Structural analysis and damage assessment of a fortified church – A case study: The Evangelical Church of Apos, Sibiu County

Porumb Ana-Maria[1*] and *Petruse Diana Eva* Larisa[1]

[1]Polytechnic University of Timișoara, Piata Victoriei 2, Timișoara 300006, Romania

Abstract. Globally, there is a wide range of monuments that require conservation and restoration work in order to maintain their values as a whole, both from the aesthetic and historical perspective and to ensure their preservation for future generations. The aim of this paper is to showcase the historical development of the fortified church structure in Apoș, in addition to examining the reasons for its structural damage and exploring possible ways to strengthen the entire church – tower complex. The Evangelical Church is located in the village of Apoș, in the central region of Transylvania, along the Hârtibaciu Valley. This region is of national importance, being part of the Hârtibaciu Plateau and also within the Natura 2000 sites. The church complex consists of the church itself, which is also listed in the Historical Monuments List with the code SB-II-a-B-12313, the bell tower and the clergy house. However, this paper concerns only the church and the tower. The evolution of the church spans over several centuries, during which its structure underwent reconfigurations, consolidation works, but also invasive interventions with incompatible materials that further altered the entire structure and its behaviour. Thus, from the point of view of interventions, they were carried out progressively, the most extensive works being the replacement of the nave ceiling with cylindrical vaults and the replacement of the choir ceiling with a semi-spherical vault, as well as the consolidation works of the building in the 20th century. The investigation of the Evangelical Church was carried out, first of all, by conducting an on-site investigation, followed by using traditional survey methods in order to identify the structure failures. Additionally, contemporary visualization methods, such as three-dimensional laser scanning, were utilized to gather information on dimensions, heights and ornament details. Through these steps, a survey was obtained that includes accurate data on the church complex. Following these stages, the main degradations identified were a series of cracks caused by differential settlements and the lack of cooperation between structural elements, mechanical damage caused by the detachment of the buttresses from the walls and due to the sliding of the land towards the south, after the demolition of the fortifications. Additionally, two types of brickwork damage were identified: pronounced crack indicating its displacement, contributed by seismic activity and smaller but numerous cracks indicating the disintegration of the brickwork caused by differential settlements combined with prolonged moisture. Besides these, human factors and

[*] Corresponding author: ana.porumb@student.upt.ro

execution defects were identified, as well as physicochemical degradations with internal causes, such as composition defects or crystal cohesion defects. The repair and consolidation works, including seismic safety measures, have proposed technologies based on the principles of reversibility and preservation of the church's authenticity. Thus, the main interventions aim to strengthen the structural walls, arches and vaults, eliminate the source of humidity causing the erosion of the masonry through capillary water infiltration, strengthen the floors, roof structure and openings, as well as the interior elements, such as balconies and stairs.

1 Introduction

Located in the central region of Transylvania, the Evangelical Church in Apoș village, which is a constituent of the Bârghiș commune, lies alongside the Hârtibaciu Valley. This region is deemed nationally significant due to its positioning in the Hârtibaciu Plateau and is further recognized under the Natura 2000 sites, code ROSCI0304. The Church Complex is composed of the church, which is officially recorded under the code SB-II-a-B-12313 in the Historical Monuments List, the bell tower and also the clergy house.

The village's geographical and cultural position is highly advantageous, given its proximity to several historically and culturally significant cities in the area, such as Sibiu, Sighișoara, Agnita or Mediaș, as shown in Fig. 1. Moreover, Apoș belongs to the fortified churches area in Transylvania, which is renowned as the cradle of Saxon culture in Romania. This area is highly diverse in terms of its biodiversity and has also managed to maintain its traditional values to date.

