Principle, Practice and Experience of Rehabilitation of the Historical Buildings in Seismic Regions

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SUMMARY:
This paper considers three different modes of preservation of architectural-historical monuments: Conservation, Restoration, and Maintenance. Examples are given of restoration and strengthening of three historical buildings in Georgia, two of which were damaged by an earthquake on April 30, 1991 (a temple in Nikortzminda and a synagogue in Oni, built in the 11th and 19th centuries, respectively), and an architectural-historical monument (former mosque) in Ahaltsihe (project), built in the 18th century. Temporary conservation of the temple in Nikortzminda was carried out immediately following the main shock of the earthquake so that its collapse caused by possible aftershocks could be prevented. Retrofitting of these structures was aimed at preservation of initial geometry and appearance by creating composite structures. It is worth mentioning that both the temple in Nikotzminda and the synagogue in Oni survived the Richter magnitude 6.2 earthquake in this region on September 8, 2009, without any substantial damage caused.

Keywords: conservation, seismic regions, historical buildings

1. INTRODUCTION

Many heritage buildings in the Mediterranean region include stone domes as a structural and architectural element and have utilitarian value. Numerous ancient buildings, although not as large as the Pantheon or the Hagia Sophia, can be also of certain value in historical, architectural, and engineering aspects. The evaluation of a building in these aspects predetermines the significance of its preservation. In addition, a possibility of its utilization is to be considered. Ancient buildings can serve as museums, libraries, mosques, temples, etc., which is maintenance consuming and helps to improve the building condition. Built mostly centuries ago, heritage buildings often need restoration and strengthening, especially in seismic regions. Preserving architectural-historical monuments in their original state is one of the responsibilities of a civilized society. At the end of the XIX century, the new material, the reinforced concrete, having good compression and tension resistance capacity began to oust stone constructions. It has to be noted that concrete retains its properties for a long period of time; for example, the dome of the Pantheon of Rome was constructed of concrete 2000 years ago (Krautheimer, Ćurčić 1986). For strengthening or conservation of Historic Heritage different traditionally and modern methods and principles can be used. International conferences on seismic resistance of structures devote special sections to this problem; it may also be the subject for debate at special international conferences (5th International Conference "Structural Analysis of Historical Constructions", New Delhi, India, 2006 and others). Their study and summarizing are important.

2. PRINCIPLES

As far as preservation is concerned, it can be done in three different modes of construction techniques, namely: Maintenance, Conservation, and Restoration (Podiapolski at al.1988) Different as they are, these modes may include similar techniques. Maintenance refers mostly to utilization of buildings. It implies a large variety of checkouts and repair works carried out periodically and based on a detailed program. The major purpose of maintenance is to prevent malfunctioning of engineering systems, e. g. water supply, losing of structural integrity as well as to prolong the structure durability. Repairs are done only if needed, according to the results of periodical checkouts. Conservation is aimed at preventing damage by maintaining and improving loading capacity to fit a required level. Thus, conservation is based on proper structural design in each individual case. One should distinguish between Temporary and Permanent conservation**.** Temporary conservation is used when a building is threatened with rapid destruction, such as earthquake aftershock. Maintenance and Conservation have much in common, since their purpose is preservation of an architectural monument as it exists at present. Restoration is primarily aimed at architectural aspects, such as external and internal appearance, and functional roles of internal spaces, courtyards, etc. Restoration is most important also in historical aspects. Restoration is the most complicated of all the works done on the historical building. It usually includes elements of both conservation and repairs. Conservation often includes certain elements of restoration. All three different modes mentioned above have their specific purposes. Assigning to this or that category depends on the prevalent nature of works. All three different modes almost invariably involve the necessity of strengthening structural elements.

