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Review paper
Doi 10.61892/STP202601021G
ISSN 2566-4484

STEPGRAD
СТЕПГРАД

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A NON-DESTRUCTIVE APPROACH TO THE SUSTAINABLE CONSERVATION OF BUILT HERITAGE

Abstract:

Heritage buildings represent tangible links between present and past; embody the creativity and traditions from past generations. The distinctive character of these buildings, primarily expressed through their authenticity and inherited values, emphasizes the need for innovative and carefully adapted conservation approaches. In this context, the present study explores the potential and limitations of non-destructive techniques (NDTs) in the diagnosis and conservation of cultural heritage buildings. By presenting relevant examples from professional literature, the role of NDTs to support sustainable conservation goals is demonstrated.

Keywords: heritage buildings, non-destructive techniques, sustainable conservation, diagnosis

НЕДЕСТРУКТИВНИ ПРИСТУП ОДРЖИВОЈ КОНЗЕРВАЦИЈИ ГРАДИТЕЉСКОГ НАСЉЕЂА

Сажетак:

Објекти градитељског насљеђа представљају опипљиве везе између садашњости и прошлости и утјеловљују стваралачки дух и традицију претходних нараштаја. Посебан карактер ових грађевина, који се прије свега огледа кроз њихову аутентичност и наслијеђене вриједности, указује на потребу за иновативним и пажљиво прилагођеним приступима конзервацији. У том контексту, овај рад истражује могућности и ограничења недеструктивних метода тестирања (НДТ) у дијагностици и конзервацији објеката градитељског насљеђа. На основу релевантних примјера из стручне литературе приказана је улога недеструктивних метода тестирања у остваривању циљева одрживе конзервације.

Кључне ријечи: објекти градитељског насљеђа, недеструктивне методе тестирања, одржива конзервација, дијагностика

1. INTRODUCTION

Cultural heritage is a rich and diverse mosaic of tangible and intangible assets, inherited from past generations. As a reflection of the history, beliefs and traditions of past generations, it contributes in shaping the cultural identity, economic growth and sustainable development of contemporary societies. Today, cultural heritage encompasses a wide range of assets - from historical buildings, archaeological sites and artifacts, to living traditions such as music, dance, crafts, etc. [1].

Republic of North Macedonia is a country with exceptionally rich cultural heritage, created over the centuries. A substantial part of this heritage consists of historical buildings of varying typologies - from religious buildings (churches, monasteries, mosques), traditional residential architecture, to public and administrative buildings (schools, municipal buildings, baths, etc.) [2], [3].

The long exposure to various natural and human factors, often can lead to damage or even loss of these valuable assets [4]. In that context, timely interventions are essential to ensure long-term preservation of historical buildings. However, the uniqueness of these buildings, which derives from their authenticity and inherited values, imposes the need for balanced and appropriately adapted preservation approaches, aligned with the sustainability criteria. In this process, modern NDTs gain particular value and significance, as they allow significant insights into the condition of the monument, without affecting its authenticity. There is wide range of techniques applicable in the field of cultural heritage, from traditional ones - those used for over 100 years, to ones based on the latest technology. Some of them are oriented toward surface analysis, while others investigate the internal - invisible parts of the building.

2. NON-DESTRUCTIVE TECHNIQUES IN THE STUDY OF HISTORICAL BUILDINGS

A wide range of analytical techniques are available within the field of cultural heritage; however their application is often limited due to the specific character of historical buildings, especially in terms of accessibility and limitation on samples collection. Consequently, in the past few decades, NDTs are becoming increasingly important. Techniques such as: fiber optic microscopy, infrared thermography, 3D laser scanning, ground penetrating radar etc., aided by computer programs and laboratory analyses, provide a successful, science-based approach for safeguarding tangible assets [5].

2.1. FIBER OPTIC MICROSCOPY

Nowadays, visual inspections on historical buildings are often assisted by additional devices, such as the fiber optic microscope - a non-destructive tool that can be used to acquire magnified images (up to x600) of the examined surfaces in real time, without causing physical damage [6]. This technique is widely applied in identifying surface damages and the factors responsible for this, such as salts, pollution, biodegradative agents, etc. [7], [8], investigation of surface morphology [9] etc. In certain cases, the use of the microscope even enables to trace previous interventions and evaluate the effectiveness of protective, cleaning or consolidation treatments on the surfaces [9], [10].

