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A Sustainable Approach to Reconstruction: Historical Roof Structure Interventions

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Abstract: The reconstruction of structural subassemblies in historic buildings is a widely debated topic that often arises throughout a building's lifespan. The most vulnerable structures and, consequently, the most frequently modified are roofs, due to the materials used, which render them susceptible to biological decay or fire. This paper aims to analyse roof reconstructions across various historical periods and under different circumstances depending on the necessity for construction or reconstruction. Several exceptional reconstructions from Europe are examined, where the final solution was determined based on sustainability criteria from the construction period. Wood in roof trusses is often replaced with alternative materials such as metal or reinforced concrete. In the case of the Evangelical Church in Bistrița, destroyed by fire for the second time in 2008, the solution of replication using wood was adopted, and the wooden elements were calculated for fire resistance, according to the Eurocodes. Another important aspect to consider when constructing new roofs is the need for protective or temporary roof structures, where sustainability and reusability are fundamental requirements. The principles used to choose the covering method were different depending on the reconstruction period. Three analysis criteria were defined to compare historical solutions with current sustainability principles in the reconstruction and construction of new roofs for existing buildings.

Keywords: sustainability; roof structures; reconstruction; hazard

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1. Introduction

Recent fires and other hazards have brought attention to the vulnerability of historic buildings, particularly regarding their roofs. Many of these structures were constructed using wood, which is prone to biological decay from fungi and xylophagous insects, as well as fire damage. Following such incidents, stabilizing the remaining structure becomes an urgent matter for protecting and reconstructing the damaged sections. Reconstruction is important not only for protection purposes. Roofs are definitory elements for the final appearance of historic buildings. Considering the outer shape and materials used, roofs have an important role from an urbanistic, architectural, and also technical point of view. As they are exposed to various hazards, roofs have very often been rebuilt in whole or in part. Rebuilders either used old material and the initial concept, or they changed everything and used techniques and requirements specific to the time of reconstruction. Rebuilding, as such, is subject to wide debate in the field of immovable cultural heritage conservation in general and in roof conservation in particular.

Consequently, this paper will perform a multi-criteria analysis of building and roof structure reconstruction, covering the phenomenon throughout the life of a building, whether it be religious or secular, or the reconstruction of larger parts such as walls or roof ceilings connected (or not) to the roof structures. To analyse the roof structure reconstructions, we considered several criteria in order to choose the intervention method [1]. To validate the criteria, we selected various reconstructions examples. We analysed several types of roof construction found in existing historic buildings, drawn from documented cases in the literature, as well as from ongoing projects in which we participated either as authors (Bistrița, Vințu de Jos, Comlod) or as team members.

The four categories of roof constructions are as follows:

1. Historical roof structure reconstructions: The lives of certain historic buildings have undergone significant changes due to damage caused by wars, fires, and the installation of new roofs, as demonstrated using European examples from Romania (church building in Sighișoara, Aiud, Timișoara, and Turda).
2. Reconstructions following hazards since the 19th century (Chartres, Reims in France, Lübeck in Germany, St. Stephen's Dome in Vienna, Venice Theatre in Italy), during which unique reconstructions were chosen based on specific criteria, utilizing materials other than wood.
3. Current reconstructions (Church in Bistrița, Monastery in Vințu de Jos).
4. Roofs for ruins or heavily degraded buildings (Păuca, Comlod).

2. Importance of Roofs for Buildings: Analysis Criteria

The roof ensures the upper closing of a building; it is a sort of crowning of a building, and it is related to the context and to the building construction period. A roof is made of a covering and a roof structure. The latter reflects the engineering thinking and the material processing and implementation technique. The traditional method of constructing the roof truss took sustainability into account.

The analysed historic roof structures are mainly made of wood of local species, handcrafted and implemented according to specific principles to ensure load transmission directly through the wall plates to the foundations and then to the founding ground. But the replacement of roof structures over time was due to hazards such as war or fire, or to building reshaping through horizontal or vertical expansion.

The covering used in Transylvanian buildings is less frequently found than the coverings found in Europe in general. These roof structures can be classified by shape and by their initial architectural style. The differences arise from the roof pitch, the structural system, and the material used. The roofing material frequently changed over the lifespan of the building. For instance, wooden shingles, commonly used in rural churches, typically require replacement every 30 years, making it almost impossible to keep parts of them.

Conversely, ceramic tiles, with their extended lifespan, provide the option of replacing damaged pieces. When replacing the roofing, it is crucial to consider the technical weight to avoid overloading the structure (refer to Table 1).

