COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27May 2015

EVALUATION OF THE DYNAMIC RESPONSE FOR A HISTORIC BYZANTINE CROSSED-DOME CHURCH THROUGH BLOCK-JOINT AND KINEMATIC ANALYSIS

Constantine C. Spyrakos[1], Francesco Pugi[2], Charilaos A. Maniatakis[1], and Alessio Francioso[1]

[1]Laboratory for Earthquake Engineering, National Technical University of Athens
HeroonPolytechniou 9, 15780 Zografou, Athens, Greece
{cspyrakos@central.ntua.gr; chamaniatakis@gmail.com; alessiofrancioso@gmail.com}

[2]Aedes Software
56028 San Miniato Basso, Pisa, Italy
info@aedes.it

Keywords: Historic Masonry Structures, Crossed-dome Byzantine Church, Seismic Response, Pushover Analysis, Kinematic Analysis.

Abstract. *The protection of historic masonry structures against earthquakes constitutes a rather complex problem. The calculation of their anticipated response involves significant difficulties, such as the selection of the proper simulation in conjunction with the measurement of the materials mechanical properties. In the present research the central church (Catholicon or Katholikó) of the Monastery of Kaisariani located on a hillside at the foot of Mount Hymettus on the east of Athens, Greece, is selected as a case study of a historic structure to study its seismic response. The Catholicon is a Byzantine crossed-dome church constructed during the 11th/12th centuries. Full survey and detailed in-situ and laboratory tests were carried out by the multidisciplinary team of an on-going research program in order to document its geometry, the construction details and the mechanical properties of the constituent materials. The current condition of the structure and its seismic behavior were assessed by means of a block-joint and kinematic analysis. Specifically, the stability of selected macroelements was evaluated through (a) pushover analysis applied to block-joint models of arches and vaults and (b) kinematic analysis of rigid bodies.*

The investigation was performed within the research project "Seismic Protection of Monuments and Historic Structures - SEISMO" which is co-financed by the Greek Ministry of Education and Religions and the European Union under the action "Thales" within the context of the Operational Programme - Education and Lifelong Learning, NSRF 2007-2013.

1 INTRODUCTION

The protection of monuments under seismic excitations is an issue of critical importance for countries that present significant seismic activity [1, 2]. In the Mediterranean basin, a region of intense seismic activity, there is a significant number of monuments of world cultural heritage representative of a wide range of historical periods: Minoan, Mycenaean, Archaic and Classical, Hellenistic, Roman, Medieval, Byzantine, Ottoman and modern. Between those countries that combine rich cultural heritage and considerable seismicity, Greece presents the most significant seismic activity in Europe while ranks among the most seismically active regions on global scale [3]. The same time Greece is a country well celebrated for its cultural heritage with monuments belonging to the classical era like the Acropolis in Athens (5^{th} century BC) and monuments of the byzantine era like the Monasteries of Daphni, Hosios Loukas and Nea Moni of Chios (11^{th} – 12^{th} centuries AC) all inscribed in the World Heritage List of UNESCO [4]. Seismic activity is also important for other countries located within the Mediterranean basin well known for their cultural heritage such as Italy, the Balkan counties, Cyprus, Turkey and the north coast of Africa [5].

The need for the reservation of monuments led to the adoption of “The Athens Charter” for the Restoration of Historic Monuments in 1931 [6] and later with the contribution of international organization like UNESCO, ICOMOS and the European Council “The Charter of Venice” was adopted in 1964 for the Conservation and Restoration of Monuments and Sites [7]. Nowadays, the use of contemporary computational tools, the application of instrumentation and non-destructive evaluation and the use of new materials, allow for a more thorough confrontation of the reservation problem. However, seismic activity still represents an important parameter of vulnerability for monuments and historic structures. For that reason significant efforts have been made towards the establishment of provisions for the seismic strengthening of monuments [8-10].

The ongoing research project entitled “Seismic Protection of Monuments and Historic Structures - SEISMO” which is conducted under the coordination of the Laboratory for Earthquake Engineering of the National Technical University of Athens, LEE-NTUA [11], aims at the development of an integrated, interdisciplinary and innovative methodology for the evaluation of the seismic behavior of monuments and historic structures.

Two monuments of major historical and architectural significance were selected as case studies in the context of the SEISMO Project both located in Athens, Greece: a) the temple of Hephaestus or "Hephaisteion" (449-444 BC) dedicated to Hephaestus and Athena, in the Ancient Agora and b) the Catholicon of the Kaisariani Monastery (11^{th}-12^{th} century AC) dedicated to the Presentation of the Virgin, at the foot of Mount Hymettus. This work focuses on the second monument, the central church of the Kaisariani Monastery constructed during the byzantine period and presents only a part of the analyses carried out in order to study its seismic behavior.

The vulnerability of church-type structures under earthquake loadings was confirmed during major recent earthquake events, i.e., the M=7.1 Christchurch 2011 earthquake in New Zealand [12] and the two earthquakes with magnitudes of M=6.0 and M=6.1 Cephalonia, Greece 2014, earthquakes that provoked extensive damages to churches made of unreinforced masonry [13]. The topic has been extensively studied in the literature, e.g. [14-18].

