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Research paper

NON-DESTRUCTIVE INVESTIGATION ON HERITAGE BUILDINGS - CASE STUDY ON ST. NIKITA CHURCH

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Abstract

Historic buildings are a significant part of the world's cultural heritage. These buildings act like a bridge that connects us to the certain time, people and culture, providing invaluable insight into our past.

The long-term exposure to different natural, biological and human factors increase the vulnerability of the heritage buildings, therefore their condition needs to be carefully considered and monitored. Knowing the condition will significantly contribute to their long-term protection; underestimating the actual condition may lead to pointless interventions and overestimating it may lead to no interventions and further damage.

This paper presents the investigation campaign carried out to one heritage building – the Byzantine church of St. Nikita near Skopje, North Macedonia. The methodology involved archival research, review of the monument's documentation and in-situ investigation using several Non-Destructive Techniques (NDTs): visual inspections, microscopy, infrared thermography, 3D laser scanning and ambient vibration tests. This integrated methodology provided information for both, historical context and current condition of the building. NDTs proved to be a useful diagnostic tool for condition assessment of the monument without affecting its authenticity, which is especially important for this type of buildings.

Key words: *Architectural Heritage, Byzantine Churches, Protection, Investigation Campaign, Non-Destructive Techniques*

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1. INTRODUCTION

Cultural heritage is the legacy inherited from previous generations, which plays crucial role in modern societies as it connects us to the past and fosters a sense of social and collective identity [1]. The treasury of cultural heritage in North Macedonia, built over the centuries, includes numerous monuments from different historical periods, representing the rich and creative ideas of this region [2]. Among them, Byzantine churches stand out as some of the most valuable and well-preserved medieval monuments, with exceptional architectural and artistic values [3].

Heritage buildings are inevitably exposed to a range of natural, human and climatic threats, which can lead to damage or even loss of these valuable assets. Furthermore, many heritage buildings are situated in seismic-prone regions, such as in North Macedonia, which make them particularly vulnerable to the devastating effects of earthquakes [4].

Regular assessment of building's condition helps to identify any potential risks and helps to detect early signs of damage, encouraging the timely interventions and preventing further harm of the asset. In this context, the diagnostic study plays a pivotal role in the process of sustainable and long-term preservation of our tangible heritage.

In accordance with modern worldwide protocols and practices for protection of significant cultural and historical monuments, a case study was conducted, to assess the condition of a representative Byzantine monument – St. Nikita church. This integrated diagnostic study involved several phases: archival research, documentation review, assessment of existing hazards and field surveys. Particular emphasis was placed on NDTs which enabled to investigate the monument without compromising its condition or authenticity [3].

St. Nikita church is a medieval monument that reflects the features of many Byzantine churches in the county. Its selection is based on several criteria:

- Location: the church is located in Skopje region, one of the areas with the highest seismicity in the country and wider.
- Typology: the church belongs to the group domed cross-in-square plans, which is the most prevalent architectural plan found in the country.
- Authenticity: this church has maintained its high level of authenticity [3].

2. OVERVIEW OF ST. NIKITA CHURCH

2.1. Historical Background and Architectural Design

The Church of St. Nikita is a typical late Byzantine monument. From a typological perspective, it belongs to the group of domed cross-in-square churches with a five-sided apse on the eastern side (fig. 1). The external dimensions of the church are as follows: length 11.45 meters (including the apse), width 7.72 meters, and height 12.78 meters. This church is located on the western slopes of Skopska Crna Gora, in the village of Banjani, which is 15 km northwest from the city of Skopje. According to written documents (charters), it is believed that the church dates back to the early 14th century, when King Milutin (1282–1321) rebuild the church on the site of an older ruined structure from the 11th or 12th century, which was dedicated to the same saint [5].

