SEISMIC PROTECTION OF BYZANTINE CHURCHES

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SUMMARY

Traditional masonry structures should be seismically strengthened using as minimum of intervention as possible. Traditional masonry structure types in the Republic of Macedonia are introduced. The case of strengthening Byzantine churches in this area is considered. Two options of strengthening have been analyzed on a shaketable and the results are presented. The advantages and disadvantages of these techniques are discussed.

INTRODUCTION

Historic buildings provide the most tangible legacy of our past civilization and in some cases they speak clearer than any remaining manuscripts. Historic masonry structures have low ductility, and, due to their stiff and brittle structural components, are usually severely damaged during strong earthquakes. The main reason for damage is a lack of ductility that prevents a structure from being able to sustain the displacements and distortions caused by severe earthquakes. Damage caused by earthquakes to historic buildings is irreversible and these lost “documents” can not be retrieved. The goal should then be to strengthen these structures in a manner that requires the least intervention[4] and the greatest care to preserve authenticity. This goal, reflected in such conventions as the *Venice Charter*, poses real challenges with traditional masonry structures subjected to earthquakes.

In evaluating the seismic resistance of a historic structure, unique conditions are encountered that do not occur in modern structures. The structural typology, the variability of the construction materials, the complex history of modifications, as well as the degree of deterioration make each historic structure unique. Since the beginning of the 20th century, traditional building techniques and construction typologies have been rapidly replaced by modern methods and materials. The knowledge and skill of traditional construction techniques has slowly disappeared, while construction methods developed primarily for modern structures have dominated the practice of engineers and builders. This practice includes the application of techniques and materials that are neither reversible, nor durable, nor compatible with the original materials.

To develop appropriate approaches for repair and strengthening of Byzantine churches, in general, and particularly churches located within Macedonia, a research project "Study for Seismic Strengthening, Conservation and Restoration of Churches Dating from the Byzantine Period (9th - 14th Century) in the Republic of Macedonia" was realized in the period 1990-2000. These investigations were realized at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) within the framework of the joint US-Macedonia research project. The objective of the project, hereinafter referred to as the IZIIS Project, was to develop and test methods to obtain seismically resistant structures using minimal intervention concepts that achieve adequate protection.

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[4] Kelley, S. J., and T. M. Crowe. "The Role of the Conservation Engineer," in ASTM STP 1258: Standards for Preservation and Rehabilitation. S. J. Kelley, editor. ASTM: Philadephia, PA (1995).

TRADITIONAL MASONRY STRUCTURES IN THE BALKANS

Masonry structures consisting of stone and unbaked bricks as the main components are probably the oldest remaining structures built by the hand of man, and are typical to Macedonia. The main characteristic of antique masonry assemblies is low tensile strength. Due to the high ratio between the specific weight and the bearing capacity of the material, antique masonry structures bear loads in massive and rigid forms, different from modern structures composed of relatively flexible systems.

Vernacular Structures

The main material found in traditional buildings in the Balkans are masonry (the earliest of stone and brick masonry together) and wood used, besides the roof structure, for the formation of timber belts inside the wall mass or as ties placed at the base of vaulted elements to resolve arch thrusts by sustaining tensile forces. Vernacular architecture found in the villages of Macedonia, as shown in Figure 1, also reflect these material compositions. Traditional multi-story dwellings are constructed with a bottom level of stone masonry. Intermediate levels are composed of unbaked or adobe brick interwoven with a wood frame. The top story is wood frame with infilled walls of adobe brick. Horizontal bands of wood are found laid within the masonry at all levels. These bands of wood, thought to aid in settlement of the masonry walls, are a technique known for at least 2500 years.[5]

These simple construction techniques provide seismic enhancement in many ways. The greatest mass is found at the base, the structure becomes exceedingly lighter at the upper reaches, and thus the center of gravity of the entire structure is closer to grade. The wood frame at the top is more ductile and therefore more able to handle the higher seismic demands that occur at upper levels. The wood banding acts as a kind of reinforcement to hold the masonry together in the event of seismic shock.

Byzantine Churches

In the Byzantine period, construction techniques remained stable on a regional basis from century to century because these techniques relied on local building materials and workshop traditions that persisted locally and overshadowed upheavals such as foreign occupation.[6] The territory of Macedonia is known for the large number of its historic monuments among which are churches dating from the Byzantine period. The churches are important architectural structures and contain extraordinary collections of highly important frescoes.

