USING SOFTWARE PACKAGES TO ANALYZE THE VULNERABILITY OF CULTURAL HERITAGE BUILDINGS

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ABSTRACT

The seismic protection of buildings and masterpieces which have ecclesiastical and monumental architecture calls for further actions. The paper presents the construction planning of trilobite churches and the evolution of the vulnerability concept regarding the Romanian cultural heritage buildings, focusing on the role of geometry in preventing seismic damages and how the program ROBOT Millenium can be used to analyze a masonry structure. The examples provided in the paper reveal the fact that geometry is a measure of induced intelligence and it plays an essential role in preventing rotation.

KEYWORDS: *churches, hazard, seismic risk, software package, vulnerability.*

1. INTRODUCTION

The fundamental concepts developed by UNDRO-1979 (United Nation Disaster Relief Coordinator) applied in seismic risk assessment systems developed by EAEE (European Association on Earthquake Engineering) are based on specific mathematical concepts and provide the necessary conditions for thorough analyzes of seismic hazard and seismic vulnerability associated with the seismic risk;

Unanimously accepted, the link between seismic risk (SR), seismic hazard (SH) and seismic vulnerability (SV) can be expressed by means of formal relationship:

$$SR = SH \times SV$$

From the interpretation of the above relationship it results that the associated seismic risk (SR) of both the locations and the exposed objectives is based on the combination of seismic hazard (SH) and seismic vulnerability (SV), expressed in terms of maximum acceleration (PGA) (PGV), maximum displacement (PGD) of ground area, and maximum spectral values of absolute accelerations (SA), relative speeds (RS) and relative displacements (RD).

The Seismic Vulnerability (SV) means the destructive effects caused by a strong seismic action on exposed elements or systems built. Vulnerability can be expressed through specific source parameters (focal mechanism), the ground motion from the site (local

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conditions), and the structural feature of exposed elements (conditions for seismic protection of buildings). Therefore, we can say that the seismic vulnerability has a random nature as the action of a particular earthquake can cause structural damage to all buildings in the same location.

A recent study proposes a new and effective type of composite bonding as a temporary seismic intervention for quickly protecting masonry structures against aftershocks, giving time to authorities for making decisions on a proper permanent repair intervention of the heritage structure. This innovative composite strengthening system is based on highly deformable adhesives made of special polyurethane that can be applied very quickly and is mechanically removable; therefore, it could play an important role during interventions on historical structures (A. Kwiecie´n et ali., 2016).

2. SEISMIC PHENOMENA

2.1. Seismic Vulnerability (SV)

Defining seismic vulnerability displays a variety of aspects:

- It is the damage that will be faced by a building or its exposure to the action of an earthquake. Therefore, the seismic vulnerability can be defined as a relationship between the intensity of the action and the level of seismic damage that is expected to occur;

- It is based on the susceptibility of exposed elements, or a system built exposed to suffer damage or certain specific losses due to the incidence of an earthquake, and expressed in terms of probabilistic or statistical terms;

- It shows the degree of loss of a given element at risk, or a group of such elements, due to the occurrence of a natural phenomenon of a given magnitude, expressed in relation to a certain scale;

- In order to assess the seismic vulnerability, specific details are needed for statistical-probabilistic analyses and/or approaches of structural engineering, economic analyses, etc.;

- It is defined as the sum of damages, loss of life due to the degree of intensity of a place or an area;

- Estimating the vulnerability of a structure means linking the seismic risk and intensity of the expected earthquake to the level of structural damage if the earthquake occurs (Slave, 2010).

2.2. Seismic Risk (SR)

The notion of seismic risk is complex. There is a practically generalized inconsistency regarding the definition of the seismic risk concept in most specialized papers published in Romania and abroad as shown below:.

- It represents the degree of expected loss, in a probabilistic sense, caused by a natural phenomenon, depending on the natural hazard, degree and duration of exposure;

- It is the expected number of lost lives, injured persons, property destruction, disruption of economic activities due to a natural phenomenon being, as a result, the consequence of a specific risk;

- Risk is considered as an anticipation of losses and other negative events, assessed on the basis of existing consequences;

- The seismic risk is the synthetic characterization of the expected sequence of occurrence cases: (a) effects of different degrees of gravity (damage cases, various losses), (b) degradation of a system of exposed elements that are object of analysis and (c) a current situation regarding the seismic vulnerability of various elements and their exposure;

- It is likely that the social or economic effects expressed in money or victims exceed the expected values in a given place and time;

- It represents the possibility of incidence of a negative social impact;

- It is defined as the probability of occurrence of expected adverse effects due to earthquakes over the lifetime of a construction. The expected adverse effects include loss of life, economic and social disturbance, and damage to the physical state of construction;

- It consists in the probability of producing a disastrous event, of a certain magnitude, at a given place and within a given time;

- The seismic risk is proportional to both the frequency of occurrence of the disastrous phenomenon considered and the extent of its consequences for the population, the environment and the technological infrastructure;

- The seismic risk that is accepted by society is regulated at government level, by establishing the hazard areas, enacting the rules and regulations of construction, and by imposing measures regarding spatial planning.