2 THE CATHOLICON OF KAISARIANI MONASTERY

2.1 History, Architectural Perspectives and Structural Characteristics

Several different names were used in the literature for the Monastery during its long life including “Kaisariani”, a name of unconfirmed origin, “Kyriani”, “Sancta Siriani” during the period of Frankish rule, and the Monastery of “Koç basi” (“Ram’s Head”) during the Ottoman period. The first Christian center had been founded southwest of the Monastery on the hill of the Cemetery of the Fathers where ruins of a 10th century Byzantine church built on the foundations of a 5th-6th c. three-aisled basilica are preserved. The Monastery was moved to its present location during the late 11th century [19].

The central church, Catholicon, of the Kaisariani Monastery is considered to be one of the finest byzantine monuments of Attica. It is dating back to the end of the 11th– beginning of the 12th century and has been preserved from the Byzantine era. It is constructed according to the cross-in-square or crossed-dome architectural type and is dedicated to the Presentation of the Virgin [19, 20], probably firstly introduced in Constantinople in the 9th century during the reign of Vasileios A (867-886 AD) and spread quickly all over the Byzantine Empire. It is considered to be the most representative byzantine architectural type. The main feature of this rhythm is the formation of a cross inside and outside the nave, which is almost square, with one or five domes [21-23].

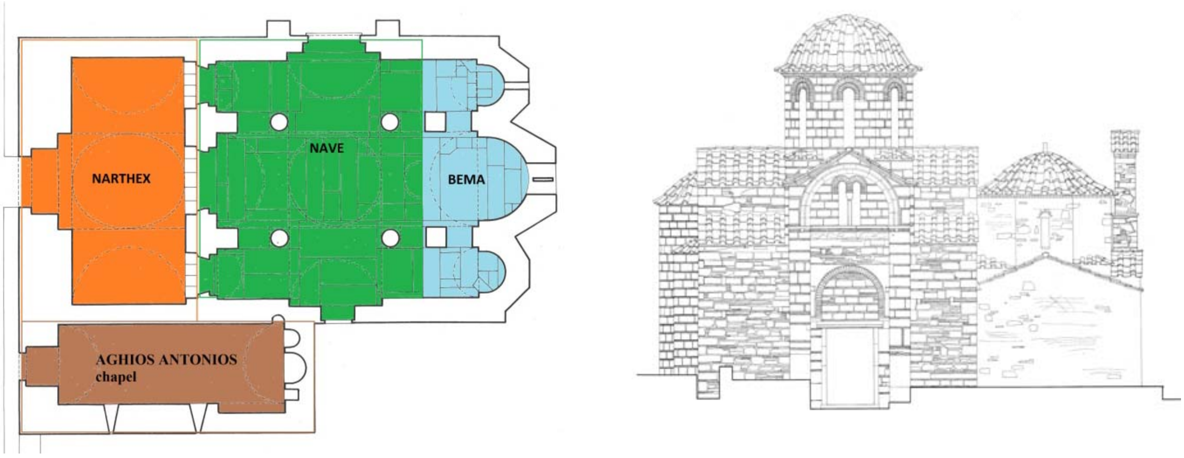
In a typical cross-in-square church the nave is divided into nine bays by four columns (or piers). The central bay is roofed by a central dome which is supported on the four columns. The inner five divisions form the shape of a cross. Barrel vaults usually cover the four rectangular bays that directly adjoin the central bay while groin-vaults usually cover the four remaining bays in the corners. The spatial hierarchy of the three types of bay, from the largest central bay to the smallest corner bays, is mirrored in the elevation of the building with the domed central bay being the taller [21-23].

The so-called “Athenian dome” is constructed in the Catholicon that may be found in many other Byzantine churches of Athens and Greece. This type of dome consists of eight sides with its corners decorated by small upright marble columns; a semi-circular eave forms at the top of each hexagon. As a rule, there is one simple window on each side of the octagon.

In the case of the Kaisariani Catholicon the octagonal dome has a straight horizontal dentil cornice on its roof, as an exception to the usual corrugated cornice of the "Athenian type" domes. Also the four central pillars that support the dome are made of marble while in this architectural rhythm it was also common the construction of brick piers [19, 23].

At the western wall of the nave usually a narthex is placed that is practically an entrance hall. A narthex and a single-room, vaulted chapel of Aghios Antonios were added to the western and southern side of Catholicon, respectively, in the 16th or 17th century as depicted in Figure 1. The narthex is consisted by three bays with the central one crowned by a lower dome [19].

To the eastern part of the nave stands the bema, or sanctuary, separated from nave by a templon made also by marble. Three additional bays form the sanctuary adjoining the easternmost bays of the nave, each of which terminates in an apse crowned by a conch (half-dome). The central apse is larger than those to the north and south. The plan view of the nave is nearly quadrangle with length and width approximately equal to 8.5 meters. The height up to the base of the dome is 7.4 m and the internal height of the dome is approximately 4.2 m.