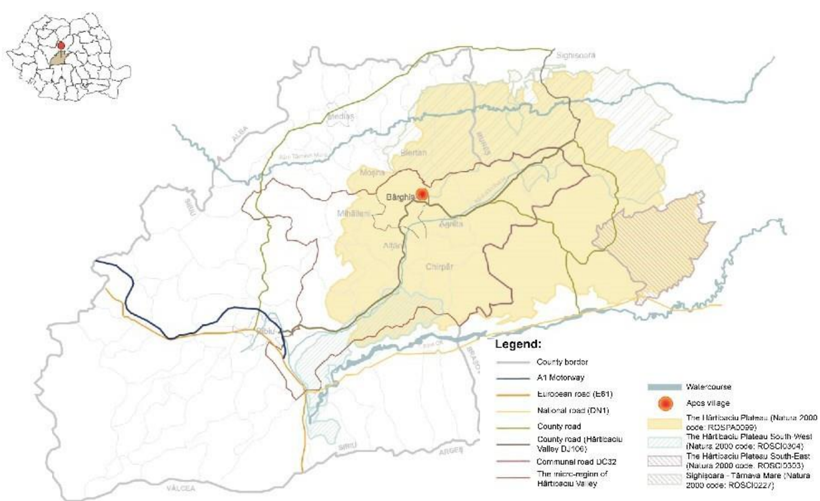


Fig. 1. Geographical location of the Apoș village within the territory.

On the exact location of the current church, a wooden church surrounded by a wooden fence existed as early as 1300, with the current building being erected from more durable materials from the middle of the 15th century onwards. Over the following centuries, the entire complex underwent continuous modifications, with the enclosure wall being built, a series of constructions being annexed and the bell tower being constructed. Interventions were carried out progressively over time and in line with the time's needs. Thus, a series of transformations took place during the 18th and 19th century, marked by the replacement of the nave ceiling with cylindrical vaults and consolidation works of the building. During this time, openings began to appear along the fortified wall, illustrating the loss of the defensive character of the building [1].

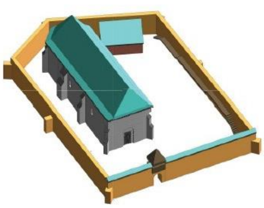
From a territorial standpoint, the Apoș village is a linear, valley settlement, concentrated along a watercourse, surrounded on three sides by hilly formations. From an urbanistic point of view, a strict organization is noticeable, given by the linear arrangement of the streets and the rhythm of land plots, as well as the buildings within them. Due to the topography of the area, traffic flows smoothly along two main streets, one following the watercourse and the other parallel to it.

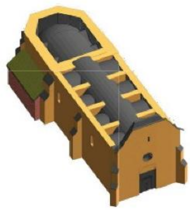
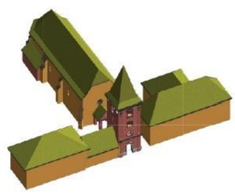
The church complex is located at the northeastern extremity of the village, behind the main row of houses, at a slightly higher elevation than the general topography of the settlement. Considering the arrangement of major elements and the slope of the terrain, as well as the topographic modifications caused by landslides on the southern side of the complex, the strategic placement of the church within the village is evident, as it facilitated its defense. Furthermore, the church's location illustrates a relationship of subordination between the village and the church, both volumetrically and symbolically, as it is situated on a higher area of the land. Thus, the church is oriented towards the anthropized landscape, with its western side, and towards the natural landscape, with its eastern side. Additionally, the southern side faces the road leading to the roof tile factory, while the cemetery is located in the vicinity of its northeastern zone.

2 The evolution of the complex over time from a volumetric and structural perspective

The chronological evolution of the fortified church complex can be traced over six centuries, which unfolded as follows in Table 1.

Table 1. Evolution over time.

Chronology	Volumetric	Changes in the volumetric and structural nature
1450 – 1700		The church is made of stone with a shingle roof. Buttresses are added. The enclosure wall, made of stone and brick, is erected.
1750		A thorough restoration of the church is undertaken, encompassing the repair of the walls and buttresses, as well as the incorporation of brick inserts. The roof undergoes modification, accompanied by the replacement of shingle roofing with tiles. The entrance opening is framed by a sandstone block.

1763 – 1800		The choir of the church is rebuilt and the ceiling is replaced with a semi-spherical vault. The ceiling of the nave is replaced with cylindrical vaults.
1800 – 1900		The enclosure wall undergoes repairs, although a section of its eastern side is abandoned towards the end of the 19th century. The bell tower's ground floor is built with a vaulted ceiling. Moreover, the walls of the bell tower are built using stone up to a height of one meter and above that, brick masonry is used. Modifications are made during this time to the entrance opening on the western façade.
1913 – 2000		The enclosure walls are completely demolished. Between 1961 and 1964 a new series of consolidations are carried out. The porch on the western side is built.
2000 – 2022		Interventions are carried out on the church's roofing due to the exfoliation of historic manufactured roof tiles, cracks in the roof tiles caused by mechanical shocks, slippage of roofing elements from the battens, as well as incorrect placement of battens in specific areas. Autoclaved aerated concrete interventions are made above the access opening on the western façade.

