Post-seismic strengthening of churches

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Post-Seismic Strengthening of Churches

Renforcement d'églises après des séismes

Verstärkung von Kirchen nach Erdbebenbeanspruchung

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SUMMARY

The paper refers to churches of three-cusped plane wide-spread in the Carpatho-Danubian-Pontic area, where tectonic earthquakes frequently occur. Firstly it is shown that centuries ago two anti-seismic shapes were conceived, one in Moldavia by means of buttresses and another in Wallachia by overwidening the ante-naves. As a diagnosis method it is suggested that the results of lateral bending and general torsion analyses be combined with the map of seismic damages. As therapy for the damaged churches, some strengthening techniques with R.C. coatings, belts and/or buttresses are recommended.

RESUME

L'article se réfère aux églises au plan trilobé largement répandues dans la région des Carpates et du Danube où ont lieu de fréquents tremblements de terre. Aux siècles passés deux configurations antisismiques étaient conçues, l'une en Moldavie avec des contreforts et l'autre en Wallachie surélargissant les pronaos. Pour le diagnostic, il est suggéré de combiner les résultats d'analyse de la flexion latérale et torsion générale avec la carte des dommages sismiques. Des techniques de renforcement avec des couvertures, ceintures et/ou contreforts de béton armé sont proposées pour la réparation de ces églises.

ZUSAMMENFASSUNG

Der Bericht bezieht sich auf Kirchen mit Dreispitz-Grundriss die im Karpaten-Donau-Gebiet, wo häufig tektonische Erdbeben auftreten, weit verbreitet sind. Zuerst wird gezeigt, dass vor Jahrhunderten zwei antiseismische Formen ausgedacht wurden: eine mit Strebenpfeilern in der Moldau und eine mit einer Vorschifferweiterung in der Wallachei. Als Diagnosemethode wird vorgeschlagen die seitliche Biegebeanspruchung und die allgemeine Torsionsbeanspruchung mit der Karte der seismischen Schäden zu verbinden. Für die beschädigten Kirchen werden Verstärkungen mit Stahlbetonverkleidungen, Gurten und/oder Strebenpfeilern empfohlen.

INTRODUCTION

The oldest monumental buildings preserved in the Carpatho-Danubian-Pontic area are churches. For centuries they were the most representative creations of ecclesiastic and monumental architecture. Erected with stone or brick masonry these Eastern Churches of Balkan-Byzantine style were always an evidence of the level of technical knowledge and artistic refinement reached during their epoch. They also reflect the foreign influences on the autochthonous art of building.

Unfortunately, strong tectonic earthquakes frequently occur in this area. The main focus being located in the Carpathian curvature and at a depth of about 150 km, it influences the whole area. The Eastern churches of three-cusped plane seeming to show an intrinsic sensitivity to earthquake actions. In the course of time some of them were completely destroyed. Others survived being, however, more or less damaged. Often by strengthening parts of the original work were altered or even definitely sacrificed.

The aim of this paper is to show that history's lesson was, however, useful. The structural systems were gradually adapted to the local seismicity of the ground and even some unwritten safety rules were conceived. Further is shown how a simple technique of analysis can be used as a diagnosis tool of the damages caused by earthquakes. Finally some strengthening techniques are presented.

1. STRUCTURAL SYSTEMS

Centuries ago, for strategical reasons, human settlements were located in hilly areas. Among the first Eastern churches of those early times are the Trinity Church, without any steeple, of Siret in Moldavia, built in 1376 (Fig.1) and the church, with a steeple devoted to Pantokrator, of Cozia Monastery - Wallachia, built in 1388 (Fig.2). Both are well preserved until today as at their emplacement the ground seismicity is low.

