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## FAILURE MECHANISMS FOR ORTHODOX CHURCHES IN ROMANIAN SEISMIC AREAS

BY

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**Abstract.** Masonry historical churches were built only with experimental indications from previous constructions and without taking into account the basic principal of structural seismic behavior. Also, given their age, the orthodox churches are prone to damages and partial or global collapse when subjected to horizontal loads. This article studies the construction typologies in relation with their structural sensibilities. Based on damage surveys from previous seismic events and by applying finite element models that simulate the masonry behavior with both solid and surface elements, the typical three-dimensional damage mechanism of the main types of orthodox church structures are to be explained and detailed. This aspects can be crucial in assessing the safety level and choosing the proper retrofitting solutions.

**Key words:** masonry churches; structural sensitivities; three-dimensional damage mechanism.

### 1. Introduction

According to the specific architectural conception, the typical spatial structure of an orthodox church consists of a well established sequence: narthex,

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nave and altar (Fig. 1). The orientation of the church is symbolically, with the altar to the east. The narthex was originally reserved for penitents or women and the nave represents the main space for congregation and performing the ritual. After the nave, the altar apse follows which delimits the church to the east. The altar is slightly elevated compared to the nave being separated from the latter by the iconostasis.

Compared with the initial/classic orthodox structure, architectural innovations have resulted in slight alteration of spatial configuration of the nave, in adding spaces with specific functions (crypt, exonarthex) or by the presence of a symbolic number of domes or towers (Crişan, 2010).

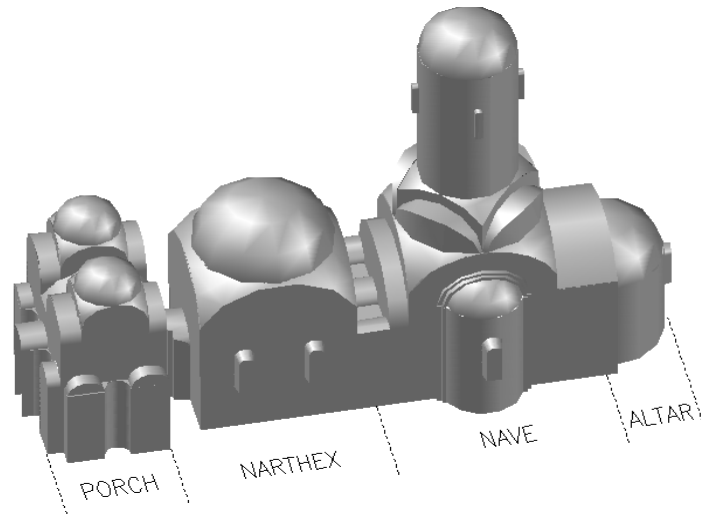


Fig. 1 – Functional organization of an orthodox church (the spatial interior of Aroneanu Church in Iaşi).

## 2. The Typology of Orthodox Church Structures

Taking into account the necessity of advanced knowledge regarding the typology of orthodox church structures, Professor Alexandru Cismigiu proposed a methodology for describing and examining the morphology of these religious monuments, in three stages (Cismigiu, 2002)(Fig. 2):

- a) simple structural elements (foundations, walls, cylindrical vaults, arches, caps, semi caps, pendants);
- b) complex structural elements (wall door opening, wall window, wall with pillars and spring, dome with pendants, apse, bell tower, belfry);
- c) structural subsets (units composed of simple and complex structural elements which delimit a space).

Considering the building as a complex structure an analysis of behavior can be made in relation with gravitational and seismic behavior of assembly, but also to every component apart.

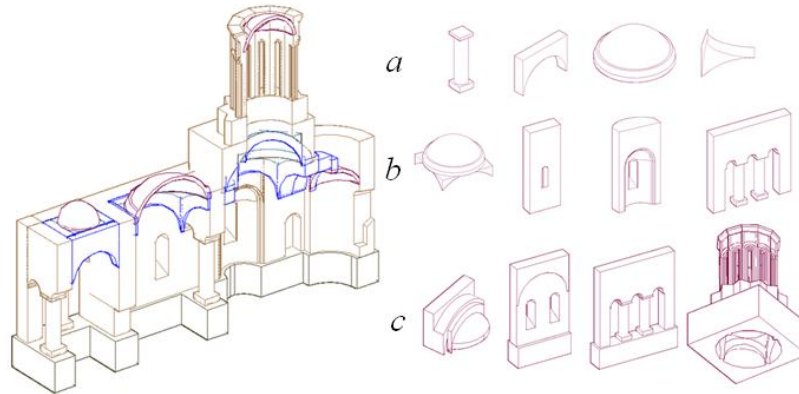


Fig. 2 – Section in isometric view for the identification of the structural components: *a* – simple structural elements; *b* – complex structural elements; *c* – structural subsets (Aroneanu Church).