3 The current state of conservation

3.1 General Characteristics

The conservation state of the building is precarious, with forms of degradation increasing over time. The most affected areas are located on the facades and also at the entire structural system. Some of the main problems that have led to progressive damage are manifested by the presence of capillary water, the tendency of the terrain to slide towards the southern area, degradation caused by seismic activity, but to a large extent, human factors have contributed to accentuating all forms of degradation due to the lack of proper maintenance. Table 2 presents general data regarding the church - tower complex.

Table 2. General data regarding the church complex

Criteria	Type
Importance category	B – Buildings of special importance (according to Government Decision no. 766/1997) [2]
Seismic importance class	II – Buildings from the national cultural heritage (according to table 4.2 "Seismic Design Code - Part I - Design Provisions for Buildings - P100-1/2013" [3]
Monument classification	SB-II-a-B-12313 (according to The List of Historical Monuments) [4]
Seismic zone	Macro seismicity zone I=71
Wind action zone	qb = 0.4 kPa
Snow loading zone	sk = 1.5 kN/m^2

3.2 Analysis of the existing load-bearing structures

The church has a wooden roof structure with a five-pitched roof and a slope break towards the cornice area. In the choir area, the roof structure is arranged radially, following the polygonal shape of the choir, while in the main access area, on the western side, the roof is shingled, typical of the Transylvania region. The bell tower has a wooden roof structure, with a four-pitched roof and similar to the church, with a slope break towards the cornice area.

From the point of view of the floor system typology, the church has cylindrical vaults with perforations in the nave area, supported by brick pilasters, while in the choir area, the ceiling is made of a semi-spherical vault. The bell tower is also vaulted in the ground floor area, with intermediate floors made of wood, but currently they no longer exist.

The structural walls are made of brick and stone masonry, having different thicknesses, while the access area in the western façade is made of a sandstone block. The bell tower's walls are made of stone masonry up to one-meter height, while at a greater height, they are made of brick masonry. The foundations are made of stone masonry, but in the choir area, a series of underpinnings was carried out during the 1960s - 1970s.

a) b)

Fig. 2. (a) Aerial perspective - 3D Drone Survey, (b) Aerial perspective of the church, bell tower and clergy house - 3D Drone Survey

3.3 The current structural state of the buildings

The identification of deterioration forms and their nature, as well as the pathology of the existing structures were carried out by categorizing the elements, as illustrated in Table 3.

Table 3. Damage assessment survey

Identified damaged area	Affected area	Pathology
Fish-scale roofing – the nave	Minor degradation	1. Lack of performing regular maintenance operations at regular intervals. 2. The cornice area presents unevenness that favours the runoff of rainwater on the façade.
Fish-scale roofing – the choir	Local, minor forms of degradation	3. Lack of performing regular maintenance operations at scheduled intervals. 4. The cornice area exhibits gaps that promote the drainage of rainwater along the façade.
Fish-scale roofing – the bell tower	Local, minor forms of degradation	5. Lack of performing regular maintenance operations at scheduled intervals. 6. The cornice area exhibits gaps that promote the drainage of rainwater along the façade.
Buttresses' roofing	Widespread, major deterioration	7. The roofing was applied on an uneven support layer, causing detachment from the support layer, thus exposing the masonry to atmospheric factors.
Porch's roofing	Widespread, major deterioration	8. The roofing is missing completely.
Exterior elevations – church and bell tower	Widespread, medium and major degradation, structural damage	9. Pronounced cracks caused by differential settling due to the lack of cohesion of the foundation soil. 10. Outward displacements of the masonry above the main entrance arches. 11. Structural damage is mainly caused by the non-conformance of the structural elements, which was attempted to be remedied with interventions in the 1960s by inserting concrete beams above the choir and a perimetral reinforced concrete belt, however it was never completed. 12. Vertical fractures separating the porch from the main church volume caused by the non-conformance of the structural elements. 13. Compromise of the buttress arch and subsequent incorrect intervention with inadequate materials. 14. Cracks on the western facade are not mirrored on the opposite façade due to the circular arch shape of the eastern façade, which is more resistant to differential settling due to its geometric shape. 15. Areas with weathered mortar between bricks due to external atmospheric factors. Locally, the plaster is made of cement and was directly applied to the old lime-based plaster. 16. Moisture in the field of the façade, especially at the base of the walls.
Rainwater drainage systems	Local, minor forms of degradation	17. Irregularities. 18. Due to the possibility of water run-off onto the façade surface prior to the roof repair interventions, there may be a wet area adjacent to the downspouts in its field, which could be attributed to this run-off.

