

METHODOLOGY, METHODS AND TECHNIQUES FOR REPAIR  
AND STRENGTHENING OF HISTORICAL MONUMENTS AND  
OLD URBAN NUCLEI IN SEISMIC ACTIVE REGIONS

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ABSTRACT

This paper presents some methods and techniques for repair and strengthening of historical monuments in seismically active regions on the basis of detailed study and assessment of seismic hazard, local soil conditions, determined dynamic characteristics of structures as well as bearing and deformability properties of built-in materials. The results of these studies and the applied experience will be presented as a general approach, in the first part, and through some typical examples, in the second part.

INTRODUCTION

The repair and/or strengthening of historical monuments is highly dependent on the earthquake conditions to which they have been exposed in their past history and the ground motion to which they will be frequently expected to be exposed in future, as well as the materials and methods used for their construction. Due to these reasons, it will be of importance that repair and/or strengthening, as a part of preservation, conservation and restoration of historical monuments located in seismic active regions, be planned based on detailed studies of the expected seismic hazard, the local soil conditions and the dynamic behavior of soil media under earthquake loading, the dynamic properties of the structural systems, the strength and deformability characteristics of the structural elements and their materials, and the dynamic response of the structural systems under the expected ground motions.

Having in mind that most of the historical monuments are constructed of brittle materials with large cross sections of the structural elements and heavy structural systems, as well as considering the limited possibilities for improvement of the ductility of the structural elements, it should be recognized that their earthquake response will be mostly limited to elastic

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range of structural behavior. This will require that the expected earthquake ground motions, as the first important influencing factor, be determined not only by the amplitude content but also by the expected frequency content of the close and far distant seismic zones with consideration of the influence of the local soil conditions on modification of the amplitude and frequency content of the earthquake ground motions. The second influencing factor are the dynamic properties (resonant frequencies, mode shapes and damping capacity) of the structural systems which will assure appropriate formulation of the mathematical models and analysis of the dynamic response. The third influencing factor on which the structural response and the methods for repair and strengthening will depend in the process of preservation of the historical monuments, are the strength and deformability characteristics of the structural materials and the main structural elements, and the possibility for improvement of their ductility. The fourth factor which will have an important influence on the structural response due to the pronounced rigidity of the structural systems of the historical monuments and the relatively soft soil conditions, is the effect of the soil-structure interaction.

Considering that the above mentioned factors are of basic importance for determination of the earthquake response of historical monuments, as well as the fact that seismic analysis of this type of structures cannot be performed using seismic design codes for modern buildings and structures, determination of the criteria and the methods and techniques for strengthening of historical monuments and the process of restoration and preservation should be based on detailed studies of relevant influencing factors with consideration of the economic effects of the alternative solutions for repair and strengthening. It will be also important to recognize that in the case of larger number of similar or the same historical monuments concentrated at the same location, the seismic risk is several times larger than in the case of a single, isolated monument.

In general, considering that structures of monuments in seismically active regions by the process of repair and strengthening should not change their basic structural system, seismic design criteria and dynamic response analyses for monuments, as well as adequate repair and strengthening methods and techniques should be developed in order to provide economically justified and technically consistent seismic safety with sufficient bearing and deformability capacity as well as acceptable damage level in case of future earthquakes.

## **Approaches and Methods of Repair and Strengthening of Monuments**

The obtained data enables elaboration of the structural concept for repair and strengthening, which includes the following characteristic phases:

- analysis of the existing structural state,
- solution for structural repair,
- analysis of the state of the repaired structure.

Each of these phases will be described in details from methodological point of view.

**Analysis of the Existing State of the Structure.** Weak points as well as basic failure mechanism should be defined by simultaneous study of the geometry of the monument, distribution of masses and changes of stiffness along the height and damage analysis.

The following analyses should be performed by using data on the characteristics of the material and the defined seismic effect:

- analysis of the bearing capacity and deformability of the existing state of the structure,
- preliminary estimation of equivalent seismic forces,
- comparison of the bearing and deformability capacity of the existing state of the structure and estimation of seismic forces and capacity of deformability.

This state being accomplished we start with strengthening.

**Design Solution for Repair and/or Strengthening of Monuments.** Taking into account the basic masonry and stone masonry materials, which have low tensile and shear strength, as well as the massive and heavy structures, one of the principal problems which is imposed is to attain structural integrity at storey level. This is necessary from two aspects: first, to assure that rigidity pre-conditions force distribution according to the rigidity characteristics, and second, to avoid individual behavior of some members after development of cracks between the large and relative flexible members.

