Seismic strengthening of historic monuments and experimental investigations

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Abstract
The methodology for strengthening of Byzantine monuments, developed in full compliance with the traditional ways of construction, the specific characteristics of the monuments and modern requirements for seismic stability, within the framework of the research project «Study for Seismic Strengthening, Conservation and Restoration of Churches Dating from the Byzantine Period in Macedonia», has been experimentally investigated. The church of St. Nikita located in the village of Banjani was selected as a prototype for detailed experimental and analytical investigations of the existing state and a 1:2.75 scale model was constructed for shaking table tests to establish the basis for development and verification of a methodology for repair and strengthening of historic monuments. After testing the model by a gradual increase in the intensity of the simulated earthquakes, the damaged model was repaired and retrofitted using tie rods contained within the wall structures to minimize the visible effects of structural intervention, and the model was tested again. Comparison of the experimentally obtained results for the original and the strengthened model undoubtedly proved the efficiency of the method for improvement of the seismic resistance of these structures. The method is easily applied and fully satisfies the principle of minimum intervention – maximum protection.

Key words *Byzantine churches – repair and seismic strengthening – shaking table testing of a church model*

1. 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 are 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/or strengthening, as a part of preservation, conservation and restoration of historical monuments located in seismically 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.

Bearing 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, their earthquake response is mostly limited to the elastic 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 and modification of the amplitude and frequency content of the earthquake ground motions. The second influencing factors 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 factors 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 has 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 the seismic analysis of this type of structure cannot be performed using seismic design codes for modern buildings and structures, determination of criteria, 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 alternative solutions for repair and strengthening. It is still also important to recognize that in the case of a large number of similar historical monuments concentrated at the same location, the seismic risk is several times higher than in the case of a single, isolated monument.

In general, considering that structures of monuments in seismically active regions should not change their basic structural system by the process of repair and strengthening, seismic design criteria and dynamic response analysis of 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 an acceptable damage level in case of future earthquakes.

2. Study of the existing state of the monuments and seismic strengthening

For the purpose of development of appropriate methods and techniques for repair and strengthening of monuments of Byzantine type, in general, and particularly the Byzantine monuments located within Macedonia, the research project «Study for Seismic Strengthening, Conservation and Restoration of Churches Dating

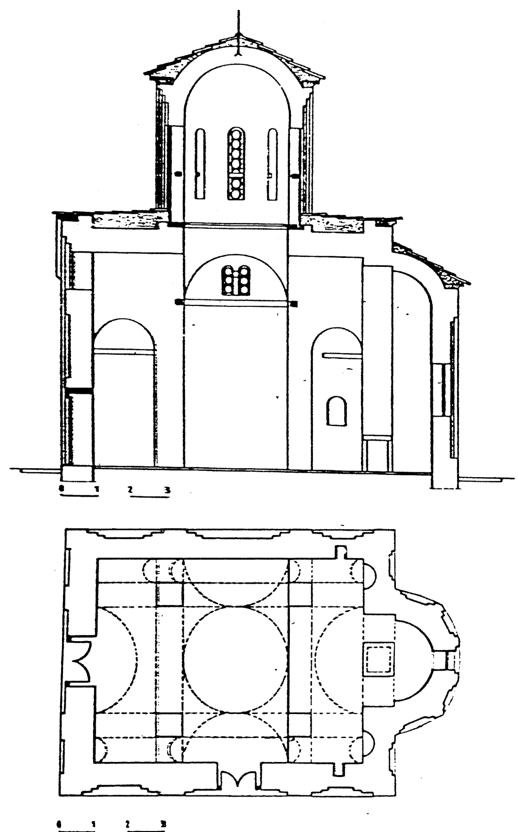


Fig. 1. Plan and cross section of «St. Nikita» church of Banjani (Macedonia).

from the Byzantine Period (9th-14th Century) in Macedonia» has been proposed to the Getty Conservation Institute – Marina del Rey. The programme of the project involves all the phases of the investigation, *i.e.*, definition of seismic hazard, seismic parameters and local soil conditions, performance of ambient vibration tests and tests for the characteristics of mortar, as well as shaking table tests as a basis for verification of the methodology.

