element;
- type 2: 4-node linear quadrilateral thick shell element;
- type 3: 2-node linear 3-D elastic beam element.

The shell elements have bending and membrane stiffnesses. The shear deformations are taken into account. Elastic and isotropic material is assumed. The particular structural elements are defines as ‘regions’. The finite element mesh of each ‘region’ has a maximal dimensions up to 1,5 m (Fig. 24). The adjacent ‘regions’ are connected each other by common nodes which guarantee displacement and rotation compatibility. Supporting nodes are entirely fixed. The geometrical characteristics of the structure are the following: the wall thickness varies from 1,10 to 2,00 m, the masonry vault thickness is 0,30 m, the new r/c shell is 0,10 m thick. The material properties of the brick masonry are: the Young’s modulus is E=1350 MPa, the shear modulus is G=0,4E=540 MPa, the mass density is γ=1800 kg/m^3, but for the concrete they are: E=25000 MPa, G=0,425E=10625 MPa, γ=2500 kg/m^3.

The basilica structure is analyzed under vertical load and seismic actions of 9th degree according to MSK-64 and Bulgarian design codes [7]. The first 6 periods of the undamped free vibration are obtained as T_1=0,287 sec, T_2=0,216 sec, T_3=0,197 sec, T_4=0,178 sec, T_5=0,154 sec, T_6=0,153 sec. The internal forces and stresses are computed considering the first 50 natural mode shapes. The seismic analysis is accomplished by two simultaneous horizontal seismic signals given by two correlated horizontal spectra. As a result the stresses in the dangerous points of the structure are obtained for the following two combinations:

1st combination - max stress = stress caused by the vertical load + stress from the seismic action; 2nd combination - min stress = stress caused by the vertical load - stress from the seismic action.

The characteristic stresses of the wall masonry are: compression stress is 0,9 MPa, tension stress is 0,03 MPa, tension stress under bending is 0,04 MPa, shear stress is 0,05 MPa but for the roof masonry they are 0,5 MPa, 0,005 MPa, 0,01 MPa, 0,01 MPa respectively. The vertical stresses σ_z and the tangential stresses in walls and columns caused by the vertical and seismic loads exceed the material strengths. As a result brick elements are in danger. The stress concentration around the tension members is observed. Full scale dynamic experiment is realized too [4]. The numerical and experimental results have good agreement.

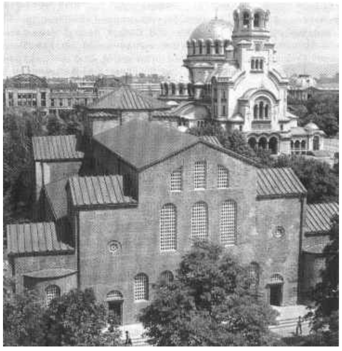


Fig. 22. St. Sofia basilika

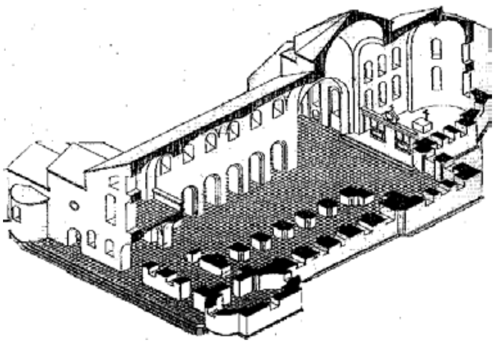


Fig. 23. Axonometric plan-section

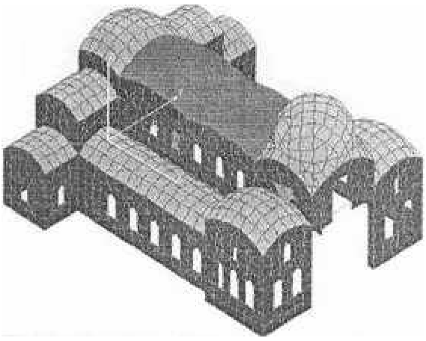


Fig. 24. FE model of the St. Sofia basilika

Many structural damages are detected [13]. Large cracks in vaults, domes and walls, soil settlements, deformations, decrease of the material strengths by the surrounding environmental effects, etc. are available. The main reason for damages are the past strong earthquakes. Some structural interventions are made during the last years to safeguarding of this unique and important monument in the center of Sofia. The investigations discovered that the structure responses as it is comprised of particular (isolated) fragments due to the deep and large cracks between them and insufficient contacts between the interventions. The structural spatial unity is slightly expressed. The basilica was very vulnerable to seismic actions. Therefore the effective structural measures were accomplished to restore the entire response of all structure.

