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IR THERMOGRAPHY IN MOISTURE AND EARTHQUAKE DAMAGE DETECTION PERFORMED IN THE ŽIČA MONASTERY, SERBIA

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Abstract

This paper presents the results of the IR thermographic diagnostics of the seismic damage inflicted upon the Žiča Monastery after the earthquake on 3rd November 2010. The Žiča Monastery founded in 13th century is located in central Serbia. The moisture content in the structure was detected too. The obtained results document the current state of the buildings and, at the same time, confirm the advantages of IR thermography as a method in the diagnosis of earthquake cracks, useful for the seismic retrofit study. The obtained results enable the identification of the structure parts where more in-depth investigations need to be concentrated. The procedures and activities for curative conservation and protection of the Žiča Monastery should include the thermographic test results. The results and the conclusions obtained in this case study could be used as example for further extensive studies of historical and cultural heritage buildings.

Keywords: *thermography; cultural heritage; monastery; moisture; structural damage; earthquake*

Introduction

The Žiča Monastery complex is located between two towns, Kraljevo and Mataruška Banja, in Serbia. At the time when the monastery was built, it was equally distant from Constantinople and Rome. Žiča is an early 13th century Serbian Orthodox monastery. The monastery, with the main Church of Saint Savior (Ascension of Christ), was built by the first King of Serbia, Stefan the First-Crowned and the first Head of the Serbian Church, Sava Nemanjic (later Saint Sava).

The monastery was burned down in a raid at the end of the 13th century and subsequently deserted. Multiple renovations were carried out during the late 13th and early 14th century. Žiča underwent the most complete renovation works during the reign of King Milutin (1282-1321), as pointed out in web site [1].

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In 1979, Žiča became as a Cultural Monument of Exceptional Importance under the protection of Serbia. This monastery of great reputation is called "the seven-door Žiča" because seven Serbian kings were crowned in this place and a new door was opened for each coronation. The red façade of the monastery is a symbol of the kingdom. In 2008, the Žiča Monastery celebrated 800 years of its existence.

The earthquake occurred on 3rd November 2010 and damaged a number of buildings in the complex of Žiča Monastery. Cracks of different lengths appeared on the St. Savior and St. Sava churches in several areas with a long one appearing on the northern façade of the main church. The first tests have shown that the cracks do not endanger the stability of the structure; however, they constantly propagate. The project of restoration of the monastery complex is of a great importance to the Serbian heritage. A thermographic survey of the Žiča Monastery was conducted in December 2010 with the main aim to detect cracks and moisture in the walls.

There are many historical buildings in the seismically active region around Kraljevo. Most of these buildings have not been designed for seismic loads. Recent earthquakes have shown that many such buildings are seismically vulnerable and should be considered for retrofitting. Different conventional diagnostic and retrofitting techniques are available to increase the strength and/or ductility of unreinforced masonry walls [2-7].

It is known that a multidisciplinary approach to cultural heritage protection is based on all the necessary measures to protect objects and artifacts determined as natural and cultural values. The mentioned approach to these problems involves a variety of methods such as thermal techniques, processing techniques, materials science technology, laser technology, fluid mechanics, heritology, meteorology, ecology, archaeology, computer science, art history and many other disciplines [7-14].

This approach to protection is particularly important in accident situations such was the earthquake in Kraljevo, Serbia. During the earthquake, several heritage buildings were damaged. For the analysis of structures subjected to earthquakes, different test methods are used [2, 3]. The authors of paper [15] provide the evaluations of in situ and laboratory tests on materials for the existing masonry structures, and the difficulty of interpreting the results of NDE tests.

Besides for moisture mapping, infrared thermography was applied in preliminary tests for assessing the seismic safety level as well as the earthquake damage to the Žiča monastery buildings. Retrofitting is the process of bolting together and strengthening a building understructure so that it can resist earthquakes better. The retrofit study and the procedures for curative conservation and protection of the Žiča Monastery, as a historical and cultural heritage object, include the thermographic test results.