Table 1. Dead loads of different roofing types; excess load resulted from changing the shingle covering (according to the Romanian Standards). Materials embodied carbon values (kg CO_2e).

Type of Roof Covering Material	Gravity Load daN/m^2	Overload [%]	Reusable	Recyclable	Guaranteed Lifetime Years	kg CO_2e/kg
Pinewood shingle	40		NO	YES	20	8.9
Metal sheet (flat)	30		NO	YES	50	17.5
Beavertail plain tile with single lap tiling	65	A surplus of 62.5% as compared to shingle	YES	YES	40–50	31.2
Ceramic tile with double or compact lap tiling	85	A surplus of 112.5% as compared to shingle	YES	YES	40–50	38.4
Extruded tile	50	A surplus of 25% as compared to shingle	YES	YES	40–50	28.8

In addition to replacing the roofing material, there is often a need to replace the roof structure itself for various reasons, such as roof overload, reconstruction following a hazard, or installing a protective roof for ruined buildings.

With regard to roof reconstruction, analysis is based on the following criteria (refer to Table 2):

- Conceptual criterion;
- Structural performance criterion;
- Sustainability criterion.

Table 2. Analysis criteria.

Analysis Criteria	Main Problems
Conceptual criterion	Cultural heritage recovery versus general recovery Rebuilding, nearly rebuilding, contemporary redesign Materials, roof shape Fire resistance, weight
Structural performance criterion	Durability Strength, stability, service safety Structure behaviour
Sustainability criterion	Materials for structural interventions (joints) Material's renewability

2.1. Conceptual Criterion

The principles for a sustainable recovery process [2] include the recovery of cultural heritage versus general recovery processes. The effects of disasters extend beyond the damage to the cultural significance of a heritage site or to the attributes that support the Outstanding Universal Value (OUV) of the heritage property. They affect the social, environmental, and economic structures that underpin the viability of cultures. The guidance framework affirms that the recovery of cultural heritage has the potential to mitigate the negative effects of disasters and catastrophes. The recovery of heritage places of cultural significance is often part of larger and more general recovery processes with their own goals and agendas. Coordinating heritage recovery with these larger processes is fundamental.

The reconstruction of roofs may be necessary due to a change in the shape of the roof or roofing material, or even for the purpose of providing additional protection to ruins. In particular, in the case of protective roofs, which are often temporary, sustainability conditions and the possibility of reuse are mandatory [3].

Conceptually, the selection of roof shape is influenced by the original appearance, the roofing material, and performance criteria. The appropriate option will be chosen according to the principles of restoration.

The initial preference for reconstruction material is typically wood, although the analysed case studies illustrate that many alternatives in metal or ferrocement have been selected to mitigate various hazards. Historical examples show that wooden options have been implemented using traditional techniques, with the wood sourced from nearby areas. When reconstruction was undertaken after a fire, the predominant selection criterion was fire resistance, leading to the consideration of alternative materials such as metal. However, metal necessitates different maintenance, resulting in higher upkeep costs. Moreover, the use of wood was abandoned because of insufficient quantity after the wars. For protective roofing structures, the guiding principles consist of replicating the original form, using lightweight materials to avoid overloading the structure, and employing sustainable materials.

The type of reconstruction following various disasters, including fires, can be differentiated [4,5] into the following: (a) "rebuilding" (intended here to signify accurate reconstruction); (b) "nearly rebuilding" (involves creating something "reminiscent" but simpler), with this option suggested as potentially being disappointing if it does not closely resemble the lost building; and (c) contemporary redesign (entails building something new in the place of what was lost). All these variations can be identified in the studied examples (refer to Table 3).

Table 3. Comparison between studied examples. Main characteristics.

Location (Locality/County)	Span (m) Slope (°)	Roof Structure Roofing	Reconstruction Variant	Reconstruction Period	New Materials
Reims/France	15.00 64.2	Timber (oak) Lead	c	1920	Reinforced concrete Lead
Chartres/France	14.20 58.10	Timber (oak) Lead	c	1841	Iron, cast iron Copper
Lübech/Germany	15.50 51.10	Timber (oak) Lead	c	1947–1952	Reinforced concrete Copper
Aiud/Romania	18.80 44.40	Timber (spruce) Ceramic tiles	b	1790, 1850	Timber (spruce) Ceramic tiles
Turda/Romania	19.20 49.50	Timber (spruce) Ceramic tiles	b	1820	Timber (spruce) Ceramic tiles
Sighișoara/Romania	14.00 72.20	Timber (oak) Ceramic tiles	c	1677	Timber (spruce) Ceramic tiles
Timișoara/Romania	17.80 39.90	Timber (oak, spruce) Ceramic tiles	c	1735–1774	Timber (spruce) Ceramic tiles
Bistrița/Romania	21.50 59.90	Timber (spruce) Ceramic tiles	a, b	2009–2023	Timber (spruce) Ceramic tiles