The cracks are filled up by injection of mix prepared by epoxide resin, stone powder and marble sand (Figs. 25, 26) [13]. A SIKA injection technology for restoration of the masonry continuity is applied. The large cracks are excavated 10 cm deep and enlarged to ease their injection. Some of cracks are filled up gravitationally discharging carefully the mix mortar from the roof after the cracks were preliminary closed by a thin surface coating. About 2 tones epoxide resin are used. Some masonry and masonry joints are rebuilt. The r/c floor plate and beams are strengthened. The new r/c vaults and domes with their supporting beams and rings are cast-in-situ on the old cracked brick masonry ones. The cracked masonry roof elements are hanged on the new ones by steel dowels (Fig. 26). The tension members of high strength steel bars are mounted in the arches and vaults. Their anchorage is in holes 50-60 cm in a diameter and 120 cm deep drilled in the walls or outside of the walls using the epoxide resin or cement mortar. They were tensioned by thread studs or nuts. Soil injection ate executed also. Some stone masonry foundations are enlarged and made deeper. Some temporary openings were blocked. An external r/c belt course is built at a level 0,00.Some tension members are assembled under the floor plate too.

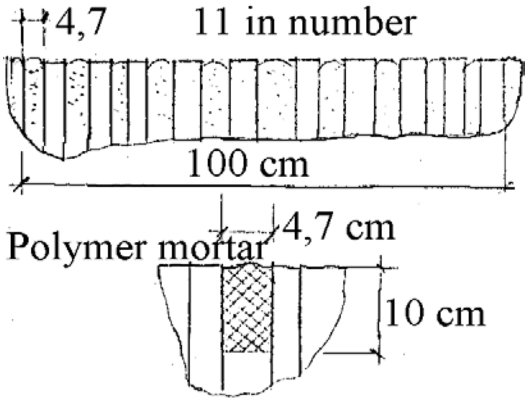


Fig. 25. Filling of cracks

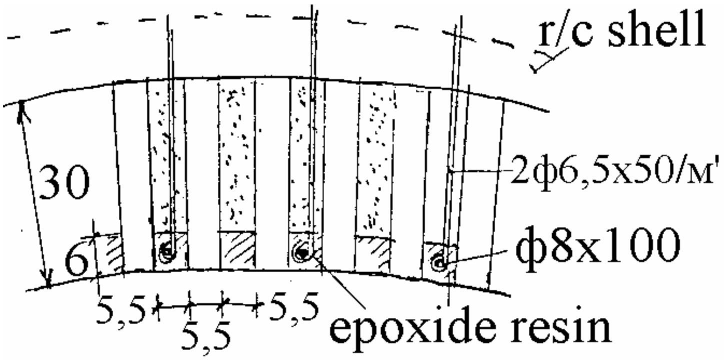


Fig. 26. Anchorage of anchors in the domes (vaults)

7.3 Strengthening of the church “St. Iliia” in Iliiantzi

The vault of this church has numerous severe cracks (Fig. 27) [14]. The large cracks cross through the whole thickness. As result the vault consists of 4 particular parts and it is strong deformed. The new roof is built directly on the old one as a thin cover constructed by structural polymer mortar reinforced by thin steel meshes and strips of geotextile (geo-nets) (Figs. 27, 28). The holes were remained in the cover to breath the old roof. The old roof and its covering are suspended on the new transverse steel frames structurally connected by vertical legs to the r/c beam hidden in the masonry walls. The suspension members are anchored through the joints in the old roof connecting with longitudinal reinforcement mounted in the longitudinal joints. In this way the braces are united at two levels. The large cracks are filled up by the epoxide resin from inside. A trial fragment was prepared and tested. The deflections during the disassembly of the scaffold after the strengthening are controlled by transducers. The total deflections were up to 1-2 mm only.