Being one of the most effective techniques for contactless testing and monitoring of complex buildings (e.g., hidden structures of walls [16-18]), thermography is one of the methods widely used in the preventive and curative conservation. It is a valuable tool in the diagnosis of the moisture content in buildings and concrete structures [18-22], in reviewing floor heating systems, in locating poor insulation and leakage of water or heating pipes, in estimating thermal performance of seals and gaskets, in detecting de-laminating on façades, for concrete bridges, etc. Thermography is used for detecting capillary water penetration in buildings and potential areas of moisture condensation from the atmosphere. Some examples of thermography investigation applied to the earthquake damage to the Žiča Monastery are presented in this paper.

Experimental method

Thermography can be defined as a technique by which the infrared radiation, characteristic for each object (having its temperature above absolute zero) can be recorded. Nowadays, very sophisticated equipment for thermography is used, supported by complex software for investigating the state of objects, based on their infra red radiation [20]. To perform the thermoraphic investigations in situ, some temperature and meteorological conditions must be fulfilled. All data related to the properties of the object surface (emissivity, transparency and reflectivity), the temperature of the surrounding objects, the camera distance to the observed object, the temperature and the relative humidity of the air must be set up previously as input parameters in the camera software.

Thermography can be carried out through passive or active heating of the surface under investigation. Active thermography uses external sources such as flash lights and lasers for heating the tested object uniformly. The thermal gradient established in this case on the surface of the test object can be recorded using thermographic devices. Cracks, inclusions, delamination, moisture presence or air inclusions inside the object are the elements causing the temperature gradient because they have different coefficients of heat transfer [23]. The requirement for correct visualization of the structure using thermography strictly depends on the uniform test object heating. There are several ways to generate temperature into test objects. According to this criterion, thermography can be divided into pulse, step-heating, lock-in thermography, vibrothermography, etc.

Passive IR thermography is based on the natural temperature distribution over the surface of the object and spontaneous IR radiation. It can be used to perform structural investigations from one side of building elements up to a certain depth. In most studies, passive thermography has been associated with the determination of qualitative anomalies in structures. Therefore, thermography is, in general, suitable for the detection of plaster and tile delamination, for the investigation of cracks, for the location of detached parts behind the plaster [22], for the characterization of the masonry structure behind plaster, for the location of empty joints, and for the detection of active moisture [12, 13, 24-26].

The historic monastery of Žiča has a very inhomogeneous structure, containing several different materials (brick, stone, mortar, plaster, wood, metal, etc.) with different thermal properties. Thermograms were recorded by the infra red camera Therma CAM T-335, FLIR Systems [21]. Recordings were performed in the following temperature conditions,

- Outside temperature, 10°C
- Inside temperature of 14°C (the church of St. Savior, with the floor heating system on)
- Inside temperature, 6°C (the church of St. Sava, and the tower of St. Savior without heating)
-Weather conditions, sunny, no wind.

Results and discussion

The thermograms and digital photos of some parts of the monastic buildings are presented together. Figure 1 shows an architectural drawing of the Žiča Monastery, Church of the Saint Savior, illustrated by photos and thermograms.

The monastery church was built in the Raška architectural style. The layout of the church is a free cross shape. The church base length is 44 m, being among the largest ones in medieval Serbia. On the west side, a spacious narthex with cross-ribbed vaults was built. There is a high tower at the church entrance. The façade is painted in red, as in the Athos monasteries.

The video photos (Fig. 2a and 2b) and a thermogram of the monastery complex entrance, the ceiling of which was full of cracks and places with moisture (dark parts in Fig. 2c) illustrated the state of the monastery buildings. One major flaw is in the middle of the ceiling (Fig. 2c) and it presents the retaining moisture. Some parts of the frescoes appeared on the thermogram as areas with different temperatures and indicated the presence of moisture.

The nave of the church is divided into three bays separated by pilasters. At the intersection of the eastern bay of the transept, the dome was built on pedantries in the form of an irregular circle. The dome is octagonal on the outside. The monastery was originally painted in red, according to the tradition of the Mount Athos monasteries. There are few frescoes dating back to the 13th century. Today most of the existing ones are from the early 14th century.

