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Recent methods of visualization used in the diagnosis and consolidation of historic structures

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Abstract. The subject addresses heritage objects that are subject to degradation processes caused by both natural and anthropogenic factors. One of the current solutions is directed towards a varied range of scientific instruments, thus facilitating the analysis and diagnosis of the concerned buildings, contributing also to the identification of materials and techniques used and providing information about any previous interventions of conservation attempts. Recent visualization methods used in the diagnosis and consolidation of historic structures can utilize both three-dimensional laser scanning technology and laser interferometry as a diagnostic method, as well as alternative methods such electrometry, magnetometry and ground penetrating radar devices. The subject aims to address how heritage objects can be secured using 3D scanning technologies. The case studies were conducted on the Bezdin Monastery Complex, the "Saint Martyr Gheorghe" Church, the "Saint Martyr Filimon" Monastery and the former Metropolitan Summer Residence in Sibiu. The selected case studies illustrate the methodology for obtaining and processing field data, as well as the use of this data in the diagnosis process and in selecting appropriate consolidation options for these historical structures based on obtained results. These technologies have provided specialists with the possibility of extracting vital information both in the diagnostic phase and throughout the implementation of restoration works. Advanced scanning technologies of today have enabled the creation of a database with the capability of providing pertinent information about a building's past, starting from its initial stage, up to the completion of execution works, which significantly aids in facilitating the process of diagnostic analysis and structural calculation.

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1 Introduction

A wide range of heritage objects are subject to degradation processes caused by both natural and anthropogenic factors. One of the current solutions involves various scientific instruments, facilitating the analysis and diagnosis of the buildings in question, identifying on any previous conservation efforts or attempts.

Recent visualization methods used in the diagnosis and consolidation of historical load-bearing structures can use both three-dimensional laser scanning technology and laser interference as a diagnostic method, as well as alternative methods, including electrometry, magnetometry, and geo-radar devices. Although these technologies present a high degree of efficiency in terms of data collection, they are usually designed to serve other fields of applicability, so calibration and adaptation to the situation in which they are used represent an essential step in all methodologies applied.

Traditional techniques for analyzing and diagnosing heritage objects are usually based on invasive processes, such as taking material samples to determine their characteristics and conservation status, which can be extremely disputed. The advantage of using these contemporary methods involves collecting information in a much more sustainable and non-invasive manner. Additionally, these scientific techniques are necessary to properly determine how heritage objects behave under current environmental conditions and to monitor the implementation of conservation treatments or repairs to evaluate their success. Given the urgent need for this specific information in numerous cases, the conservation field requires data collection technologies for diagnosis and consolidation adapted to current needs.

These new technologies offer specialists involved in the restoration process the possibility of extracting vital information, both in the diagnosis phase and during the implementation of restoration work. Contemporary scanning technologies create a database capable of providing relevant information about the building's history, from its initial stage to the completion of construction work. Moreover, these technologies represent a valuable tool in monitoring structural behaviour over time, with the evolution being directly monitored by comparing previous virtual models with current ones.

The selected case studies aim to illustrate the methodology of obtaining and processing field data, as well as their use in the diagnostic process and in selecting appropriate consolidation options for these historical load-bearing structures based on the results obtained. The analysis of three-dimensional laser scanning as a visualization method in diagnosing and consolidating historical load-bearing structures involves describing the functional mechanism, advantages and concrete use in the field of cultural heritage conservation. The introduction of this type of analysis into computer-assisted programs is a real advantage of this technology, thanks to the compatibility of different types of software. Concrete cases in which it has been applied are illustrated as case studies in the presentation of the possibilities of laser technology, with laser interference also being presented as a diagnostic procedure.