Today there are many research projects concerning conservation and restoration of historic buildings, in the seismic regions, and several technologies are used to their strengthening: metal strengthening (Penelis at al. 1992; Danieli at al. 2002; Sesigur at al. 2006), straining beams (Poland, Reis 1992; Gabrilovich, Richard 1984; Rabin 2000), doubling structures (UNDP/UNIDO 1984), carbon fiber cords (Ziyaeifar at al. 2004), reinforcement systems consisting of carbon fiber tapes and epoxy raisins (carboniar structural reinforcement system), masonry injection using cement or a polymer solution (Pizzetti, Fea 1988), polymer grids (Sofronie at al. 2003), concrete spraying (Danielashvili 1988), reinforced concrete jackets (Paret at al. 2006), and reinforced concrete; one-or two-sided thin coatings (UNDP/UNIDO 1984) are traditionally applied. Nontraditional components, innovative methods and materials are also applied (Paret at al. 2006). All methods of strengthening mentioned above have advantages and disadvantages. Successful application of these methods depends on several factors: importance of the historical monument, its engineering state, safety demands, possible level of technology to fulfill these jobs on the exact site, special considerations of engineers, owners of monuments, and so on. Use of reinforced concrete provides wide possibilities in strengthening historic buildings, include stone domes, as reinforced concrete is a material well compatible with stone masonry. At the same time, in many cases the use of reinforced concrete for strengthening constructions for conservation, enables creating almost invisible elements in order not to distort the look of the monument.

Most often the need for conservation arises when cracks or some other damage is detected in the ancient stone domes of the buildings having historical and architectural importance. Strengthening is also needed to withstand seismic loads, in the regions where severe earthquakes are anticipated. According to proposed design for strengthening the stone dome of Ahaltsihe (Fig. 1), a novel strengthening structure is proposed hereby (Fig. 2). It is proposed to carry out the strengthening of the existing dome from its outer surface in order to preserve the appearance of the interior authentic surface of the dome; for example, the stone dome of Ahaltsihe with its stone masonry having cracks in its lower part (Fig. 3, A, B) and the Hagia Sophia Dome (Hagia Sophia 1992), with its rich colorfully ribbed decoration on the inner surface.

Execution of the construction work in such manner has some advantages: the strengthening structure is located under the roof covering and the stone dome is used as scaffolding for the structure. The strengthening structure consists of a thin-walled reinforced concrete shell, cast on top of the existing stone dome, and a supporting ring at its bottom (Fig. 2). The reinforced concrete supporting ring is placed in a groove engraved into the stone. The necessary connection to provide interaction of the stone dome and the reinforced concrete shell is achieved by means of reinforced concrete connection elements. These elements (such as pins), in the shape of a truncated pyramid or cone (with the large base in the stone dome), protrude from the reinforced concrete shell and penetrate into the stone dome, distributed through the entire dome surface. An additional linkage is the adherence force between the neighboring surfaces of the stone dome and reinforced concrete shell. The upper surface of the stone dome may be roughened to increase this force. In certain cases this adherence force may become the principal way of connection. Thus, the interconnected stone-reinforced concrete shell is achieved. The application of the proposed method enables strengthening a stone dome through practically all its thickness, which is important, as seismic action could be from a non-predictable direction. The stresses in a stone dome may be decreased significantly as a result of strengthening by the proposed method; it could significantly raise the earthquake resistance of a stone dome; the thrust forces are perceived by the reinforced concrete ring and so the dome supporting structures are relieved of effects from horizontal forces. An actual example of a similar strengthening for a reinforced concrete shell of 10 m diameter with a very moderate slope is given by (Danielashvili at al. 1998).

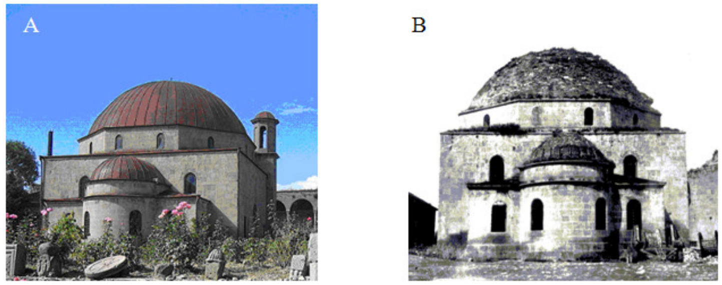

Figure 1. Dome (former mosque) in Ahaltsihe: A – view; B – historical view without roof