In case the analysis shows that the walls bearing capacity and deformability do not meet appropriately the requirements, strengthening should be performed by either increasing the bearing capacity or providing adequate ductility (or both). Special attention should also be paid to the soil conditions and the soil-structure interaction.

Based on the above, the general concept for repair and strengthening is elaborated. In this phase, it is necessary to consult architects, conservators and other professionals, involved in the project activities.

The design of repair and strengthening should contain all the elements concerning construction and detailing, as well as performance and its supervision.

As concerning the strengthening techniques for the structure, it is essential to point out that they result from the structural requirements. Due to the fact that some techniques will be presented here through given examples, they will also be listed as different possibilities.

In principle, repair is performed by reconstruction of parts, built of identical or similar material, by improving of the mortar, injecting of the cracks, connecting, locally, reinforcement and other metal parts. The strengthening can be carried out applying a number of techniques and ways.

i) to provide integrity of the structure, steel ties or R.C. belts are frequently used (in case of churches, mosques, etc.) or R.C. floor slabs are introduced (in case of structures of old towns);

ii) to improve the bearing characteristics of walls and columns, as structural elements, and make them resistant to horizontal forces several techniques can be used as follows: injecting of masonry, injecting by jacketing, placing R.C. vertical columns, adding new R.C. shear walls and other elements (in buildings of old towns);

iii) by strengthening of the whole structure the ultimate strength is increased as well, so it is necessary to control the ultimate bearing capacity of the soil and the foundation and strengthen them by extending and connecting them to the strengthened elements of the vertical bearing structure (walls and columns).

#### **ANALYSIS OF THE STABILITY OF THE REPAIRED AND/OR STRENGTHENED STRUCTURES**

Evaluation of bearing and deformability characteristics of the structural members and the structure as a whole is given on the basis of the adopted concept for repair by using the engineering procedure on the basis of the properties of the strengthened material. If the results satisfy the safety coefficient and deformability requirements, the adopted concept is verified and the plan for repair and strengthening of the monument is prepared. If it is not the case, all the necessary interventions for improvement of the basic concept have to be performed and the procedure repeated until results, satisfying the previously stated criteria for seismic stability and safety, are obtained.

As mentioned in the introduction, from a structural viewpoint, it is necessary to determine the seismic effects in function of the return period, the maximum ground acceleration and the time histories of typical earthquake records.

If we consider the seismic force definition given in the Codes, it is clear that it can not be used for historical monuments since they do not represent the specific features of this type of structures, therefore it only applies to new, modern engineered structures.

The principal objective of the design engineer in the design of the repair and strengthening of cultural and historical monuments is to determine the design parameters according to the physical values of the coefficients taken in the preceding equation.

The next design and calculation procedure is the force distribution along the height and the structural members which is known to the design engineers and should not be explained in details. It also applies to the design procedure of stiffness and deformation characteristics and the load carrying capacity of walls, walls with strengthening, walls and elements with jacketing, etc. The main objective is to define the load carrying and deformability capacity and compare them to the seismic stability criteria of the structures defined in the preceding investigation process.

The suggested methodology and some of the applied techniques are illustrated by several characteristic studies.

## 1. REPAIR AND STRENGTHENING OF HISTORICAL MONUMENTS IN PAGAN, BURMA

The Pagan plateau, in the central part of Burma, is a world-wide known place by the high concentration of magnificent historical monuments (Fig. 3.1) from the past, like temples and pagodas, unfortunately most of which have been severely damaged by natural disasters, including earthquakes.

The earthquake of July 8, 1975, with a magnitude of 6.8 destroyed or heavily damaged many monuments - temples or pagodas. On the basis of the study of the neotectonic and seismotectonic characteristics of the wider Pagan region (where earthquakes with magnitude up to 8 can be expected), and based on the methodology for probabilistic seismic hazard modelling, statistical analysis of earthquake data and selected attenuation relationships, seismic hazard data are presented in terms of peak ground acceleration for average soil conditions for return periods as follows: for a return period of 50 years,  $a_{(g)}=240$ ; return period of 100 years,  $a_{(g)}=300$ ; for a return period of 500 years,  $a_m=300$ ; for a return period of 500 years,  $a_{(g)}=460$ ; and for a return period of 1000 years or maximum expected ground acceleration  $a_{(g)}=530\text{cm/sec}^2$ .