In the period from the 9th to 14th Centuries, a church form was developed that utilized smaller spaces and a different arrangement than the Basilica form. Church plans from this period are in the form of a cross with three or four apses. The largest group of medieval monuments, dating back to the final stage of the Byzantine period are either the single or five-domed churches, whose plans are an inscribed cross in a rectangular area and a dome supported by four columns via a tambour and pendentives, as shown in Figure 2.

The structural system of these churches consists of columns, walls, and vaults that, with their massive cross-sections, sustain compressive stresses due to gravity loads. In almost all of the structures, there are visible timber ties placed inside the structure, at the spring points of the main and the side vaults as well as at the base of the tambour and the dome. To mitigate the

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[5] This technique was used in the construction of the Minoan Place at Knossos, Crete.

[6] Mango, Cyril, Byzantine Architecture, Harry N. Abrams: New York (1974) p. 11.

effects of regular settlement of the structure, hidden timber belts were incorporated into the wall mass, along their whole perimeter and at several levels, most frequently the same level as that of the timber ties, as shown in Figure 3.

The wall elements were constructed exclusively of stone and bricks in lime mortar, in the typical Byzantine style of building with two faces of brick and stone masonry and the intervening space filled with a core of rubble set in a great quantity of mortar. The stone (tufa, limestone, or sandstone) was either hewn or unhewn. The columns were constructed of the same materials or were constructed of marble or granite blocks. The vaults and the arches were typically constructed of hewn tufa, while the tambour and the domes were constructed of bricks in lime mortar. The walls were set on massive masonry foundations, but frequently to an insufficient depth.

Architecturally, the inner walls were flat, rarely perforated by window openings, and were completely covered with fresco paintings presenting scenes from the Bible. The frescoes were rendered on plaster that was applied directly to the masonry wall structure. Unlike the modest architectural finishes of the interior, much attention was paid to the finishing of the facade. Stone, bricks, and lime mortar were used for the expression of the wall masses.
In the upper horizontal rows, each stone, either squared or amorphous was framed by horizontally and vertically placed bricks resulting in a *cloisonée* pattern that is typical for Byzantine walling. Apart from this type of surface finishing, the wall areas were articulated three-dimensionally by construction of pilasters, arches and niches.

Thus the builders of the Byzantine churches of Macedonia incorporated seismic strengthening techniques into these structures either by intention or by chance. The cross-vaulted plan utilized is symmetrical with main mass in middle and four symmetrically laid buttresses. The only element that affects the overall seismic harmony of such a structure is the central dome that acts as a separate entity during earthquake shock and is prone to collapse. Horizontal wood timber belts hidden within the walls act as a kind of reinforcing and increases the stability of the structure under seismic effects. Timber belts introduced at vault spring points and at the bases of domes further provided stability of support walls below during seismic vibration.

SEISMIC STRENGTHENING FOR BYZANTINE CHURCHES

Seismic strengthening of existing structures is based on a detailed study of the expected seismic hazard, the soil conditions, the dynamic characteristics of the structure, the strength and ductility of the structural elements and construction materials, and the dynamic response of the structures under expected seismic motions. With historic structures, strengthening should also be based on a cost benefit analysis[7] of alternative solutions in order to determine the scheme that will preserve historic fabric.

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[7] Costs and benefits refer to general rather than monetary terms. Costs can be measured also in the potential loss of fabric due to the invasiveness of the intervention, and benefits can be those gained by the intervention as well as knowledge that will prove useful in the future.

As stated by Fielden, any proposed interventions should be reversible, if technically possible, or at least not prejudice any future intervention, or hinder later access to all evidence incorporated in the structure.[8] Reversibility can be the defined as the ability to undo a process or treatment with no change to the object. Total reversibility, however, is an ideal that is impossible to achieve. Many of the processes considered reversible are only approximately reversible in real practice. Achieving this "reversibility" poses additional obstacles in seismic retrofit as discussed below.