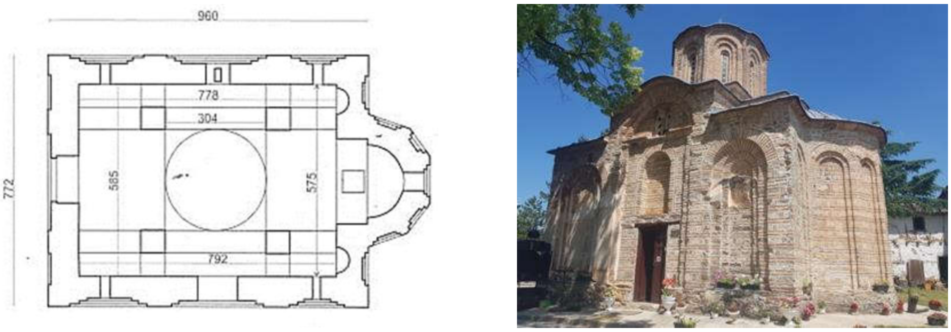


Figure 1. St. Nikita church, floor plan (left), view (right), [3][5]

The structure is built from traditional materials: local stones, bricks and lime-mortar. The structural system consists of massive peripheral walls and four interior columns that support the roof structure: central dome and vaulted elements. The additional wooden system of belts and ties contributes to the seismic performance of the building [6].

The facades of the church are playful with arches, pilasters, niches and cornices. Decorative patterns of bricks are characteristic for the apse area. Interior surfaces of the church are flat, with small perforations for windows and blind niches. These surfaces are covered with frescoes from different periods (14th, 15th and 19th centuries), which are largely preserved today.

The archival research and the review of available documentation for the church (found in NI Conservation Center - Skopje) provided information about its historical development, presented in table 1.

Table 1. Historical evolution of St. Nikita church, [5][7][8]

1307	Period of construction of the church
Ottoman period	Addition in form of small single nave structure on the south side of the church, fig. 2 (demolished in 1928)
XIX century	Reconstruction activities on the dome of the church; Addition of a closed porch along the south and west side, fig. 2, (demolished in 1928)
1963 (Skopje earthquake)	Damages in the interior of the church in form of cracks and detachments of the frescoes
1964 -	Vibrations produced by the nearby mining processes
1967	Conservation activities on the frescoes in the interior
1968	Conservation activities on the architecture
1978-80	Extensive intervention on the roof parts: reconstruction of the roof and replacement of the roof tiles with a lead sheet, fig. 3

In the 1990s, the church became the focus of research as part of the project "Seismic Strengthening, Conservation, and Repair of Byzantine Churches in Macedonia." During this time, comprehensive laboratory, field, and experimental studies were conducted on the monument using the techniques and methods available at the time [6].

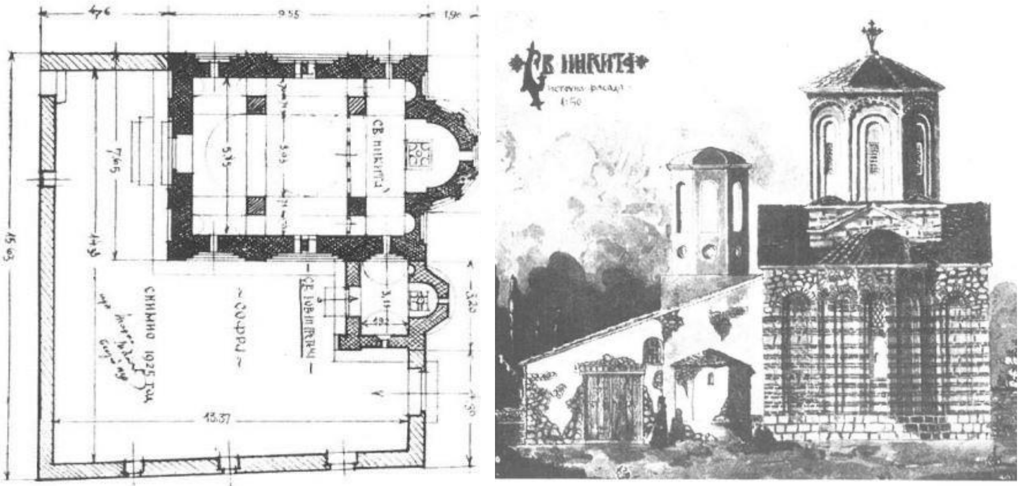


Figure 2. Later additions on St. Nikita church, floor plan (left), view (right), [5]