The Pagan region is mainly characterized by two types of historical monuments, temples and pagodas (or stupas). The

structural systems of the temple monuments consist of bearing massive walls combined with massive central pillars which form corridors or halls interconnected with domes or arches (Fig. 1.2 and 1.3). The pagoda monuments are constructed as massive solid stupas with changeable form along the monument height (Fig. 1.2). It is important to be mentioned that large disproportion exists in respect to the size, both in temples and pagodas, starting from the impressive temples (Ananda, Gawdawpalin, etc.) up to 60 m high, and plan proportions from 50 to 60 m, to small one-storey temples of about 10 m in plan and height. Taking into account the above described modes of failure, the material properties and the structural systems, the dynamic characteristics and the expected possible earthquakes, the following method of strengthening and repair of monuments in Pagan has been proposed:

(i) Preserving of structural system integrity at each storey level by inserting of steel bracings, for small and medium size temples (Fig. 1.4) and/or by construction of reinforced concrete belt courses (Fig. 1.5) around the structure and at each storey as defined by the free height of corridors and halls, in the case of medium size temples.

(ii) Strengthening of the upper slender parts of the monuments (shikaras) by inserting of horizontal R.C. belt courses and injection of the massive masonry for increasing of the shear load carrying capacity and inserting of vertical R.C. belt courses to prevent bending failure (Fig. 1.8 and 1.9). In other words, these parts of the structure are repaired and strengthened in such a way to provide the required ductility and shear resistance capacity.

(iii) Strengthening of structural walls (massive and/or medium size) or central pillars is generally carried out by injection of the existing masonry by cement emulsion increasing thus the shear resistance capacity and the bending or tension effects. It should be pointed out that the analysis of the load carrying and deformational capacity of structural systems through equivalent mathematical models and calculations of load carrying capacities showed that in most cases, the seismic stability criteria of the structural systems satisfy the safety requirements if injection of masonry is applied (due to the massiveness, the size and the proper concept of the structural system) avoiding thus the conventional way of strengthening the masonry by construction of vertical R.C. columns or frames which in the case of massive sections proved to be ineffective due to their different bearing and deformational characteristics.

If in some cases it becomes necessary to increase the load carrying and deformational capacity of masonry, either of the entire structure or in some levels, then the so called "jacketing" method is suggested in order to promote the confinement effect and increase the shear and bending capacity of walls or pillars.

## 2. RECONSTRUCTION, REPAIR AND STRENGTHENING OF BUILDINGS IN THE OLD TOWN OF BUDVA

The old town of Budva was severely damaged due to the April 1979 Montenegro earthquake. Considering the cultural and historical value of most of the buildings in this town, the Institute for Protection of Historical Monuments in Montenegro in cooperation with the Town Assembly of Budva ordered investigation studies for the purpose of searching for the optimum conditions and methods for reconstruction, repair and strengthening of structures, taking care, primarily, of their cultural and historical value, as well as the vulnerability and reliability level, depending upon the seismic hazard.

Almost all the buildings in the old town of Budva are constructed of crashed stone, mostly unfinished, with walls built up of two layers of large-size stones and smaller-size stones in the space between. The masonry is constructed using lime mortar, while the exterior walls are mainly not plastered. The buildings have suffered heavy damage, even partial failure. There is special technical documentation describing the post-earthquake condition of the buildings. Considering the dilapidated state of the buildings (their timber floor structures, roofs and installation) and the earthquake attributed damage, it can be concluded that they are in very bad conditions, however, since they have cultural and historical value the economic justification of their repair has never been questioned.

The general method for repair and strengthening of structures in the Old Budva Town consists of the following:

-- Each structural unit is analyzed as a separate structure repairing and strengthening the walls by jacketing and injection at the lower storeys as well as injection of walls at the upper storeys. New reinforced concrete walls or combined stone and concrete walls (in case of failure of facade walls) are added if necessary. Reinforced concrete floor slabs supported by monolith reinforced concrete belt courses are added to all the structures. Strengthening of foundation is also required. Presented in Fig. 2.2 is an example of a part of a structural unit, and details.

- Repair and strengthening of existing walls. The repair and strengthening is carried out by systematic grouting of the walls according to the developed procedure.

- Strengthening of walls by reinforced concrete jacketing. Reinforced concrete jacketing is carried out on one or more storeys of the building, where necessary, and the jacket is 6 - 10 cm in thickness. The jacket is placed down to the foundation level, i.e., it is placed both on the walls and foundation below the ground surface.

- Connection of the floor structure to the existing walls is carried out with R.C. slabs (Fig. 2.2).