2.2. Structural Performance Criterion

Structures must ensure safety for users, protecting functions, and comfort provision (meeting strength, stability, and operation safety conditions). For roof structures, the structural concept should assure the appropriate taking over of loads, thrusts, and good resting conditions. Timber's lighter weight is an advantage, given the fact that historic buildings can sometimes have poor foundations.

A series of factors impacts timber structure durability: material quality, design quality, structural design and details adapted to stress on the structure elements, execution method, fungi protection applied as necessary, environmental conditions during operation, appropriate covering, and regular maintenance.

In terms of protection against biologic agents, chemicals used in preservative treatments can pose some concerns regarding health. If the material has the appropriate quality (for example, used without bark, sawn without sapwood, and with a humidity under 17%) and if it is protected from water, then it is usually immune to fungal/insect attack; therefore, preservative treatment can be omitted. This is valid especially when dealing with hardwood.

2.3. Sustainability Criterion

The intervention method most often implies one-off replacements of damaged element parts and the use of joints for ensuring continuation, which can be performed using full wood or wood and metal. Depending on the type of joint and stress, full wood can have lower load-bearing capacities as compared to wood and metal, but its overall behaviour is better. Concerning replicas, the full wood solution is more sustainable than the wood and metal or reinforced concrete solution.

In terms of material [6], wood is a renewable resource that can theoretically survive forever if managed appropriately. Deforestation is one of the main concerns related to environmental issues in the last 50 years. Therefore, reasonable wood management is very important—in particular, setting up a wood reserve to be used in the future exclusively for interventions in historic timber structures. Wood quality is important for all wood constructions, and wood quality for historic buildings is all the more important.

Establishing a dedicated planted tree stock ensuring adequate growing conditions to obtain elements with high physical and mechanical features might be a solution to the many issues occurring in conservation sites in Romania. A significant part of the elements not used during interventions could be reused on other sites.

3. Historic Structures and Disasters: Learning from Historical Case Studies

Historic buildings are exposed to the risk of significant damage, either due to natural disasters such as earthquakes, floods, storms, and fires, or to technological or industrial accidents, armed conflicts, pandemics, and other similar phenomena. Disasters enact major negative effects upon buildings and the environment and require immediate interventions for management and repairs.

Partial or full restoration of historic buildings after all types of disasters has always been an engaging topic carefully approached by multidisciplinary teams worldwide. The debates and research related to this topic cover a wide range of issues, including the analysis of building vulnerability to different disasters, disaster prevention, effect removal, safeguarding, and post-disaster intervention. Other than choosing adequate technical solutions, which involve the methods and materials used for executing these, the choice of solutions must meet the principles and doctrines [7–9] specific to historical building protection—in particular, the issue of reconstruction.

3.1. Roof Structures and Disasters

The Paris Notre-Dame Cathedral fire in 2019 [4] has significantly influenced the approach to fire safety for historic timber structures. The incident again underscored the vulnerability of historic wooden roofs, prompting a re-evaluation of fire prevention and mitigation strategies for such iconic structures. Professionals in the field of historical carpentry and structural preservation are now placing greater emphasis on the implementation of advanced fire detection systems, enhanced compartmentalization measures, and the integration of fire-resistant materials. This unfortunate event led to a collective effort within the industry to develop and adopt more stringent fire safety standards specifically tailored to the unique challenges posed by historical timber roof structures, ensuring a more resilient and protective approach to safeguarding these architectural treasures against future fire-related risks.

Post-disaster interventions, such as restoration and reconstruction, become crucial actions in bringing buildings back to their initial state, or the implementation of "modern intervention". Reconstruction is defined by the Burra Charter as "returning a place to a known earlier state and is distinguished from restoration by the introduction of new material" [8]. However, reconstruction remains a controversial topic requiring in-depth discussions, mainly regarding the acceptable time and the adequate methods for such interventions. Different reconstruction types [5]—from replicas of original structures to the insertion of "contemporary" structures made of iron and reinforced concrete in examples from the 19th–20th century period—have tried to meet fireproofing criteria. Current approaches consider the fire design of timber structures as the most sustainable option.