2.3. Seismic Hazard (SH)

Several definitions of the seismic hazard from the existing literature in the field of Engineering Seismology and Geophysics are presented below:

- It characterizes the likelihood of an earthquake with destructive potential in the site chosen for a building, throughout its lifetime. In this regard, the seismic hazard can be defined as a relation between the degree of seismic damage and the probability of manifestation of an intensive seismic movement;

- It represents the expectation of a series of seismic events which, according to the methodological needs, can be considered in relation to the sources or the locations which correspond to a Poisson process, starting from the premise of the probabilistic independence of different earthquakes;

- It is the probability of occurrence of a potentially destructive natural phenomenon within a specified time frame in a specified area;

- It provides a synthetic characterization of the expected sequence of seismic events with different levels of severity by using probabilistic concepts;

- It is defined as the probability of an earthquake of a certain magnitude at a specific place and time;

- It represents the natural physical degree of exposure of a particular geographical area;

- It is the likelihood of occurrence when a certain level of maximum acceleration is exceeded within a certain timeframe;

- In order to characterize the seismic hazard, it is necessary to specify for each case study whether there are considered several types of events, surface earthquakes or medium depth earthquakes;

2.4. The construction planning of trilobite churches

The oldest monumental buildings preserved in the Carpathian-Danubian-Pontic region are churches. For centuries, they have been the most representative masterpieces which boast ecclesiastical and monumental architecture. These have always been Orthodox churches, because Romanians are the only Latin nation of Orthodox religion, while all other peoples of Latin origin are Catholic. Being erected in stone and brick, these Eastern Balkan-Byzantine-style Churches have always been the proof of the level of technical knowledge, cultural receptiveness and artistic refinement achieved during their time (Sofronie, Popa, 1999).

As a general rule, the Byzantine model was based on the standard Greek system, with the right-cross type, rectangle inlaid and dome supported on pendants or pillars. However, they were creatively adapted to the regional traditions of secular architecture. Moreover, these Orthodox churches still reflect the foreign influences on the native art of buildings.

Originally made of wood, in the fourteenth century, trilobite churches were made of stone and brick. At the beginning, these churches were provided with a unique bell tower, called Pantokrator. Later, two, three or four towers were added to decorate the ecclesiastical monuments. Sometimes one of the rear turrets is used as a bell tower and /or as an oriel. The two geometrical characteristics of the turrets are the outer diameter D and the height H from the base to the top of the masonry dome, while their slenderness is defined by the D / H aspect ratio, which is usually between 1/2 and 1/3.25. The size of the trilobite churches is quite small, like that of a two or three-storey building (Sofronie, Popa, 1999).

Under seismic phenomena, some of these churches were dramatically damaged or even destroyed. The trilobite shape is far from being the most suitable for churches to face the earthquakes. However, they have been faithfully preserved over the centuries.

3. CASE STUDY –THE ARGES MONASTERY

Harun emphasizes the fact that the concept of heritage is invariably. UNESCO"s Convention Concerning the Protection of the World Cultural and Natural Heritage (1972) which has defined cultural heritage by the following classifications (Harun, 2011: 42-43):

- Monuments: architectural works, works of monumental sculpture and painting, elements or structure of an archeological nature, inscriptions, cave dwellings and combinations of features, which are outstanding universal value from the point of view of history, art or science;

- Groups of buildings: groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science.

- Sites: works of man or the combined works of nature and of man, and areas including archeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological points of view;

One of the most representative trilobite churches in Romania is The Argeş Monastery. It was built in six years, between 1512 and 1518, under the reign of Neagoe Basarab, as a church mausoleum, where the prince and his family were buried. Later, a monastery was built around the church. Due to its special beauty and fame, many other churches were modeled in a similar way. Today it is an Episcopal Church and a heritage monument

3.1. ROBOT Millennium Software Package

For the determination of gravity centers (GC) and rotation centers (RC), the structure was analyzed using ROBOT Millennium. It is a single integrated program used for modeling, analyzing and designing various types of structures. The program allows users to create structures, to carry out structural analysis, to verify obtained results, to perform code check calculations of structural members and to prepare documentation for a calculated and designed structure.