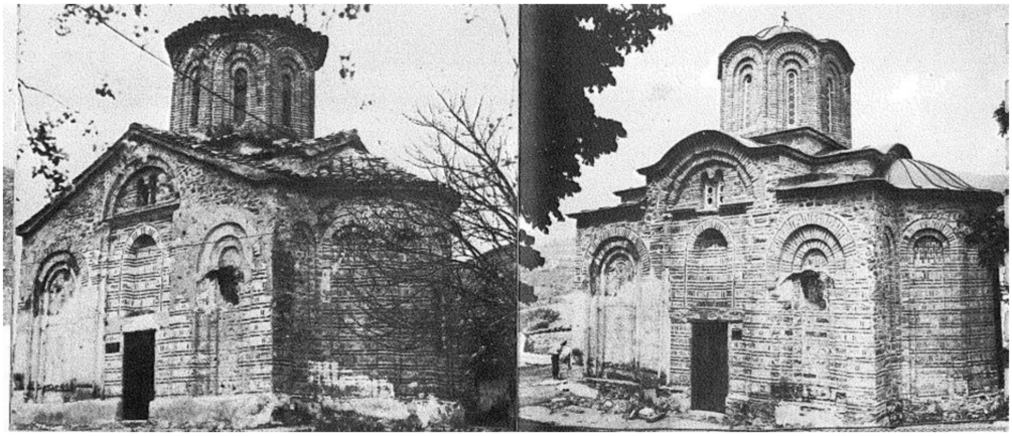


Figure 3. St. Nikita church, before (left) and after (right) the extensive intervention on the roof parts, [9]

2.2. Location: Specific Characteristics

The church is located in natural surroundings, distanced from urban infrastructure, which offers a degree of protection to the monument against pollution, urban growth, traffic –related vibrations and similar factors.

However, this area is highly susceptible to earthquakes. Since 1900, Skopje region has been affected by both nearby and distant earthquakes of varying intensity. The most destructive was the 1963 earthquake, with a magnitude of 6.1 on the Richter scale, with its epicenter located 7 km west of the city of Skopje. In the past 10 years, several earthquakes with a magnitude greater than 4 have occurred in this region, among which the 2016 earthquake was the strongest, with a magnitude of 5.1 [10].

During 1990s project [6], detailed investigations were carried out to determine the seismic characteristics of the church site: earthquake frequencies, characteristics of the macro-seismic field, spatial and temporal distribution of earthquakes, etc. It was demonstrated that the church was subjected to earthquakes with magnitudes greater than MCS 6 on numerous occasions between 1900 and 1999. Table 2 presents the defined seismic parameters for the church of St. Nikita, specifically the maximum expected ground acceleration (a_{max}) and the expected intensities (I) for different return periods. The acceleration is presented as a combination of near earthquakes (up to 40 km) and distant earthquakes (more than 40 km).

Table 2. Maximum ground accelerations (a_{max}), corresponding return periods, and defined MCS intensities (I) for the Church of St. Nikita, [6]

St. Nikita church		Return period (years)						
		25	50	100	200	500	1000	10000
Summary effects of local and distant earthquakes	a_{max}	0.093	0.117	0.146	0.198	0.292	0.340	0.360
	I	6.73	7.06	7.36	7.82	8.38	8.60	8.68

These parameters suggests that over the course of its long history, the church of St. Nikita was most likely exposed to one or more earthquakes with the intensity of so called "design" earthquake, corresponding to a return period of 100-200 years. However, there is no indication that the church experienced a "maximum expected" earthquake with a 1000-year return period, since such an event would have caused significant damage or even structural collapse [6].

3. NON-DESTRUCTIVE INVESTIGATION OF ST. NIKITA CHURCH: METHODS AND FINDINGS

Over the past few decades, NDTs have become indispensible tool in diagnostic assessment of heritage buildings. The field survey on the church employed several NDTs: visual inspections, microscopy, infrared thermography, 3D laser scanning and ambient vibration tests. These techniques are crucial for heritage buildings since they enable to investigate the monument without causing any damage to the materials or affecting building's authenticity [3]. The choice of techniques was primarily determined by their accessibility and applicability.

3.1. Visual Inspections Aided with Drone

The oldest and maybe the most important non-destructive technique in the field of cultural heritage is the visual inspection. This technique provides instant results regarding visible irregularities, such as cracks, signs of moisture and other critical areas of the monument. The technique is usually aided by means of optical devices and documented by photographs. However, due to its limitation to surface analysis, it is often supplemented by other techniques, [11][12].

Visual inspections were the first direct contact with the monument and served as the initial step in the in-situ diagnostic study, providing a general overview of the monument's condition. It involved a detailed examination of the church's facades and interior, providing immediate results regarding visible surface irregularities and damages.