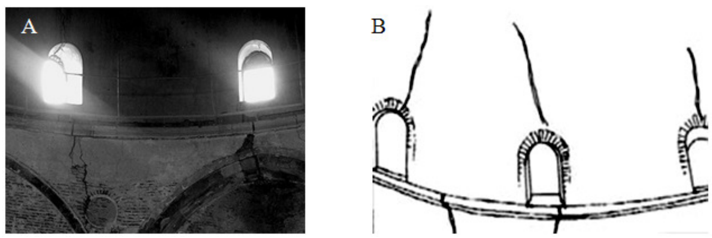

Figure 2. Cracks at the inner surface: A – picture; B – scheme

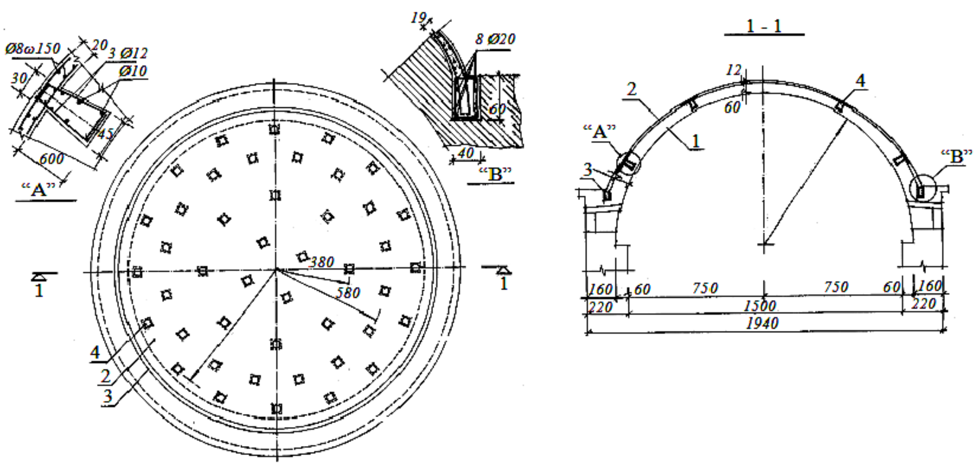

Figure 3. Dome in Ahaltsihe strengthening construction:
1 - stone dome; 2 – reinforced concrete shells; 3 – supporting ring; 4 – connection elements

3. PRACTICE

This paper deals with examples of restoration and strengthening of three structures in Georgia, two of which were damaged by an earthquake on April 30, 1991 (a temple in Nikortzminda and a synagogue in Oni built in the 11th and 19th centuries, respectively) and an architectural-historical monument (former mosque) in Ahaltsihe (conservation project) built in the 18th century (Danieli at al, 2006). A temple in Nikortzminda and the building of the synagogue in Oni are located in an active seismic zone in North Georgia. The building of the former mosque in the town of Ahaltsihe is located in South Georgia.

3.1. Seismic Situation of the Building Location

On April 29, 1991 there was an earthquake in northern Georgia. Magnitude of the earthquake in Racha, Georgia, on April 29, 1991 by Richter scale according to the accepted estimations was Ms = 6.9. This magnitude corresponds to the intensity of I_0=9.5 on the MSK-64 twelve-step scale. Several thousands of aftershocks were registered later on, during four months. Their magnitudes varied between M = 6.2 and M = 5.3, being sometimes almost as powerful as the primary shock. The following chart (Fig. 4) illustrates this situation (Danieli al. 2002). Over 46 thousand buildings were damaged or destroyed. Several historical buildings, like a temple in Nikortzminda and a synagogue in Oni, faced an earthquake with the Richter magnitude M = 6.9, which occurred in Racha, Georgia, on April 29, 1991 (Engineering. 1996).

A temple in Nikortzminda: the distance to the earthquake epicenter was about 45 km. The estimated intensity of the primary shock was 7 on the seismic scale MSK-64 (a=0.5÷1.0 m/sec^2 at the foundation).

The synagogue in Oni: the distance to the earthquake epicenter was 25÷30 km. The measured intensity was a=2 m/sec^2. The building in Ahaltsihe: the expected Richter magnitude for the Akhaltsikhe area is M=7. The mosque in Akhaltsikhe, built in the 18th century in South Georgia, was damaged by a series of major earthquakes: (a) in Akhalkalaki, Georgia, in 1899, at the distance of 45 km, M=5.4; (b) in Spitak, Armenia, in 1988, at 125 km, M=6.9; and (c) in Racha, Georgia, on April 29, 1991, at 125km, M=6.9 ((Engineering 1996).