(a) (b)

Figure 1: Catholicon of Kaisariani monastery in Athens: (a) Plan view; (b) North façade [24].

The masonry construction is mixed including rubble masonry and carved stones. The external walls of the Catholicon are constructed in the cloisonné system that is made by shelly limestone surrounded in many places by bricks.

The north side placed at the initial entrance of the monastery was sculpturally rendered carrying arches of well-hewn limestone, as shown in Figure 1b, while the south side presents parts of rubble masonry. The Catholicon is partly covered by frescoes dating back to the early 18th century while the oldest one is a mural of the Theotokos Praying of the 14th century located on a wall initially exterior and today incorporated into the Aghios Antonios chapel. Of particular interest are also the brick decorative frames of the arched openings.

In 1921, the Kaisariani Monastery was declared an archaeological monument and came under the jurisdiction of the State Archaeological Service [19].

2.2 Research Outline

As already mentioned the Catholicon of the Kaisariani Monastery was selected as a representative monument of the byzantine period to be studied in the context of the SEISMO Research Project.

A thorough methodology is currently in progress in order to assess the current condition of the monument and evaluate its vulnerability under seismic loading. The implementation of the proposed methodology includes: (a) documentation of the existing state through surveys and architectural studies; (b) recording of the pathology of the structure; (c) identification of the construction materials with non-destructive and laboratory testing; (d) assessment of the seismic hazard based on regional seismicity and soil conditions; (e) proposal for a monitoring scheme; (f) development of mathematical models in order to analytically assess its seismic response.

Given the importance and complexity of monuments and historic structures in terms of design, construction techniques and materials, advanced computational tools and methods are utilized to meet the needs of the proposed research. Several types of analysis, failure criteria and innovative applications, such as base isolation will be utilized to study the dynamic behavior. Moreover, the methodologies established for the study of the monument, will be assessed in terms of their reliability, accuracy and effectiveness by comparing analysis results with experimental data. In the following the dynamic behavior of the Catholicon is studied applying local analysis with macroelements [17, 18, 25, 26]. Macroelements are local parts of the structure that may deform almost independently from the whole bearing body. These parts may be determined with acceptable reliability based on a survey of the damaged structure [18, 27]. The macroelement approach is followed herein by a kinematic limit analysis with different collapse mechanisms and a non-linear static analysis with a “blocks and joints” finite element model that includes arches and pillars of the central nave [17, 18, 25, 26].

3 LOCAL ANALYSIS

The importance of studying the dynamic behavior of the Catholicon of Kaisariani Monastery is justified by the fact that it regards a monument of well known historic and aesthetic value. Furthermore, this significance is enforced by the fact that its structural type is typical for a series of byzantine monuments constructed according to the cross-in-square rhythm located in seismically active regions. Thus, the results may be applicable to other cases given that the basic assumptions made for the analysis conducted herein are met.

The inspection of the damages suffered by the churches after major earthquakes revealed that the seismic behavior of this kind of structures can be assessed by local analysis of several architectonic portions whose seismic response is actually independent from the church as a whole. Such portions referred to as macroelements, can be identified for example as the façade, the apse, the bell tower or the triumphal arch. The selection of the significant macroelements should take into account the architecture of the church, the knowledge of its constituent materials and construction details, the presence of any earthquake-resistant presidium and the visual inspection of existing cracks and damages.

The local analysis of each macroelement consists in the definition of its collapse mechanism and the relevant collapse multiplier by means of kinematic analysis and/or pushover analysis.

Through kinematic analysis the collapse multiplier α_0 may be calculated using the principle of virtual work given in the following form [8, 9]:

$$\alpha_o\left(\sum_{i=1}^{n} P_i \cdot \delta_{x,i} + \sum_{j=n+1}^{n+m} P_j \cdot \delta_{x,j}\right) - \sum_{i=1}^{n} P_i \cdot \delta_{y,i} + \sum_{h=1}^{o} F_h \cdot \delta_h = L_{fi} \tag{1}$$

where: n is the number of the weights applied to the different blocks of the kinematic system; m is the number of the weights non-directly applied to the blocks, which because of the seismic action transfer a horizontal force to the blocks; o is the number of the non-related to masses external forces applied to the blocks; P_i is the generic weight applied to the block (self-weight applied to the centroid or any other carried weight); P_j is the generic weight (non-directly applied to the blocks) which, because of the seismic action, transfers horizontal forces to the blocks; $\delta_{x,i}$ is the virtual horizontal displacement of the weight application point; $\delta_{y,i}$ is the virtual vertical displacement of the weight application point; F_h is the absolute value of generic external force applied to the blocks; δ_h is the virtual displacement of the force application point in its direction and L_{fi} is the work of internal forces. In eq (1) the x direction is the direction of the collapse of each mechanism that is normal to the direction of the axes of rotation in case of overturning.

Through pushover analysis the collapse multiplier α_0 is pursued as the maximum static multiplier instead of the minimum kinematic multiplier and it is calculated with the following formula:

$$a_0 = \frac{F_{\max}}{W} \tag{2}$$

where: F_{max} is the maximum lateral force that the structure can sustain; W is the total weight of the structure.

