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Seismic rehabilitation of an historical church based on computational monitoring

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Summary

This paper presents the computational monitoring of an historical church performance, while taking account of the deteriorations revealed during the quality inspection aimed at ensuring the seismic serviceability of the structure. The modeling, simulation and seismic analysis were made on a class of non-damaged and respectively damaged models of this structure in order to determine the degree of serviceability, the strength and stability of this edifice.

1. Introduction

The Northeastern part of Romania has many historical monuments of religious and cultural patrimony, which have withstood, for centuries, the interactions with the environment and its exceptional actions. The church dedicated to "The Assumption of Mother of God", from N-E Romania, is such an example and it is the object of seismic rehabilitation by modeling, simulation and based on quality inspection. The structure dates back to 1855. At present, the building is in a damaged state, due also to the repeated earthquakes in the 19th and 20th centuries, and to long lasting physico-chemical factors. The visual screening made during seismic serviceability inspections involved surveying of the damage, terrestrial photography, geo-technical survey of the foundation soil, as well as the foundations survey [4, 7].

2. Structural monitoring of the historical monument.

2.1. Present state

The infrastructure of this monument consists of stone masonry foundations and base plate of brick masonry of variable height. The church structure has a nave with two lateral apses and a steeple situated over the narthex, trefoil shape in plane. The total length is 23,80m and breadth is of 9,90m. The masonry of the structure is the old type, solid brickwork with clay, lime and sand mortar and the exterior walls thickness is 70 cm, varying with its height. The vaults and the roof framing are made of wood, the springing line of the cylindrical vault is situated at +5,10m from the elevation of the stone floor. The steeple over the narthex reaches the elevation of +20,50m.

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The recesses are wide and skirted by the cornice, the interior walls are painted in a Neo-Byzantine style, on an oil prime paint, while the roof is of wooden trusses, in low slopes, coated with zinc-plated sheet.

The structure of the church “The Assumption of Mother of God” reveals certain seismic non-conformities, generated by its very design, which have led to its present-day state of pre-collapse, after having been subjected to repeated earthquakes. Some of important non-conformities refer to the placement of the western steeple non-symmetrically and eccentrically to the torsion/stiffness centre of the entire ensemble, an insufficient number of transverse and horizontal bracings in the upper part of the walls, the relatively great height of the church, the lack of adequate adhesion bond between the brick layers, poorly bonded or un-bonded stone foundations and the low strength building materials. After the major earthquakes of 1977, 1986, and 1990, in Romania, no further interventions have been made, and these exceptional loadings have heightened the effects of differential settlement and led to the present-day degrading of the building.

2.2. Evaluating the seismic risk by computational simulation

The evaluation of seismic risk in the existing buildings is made, according to [6], by expert appraisal, taking account of the class of importance of certain buildings, period of time for initial design, number of levels or height of the building; structural system, class of importance, seismic zone of building location; time of construction (up to 1940); structural material, [1]. The purpose of the expertise is to evaluate the level of protection from gravitational loads, seismic actions and other loads of significant intensities and to document and recommend the necessary intervention.

The seismic forces are computed with the relationship (1):

$$S_{kr} = \alpha \cdot \beta_r \cdot k_s \cdot \varphi \cdot G_k \tag{1}$$

where: α=1.2 is the importance coefficient corresponding to class II of building importance; k_s = 0.25, is the dynamic coefficient; ψ = 0.30 is the reduction factor due to damping and other effects. The term G_k represent the weight of model located at the k degree of freedom of the lumped structural model, following recommendation of [6].

3. Performance based computational monitoring

3.1 Structural modeling

For structural modeling, basically two classes of computational models have been considered, damaged and undamaged. First model is an undamaged model A1, having structural characteristics corresponding to the new ones, damaged model A2, that simulates the present-day structure, with plastic joints in the connection between the damaged structural elements. For model A2, laboratory and in-situ analyses identify the materials characteristics out. The model A3 simulates the present-day structure formatted on elastic medium, having same materials characteristics as mentioned of model A2. Model A4 is obtained by remodeling, after structural rehabilitation for a given seismic safety. The structure is discretized with finite elements 3-D PLATE/SHELL type, interconnected in the nodes with 6DOF per node for a rigorous representation of the complex topology of the building, presented in Fig.1 along with spectral input used in simulations.