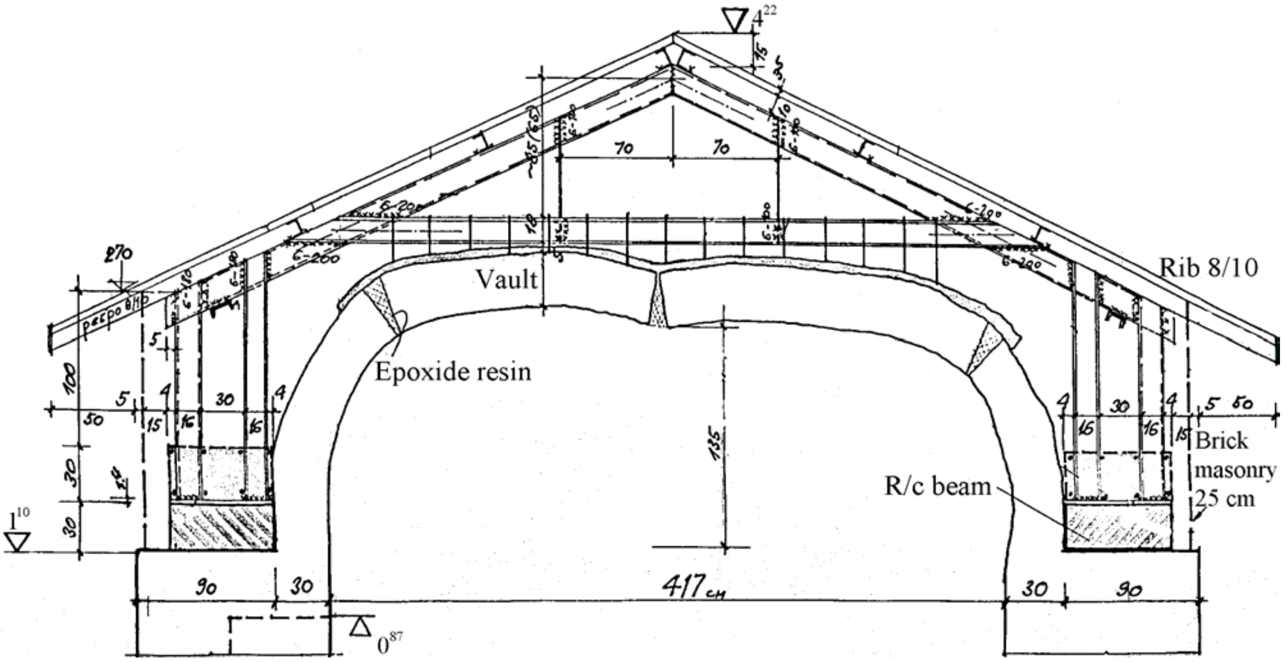


Fig. 27. Strengthening of the vault by polymer mortar and suspending on the new steel frames