Figure 1 shows the microstructure of porous stone before and after the treatment with different consolidation agents. The application of the microscope provides a clear insight into the distribution of the consolidant and the changes at the microstructural level [10].

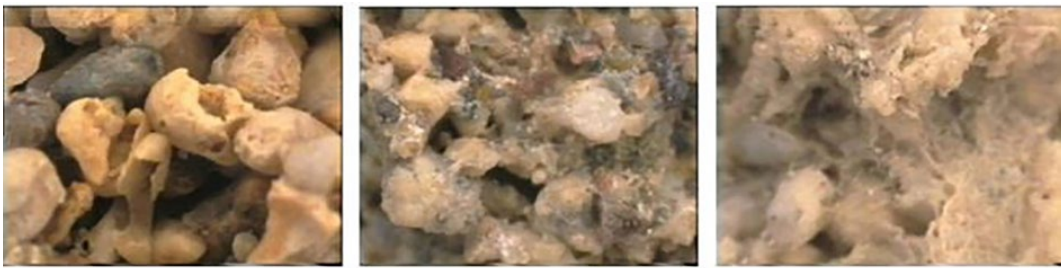


Figure 1. Figure 1. Fiber optic images from consolidation interventions (x50), untreated porous stone (left), treated porous stone with different consolidants (middle and right) [10].

2.2. INFRARED THERMOGRAPHY

Infrared thermography is a non-destructive and non-contact method which employs a thermal camera to detect and record the infrared radiation emitted by different materials, producing thermal images as a result. Temperature variations in thermal images can be correlated with variations in material properties, morphology, and microstructure of surfaces, which allows for the detection of certain subsurface anomalies that are not visible to the "naked" eye. The advantages of this method are related to its user friendly operation, fast and non-contact nature, large surface application, ability to access difficult or irregular surfaces, etc. The limitations are associated with the limited penetration capacity, which is only a few centimeters [5], [11].

In recent decades, this technique has been widely applied in the analysis of historical buildings in different aspects: detection of hidden damage [12], [13], [14], identification of different construction phases [7], [15], moisture mapping [16], [17], investigation on frescoes, mosaics and other works of art [14], [18].

Figure 2 shows the results of two thermographic surveys conducted by Paoletti et. all on the 13th century church of Santa Maria in Fossa, Italy. The first survey was conducted in 2007, while the second followed in 2009, after the L'Aquila earthquake. In the first examination (2007), thermal images detected incipient cracks invisible to the naked eye. The second analysis (2009) showed that some of the damage to the masonry caused by the earthquake corresponded to the thermal anomalies identified by infrared thermography in 2007 [13].

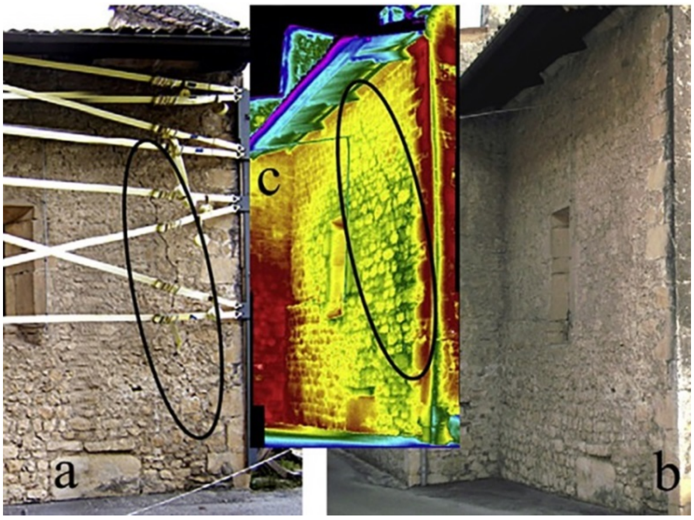


Figure 2. Figure 2. Survey campaign of St. Maria church in Fossa, a) photo of the facade in 2009 (with visible cracks), b) photo of the facade in 2007 (without visible cracks), c) thermogram in 2007 [13].