2 Methodology for integrating recent visualization methods in the structural analysis

The technological and scientific advances of the last century have manifested in all technical fields, including civil construction and architecture, as illustrated by the increased use of scanning systems for the development of restoration projects. The popularity of these modern systems is due to the ease with which information can be extracted through rapid and precise data processing. Historical load-bearing structures undergo constant changes in theirs structure due primarily to the time passing, which directly indicated the restoration process, compounded by the actions of natural and anthropogenic factors. This perpetual change caused by environmental conditions requires systematic management based on the need to generate geospatial information based on numerical data. The complexity of a restoration project lies in taking into account the entire context associated with the monument in question and this can only be satisfied by increasing the level of detail associated with the analyzed information.

Laser scanning technology can be divided into two working hypotheses: the first involves a controlled deviation of the laser beams, while the second involves controlled direction of the laser beams along with the measurement of the distance covered by each beam. For instance, the first scenario encompasses laser systems utilized in ophthalmology or laser printers [1], while the second scenario is based on the three-dimensional laser scanning of a particular object.

The practical analysis method is based, first and foremost, on establishing and demarcating the positions of the three-dimensional scanning station with the help of the topographic station and their georeferencing in the stereo 70 systems. The entire building or complex needs to be covered, so the scanning is of the multi-positional type. However, if this could not be achieved in the first attempt, subsequent scans of the areas that were not covered before can be performed, resulting in these scans being corroborated with the previous ones. As a result, a complete survey is emerged, containing precise information.

From a structural analysis perspective, the first step involves creating a regular-shaped volume that encompasses the entire building, allowing for a complete count on different levels and sections that lead to certain conclusions, such as: wall or vault inclination, wall bending, arch deflection, present cracks, with the possibility to measure them, the state of the roof structure, roofing and even the attic. Thus, through this type of analysis, but also by applying other non-invasive technologies, it is possible to deduce degradation, defects, non-conformities, such as: if there are displacements in the lower area, the existence of foundation displacements can be deduced, if sizing results in bending in the central area of the wall, a significant load in the upper part of the construction can be discussed, if there are displacements in the upper area, areas with floor detachments or significant degradation at the roof level can be deduced, leading to an uneven distribution of forces or conclusions on the faulty mode of execution of the roof structure. Moreover, if the scanning analysis shows areas with major differences in thickness, delamination caused by infiltration or faulty execution can be discussed and in this case, depth scanning can be applied to further research in order to determine the presence of voids in masonry. Additionally, through depth scanning, modifications in the material's structure can also be detected.

After the 3D scanning process has been finished, the resulting model can be overlaid onto the technical project, allowing for a precise and accurate verification of the planned interventions. Subsequently, if a new scan is conducted after the execution of the interventions, a complete radiograph and a comprehensive database can be obtained. This can be used during inspection phases to determine the behaviour over time and identify any defects, displacements, cracks or settlements.

2.1 Case Study – Bezdin Monastery Complex

The Bezdin Monastery Complex is located in the western region of Romania, in Arad County, near the city of Pecica, on the left bank of the Mureș River. The complex consists of two architectural elements: the "Dormition of the Mother of God" Church and the enclosure with cells, both of which are classified as Category A monuments and are considered local landmarks.

The church, built in Byzantine style with Baroque influences in the later added areas, has a triconic floor plan with the naos directly connected to the pronaos. However, the original floor plan was modified with the construction of the bell tower above the naos. The church structure is entirely made of brick masonry, including the foundations. The nave of the church has a vaulted ceiling and the altar has the shape of an octagonal apse. The bell tower was built simultaneously with the pronaos and is supported by two brick masonry pillars.

a)

b)

Fig. 1. (a) Aerial perspective, (b) Aerial perspective - 3D Drone Survey.