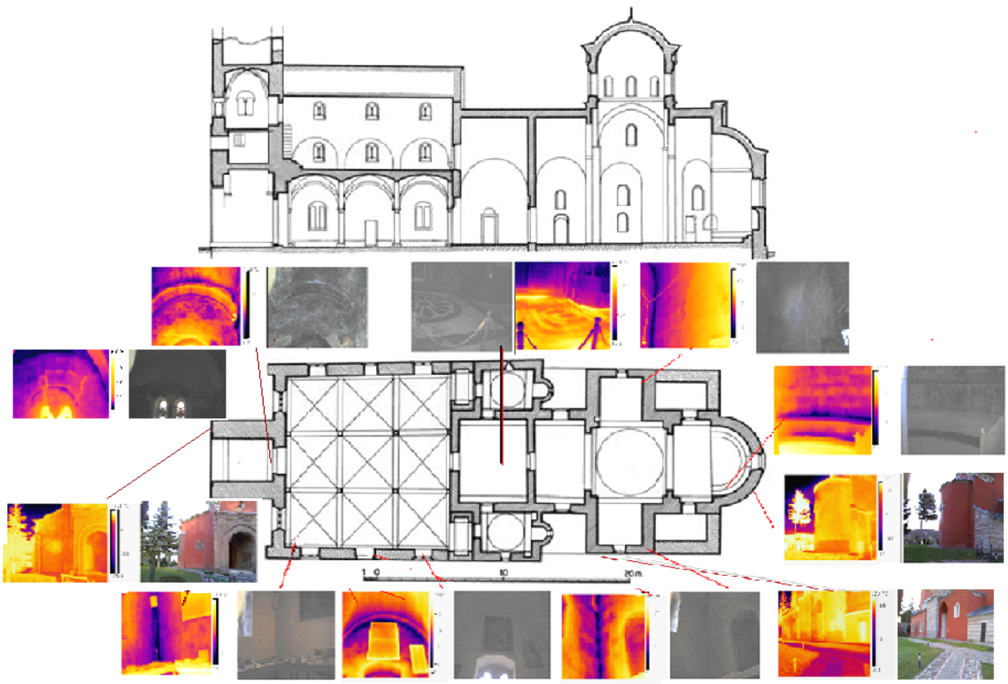

Fig. 1. Architectural drawing of the Žiča Monastery, the Church of St. Savior, illustrated by photos and thermograms

The badly damaged wall paintings allow distinguishing three chronological and stylistic periods. The most important frescoes from 1309 and 1316 are located in the main part of the church. After the fire damage at the end of 13th century, a great part of the original fresco layer was lost. During the 14th century, new fresco layers were added. The most significant frescoes from this period are those representing Apostle Peter and Apostle Paul. A part of the wall paintings on the right inside wall of the Church St. Savior can be seen in figure 3a. The presence of moisture is detected by thermogarphy in this area (Fig. 3e).

Figures 3b and 3f show the damage of moisture in the corner and in the walls while figures 3c and 3g show the floor heating system. On the ground was a beautiful domed baptistery, reconstructed from some of the original fragments.

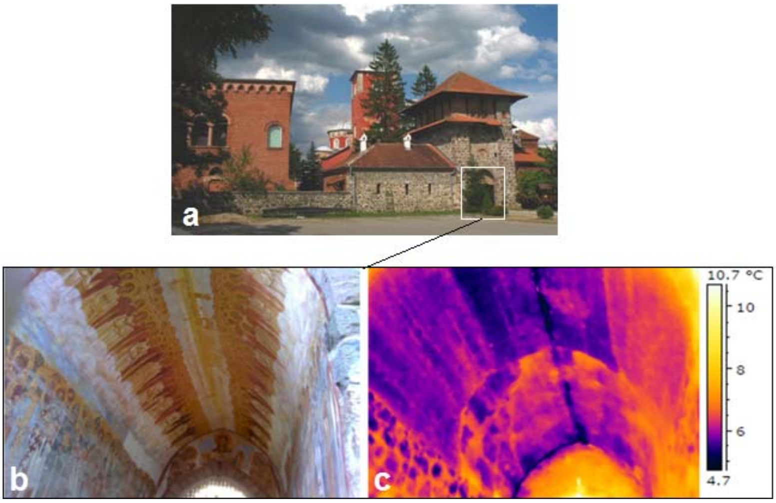

Fig. 2. Digital photos (a and b) and c thermogram of the monastery complex entrance