In the first phase of this project, data acquisition on 54 Byzantine churches was performed as a basis for investigation of their existing state, main characteristics and structural systems. Four representative buildings were selected for investigations that provided applicable and useful results for definition of a seismic strengthening methodology. Out of these, St. Nikita church was selected for detailed analytical and experimental investigations, including seismic shaking table testing of a model. The structural system of these buildings consists mainly of massive walls and two rows of symmetrically placed columns that support the vaulted areas and the dome via a system of arches and pendentives (fig. 1).

For the structure of the prototype church St. Nikita – v. Banjani, definition of the physi-

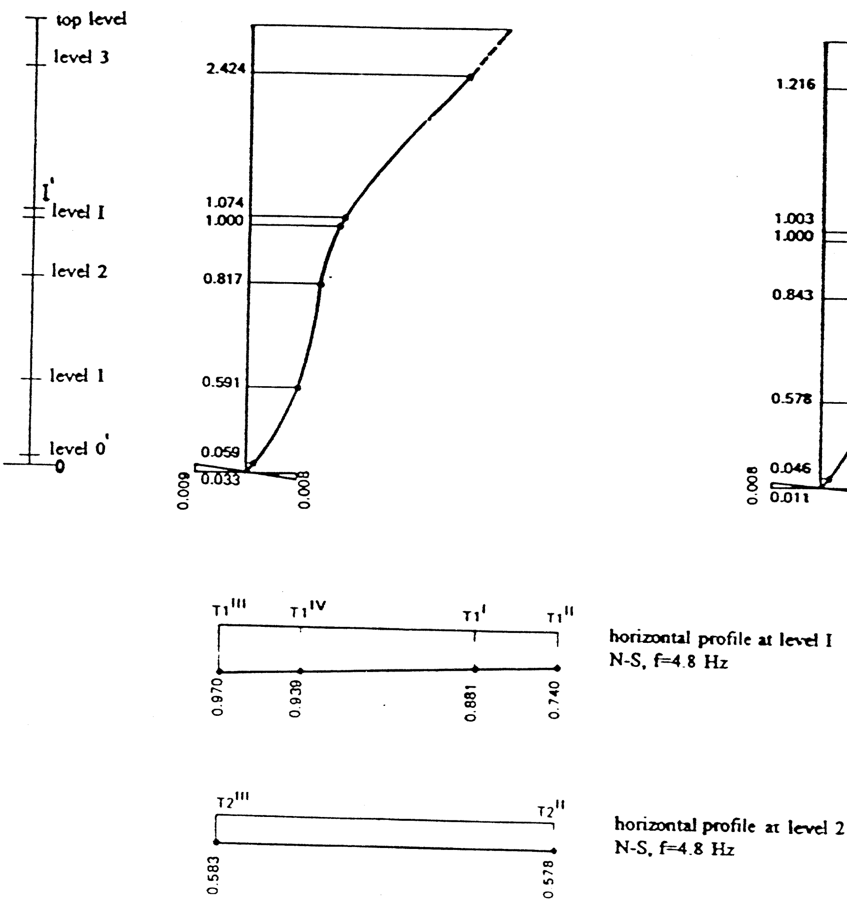


Fig. 2. Natural dynamic characteristics of the prototype church.

cal-mechanical and chemical characteristics of the built-in materials, as well as definition of seismic parameters were performed. Apart from this, detailed investigations of the main dynamic characteristics were carried out by application of the ambient vibration technique (fig. 2), and analysis of the seismic stability of the existing structure was performed for the purpose of evaluating the ultimate bearing capacity.

3. Design and construction of the scaled model

Shaking table tests of the prototype model were performed to define the existing characteristics of the building and to verify the developed methodology for repair and strengthening. To design a model to be tested on a seismic shaking table it is necessary to define the parameters of similarity between the model and the prototype in compliance with the basic principles of model analysis on the one hand, and the precisely defined objectives of the investigation on the other. Satisfying these requirements, the three main scales were adopted, *i.e.*, the geometrical scale of $1r = 1:2.75$, the scale of the specific density of the material to be used for the construction of the model $rr = 1$ and the scale of the stresses $Er = 1$. On this basis, the scales of all the remaining characteristics of the model were defined by using the corresponding scaling factors.