The old church structures are predominantly composed of curved elements and massive walls due to which, for gravitational actions, the main structural subsystem is subjected to significant bending efforts. Often, the damage in structural elements is mainly due to the lateral acting forces and subsequently to other causes such as earthquakes, subsidence, fire (Olaru, 2002).

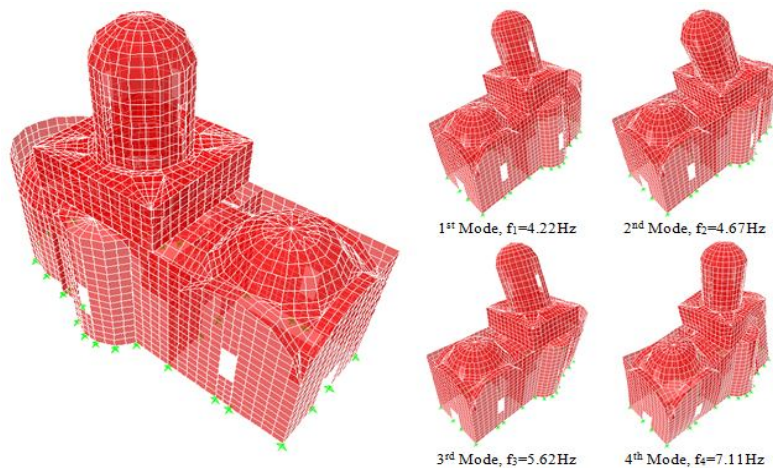


Fig. 3 – The first 4 vibration modes in the case of Patrauti Church.

In case of an orthodox church structure, for an extended comprehension of the vulnerability, special attention should be paid to its towers, considering their number and structural sensibilities. Each tower can be analyzed according to its cross-sectional shape, number of sides, embrasure area percentage, changes in the thickness of the walls, height (which determines the points of application of the seismic forces) and weight (the main factor in the evaluation of the overturning moments). In most of the common cases, the general vulnerability of an old church increases significantly with the number of towers and their structural deficiencies (Crişan, 2010).

Analysing the structural behavior of the church towers in case of response oscillations during seismic actions (Fig. 3), it results that this appendix tends to produce distortions of the response parameters due to high dynamic amplifications. Under this circumstances, the church towers are prone to severe damages and even collapse (Olaru *et al.*, 2001).

### **3. The Spatial Damage Mechanism of Orthodox Church Structures**

#### **3.1. Damages of the Main Body**

Based on the investigation of the damages due to seismic actions in case of over one hundred orthodox churches, Al. Cişmigiu found a typical mechanism of damage, with a three-dimensional character, that mainly affects the superstructures of the churches. Therefore, two main processes were highlighted (Olaru & Mitroi, 2001):

a) a longitudinal fracture that, in almost all cases extends from the porch to the altar, causing the division of the main body into two relatively symmetrical halves along the longitudinal axis;

b) transversal fractures in the porch, nave and narthex axes, systematically arranged in vulnerable areas (wall sections weakened by doors and windows).

These two types of processes, graphically exemplified in Fig. 4, lead to the separation of the church structure into independent quasi-rigid blocks, each being in its own static equilibrium (Olaru & Mitroi, 2001).

The number of the separation blocks reflects the vulnerability of the church structures. The most important factors affecting the vulnerability are: the increasing complexity and size of churches, the large embrasures areas, the decrease of the thickness of masonry walls and the adjunction of open porches. Thus, the more complex the structure of the building is, the higher will be the risk of block separation.

In this context, the spatial damage mechanism has been illustrated in Figs. 4 and 5 for several examples representing the most common types of orthodox churches plans (Cosma, 2013).

