RESULTS OF THE INFRARED THERMOGRAPHY AND LASER DOPPLER VIBROMETRY APPLICATION IN THE DIAGNOSTIC OF STRUCTURAL PATHOLOGIES IN MONASTERIES OF ROMANIA

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Abstract. *The acknowledgement of the scientific research importance and its applications in the determination of the works of art conservation state has had a great increase with passing of the years, allowing that, in the current days, diverse diagnostics methodologies be available. Amongst the techniques used in the diagnostic of pathologies in work of arts are the infrared thermography and the laser Doppler vibrometry. This work presents the results obtained from the application of the infrared thermography and of the laser Doppler vibrometry over some walls of three medieval monasteries of Moldavia, region placed in the northeast of Romania. The tests allowed identifying the presence of humidity, non-visible structures, non-apparent inclusions and materials of diverse origins, as well as some detachments of the frescoes layers. It was also possible to characterize the masonry that constitutes the Church of San Nicholas in Bălineşti, the Church of the Popăuți Monastery in Botoşani and the Church of the Resurrection located in the intern of the Sucevița Monastery walls. The tests have been carried out during the workshop "Saving Relics of European Medieval Cultural Heritage".*

Keywords: *Infrared thermography, laser Doppler vibrometry, structural diagnostic, medieval monasteries of Moldavia*

1. INTRODUCTION

During the last years, the growing importance of the correct determination of the state of conservation of artworks has been stated by all personalities in care of Cultural Heritage. There exist many analytical methodologies and techniques to individuate the physical and chemical characteristics of artworks, but at present, their structural diagnostics mainly rely on the expertise of the restore.

Amongst the techniques used in the diagnostic of pathologies in work of arts, the infrared thermography and the laser Doppler vibrometry have been implemented, with success, in diverse situations. The biggest advantage of these techniques is exactly its non-subjective character, what does not place them subjugated to the restorer knowledge. By other side, the capacity to identify diverse structural pathologies, in non-invasive e non-destructive way, put the both the methodologies as a valuable tool of analysis.

This work regards structural and frescoes investigation by the integration of Scanning Laser Doppler Vibrometry (SLDV) and InfraRed Thermography (IRT). The tests have been carried out in three medieval monasteries placed in the northeast of Romania. The objective was to identify presence of humidity, non-visible structures, non-apparent inclusions, and materials of diverse origins. Another objective was the identification of detachments of the frescoes layers and the characterization of the masonry that constitutes the Church of San Nicholas in Bălineşti, the Church of the Popăuți Monastery in Botoşani and the Church of the Resurrection, located inside of the Sucevița Monastery walls.

The Romanian Ministry of Culture has done the choice of the tests places. The tests have been carried out in July of 2006 during the workshop "Saving Relics of European Medieval Cultural Heritage", event organized by the INOE – National Institute of Research and Development for Optoelectronics (Bucharest, Romania) with financial support of the European community.

2. IN SITU EXPERIMENTAL TESTS

Next, it will be done a brief description of the three monasteries where the tests have been carried out, as well as of its state of preservation and of the apparatus used in the diagnosis. The methodologies used in the implementation of the IRT and the SLDV come then described.

The localization inside of each one of the monasteries in which each technique has been implemented and the final objective of the tests have been determined by the staff of the INOE and by the Professor Tereza Sinigalia, PhD., local historian and project leader, in agreement with the necessities of the restorers.

For solicitation of the restorers, the thermographic analysis assumed a qualitative target. It was used in the evaluation of the humidity and in the identification of inclusions and non-visible structures, presents in the masonry that constitutes the monuments. The SLDV was used in the identification of detachments in the frescoes.

2.1. Church of San Nicholas – Bălineşti

Historical researches indicate that the San Nicholas Church began to be used to religious celebrations in the end of the century XVI or in the beginning of the century XVII (Sinigalia and Vetros, 2006). Throughout the time, the church did not pass by substantial modifications in its structure; however, it suffered serious processes of degradation of its frescoes: the outer frescoes, typical of the region, have been totally destroyed; the internal have been strongly damaged.

The IRT has been used, in its passive form (Tavares *et al.* 2006), for the evaluation of the conservation state of the external masonry of the entrance portal. It allowed identifying humidity and detachments of the finishing used during previous works of restore. The entrance portal and details of its decoration can be seen in Fig. 1.

Figure 1. San Nicholas Church (Bălineşti) – entrance portal and details of the external decoration

The IRT has been also carried out in the remaining frescoes, located in the south sector of the church. Figure 2 presents these frescoes. The area delineated in the plant of the construction indicates its localization.