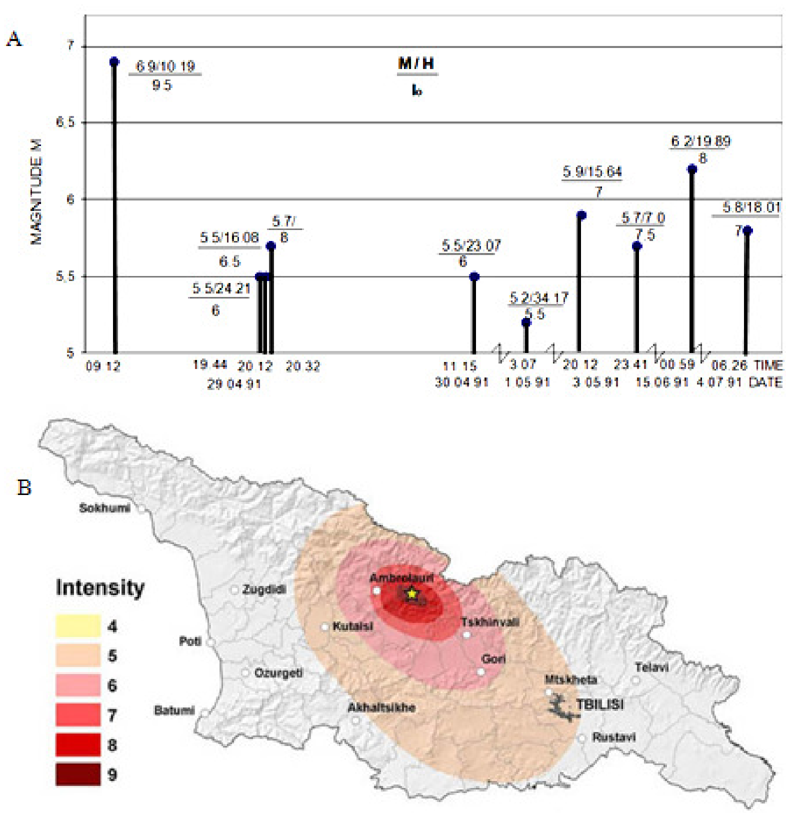

Figure 4. Seismic situation caused by the earthquake in Racha, Georgia, between April 29 and July 04, 1991, in the epicenter.
A - diagram :M – Richter magnitude; H – focus depth, km; I_0 – intensity on MSK-64 scale. B – calculated earthquake intensity map.

3.2. Nikortzminda Temple

This temple was built in the 11th century (approx. in 1014). It has a cross – shaped structure with a drum and a brick dome (Fig. 5). The overall height of the structure is approximately 26 m, the dome span is 6.4 m, and its rise is 2.8 m. The dome shell thickness is 0.6÷0.8 m. The drum has three-layer walls with overall thickness 1.0÷1.5 m, although weakened by windows. That shock caused cracking of the drum, and actually divided it into a group of vertically separated segments. In the dome, this generated a series of radial cracks and a closed-loop horizontal crack at the shell top. The central disk of the shell thus moved downwards by 60÷100 mm, but was wedged by surrounding parts of the dome, and so did not collapse (Fig.5, B).

Temporary conservation of the temple in Nikortzminda was carried out immediately after the main shock of the earthquake in order to prevent its collapse by possible aftershocks. The following measures were taken (Fig. 5,A): external reinforcement of the dome ring beam, at the top of the drum (this included a ring bundle of ø10 mm steel wires); external reinforcing "hoops", each consisting of several ø10 mm wires, mounted atop vertical timber boards; internal scaffolding, designed to support damaged areas of the structure, including the drum and the dome. The temple performed at no further damage.