The model was constructed in the Dynamic Testing Laboratory of IZIIS to a scale of 1:2.75 (fig. 3) and according to the designed proportions. Original materials taken from areas surrounding the church were used for the construction of the model. The walls of the model were constructed in typical Byzantine style with two faces filled with limestone and small pieces of stones and bricks in between. Apart from the static tests of samples of built-in materials (tufa, bricks and mortar), quasi-static tests of three wall elements (1 m × 1 m) were performed under axial and shear pressure in order to obtain the experimental values for the elasticity modulus, the compressive and tensile strengths as well as some of the failure mechanisms.

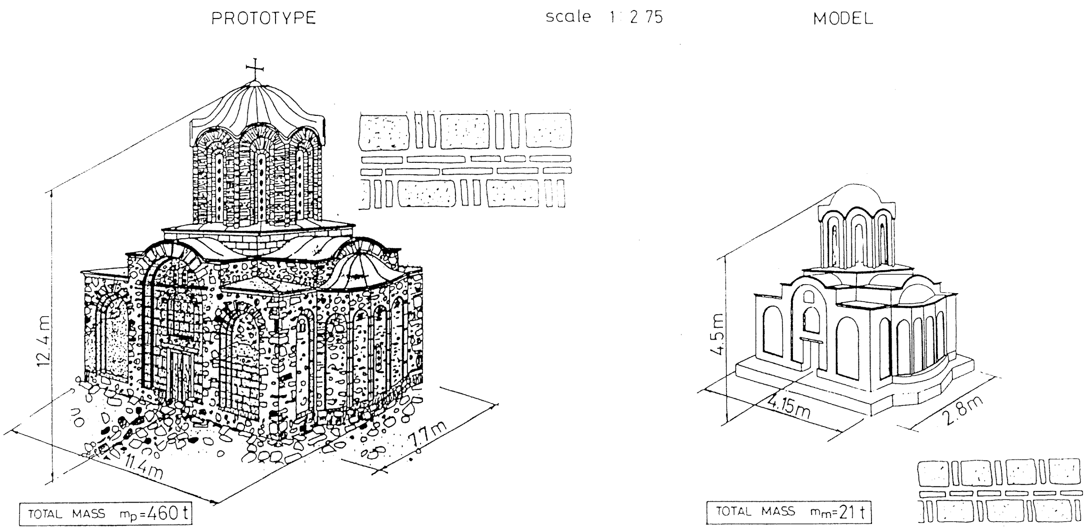


Fig. 3. Comparison between the prototype and the model.

4. Shaking table testing of the model

The main objective of this experimental testing is the evaluation of the building vulnerability under different earthquake intensities as well as selection of a procedure for repair and strengthening of the damaged building.

A programme was adopted for experimental testing under earthquake excitations performed by gradual increase of intensity for the purpose of monitoring the progressive development of cracks, the modification of the dynamic characteristics, the behavior phases and the failure mechanisms. The model was exposed to different types of earthquakes, *i.e.*, the Breginj earthquake (type of a local shock), the Petrovac earthquake and the El Centro earthquake (earthquakes from distant foci) that were selected from both seismic hazard and structural response aspects. These were properly scaled and applied with maximum amplitudes from 0.02 g to 0.43 g. Table I shows the testing programme with the maximum accelerations and relative displacements recorded at two characteristic locations, *i.e.*, the top of the dome and the level of the vaults (level 1).

It can be concluded that the elastic limit in the model structure takes place at $a_{max} = 0.17$ g (El Centro). $A_{max} = 0.19$ g (Petrovac) already induces the first larger cracks in the upper part of the tambour accompanied by minimum crushing and loss of material from the arches and cornices as well as formation of micro-cracks in the bearing walls – a state of initial nonlinearity in the behavior of the main structure and initial stage of occurrence of large damage to the secondary parts (fig. 6).