Once the collapse multiplier is calculated, according to the Italian Structural Standards [8, 9] the verification in terms of Ultimate Limit State can be applied with the following procedure. The spectral acceleration a_0^* that causes the collapse mechanism is given by:

$$\alpha_0^* = \frac{\alpha_o \cdot g}{e^* \cdot FC} \tag{3}$$

where: e^* is the participating mass ratio (it can be taken equal to 1) and FC is the confidence factor (taken equal to 1.35 for kinematic analysis).

The macroelement response fulfils the Ultimate Limit State when

$$a_0^* \geq Max\left(\alpha_{Rig}^*, \alpha_{Def}^*\right) \tag{4}$$

where: α_{Rig}^* and α_{Def}^* are the accelerations that the structure should sustain. Assuming that the structure is either rigid or deformable the α_{Rig}^* and α_{Def}^* are given by the following expressions:

$$\alpha_{Rig}^* = \frac{a_g \cdot S}{q} \qquad \alpha_{Def}^* = \frac{S_e(T_1) \cdot \Psi(Z) \cdot \gamma}{q} \tag{5}$$

where: $a_g = \gamma_I \cdot a_{gR}$ is the ground acceleration, S is the soil factor, q is the behavior factor, $S_e(T_1)$ is the elastic spectrum calculated for the first period of vibration of the structure T_1 in the considered direction, $\Psi(Z)$ is the first mode of vibration in the considered direction normalized in order to be equal to 1 at the top of the structure, Z is the height of the rotation axis with respect to the building foundations and γ is the correspondent modal participation coefficient.

The following Figures 3-5 show the macroelements for which a kinematic analysis was performed with the aid of [25]. The values of the collapse multipliers are given in Table 1. The specific weight of the masonry rigid bodies was taken equal to 18 kN/m^3.

The transversal behavior of the church was assessed through pushover analysis applied to the “block-joint” model [26] of the three arches and relevant pillars shown in Figure 6.

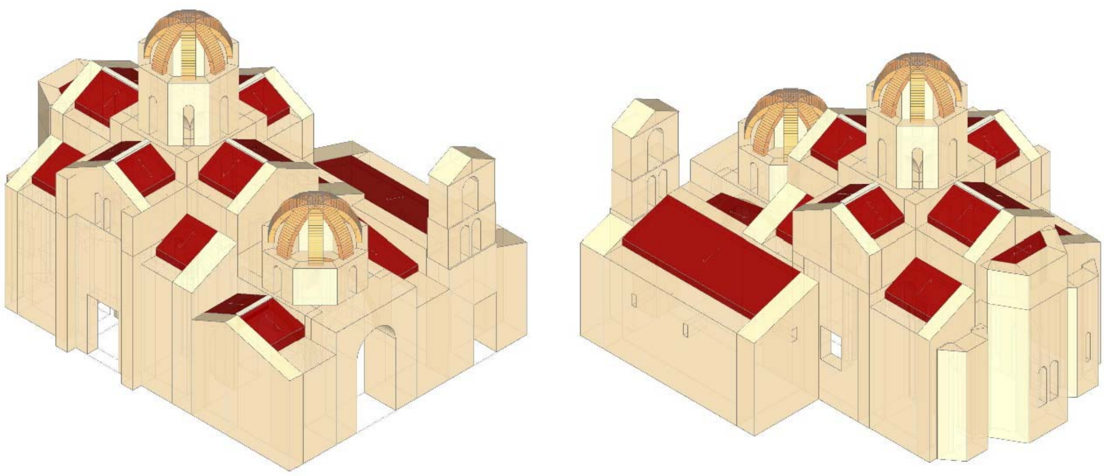
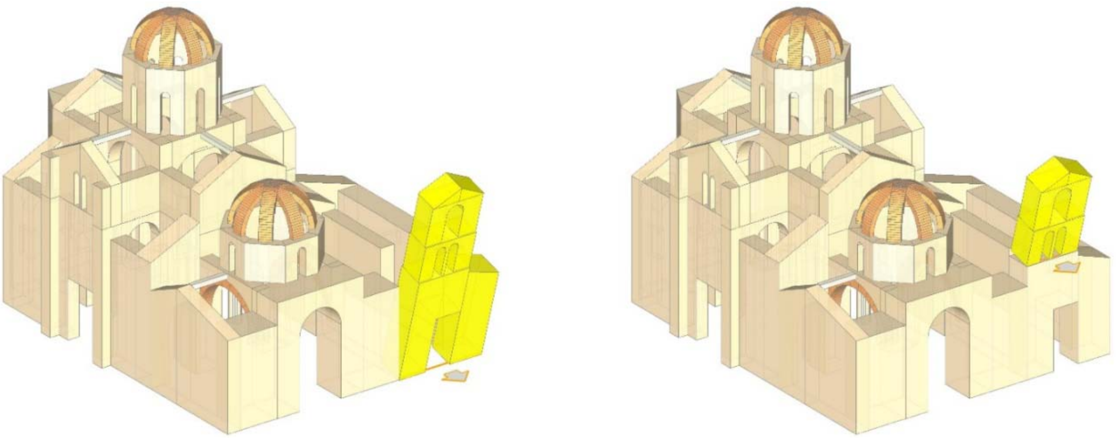
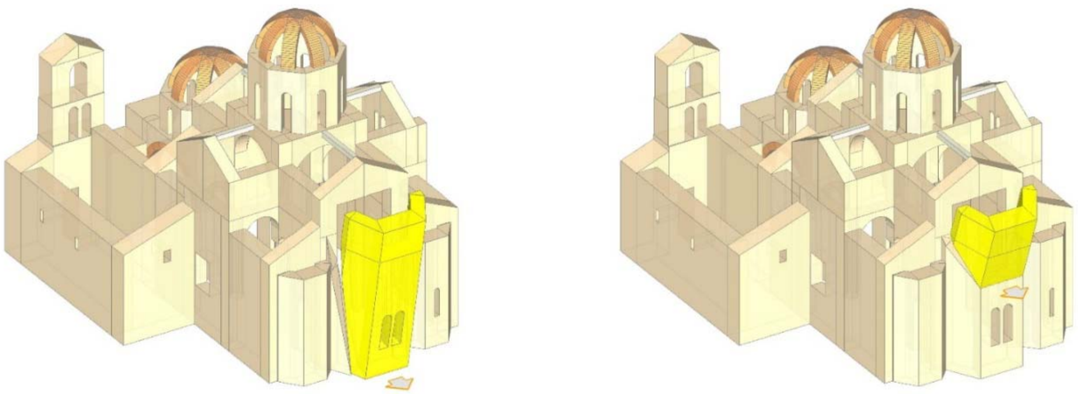