Preservation is maintenance. With maintenance, it is easier to adhere to the principle of using only traditional materials and techniques. Maintaining a certain degree of reversibility is guaranteed when following this principle, certainly more so than if modern materials and techniques are utilized. However if an intervention is required that goes beyond the preservation equals maintenance axiom, then the "reversibility" becomes much harder to achieve. In these cases, degrees of compatibility, defined as a material or technique that can be adapted in its nature to the original material, should try to be achieved.[9]

In seismic retrofit of traditional masonry structures, it is almost always necessary to introduce an intervention that is beyond what would be considered a part of the original system of the structure. This is a requirement that will add strength and ductility to a structure that was not present before and was not part of the concept of the original builder. Therefore in seismic strengthening of historic monuments of masonry, achieving "reversibility" is a practical impossibility.

In the case of the seismic strengthening of Byzantine churches where the salvage of historic fabric is paramount, numerous seismic strengthening techniques are not appropriate. Following is a brief discussion of those techniques that, though irreversible, may be appropriate.

Injection of Cracks

Damage to walls, vaults, domes, and columns during seismic events are manifested by the occurrence of cracks due to tensile, shear, or compressive strengths being exceeded. Filling of cracks caused by earthquake forces in traditional masonry walls is an age-old repair strategy.[10] Not only can crack injection restore some of the lost strength capacity, but it can address somewhat, the separate vibration of masonry elements created after the appearance of the cracks. The injection technique, the materials, and the pressures under which the prepared mixtures are to be injected are selected depending on the size, position, and shape of the cracks. In considerably damaged wall elements it is necessary to replace parts of the wall mass, while in the case of visible out-of-plane deformations in the wall, it is necessary to rebuild it.

Addition of Steel Ties

In order to improve the behavior of traditional masonry structures under the action of seismic forces, rational strengthening measures have been adopted using reinforcing steel. Post-tensioned steel reinforcement is placed at critical areas to compensate for the lack of tensile strength and ductility and to increase the stiffness of walls and piers. Steel ties avoid separate vibration of the masonry elements formed after cracking occurs. Horizontal bands are provided

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[8] Fielden, Bernard, Conservation of Historic Buildings, Butterworth Architecture:Oxford,UK (1996) p. 6.

[9] "Grundsätze der Denkmalpflege/Principles of Monument Conservation/Principes de la Conservation des Monuments Historiques," Journal of the German National Committee of ICOMOS, Volume X.

[10] Zeynep Ahunbay of Istanbul Technical University reports the recent discovery of a seismic crack in the 12th Century Zeyrek Djami that was filled in the distant past with molten lead.

at different levels in order to ensure "box-like" action of masonry buildings and to reduce the possibility of "out-of-plane" failures.

Roof structures of monuments from the Byzantine period consist of a system of arches, vaults, and domes that do not provide adequate continuity among the supporting walls. On the contrary, they push the support walls in opposite directions making it desirable to install pre-stressed ties at their spring points thus enabling preservation of the initial span between the supports and assuring their harmonious vibration.

In Byzantine churches, the original wood banding within the walls has in many instances rotted away and the cavity left can be utilized for the insertion of steel ties and injection of grout. This is an advantage to this technique in that it can be hidden from view after it has been installed. A definite disadvantage, in the case of the Byzantine churches of Macedonia, is the adverse effect that the lime grout can have on the precious frescoes as the water from the grout seeps through the masonry and salts effloresce on the interior plaster surface.

Reinforced Concrete Strengthening

To increase the bearing capacity and ductility of walls, jacketing with mesh-reinforced concrete on one or both sides is implemented. These treatments, being extremely intrusive, would not be recommended for use on any historic fabric. However strengthening on the upper part of arches and domes by a reinforced concrete torquate or collar, has found a usefulness on Byzantine churches because the concrete can be obscured beneath the roofing.

Foundation Strengthening

Techniques for strengthening of the foundation structure consist mainly of extending the proportions of the foundation and their connection to the vertical elements, modifying the foundation structure, and consolidating or otherwise improving the characteristics of soil conditions.

Base Isolation

Kelly states that seismic isolation systems work by decoupling the building or structure from the horizontal components of earthquake ground motion by interposing a layer of low horizontal stiffness between the structure and its foundation. This layer prevents the transmission of accelerations from the ground to the building. This decoupling action is effected by mounting the building on a system of bearings that are stiff in the vertical direction (in order to support the building weight) but soft in the horizontal direction.[11]

With base isolation, the earthquake energy that would have been transferred to the structure gets absorbed at the base level. In addition the period of the isolated structure is increased which typically results in a reduction in seismic demands. In these ways, ductility demand to the structure is greatly reduced. Displacement across the isolation system can be somewhat controlled by the addition of damping.