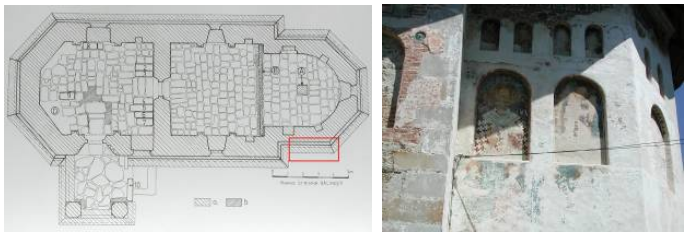

Figure 2. San Nicholas Church (Bălineşti) – outer frescoes evaluated by IRT

The diagnosis of the internal frescoes, using SLDV, has been concentrated in the entrance atrium. One of the evaluated areas is shown in Fig. 3 that also presents one of the studied frescoes.

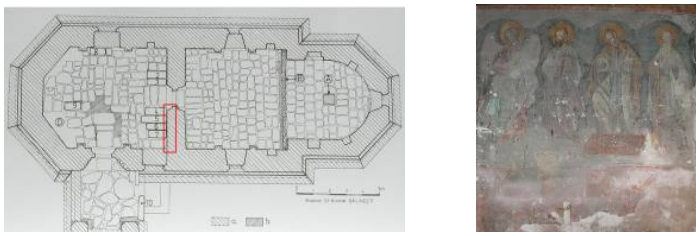

Figure 3. San Nicholas Church (Bălineşti) – fresco evaluated by SLDV

2.2. Church of the Popăuți Monastery – Botoşani

Founded in 1496, the San Nicholas Church (original name of the Church of the Popăuți Monastery) was used during the first years for the religious ceremonies of the local princely court. The church, an example of the Moldavian architecture, has wonderful internal frescoes portraying saints and facts of the Jesus life. Although originally it had been also frescoes in its external façade, these have been completely removed during a reform carried out between the years of 1906 and 1908; just some ceramics disks with heraldic sketches has been kept (Sinigalia and Vetros, 2006).

The presence of humidity damaged strongly the inner frescoes. To solve this problem, an effective restoration process was initiated in 2002. Part of the paintings located in the altar and in the aisle has been already restored. The vibrometric and thermographic tests have been concentrated in the internal area of the entrance atrium, not yet restored.

The SLDV has investigated detachments of the frescoes (some of them already visually perceptible). The IRT was used for the qualitative evaluation of structures and of non-visible structural elements. Figure 4 presents two frescoes evaluated by SLDV and two of the structures investigated by the implementation of the passive thermography.

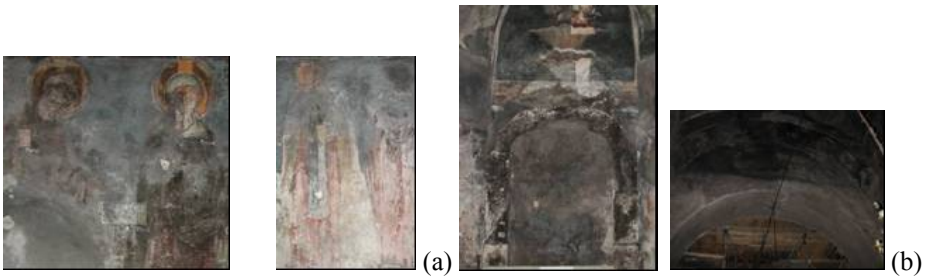
(a) (b)

Figure 4. Church of Popăuți Monastary (Botoşani) – frescoes evaluated by SLDV (a) and structures investigated by IRT (b)

2.3. Church of the Resurrection – Sucevița Monastery

The Church of Resurrection is one of the more beautiful and known Romanian monuments. Founded in 1584, by initiative of Gheorghe Movilă, then bishop of Rădăuți (Sinigalia and Vetros, 2006), it presents internal and external frescoes of very alive colors, that confer a particular aspect to the place. In comparison to the others churches of the region, the frescoes are much more preserved.

In 1989, an intense process of restoration of the outer frescoes has been initiated. It was concluded in 1998. In 1999, another project for the recovery of the indoor frescos of the altar, of main tower and of the aisle has been initiated. The next stage of restore will recuperate the panels contained in the mortuary chamber (Sinigalia e Vetros, 2006).

To collaborate on this last phase of the works, the SLDV has been implemented on the frescoes placed in the mortuary chamber. To evaluate the current state of the outer frescoes, the SLDV has been also applied on some paintings located in the north wall of the church. The same frescoes of the north wall have been evaluated by the IRT. The thermography was also applied in the south wall; it was able to identify, with success, non-visible pathologies.

Figure 5 shows the frescoes evaluated by the SLDV and presents a general vision of the north and south walls, where are delineated the sectors in which the more relevant results obtained by the implementation of the passive thermography have been registered.