During facade inspections, it was observed that the materials are generally well-preserved, showing no significant signs of degradation. However, certain irregularities were noted (fig. 4) such as: pronounced porosity of the limestone and carbonation of the lime plaster; presence of capillary moisture in the lower zones of the northern and western walls; presence of bio-organisms (mostly lichens) in the lower and middle zones of all facades.

Figure 4. Porous limestone (left), presence of capillary moisture (center), presence of bio-organisms (right), [3]

The interior of the church is entirely plastered and painted with frescoes, which prevents any direct investigation of the condition of the underlying construction materials. Fine cracks are visible in the upper areas at several locations (fig. 5) and the most prominent is an old crack on the western wall, above the door. More substantial damage was noted on one of the wooden tie beams - the beam linking the altar area to the north-east pillar is disconnected (fig. 5).

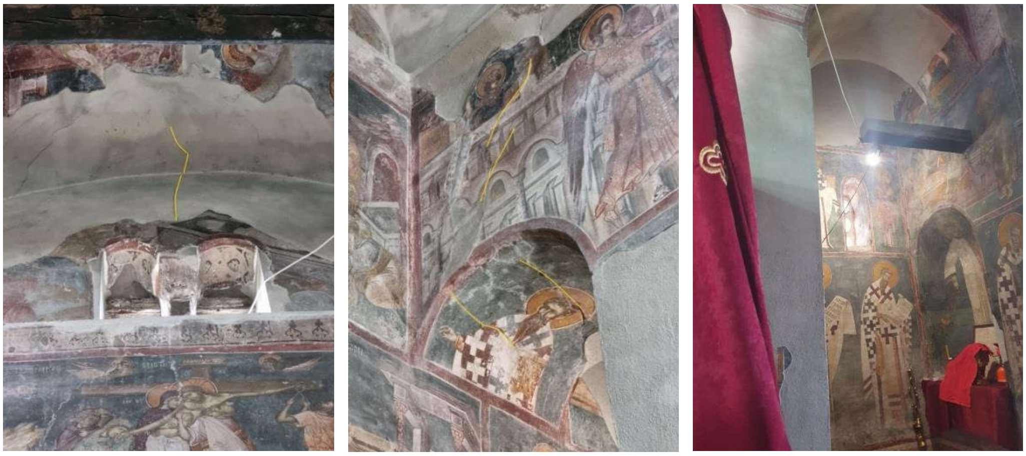


Figure 5. Presence of damages in the upper zones of the church, fine cracks (left and middle), disruption of wooden tie (right), [3]

The use of a drone provided access to hard-to-reach areas that posed challenge during visual inspections. High-resolution aerial photographs (fig. 6) provided a detailed perspective of the church's positioning within its immediate surroundings and enabled inspection of the roof covering. It was noted that the roofing material is overall in good and well-maintained condition, except of the dome area, where some material cracking was observed (fig. 6 right), likely resulting from improper joint installation.

Figure 6. Aerial perspective of St. Nikita church, [3]

3.2. Digital Microscopy

For a more detailed analysis of the church's facade materials, a Natoli digital microscope with 40x magnification was used. This technique is cost-effective and involves a portable device, allowing for in-situ use. The microscope images (fig. 7) show presence of several types of lichens on the church's surfaces. The majority are crustose lichens, which firmly adhere to the substrate. Another type consists of lichens that group together in the form of small stones, and there are also lichens resembling moss.

Figure 7. Different types of lichens present on the facade surfaces (images from a digital microscope with 40x magnification), [3]

So far, the presence of lichens has not caused any significant damage on the facade materials (some micro cracks and color change of materials were observed). In fact, it requires long period of time for certain degradation processes to occur. Additionally, most of the lichens are tightly connected to the surface and their mechanical removal is practically impossible without damaging the underlying material.

The use of microscope also allowed observing the distinct morphological characteristics of the facade stones, with the limestone being characterized by pronounced porosity.

