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Failure mechanisms for historical religious buildings in Romanian seismic areas

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Historic religious buildings located in seismic areas have developed different failure mechanisms. Simulation of failure modes is done using the method of failure blocks. Currently, there are simulation methodologies of failure modes based on the failure rigid blocks method only for Roman Catholic churches type. Due to differences of shape in plan, elevation and construction systems between Orthodox and Catholic churches, there were initiated researches in the development of this methodology for Orthodox churches. The theoretical results were compared with real failure modes recorded at an Orthodox church from Banat region, damaged by earthquakes of 1991.

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1. Introduction. Research aims

Generally, the seismic behaviour of historic buildings is studied using computer software which simulate the seismic response of the buildings only in elastic domain and for isotropic and homogenous materials. But a masonry structure does not respect these hypotheses. For ultimate state, nonlinear models, 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 the spatial structure. Therefore, the development of a simple model, able to determine the ultimate state for complex masonry structures, is a very expected methodology by the designers. A rapid and efficient method for simulation of the response of buildings with complex shapes in ultimate limit state can be developed by examining the cracks formed after an earthquake, which divides the structure in some rigid blocks. So, the structure failure occurs by formation of a collapse mechanism. In this case, computational models use some rigid body macro-elements and the discontinuities are concentrated only along the borders of these elements. This article confirms the results of the first scientific researches performed with the methodology of ultimate seismic forces on masonry churches from active seismic zones in Romania.

2. Seismic design of masonry buildings. Theoretical and experimental studies

2.1. Performance based design methodology for masonry buildings

A current trend in seismic design of masonry buildings is the incorporation of performance-based design methodology. In this methodology, every building is designed to have the desired levels of seismic performances corresponding to different specific earthquake ground motion. To achieve this goal, elastic analysis is insufficient, because this cannot realistically predict the forces and deformations during earthquakes. Inelastic analytical procedures become necessary to identify the mode of failure. Therefore, inelastic time-history analysis is the most realistic approach for evaluating the building performances. However, this inelastic analysis is too complex and time-consuming in the design of most buildings, especially if the spatial behaviour is considered. As a compromise, a simplified procedure commonly accepted is the 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 mechanical properties of the materials, definition of constitutive laws for decayed materials and structure rigidity degradation due to the cracks formation. The behaviour of a masonry triumphal arch is presented in Fig. 1. In the first stage, the arch works as a compact element until the first fissures. In this field, the masonry can be characterized as an elastic medium with heterogeneous properties. The first fissures produce a reducing of arch rigidity, but the elastic behaviour is not modified very much. At superior level of load, the fissures are turned in a

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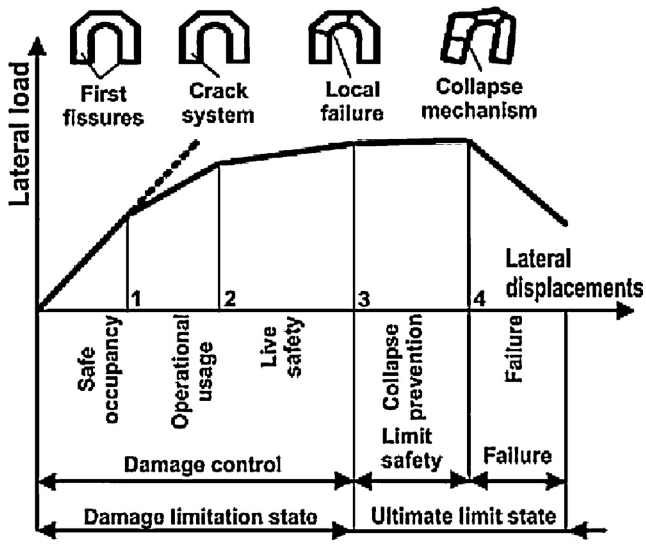

Fig. 1. Behaviour of a masonry triumphal arch.

system of cracks, which began to affect very much the arch behaviour. The increasing of load produces a local failure, where the first very important damage occurs. In the ultimate limit, a collapse mechanism is formed, which, finally, generates the arch failure. Therefore, the masonry structure behaviour until the formation of crack system can be considered as the range of damage limitation stage, while the behaviour near to formation of collapse mechanism as the ultimate limit state. Therefore, analyzing the behaviour of historical buildings, it is need to be adopted a two step procedure (Fig. 1).