### 3. MONASTERY OF ST. PANTELEJMON - NEREZI, SKOPJE - AND KURSUMLI HAN IN SKOPJE

Presented through in the next two examples will be the ways of repair of only two from the numerous historic monuments in Skopje, Macedonia, i.e., the Monastery of St. Pantelejmon - Nerezi (12th century) and Kursumli Han (15th century).

Repair of structures damaged by the Skopje earthquake of July 1963, has been performed for a relatively short period of time. Unfortunately, we cannot say that the reconstruction, repair and strengthening have been performed in compliance with the principle and the methodology presented and applied in the previous examples as these were our first pioneer steps when we were facing earthquake engineering as a new scientific-technical discipline on one hand our limited knowledge and experience as well as the needs to protect cultural monuments against further dilapidation (climatic effects, humidity, etc.) on the other. One of the frequently applied ways of repair at that time was the introduction of reinforced concrete belt courses (vertical and horizontal) as well as rebuilding of the severely damaged parts of walls, cupolas and other elements. From the point of view of new developments in this field, these solutions will certainly be exposed to a criticism mainly from the aspects of conservation as they imply the use of too much concrete, difficulty in performing the intervention and unknown behavior of the contact between the old and the new materials.

The monastery of Nerezi was characterized by relatively slight damages. The analysis of the structure has pointed to the fact that the damages were mainly due to soil conditions, i.e., lack of elementary protection against surface water. The main repair concept consisted of strengthening of the foundation structure, improvement of the soil conditions and very slight strengthening of upper part of the structure by introducing reinforced concrete vertical and horizontal belt courses (Fig. 3.1 - 3.3) including profound strengthening of foundation and protection against surface water which was the main cause of soil instability. The quite strict criteria required by the conservation and protection of the frescos (avoiding concrete and the effect of cement) has imposed application of reinforced concrete elements of minimum proportions as well as reinforcement and circular lay-out of elements in horizontal and vertical belt course to sustain the tensile stresses.



## CONCLUSIONS

In the process of prevention of historical monuments against disastrous earthquakes, three significant activities should be pointed out:

- pre-emergency activity
- development of appropriate methodology, methods and techniques
- research activities

It is not necessary to talk about each of these aspects on this occasion, however, it is the only way to preserve the historical heritage for the generations to come.

For repair and strengthening of historical monuments a new chapter of engineering must be developed which should unify the efforts of architects, engineers and preservers and of all other participants in this rather delicate task. Let's hope that our works presented in this meeting will contribute to the establishment of the "new chapter" which most of us are lacking.

## ACKNOWLEDGEMENT

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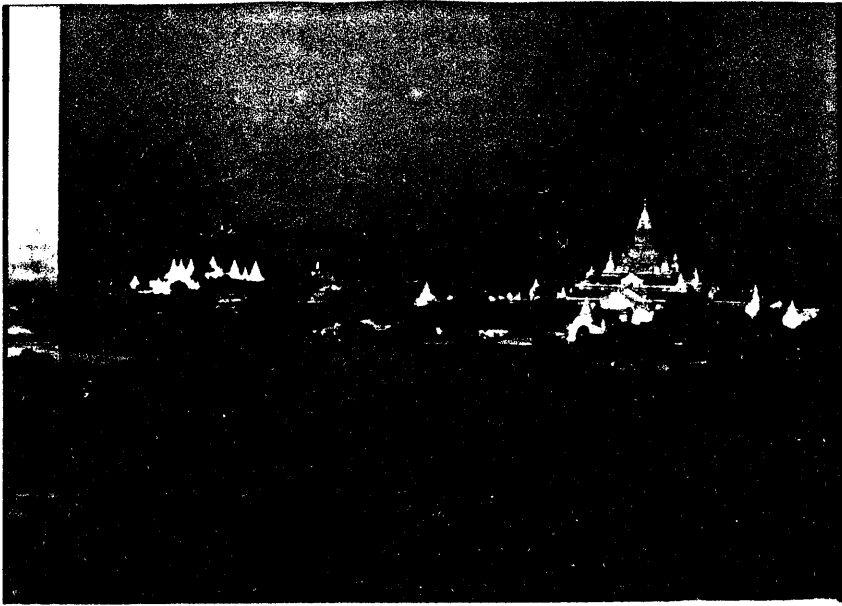