The investigation of the Bezdin Monastery Church was carried out using traditional methods of measurement and degradation identification, as well as recent visualization techniques, such as 3D laser and drone scanning. The scanning allowed for the collection of relevant information, such as degradation, dimensions, heights and details of inaccessible areas. The analysis included placing the entire building in a parallelepiped and conducting internal and external measurements to determine deviations, rotations, cracks and conservation status. The analysis also identified degradation caused by differential settlements, as well as architectural defects caused by water damage. To summarize, the investigation used a combination of traditional and modern techniques to collect detailed and accurate information about the current condition of the church.

a)

b)

Fig. 2. (a) Cracks and degradation caused by differential settlements, (b) Deteriorations on the facades of Bezdin Monastery Church captured through 3D laser scanning

On the exterior, the main deteriorations are found in the cornice area, caused by the progressive degradation of the roofing, as well as the water drainage system - gutters and downspouts. Additionally, there are also deteriorations at the level of the finishes, mainly caused by capillary water, as well as previous interventions made with cement-based mortars.

2.2 Case Study – The ”Saint Martyr Gheorghe”

The "Saint Martyr George" Church in Beregsău Mare village, Săcălaz commune, was first mentioned in 1793 and was later built between 1809 and 1812 [2]. It is currently listed as a historical monument in Timiș County, with the code LMI: TM-II-m-A-06186.

The church was constructed using fired brick masonry for both the walls and the foundation. The thickness of the structural walls varies between 65 to 92 cm and the vaults are also made of brick masonry. The building has a regular plan, with a maximum dimension of 24.15 x 9.80 meters. The height of the church reaches approximately 12 meters, except in the area of the tower, where it has 23.65 meters.

The current state of conservation of the building reveals a series of cracks in the area of the vaults and arches, especially on areas where the plaster has detached from the underlying layer. Analysis of the building's different behaviours was carried out using point cloud technology, combined with laser measurements and field investigations, in order to obtain direct and accurate information on the structural damage of the building. By analysing each façade separately, the following information can be extracted.

Through the analysis of the point cloud and the creation of vertical lines at a distance of one meter from each corner, the following differences were obtained: The lower left side measures 0.96 meters, while the upper left side measures 1 meter; the lower left side of the tower measures 1 meter, while the upper left side of the tower measures 0.97 meters; the lower right side measures 1 meter, while the upper right side measures 1 meter; the lower right side of the tower measures 1 meter, while the upper right side of the tower measures 1.03 meters. Additionally, there is a visible crack in the pediment area, with a length of 3.92 meters, starting from the corner of the window opening and continuing to the portico area. Preliminary conclusion: there is an outward displacement of the upper part of the building's masonry on the left side facade, as well as a displacement towards the right of the tower without major structural damage, (see Fig. 3a).

On the vertical axis, the following measurements were obtained (see Fig. 3b): Left side lower area = 1.02 m, left side upper area = 1 m; left side lower area of the tower = 0.90 m, left side upper area of the tower = 0.91 m; right side lower area = 1 m, right side upper area = 1 m; right side lower area of the tower = 1.02 m, right side upper area of the tower = 1 m.

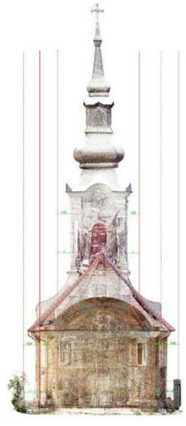
a) b)

Fig. 3. (a) The main façade of the church, (b) The right lateral façade of the church.

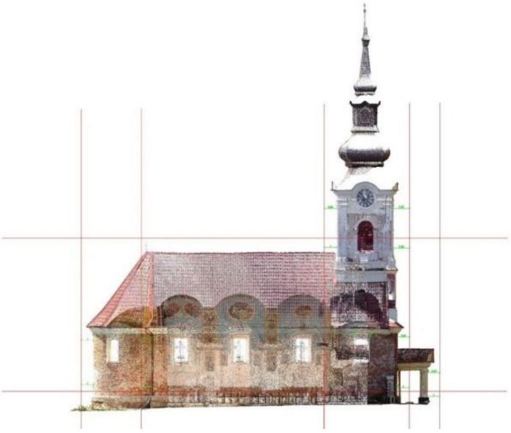
Additionally, there are visible external cracks, approximately 0.7 m in length, on the facade, starting from the corners of the void and extending to the cornice area. Preliminary conclusion: there are no major structural damages. The upper masonry in the main facade has shifted inward. In the choir area, the masonry on the rear facade does not show any displacement.