3.3. Infrared Thermography

Infrared thermography is an established non-destructive and non-contact technique with a wide range of applications in the field of built heritage. This technique enables to investigate large architectural surfaces, and to evaluate their condition or degree of preservation, in real time, [13]. A particularly significant advantage of the technique is the possibility to detect certain subsurface (near surface) irregularities that cannot be detected only by visual inspection of the monument. The thermal camera detect and records the infrared radiation emitted by materials and creates a thermal image (thermograph) that shows the temperature distribution on surfaces, which can further be correlated with certain variations in material properties, morphology and microstructure of the surfaces, [12]. The limitations of this technique are related to the external conditions (sun, rain or cold) that can affect its accuracy.

For the church of St. Nikita, the infrared thermography technique enabled a real-time examination of the monument's architectural surfaces, including: evaluation of material surface condition, mapping moisture-prone areas, detecting potential subsurface anomalies, and studying the frescoes in the interior of the church. The research was conducted using an infrared camera model Testo 875-1i, with an accuracy of ± 2°C, and the data were processed using the software package IR Soft V3.4.

Figure 8 shows a segment of the masonry on the western facade of the building along with the corresponding thermal image. The thermal image displays temperature variations ranging from 16°C to 20.5°C, with the lowest temperatures observed in the stone and the highest in the bricks, due to the different thermal properties of the materials. Additionally, the surface temperatures of the stone pieces showing signs of degradation are lower compared to those with better surface conditions, which can be attributed to porosity or moisture retention. This temperature difference is approximately 1°C.

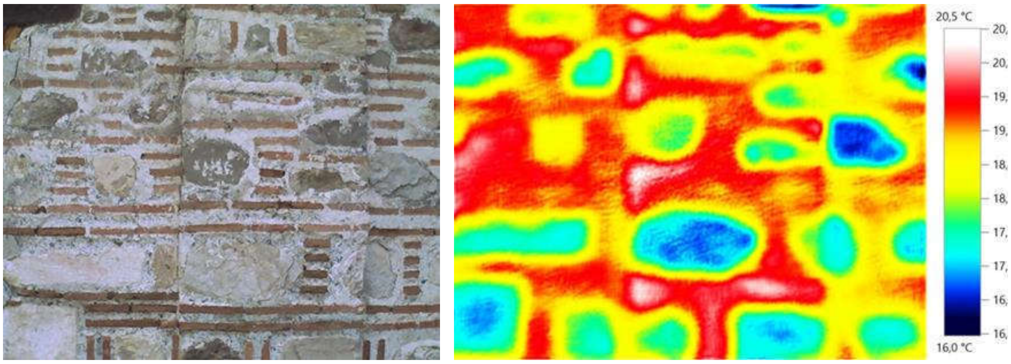


Figure 8. A segment of the masonry of St. Nikita Church (left), corresponding thermal image (right), [3]

The thermal camera enabled more accurate detection of moisture distribution within the walls. Figure 9 shows part of the northern wall (exterior side), along with the corresponding thermal image. The thermal images display irregular patterns of thermal anomalies, characteristic for moisture areas. Changes in moisture content can be correlated with surface temperature variations, and the moisture-affected areas show lower temperatures (indicated in blue color), compared to the rest of the facade’s surface. It was concluded that the highest moisture levels are in the bottom of the walls, rising up to 60-80 cm.

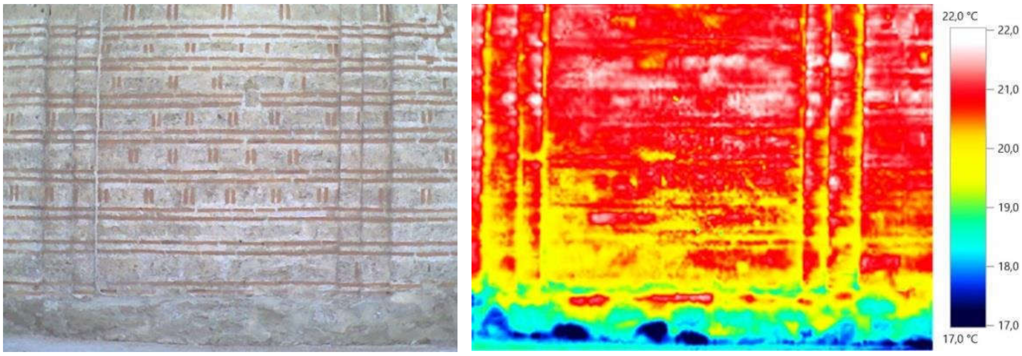


Figure 9. A segment of the northern facade of St. Nikita Church and the corresponding thermal image, [3]

The original frescoes in the interior of the church date back to the 14th century. In a later period (15th and 19th centuries), some of the damaged frescoes were partially restored, and some were repainted on a new layer of plaster, in a manner similar to the originals, making it often difficult to distinguish. The frescoes, which belong to different periods or masters, vary in composition and characteristics and have different emissive values, which can be detected on thermal camera. Figure 10 shows one composition of the southern wall, where no visible surface changes are observed. However, the thermal image of this part reveals temperature variations, precisely an area with a lower temperature (indicated by a black circle), which could suggest that part of the composition belongs to a different period.