Figure 2: 3D model of the church.



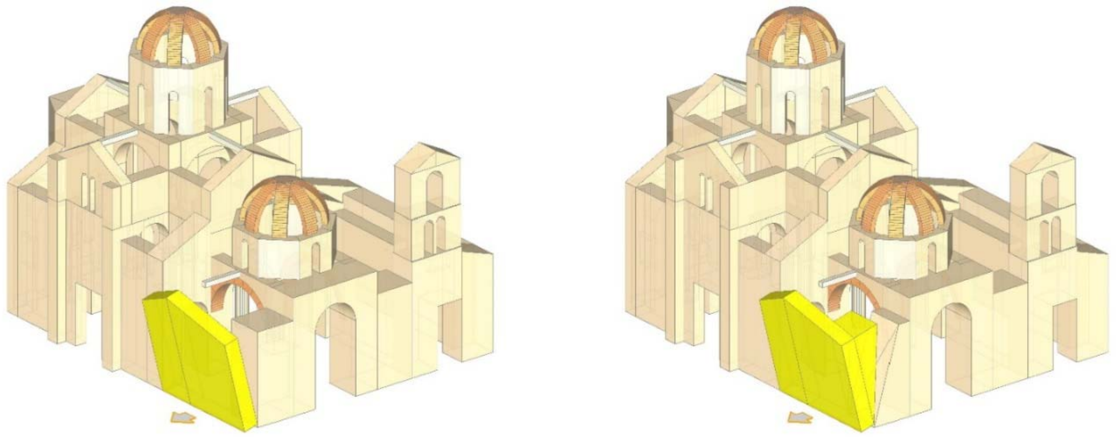
(a) (b)

Figure 3: a) M01 - Overturning of the belfry façade; b) M02 - Overturning of the belfry.



(a) (b)

Figure 4: a) M03 - Overturning of the central apse; b) M04 - Partial overturning of the central apse