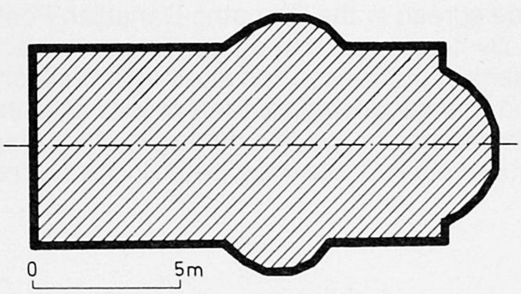

FIG. 1 SIRET 1376

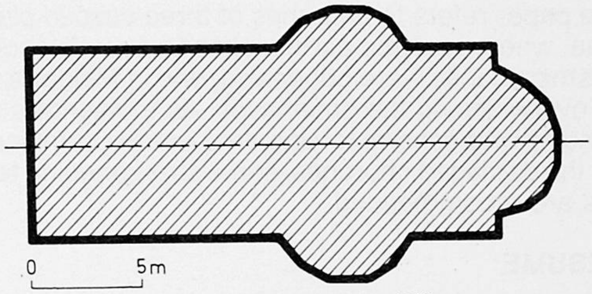

FIG. 2 COZIA 1388

Later, when the danger of invaders decreased and the settlements gradually enlarged, they were moved towards the plains where by agricultural means the increased needs of food were easier satisfied. Naturally, in this process the shape and size of Eastern churches knew some changements. They were developed on larger areas, increased in height and enriched by steeples and ornamentations. But simultaneously, due to the higher ground seismicity the danger of damages became imminent.

The three-cusped plane was also endowed with lateral buttresses. The first such shaped church was St. Procopie Church at Milişăuţi, built in 1487. Beginning with that year all Moldavian churches were provided with lateral buttresses. Originally they had a prevailingly ornamental function and were probably adopted under the influence of Transylvania's Romanesque and Gothic architecture. Generally, lateral buttresses were not connected to the lateral strengthening parts of the church-body, but contributed to some extent to discharge the heavy masonry walls into the foundation ground. However, in Wallachia lateral buttresses were seldom adopted.

Alternatively, the three-cusped plane was developed by a slight widening of the ante-nave. This structural measure was first adopted to the so-called town churches, built in Moldavia between 1490 and 1496. The aim of this widening was apparently to enlarge the inner space of the ante-nave for the believers. But along the longitudinal walls of the widened ante-naves lateral buttresses were omitted, which means that it was considered their function was taken over by the lateral walls appearing as a consequence of that widening. Instead, lateral buttresses were maintained in front of the altar apses of the same churches.

Finally, beginning with the sixteenth century the churches of three-cusped plane are endowed with pairs or even several steeples. The main steeple is further devoted to Pantokrator while one of the additional steeples got a belfry function, being also used, as observation point against fires or invaders. It should, however, be mentioned that the steeples of Moldavian Churches are essentially different from the Wallachian ones. In Moldavia, under Gothic influence, steeples were disposed in a single line, following the church axis, being conceived like castle towers with few and narrow openings as windows. On the contrary in Wallachia, under Byzantine influence, steeples were arranged in both directions of the church, being erected with wider openings as windows and slender columns [1].

2. SEISMIC DAMAGES

According to the first written documents, between 1471 and 1846, on the Carpatho-Danubian-Pontic territory over 60 earthquakes were felt, which means more than 16 in one century. Fortunately, only a few were violent as those of Nov. 8th, 1620, June 11th, 1738 and Nov. 26th, 1802. During our century earthquakes were recorded in 1903, 1912, 1929 and 1938, but the strongest occurred on Nov. 10th, 1940 and March 4th, 1977 [2].

As concerns the damages caused by earthquakes, first there should be mentioned the steeples. As a rule the masonry columns of the steeples are horizontally sheared at their bottom and top. The steeples of Wallachian churches yielded easier to shearing forces than those of Moldavian churches. Consequently, now, in Bucharest one church out of three has false, wooden steeples.

Apse walls of the nave and altar were also severely damaged. The typical damages consist in vertical cracks when these curved or polygonal walls are completely closed, and in 45° inclined cracks when there are e.g. openings for windows. The same two types of cracks have been developed in the straight walls of the ante-naves, especially when they were not braced at their tops.

The semi-circular arches as integral parts of the surrounding walls, designed to narrow the vaulted space and to support the cupola or steeples have also been damaged by earthquakes. Generally, the cracks appear at the arch crown as well as at the quarter of the free spans. Such damages are often caused by the ties mounted too eccentrically. A faulty foundation also allows damages to the apse walls and transverse arches. This is the particular case of churches rebuilt in a new masonry style over ancient foundations of wooden churches burnt or stone churches destroyed by earthquakes [3].

There were, however, churches of three-cusped plane which lasted for centuries without to be damaged by earthquakes. It has been observed that in certain rather restricted areas churches of about the same size, being erected in the same period and with a comparable kind of foundations and brick-work behaved quite differently. Some of them were dramatically damaged while others remained as if untouched. The explanation of this different behaviour seems to be in the variety of the adopted shapes. Therefore, it could be assumed that since long ago certain antiseismic shapes were more or less consciously searched for. But no written rules or documents were preserved so far. They remained as professional secrets. Instead, an old legend about Wallachian church builders is going on.