2.4. Methodology to IRT and SLDV implementation

The standard procedure to the implementation of vibrometric tests by SLDV systems is described in Esposito (2002). The methodology suggests initiating the tests using the system of acquisition in RMS (Root Mean Square), which evidences, by peaks in the specter of vibration speed, areas with presence of potential defects in the structure. When used a system of acquisition in RMS (Root Mean Square), the structure is excited using a mix of frequencies and for each point of a defined mesh is measured a value of signal using an analogical/digital system. The main advantage of this system is the high speed of measurement that arrives to 50 points/second (Esposito, 2002). It supplies a first notion of the irregularities presence: the defects are presented in the RMS map as points with higher speed of vibration.

In some cases, where it is desired to obtain amplitude and phase maps of the vibrometric signal, analysis in FFT (Fast Fourier Transform) is carried out over the points of the mesh located on supposedly damaged areas. With this, the vibration resonance of the defects is identified. Then, the lock-in method is applied, where the values of the frequencies of excitement are the ones obtained during the analysis in FFT to the damage areas. This procedure offers detailed answer with low noise, leading to better identification of the imperfections (Tavares, 2006).

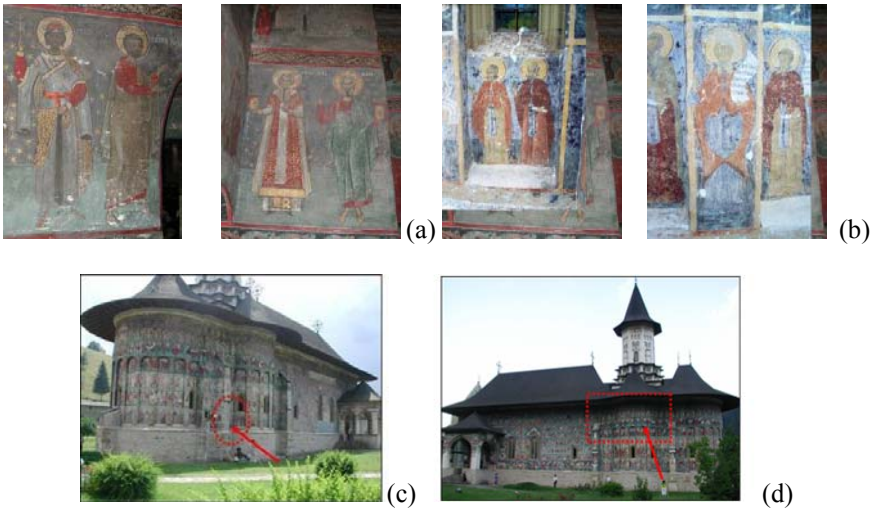

Figure 5. Church of Resurrection (Sucevița Monastery) – indoor frescoes evaluated by SLDV (a), outer frescoes evaluated by SLDV (b), area of the north wall evaluated by IRT (c), area of the south wall evaluated by IRT (d)

However, due to the available time to the implementation of the tests and the good results obtained in a first study, in this work the analysis has been done just in RMS. A horn loudspeaker has been used as the source of the exciting signal.

The OMETRON® VPI 4000 vibrometer used in this study presents configuration based on the Michelson interferometer and, as well as all systems SLDV, is monitored by a specific hardware that presents as result, for analysis in RMS, maps of vibration speed. It can be said that the different way to vibrate of an area with presence of imperfections allows the identification of the defects by SLDV.

The OMETRON® VPI 4000 vibrometer allows data acquisition to a maximum speed of vibration of 10 m/s, with a also maximum frequency of 100 kHz, displacement resolution of, approximately, 10 nm and speed of 1 μm/s. The uncertainty of measurement is ±1 a 2% of the RMS. The used laser is of Helium-Neon, with power of the mW order. Although the low power of the laser, it is possible to carry out measurements to distances superior to 10 m, with space resolution of the millimeters order (Esposito, 2002; VPI 4000 Scanning Laser Vibrometer Operator's Manual, 1997).

The methodology suggested in Tavares (2006) has been followed during the thermographic tests. In all cases, the passive thermography has been used. In passive thermography, natural contour conditions are used in the analysis, a time that no thermal stimulation is used. In this case, it must exists a natural temperature difference between the object under study and the environment where it is inserted (Maldague 2000, Tavares and Andrade, 2003).

In evaluation of art works is normal to exist a predilection for the use of the passive thermography due to its non-intrusive character and due to the restriction of submitting the surface to high temperatures. Indeed, for studies in situ, which aim just the qualitative analysis of structure as, for example, the identification of points with humidity presence and non-apparent structures, the passive thermography, most of the time, offer satisfactory results (Tavares, 2006).

Obviously, some factors must be taken in consideration when of the passive thermography application.