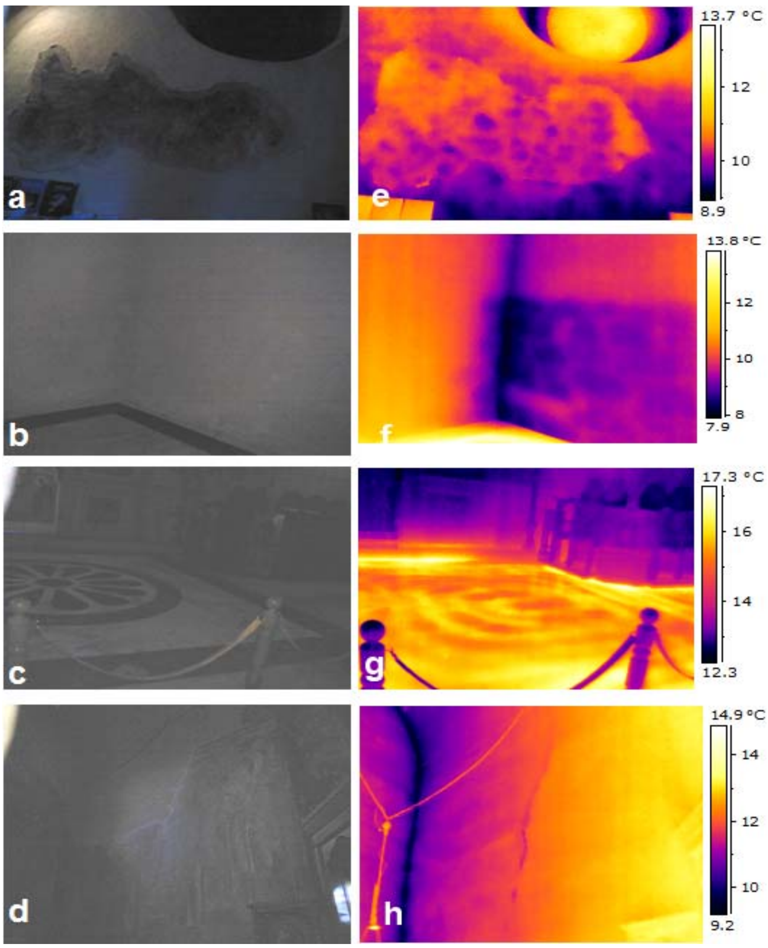

Fig. 3. Digital photos and thermograms of the interior areas of the Church of St. Savior

The cracks of the west church wall (Fig. 3d) can be seen on the thermogram (Fig. 3h) as colder zones. The cracks propagate through the total thickness of the wall, letting colder air enter inside and cool the church wall in the vicinity of the cracks.

The catechumen is a room on the first flour and some parts of this space are preserved. From there, the stairs lead to the chapel tower where the residence of St. Sava in Žiča is thought to have been.

The temperature inside the tower was lower than the outdoor temperature for 4°C. The cracks are visible as light lines on the thermograms (Figs. 4c and 4d). Due to the fact that the plaster is detached in some areas, the plaster peeling layer was at a lower temperature when compared to the compact part of the wall (Fig. 4d). The moisture is present at the top of the wall and in the tower dome and it is registered as a darker area in comparison with the rest of the wall (Fig. 4c). The cracks are partially visible through visual inspection (Figs. 4a and 4b). Thermography has enabled a more precise definition of the position, length and width of cracks (Figs. 4c and 4d) [14].

The presence of moisture in building materials causes much damage. Visual examination is a reliable means of moisture detection in building walls after serious damage. Traditional spot measurement instruments are inexpedient devices for elusive moisture detection in heterogeneous materials.