Seismic base isolation has so far been applied mainly in newly designed structures but has shown great promise in the improvement of existing structures with stiff and brittle structural systems. The advantage of this method is in the minimal intervention on the existing structure and the protection of architectural integrity. A disadvantage is the loss of the cultural layer and

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[11] Kelly, James M, "The Application of Seismic Isolation for the Retrofit of Historic Buildings," Earthquake Engineering Research Center, University of California at Berkeley.

any archaeological remains as part of the base isolation installation. In the case of compact and exceptionally valuable historic structures of smaller proportions, base isolation becomes an acceptable, although expensive solution.

REVIEW OF THE IZIIS PROJECT

In the first phase of the project, detailed information on fifty-four Byzantine churches was gathered as a basis for investigating their condition, main characteristics, structural systems, and typology. Based on the following criteria - typology, condition, past interventions, and authenticity - four representative structures: the church of the Holy Virgin, (St. Mary Zahumska) in Trpejca; St. Nikita in Banjani; St. Nicolas in Psacha and the church of the Holy Virgin, (St. Mary) in Matejche were selected for more detailed study. All churches are single dome structures with a cross-in-square plan. Of these, the Matejhe church had the least authenticity and the Trpejca church, the most. St. Nikita was finally selected as a prototype church most representative of the Byzantine churches in Macedonia.

St. Nikita in the village of Banjani on the outskirts of Skopje is a single-domed church with a developed cross inscribed in a rectangular plan, as shown in Figure 4. The structural system of the church consists of massive, 85 cm thick peripheral walls, which were constructed partially of hewn stone and brick, and two rows of symmetrically placed columns, supports over the vaulted roof elements and a central dome. All the wall areas in the interior are flat and were decorated by the prominent 14th Century fresco-painters - Michael and Eutihios. The walls of the building are original and date back to the 14th century. They are constructed in a typical Byzantine style - two faces of masonry and the intervening space filled with a core of rubble set in mortar.

Detailed field studies, laboratory testing, and structural analyses were performed on the existing structure of the St. Nikita church to define the physical and chemical characteristics of the building materials, the dynamic characteristics of the structure, and the seismicity of the terrain. A preliminary analysis of the seismic stability of the existing structure was performed to estimate the ultimate bearing and ductility for different intensities and types of seismic excitations. The results of these studies predicted the partial or total failure under earthquakes of return periods of 500 and 1000 years, which does not comply with the established design criteria for seismic safety.

To experimentally verify the methodology for repair and seismic strengthening of Byzantine churches, a model of the church of St. Nikita, labeled M-SN-EXIST, was constructed and tested on the seismic shaking table in the Dynamic Testing Laboratory of IZIIS. The model, designed to a scale of 1:2.75, was based on results obtained from laboratory and experimental tests on materials and wall elements. Testing parameters were based upon simulating two types of earthquakes: the Friuli (Italy) earthquake of 1976 (Breginj record) as a local earthquake, and the 1979 Montenegro (Petrovac record) and 1940 El Centro earthquakes as earthquakes from distant foci.

The focus of the testing was two-fold - assess the vulnerability of selected elements of the original model, and select the most appropriate procedures for repair and strengthening of the earthquake-damaged model. More globally, findings from testing of the model would hold true for the church of St. Nikita as a prototype and for similarly constructed Byzantine churches.

Testing of the Unaltered Church Model (M-SN-EXIST)

Initial testing on the prototype model was performed in 1994. From the general behavior of the model, as shown in Figure 5, it was concluded that it behaved as a rigid body in the elastic range up to a_{max}=0.17g. At occurrence of the first larger cracks, there was separation of the bearing walls and development of damage up to a state close to complete failure. Failure was accompanied by the decrease in natural frequency from 11.0 to 6.6 Hz.