2.3. GROUND-PENETRATING RADAR (GPR)

GPR is a non-destructive method that uses electromagnetic waves to examine subsurface changes in the ground or buildings. The system consists of data acquisition unit and two antennas (transmitter and receiver), which enable the transmission and detection of electromagnetic waves at given frequencies [19]. While higher frequencies result in better spatial resolution, they correspond to reduced penetration depth [19].

In the field of tangible heritage, GPR is widely used in archaeological research of buried structures, most often in combination with other geophysical methods [20], [21]. In the past few decades, this technique has been applied in diagnostic studies and monitoring of historical buildings and monuments. Within this context it is used to examine internal surfaces of structural elements, [22], to detect internal damages - cracks, voids or other irregularities [19], [23], [24], [25], identify morphology of multilayered walls [15], [19], [26], to detect presence of rods in structural elements [27], identify presence of moisture as a possible source of damage in the walls of historic buildings [28], [29], etc. In certain studies, GPR has proven to be an effective technique to assess the state of mosaics preservation and discover subsurface works of art such as murals or mosaics [30], [31].

Barone et. all applied the technique in the investigation of two historic buildings in Rome. In the first study, the use of GPR enabled to detect internal cracks and other irregularities in the architrave of the Porticus Octaviae, a component of a Roman historic building (fig. 3). In the second study, GPR was applied to determine the internal structure of the vaulted surfaces in the Zuccari Palace, which are covered with 16th century frescoes. The researchers conclude that the application of GPR can provide qualitative and quantitative data on structural damage in elements (cracks and irregularities) and consequently define the preservation state of those elements. The method can be also useful to determine the construction techniques used in historic buildings, especially in instances where this type of information is lacking [25].

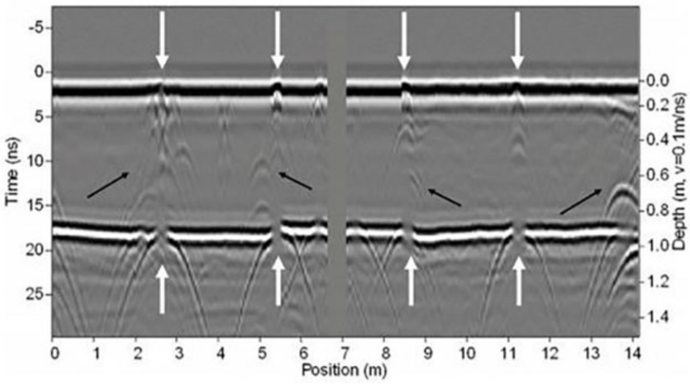


Figure 3. Figure 3. GPR section across the architrave of the Porticus Octaviae, , internal damage (black arrows), cracks throughout the architrave (white arrows) [25].

2.4. 3D LASER SCANNING

3D laser scanning is a non-invasive and non-destructive technology with wide application in many fields, including built heritage. In the context of historical buildings, the technology is used to investigate irregular and complex buildings [32], monitor changes over time [33], and especially for mapping and documenting [34], [35], [36] since it provides precise recordings and significantly facilitates the documentation process.

3D laser scanning technology enables the acquisition of millions of data points by measuring the distance between the scanner and the surveyed surfaces. This process generates a so-called "point cloud", providing dimensionally accurate representation of the surveyed building. Furthermore, this data is processed in suitable software (such as Autodesk ReCap or Leica Cyclone) resulting in a precise 3D digital model, which reflects the real characteristics of the building. This enables for architects, structural engineers and all other engaged researchers to study the building from multiple aspects, to understand its complex geometry and construction details [34], [37].

In 2015 the 3D laser scanning technology was applied on the Notre Dame Cathedral in Paris, resulting in a high detailed digital model of the church, figure 4. The scanner was positioned in 50 different locations in in the exterior and interior of the church in order to provide complete and precise definition of the building's geometry. The precision of the scanned data had great impact during the restoration project of the church, after the fire in 2019 [38].