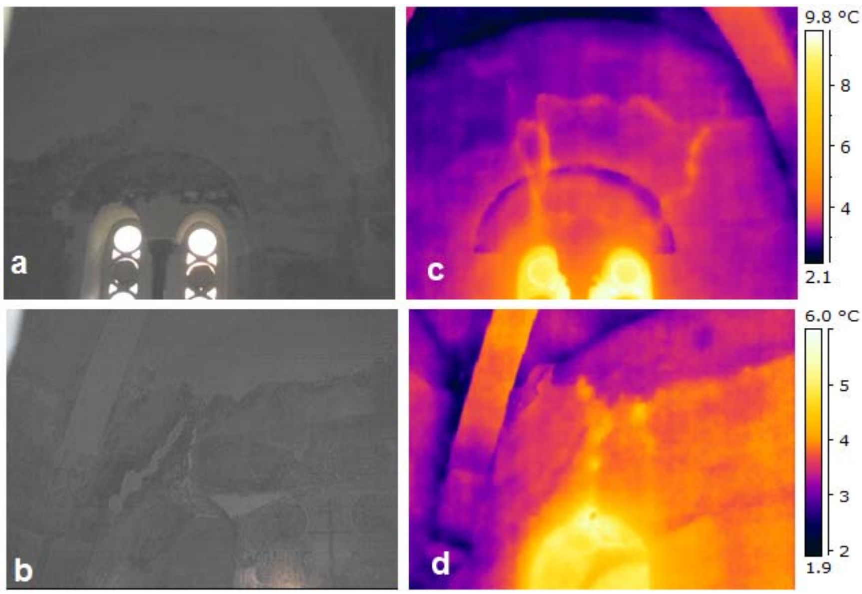

Fig. 4. Digital photos and thermograms of the tower interior

NDT methods are successfully applied to map moisture distribution, to localize the source of water and to determine micro climatic conditions. The infra red thermography was found to be a more useful tool for on-site moisture detection because of its unique characteristics. IR thermography allows the investigation of large surfaces at once and has many advantages over other non-destructive testing techniques.

As mentioned before, the main aim of the investigation was to gather more information about cracks and other earthquake damage. The other aim was to make the moisture mapping of the Žiča Monastery buildings. In the open literature, there are a lot of examples of IR thermography application for moisture detection as an important part of cultural heritage preservation [22] which can help achieve a seismic retrofit strategy consistent with the conservation principles in attempting to meet the challenge of preserving and protecting historic buildings [4].

Figures 5a to 5f show some results of the church façade moisture investigation. In general, the temperature of the damp areas can be colder than the dry ones due to surface evaporation, or it can be warmer because of the higher thermal inertia of water content versus building materials. The apparent discrepancies between the two results are a consequence of different micro climatic conditions of the scanning.

The south façade of the Church of St. Savior has a visible cold zone in the lower part due to the presence of rising damp. There is no moisture in the part of the building where the red plaster is missing because of drainage (Figs. 5a and 5d). The round eastern end of the church (where the altar is) is presented by a digital photo and a thermogram (Figs. 5b and 5e). Moisture is detected up to the height of 1.5m. The north side of the monastery façade (Fig. 5c) has moisture content up to the height of 2m. The thermogram (Fig. 5f) shows the complex structure of the wall as well.