3. MASTER MANOLE'S LEGEND

In the former Wallachian capital of Curtea de Argesh, the Prince Neagoe Basarab (1512-1521) founded the church of Argesh Monastery. This church was consecrated on August 15th, 1517 and became immediately famous due to its outstanding architecture. According to some documents this church replaced the ancient metropolitan church of three-cusped plane, like Cozia church, founded by Dracula's father. It seems that a good part of the old foundations were preserved, namely that of the altar apse and that of the ante-nave walls sustaining now the twelve stone columns. The church body and its four steeples are entirely achieved of stone masonry, and the monument has no precedent as architectural conception and development in plane and space. That is why a legend has been embroidered around this church.

According to the legend Voivode Negru entrusted a team of ten masons under the leadership of Master Manole to implement somewhere on the Argesh River, on the site of an ancient church "broken down and unstrengthened", an unequaled church. They started to work carefully, but beginning with a certain instant the walls they erected during the day tumbled down during the night. The accidents recurred till they decided to immolate Master Manole's wife. Only thus the walls were stopped to fall, and the church could be finished, lasting over centuries [4].

Viewing Master Manole's legend from the angle of construction art it is easy to conclude that of all possible actions, able to cause the repeated collapse of the masonry walls, there could be nothing else than earthquakes. Indeed, tectonic earthquakes, typical to the Carpatho-Danubian area, occur frequently during the night, are recurring and present a particular aggression against curved walls and arches or vaults of masonry. Otherwise, it is very likely that the ancient metropolitan church, mentioned in the legend, has also been destroyed by earthquakes. As concerns the immolation consequence, it consists in the overwidening of the ante-nave and thus the church has been anti-seismically shaped. It was an inspired solution because for 466 years, from 1517 to 1983 the church behaved perfectly in earthquakes (Fig. 3).

The three-cusped plane with an enlarged ante-nave of the Argesh Monastery Church became a model for the following Wallachian churches. Indeed, all churches which preserved rigurously the shape of this model behaved excellently in earthquakes, although some of them, namely those in Bucharest, were located on a ground of a higher seismicity degree. Thus the anti-seismic qualities of this shape were definitely proved.

Master Manole's legend carried as far as Moldavia the fame of the Argesh Monastery Church. However, that shape was not at all adopted there, although the ground seismicity is the same. Moldavian ecclesiastic architecture followed its traditional style of three-cusped plane with buttresses of Gothic influence. As anti-seismic protection the church bodies were somewhat longitudinally extended while the lateral development of nave apses was slightly reduced. In 1639, on this principle was built the famous Church of Three Hierarchs Monastery founded in Jassy by Prince Vasile Lupu (Fig. 4). A faithful copy of this church was immediately tested under more severe seismic conditions on the Wallachian ground and it behaved splendidly. Therefore, with the aid of lateral buttresses an alternate anti-seismic shape of three-cusped plane was achieved.

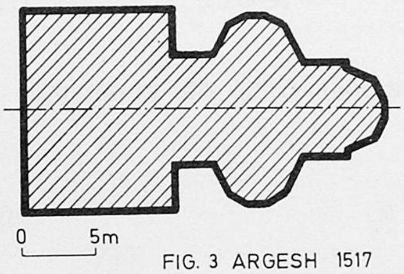

FIG. 3 ARGESH 1517

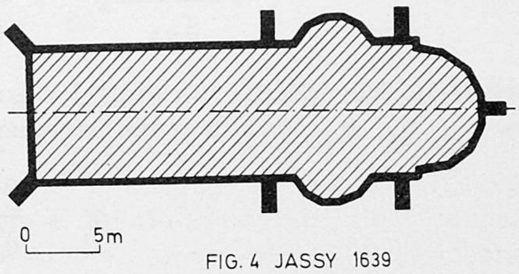

FIG. 4 JASSY 1639

4. DIAGNOSIS OF SEISMIC DAMAGES

The resultant of inertial forces developed by the church body during an earthquake is a horizontal force S proportional with the church weight W and it is applied at the centre of mass C.M. (Fig. 5). In Bucharest for example.

