Risk evaluation of orthodox churches, using collapse plastic mechanism

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Abstract: Paper presents a case study of Orthodox Church affected by earthquake using collapse mechanism as method of analysis. In the first part, the principle of this methodology is presented in comparison with other structural analysis that is use in current practice. Orthodox Churches has special characteristics of seismic behavior and damage which was observed during Romanian earthquake. During analyses of the data obtained is seen a spatial mechanism of failure, mechanism consisting essentially in the combination of a longitudinal fracture along the entire building and multiple transverse fractures at the body of the church and the infrastructure. These cracks lead ultimately to block separation that tend to work independently. Finally, have been presented several solutions of intervention depending on the nature of damage.

Key-Words: Seismic risk, church, orthodox, collapse mechanism, earthquake analysis, fissure;

1 Introduction

In the Carpathian area, most of the historical building are made of masonry, using brick block, stone, or adobe. These masonry unreinforced structure cannot be considered as a continuum, but rather as assemblage of compact elements, stone or bricks linked by mortar joist. Seismic events that have occurred in recent years have produced extensive destruction to the historic buildings, mainly due to poor knowledge of optimal methods of prevention collapse. Today structures, because of existing codes and analysis methodologies and because knowledge of materials behavior over time, can be more easily evaluated in seismic risk and calculated to withstand at seismic action. On the other hand, historic structure do not benefit from sufficient knowledge of the behavior over time, lack of norm of design, or methods of analysis, resulting in inability to protect the building heritage and the losses of cultural identity. Into masonry constructions, due to special character that they have, homogeneous and compact and because of the multitude of uncertainties that occur in a building (how the settlement of bricks, mortar quality and quantity, dimension joints), the seismic risk assessment can’t be obtained by using usual methods of calculation and analysis.

Reaction to earthquake of masonry structures represents a very complex problem due to the constitutive characteristics of the structural material behavior when subjected to strong ground motion. The main problem is the importance of discontinuities between the masonry units and the joining materials such as mortar, so the masonry exhibits as a heterogeneous structure and discontinuous system. The ultimate limit state, governed by the blocky nature of the collapse mechanisms, can remove these difficult problems.

2 Calculation models of masonry buildings for seismic design

In the latest years, along with computer aided design, seismic design has changed, and even if they started to show a series of specialized programs to calculate structures, on historical structures is necessary a more careful analysis of the objective to properly define the parameters that can influence the results. Also, recent research in the field have shown that, in the case of masonry structure, the usual methods of calculation give erroneous results of the seismic behavior of masonry. Elastic analysis is not sufficient because it can not determine the exact deformation during an earthquake. Therefore, inelastic analysis is used to identify the structural failure limit states. As a compromise between the 2 methods in current practice, using a simplified procedure, is the usage of pushover analysis, where a sequence of inelastic static analysis is performed for a set of monotonically increasing lateral loads. For the historical masonry buildings, the pushover methodology is complicated by the definition of the mechanical material properties, the definition of constitutive laws for decayed materials and structure rigidity degradation due to the cracks formations. The pushover analysis provide very accurate results in case of a single frame
calculation. When calculating the overall structure, this method can not be used because it gives results that are not accurate. Since masonry does not respect any hypothesis (isotropy, elastic behaviour, homogeneity) assumed for other materials, numerical modeling of a masonry is a very difficult task. The elastic model used into homogeneous and continous structures can not give accurate results because by this, can be detected only areas where cracks will appear. For ultimate state, nonlinear models that are using complex finite elements, based on plasticity theory and considering the joint and interface elements to model the planes of weaknesses, can be used only for simple masonry elements, being inadequate to model a full structure. Based on plasticity theory and considering the joint and interface elements used to model the planes of weaknesses, nonlinear models- the ultimate state- that use complex finite elements-could be used only for simple masonry elements, being inadequate to model a full structure.

![Diagram of a masonry triumphal arch](image)

**Figure 1 Behavior of a masonry triumphal arch**

The following figure presents an arch that is affected by seismic actions. (Fig.1) We can see moment when the collapse mechanism occurs, just before collapse in the latest stage. Direct observation of cracks after the occurrence of an earthquake into a masonry structure lead to the conclusion that the collapse often occurs following a transfer mechanism involving one or more elements of the building. Very good results are obtained using rigid blocks to determine the limit state of masonry constructions. This approach is better because they avoid using the long, time consuming calculation.

To determine the rigid blocks of collapse must be made following steps:
- Establish the horizontal and vertical loads applied to the structure.
- Establish possible collapse mechanisms for the structural system.
- Determining for each mechanism element the vertical forces and the position of these forces.
- Imposing the collapse mechanism of horizontal virtual displacements.
- Determining the compatible virtual displacement for each element of the mechanism.
- Using the principle of the minimum of total potential energy (compose by internal and external parts), the amplification of factors for horizontal forces, corresponding to the all established collapse mechanisms, are determined.
- The collapse mechanism for the ultimate limit state is the minimum value of the determined amplification factors.