Due to the direct dependence of the ambient conditions, especially when operated in open environments, the choice of the year period for the tests implementation is an important factor in order to maximize the results. Generally, summer conditions, represented by high sunstroke, increases the differential of temperature between the region with and without non-visible pathologies (Tavares, 2006).

Special attention must be given in order to prevent shadowed and the solar influences in the images. These factors can influence significantly the information. By other side, the realization of tests in the first hours of the morning and soon after the sunset generally prevents the problem and permits the uniform heating of the surface that, by consequence, favors the evaluation (Tavares, 2006).

With the objective of studying the thermal comportment of the structure, it is important that the observation be realized, always that possible, during its heating (from dawn until the hour of higher solar incidence, which is a function of the local latitude, longitude, and year period) and during its cooling (from the hour of higher solar incidence until the sunset). The images must be taken observing regular intervals, in order to identifying the pathologies during these two periods.

The procedures described to the implementation of the SLDV and of the IRT have been used in this work in order to identifying the pathologies in the churches analyzed.

The thermal camera used in this study was a Nippon Neo Thermo TVS-600 Series whose specifications are presented in Tab. 1.

Table 1. Nippon Neo Thermo TVS-600 Series thermal camera specifications

ITEM	SPECIFICATION
Operational frequency	30 Hz
Focal distance	0,33 m to ∞
Observable temperature range (based on dark body temperature)	- 20ºC to 150ºC 100ºC to 300ºC
Measurement uncertainty (for 30ºC on the dark body)	± 2ºC or 2% of reading
Field of vision	25,8º (horizontal) x 19,5º (vertical)
Detector cooler system	Uncooled microbolometer
Spectral answer	8 to 14 μm;
Pixel numbers	320 x 2408
Thermal sensibility	<0.1ºC

The images analysis has been conducted using the software PE Analyser 2.03, supplied by the thermal camera manufacturer.

3. RESULTS

3.1. Church of San Nicholas – Bălineşti

The thermographic studies in the Church of San Nicholas have been initiated in the east sector of the entrance portal. The images were taken in two moments. The results obtained for the superior area can be seen in Fig.6. The photos identify the analyzed area and the conditions of shadowed in the moment in which the thermal image was registered. The pathologies found are related.

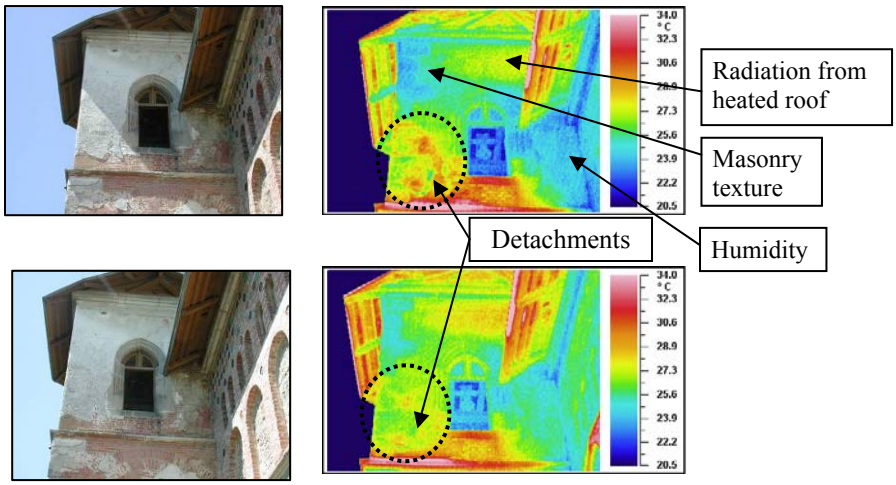

Figura 6. San Nicholas Church (Bălineşti) – entrance portal (sector superior east)

The humidity presence, characterized by areas of low temperatures, has been identified in the regions next to the walls junction. This occurrence is very frequent and here it is favored by the vegetation presence that reduces the arrival of direct solar radiation. For the restorers, the identification of these points has been interesting once that the occurrence is reflected in the interior side of the wall, favoring the frescoes detachments that, currently, are in initial process of restoration. Although simple, the diagnostic was decisive for the adoption of preservation actions in that sector.

Beyond the humidity, it could be identified the presence of some detachments in specific points of the plaster used for the wall recovery. Some structural characteristics could be identified, as masonry bricks and the stones used as base for the vertex.

An area with high temperatures has been identified in the superior part of the construction. However, this occurrence has no relation with detachments; it is originated by solar reflections from the roof, constituted of metal plates (typical in the region architecture).

The inferior part of the entrance portal has been analyzed during the cycle of heating and cooling. Figure 7 shows the results obtained and photos of the local.