Fig. 1.1. Panorama of Pagan Plateau

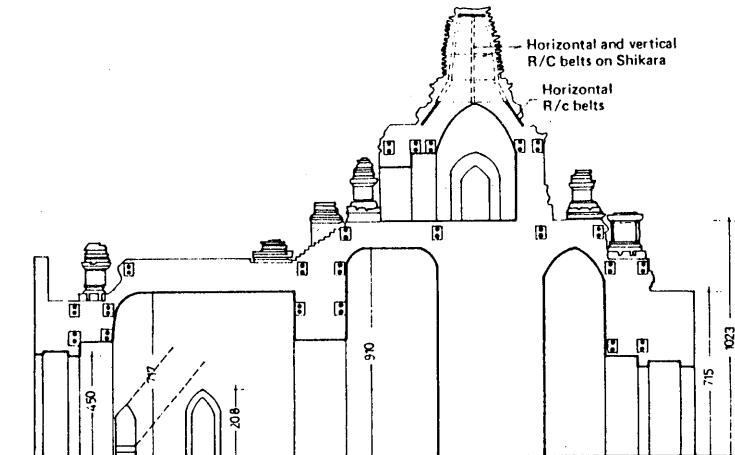
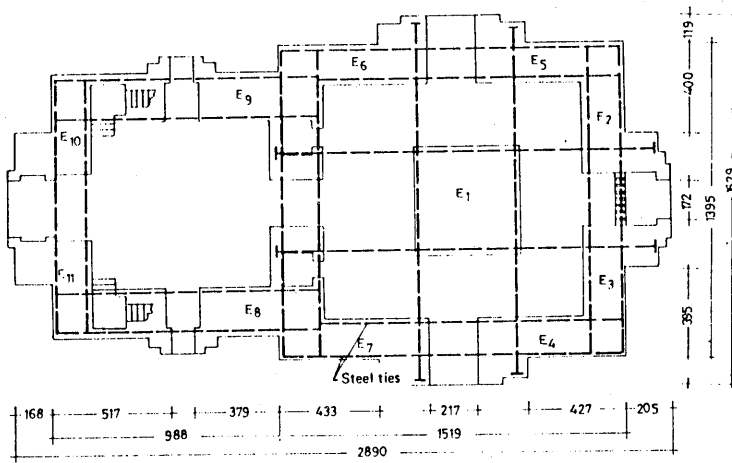


Fig. 1.2. Strengthening and repair of South Guni Temple

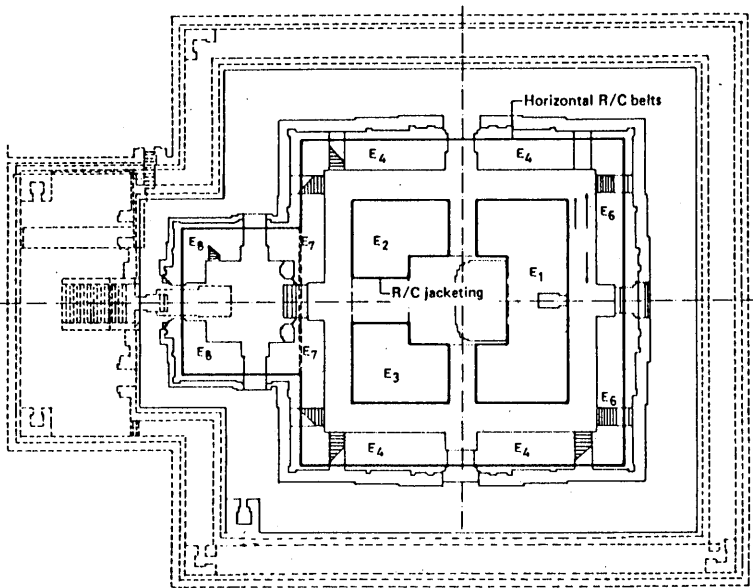
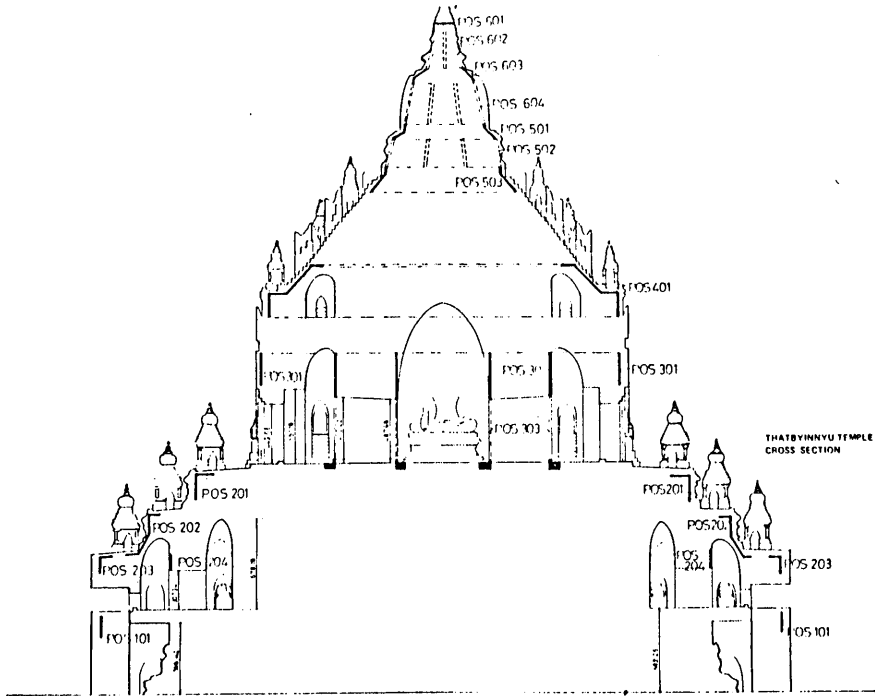