On the vertical axis, the following measurements were obtained (see Fig. 4. (a)): Left side lower area = 1 m, left side upper area = 0.97 m; left side lower area of the tower = 1 m, left side upper area of the tower = 1.01 m; right side lower area = 1 m, right side upper area = 0.92 m; right side lower area of the tower = 1 m, right side upper area of the tower = 1.02 m. Preliminary conclusion: there are no major structural damages. The upper masonry on the left side of the lateral façade has shifted outward.

On the vertical, the following measurements can be found (see Fig. 4 (b)): the left side of the lower zone is 1 m, the left side of the upper zone is 1 m, the left side of the tower's lower zone is 1 m, the left side of the tower's upper zone is 0.99 m, the right side of the lower zone is 1 m, the right side of the upper zone is 0.97 m, the right side of the tower's lower zone is 1.33 m, the right side of the tower's upper zone is 1.33 m. There are cracks present near the window opening, starting from its corners and continuing towards the cornice, with a length of approximately 0.70 m. Preliminary conclusion: There are no major structural damages. There is an outward displacement of the masonry in the upper zone of the main facade and at the upper part of the porch.



a)



b)

Fig. 4. (a) The back façade of the church, (b) The left lateral façade of the church.

After analysis, it is evident that the heritage object is in a good state of preservation, with the main affected areas being the front façade, as well as the right and left lateral facades, due to the presence of visible exterior cracks that may affect the structural integrity of the church. These cracks extend from the corners of some openings to the cornice, with lengths of approximately 70 cm, and up to 3.92 m in the area of the pediment in the front façade.

2.3 Case Study – The ”Saint Martyr Filimon”

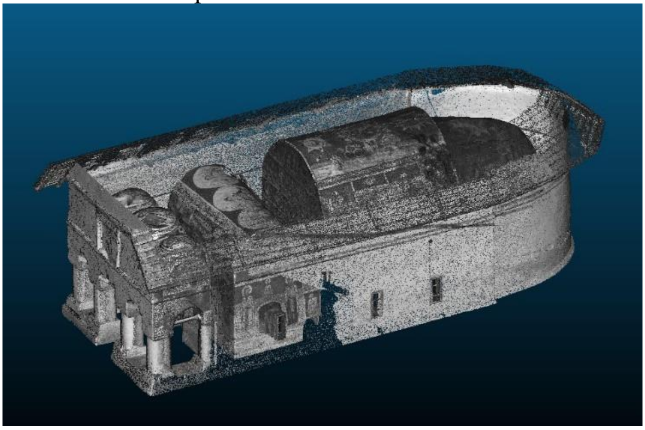
The "Saint Martyr Filimon" Monastery is a heritage building, built in the early 19th century, located in Golești commune, Țânculești village, Vâlcea county. The church is a typical construction, specific to the Eastern Orthodox religion, without lateral apses. The maximum dimensions in plan are 14.75 m in length and 5.50 m in width. In terms of floor plan, it has an open porch, a vestibule, a nave, and an altar. The dimensions of the interior spaces are presented in Table 1.