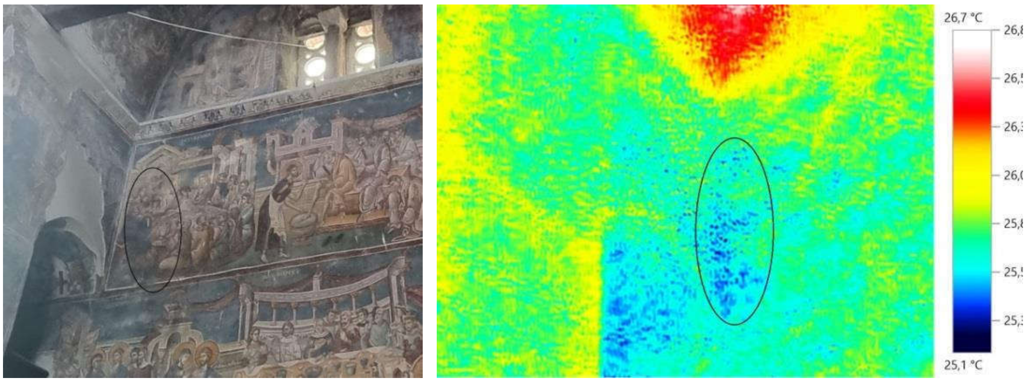


Figure 10. Fresco painting on the southern wall with corresponding thermal image, [3]

3.4. 3D Laser Scanning Technology

3D laser scanning is a non-invasive and non-destructive technology widely implemented in the field of built heritage, where it is used for surveying irregular and complex buildings [14] analysis and condition assessment, [15][16] and mainly in mapping and documenting [17][18], since it provides precise records. The limitations of this technique are related to the need for technical expertise – skills for data collection and processing.

As part of the diagnostic study of the St. Nikita church, the use of the laser scanner generated accurate digital records for the building, both in 2D and 3D, which significantly enriched the already existing documentation, which did not include this type of graphical data. The process was carried out using the Leica ScanStation P40, one of the latest scanner models, known for its exceptional accuracy and ultra-fast scanning speed of 1 million points per second. The scanner was positioned at various locations both inside and outside the church, which combined with drone footage, provided comprehensive and highly precise definition of the building's geometry.

Figure 11. Generated 3D model of St. Nikita church [3]

The data from the 3D laser scanner generated highly accurate 3D model, i.e. digital replica of the monument, fig. 11. The accuracy of this model gives opportunity for the architects, conservators and others researchers to analyze and operate the building from different angles, at any time, regardless the real physical limitations. It also gives opportunity to measure any dimension which has significantly facilitated the creation of the mathematical model used for further structural analysis of the building. Moreover, the 3D model was imported into AutoCAD program, where two-dimensional drawings such as floor plans, sections, elevations were generated, fig. 12. With some additional processing in the program, such drawings represent important documentation for the monument.