At an $a_{max} = 0.43$ g (El Centro), the model suffered large nonlinear damage, close to the state of failure. The main failure mechanism in the initial stage is the loss of structural integrity and development of cracks through the main vaults after which damage occurs in the bearing walls. This is confirmed also by the drop in the natural frequency of the model from 11.2 to 6.6 Hz.

Generally, it may be concluded that the model behaves as a rigid body (type of box system) in the elastic stage. At the stage of oc-

Table I. Specification of earthquake excitation tests performed for the original model.

Test No.	Test code	Earthquake	Input acc. (g)	Maximum response: Acc. (g) level 1	Maximum response: Acc. (g) top	Maximum response: Disp. level 1 (mm)	Maximum response: Disp. top (mm)	Cracks
6	PET005N	Petrovac	0.02	0.02	0.04	–	–	
7	ELC005N	El Centro	0.02	0.02	0.04	–	–	
8	BRE003N	Breginj	0.02	0.05	0.10	–	–	
9	PET012N	Petrovac	0.04	0.18	0.16	0.7	0.7	
10	ELC015N	El Centro	0.04	0.05	0.11	0.8	0.7	None
11	PET035N	Petrovac	0.10	0.22	0.49	1.9	2.2	
12	ELC045N	El Centro	0.12	0.18	0.40	1.8	1.8	
13	BRE006N	Breginj	0.08	0.17	0.41	0.9	2.3	
14	ELC085N	El Centro	0.17	0.29	0.55	2.5	2.6	
15	PET075N	Petrovac	0.19	0.39	0.76	5.3	11.1	On tambour
16	BRE012N	Breginj	0.17	0.22	0.52	1.8	4.5	
18	ELC130N	El Centro	0.43	–	–	–	–	Failure

currence of the first cracks, separation of the bearing walls takes place, the west and east walls being more extensively damaged due to the testing direction (N-S).

5. Repair, strengthening and testing of the strengthened model

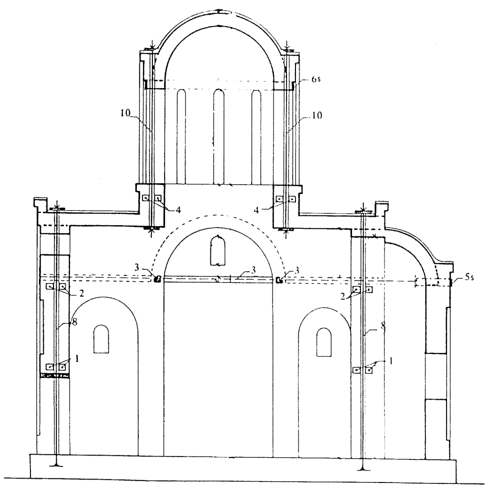
The methodology of strengthening and the seismic safety criteria have been defined on the basis of investigations of the structural response to expected earthquakes and seismic stability analysis taking into account the main characteristics and artistic-historic value of the structure.

Three seismic safety criteria have been defined in practice. For the considered historic monument, they can be classified as follows:

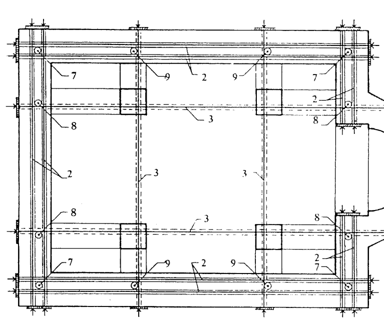
a) under slight earthquakes, the dynamic behaviour of the structure should be such that it assures no damage to both structural and nonstructural elements;

b) in the case of stronger earthquakes (design earthquakes), damage to the main structural system is not allowed, while there may be slight deformations of nonstructural elements;