The most important features are: number units and formats (dimensions, forces, possibility of unit edition) materials (selection of material set, according to the country and the possibility of creating user-defined material) section database (selection of the appropriate database with member sections) structure analysis parameters (selection of the static analysis method and definition of basic parameters for dynamic and non-linear analysis; selection of analysis types, possibility of saving results for seismic analysis – combination of seismic cases).

The menu consists of two parts: a text menu and toolbars with appropriate icons. They can be used interchangeably, according to the users' needs and preferences. Both are displayed in the same way - as a horizontal bar at the top of the screen (additionally, for some layouts in the ROBOT Millennium system, another toolbar with most frequently used icons is displayed on the right side of the screen). Basic options available within the modules are accessible both from the text menu and the toolbar. (Figure 1)

The second method of work with ROBOT Millennium is by using the special layout system. ROBOT Millennium has been equipped with a layout mechanism that simplifies the design process. The layouts in ROBOT Millennium are specially designed systems of dialog boxes, viewers and tables that are used to perform specific defined operations. Layouts available in ROBOT Millennium were created to make consecutive operations leading to defining, calculating, and designing the structure easier.

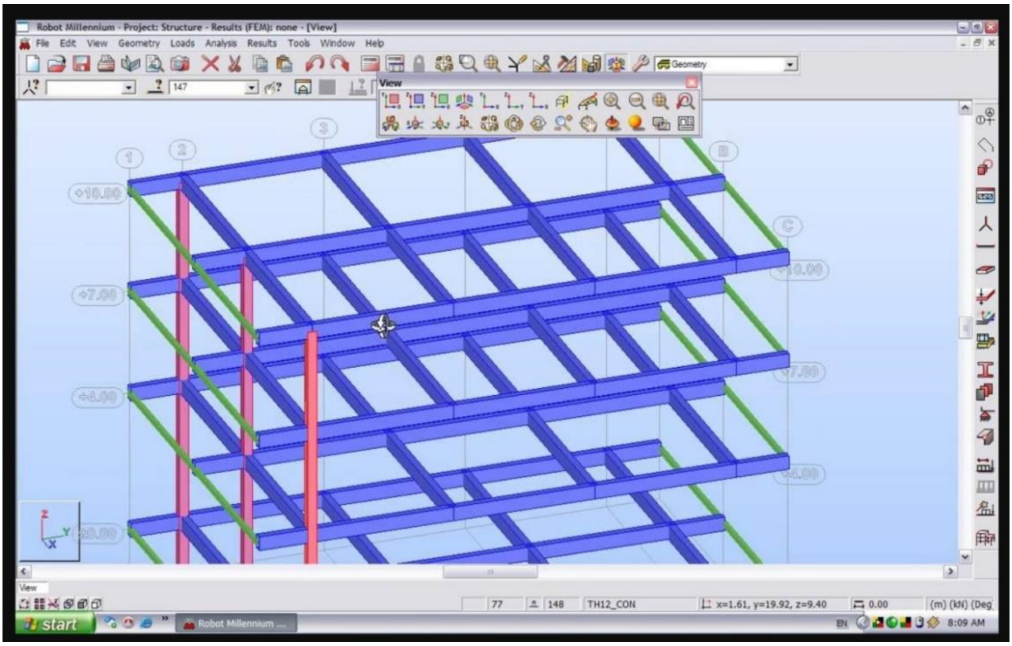

Figure 1. The Robot Millennium interface
(*Source: https://i.ytimg.com/vi/m1cf4hv_EMQ/maxresdefault.jpg*)

3.2. The Sacrifice Myth and Further Analysis

According to the famous legend of Negru Voda, a Romanian prince ordered a masonry team to build a church on the upper course of the Arges River at the foot of the Carpathians. The work was carefully organized and well-structured until the walls began to rise. Then, surprisingly, everything that was built daily, collapsed overnight. Only after the sacrifice of the head mason’s wife was the church built entirely. The beauty of the church charmed the Prince. To prevent masonry from building more beautiful churches, he decided to sacrifice the head mason and his masonry team (Eliade,1943).