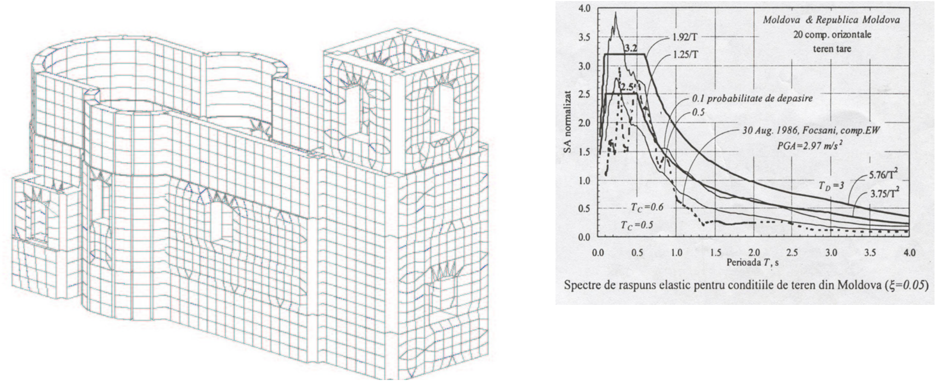


Fig.1 Computation model of the church and spectral input in simulations

3.2. Analysis of computational results and structural rehabilitation

The monument structure was analyzed under gravitational and seismic loads, combined within fundamental, special and spectral group of loading [1, 2, 4]. The maximum Stress-Strain State was achieved for spectral group, in compliance with the design response spectrum, recommended in [6]. The Modal Analysis in free vibrations led to the selection of certain significant vibration modes of analyzed models, listed in Table 1.

Table 1. Vibration period for models class

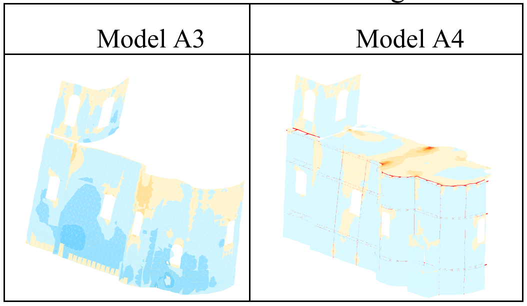
Period of vibration (sec)	Class of models			
	Model A1	Model A2	Model A3	Model A4
1st Mode of vibrations	0,61	0,61	1,34	0,41
3rd Mode of vibrations	0,43	0,42	0,96	0,32
7th Mode of vibrations	0,30	0,301	0,41	0,18

Several results following the Spectral Analysis Methods has been obtained, and a selection is presented in Table 2.

Table 2. Stress – Strain State results in models classes

Numerical Results				Class of models			
				A1	A2	A3	A4
Main Stresses	Special group of loading	σ_1 (MPa)	max	0.61	0.55	1.78	0.25
			min	-0.14	-0.10	-0.13	-0.42
		σ_2 (MPa)	max	0.08	0.12	0.24	0.02
			min	-0.40	-0.37	-0.61	-0.32
	Spectral group of loading	σ_1 (MPa)	max	0.51	0.52	1.31	0.35
			min	-0.11	-0.10	-0.15	-0.15
		σ_2 (MPa)	max	0.10	0.12	0.17	0.10
			min	-0.36	-0.37	-0.42	-0.33
Maximum values of models displacements		u_x (m)		8.7 10^{-3}	8.5 10^{-3}	2,32 10^{-2}	1,06 10^{-2}
		u_y (m)		4,92 10^{-2}	5,10 10^{-2}	11,30 10^{-1}	3.30 10^{-2}

Figure 2 presents the stress state distribution for σ_2 considering the special group of loading, which includes the seismic loading.