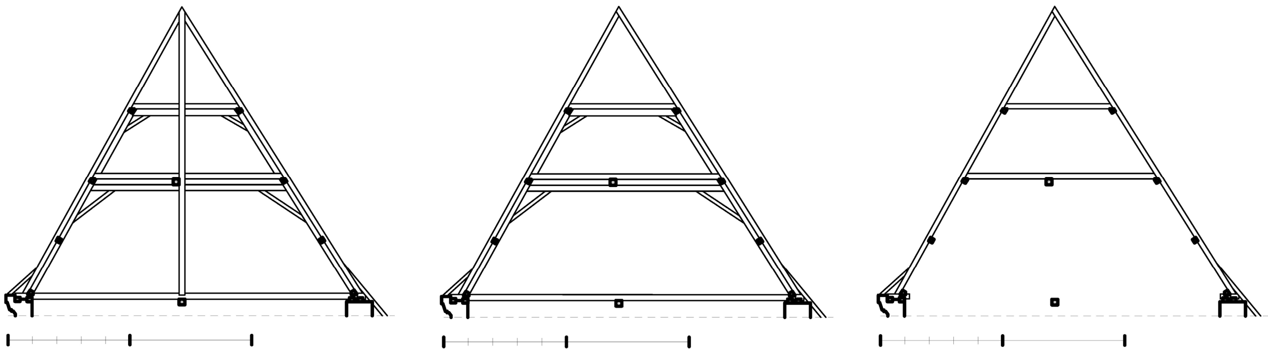
Almost eleven years before the complete destruction of Notre-Dame's medieval roof structure (Viollet Le Duc's additions included), part of the historic roof structures of the Evangelical Church in Bistrița was destroyed by a second fire. The fire on 11 June 2008 affected the roof structure of the tower, completely destroying it, as well as the roof structure of the church nave, where most of the trusses were damaged to a certain extent. The tower roof structure, 21.60 m high, of an Eclectic style, and dating back to the period that followed the 1857 fire, was entirely rebuilt. The nave roof structure has one of the widest spans among the European Gothic-type roof structures (over 21.00 m) without internal supports. What the two churches have in common is the fact that the fire spread during construction. In the specialized literature, a relatively low number of cases [10] are mentioned where fire develops during restoration.

Immediately after the fire was extinguished and the building was safe, the possible means to protect the church until roof reconstruction, as well as to conduct reconstruction meant to increase fire resistance, were analysed.

3.2. Other Interventions on Historic Roof Structures after Disasters: Examples—Learning from Historical Interventions

Many churches have been destroyed by fires and wars. The most vulnerable parts are the roof structures, the roof/upper ceilings, the vaults, and the coffered ceilings. Several historic roof structures were damaged by various disasters over time. The roofs not only offer overhead protection to the buildings, but through their volumetric design, they also shape the urban space [11]. The reconstruction of roof structures depended on the surviving elements—their type, number, and position within the structure. The approach involved either replicating the remaining elements or introducing contemporary structures as necessary.

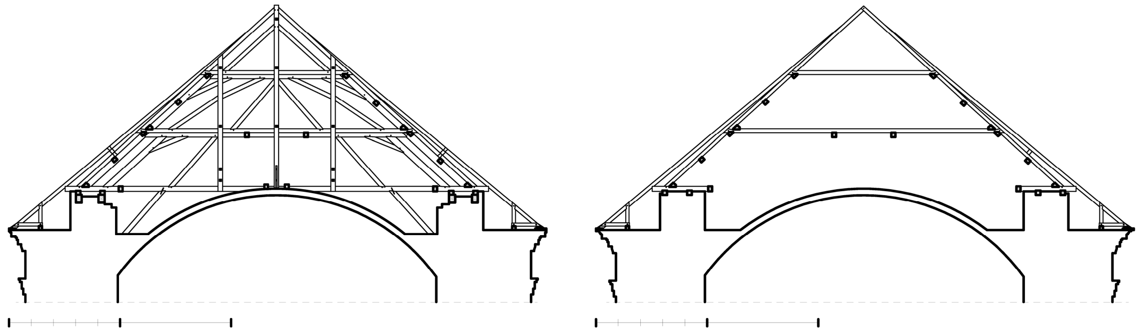
In the history of the evolution of roofs, we can find many examples when medieval buildings apparently received other roofs after destruction. These roof structures have various characters, and the date of the disaster can help to date the roof structure. An interesting example is the church of the Dominican monastery in Sighișoara, where fire helps to date the emergence of the Baroque roof structure. After the 1676 fire, the church of the Dominican monastery in Sighișoara received new nave (Figure 1) and chancel roof structures. Although built during the same period, the new structures were different in terms of concept, wood processing, joints, and typology, according to recent dendrochronological research [12]. The structural concept adopted by carpenters in the 17th century for naves is later observed to be built in the Baroque style, as seen in the Roman Catholic Dome in Timișoara, built between 1736–1774 [13] (Figure 2), as part of a grand revitalization concept after a large conflict, or in the newly added roof structures on medieval churches.