Table 1. Interior spaces list

Room	Dimensions	Maximum keystone height
Porch	1.50 x 4.10 m	4.60 m
Narthex	2.35 x 4.15 m	4.30 m
Nave	4.42 x 4.15 – 4.20 m	5.25 m
Altar	2.75 x 3.65 m	4.75 m

The monastery, built in 1806, has a structure made of un-reinforced brick masonry with continuous foundations made of river stone masonry and fragments of crystalline schist, with fine/medium sand as a binder that played more of an equalizing role than a bonding one and with a foundation depth of -0.70 meters relative to the level of the terrain. The roof system of the space is composed of brick masonry vaults and arches, and a wooden turret is located in the porch area. The roof is made of wood and covered with shingles. Therefore, the main non-structural elements are represented by the wooden turret and the masonry pediment with a wooden frame, located above the entrance to the porch.

a)

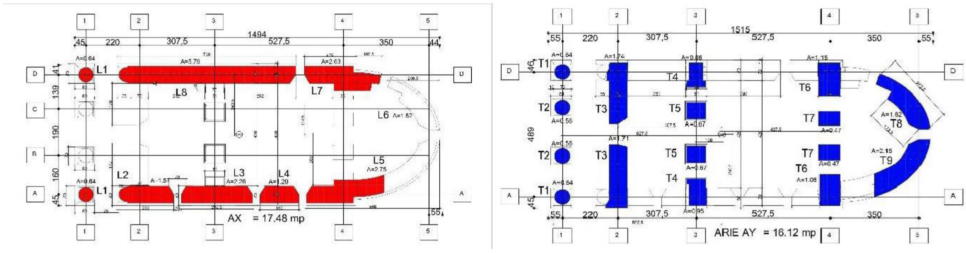


b)

Fig. 5. (a) The ”Saint Martyr Filimon” Monastery, (b) 3D Laser Survey.

The height of the church at the eaves level is 4.25 meters and at the ridge level is 8.10 meters. The roof of the turret is positioned at a height of approximately 9.75 meters and the peak of the turret covering is at a height of approximately 11.35 meters. The church is heated by a wood-burning stove, and the exhaust gases are evacuated through an improvised chimney located laterally, towards the southern facade. The electrical system is surface-mounted.

Following observations made on-site, it was revealed that a structural analysis was needed in order to consolidate the building, which showed multiple deteriorations caused by differential settlements, as well as the existing loads. The distribution and configuration of the load-bearing walls in the plan are shown in Fig. 6 (a) and (b). Thus, it can be observed that the area occupied by them on the OX axis is 17.48 square meters, and on the OY axis it is 16.12 square meters.



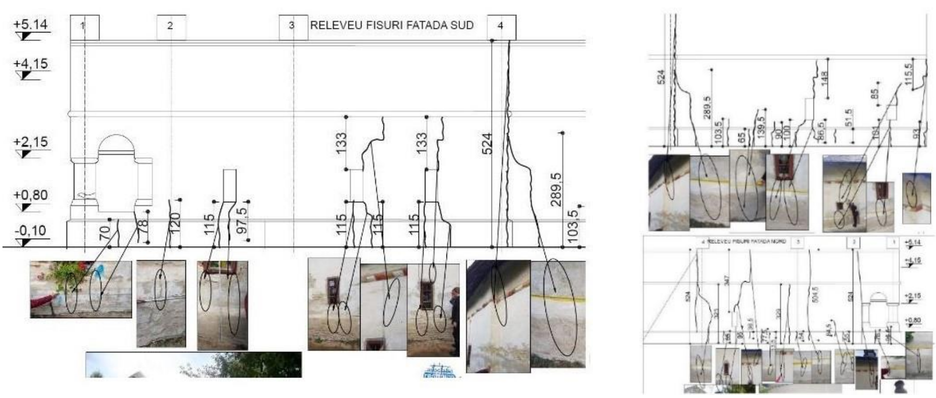
a) b)

Fig. 6. (a) The distribution of the load-bearing walls in plan along the Ox axis, (b) The distribution of the load-bearing walls in plan along the Ox axis.

In terms of the building's state of preservation, a significant advantage can be observed compared to other heritage objects. Throughout its existence, the building served only one functional purpose, that of a place of worship, so no interventions were made on the configuration of the load-bearing structure, except for the area of the roof truss. According to the votive table, the wooden spire did not exist at the time of construction, but was added later. Repairs were carried out both inside and outside in 1928, and the roof underwent interventions on several occasions.