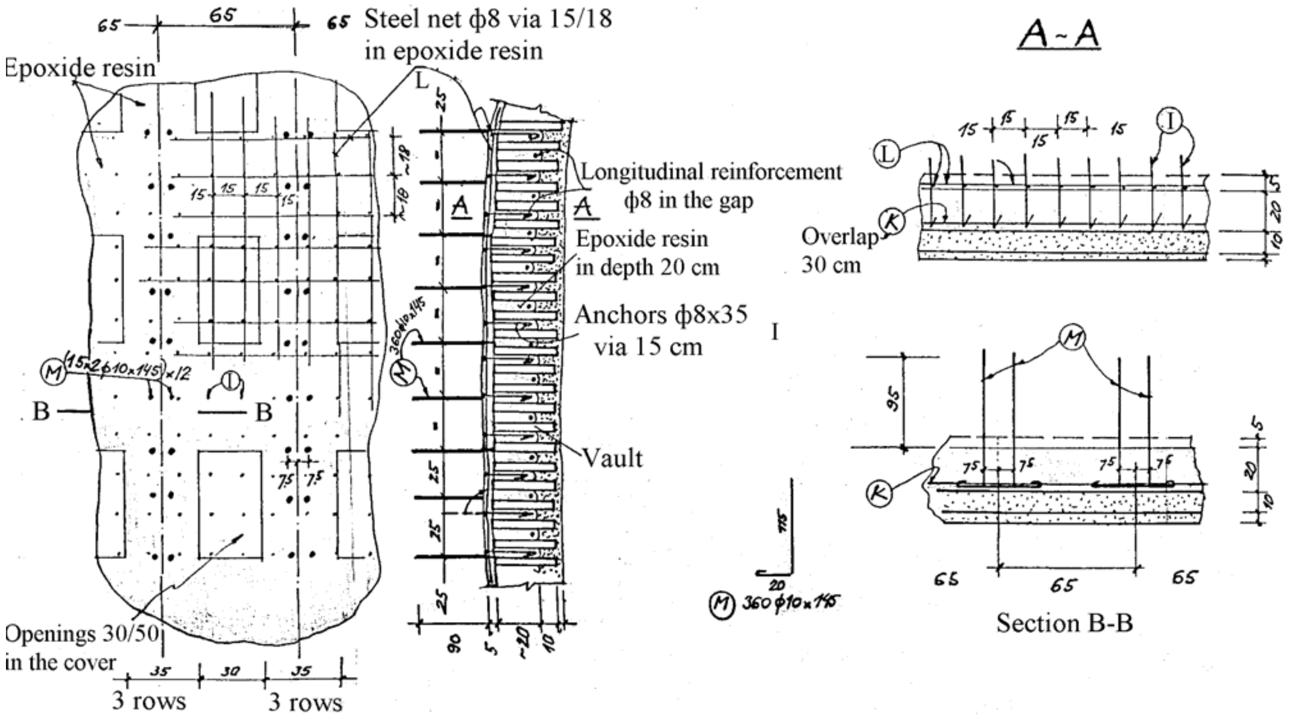


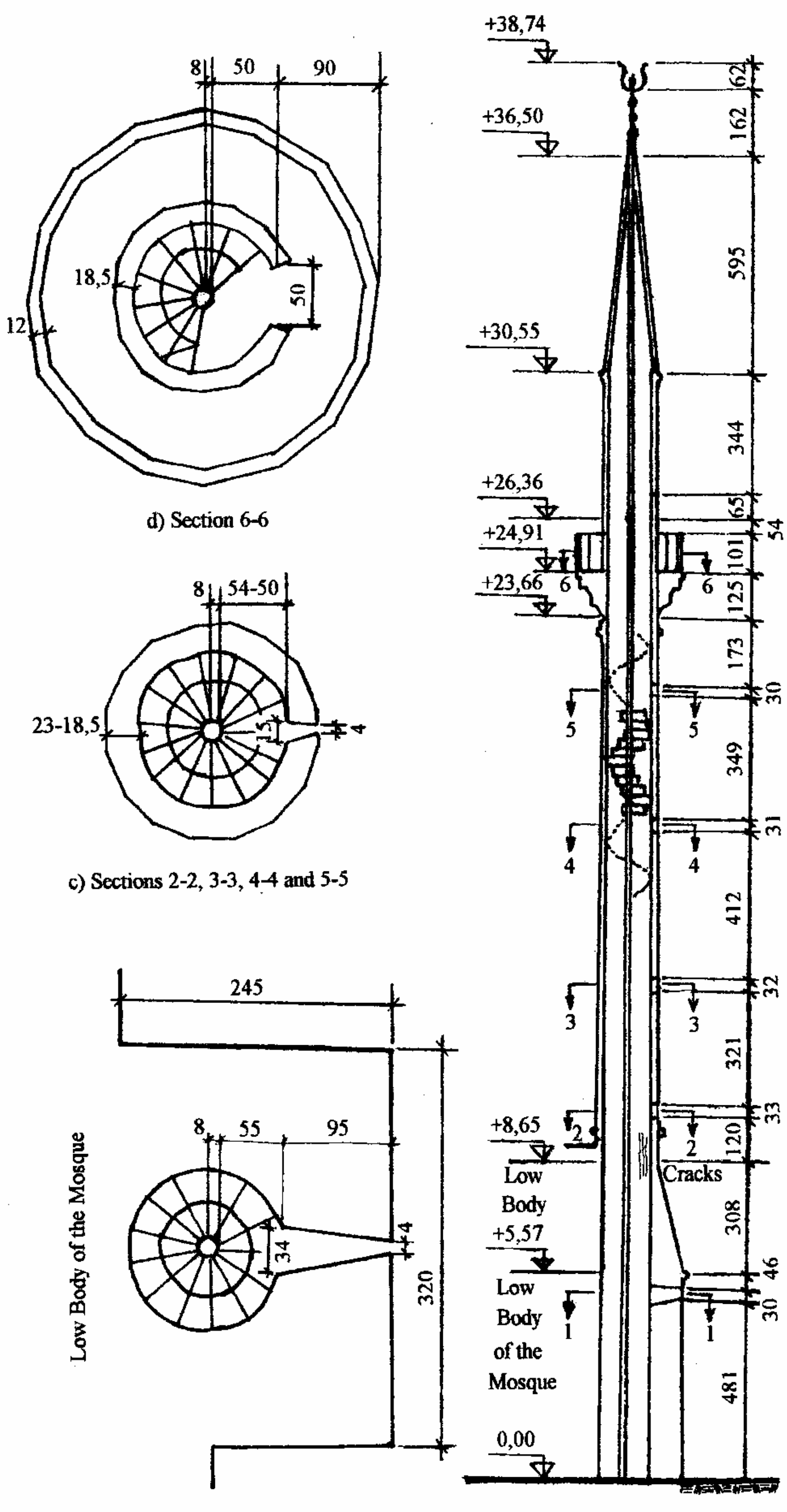
Fig. 28. Anchorage of the suspension braces and filled up the cracks by epoxide resin