(**a**) (**b**) (**c**)

Figure 1. Sighișoara church roof trusses: (**a**,**b**) main trusses; (**c**) secondary truss.

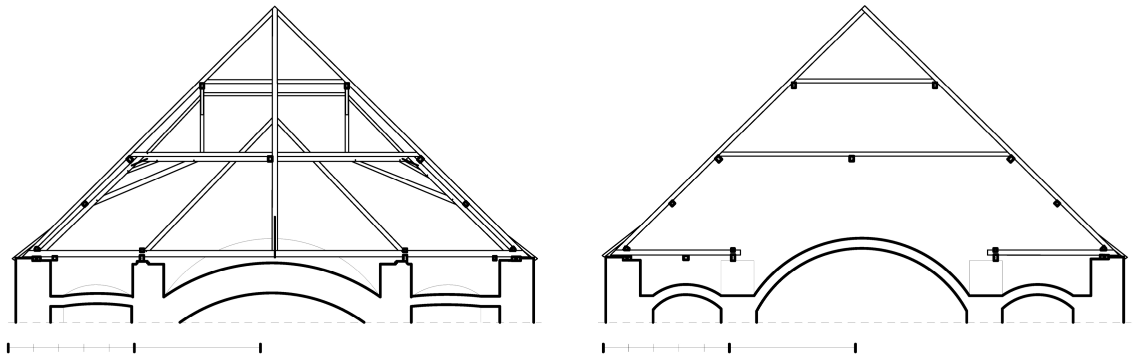
Church roof structures were also destroyed by fire in Turda and Aiud. These churches with medieval exteriors also received Baroque-type roof structures [14,15] in the 18th and 19th century, but we also find elements characteristic of the roof structure from Sighișoara. These examples refer to reconstructions made exclusively of traditionally processed timber structures.



(a) (b)

Figure 2. Timișoara Dome roof trusses: (**a**) main truss; (**b**) secondary truss.

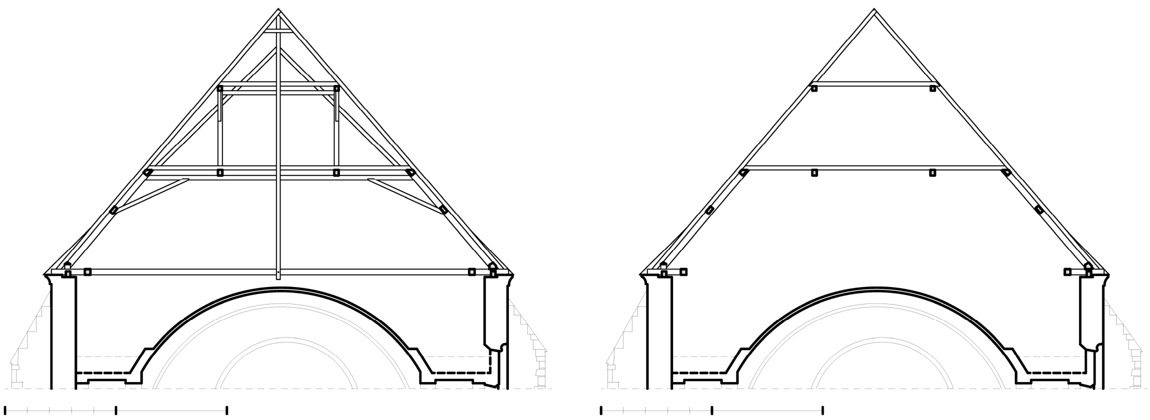
The roof structure over the Aiud church nave (Figure 3) was dendrochronologically dated. Some common rafters and trimmers were dated back to 1790, which is an indication of the roof structure's reconstruction period. The current Baroque vault dates to 1784–1804. The elements dated to 1850 are related to the 1849 disasters that affected the entire town.



(a) (b)

Figure 3. Aiud church roof trusses: (**a**) main truss; (**b**) secondary truss.

The roof structure of the nave in the Turda church (Figure 4) is dated to 1818 and 1820/1821. It is unitary, without reused elements. The destroyed church was rebuilt as of 1803. The roof structure was built at the end of the intervention, after the construction of the vault.