Identified damaged area	Affected area	Pathology
Buttresses	Local, medium and major forms of degradation	19. Peeling of the paint from the support layer. 20. Vertical fractures separating the buttresses from the main church volume caused by the non-conformance of the structural elements.
Cornice – church and bell tower	Local forms of degradation, minor in terms of affected surface area but medium in terms of implications	21. Wet areas. 22. In the upper area of the choir, the plaster is cement based.
Openings and joinery	Degradation caused by human intervention	23. Lack of performing regular maintenance operations at scheduled intervals. 24. Alteration of the shape of window openings. 25. Cracks near the window openings on the western and northern facades of the bell tower.
Interior elevations	Local, medium and major forms of degradation	26. Erosion of masonry caused by capillary water infiltration in the lower area of walls and pilasters. 27. Lack of regular maintenance operations at proper intervals. 28. Cracks near window openings on the southern façade.
Balcony	Major forms of degradation	29. Lack of regular maintenance operations at proper intervals.
Vaults and floor systems	Local, medium and major forms of degradation	30. Exfoliation of plaster caused by the infiltration of water. 31. Seismic structural damage found on the nave's vaults.

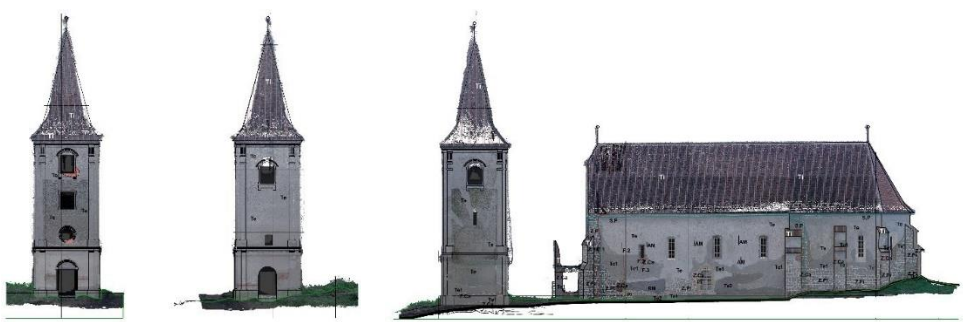
Based on the visual inspection, drone survey, illustrated in Fig. 2, as well as the damage assessment survey, the following conclusions have been drawn:

Surface degradations can be classified into the following categories, considered the main causes of degradation:

1. Degradations affecting the whole structural integrity, as shown in Fig. 3 and Fig. 4, caused by the appearance of cracks due to differential settlements and lack of cooperation between structural elements, as well as degradation of the layers' structure due to the influence of atmospheric factors such as meteoric and capillary waters, UV rays, and wind action, which together caused discoloration, crusts caused by the presence of salts, peeling, detachment of plaster and its grinding. Mechanical degradations resulted from the detachment of buttresses from the walls, as well as due to the sliding of the terrain towards the south after the demolition of the fortified enclosure wall. Also, in the case of brick masonry, two types of damages are distinguished: pronounced cracks indicating massive displacements of masonry and/or smaller but numerous cracks indicating masonry disintegration. In the case of the Apoș Ensemble, differential settlements combined with prolonged states of high humidity levels led to the disintegration of the load-bearing masonry. Also, seismic activity can be considered one of the factors contributing to the occurrence of damages, but these damages are difficult to identify given the current state of the

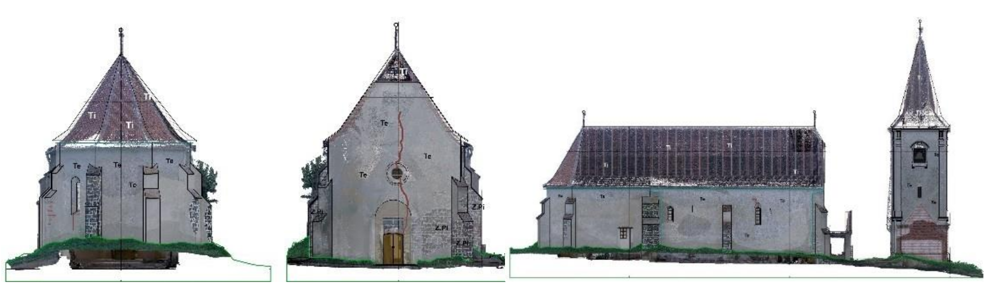
construction. Thus, both hypotheses can be considered determinant factors in the structural degradation process, but the most visible one is the uneven settling of the terrain.