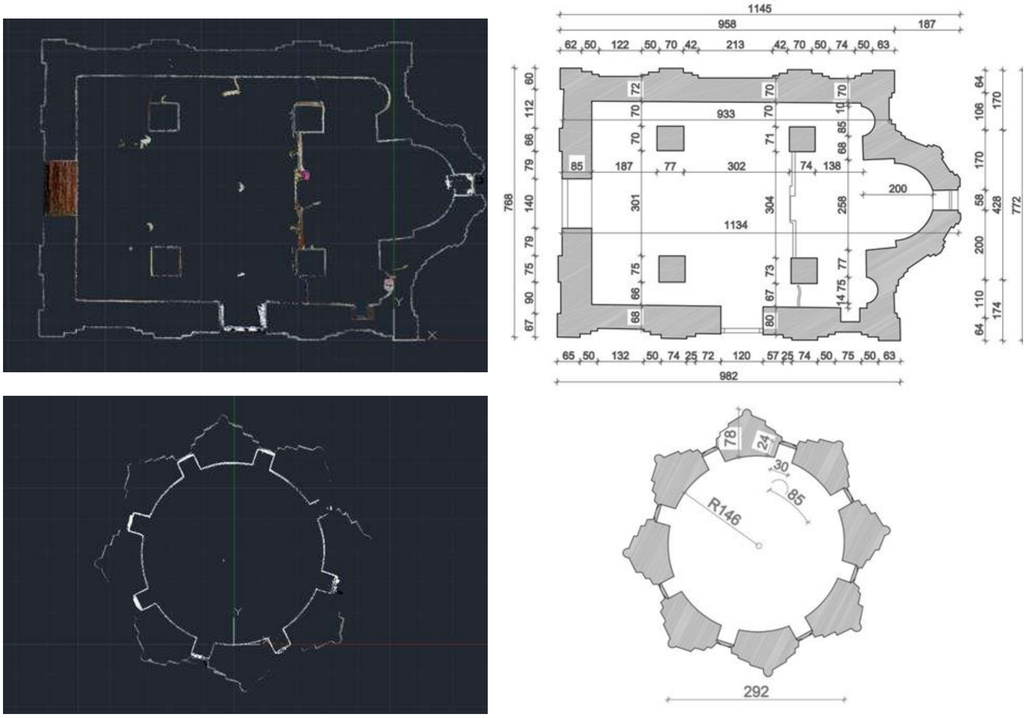
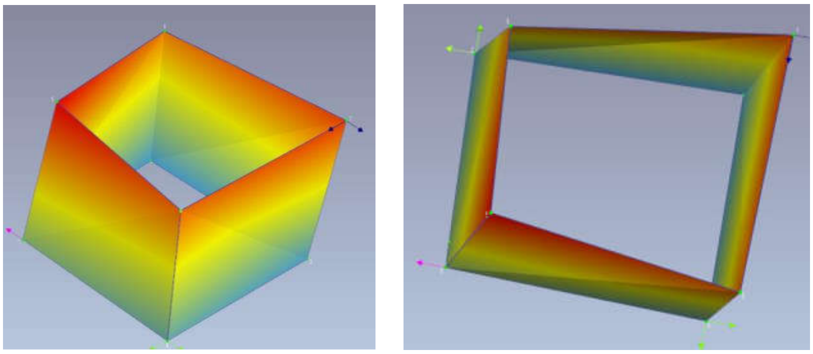


Figure 12. Floor plan of St. Nikita church - extracted from the 3D model (left) and further processed in AutoCAD (right) [3]

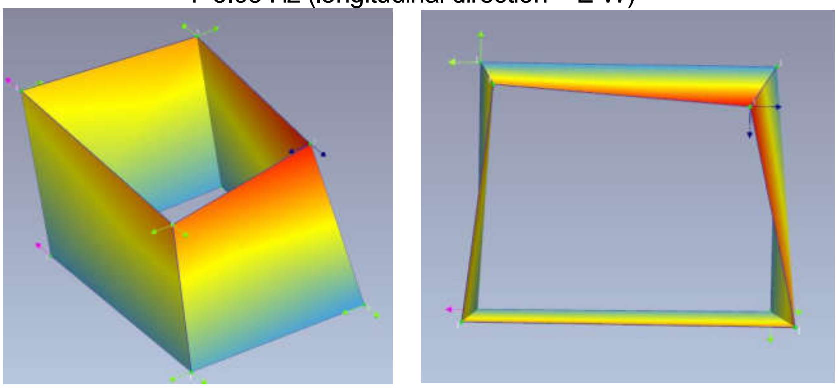
3.5. Ambient Vibration Tests

Given that dynamic parameters are related to the physical and mechanical properties of the structure (mass, stiffness, and energy dissipation), any significant structural alteration within the system will inevitably influence these parameters; therefore, the importance of their continuous monitoring, [19] .To determine the dynamic characteristics of the St. Nikita's structure (vibration periods and mode shapes) the ambient vibration method was employed. The method involves in-situ measurements of structural vibrations caused by ambient forces, such as wind, and processing of the recorded data, [20]. The advantages of this method are considerable: it offers a simple approach that does not interfere with the normal functioning of the structure, requires only a small research team, and it is both cost-effective and time-efficient. However, the sensitivity to noise can interfere with the quality of the data, which implies additional work.