(a) (b)

Figure 4. Turda church roof trusses: (**a**) main truss; (**b**) secondary truss.

The Baroque concept endured due to its effective structural design, encompassing main and secondary trusses, efficient longitudinal stiffening in the rafter plane, and minimal timber consumption.

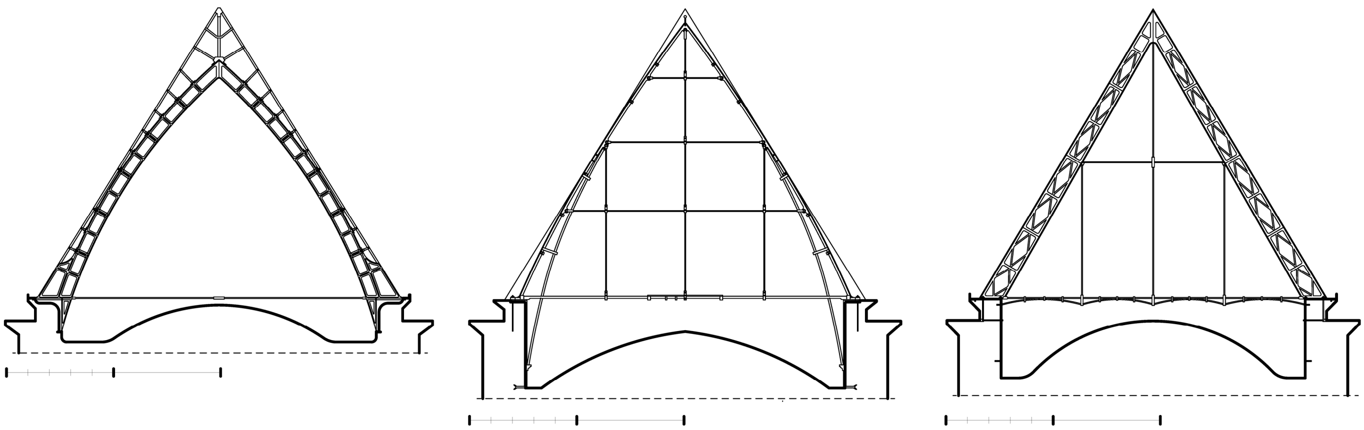
The two World Wars caused enormous damage to historic buildings [16]. Gothic cathedrals and churches were no exception. They needed consolidation and reconstruction. In general, they were restored to the initial state, using similar materials, without calculations or special analyses. In many cases, destruction affected not only the roof structures but also the vaults (partially or entirely).

When studying the international literature, we identified several fascinating examples of reconstructing roof structures after different disasters. Cathedrals like those in Chartres, Reims, and Lübeck used to have medieval roof structures like the one in Bistrița with, of course, the specific characteristics of the area. They were destroyed by fire or bombardment and rebuilt in various ways. As compared to the reconstruction of the vaults under discussion [16], the roof structures were not always rebuilt by replicating the original structure. The reconstructions were based on the principle of ensuring a fire-resistant and low-impact structure, namely low gravitational load, and a low thrust over the superstructure. The damage caused by fire on roofs over the last centuries has triggered some modern solutions, which have already become historical themselves. And timber has not been the only solution used for reconstruction.

3.2.1. Chartres Cathedral Roof Structure

The roof structure of the Notre-Dame de Chartres Cathedral was destroyed two times. In May 1825, it was partially destroyed by a lightning strike. As a result, a lightning rod was installed. In 1836, the roof structure and lead roofing were destroyed due to the negligence of the tinsmiths who carried out repair works [17].

The reconstruction solution included non-combustible materials made of iron and cast iron, as well as a copper covering. The solutions were chosen based on cooperation with metalworking companies such as M. Roussel, Leturc, or Mignon [18] (Figure 5). The selection criteria included the use of non-combustible, low-weight materials, easy fastening, and, last but not least, low costs. Additional ornaments were thus avoided.



(**a**) (**b**) (**c**)

Figure 5. Chartres cathedral roof structure. Reconstruction versions: (**a**) E. Martin; (**b**) M. Roussel; (**c**) Leturc.