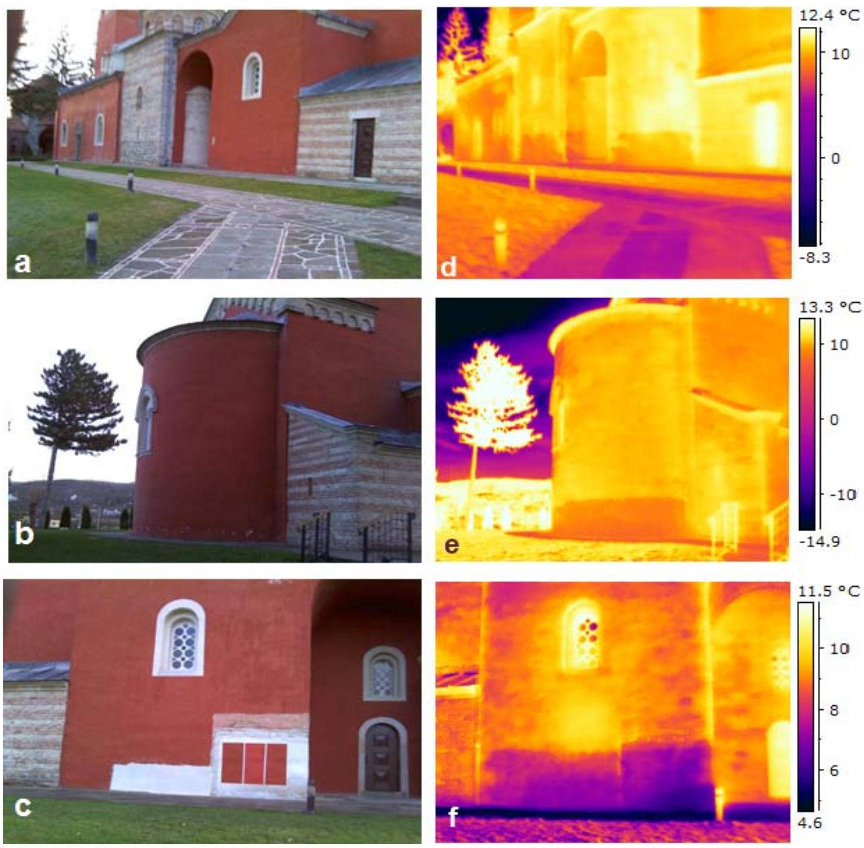

Fig. 5. Façade of the Church of St. Savior

Conclusions

Application of new techniques in the preservation of cultural heritage is an internationally accepted modern standard. The thermographic tests of the Žiča Monastery buildings in Kraljevo have shown the benefits of thermography as a non-contact, non-destructive method in the diagnosis of the damage caused by earthquake.

The results have confirmed the presence of cracks, penetration of moisture through the cracks, roof damage and rising moisture. It should be pointed out that the tests using active thermography were recommended to provide for a detailed analysis and detection of damage invisible to the naked eye. The implemented activities under this project belong to the preventive and curative conservation procedures of buildings concerning the protection of artefacts of national cultural heritage.

The results of this research clearly demonstrate that IC thermography can support effective analysis, intervention or restoration actions thus achieving a deeper level of knowledge about the materials, structures and special features of monastery walls. The research has confirmed the advantages of thermography as a method in the diagnosis of earthquake cracks for the seismic retrofit study.

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References

[1] * * *, **Zica Monastery** (Serbia), http,//orthodoxwiki.org/Zica_Monastery#Architecture .

[2] P.B. Lourenço, A. Trujillo, N. Mendes, L.F. Ramos, *Seismic performance of the St. George of the Latins church, Lessons learned from studying masonry ruins,* **Engineering Structures, 40**, 2012, pp. 501–518.

[3] E. Leroy Tolles, E.E. Kimbro, W.S. Ginell, *Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures*, **GCI Scientific Program Reports,** The Getty Conservation Institute, 2002.
http,//www.getty.edu/conservation/publications_resources/ pdf_publications/seismic_retrofitting.pdf.

[4] M.P Luong, *Introducing infrared thermography in soil dynamics*, **Infrared Physics & Technology**, **49(**3), 2007, pp. 306-311.

[5] E. Curti, S. Podestà, S. Resemini, *The Post-Earthquake Reconstruction Process of Monumental Masonry Buildings, Suggestions from the Molise Event (Italy)*, ***International Journal of Architectural Heritage,* 28**, 2008, pp. 120-154.

[6] V. Bosiljkov, Maierhofer C, Koepp C, Wöstmann J., *Assessment of Structure Through Non-Destructive Tests (NDT) and Minor Destructive Tests (MDT) Investigation, Case Study of The Church at Carthusian Monastery at Žiče (Slovenia)*, **International Journal of Architectural Heritage**, **4**(1), 2009, pp.1-15.

[7] V. Bosiljkov, M. Uranjek, R. Žarnić, V. Bokan-Bosiljkov, *An integrated diagnostic approach for the assessment of historic masonry structures*, **Journal of Cultural Heritage**, **11**, 2010, pp. 239–249.