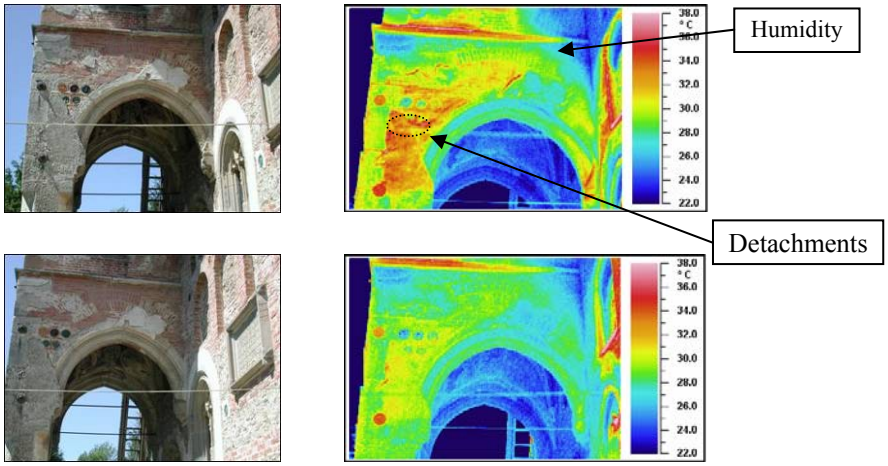

Figura 7. San Nicholas Church (Bălineşti) – entrance portal (sector inferior east)

It can be observed that the humidity presence continues in the inferior sector, in regions next to the walls junction. It has been identified some detachments in the areas re-covered by plaster, beyond the basic structure of rocks. This identification has been possible due to the lower conductivity of the rocks that delayed its process of heating, resulting in colder points in the thermal image.

It has been possible to identify some points of high temperatures in the west superior sector of entrance portal, related to ceramic disks that began to detach from the structure. It can be seen in Fig. 8.

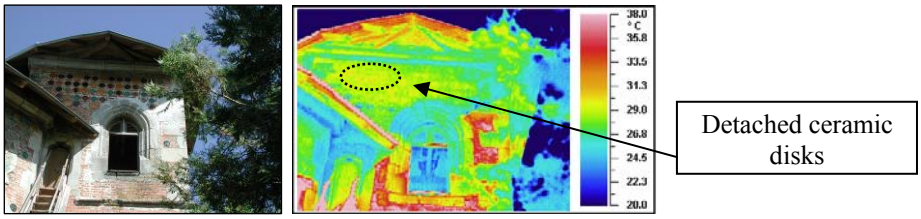

Figura 8. San Nicholas Church (Bălineşti) – entrance portal (sector superior west)

In the remaining frescoes located in the south sector of the church, a small area with a non-identified material used in a previous restore has been identified by the IRT. There was no information about it in the historical documents or in the restoration reports. The thermal conductivity of this material made possible its identification by IRT. Chemical analyses will be done in order to identify the characteristics of the used resin. Figure 9 shows these occurrences.

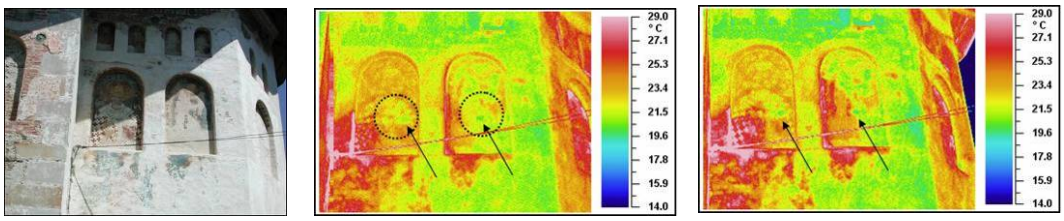

Figura 9. San Nicholas Church (Bălineşti) – frescoes (south sector)

With the objective to identify detachments, SLDV has been implemented in the internal frescoes of the entrance atrium. Figure 10 presents the evaluated areas of a fresco located in the east wall of the entrance atrium. The results have been presented in form of RMS maps where the pathologies found are also related.

SLDV has identified consolidated areas and areas with detachments of the layers that compose the frescoes. The detachments have come characterized in the RMS map by high speed of vibration. Some areas have presented low signal-noise relation, which has rendered difficult the analysis. During the tests the transit of people over the wooden floor where has been placed the vibrometer generated a signal that could be configure false alarm of irregularity. The occurrence of this type of measurement noise could represent a problem to the SLDV implementation in places of elevated visitation; it does not occur with the IRT. On the other hand, the detachments have been identified, even in areas where low signal-noise relation existed.