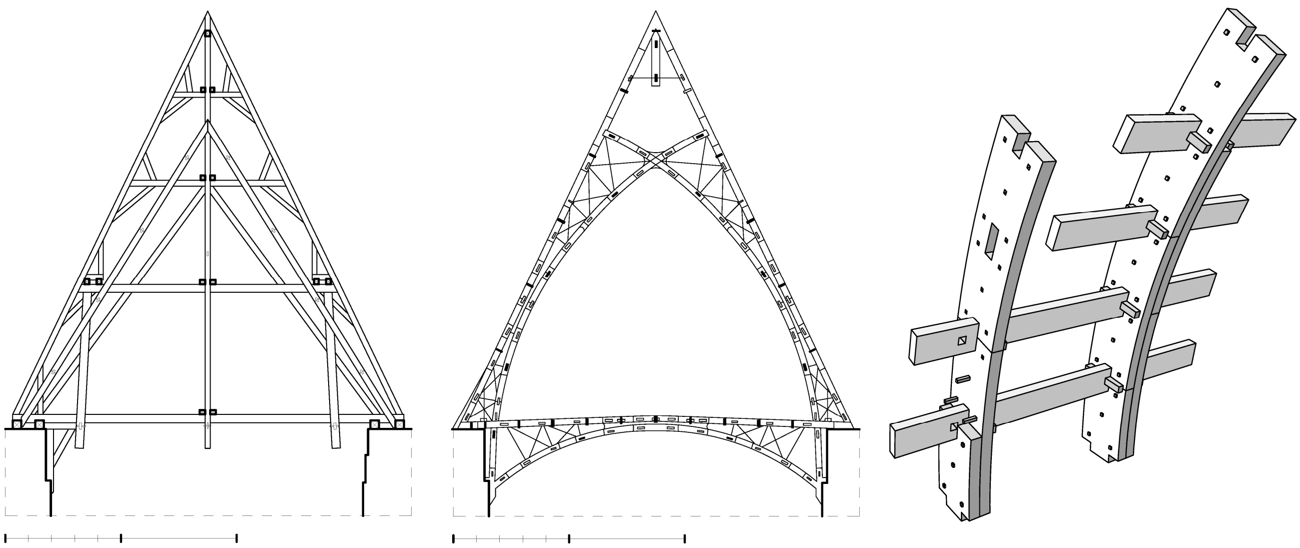
The Chartres Cathedral roof structure was rebuilt in 1841, when the choice was made for the installation of a non-combustible roof structure, which has since become a heritage value. The solution designed by Emile Martin and implemented by Mignon was a repetitive structure made of frames interconnected with longitudinal bracing frames. Each frame is made of a pair of iron common rafters unloading on a system of arched compound rafters made of cast iron, consisting of latticed modular elements. Each module is approximately 60 cm × 2.00 m and 9 cm thick. In the cornice area, the thrusts are taken over by ties connecting the common rafters. Unloading in the support areas is accomplished through precast plates.

The conservation works conducted between 1995 and 1997 under Guy Nicot's careful supervision, as the chief architect for historic buildings, revealed the good preservation condition of the structure, despite corrosion having affected the roof structure joints and studs supporting the copper covering due to a copper–iron electrolytical reaction occurring because of missing parts in the original insulation. Several bolts, connectors, and shims were fissured, cracked, or absent due to differential expansions caused by temperature variations.

3.2.2. Reims Cathedral Roof Structure

The Reims Cathedral was destroyed by the 1914 bombardment [19]. Quality surveys were published by Henri Deneux, Ostendorf.

First, in 1481, a fire destroyed the original timber trusses; the vaults worked as a kind of firewall, preventing the fire from spreading inside. The oak truss roof and lead roofing were completed in 1492 (see Figure 6a). This structure burned down in the bombing of World War I, on 19 September 1914.



(**a**) (**b**) (**c**)

Figure 6. (**a**,**b**) Reims cathedral roof trusses: before and after reconstruction; (**c**) De l'Orme system.

The selection of the reconstruction approach was guided by the aim to minimize the use of wood and metal components, as well as simplify implementation, including transportation and handling. As a result, the decision was made to avoid replicating the original wooden structure, primarily due to the substantial post-war shortage of wood, and to steer clear of using metal joints susceptible to corrosion. Instead, reinforced concrete elements measuring 4 cm × 20 cm and varying in length from 2 m to 3 m were fabricated. These elements are uniform in size, resulting in reduced variety, and many of the moulds for in situ casting were reused (see Figure 6b).

The mounting principle was similar with Philibert De l'Orme's principle [20,21], where small wooden pieces with wooden fittings were used because of the lack of good quality and enough quantity of available wood (Figure 6c). Full reinforced concrete construction would have meant consistent temporary works and too cumbersome unfolding upon removal. The advantage of the solution choice was to allow easy construction and deconstruction with possibility for reuse. The reconstruction of the Reims Cathedral aimed to reduce wood consumption. This would have involved about 1500 cubic meters of timber. Since wood was used only for formwork, its quantity was reduced by 40%.