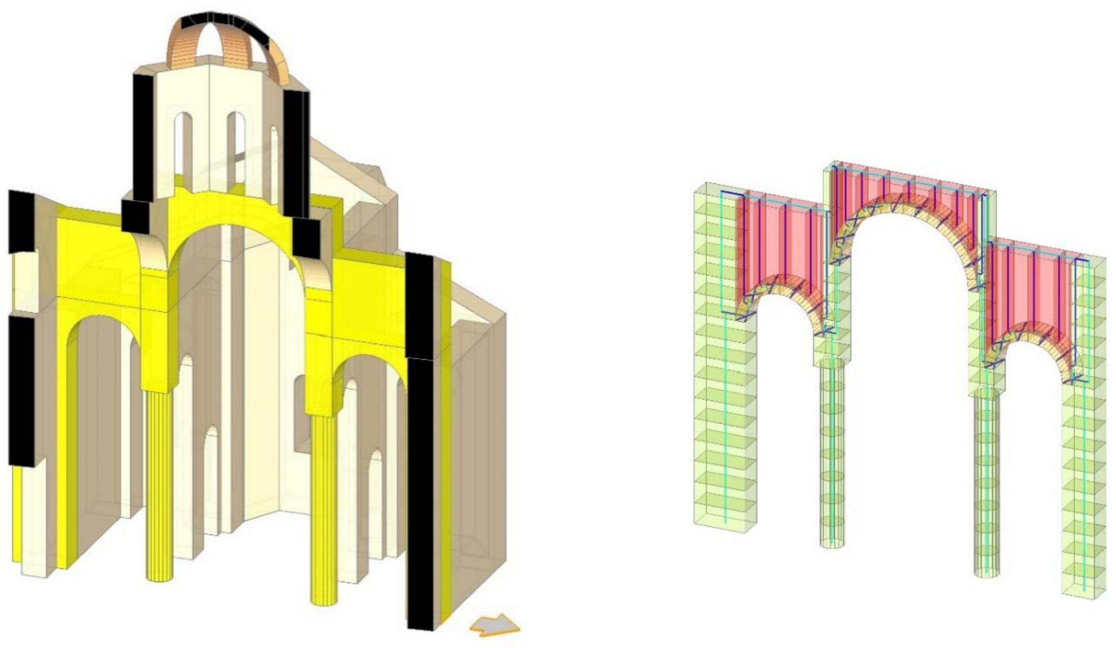


(a) (b)

Figure 5: a) M05 - Overturning of a north wall; b) M06 – Overturning of a north wall wide one side wing.

Macroelement	**Collapse multiplier**
M01 - Overturning of the belfry façade	0.128
M02 - Overturning of the belfry	0.234
M03 - Overturning of the central apse	0.111
M04 - Partial overturning of the central apse	0.307
M05 - Overturning of a north wall	0.120
M06 – Overturning of a north wall wide one side wing	0.173

Table 1: Collapse multiplier for the different mechanisms considered.



(a) (b)

Figure 6: a) Transversal behavior of the church; b) Block-joint model of the macroelement.

The mechanical properties of the constituent materials are shown in Table 2.

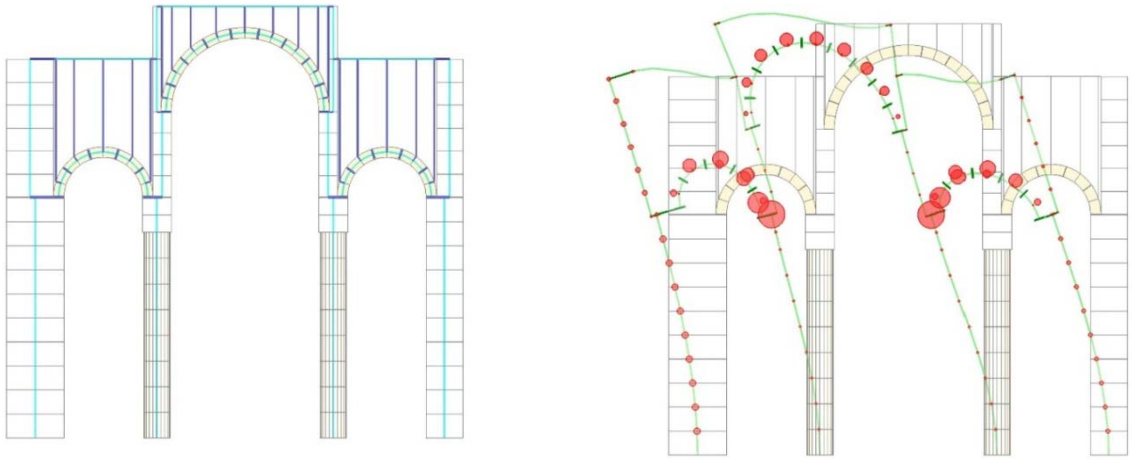
Masonry	Specific weight	18	kN/m^3
	Elastic modulus	1300	N/mm^2
	Shear modulus	500	N/mm^2
Blocks	Specific weight	20	kN/m^3
	Elastic modulus	1800	N/mm^2
	Shear modulus	720	N/mm^2
Joints	Elastic modulus	500	N/mm^2
	Shear modulus	200	N/mm^2
	Tensile strength	0.30	N/mm^2

Table 2: Mechanical properties of the materials.

The characteristics of the masonry constituting the walls and the pillars were based on the literature [28], while the mechanical properties of blocks and joints were chosen as the ones that led to a balance configuration at the beginning of the pushover analysis. A more accurate evaluation of the structural behaviour of this macroelement will be feasible when the actual values of the material properties will be available from the SEISMO Project.

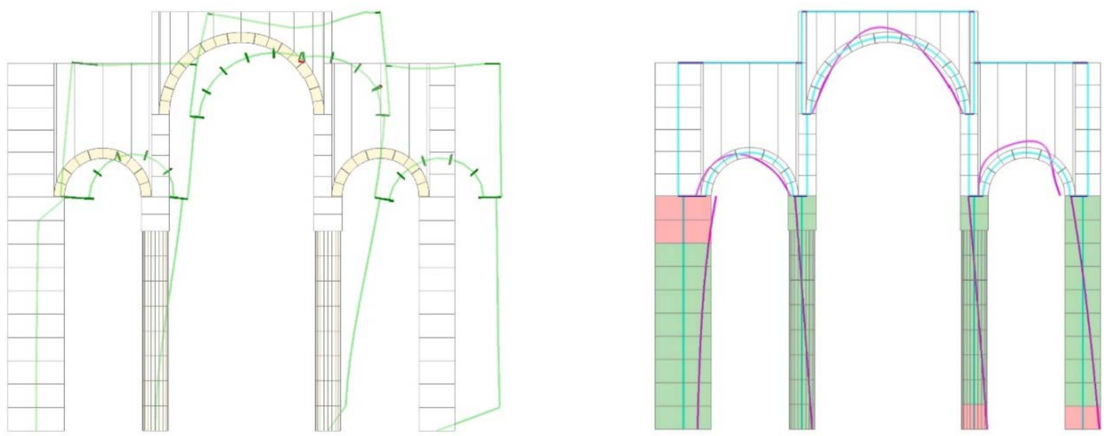
Figure 7 shows a front view of the block-joint model and the modal shape of the first mode of vibration. Moreover, the red spheres symbolize the mass applied at each node and highlight how the loads were distributed in the model.