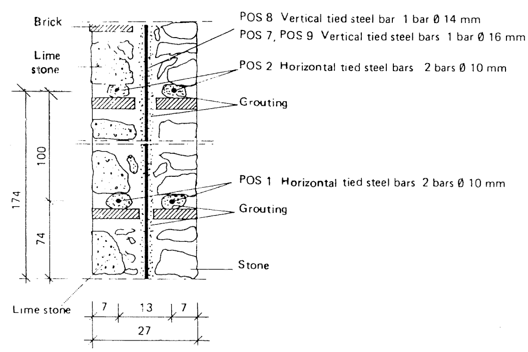
c) the maximum expected earthquakes should not disturb the stability of the main structural system. More severe deformations to nonstructural and structural elements are al-

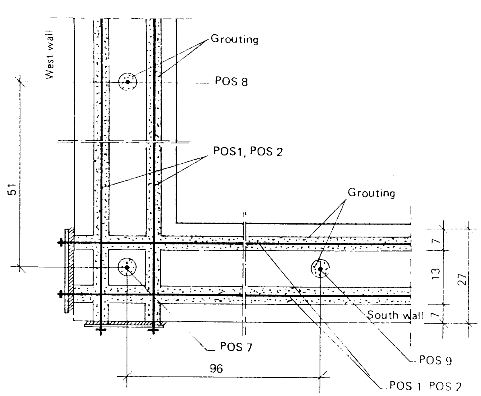


Longitudinal cross section



Section at timber ties level





Details of strengthening

Fig. 4. Applied method of strengthening.

lowed only if the elements of the whole structure have suffered repairable damage.

For each historic monument, the design criteria are defined on the basis of special conditions depending on the historic value of the building, the seismic hazard and the possibility for application of the corresponding measures for repair and strengthening which are directly related to the conservation and restoration criteria and the corresponding seismic safety measures.

On the basis of the evaluated seismic stability of the model of «St. Nikita» church, a repair and strengthening method has been adopted for increasing the strength of the existing structure and improvement of its ductile behaviour.

The strengthening method that has been adopted in the considered case implies incorporation of steel ties at places of formerly existing timber ones, and filling the space around them which an adequate material in order to enable connection (adhesion) with the existing masonry. It provides integrity of the structural system and enables simultaneous behaviour of all the bearing walls. Also, at the state of occurrence of cracks, *i.e.*, exceedence of the bearing capacity of masonry, the steel ties are activated and enable further vibration of the structure.

Apart from the horizontal elements, from the aspect of increasing the moment resistance and ductility capacity of masonry, this strengthening method also anticipates incorporation of vertical elements at the ends of the walls and besides the openings for the purpose of sustaining tensile forces from the overturning moments during dynamic vibrations.

The model was repaired and strengthened in accordance with the defined methodology that was applied and demonstrated in a laboratory by a realistic approach (fig. 4).

1) the strengthening method involved incorporation of horizontal steel ties at locations formerly occupied by timber belts, at levels of 0.74 m, 1.76 m (in the bearing walls), 2.60 m (at the base of the tambour) and 4.00 m (at the base of the dome);

2) repair of the model was done by injection of the larger cracks after a corresponding surface treatment and cleaning. The injection of the specially prepared emulsion was performed through metal tubes placed at separations of 20 cm, under a pressure of 0.6 to 1.2 atmospheres;

3) for the purpose of increasing the bending resistance and the capacity for ductile behavior, a concept of structural strengthening was adopted involving incorporation of vertical steel ties at the ends of the walls, around the openings and through the tambour columns. A certain amount of prestressing was applied, whereby the axial stresses are increased at plan (so) and hence the tensile bearing capacity (fig. 4).

6. Shaking table test of strengthened model

The strengthened model was subjected to the same series of dynamic tests as the original model in order to make a direct comparison of the values of interest and to check the efficiency of the strengthening method. Because of the obviously higher resistance of the model, it was further tested under higher input acceleration levels. A listing of the tests that were performed along with the characteristic output accelerations and relative displacements is given in table II.

It should be pointed out that in all the tests of the original and strengthened model high amplification values of acceleration of the dome top were obtained due to the significant damage inflicted to the main vaults (level 1), (fig. 5, table II). It can be concluded that the nonlinear state of the repaired model started when applying the Petrovac earthquake with $a_{max} = 0.40$ g. In order to obtain the stages of nonlinear behavior and estimate the damage level for higher expected earthquake effects, tests were carried out by applying the El Centro earthquake with a gradual amplitude increase up to 0.49 g. At this level, cracks in the load carrying walls, the tambour arches and damage to the dome occurred. The application of a series of tests with a higher intensity

Table II. Specification of earthquake excitation tests performed for the strengthened model.