The legend is meant to convey certain professional standards, but only to clever people who could understand their true meaning. Indeed, if the ideas presented above are carefully analyzed, the ancient concept of durability can be expressed as follows:

a. The mysterious forces that cause the destruction of the church walls overnight can only be those caused by earthquakes. Therefore, in seismic areas the construction site should be carefully chosen. That depends mainly on the seismic hazard of the site and the seismic risk as well. The most important source of information comes from the location history. It is a long tradition to build churches and monuments on the hills or local heights where the seismic intensity is somewhat smaller. This rule was applied in Bucharest, when a location with a lower seismic intensity was chosen for The Palace of Parliament (Sofronie, Popa, 1999).
b. The idea of centering the church from the very beginning is, in principle, related to the need for balance. Each church has two intrinsic centers, the former center of mass or gravity, and the latter center of rotation or rigidity. Both centers, GC and RC, lie on the longitudinal axis of symmetry. Inertial forces induced by earthquakes

are applied in the CG and in compliance with the RC of torsion as a whole. Going up, the seismic action reaches the turrets and its own inertial forces produce shearing. The seismic vulnerability of churches depends on the relative position of the two centers. According to the Eurocode 8, ENV 1998-1-2 Part 1-2, for seismic protection, the distance between the two centers, which is, in fact, the eccentricity of seismic forces, should be reduced to less than 10% of the length of the church. In the case of The Argeş Monastery, it was found the following (Sofronie, 2004):

In the areas of fullness:

$X_M = 9.184$ m

$Y_M = 5,500$ m

$X_R = 8.736$ m

$Y_R = 5.500$ m

The difference between $X_M$si X_R is 9.184-8.736 = 0.448 m

The length of the church is 20.4 m (between the axes of the walls), so the eccentricity between $X_M$si $X_R$esse of 2.2% <5% <10%

In the areas with voids:

$X_M = 9,000$ m

$Y_M = 5,500$ m

$X_R = 8.250$ m

$Y_R = 5.500$ m

The difference between 〚X〛 $_M$ and X_R is 9.00-8.25 = 0.75 m

The length of the church is 20.4 m (between the axes of the walls), so the eccentricity between XM and XR is 3.7% <5% <10%.

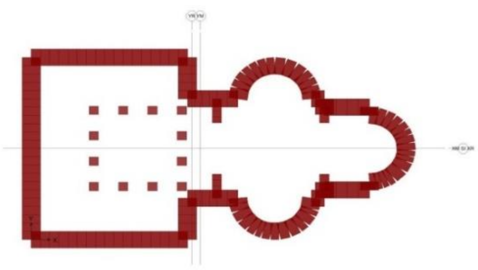

Figure 2. Positions of centers of gravity and rotation in areas with fullness

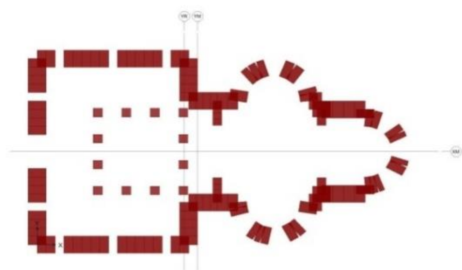

Figure 3. Positions of centers of gravity and rotation in areas with voids

The shape highlights the geometry of the church towards the building materials. Geometry means not just creating a balance, but also plays an essential role in preventing the rotation. It is also a measure of induced intelligence. In the case of the Arges Monastery, the sacrifice myth had geometric consequences. Indeed, in order to create space for the sacrificed person's body, the head mason was forced to change the original form of the church by extending the narthex. For reasons of symmetry, both parts of the church were changed identically. In this way, the relative position of the two centers changed. The general torsion phenomenon has been modified accordingly.

Oriental churches which comply with the Trilobite Plan were sanctified during the sixteenth and seventeenth centuries when religion played a decisive role in all European societies. This typical form was developed for structural reasons, as well as by the use of plastic behavior of masonry as a building material. The shape allowed physical connections between curved and straight surfaces, from horizontal to vertical planes. Trilobite churches are spatially balanced buildings as they are able to safely handle gravitational and side effects, in accordance with the durability requirements. Balance is the main condition of aesthetics and beauty (Sofronie, 2004).

The original planning is shown in Figure 4. The two intrinsic centers of GC and RC are behind the central axis, and as dimensions, given the distance between them; they are below 1.27% of the total length of the church. It is even smaller than the accidental eccentricity which, according to the same provision of Eurocode 8, is 5% of the total length. The two centers almost overlap (the difference between them is 45 or 75 cm (depending on the section - full or void). However, the result is far from being as favorable as it appears.