The pushover analysis was performed in the direction shown in Figure 6, considering a lateral force distribution proportional to the nodal masses and a base shear increment equal to 1 kN. Figure 8a shows the displacements registered at the last step of the analysis when the base shear is equal to 32 kN, while Figure 8b shows the position of the thrust-line for arches and pillars as well as the state of the verification applied to the pillars. The red drums are the ones where the thrust-line has come out of the cross section and therefore feature a plastic hinge.



(a) (b)

Figure 7: a) Block-joint model. b) First mode modal shape.



(a) (b)

Figure 8: Pushover analysis, last step: a) displacements; b) Thrust-lines and verifications.

Blocks Elastic Modulus	Collapse multiplier
1200 N/mm^2	0.069
1500 N/mm^2	0.066
1800 N/mm^2	0.071
2100 N/mm^2	0.038

Table 3: Relation between blocks elastic modulus and collapse multiplier.

The value of the collapse multiplier was proved to be quite sensitive to the value of the modulus of elasticity of the arch blocks. Table 3 shows the relation between these two values.

4 CONCLUSIONS

This work presents preliminary analytical results of the central church (Catholicon) of the Kaisariani Monastery in Athens. The church is constructed during the 11th and 12th centuries according to the crossed-dome architectural rhythm and is considered to be one of the finest byzantine monuments of Greece. This monument was selected as a case-study of a historic structure located in an earthquake active region to be studied in the context of the ongoing research program entitled “Seismic Protection of Monuments and Historic Structures - SEISMO”.

The preliminary analysis includes the study of selected macroelements, i.e., parts of the structure that are susceptible to behave independently from the whole structure. Six different macroelements were considered to perform kinematic limit analyses: M01 - Overturning of the belfry façade; M02 - Overturning of the belfry; M03 - Overturning of the central apse; M04 - Partial overturning of the central apse; M05 - Overturning of a north wall; M06 – Overturning of a north wall wide one side wing. Also, pushover analysis was conducted to assess the transversal behavior of the church by means of a macroelement that isolates three arches and the supporting pillars of the central nave with the “block-joint” approach.

In summary the results show that the collapse mechanism that is more hazardous for the overall stability of the monument is the mechanism M03 that presents the smaller collapse multiplier and suggests out-of-plane overturning of the central apse. The second most likely to occur mechanism is the mechanism M05 that suggests overturning of a wall in the north facade of the outer narthex. The collapse multiplier for the block-joint model is even smaller and presents considerable sensitivity in the assumptions made regarding the material properties.

The assessment of the current condition of the monument is made by the application of detailed surveying, in-situ and laboratory testing which are currently in progress and will allow for a more thorough assessment of seismic behavior of the monument in the near future.

ACKNOWLEDGEMENTS

The financial support of the research project “Seismic Protection of Monuments and Historic Structures - SEISMO” which is co-financed by the Greek Ministry of Education and Religions and the European Union under the action “Thales” within the context of the Operational Programme - Education and Lifelong Learning, NSRF 2007-2013 is gratefully acknowledged. Also the assistance of the technical and administrative personnel of the Archaeological Service of Athens is acknowledged.

REFERENCES

[1] T.P. Tassios, Seismic Engineering of Monuments. M. Garevski, A. Ansal. Editors, *Earthquake engineering in Europe*, Springer Netherlands, 1-42, 2010.

[2] C.C. Spyrakos, Seismic Risk of Historic Structures and Monuments: A need for a unified policy. *In proceedings of COMPDYN 2015, 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering,* Crete, 2015.

[3] T.M. Tsapanos, P.W. Burton, Seismic hazard evaluation for specific seismic regions of the world. *Tectonophysics*, **194**, 153–169, 1991.

[4] UNESCO. Greece: Properties inscribed on the World Heritage List. (http://whc.unesco.org/en/statesparties/gr) retrieved 2015-03-15.

[5] A. Udías, Seismicity of the Mediterranean Basin. In: Geological Evolution of the Mediterranean Basin, Raimondo Selli Commemorative Volume, D. J. Stanley, F.-C. Wezel Editors, 55-63, 1985.

[6] *The Athens Charter for the Restoration of Historic Monuments*. First International Congress of Architects and Technicians of Historic Monuments, Athens, 1931.