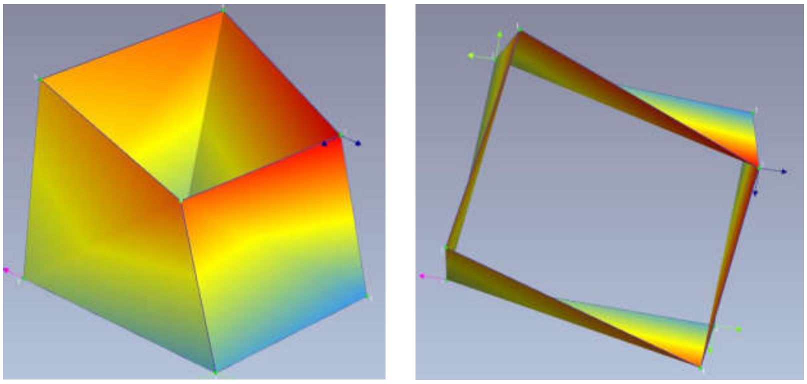
To record the vibrations, equipment comprising high-sensitivity PCB Piezotronics accelerometers, model 393B12, was utilized. These accelerometers feature a sensitivity of 10,000 mV and a measurement range of up to 4.9 m/s² (0.5g). A total of eight accelerometers were deployed, arranged across various measurement locations and orientations. A commercial software package, ARTeMIS Modal 7.0, was used for the analysis of the ambient vibration records.



f=5.98 Hz (longitudinal direction – E-W)



f=4.70 Hz (transverse direction – N-S)



f=8.05 Hz (torsion)

Figure 13. Natural frequencies and mode shapes [3]

These tests led to the identification of the natural frequencies fE-S = 5.98 Hz and fN-S = 4.70 Hz, corresponding to the natural periods TE-W = 0.167 sec and TN-S = 0.212 sec, in the two orthogonal directions, respectively. From the vibration modes, (fig. 13) it can be observed that the object, in its current state, vibrates as a single global unit. Displacements in both the longitudinal and transverse directions are generally translational, with minimal rotational movement in certain sections, more pronounced in the longitudinal direction, which is expected, given the imperfect symmetry of the plan (elongation of the altar area).

When compared with data from similar tests conducted in the 1990s (f_{E-W} = 6.00 Hz and f_{N-S} = 4.80 Hz) [6], which were measured using different equipment that required a longer testing time, it can be concluded that there have been no changes in the dynamic characteristics of the structure over the past 30 years.

4. CONCLUSION

Today, protection of cultural heritage goes far beyond than a simple “saving the old buildings”. It focuses on preserving their authenticity and safeguarding the material and semantic values that make each monument a unique creation of its time.

St. Nikita church is a well-preserved medieval monument, which has largely maintained its original state, despite the occasional past interventions. The church was studied in the 90s during the project "Seismic Strengthening, Conservation, and Repair of Byzantine Churches in Macedonia." The comparison between the findings from that period and current research indicated that the monument’s condition over the past three decades is practically unchanged.

The research underscores the importance of the integrated diagnostic study as a vital prerequisite and crucial factor for making well-informed decisions about sustainable and long-term monument preservation. Within its context, it highlights the importance of NDTs as essential diagnostic tool that provide valuable insight into building’s condition, without compromising its authenticity. In the study of St. Nikita Church, the application of several NDTs enabled complementary data for the monument, considering the fact that each method contributed different types of information. Visual inspections indicated on surface condition of the monument, while thermal camera pointed to some subsurface irregularities; the use of a 3D laser scanner enabled to generate precise digital documentation of the monument. The ambient vibration method enabled to evaluate the dynamical parameters of the structure and assess its integrity.

This overall research indicates that the current condition of the monument is relatively good, with no significant damage to the architecture or structure that would pose a risk to the stability of the building. Accordingly, no immediate interventions are necessary, but regular annual monitoring of the monument is recommended.

In line with the contemporary global scientific trends, there is an increasing need to modernize existing protection protocols in North Macedonia by exploring the potential of modern technologies and integrating them into regular conservation practice.

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