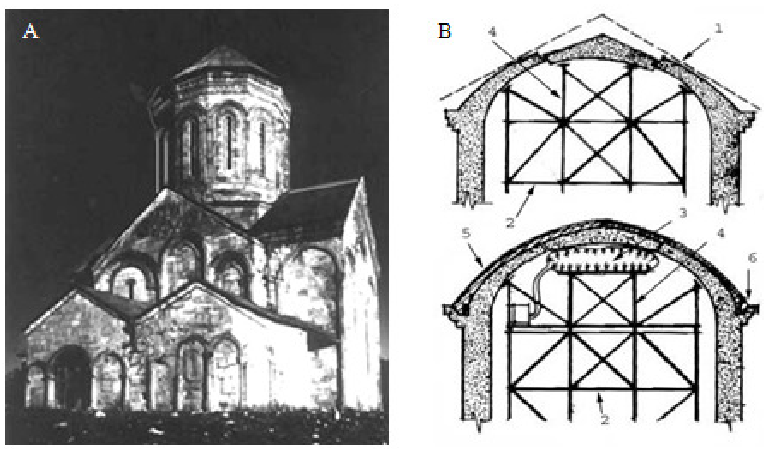

Figure 5. The temple in Nikortzminda.
A - general view; B - damage of the dome and repair works: 1-dome; 2- scaffolding; 3- air pillow; 4- pillow support; 5- reinforced shell; 6- ring beam

The permanent conservation project was completed two years later. Its major steps were as follows (Fig.5): construction of a steel belt around the ring beam of the dome; lifting of the central disk, weighing about 4 t, back to its original position (this was done using air pillows situated on the scaffolding, the gap between the disk and the surrounding shell, which remained after lifting, was filled with a lime-based mortar under pressure); filling of all radial cracks in the drum and in the dome by a lime-based mortar under pressure; construction of a reinforced concrete shell atop the dome (thickness-80÷90mm,

f_{ck} = 30 MPa). As a result of these works, the dome was turned into a two-layer composite structure. Its original shape was restored and strengthened by an external reinforced concrete shell. Therefore the internal appearance of the dome did not change, which allowed further restoration of ancient paintings.

3.3. Synagogue in Oni

The synagogue was completed in 1895. It is a rectangular symmetrical structure (18.5x14.9 m) built of local stone, its maximum height being 15 m (Fig. 6). The dome, built of the same stone, has the 6.7 m span and the 3.0 m rise. It is situated in the center of the structure, atop a drum, which is supported by arches. A cement-lime mortar was used for construction. The arches are tied at their bottom by steel rods with square cross section (25x25 mm), for taking horizontal tensile forces (Fig. 10).The stele and sculptures are made of separate stones connected to each other by metal staples. Portico of the building is made of stone columns covered by stone vault. The columns are made of separate stones. Their bottoms are tied on the edges by metal tie bars, and rear columns of the portico are connected with the building by metal staples, located in the body of the vault and preventing free horizontal shift of the portico's structures.

The earthquake caused substantial damage to the building, which did not collapse, however, due to its symmetrical structure, rigid walls, steel ties, and small arch spans. Cracks developed in actually all bearing elements, such as arches, shell, external walls, and in the drum. The crack opening in the arches was 5÷10 mm. Many architectural elements and sculptures situated outside, at the facades, were severely damaged. Some of them collapsed, including fragments of walls (Fig.6A, B).

A method for estimation of structural seismic resistance (Danieli and Bloch, 2006) was applied to this building. Relative earthquake resistance coefficient was estimated based on the design data and the results of the inspection. Temporary conservation was not carried out, but it was no further damage during the aftershock. Permanent conservation was aimed primarily at strengthening of bearing elements and the works on the strengthening and restoration were completed two years later (architect S. Bostanashvili, structure engineer M. Danieli). The drum has been reinforced as well.

The project included the following major steps (Danieli at al., 1998; 2002):
- Removal of plaster, filling of cracks by cement-lime mortar. Steel wedges were used to for filling of wide cracks (> 6 mm).
- Reinforced plastering of arch and shell surfaces in damaged areas. One steel meshes layer (150x150 mm of ø6 mm wires) served as reinforcement. The meshes were tied to ø10 mm steel anchors, each situated in a pre-drilled hole at a 30º angle to the surface. Cement-lime mortar was applied (f_{ake} = 10 MPa), the layer thickness was 40 mm.
- Drum strengthening. A 10 x 10 mm mesh of ø1 mm wires was used for external reinforcement. Cement lime mortar (f_{ake} = 10 MPa) was used to provide a 30 mm layer.
- Restoration of non – bearing external parts and architectural elements.

Fragments of strengthening are shown in Fig. 7.