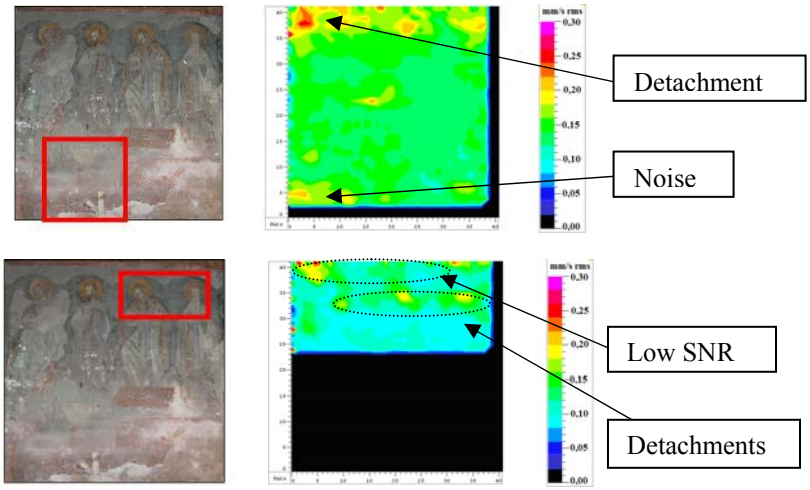

Figura 10. San Nicholas Church (Bălineşti) – fresco (entrance atrium – east wall)

3.2. Church of the Popăuți Monastery – Botoşani

The thermographic studies in the Church of the Popăuți Monastary have identified structural alterations effected during interventions realized, throughout the time, in the wall that divides the narthex of the aisle. Figure 11 presents the analysis realized in that sector.

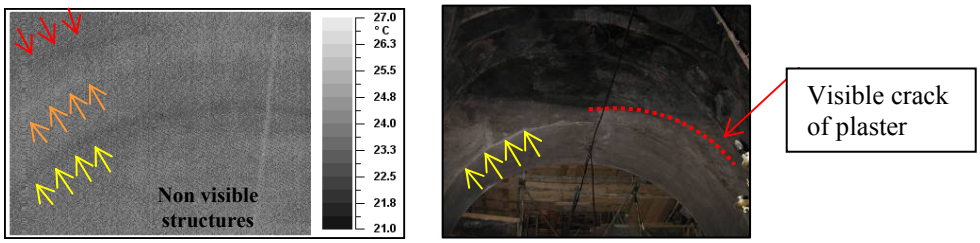

Figura 11. Church of Popăuți Monastary (Botoşani) – narthex arch

In the arch that divides the narthex of the aisle was possible to identify a visible line of crack. The IRT has identified not only this visible crack, but it has also indicated that the crack was continuing, although no visible, in the opposite side of the arch. This crack is the result of a registered previous reform, which enlarged the arch, before of small dimension. The IRT has identified a second line of crack; probably result of a previous non-registered reform, which, once more, enlarged the arch dimensions. This information has been important to the restorers in order to prevent other cracks, especially because the restorative works of the frescoes placed in the internal part of the arch has already concluded.

Originally, the main entrance of the church was situated in the north sector of narthex. In reform carried out at the beginning of century XX, this entrance has been substituted by another one, located in the south direction (Sinigalia e Vetros, 2006). The IRT application has permitted identifying the diverse materials used to close the door, as seen in Fig. 12. Once more, the thermal conductivity of the materials used has permitted the pathology identification.

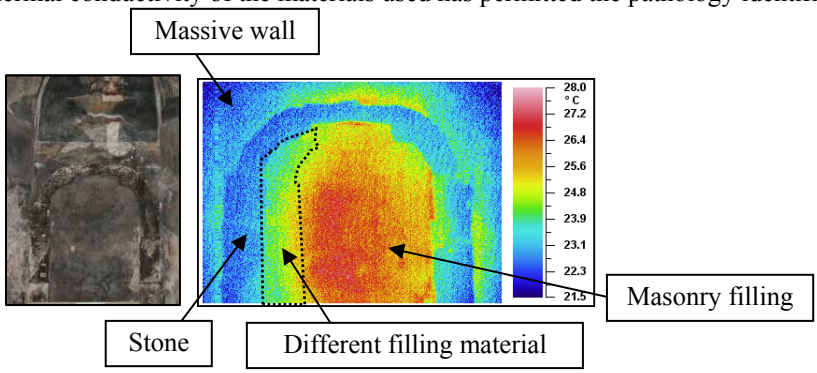

Figura 12. Church of Popăuți Monastary (Botoşani) – old narthex entrance

The SLDV has been used in the diagnostic of the frescoes. It confirmed the problems already pointed by the restorers: presence of great areas of detachments, which can cause the total loss of the paintings. The RMS maps obtained for two frescoes are presented in Fig. 13 and confirm this information: large areas of high speed of vibration, related to the detachments, have been located.