[8] M. Nady, A. Saïd, *Measurement Methods of Moisture in Building Envelopes – A Literature Review*, ***International Journal of Architectural Heritage***, **1**(3), 2007, pp. 293-310.

[9] T. Poli, L. Toniolo, M. Valentini, G. Bizzaro, R. Melzi, F. Tedoldi, G. Cannazza, *A portable NMR device for the evaluation of water presence in building materials*, **Journal of Cultural Heritage**, **8**, 2007, pp. 134-140.

[10] Ambrosin D, Daffara C, Di Biase R, Paoletti D, Pezzati L, Bellucci R, Bettini F., *Integrated reflectography and thermography for wooden paintings diagnostics*, **Journal of Cultural Heritage**, **11**, 2010, pp. 196–204.

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

[12] S. Ristić, S, Polić-Radovanović, M. Popović-Živanćević, B. Jegdić, *Some examples of thermography application in detecting earthquake damages in buildings of cultural heritage protection*, ***Building Materials and Structures***; **54(**3), 2011, pp. 83-96.

[13] S. Ristić, S. Polić-Radovanović, M. Popović-Živanćević, B. Jegdić, B. Radojković, *Application of thermography in detection of moisture in aeronautical museum depot,* **Proceedings of the *International Conference OTEH 2011*,** 6-7 October 2011, Belgrade, Serbia, M(33), ISBN 978-86-81123-50-8, COBISS.SR-ID 186492428, 2011.

[14] S. Imposa, I*nfrared thermography and Georadar techniques applied to the "Sala delle Nicchie" (Niches Hall) of Palazzo Pitti, Florence (Italy)*, **Journal of Cultural Heritage**, **11**, 2010, pp. 259-264.

[15] U.L. Binda, A. Saisi, C. Tirabosch, *Investigation procedures for the diagnosis of historic masonries*, **Construction and Building Materials**, **1**, 2000, pp. 4199-4233.

[16] ***, **AB, Agema Infrared Systems, User Manual for Installation and Operation of Thermovision®900**, Stockholm; Elec. series, Editor: F.E. Terman., New York, McGraw-Hill Book Company, 1993,. www.x20.org/category/ catalog/used/agema-infrared-systems.

[17] ***, **Thermography**, ***Level I, Course Manual***, Infrared Training Publ., Stockholm (1 560 093)

[18] C. Kittel, H. Kroemer, **Thermal Physics**, First edition, W.H. Freeman and Co., New York, 1980.

[19] N.P. Avdelidis, A. Moropoulou, *Applications of infrared thermography for the investigation of historic structures*, **Journal of Cultural Heritage, 5**, 2004, pp. 119-127.

[20] S. Švaić, I. Boras, M. Drought, *The application of thermography in the building construction*, **Proceedings Matest 2004** (Editor D. Markučić,), Croatian Society for Non-Destructive Testing, Zagreb, 2004, pp. 63-71.

[21] * * *, FLIR, prospectus, www.flir.com/us/.

[22] J.L. Lerma , M. Cabrelles, C. Portalés, *Multitemporal thermal analysis to detect moisture on a building façade*, **Construction and Building Materials**, **25**, 2011, pp. 2190-2197.

[23] P. Litos., M. Honner, J. Kunes, *Thermography Applications in Technology Research*, **InfraMation** 2004, Proceedings ITC 104 A 2004-07-27, 2004.

[24] C. Maierhofer, M. Roellig, *Active thermography for the characterization of surfaces and interfaces of historic masonry structures*, **NDTCE'09, Non-Destructive Testing in Civil Engineering,** Nantes, France, June 30th – July 3rd, 2009.

[25] E. Grinzato, P.G. Bison, S. Marinetti *Monitoring of ancient buildings by the thermal method*, **Journal of Cultural Heritage, 3**, 2002, pp.1-29.

[26] F. Bastianini, M Corradi, A Borri, A. di Tommaso, *Retrofit and monitoring of an historical building using ''Smart'' CFRP with embedded fibre optic Brillouin sensors*, **Construction and Building Materials**, **19**, 2005, pp. 525-535.

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