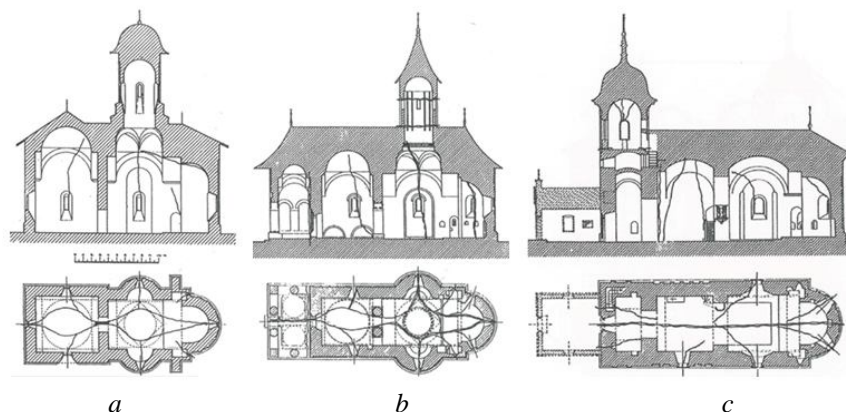


Fig. 4 – Spatial damage mechanism of orthodox church structures: *a* – trefoil shape plan with widened narthex; *b* – trefoil shape plan; *c* – rectangular plan (Crișan, 2010).

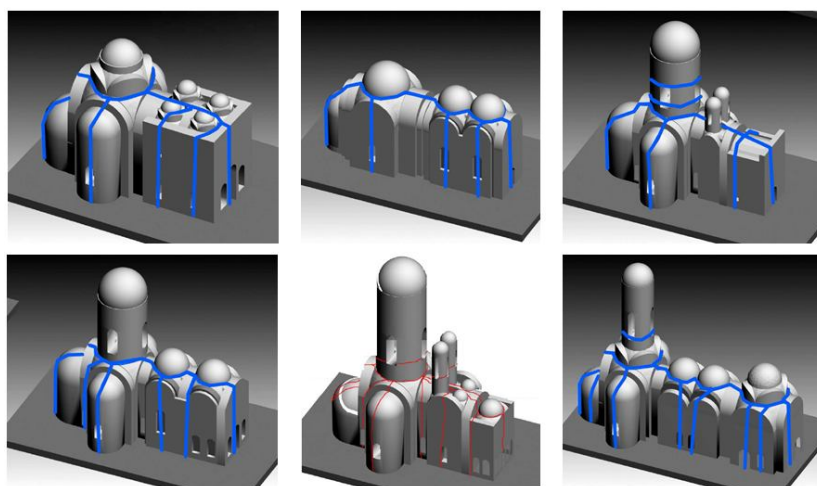


Fig. 5 – Spatial damage mechanism of church structures (Cosma, 2013).

### 3.2. Damages to the Churches Towers

For the church towers, the damages consist in fractures at the base of the tower related to the general longitudinal and transversal fractures, shear failure in the contact zone between the tower base and the tower itself (due to changes in stiffness), damages at the arcs above the tower windows and inclined cracks in the tower walls.

The spatial damage mechanism of orthodox church structures is confirmed by existing damages and by the results of the finite element analysis. For the analysis of the Aroneanu Church, in seismic load combination, load

concentrations have resulted in the weakened walls sections (door and window openings), at the base of the tower, at the contact zone between the tower base and the walls and at the arc between narthex and nave (Fig. 6).

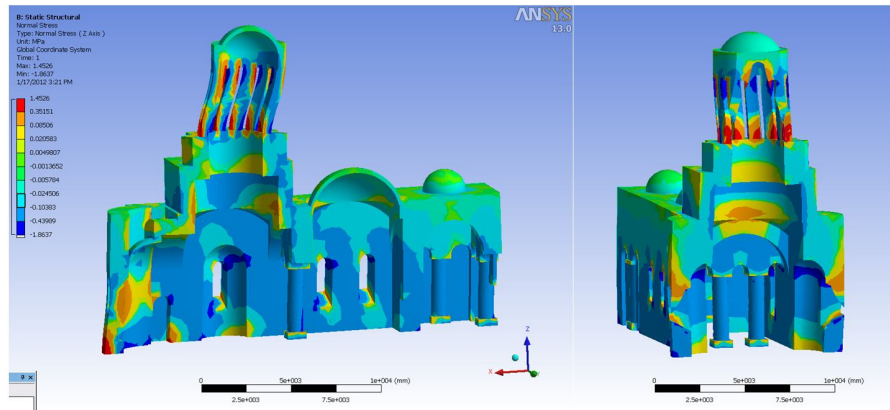


Fig. 6 – Efforts concentration in characteristic zones according to the spatial damage mechanism at Aroneanu Church.