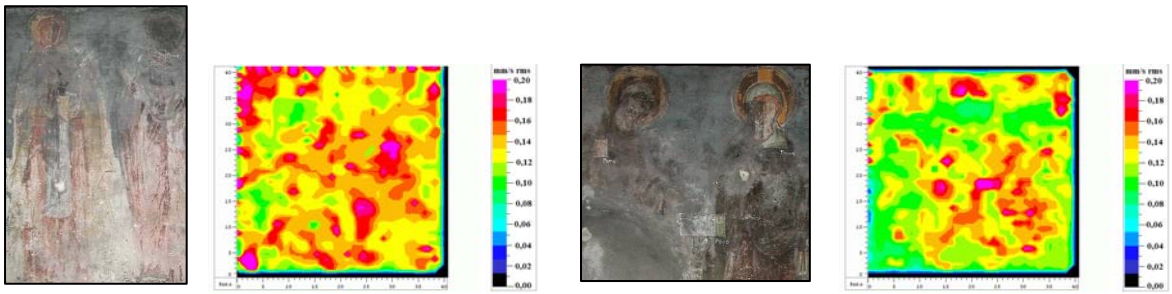

Figura 13. Church of Popăuți Monastary (Botoşani) – frescoes of the narthex

3.3. Church of the Resurrection – Sucevița Monastery

The thermographic tests have been realized outside of the Church of the Sucevița Monastary and have revealed non-visible structures, not identified by other techniques or by the restorers. The most interesting pathology has been found under the frescoes of the north wall, in an area analyzed by SLDV. The IRT has identified a small window that was filled by masonry material, this one different of the original material (the thermal properties of the fulfilling material enabled the identification of the pathology by IRT). This occurrence has called the attention of the restorers. There was no information about it in the historical documents or in the reports of anterior restorations. On the other hand, nothing has been identified by the SLDV. The restorers believe that it could be an execution error, which has been corrected during the church construction or later, during some non-registered reform. This because the location of the small windows is extremely symmetrical throughout the all construction; this fulfilling window is completely out of this symmetry. The thermographic image that identified the hidden window and local photos can been seen in Fig. 14.

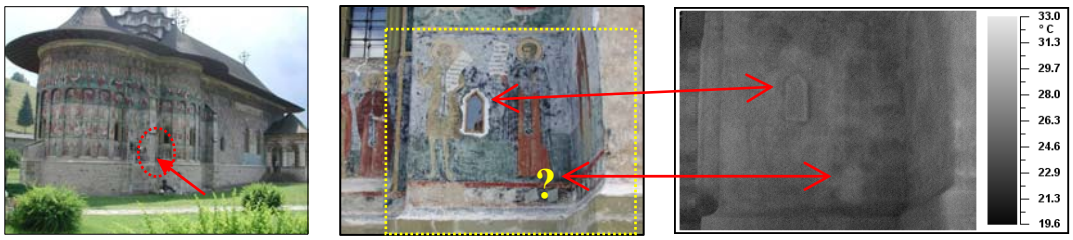

Figure 14. Church of Resurrection (Sucevița Monastery) – frescoes of north wall

The IRT has been applied to the south wall where has identified the bricks of masonry that constitute the first layer of the frescoes structure. Figure 15 presents these results.

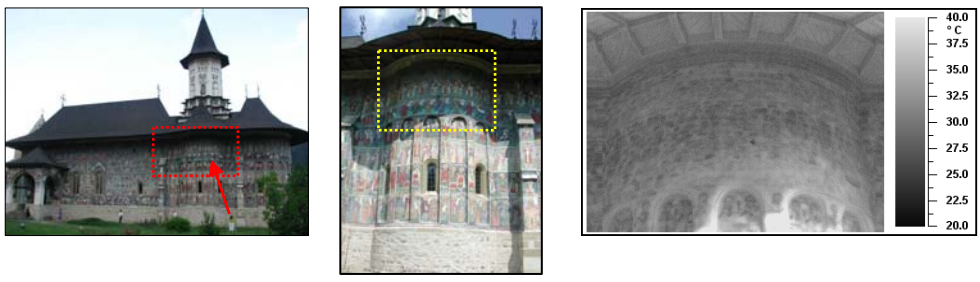

Figura 15. Church of Resurrection (Sucevița Monastery) – south wall

The outer frescoes are a characteristic of the Moldavian architecture. However, as in the Church of Resurrection, they are exposed to meteorological conditions, what increase the damages. In order to evaluate the actual state of the outer frescoes of the north wall (recently restored) SLDV has been applied in some of them. In Figure 16 are presented the results obtained and photos of the local, where the testing areas have been delineated.