2.2. Analysis methods for various limit states

Function of the limit state in which the analysis is performed for buildings, it can be used the following calculation methods:

- global behaviour analyses for damage limit state, in the linear elastic range, through a complete and refined FE Method-3D model. This analysis can give indications on the global behaviour in the undamaged range and can only detect the weak part of the structure and the position of the cracks, forming in the ultimate limit state the collapse mechanism;
- global behaviour analyses in the ultimate limit state, using the Collapse Mechanisms Method, considering the structure composed by some rigid body macro-elements with discontinuities concentrates only along the borders of these elements. This methodology is based on the observation in situ or on the models concerning the cracks system of a damaged building, leading to a collapse mechanism. This analysis is very useful to establishing the most efficiently strengthening method. The use of theory of rigid blocks to determine the ultimate limit state of historical building has the potential to become a powerful tool in engineering practice. In particular, this approach avoids the use of sophistically and time-consuming nonlinear finite element technique. The applicability of this theory to masonry structures modelled as assemblage of rigid blocks interacting through joints depends on some basic hypothesis, confirmed by in-site observations and experimental results:
  - limit loads occur at small displacements, so the linear theory can be used,
  - masonry has no tensile strength,
  - compression and shear failure at the joints are perfectly plastic,
  - hinging failure at joint does not consider the effects of local crushing.

This methodology was successfully applied for determining the collapse mechanisms and ultimate limit state for Romanesque churches [1–5] and for Orthodox churches in [6–10].

These calculation methods for different limit states were performed for churches and mosques through theoretical methods, based on the analysis of the finite elements and through experimental tests within the research project PROHITECH [11–16]. Generally, the results were obtained using numerical analysis and confirmed by the experimental tests.

2.3. Seismic behaviour of Romanian Orthodox churches

The buildings of Romanian Orthodox churches are based on the Byzantine style, being characterized by the using pendants and dome on pendants (Fig. 2). This is an unique way of adjusting the circular form of a dome or tower to a square plan and to transfer the total load of the roof to the four corners of the building. The surrounding infilled zone and exterior masonry walls also contribute to carry out the loads, forming very rigid corner.

The typical plans of Orthodox churches are presented in Fig. 3: rectangular nave with one lob or three-lobed nave. Unlike the Catholic churches, the Romanian Orthodox churches are relative small in size. The main typical Romanian Orthodox churches are the three-lobed plan. This form plays a crucial role in the improving the church behaviour during the earthquakes, because it reduces the distance between stiffness centre and centre of gravity on the longitudinal axis of symmetry. In some cases, some churches were provided with buttresses in order to reduce the distance between these two centres.

Many damaged churches were recorded during 1977 and 1986 Vrancea earthquakes and 1991 Banat earthquakes. Analyzing the occurred system of fissures and cracks, it is very clear that the spatial collapse mechanism is formed by a longitudinal fracture and multiple transversal fractures which round the pendants, due to the great rigidity of these ones. In addition, cracks occurred at the base of tower. The cracks start always from the windows, due to reduced rigidity in these zones. Considering the system of fractures, it is very clear that, in the ultimate limit state, the churches form a block system, working independently each other (Fig. 4). The blocks are formed by the wall delimited by two windows and the corresponding corner pendants.

2.4. Seismic behaviour of Orthodox Church St. George – Birda, Banat region, Timis County

In the Banat region, two earthquakes of July and December 1991 have produced significant damage to some churches made of brick. Among these damaged churches is the one of St. George Monastery (Fig. 5) in the village Manastirea, Timis County, erected in 1791. Currently, it is declared a historical monument.

The length of the church is 21 m and the width 9,80 m. Walls are 75 cm thick, reinforced with brick pillars in front of the roof arches. Hall-type church building is covered with brick arches and wood framing. The church has two towers: the West Tower and East Tower. The East tower is circular and it is supported by the pendants of the middle dome. Two domes on brick pendants supported by arches cover the middle area. The West tower is the bell tower and it has a rectangular section, being supported on one side by the church walls and on the opposite side by a brick arch with cracks and no tie. The masonry structure presents a longitudinal symmetry, except on the West side where the presence of stairs introduces an asymmetry; hence, the centre of rigidity of the structure is shifted to the West. At the same time, taking into account the

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