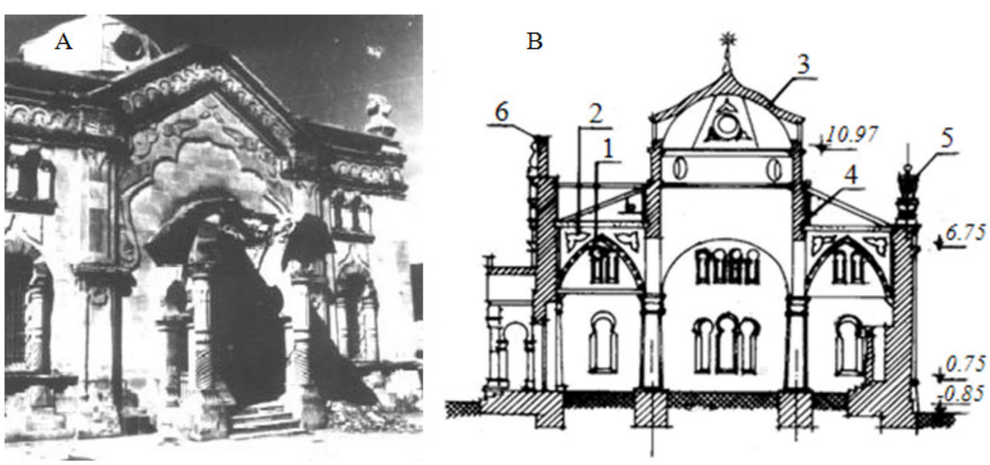

Figure 6. The synagogue in Oni. A - view after the earthquake. B - the cross section:
1- arch; 2 - ceiling; 3 - dome; 4 - drum; 5 - collapsed sculpture; 6 - collapsed facade element

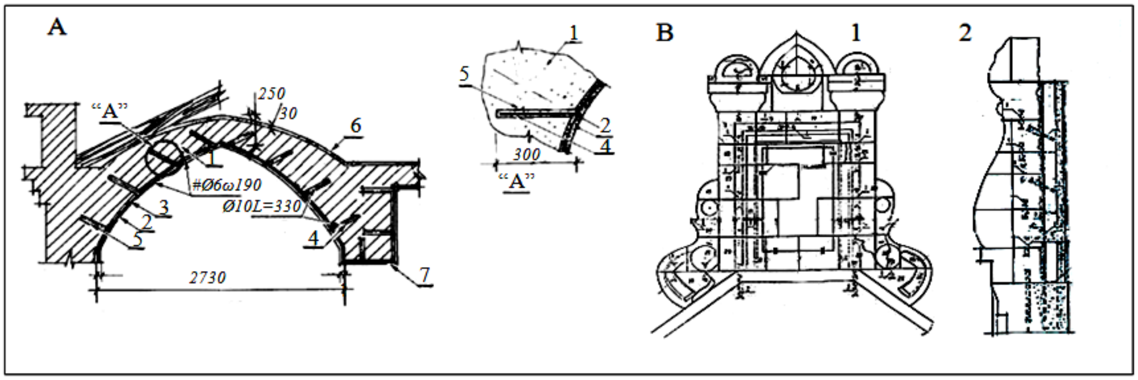

Figure 7. Fragments of strengthening (dimensions in mm).
A - details of arches and vaults reinforcement: 1 - arch; 2 - reinforced plastering layer; 3- steel mesh; 4 - drilling; 5- steel anchor
B - strengthening of the frontal stele: 1 - frontal facade; 2 -lateral façade