Test No.	Test code	Earthquake	Input acc. (g)	Maximum response: Acc. (g) level 1	Acc. (g) top	Disp. level 1 (mm)	Disp. top (mm)	Cracks
19	BRE012S	Breginj	0.15	0.29	0.54	1.9	2.0	None
21	ELC130s	El Centro	0.25	0.50	0.79	7.8	15.8	
22	PET100S	Petrovac	0.28	0.53	0.80	7.5	9.8	
23	BRE020S	Breginj	0.28	0.20	0.40	5.0	6.5	
25	PET140S	Petrovac	0.42	0.77	1.36	18.8	21.2	First crack
26	ELC175S	El Centro	0.33	0.65	1.10	15.2	18.3	Development of cracks
27	BRE027S	Breginj	0.38	0.34	0.79	7.4	10.1	
29	ELC220S	El Centro	0.41	0.87	1.49	17.7	28.3	
30	ELC280S	El Centro	0.48	0.91	1.59	18.0	57.0	
33	BRE020S	Breginj	0.28	0.20	0.40	5.0	6.5	
34	ELC150S	El Centro	0.29	0.41	0.79	12.8	20.8	
35	BRE040S	Breginj	0.55	0.33	0.55	8.5	12.8	
36	ELC280S	El Centro	0.48	0.91	1.59	18.0	57.0	
37	BRE053S	Breginj	0.75	0.64	0.50	8.0	17.1	
38	ELC320S	El Centro	0.76	0.77	1.41	20.6	56.7	

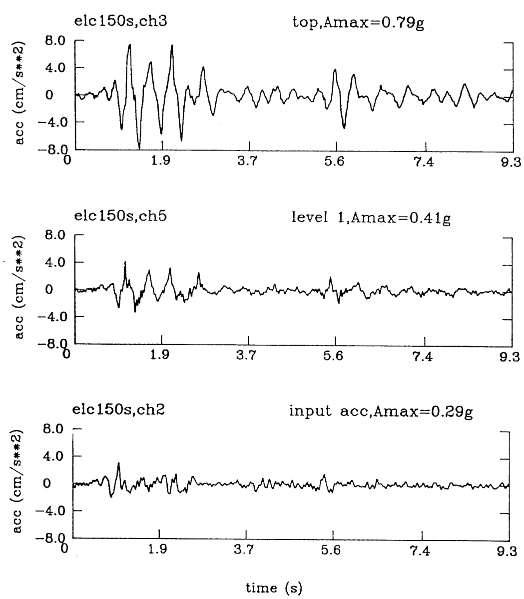


Fig. 5. Acceleration time histories (ELC150S).

(up to $a_{max} = 0.75$ g), gave rise to severe damage to the nonstructural elements (arches, cornices, lintels) and occurrence of cracks that were mainly concentrated in the west wall (fig. 7a,b). However, the overall stability of the model was not affected and the damage that did occur was repairable.

7. Comparative analysis of the original and strengthened model test results

– The comparison between the main dynamic characteristics of the original and the repaired model points to a negligible increase in the stiffness of the repaired model.

– The response under acceleration level of $a_{max} = 0.19$ g shows that the original model suffers the first nonlinear cracks, whereas complete elasticity is evident for the repaired model (fig. 6).