### 3.3. Damage at the Foundations

In most cases, the longitudinal and transversal fracture system propagates in the foundations. This phenomenon has been observed by the author during the retrofitting works of Aroneanu Church in Iași, for which, the foundations were uncovered and inspected (Fig. 7). The damages at the foundations can be amplified by the presence of the wood hangers which, in most cases, have rotted.

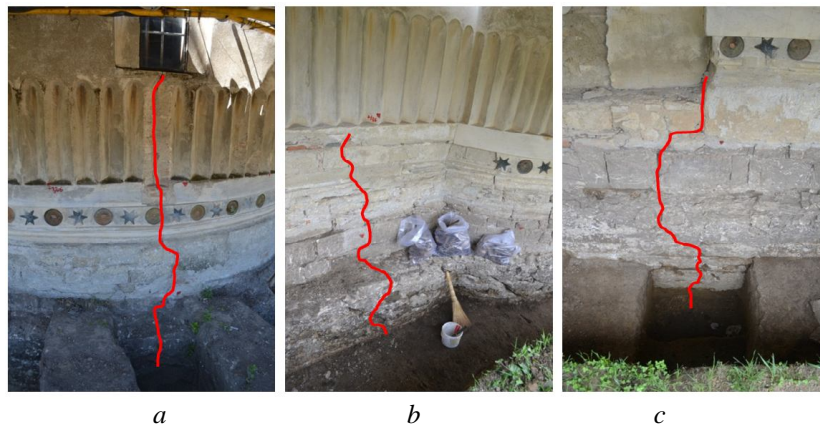


Fig. 7 – Damages at the foundations: *a* – fractures in the altar apse foundation; *b* – above the narthex window; *c* – between the porch and narthex (Aroneanu Church).

#### 4. Case Studies

A sketching of the spatial damage mechanism was conducted by the author for three case studies, based on *in situ* inspected damages.

##### 4.1. Damage Mechanism of “Sf. Gheorghe” Church in Hârlău

The structure of “Sf. Gheorghe” Church in Hârlău is affected in longitudinal direction by a fracture, which, at the towers level, follows the boundary of their plan. This fracture is accompanied by vertical cracks in the wall between the narthex and nave, in the transversal arcs and in the altar apse (Fig. 8).

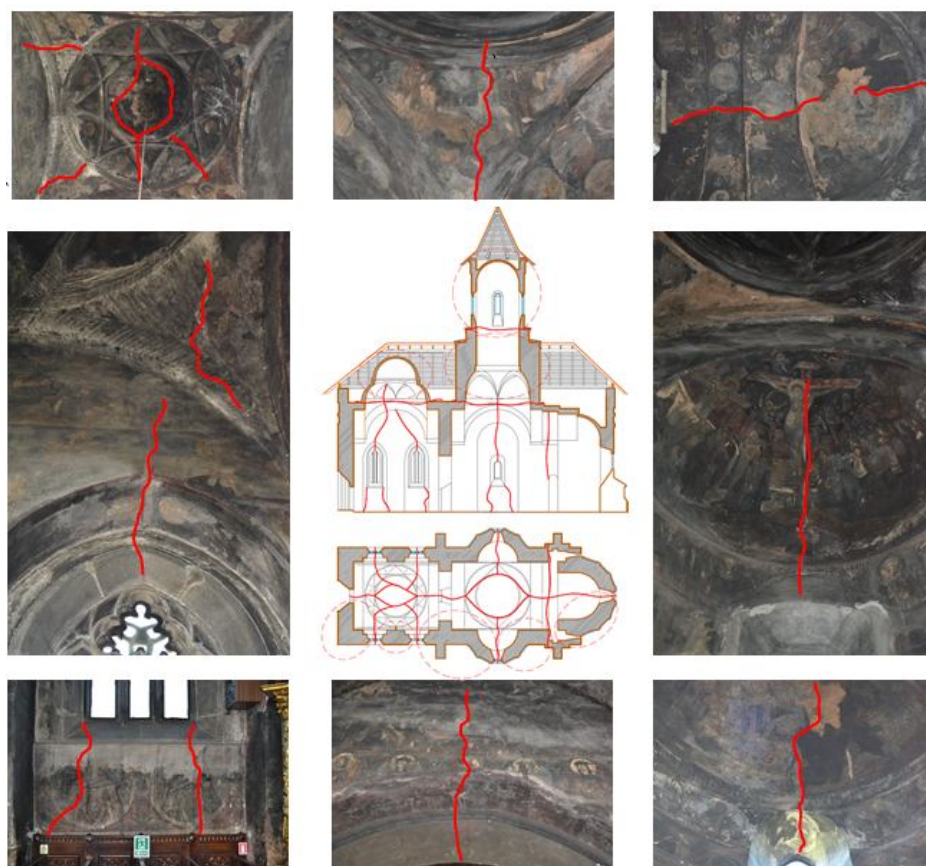


Fig. 8 – Damage mechanism for “Sf. Gheorghe” Church based on *in situ* investigations