The first observation regarding the causes of structural damage concerns the damage to the masonry and plaster caused by the combined action of rising capillary water and freeze-thaw cycles. The second component that contributed to the present damage is represented by seismic action. From observations on the case at hand, the presence of a longitudinal crack was found, starting from the porch area and continuing towards the altar area, with a tendency to separate the entire building into two fragments. Also, the presence of a set of transverse cracks is noted, located in the weakened sections of window openings, niches, and doors, as well as cracks in the masonry elements, especially at the arch keys in the masonry, continued towards the window and door openings.

In the area of the facades, detachments were identified between the transverse walls and the lateral faces, as well as inclined cracks at the corners of the openings, appearing as a consequence of dynamic actions. A series of cracks are represented in Fig. 7 (a) and (b). Also, cracks were identified at the level of the vaults made of masonry in the attic area.



a) b)

Fig. 7. (a) Cracks – South façade, (b) Cracks – North façade.

Regarding the damages found at the horizontal elements of the structure, deteriorations were detected at the level of the flooring, as well as cracks in the vault of the nave and the one in the altar. Furthermore, the structural system of the roof truss also exhibits deteriorations at the joints, as well as deformations of the rafters.

2.4 Case Study – The Former Metropolitan Summer Residence in Sibiu

The former Metropolitan Summer Residence in Sibiu is a villa-type building surrounded by an enclosed English garden and was built around 1876 in an eclectic style as a residence for the Metropolitan of Transylvania [3]. The building's floor plan is rectangular with multiple setbacks and accesses.

Structurally, the building has continuous foundations made of brick masonry, load-bearing walls made of brick and mortar based on lime, clay, and sand, with thicknesses of 50 cm on the exterior and variable thicknesses ranging from 30-50 cm on the interior. The floors are made of brick vaults in the basement, ground floor, and upper floor, with wooden beams arranged at a distance of 75 cm, with metal ties mounted at their level. The roof structure was made in a traditional manner using specific technologies of the time. The distribution of the walls in the plan is presented in Fig. 8. In the longitudinal direction, the walls occupy 21.65% of the built area, and in the transverse direction, 19.97% [4].

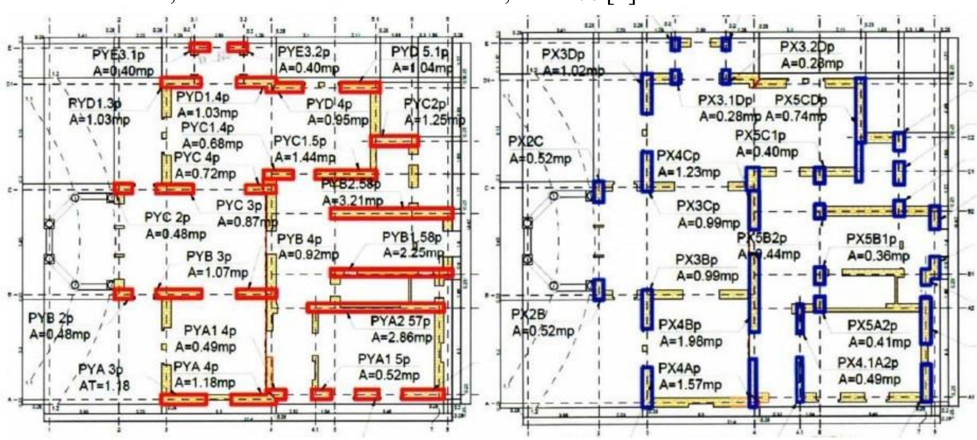
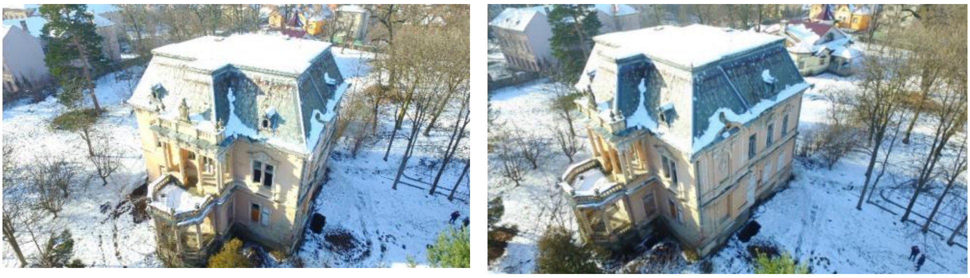