7.4 Analysis and strengthening of the minaret of Tombul mosque in Shumen

The Tombul mosque (Figs. 29, 30) has been constructed in about 1743. The mosque minaret is 38,74 m high [21]. Till the +8,65 m level the minaret is joined to the mosque lower body but this connection is structural up to the +5,57 m level only. The minaret main high prismatic part has a circumcircle diameter of 1,70÷1,53 m and wall thickness of 23,0÷18,5 cm. The aboveground minaret structure up to the +30,55 m level is constructed by stone masonry. The principal damage of the minaret masonry is series of particular almost vertical cracks at the foot of the main prismatic part (Fig. 30 a). The cracked sector is 2÷3 m high. It is need to check the minaret safety.

Fig. 29. Minaret in Shumen

The full-scale dynamic tests of the minaret part between the ±0,00 m and +25,41 m levels have been done (Fig. 30) [24]. The masonry part of the minaret structure between the levels of +5,57 m and +30,55 m is studied numerically also (Fig. 30) [21]. It is modeled as a vertical plane cantilever beam-column rigidly fixed at its bottom to the minaret low body (Fig. 31). In order to consider all structural features the beam is divided into 20 finite elements. The linear dynamic, static and stability analyses of the model are accomplished by the FEM and ROKU program [22]. The well known uniform beam-column finite element of six DOF is used. The seismic loads, the dynamic and resonant wind loads are determined by the response spectrum method according to [7] and [25]. The structure static stability is verified and then the higher-order bending moments caused by the vertical loads on the deformed beam axis in small displacements are computed by the iterative Vianello-Dischinger's method. The cross-section bearing capacity is checked by the stresses.