2. Degradations caused by human factors and execution defects, as shown in Fig. 3 and Fig. 4 - transformations, maintenance defects, lack of protection against capillary and meteoric water, thermal bridges, wind action, lack of maintenance of vegetation in the proximal area. A series of interventions are noted that are not compliant with the use of cement mortar during repairs in the 1960s, at the base of the walls, with the aim of restoring the deteriorated plaster due to moisture infiltration from the soil, thus, the cement mortar has produced additional chemical degradation, making the masonry brittle. Another area that has undergone numerous alterations is the main access arcade, being the most frequently used mobile element of the building. Some of the degradations may be due to the technological process used at that time for these materials, due to the presence of defects, from the protection of the materials used to chemical, physical, or biochemical factors. Masonry made from inferior quality, unburned or incompletely burned bricks, with inclusions, having large, uneven, and unfilled joints with mortar, has been subjected to degradation. The use of dusty bricks and the use of inadequate quality mortar favoured the creation of a masonry with low resistance. The realization of subsequent interventions, on the occasion of making gaps, slots, or piercings in masonry, contributed directly to the progressive decaying state of the buildings in question.
3. Physicochemical degradations, as shown in Fig. 3 and Fig. 4 (The legend can be found in Fig. 5) - internal causes, such as composition defects or defects in crystalline cohesion, external causes of human origin and design and execution defects were distinguished.



a) b)

Fig. 3. (a) Bell tower – western and eastern facades, (b) Bell tower and church – south façade.



a) b)

Fig. 4. (a) Church – western and eastern facades, (b) Bell tower and church – north façade.

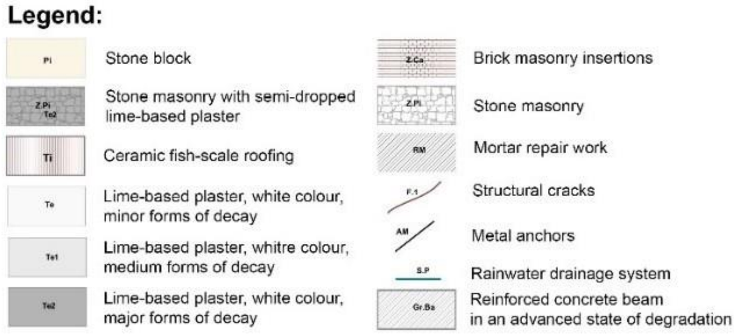


Fig. 5. Legend of figures 4 and 5.

4 Proposed repair and consolidation works aimed to enhance overall safety and structural integrity

The consolidation project of the historical load-bearing structure presents consolidation technologies based on the principle of reversibility and preservation of the authenticity of the edifice. The diagnosis of the load-bearing structure was carried out based on visual inspections performed *in situ*, analysis of historical documentation, as well as laser and drone surveys. The suggested actions are designed to be reversible and non-invasive, preserving the building's historical and artistic significance. They intend to decrease differential settlements values by implementing underpinning techniques on the current foundations and increasing the surface area for force transfer to the foundation soil. Additionally, the interventions involve consolidating the foundation soil via injection and ensuring spatial cooperation between the distinct areas of the building.

The consolidation works of the structural walls include as follows.

a) Restoring wall continuity using glass fiber mesh and hydraulic lime.
b) Repairing and rebuilding degraded external wall areas with identical original materials and ensuring proper integration with adjacent walls.
c) The consolidation of the attic will involve the use of fiberglass mesh and hydraulic lime, while the structural elements of the walls and buttresses will be reinforced with tie rods or composite material meshes and hydraulic lime mortar.
d) In order to correct outward displacements of the masonry above the arches of the main entrance, tie rods will be installed.
e) The bell tower walls will be consolidated with carbon fiber and joints in areas affected by the grinding of the plaster and mortar will be restored using hydraulic lime.