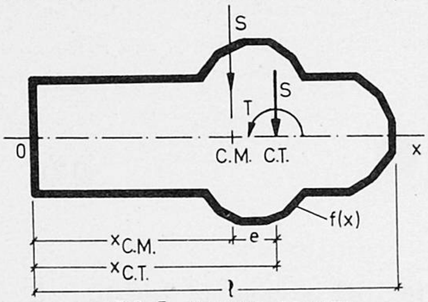

FIG. 5 SEISMIC FORCES

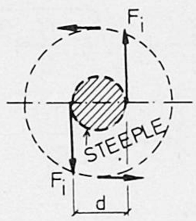

FIG. 7

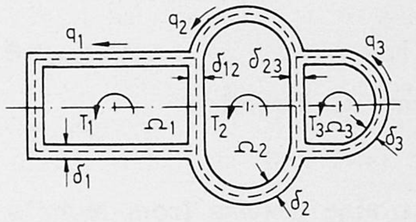

FIG. 6 TORSION MODEL

$$S = 0.09W. \tag{1}$$

By reducing this force to the centre of twist C.T. one obtains the torque

$$T = Se, \tag{2}$$

where

$$e = \frac{\int_0^{\ell} f^3 x dx}{\int_0^{\ell} f^3 dx} - \frac{\int_0^{\ell} f x dx}{\int_0^{\ell} f dx}. \tag{3}$$

Therefore during earthquakes a church is subjected to a phenomenon of general torsion and to another of lateral bending. Generally, when $e = T/S > 0.10\ell$ prevails torsion, and when $e < 0.01\ell$ prevails bending.

Stresses in torsion could be determined assuming the horizontal section of the church as a hollowed section (Fig. 6). Then, by virtute of Bredt's theory

$$2q_1\Omega_1 + 2q_2\Omega_2 + 3q_3\Omega_3 = T, \tag{4}$$

and

$$\frac{q_1}{\delta_1} s_1 + \frac{q_1 - q_2}{\delta_{12}} s_{12} = 2G\Theta\Omega_1, \qquad (5)$$

$$-\frac{q_1 - q_2}{\delta_{12}} s_{12} + \frac{q_2}{\delta_2} s_2 + \frac{q_2 - q_3}{\delta_{23}} s_{23} = 2G\Theta\Omega_2, \qquad (6)$$

$$-\frac{q_2 - q_3}{\delta_{23}} s_{23} + \frac{q_3}{\delta_3} s_3 = 2G\Theta\Omega_3, \qquad (7)$$

where Θ is the specific torsion. By solving this system one finds the shearing flows q_1, q_2, q_3, and then the stresses

$$\tau_i = \frac{q_i}{\delta_i}, \quad i = 1, 2, 3. \qquad (8)$$

Stresses in bending could be determined by Navier's theory

$$\sigma = \frac{M}{I_x} y \qquad (9)$$

and that of Jourawski

$$\tau = \frac{S}{\delta I_x} \int_A y dA. \qquad (10)$$

Further one finds the principal stress of tension

$$\sigma_1 = \frac{\sigma}{2} + \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \qquad (11)$$

and its direction

$$\tan\alpha = \frac{\tau}{\sigma_1} \qquad (12)$$

as also results from Mohr's circle.

It is possible now to construct the trajectories of the principal stress of tension σ_1, once separately for torsion and bending and then superposed. By comparing these trajectories with the map of existing cracks one can establish with a satisfactory accuracy which of the phenomena : general torsion, lateral bending or both are responsible for seismic damages.

Finally, the shearing stresses in steeples will be

$$\tau = 1.4 \frac{S_i + F_i}{nA}, \qquad (13)$$

where S_i is the shearing force given by steeple bending and F_i introduces the influence of general torsion of the church being, cf. Fig. 7,

$$F_i = \frac{T}{d}, \qquad (14)$$

while n is the number of columns, A their cross-section and 1.4 a nonuniformity coefficient. The value thus obtained is compared with the masonry shearing strength usually of 0.10 to 0.30 N/mm^2.

As concerns the two anti-seismic shapes discussed above, now it is obvious that in the case of the Wallachian solution (Fig. 3) by overwidening the ante-nave increased the torsional rigidity of the church, while in the case of the Moldavian solution (Fig.4), by extending the church length the torsion vanished, and the lateral bending was prevented by transverse walls in combination with buttresses.

5. THERAPY OF SEISMIC DAMAGES

As long as the diagnosis of damages in proved to be true any strengthening, local or of the whole church, should satisfy some rules as follows :

- To preserve as much as possible the original shape, architectural ornaments, as paintings, as well as the initial structural system and its mechanism of discharging.

- To put in value the existing strength reserves of masonry walls, columns, arches or vaults, as well as of the connections between them and the foundation ground.

- To secure an intimate and permanent co-operation between the old material and that added for strengthening.