3.4. Conservation Project for the Stone Dome in Ahaltsihe

The building of the former mosque in the town of Ahaltsihe was constructed in 1758. The historical view without roof of the building is shown in Fig. 1, A. The inner diameter of the supporting contour of the dome is about 16 m; inner height (rise) is about 8 m, thickness of the walls is 0.6–0.8 m. The dome was constructed from thin clay bricks with dimensions of $24 \times 24 \times 4$ cm, on a lime–clay mortar. The brick edges stand out horizontally in steps on the upper surface of the dome (Fig.1,A).The dome has typical cracks originating from the supporting zone in the meridian direction and opening crack width on the lower surface of 1.5–2.0 cm (Fig.3); additional weak zones of a dome are created by window openings. There is a clear need for dome conservation and strengthening, taking into account the history and architecture of the important building, the existence of developed cracks, and the need to save it from seismic loads during possible severe earthquakes without significant damage. To preserve the inner ancient look of the dome in its present state (with cracks in the brick masonry),it is proposed to carry out strengthening of the dome according to the proposed method–with a new reinforced concrete shell above the upper surface of the stone dome and connected with it .Input data for analysis are taken from results of inspection and measures, according to design proposals: for stone dome: density 1.8 t/m^3; Module of Deformation $E=1.5 \times 10^3$ MPa; span of a dome D = 15.8 m; height (at apex) f = 4.9 m (above the level of the top of light openings); thickness of stone dome – from 0.8 m (at bottom zones) to 0.7 m (at top zone, apex). For concrete shell and concrete connection elements: density 2.4 t/m^3; compressive strength for concrete 30 MPa; $E = 3.0 \times 10^4$ MPa; span of a shell – D = 16.7 m; height (at apex) f = 5.26 m; thickness of a shell 0.12 m (at zone of supporting ring 0.20 m); cross-section of ring beam $b \times h = 0.4 \times 0.6$ m; for concrete connection elements (joints): cross-section from 0.3×0.3 m at surface of concrete shell, up to 0.45×0.45 m at bottom of pyramidal sockets in a stone dome; length 0.6 m. Total number of connection elements is 44. Connection joints are distributed throughout the dome surface by 4 circular lines (Fig. 2).

To study the stress-strain state characteristics of the strengthened structure, as well as to estimate the efficiency of the proposed strengthening method, a series of analyses were executed by FEM (Danieli at al. 2004). The obtained results show the efficiency of the proposed strengthening method.

4. EXPERIENCE

On September 8, 2009, there was an earthquake in northern Georgia. The magnitude in the epicenter of the earthquake was 6.2. 1 400 houses were damaged or destroyed. The epicenter was 12 km from Oni which was the most damaged location (Fig.9). The distance from the epicenter to Nikortsminda is about 40- 45 km.

Figure 9. Seismic situation caused by the earthquake in Georgia, 8 September 2009

A temple in Nikortzminda and the building of the synagogue in Oni survived this earthquake without any substantial damage caused. It proves the effectiveness of the strengthening and rehabilitation works in these buildings performed by us. The view of the synagogue in Oni after the strengthening and restoration is shown in Fig. 10.

Figure 10. The synagogue in Oni: A - view after the strengthening and restoration; B - interior

5. CONCLUSIONS

1. All three different modes of construction techniques considered in the paper, namely: Maintenance, Conservation, and Restoration mentioned above have their specific purposes. Assigning to this or that category depends on the prevalent nature of works. All three different modes almost invariably involve strengthening structural elements. Regarding conservation of historical buildings, one can distinguish between temporary and permanent conservation. Temporary conservation of the temple in Nikortzminda was carried out immediately after the main shock of the earthquake in order to prevent its collapse by possible aftershocks. Temporary conservation, if done in time, can prevent the collapse of damaged structures and thus make their subsequent conservation (strengthening) and restoration possible.

2. An original dome strengthening structure is proposed. It consists of a new thin-walled reinforced concrete shell with a supporting ring, cast on top of the existing stone dome. It makes it possible to preserve the existing ancient appearance of the inner surface of the dome. The connection between old stone dome and new reinforced concrete shell is achieved by using special reinforced concrete connecting elements and by adhesion of the neighboring surfaces. Thus, an interconnected stone-reinforced concrete composite structure is created. As a result, the earthquake resistance of the stone domes increases significantly. The Ahaltsihe stone domes can serve as an example of the efficiency of the proposed method as is shown by numerical analysis with the use of FEM.

3. The temple in Nikotzminda and the synagogue in Oni after the strengthening end restoration survived the Richter magnitude 6.2 earthquake in this region on September 8, 2009, without any substantial damage caused. Methods and techniques offered and applied for retrofitting the temple in Nikotzminda and the synagogue in Oni may be recommended for the strengthening and conservation of other historic structures; besides, design principles applied in strengthening projects for the dome in Ahaltsihe can provide substantial contribution to successful conservation of other stone domes, along with the increase of their earthquake resistance.

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