– Under $a_{max} = 0.43$ g the original model

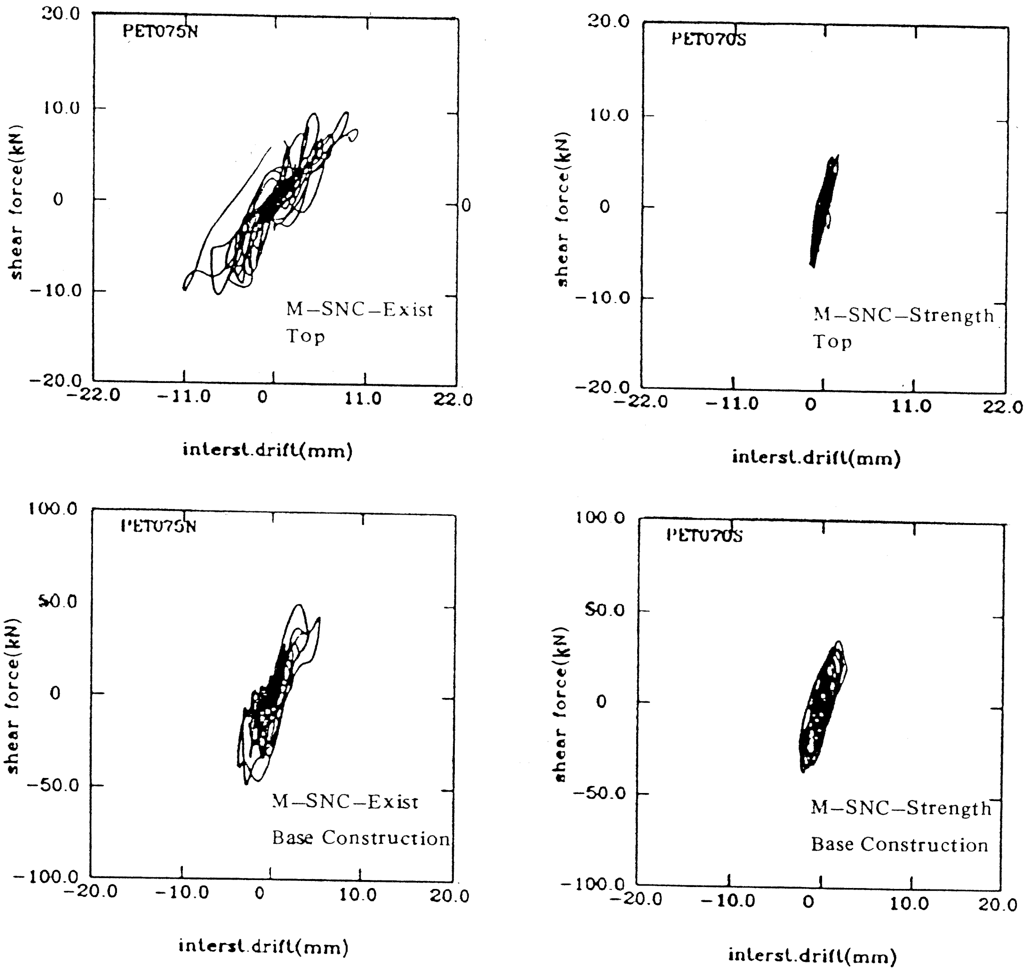


Fig. 6. Comparison between P-D diagrams for original and strengthened model (Petrovac earthquake, $A_{max} = 0.20$ g).

shows large nonlinear damage, close to the state of failure, whereas the repaired model is still in the elastic limit – initial nonlinearity stage.

– Finally, under the maximum acceleration (a_{max} = 0.75 g), the repaired model is far into the nonlinear state. However, taking into account the presence of ductile elements, this state is still far from failure.

– The comparison between the levels of the applied maximum acceleration for the original ($a_{max} = 0.43$ g) and the repaired model ($a_{max} = 0.75$ g) points to the fact that the degree of damage to the repaired model is considerably lower despite the almost doubled excitation level (fig. 7a,b).