Model A3

Model A4

Fig. 2 Stress distribution σ_2 for models A3 and A4 for special group of loading

Fig. 3 presents the displacements u_y distribution, the largest being obtained for models A3, and A4 in the case of spectral group of loading combination.

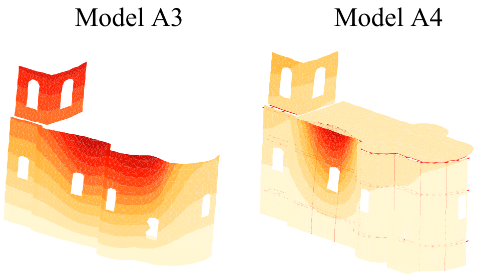


Fig. 3 Displacement distribution in model A3 and A4 for spectral group of loading

The simulations have shown interesting results. The largest displacements have been obtained for the model A3 of 0.113m considering as input the special group of loading, and 0.0567m for the spectral group of loading, respectively. The maximum stresses of 0.61MPa have been obtained for model A3 in fundamental group of loading and of +1.78MPa in special group of loading. The fundamental period of vibrations is 1.34 seconds for model A3 and respectively 0.61 second for models A2 and A1.

The analysis of computational results obtained from the above modeling and simulations allowed us to propose a seismically rehabilitated structure, whose model is simulated in model A4 of consolidated structure. For structural rehabilitation for normal serviceability conditions consolidation measures were taken. Some of them are mentioned: the restoring structural integrity, introduction of new bracing to confer the structure the capacity to take over the seismic shocks the increase of building stiffness girdles on the interior and the exterior at various elevations, infrastructure's consolidation, crosswise stirrup girdles at attic level, anchored in the capping girdles, the injection of cement grout mixed with adhesive paste in all the cracks where brick bonding is not made, etc. this way the resulting Stress-Strain State ranges identified form simulation made on model A4 could be within the limits of the current Codes [6]. Correspondingly, the fundamental vibration period of 0.41 seconds, listed in Table 1, is lower than in the models A2 and respectively A3, for a needed structural stiffness and stability.

4. Conclusions

The computational monitoring of the historical church presented within this paper highlights two types of conclusions, general one and specific for the case study of seismic rehabilitation of the church. First, is that the numerical simulation based on different models of lifetime cycle behavior of structure is an excellent procedure to be used for seismic rehabilitation of constructions. Second conclusion is that the analysis of structural performance of the church, presented in terms of dynamic behavior in linear domain and Stress-Strain State analysis led to a consolidated structure, within increased degree of safety and serviceability.

5. Reference

1 Atanasiu, G. M. (2002):"Simulation based monitoring of damaged structure's behavior during seismic events" *Computational Structural Dynamics*, A. A. Balkema Publisher, ISBN 90 5809 368 9, p. 125-133.

2 Atanasiu, G.M. (1999):"Information processing for a realistic evaluation of damaged structures within safety seismic problem", *Proceedings of the First Romanian American Workshop in Structural Engineering*, Iasi, Romania.

3 Binda, L. (1997):"Repair and investigation techniques for stone masonry walls", in *Construction and Building Materials*, Vol. 11, N.3, pp. 133-142.

4 Creazza, G.(may 1995): "Mathematical simulation of structural damage in historical buildings", STREMA 95, *Structural Studies of Historical Buildings, Crete, Greece, Architectural Studies, Materials & Analysis*, eds. Brebbia and Leftheris, Comp Mech. Publ., pp. 111-118, vol. 1.

5 P2-86 (1986): *Normativ privind alcatuirea, calculul si executarea structurilor din zidarie*, Institutul de proiectare pentru constructii tipizate, IPCT, Romania.

6 P100-92 (1992): *Normativ pentru proiectarea antiseismica a construcțiilor de locuințe social-culturale, agrozootehnice şi industriale*, MLPAT, Romania.

7 *Sofronie, R. (1999): "Geometrical approach of restoring the monuments",* Assisi-99. *Proceedings of the International Workshop on Seismic Performance of Built Heritage in Small Historic Centers*, pp. 379 – 387.