In transversal direction, from all the windows parapets and arcs, vertical fractures in walls and in the domes pendants have been observed. After sketching the spatial damage mechanism, a total of 13 distinct blocks have resulted.

#### 4.2. Damage Mechanism of Vicoveni Church in Dorohoi

In the case of Vicoveni Church, during an *in situ* survey, severe vertical fractures at the sides of the tower, in both longitudinal walls, have been observed. These damages are due to the large difference between vertical loads in the nave and the rest of the structure in addition with low masonry tensile strength and low bearing capacity of the foundation soil. These fractures are propagated in the interior, following the contour of the nave arches (Fig. 9).

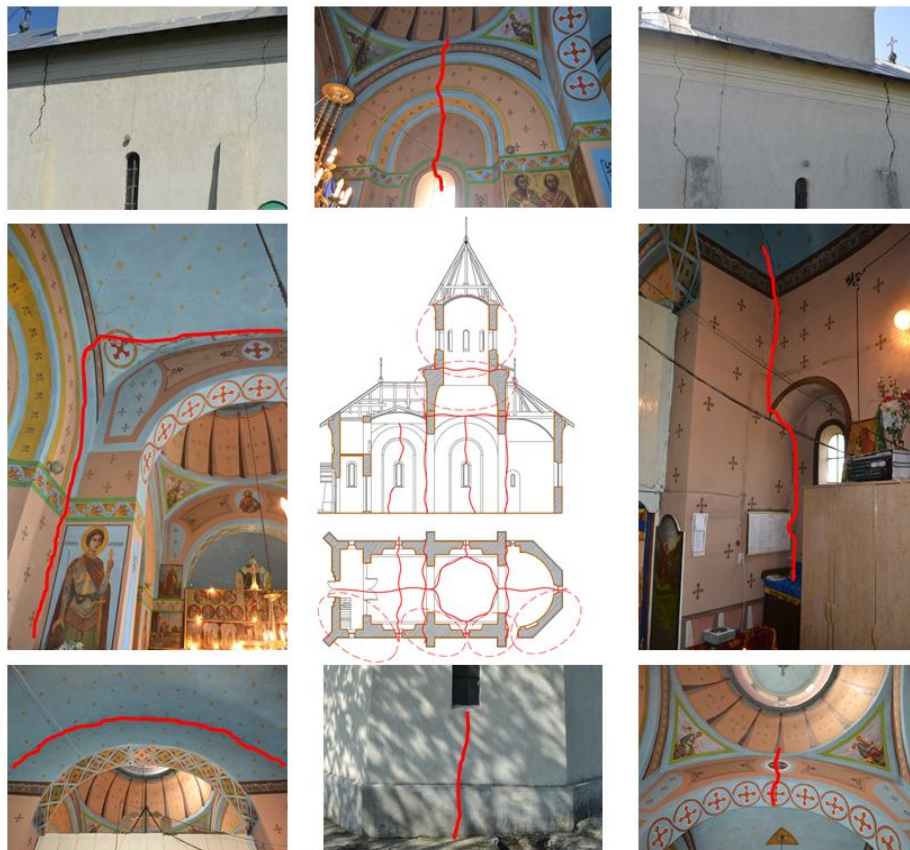


Fig. 9 – Damage mechanism for Vicoveni Church based on *in situ* investigations.

Additional, a series of cracks have been identified through window openings in transversal direction, and in longitudinal direction, in the altar apse



and in all transversal arches. After sketching the spatial damage mechanism, based on in situ survey, a total of 10 distinct blocks have resulted.

#### 4.3. Damage Mechanism of Aroneanu Church in Iași

The survey of Aroneanu Church has revealed cracks and fractures according to the typically spatial damage mechanism for orthodox church structures. In addition to the damages observed at the previous analyzed churches, a structural separation between the porch and the narthex was identified due to transversal vertical cracks in both longitudinal walls. A total of 14 distinct blocks have resulted (Fig. 10).