[7] International Council on Monuments and Sites – ICOMOS. *International Charter for the Conservation and Restoration of Monuments and Sites* (The Venice Charter 1964). Second International Congress of Architects and Technicians of Historic Monuments, Venice, 1964.

[8] Ministero delle Infrastrutture e dei Trasporti, *Circolare. n. 617 del 02 febbraio 2009. Istruzioni per l'applicazione delle Nuove Norme Tecniche per le costruzioni, §C8A.4*, Gazzetta Ufficiale della Repubblica Italiana n. 47 del 26 febbraio 2009, Supplemento ordinario n.27. (in Italian)

[9] Decreto del Presidente del Consiglio dei Ministri (D.P.C.M.). Linee guida per la valutazione e la riduzione del rischio sismico del patrimonio culturale con riferimento alle Norme tecniche per le costruzioni di cui al D.M. 14/01/2008, 2011. (in Italian)

[10] Earthquake Planning Protection Organization (EPPO) and European Centre on Prevention and Forecasting of Earthquakes (ECPFE). Draft framework regulatory document for structural interventions to and seismic protection of monuments, 2011.

[11] Laboratory for Earthquake Engineering, Structural Engineering Department, School of Civil Engineering, National Technical University of Athens. (http://lee.civil.ntua.gr/index_en.html)

[12] D. Dizhur, J. Ingham, L. Moon, M. Griffith, A. Schultz, I. Senaldi, G. Magenes, J. Dickie, S. Lissel, J. Centeno, C. Ventura, J. Leite, P. Lourenco, Performance of masonry buildings and churches in the 22 February 2011 Christchurch earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, **44**(4), 279-296, 2011.

[13] GEER-EERI-ATC. (2014). Earthquake Reconnaissance January 26th/ February 2nd 2014 Cephalonia, Greece events. GEER Association Report No. GEER-034 in collaboration with EERI and ATC, Version 1: June 6, 2014.

[14] E. Mele, A. De Luca, A. Giordano, Modeling and analysis of a basilica under earthquake loading. *Journal of Cultural Heritage*, **4**, 355–367, 2003.

[15] I.N. Psycharis, H.P. Mouzakis, A. Miltiadou, E.P. Pavlopoulou, I.M. Taflampas, Investigation of the seismic response of a Byzantine church and evaluation of the effectiveness of proposed interventions. *Earthquake Spectra*, **26**(2), 473-497, 2010.

[16] C.C. Spyrakos, P.D. Kiriakopoulos, E. Smyrou, Seismic Strengthening of the Historic Church of Sts Helen and Constantine in Piraeus. In Proceedings of the 3rd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering COMPDYN 2011. Corfu, Greece; ECCOMAS, 2011.

[17] C.C. Spyrakos, A. Francioso, P.D. Kiriakopoulos, S. Papoutsellis, Seismic evaluation of the historic church of St. Nicholas in Piraeus before and after interventions. M. Papadrakakis, V. Papadopoulos, V. Plevris eds. *COMPDYN 2013, 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Kos Island, Greece, 12–14 (pp. 3015-3029), June 2013.

[18] C.C. Spyrakos, C.A. Maniatakis, P. Kiriakopoulos, A. Francioso, I.M. Taflampas, Performance of a post-Byzantine Triple-domed Basilica under Near and Far Fault Seismic Loads: Analysis and Intervention. In *Seismic Assessment and Rehabilitation of Historic Structures*, P.G. Asteris, V. Plevris Editors, 2015.

[19] A. Pantelidou-Alexiadou, *Kaisariani Monastery*, Archaeological Receipts Fund, Ministry of Tourism and Culture, 2011.

[20] N. Gkioles, *Byzantine Church Architecture* (600-1204 AD), Kardamitsa Editions, 1987. (in Greek)

[21] C. Mango, *Byzantine Architecture* (History of World Architecture), Electa / Rizzoli Publisher, 1985.

[22] R. Krautheimer, *Early Christian and Byzantine Architecture*, The Yale University Press, 1984.

[23] C. Bouras, *History of Architecture*, Melissa Editions, 1994. (in Greek)

[24] A. Barzoukas, *Monastère de Kaisariani, Le Catholicon*. Drawings from the Collection and Archive of Architectural Research, Institute of Architectural Morphology, National Technical University of Athens, 1957.

[25] Aedes Software. PCM: Progettazione di costruzioni in muratura, www.aedes.it

[26] F. Pugi, Seismic analysis of masonry arch structures through the finite element model "block-joint". M. Papadrakakis, V. Papadopoulos, V. Plevris eds. *COMPDYN 2013, 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Kos Island, Greece, 12–14 (pp. 2997-3014), June 2013.

[27] D. D'Ayala, E. Speranza, Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings. *Earthquake Spectra*, **19**(3), 479–509, 2003.

[28] K. Syrmakezis, O. Mavrouli, P. Papaevaggeliou, E. Aggelakopoulou, A. Bakolas, A. Moropoulou, Finite element analysis and fragility curves for the evaluation of restoration mortars behavior regarding the earthquake protection of historic structures. *Soil Dynamics and Earthquake Engineering*, **54**, 61-65, 2013.