Removing the moisture causing the decay of masonry due to capillary water infiltration can be achieved through:

a) Removing excessive vegetation located in the proximity of walls.
b) Ensuring a drainage system connected to the gutter network.
c) Providing a capillary breaking layer by using sorted gravel around the walls in order to ventilate and dry the wet elements.

The following proposed consolidations aim to increase the load-bearing capacity of the arches and vaults under vertical and horizontal actions and ensure spatial cooperation between the load-bearing elements of the building. Therefore, the extrados is proposed to be reinforced with polymeric meshes and hydraulic lime.

Consolidating the floor system – bell tower:

a) Reinforcing the joints and also the wood beams by replacing degraded areas.
b) Consolidation should be made with local elements.

c) Increasing the rigidity of the floors by creating a rigid subfloor system based on using plywood sheets, fixed with beam nails.
d) Reconstruction of intermediate floors with elements similar to the original ones.

Reestablishing the roof framing connection to the structural walls:

- To attach the roof structure to the masonry, it is suggested to chemically anchor zinc rods into the attic masonry and use them to secure the eaves panel.
- Removal of the degraded area and completion of the element, replacement of degraded parts in the joints.
- Subsequent repair and maintenance of the roofing and ensuring its waterproofing.

Regarding the door and window openings, the area above the main entrance, which was previously filled with autoclaved cellular concrete, will be reopened and reinforced using double T metal profiles connected with metal tie rods.

The consolidation works include both the degraded exterior structural elements as well as the interior ones, as follows:

a) In order to maintain the historical image of the balcony, it will be consolidated with metal brackets, a solution also applied in the case of stairs.
b) Consolidation works are also proposed by rebuilding joints and replacing degraded areas and completing them.

Additionally, the following actions should be undertaken:

a) Filling the cracks in the foundation with repair mortar, a solution applied after previously preparing the surfaces by removing existing mortar or crushed debris.
b) Treatment of cracks by injecting them with lime-based mortars.
c) Creating new openings will be carried out by using metal framing in order to reinforce them.
d) Removal of the floor located directly on the ground, placement on a capillary break layer, and reinstallation in the same form.
e) Installing a rainwater drainage system.
f) Antiseptic, hydrophobic, antifungal and fire-resistant treatments on wooden elements.
g) Restoration of interior furniture.

5 Conclusion

The research and structural diagnosis have revealed a series of issues, among which the most significant are: the rotation of the church towards the bell tower, structural damages that determine the non-cooperation of the elements, vertical separation fractures, as well as numerous cracks, especially in the area of the southern façade, where there is a tendency of the ground to slide due to liquefaction susceptibility. Thus, the intervention on the entire structural system of the church and the bell tower has been deemed necessary, so that the historical, aesthetic, and cultural value of this heritage object can be fully appreciated.

The solutions for reinforcing the load-bearing structure are sustainable, with an emphasis on using local materials: reused wood from the demolition of other abandoned buildings, stone and bricks reused or newly proposed by the local kiln, local clay used for repairing masonry with mortars based on traditional local recipes. The consolidation technologies have been selected to meet the requirements for restoring historical buildings imposed by the Venice Charter [5], while also aiming to restore the load-bearing capacity of the building and adhere to the principle of sustainability in interventions. Furthermore, following the research of the ensemble, a thorough investigation was initiated on the Clergy House within the dissertation work entitled "Methodology of intervention on the Saxon cultural heritage. Case study - Clergy house in Apoș", which is currently a work in progress.

Acknowledgments

The present contribution has been prepared under a Master’s Program in Heritage Restoration and Regeneration offered by the Faculty of Architecture and Urbanism, Polytechnic University of Timisoara, under the guidance of Professor PhD Engineer Marius Mosoarca.

References

1. M. Konnerth, Abtsdorf. Ein ehemals deutsches Dorf in Siebenbürgen (Gundelsheim, 1997), pp. 345-366.
2. Decision no. 766/1997 approving regulations on quality in construction, including all subsequent modifications, The Government of Romania, in Monitorul Oficial al Romaniei No. 352, 1997
3. Technical Regulation "Seismic Design Code - Part I - Design Provisions for Buildings", indicative P100-1/20131 (Matrix Rom, Bucharest, 2013)
4. The National Institute of Heritage, The List of Historical Monuments – Sibiu County, in Monitorul Oficial al Romaniei Part I No. **113** bis, 2015
5. The International Charter for the Conservation and Restoration of Monuments and Sites, adopted at the First International Congress of Architects and Technicians, Venice, 1964