- To restore the continuity of all sections in such a way that the flow of stresses be everywhere as uniform as possible.

- By strengthening to provide the prescribed anti-seismic protection so that the church should never be damaged again.

There are no repairing and strengthening solutions equally valid for all churches of three-cusped plane. The basic principles established for masonry buildings should be applied from case to case according to the specific shape and size of each church. However, as long as only R.C. is used as a strengthening material, there are three strengthening techniques.

One of them, and perhaps the best, consists in covering the damaged surfaces with reinforced coats of mortar cement. Certainly, the coatings are carried out only on the outer sides of the walls. Such coatings can be also applied on steeple columns between window recesses. The best solution is to achieve continuous and closed reinforced coats. In front of the inlet corners and architectural ornaments the coats should be framed by R.C. cores well clamped in the masonry walls.

Another technique consists in bracing the church body with R.C. belts clamped at the upper part of masonry walls. The bracing will be carried out only at the outer and convex sides of the walls. In addition, the bracing belts should be closed around the church body. For a three-cusped plane that means to carry out two R.C. belts intersecting in four points. If the inner structure of the church does not allow such a development at the four inlet corners, R.C. cores should be applied. The outer belts could also be combined with inner tie-beams of the arches or vaults. Yet, it has to be mentioned that tie-beams are efficient only if they are perfectly centred as to the vertical symmetry planes of the arches or vaults.

Finally, the mechanism of discharging, as well as the interaction between foundation and ground could be improved by R.C. buttresses. Some corrections of the development in plane of foundations can also be achieved on this occasion. However, the solution assumes first to ensure a good connection with the strengthening elements of the church body and secondly an intimate contact with the foundation ground. In addition it must be remembered that the function of buttresses remains limited to lateral, they do not help against torsion. All these strengthening techniques were applied in Romania after the strong earthquake occurred on March 4th, 1977. They proved able to satisfy the five above mentioned basic rules, being not too difficult as manual labour and rather convenient as time and money [5].

CONCLUSIONS

1. During earthquakes Eastern churches are subjected to shearing phenomena. The shearing is caused by lateral bending and general torsion. Therefore the behaviour of these churches in earthquakes depends only on their shape. It is a matter of geometry before to be one of strength.

2. Since beginning to use masonry, the builders were concerned with the antiseismic shaping of Eastern churches. Fortunately, about five centuries ago there were found two such shapes. One in Moldavia, by means of buttresses and the other in Wallachia by overwidening the ante-naves. Both anti-seismic shapes were proved in the course of time by facing strong earthquakes without being damaged.

3. The legend of Master Manole could be looked at as an ancient technical code. Indeed, it expresses in a stylized form, first the danger of earthquakes for the most representative buildings of that epoch, the churches of three-cusped plane, and then it suggests the existence of an anti-seismic solution. The solution consists in an appropriate shaping and is unique. As a matter of fact, similar legends can be found in all seismic areas around the world.

4. The diagnosis of damages in monumental works as Eastern churches is a difficult and responsible task. Such buildings cannot be tested on reduced scale models, nor on a natural scale. Also the analysis models are approximate enough. Therefore, on only combined methods like that of finite-element used by ISMES-Italy or the one suggested in this paper could be more helpful for a correct diagnosis.

5. The therapy by the three techniques of strengthening does not eliminate the intrinsic sensitivity to earthquakes of Eastern churches. The single radical solution would be to change their shape, which practically is not possible. As concerns the new materials, different from concrete, produced by modern technology, they should be very judiciously used and only after a thorough checking up. Otherwise, irreparable losses could result. In fact, the therapy technique must be adopted on the basis of a very serious, competitive examination.

REFERENCES

1. IONESCU GR., Histoire de l'Architecture en Roumanie, de la préhistoire à nos jours. Ed. Academiei, Bucarest, 1972

2. STEFANESCU GR., Cutremurele de pămînt în România. Analele Academiei Române Tom XXIV - Memoriile Secţiei Stiinţifice, Bucureşti, 1901

3. BELES A.A., Cutremurul şi construcţiile, Bul.Soc.Politehnice, Anul LV, No.10 şi 11, Bucureşti, 1941

4. ELIADE M., Comentarii la Legenda Mesterului Manole, Publicom, Bucureşti, 1943

5. SOFRONIE R., The Behaviour of Eastern Churches in Earthquales. 7th European Conference on Earthquake Engineering, Athens, Greece, Sept.20-25th, 1982

Bucharest, March 15th, 1983