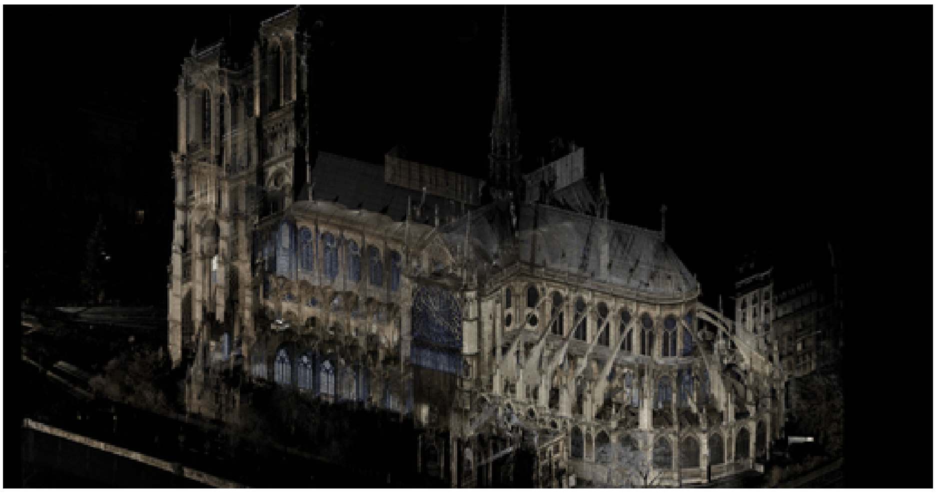


Figure 4. Figure 4. 3D scanned data of Notre Dame Cathedral in Paris [38].

2.5. AMBIENT VIBRATION METHOD

The ambient vibration method is a non-destructive technique used to determine the basic dynamic properties of the structures: natural frequencies, mode shapes and damping properties [39]. The method involves "in-situ" measuring of structural vibrations caused by ambient forces, such as wind action, and processing of the recorded data. The advantages of this method are related to its simple approach that does not disrupt the normal function of the building, short implementation time, small research team and cost-effectiveness.

The ambient vibration method is broadly employed in structural analysis of various types of buildings such as multi-story reinforced concrete structures, bridges, dams, etc. [40]. The technique is particularly suitable in the field of tangible heritage, where it is most common applied to determine dynamic characteristics of structures [41], [42], calibration of analytical structural models [39], monitoring structural stability over time [43], [44], monitoring changes in natural frequencies in damaged or repaired structures [45], etc.

Votsis et. all analyzed the dynamic characteristics of two historical monuments in Cyprus, dating from the 14th and 16th centuries. The ambient vibration method made it possible to determine the natural frequencies and mode shapes of the structures. The results of the research helped in the calibration of the finite element mathematical models for subsequent analyses, as well as for development of a monitoring strategy and study of the seismic vulnerability of the monuments [46].

3. CASE STUDY - DIAGNOSTIC STUDY OF ST. NIKITA CHURCH

The Church of St. Nikita is a typical late Byzantine monument from the 14th century, located in the village of Banjani, near the capital, Skopje. Typologically, this church belongs to the domed cross-in-square buildings, which is the predominant type of c Byzantine style church in the Republic of North Macedonia. In the base of the church there are two clearly defined areas: a central nave and an altar area that ends with a five-sided apse to the east, figure 5. The main structural elements are made of stone and brick, connected with lime mortar [47], [48].

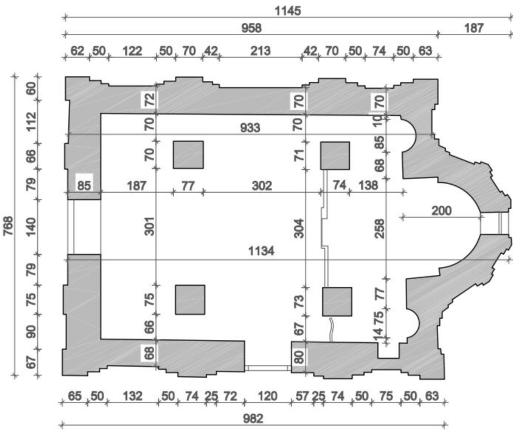


Figure 5. Figure 5. Church of St. Nikita, floor plan (left), south-east view (right) [47].