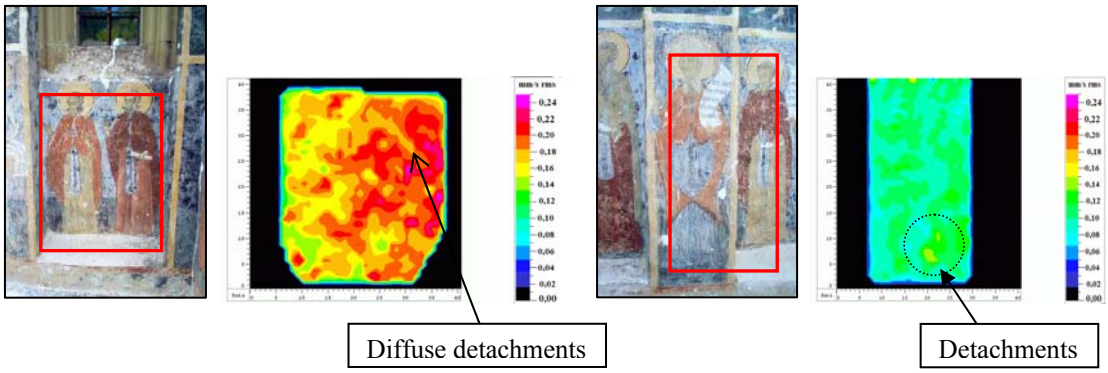

Figura 16. Church of Resurrection (Sucevița Monastery) – frescoes of north wall evaluated by SLDV

As can be seen in the RMS maps obtained by the SLDV, a great quantity of detachments has been identified in the outer frescoes of the north wall.

The analyzed internal frescoes have presented good conditions of conservation: just few detachments, of minimum dimensions, have been found. By other side, some problems, related to low Doppler signal, have been evidenced. They have been caused by the presence of measurement noises. The results obtained by accomplishment of the SLDV on the frescoes placed in the mortuary chamber can be seen in Fig. 17.

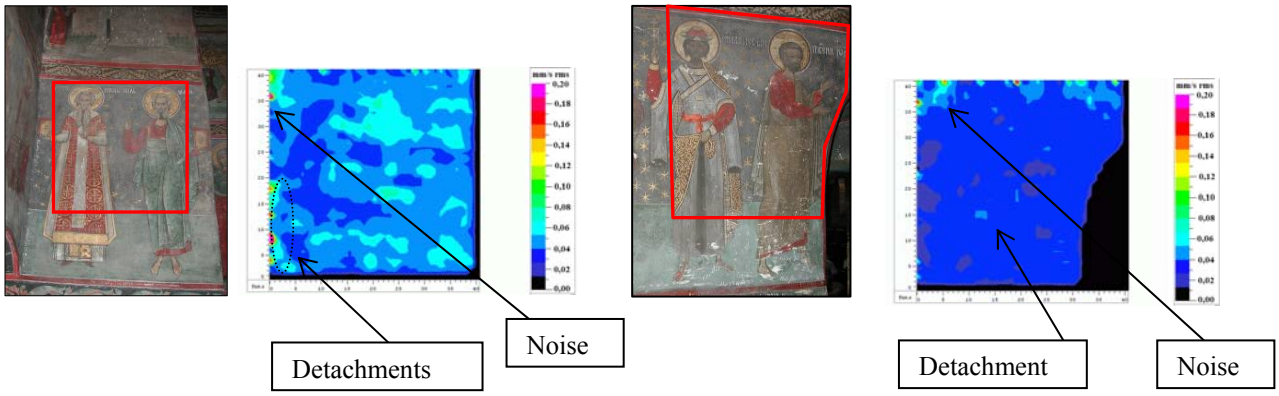

Figura 17. Church of Resurrection (Sucevița Monastery) – indoor frescoes evaluated by SLDV

4. CONCLUSIONS

This work has presented the structural and frescoes investigation by using the integration of Scanning Laser Doppler Vibrometry (SLDV) and InfraRed Thermography (IRT).

The tests have been carried out in three medieval monasteries placed in the northeast of Romania.

The localization inside of each one of the monasteries in which each technique has been implemented and the final objective of the tests has been determined by the staff of the INOE and by the Professor Tereza Sinigalia, PhD., in agreement with the necessities of the restorers.

The IRT has identified presence of humidity, non-visible structures, non-apparent inclusions, and materials of diverse origins, and characterized the masonry that constitutes the Church of San Nicholas in Bălineşti, the Church of the Popăuți Monastery in Botoşani and the Church of the Resurrection, located inside of the Sucevița Monastery walls. The SLDV has been used, with success, in the identification of detachments of the frescoes layers.

The results have permitted confirming the power of the IRT and of the SLDV in the diagnostic of art works.

5. ACKNOWLEDGEMENTS

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