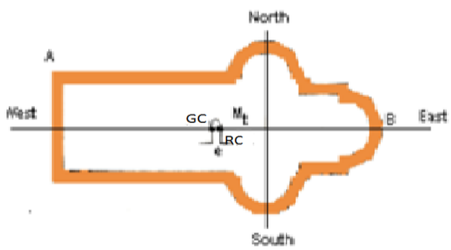

Figure 4. The original trilobite planning

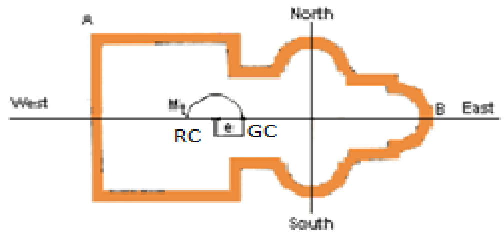

Figure 5. The extended trilobite planning

Indeed, for the same moment of torsion, the shear forces are inversely proportional to the distances from the RC to the extreme points. Since the distance from RC to B is smaller than RC to A, curved walls would be more exposed to seismic actions. That explains why so many trilobite churches have cracks on their apses and measures for their restoration must be taken.

By expanding the narthex as in the case of The Argeş Monastery, things change essentially. RC passes on the other side of the GC on the symmetry axis. What happens in this case is that the eccentricity increases by 2.2-3.7% of the total church length, but remains less than 5-10%, as recommended by the EC8 and P100-1/06. At the same time, the distances from the RC to the apex of the walls increase substantially, while the shear forces decrease. In the particular case of The Argeş Monastery, the extent of shear forces is reduced by about 32%. That explains why the apses of the trilobite designed churches were without exception so well-preserved. The same cannot be said about their turrets. Most of them are cracked on the circumference, always in the same place, namely at the beginning of the arches.

4. CONCLUSIONS

The seismic hazard (SH) can be defined as a potential threat, mainly due to the seismic action (generated by the natural tectonic or volcanic activity), to the phenomena of instability of the geological masses (landslides, collapses in karst areas or mining) or surface geomorphologic phenomena (liquefaction of sands, huge water accumulations by large dams). The seismic vulnerability (SV) refers to the destructive effects of strong seismic actions on exposed elements or built systems. Vulnerability can be expressed through source-specific parameters (focal mechanism), site movement (local conditions), and structural feature of exposed elements (conditions for antiseismic protection of structures). Therefore, it can be said that the seismic vulnerability is of a random nature, because the action of a certain earthquake can cause substantially different structural degradations on identical constructions situated in the same location.

The seismic hazard (SH) refers to the potential causes that can lead to disasters, while the seismic risk (RS) is specific to the negative effects of the earthquake. The seismic hazard (SH) is independent of man's interventions and, therefore it cannot be modified or diminished while the seismic hazard (SH), which is the consequence of hazard, can be substantially reduced by competent interventions on the seismic vulnerability of the exposed elements or built systems. A high seismic vulnerability indicates a low level of resistance to seismic actions or low antiseismic protection. Reduced or limited seismic vulnerability can contribute substantially to reduce seismic risk. The devastating effects of earthquakes can be reduced by correctly estimating the seismic hazard and the seismic vulnerability of the built environment through statistical and probabilistic analyses. On this basis, seismic risk scenarios, as well as defensive measures designed to reduce human and material losses, are being developed to cope with major and exceptional events. The notion of seismic risk is a probabilistic concept that includes material damage and loss of life.

By coincidence, in the early years of building the Basilica of St. Peter in Rome, The Arges Monastery in Wallachia was built in the form of a trilobite Greek cross. Prior to consecration, both had technical problems, St. Peter's Church, with the gravity, while the church of The Argeş Monastery with those mysterious forces occurring only during the night. In the former case, the problem was solved scientifically. By applying the most advanced theories of that era, after more than two centuries the cracks of the dome were repaired. The Argeş Monastery has resisted for almost five centuries. It is the proof of what today is called seismic protection.

At the end of the commentary on Manole's legend, Mircea Eliade mentions that in antiquity it was a tradition that some professional rules should be kept secret. That is why he admits that the myth of the sacrifice has an esoteric character. The legend is intended to convey certain professional gold standards, but only to people who could understand their true meaning.

The antiseismic design of masonry and monument buildings is a top priority because human lives must be protected and the cultural heritage buildings must be carefully preserved. Site data collection, test results, and numerical models are used to develop accurate and realistic methods for assessing the structural performance during earthquakes. The above example highlights the role of geometry in preventing seismic damage. The message attributed to the myth of the sacrifice seems to consist in the idea that trilobite churches are paraseismic masterpieces.

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