The church is well preserved and has largely retained its original appearance. In the past, extensions in form of narthex and chapel were added to the building, which significantly affected its overall appearance, however they were later removed [49]. More extensive interventions on the church were carried out in the second half of the 20th century (after the Skopje earthquake in 1963), which involved conservation of the frescoes and architecture, repair of damage to the walls and reconstruction of the roof sections [50].

To evaluate the condition of the church and its preservation state a detailed survey was conducted in the period 2021-2024. This survey comprised archival research, documentation review and on-site inspections, including several NDTs: digital microscopy, infrared thermography, 3D laser scanning and ambient vibration tests [47]. The review of the available documentation enabled insight into the historical context of the church, including different historical phases and previous interventions. On-site inspections involved examination of the facades and interior of the church. The facade inspections revealed the good condition of the surface materials but also pointed out to certain irregularities such as: pronounced porosity of the limestone and carbonation of the lime mortar; presence of capillary moisture in the lower zones of the north and west walls; bio colonization in the lower and middle zones of all facades. Additionally, the use of a digital microscope provided more detailed investigation of certain surfaces, i.e. identification of the present bio organisms - several species of lichens (fig. 6), identification of micro cracks and investigation of the morphological characteristics of the different types of façade stones. Certain minor cracks were observed in the upper zones of the church's interior and a disruption in one of the wooden ties.

Figure 6. Figure 6. Different types of lichens present on facade surfaces (microscopic images, magnification x 40) [47].

Another technique employed in the survey id the infrared thermography. In this regard, the passive approach was employed using infrared camera type - Testo 875-1i, with an accuracy of ±2°C. The survey conducted with the thermal camera provided additional information for the building's condition, including the actual distribution of moisture in the facade walls (fig. 7), and more detailed examination of certain surfaces and the frescoes in the interior of the church.

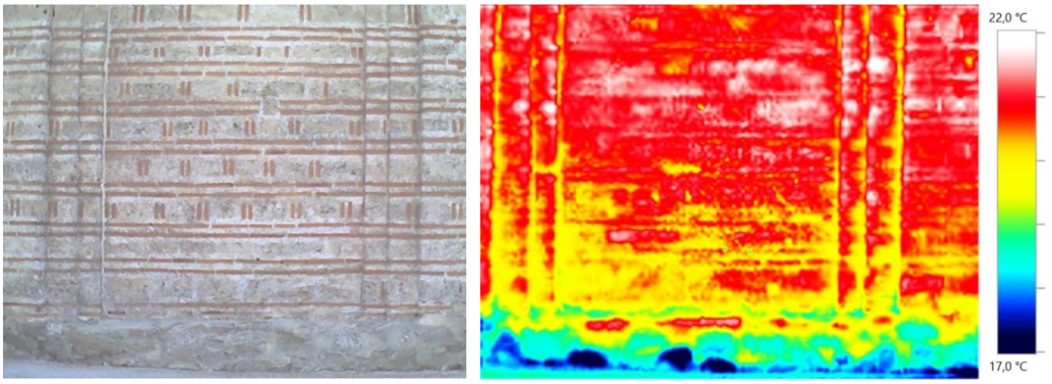


Figure 7. Figure 7. Segment of the northern facade of the St. Nikita church and corresponding thermal image [47].

The application of the 3D laser scanner provided digital documentation for the church, both in 3D and 2D. This is particularly important since no such documentation existed previously for the monument. Through the virtual 3D model, the building can be visualized and managed from different angles, regardless of the real physical limitations. The precision of the model enables to measure any dimension of the elements and identify even the smallest details (fig. 8), which particularly facilitated the creation of the mathematical model used for further analysis of the structure.