– The failure mechanism following strengthening was qualitatively different from that of the original model. Separation of bearing walls and occurrence of almost vertical cracks in these walls did not take place in the repaired model. Instead, failure occurred at the lower

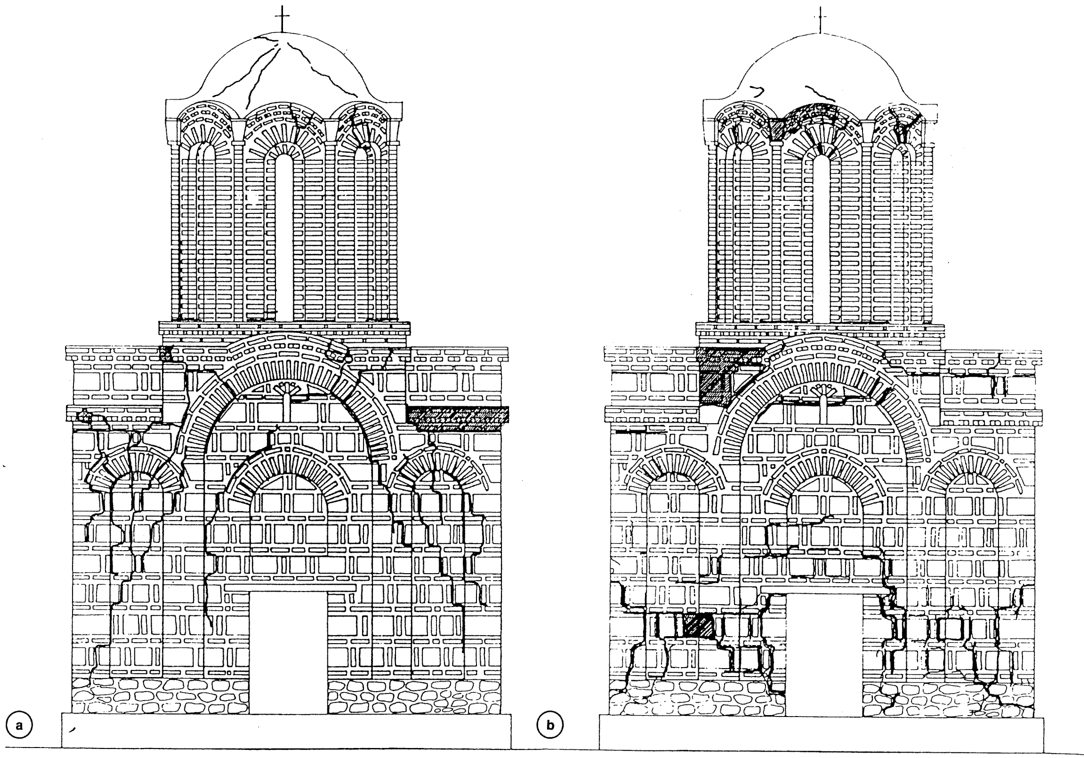


Fig. 7a,b. Comparison between types of failure (west facade). a) Original model after El Centro earthquake, $a_{max} = 0.43$ g; b) strengthened model after El Centro earthquake, $a_{max} = 0.76$ g.

part of the walls (fig. 7a,b) and, in the final stage, diagonal cracks due to shear effects were observed.

8. Conclusions

– On the basis of a detailed seismic stability analysis of the existing state of St. Nikita church (selected as a prototype) performed by consideration of the defined seismic parameters, it is concluded that the building is very likely to experience complete failure during the maximum expected earthquake. This imposes an urgent need for preventive measures.

– The proposed methodology for seismic strengthening complies with the basic principles for conservation and protection of historic monuments, it is easily applied and satisfies the criterion of «minimum intervention – maximum protection».

– The experimental results show conclusively that the applied methodology for repair and seismic strengthening increases the bearing and deformability of the structure up to the required design level of protection.

– The results of the experimental testing of the church model are also valid for the prototype, and, in view of the manner in which the prototype was selected, we believe that the knowledge gained in this study is applicable to the analysis of a large number of monuments of the same or similar types.

Acknowledgements

The results presented in this paper are part of the research project «Study for Seismic Strengthening, Conservation and Restoration of Churches Dating from Byzantine Period (9th-14th Century) in Macedonia». Support for the project was provided by the Getty Conservation Institute (GCI), Marina del Rey, U.S.A. and the work was performed at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), University «St. Cyril and Methodius», Skopje, and Republic Institute for Protection of Cultural Monuments (RZZSK), Skopje, Macedonia. The authors wish to express their gratitude to the Getty Conservation Institute (GCI), for financing the project, cooperation and participation in its realization.

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