3 Structural characteristics of Orthodox churches

Orthodox churches are based on the Byzantine style, characterized by using pendant to support the dome and towers. Until the discovery of pandantives have used other methods to download the efforts of the dome, but did not offer performance of pandant. But the greatest achievement of the Eastern and Byzantine dome-builders, was to place a hemispherical dome over a square chamber. The Roman domes, of which the Pantheon is the greatest example, were placed over round buildings, so that the junction of the two presented no geo-metrical difficulties. But a circle inscribed in a square only touches it at four points and the problem was how to fill the four triangular spaces left at the corners in such a way as to carry the dome between those points, or in other words how to bring the square plan to a circle.
A far more scientific and beautiful way was by the spherical pendantive, the discovery of which constitutes the triumph of Byzantine architecture. It is arrived at in this manner. ABCD (Fig.2) is the square and the inscribed circle E the dome to be placed over it. Imagine a larger dome FGHI circumscribed about the square. Then if the four segments ABG, BCH and the other two are cut off vertically on the lines AB, BC, etc., we get the imperfect domes shown by Fig.2, No.2. This is in fact the vault over the crossing of the cruciform mausoleum of Galla Placidia at Ravenna, and occurs in many parts of Sf. Sophia. The great invention of the Byzantines was to slice off the top of this imperfect dome on a plane level with the crown of the four side arches (Fig.2, No.3), and from the circular ring thus formed to spring their dome. The four spherical triangles on which the dome rests, relics of the imaginary dome FGHI are the pendentives, the strength of which lies in their being arched in two directions both horizontally and vertically, and the yare supported by being wedged in between the four arches of the square (Fig. 2, No.4). Plate I shows such a dome in actual process of constructionat the period when the ring is just formed, as in Fig.2, No. 3. Although there may have been tentative approaches to this method of construction before, the first real appearance of it on a grand scale was in Justinian's great church of Sf. Sophia, the Holy Wisdom at Constantinople, which was begun in A.D. 532; and the credit of the discovery is fairly due to his architects from the Greek Ionian cities of Asia Minor, Anthemius of Tralles, and Isidorus of Milletus. The great advantage of the pendant was very simple to allow passage of the round dome on a rectangular shape of the bearings. Using pendant, the main forces from the dome and tower are made from all four corners of the pendantive, having the role of energy-dissipating absorbed from the dome.

The efforts with which the pendantive are in contact are taken up by pillars or walls, forming a very rigid corner wall composed of the pendantive and the link between. In Romanian architecture, pendantive evolves, grabbing what is called “Moldovan vault”, which sit above the current pendantive, a pendantive twisted at 45 degrees to the start of the vault, archieving a support raising element. Also, by this method the desired reduction in the level of element that should be supported(dome or tower), which led to a decrease of efforts that are downloaded to support the side walls of the pendantive. A difference between the 2 way boundary of the dome is present in Fig. 3.

4 Orthodox church - typology

In Orthodox religious architecture, the church has taken various forms over time, mainly due to external influence that took place in Romania. Note such an adaptation of architectural styles depending on the origin of influence that took place over certain period of time. In area of Moldova and Bucharest is seen very strongly the influence of Greek-Byzantine type of church, Greek Cross church, the church of trefoil shape that disappeared following the intervention of pseudo restoration of Lecomte de Nouy, nava type church with a number of added features of Byzantine or western influence. The “nava” type churches are found mainly in Transylvania and Banat, due to Austro-Hungarian influences that have appeared in all fields. These churches have influences also from the Catholic church, adapted for Orthodox churches, many of the elements typically found into Catholic church are being found in Orthodox church architecture in the area. The appearance of the bell tower, or cupola made of these churches to have a special atypical architecture.
In the strong seismic zones, the main cause of degradation is the action of earthquakes, some time combined with other causes (landslides, negative movement, etc.). 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. The structural behaviors taken in consideration into the orthodox churches are:
- Simple structural elements: foundations, walls and cylindrical vaults, arches, caps, semi caps, pendant
- Complex structural elements: wall door opening, wall window, wall with pillars and spring, the dome of the pendants, apse, or bell tower, belfry;
- Structural subsets: units composed of simple and complex structural elements which delimit a space.

During the analyses of the Orthodox churches building have been taken in consideration a structural assembly that correspond to the majority of the structures into witch have been marked the most frequently and important damage that can happen. During analyses of the data obtained is seen a spatial mechanism of failure, mechanism consisting essentially in the combination of a longitudinal fracture along the entire building and multiple transverse fractures at the body of the church and the infrastructure. These cracks lead ultimately to block separation that tend to work independently.

Spatial mechanism of damage is presented as a study that presents both presentation of cracks and blocks resulting from such failure. Due to increase in complexity of churches, increase size, increase the
number of goals of windows, the decrease of thickness of masonry, adding of open porches, the degree of vulnerability increases, and this is reflected number of increasingly large blocks of separation.
In essence, the more complex the structure of the building is, the high will be the risk of block separation of church building that will break into several pieces.

![Collapse mechanism studied on several churches](image)

**Fig. 7** Collapse mechanism studied on several churches

### 6 Categories of interventions

Current guidelines in the field provide for conservation and/or improve the capacity of resistance as possible, respecting the characteristics of the old building and not getting a level of assurance determined by the assimilation of calculation methods and limit values for designing new buildings. Adaptation interventions (taking into account values comparable to those taken in account to design new buildings) will be limited to situations in which, for other reasons than the
damage of Roman church due to 1977 Vrancea earthquake; we can observe 2 large longitudinal fissure and multiple transversal fissure. This will avoid interventions likely to alter the original structural design. The main criterion for choosing the materials and techniques is the intervention of their classification into two categories: reversible and irreversible techniques. In general, materials used for reversible interventions, require very few restrictions. Instead, the materials used in irreversible interventions require compatibility with original materials and very long-term sustainability. It is widely accepted that the safest way to satisfy the need for compatibility and durability is the use of traditional materials.

7 Conclusion

The method of analysis using collapse plastic mechanism is a simplified analysis method for failure mechanism that can be very useful to achieve a good restoration. The failures with complex character, affecting the entire structural assembly, leads to the conclusion that we have to deal with a comprehensive system of damage that cause spatial separation of the entire block, with the tendency of autonomy to the action of external factors. Combining together those blocks and reunite the all the pieces, implies a concept of restoration based on a spatial vision. Finding the best intervention processes with traditional materials and techniques similar to those optimized on the basis of technological and information, constitute the main objective of research in the field.

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