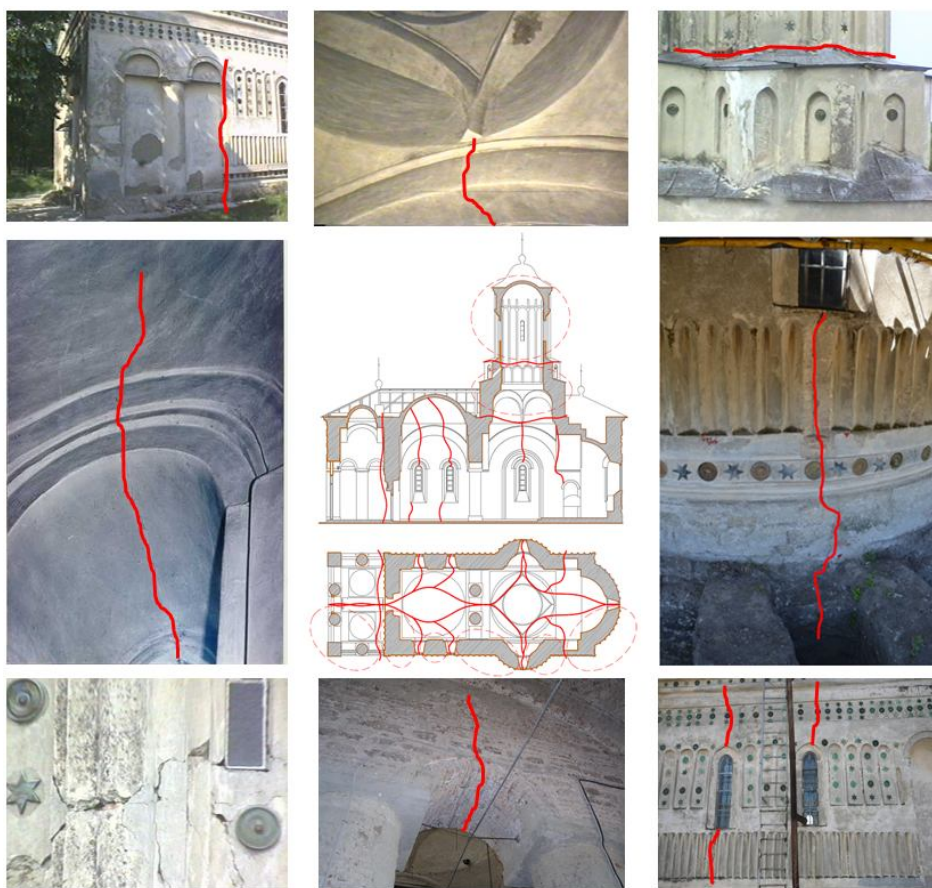


Fig. 10 – Damage mechanism for Aroneanu Church based on in situ investigations.

## 5. Conclusions

The failure mechanism of orthodox church structures has a three-dimensional character and consists mainly in a longitudinal fracture extended from the porch to the altar and multiple transversal fractures, systematically arranged in vulnerable areas. These two types of processes are leading to the separation of the church structure into independent quasi-rigid blocks, each being in its own static equilibrium. In this context, the spatial mechanism of damage has been illustrated for three case studies based on in situ surveys conducted by the author.

This complex failure mechanism implies a concept of retrofitting based on a spatial approach, which can assure the deformation compatibility between the blocks in order to develop a unitary behavior of the structure. Finding the proper retrofitting solutions using traditional materials and applying techniques similar to those optimized on the basis of technology and information, could constitute a main objective of research in this field.

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## MECANISME TIPICE DE AVARIERE A STRUCTURILOR DE BISERICI ORTODOXE

(Rezumat)

Bisericile vechi din zidărie au fost construite cu o concepție primitivă, la nivelul cunoștiințelor actuale, dezvoltată în principal în sensul acțiunilor gravitaționale.

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Având în vedere vârsta acestora, structurile de biserici ortodoxe sunt predispuse la avarii grave și colaps parțial sau global când sunt supuse la acțiuni orizontale. Acest articol studiază tipologia structurilor de biserici ortodoxe în legătură cu sensibilitățile structurale ale acestora. Pe baza investigațiilor în situ a avariilor unor biserici ortodoxe, se prezintă și se explică mecanismul tipic de avariere a acestor structuri, rezultând aspecte ce pot fi utilizate în evaluarea nivelului de siguranță și alegerea soluțiilor adecvate de consolidare.