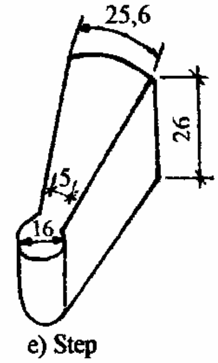


d) Section 6-6

c) Sections 2-2, 3-3, 4-4 and 5-5

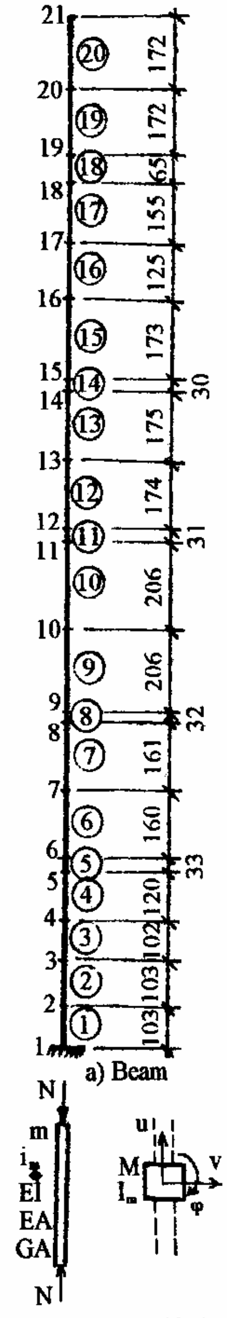
b) Section 1-1

a) Vertical Section



e) Step

Fig. 1. Minaret Structure



a) Beam

b) Element

c) Node

Fig. 2. Structural Model

A good agreement between experimental and numerical results is obtained. The structure safety is not ensured due to the horizontal loads. Therefore an urgent strengthening of the stone masonry is need to be made only from inside by an appropriate way to restore the minaret normal safety in accordance with the current Bulgarian design codes. The strengthening should cover in height the whole internal surface of the masonry wall or at least the unsafe lower portion of the main prismatic part. Two alternative ways for repair and strengthening are discussed in [21], [23]: prestressing by internal vertical tendons and construction of an additional internal reinforced concrete skin. The first seems to be a simple and elegant solution which would leave no visible traces. However it was considered as impractical because the masonry cross-sections will be too heavily loaded to withstand the additional compression from the necessary prestressing force of about 1000 kN. Nevertheless the first way was adopted but it was not been applied due to financial shortage. Moreover several cracked stones can be replaced by new hard ones.

Probably the second technology will be more rational. It has been applied in Hungary [23]. A thin reinforced concrete skin 5-8 cm thick can be constructed over the whole internal surface of the masonry wall. Concrete grade C28 has been used and injected in place. It can be reinforced by vertical steel bars N 20-25 mm and 8 mm thin helical wire following the minaret ascending internal stairs. The vertical reinforcement can be made continuous spliced by thread-bars through 30 mm holes drilled in the stairs close to the wall and by ensuring adequate laps of the bar successive lengths. To ensure the full interaction of the existing masonry and the new internal skin, the mortar internal joints have been raked out and the stones have been washed before concreting. Thus penetration of the raked-out joints by the concrete has provided continuous shear practical dowels between the two materials (stone and concrete) for their work together.

8. RECOMMENDATIONS AND PROPOSALS

Now the basic difficulties for safeguarding of the cultural monuments are the financial shortage in the last years and the activity of the treasure-hunters. The numerical reanalysis and redesign as well the full-scale dynamic and static experiments of particular phases during the structure repair are necessary. The use of high performance materials and techniques as carbon fibers, geo-nets, fiber reinforced plastics and grids, steel nets and bars for reinforcing of historic, old and new masonry should be enlarged. But the limitations should be given in applying the modern materials and technologies to keep the original architecture of the monuments and to escape unfavourable effects to the environment. The cultural heritage, restoration and preservation works of historic and old structures should be studied by students and specialists in the corresponding universities and colleges. Specializing post-graduate courses for professionals will be useful Moreover scientific problems for research and renovation of such structures are actual and important for diploma works, post-graduate diploma and Ph.D. theses. International research and educational projects are need to be elaborated in this domain. Scientific workshops, conferences and other activities should be held to discuss and exchange experience, achievements and knowledge on these problems between the professionals. More data should be collected in this area. Closer relations between the universities, institutes, companies and specialists are need. Larger amounts should be given for safeguarding of the cultural monument all over the world and especially in Europe. The national governments and the authority of EU are responsible to enlarge and support these activities and to make them reality. The cultural heritage of the world must be kept for the next generations by all means.

9. CONCLUSION

Special attention should be paid to prevention measures for safeguarding of the historic objects. As a rule the historic structures are not ensured to horizontal loads and especially to strong seismic actions. The human intervention on the historic structure should be minimal, careful and adequate. New and effective models, methods and technologies should be used to study, preservation and restoration of these unique and valuable cultural monuments. The safeguarding of the cultural heritage becomes one of the main problems of each civilization. The relation to the cultural heritage is a mark for the civilization of every nation. The European countries with their long and rich cultural history take a special responsibility to keep the roots of life at the Earth. In the future united Europe every country will keep your national cultural identity. The richness of the Europe is in its cultural and historic variety.

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