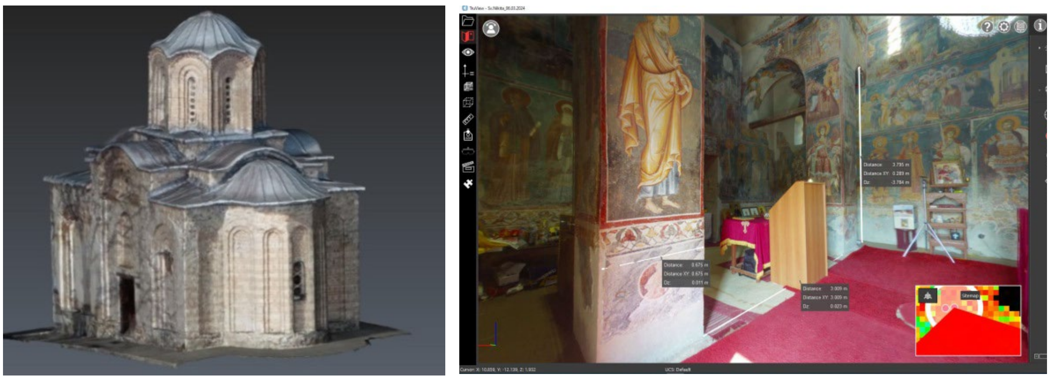
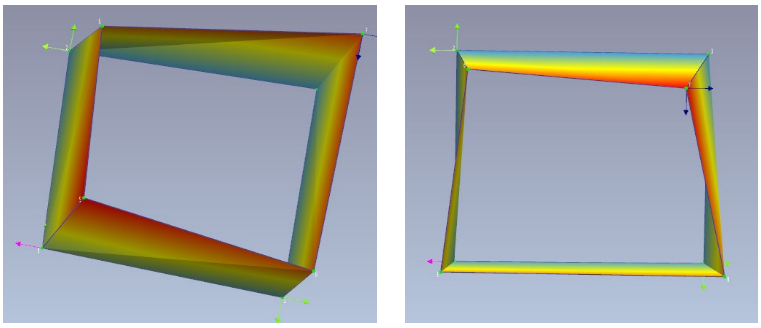


Figure 8. Figure 8. 3D model of the church of St. Nikita generated with a laser scanner [47].

To determine dynamic characteristics of the church (natural frequencies and mode shapes), the ambient vibration method was applied. These tests generated the natural frequencies $f_{E-W}=5.98$Hz and $f_{N-S}=4.70$Hz, i.e. the natural periods $T_{E-W}=0.167$sec $T_{N-S}=0.212$sec, in the two orthogonal directions, respectively. From the vibration forms (fig. 9) it can be concluded that the building in its current state vibrates as a unified structure, which indicates to undisturbed global performance of the wooden belts (beams) and a synchronous behavior of the individual walls.



f=5.98 Hz (longitudinal direction E-W) *f=4.70 Hz (transverse direction N-S)* *f=8.05 Hz (torsion)*

Figure 9. Figure 9. Natural frequencies and mode shapes [47].

4. CONCLUSION

Substantial part of the tangible heritage in Republic of North Macedonia consists of historical buildings spanning different periods. These buildings feature exceptional architectural, cultural and historical values, which should be preserved and passed on to future generations. In order to preserve these buildings it is essential to understand their current condition. Decisions related to historical buildings must be based on evidence, not assumption. In this context, the historic building survey which enables correct diagnosis of a building's condition becomes essential part of their preservation strategies. Within its framework the application of NDTs such as optical microscopy, infrared thermography, GPR, 3D laser scanning, etc., acquire special value and significance, due to their capacity to provide valuable insight into the condition of the monument, without compromising its authenticity, which in turn supports the concept of sustainability. The inclusion of these techniques facilitates regular monitoring of monuments, enables timely detection of possible damage, and modernizes existing protocols for the protection of historical buildings. The presented case study for the church of St. Nikita shows how an integrative approach, which combines multiple NDTs, can contribute to more comprehensive understanding of historical buildings, which is crucial step in developing preservation strategies.

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