Fig. 8. Wall placement – ground floor plan and first floor plan.

During the communist period, the building housed the Pioneer House, but it was later abandoned and fell into an advanced state of decay due to post-December events. At this time, the building and the land have been returned to the Orthodox Church and the ensemble is classified as a historical monument. The change of function directly contributed to the cause of structural damage due to the modification of the structural system's configuration to accommodate subsequent functions. Thus, among the modifications, there were the creation or closing of door or window openings, as well as the demolition of external access stairs. The use of point cloud technology manages to illustrate the different behaviours of the building, as highlighted below. These, combined with photogrammetry and laser measurements, provide direct and accurate information on the constructive deformations of the building.

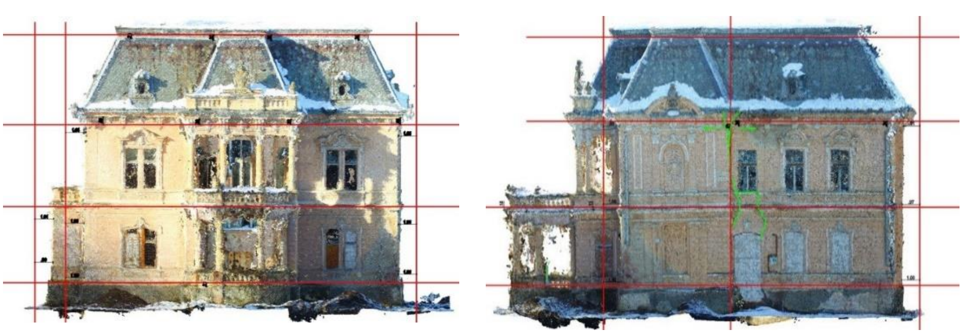


a) b)

Fig. 9. (a) Cracks – South façade, (b) Cracks – North façade.

By analyzing each façade individually, information can be extracted as follows. By analysing the point cloud and drawing horizontal and vertical lines one meter away from each corner, the following differences can be observed: On the vertical axis, the following differences can be found (see Fig. 10 (a)). The eastern side has a difference of 1 m from the base to the floor above the ground floor, and another 1m from the floor above the ground floor to the floor above the first floor; the western side has a difference of 1 m from the base to the floor above the ground floor, and 1.04 m from the floor above the ground floor to the floor above the first floor. The preliminary conclusion illustrates an inward displacement of the upper part of the building's masonry. On the horizontal axis, the following differences can be found: The floor line in the central area (balcony area) shows a settlement of 21 cm; the floor line above the first floor shows that the settlement is maintained both at the balcony level and at the central wall level; the floor line above the ground floor shows a repeating settlement in the central attic area, partially covering the balcony. The preliminary conclusion is the presence of uneven settlement in the central area of the building.