Both from the analysis of St. Nikita and the shaketable testing performed on the model M-SN-EXIST revealed that St. Nikita could not sustain the demands of a large earthquake. Therefore, after being repaired using injection of cracks and partial rebuilding, the damaged model was also strengthened with horizontal and vertical belt courses of post-tensioned steel reinforcement that were installed into the wall mass, as shown in Figure 6. The steel reinforcement was not locked into place with grout but rather was tensioned by using exterior steel plates so that the post-tensioning could be removed for later tests.

Testing of the Repaired and Strengthened Church Model (M-SN-STR)

The repaired and strengthened model, labeled M-SN-STR, was subjected to the same series of dynamic tests as before for the purpose of comparison of the effectiveness of the applied method of strengthening. However, due to the high resistance of the strengthened model, the tests were also continued to higher intensities. The response of the strengthened model was considerably different from that of the original model, as shown in Figure 7.

A comparative analysis of results obtained from the tests of M-SN-EXIST and M-SN-STR revealed the following:

- The response of the structures to acceleration levels up to a_{max}=0.20g was elastic. Beyond .20g, the first cracks occurred in the original model, whereas the strengthened model remained evidently elastic.
- Below a_{max}=0.40g, the original model suffered severe damage and was close to failure; whereas this level of demand represented the elasticity limit and beginning of nonlinearity for the M-SN-STR.
- The tests on both models show high amplification of acceleration at the top of the dome.
- A different type of failure mechanism was observed with M-SN-STR. The strengthened model does not suffer separation of bearing walls and vertical crack, but the failure occurs in the lower zone and results in diagonal cracks.
- The applied methodology for repair and strengthening is in compliance with the principle of "minimum interventions - maximum protection" and increases the bearing capacity and ductility of the structure up to a more acceptable level.

Testing of the Model on Seismic Base Isolators (M-SN-ISO)

For the third round of testing the model was again tested using the same series of dynamic tests as before. The damaged model was repaired and strengthened by crack injection and partial reconstruction. The post-tensioning of the horizontal and vertical reinforcement was completely released thus removing their effectiveness.

The model, labeled M-SN-ISO, was then placed upon a concrete base approximately 50 cm in thickness that was placed on top of 6 base isolators that had been locally fabricated. The base isolators were of the type composed of a system of multi-layer laminated natural rubber bearings reinforced by steel plates. The bearings are stiff in the vertical direction and could support the weight of the building, but are very soft in the horizontal direction, as shown in Figure 8.

The model was subjected to the same series of dynamic tests as before. However, due to the base energy dissipation characteristics of the base isolated model, the tests were also continued at higher intensities. An analysis of results obtained from the test are given in Figure 9.

These results reveal the following:

- A comparison of input acceleration (at the shaketable) and output acceleration at the model foundation revealed a de-amplification of the input acceleration due to the application of the base isolators. As the input acceleration was increased, the de-amplification decreased.
- There is negligible amplification of the output acceleration at the top of the model that is approximately 1/6 that of the model without base isolators.
- The displacement at the top of the base-isolated model relative to its base is considerably smaller than that for the strengthened model. For the acceleration input of 0.48g, relative displacement top is 21 mm for the base isolated model and 40 mm for the strengthened model.
- The failure mechanism of the base isolated model is completely different from the previous models. For all testing up to input acceleration of 0.60g, the base isolated model behaves as a rigid body without any visible cracks. When the cracks formed they were in a pattern similar to those of the original model.

CONCLUSION

The masonry Byzantine monuments in Macedonia are similar in material, construction technique, and scale to other examples of built heritage in the region and world-wide. Two types of seismic strengthening were analyzed. The first approach, the introduction of post-tensioned steel reinforcement within the walls replaces and augments wood banding that was provided by the original builders, and was found to improve the structure's seismic response. This technique is intrusive but can be installed in such a way that it is hidden from view. Unfortunately, injection techniques used with this technique can damage valuable frescoes such as those found in Macedonia.

The second approach, base isolation, decouples the structure from the ground and is effective in dissipating and damping the seismic shock to the structure. This technique lessens the necessity of intervening directly on the structure itself for seismic strengthening, but will require a significant intervention on the culture layer of the surrounding soil and thus spoil future archaeological investigations.

Neither of these approaches can be considered "reversible." However, each provides a valid technical approach to traditional masonry structures to the Byzantine monuments discussed. The most appropriate approach would therefore be directly related to specific issues that are unique to the monument being seismically strengthened.

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