Fig. 1.3. Strengthening and repair of Thatbyinyu Temple

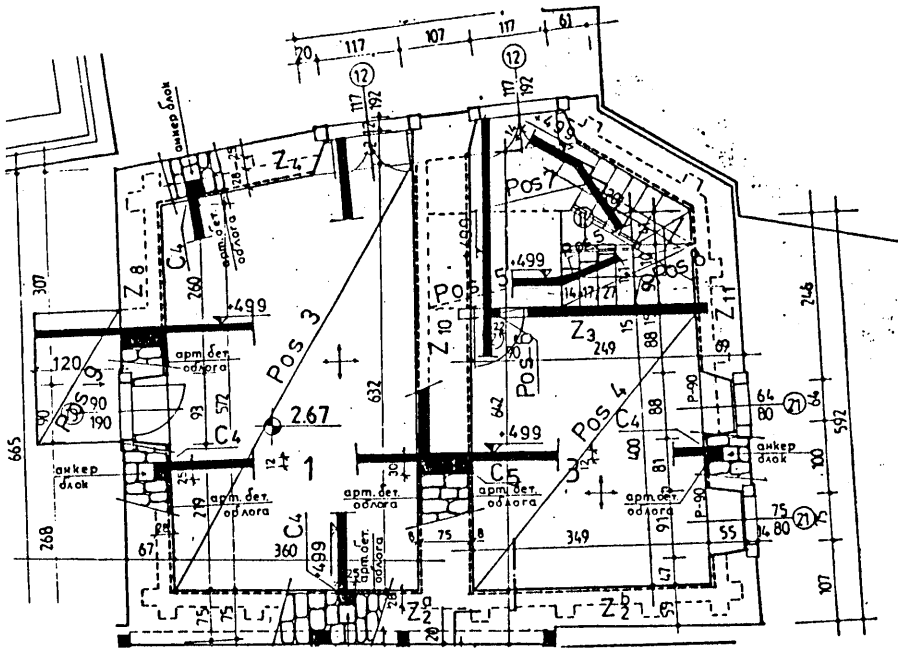


Fig. 2.1. Typical buildings in town of Budva

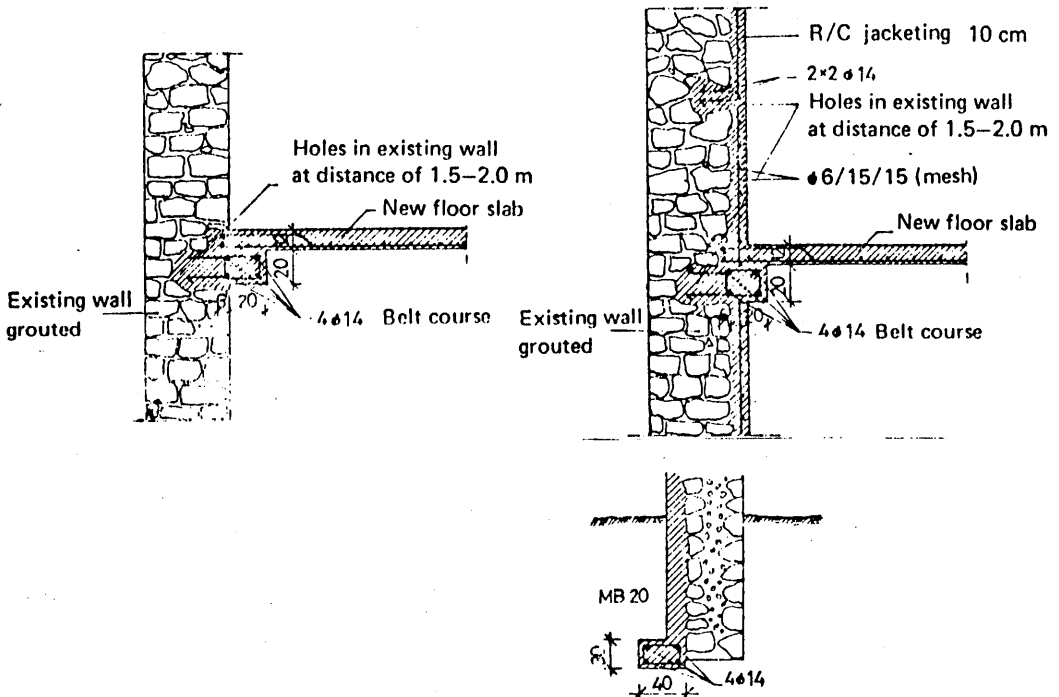


Fig. 2.2. Details of walls strengthening

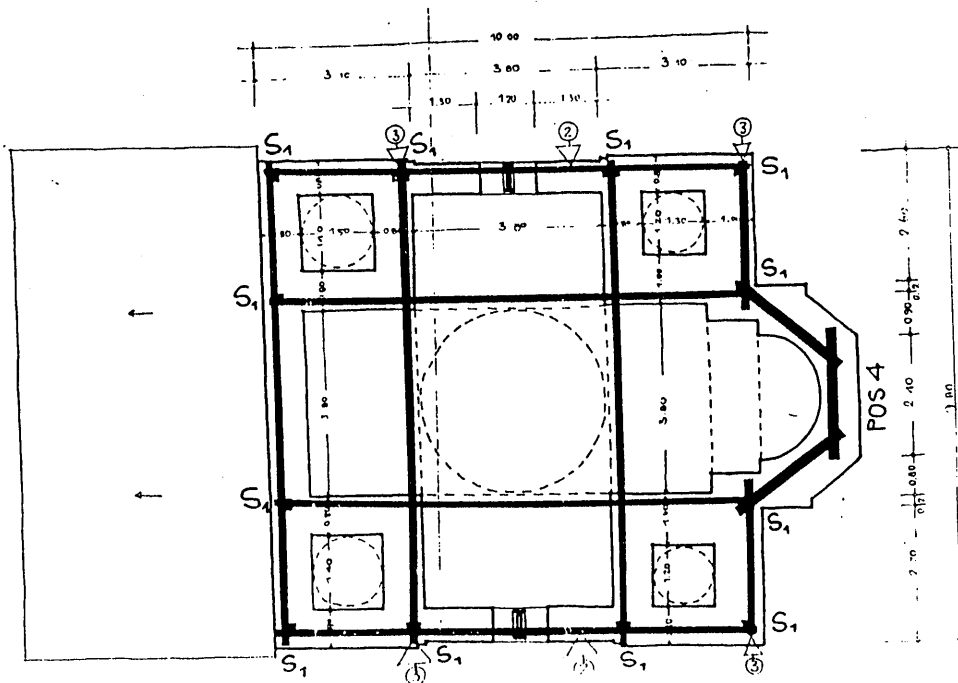


Fig. 3.1. Strengthening of the St. Pantelemon – Nerezi, Skopje

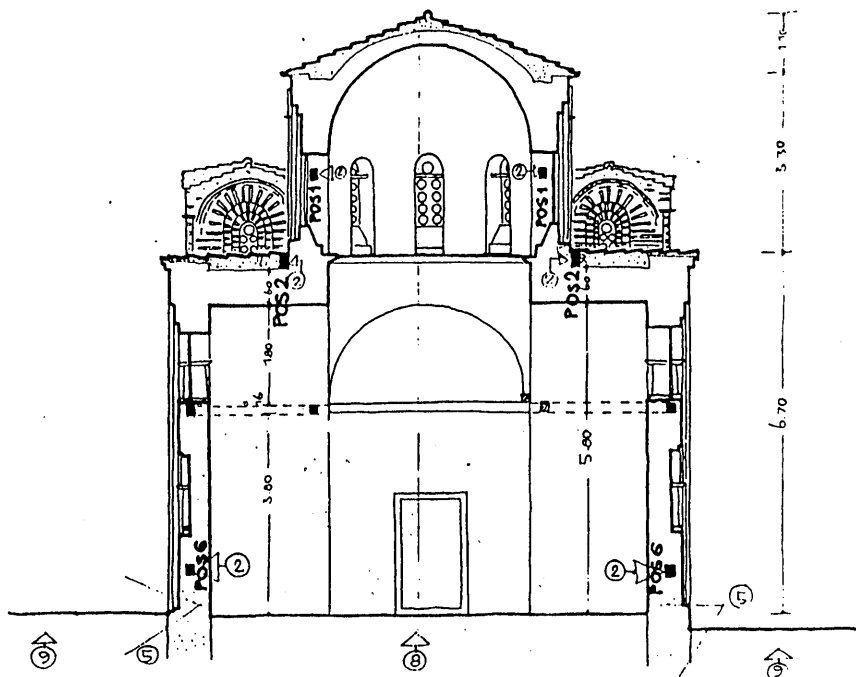