On the vertical axis, the following differences can be observed (see Fig. 10 b): Left side base = 1 m, floor above ground floor = 1 m, floor above first floor = 0.89 m. Preliminary conclusion: there is a displacement of the masonry at the upper part of 2 cm. In the central area of the facade, a double-directional cracking zone is highlighted, one towards the left, with a distance of 7 cm at the upper part, and the other towards the right with 9 cm. Preliminary conclusion: the building is cracked in two different directions with a total differential settlement of 16 cm. Right side base = 1 m; Floor above ground floor = 0.97 m; Floor above first floor = 0.91 m. Preliminary conclusion: there is an outward displacement of the entire wall, increasing from the base to the upper part by 9 cm. On the horizontal axis, the following differences can be observed: The floor line is skewed. The floor line above the ground floor shows a settlement in the balcony area with a drop of 5 cm. The floor line above the first floor shows differences from the central area, with a drop of the floor towards the right by 7 cm. Preliminary conclusion: there is a settlement on the corner on the right of 9 cm, and a settlement of the terrace on the left side of 5 cm.



a) b)

Fig. 10. (a) The main façade, (b) The right lateral façade.

On the vertical, the following differences can be found (Fig. 11 (a)): Left side at the base = 1 m, floor above ground level = 0.97 m, floor above first level = 0.96 m. Preliminary conclusion: there is a displacement of the masonry at the top by 4 cm, towards the left. On the vertical, in the central area, the following differences can be found: At the base = 1 m, floor above ground level = 0.97 m (left), and 1.03 m (right); Floor above first level = 0.96 m (left), and 1.04 m (right). Preliminary conclusion: there is a displacement of the masonry at the top by 4 cm, towards the left. Right side at the base = 1 m, floor above ground level = 0.97 m, floor above first level = 0.96 m. Preliminary conclusion: there is a displacement of the masonry at the top by 4 cm, towards the left. On the horizontal, the following differences can be found: The floor line slopes to the left with a difference of 7 cm; The floor above ground level shows a sag of 7 cm towards the left. The floor above first level shows a drop towards the left of 7 cm. Preliminary conclusion: settlement on the corner to the right of 7-8 cm.

On the vertical plane, the following differences can be observed (Fig. 11 (b)): Left base side = 1 m, floor above ground floor = 0.96 - 0.98 m, floor above first floor = 0.92 - 0.95 m. Preliminary conclusion: there is an upward displacement of the masonry of between 5 and 8 cm, towards the left. On the vertical plane, in the central area, the following differences appear: At the base = 1 m, floor above ground floor = 1.03 m; Floor above first floor = 1.08 m. Preliminary conclusion: there is an upward displacement of the masonry of 8 cm towards the left. Right base side = 1 m, floor above ground floor = 0.97 m, floor above first floor = 0.92 m. Preliminary conclusion: there is an upward displacement of the masonry of 8 cm towards the right. On the horizontal plane, there are the following differences: The floor line slopes towards the right with a difference of 10 cm; The floor line above the ground floor shows a settlement of 4 cm towards the right. The floor line above the first floor shows a fall towards the right of 18 cm. Preliminary conclusion: settling on the corner on the right of 14 cm.

a) b)

Fig. 11. (a) The back façade, (b) The left lateral façade.

In conclusion, the building has significant structural damage, with major cracks and fractures in the joint areas, mainly due to differential settlements. In the area of the attic and the cornice, there are cracks in the masonry, as well as cracks at the level of the basement vaults, cracks in the brick arch on the ground floor that supports the staircase. Deterioration is also present on the facades, where the plaster shows significant damage, and on the portions where it is missing, its absence has caused partial erosion of the mortar from the joints.

3 Conclusion

Following these case studies, it can be acknowledged that laser scanning technology represents an instrument that tends to become indispensable in the current practice of diagnosing historical load-bearing structures. The information obtained through the analysis of these scans has concisely and faithfully revealed the state of conservation of the studied buildings from a structural point of view, highlighting a series of damages such as wall inclinations or bends, arch deviations, existing cracks, displacement of structural elements, effects of differential settlements and primarily, the degree of damage associated with the entire building in question.

Furthermore, laser scanning technology has facilitated the study of the long-term behavior of the analyzed buildings, providing real time monitoring of their state of conservation and the progression of any deterioration. This data can be cross-referenced with previous analyses in order to establish a comprehensive data base and radiographic image of the buildings under investigation.

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