Fig. 3.2. Cross section of the St. Pantelemon – Nerezi, Skopje

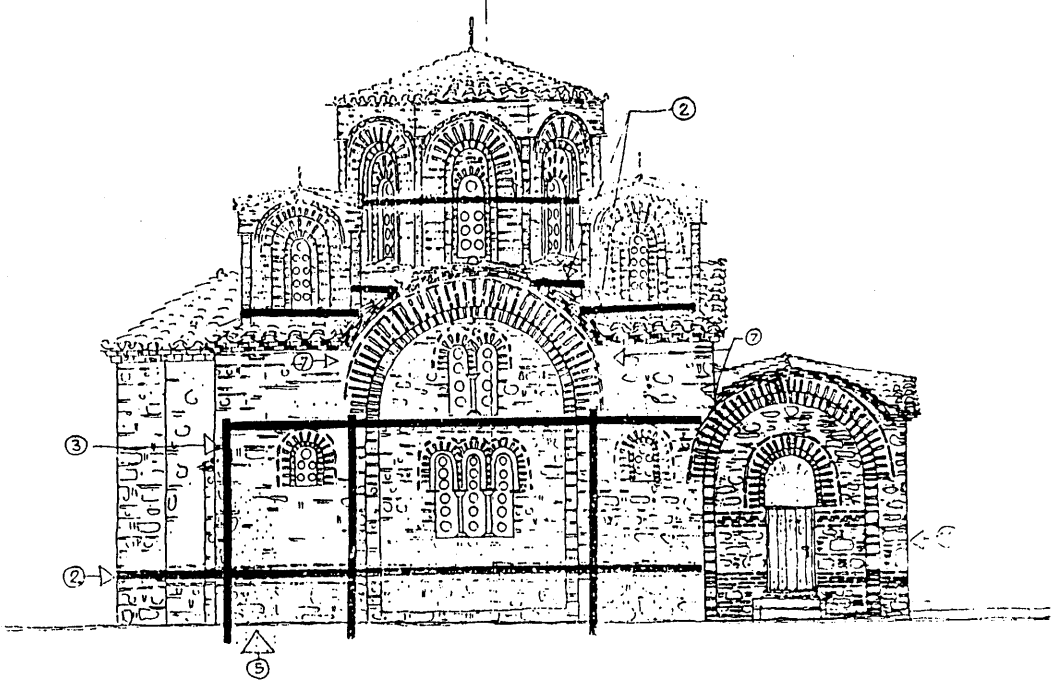


Fig. .3.3. Strengthening of St. Pantelemon

## TARİHİ YAPILARIN TAMİR VE SAĞLAMLAŞTIRILMASI

Predrag GAVRILOVIC

Bu yazı deprem yönünden aktif olan bölgelerdeki tarihi anıtsal yapıların onarımı ve güçlendirilmesi için bazı yöntem ve teknikler sunmaktadır. Genel olarak bu yollar ayrıntılı çalışmalara ve deprem riskinin, bölgesel zemin koşullarının, yapının dinamik karakteristiklerinin, kullanılan malzemenin mukavemet ve rijitliğinin kestirilmesine dayanmaktadır. Bu çalışmalardan ve uygulamaların kazandırdığı deneyimden kaynaklanan sonuçlar, çalışmanın ilk bölümünde; genel bir yol olarak, ikinci bölümünde ise örnekler aracılığı ile sunulacaktır.