3.2.3. Lübeck Cathedral Roof Structure

The church in the historic city of Lübeck was bombed in 1942, and the roof structures were destroyed and fell over a part of the vaults. Because of the lack of labour force and specialists during World War II, the only intervention consisted of building a 20-degree-slope protection roof covered with galvanized tin. There were other attempts to support the building through the insertion of reinforced concrete elements, which were exposed to overloads upon transportation and straining.

When the reconstruction of the roofs and vaults was accepted, a contest was launched to choose the best option available at the time [22]. As the image of the church in flames was still alive, a potentially non-combustible and non-inflammable structure option was chosen. Several proposals were made (Figure 7), from the reconstruction of the initial timber roof structure based on existent surveys (Figure 7a) to other timber (Figure 7b), various metal (Figure 7c–g), and reinforced concrete (Figure 7h,i) solutions.

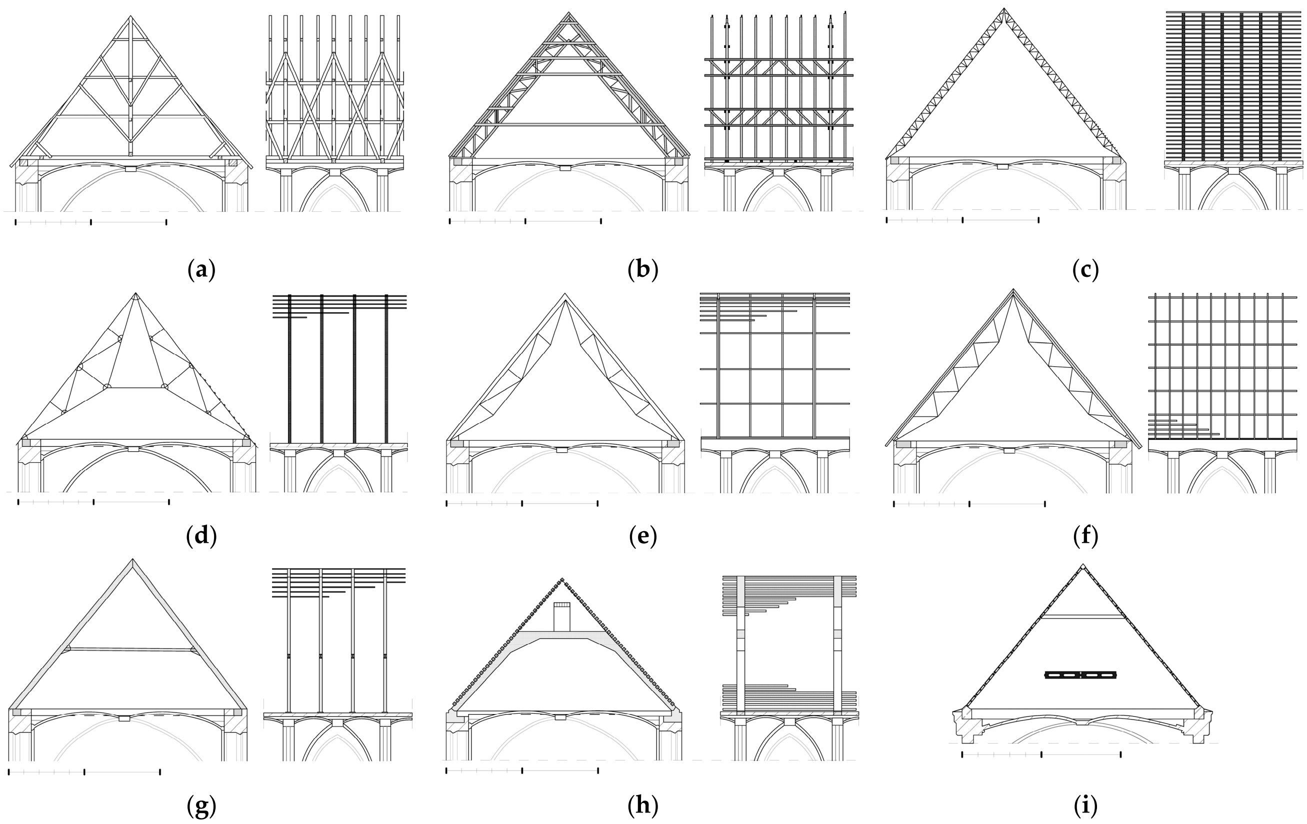
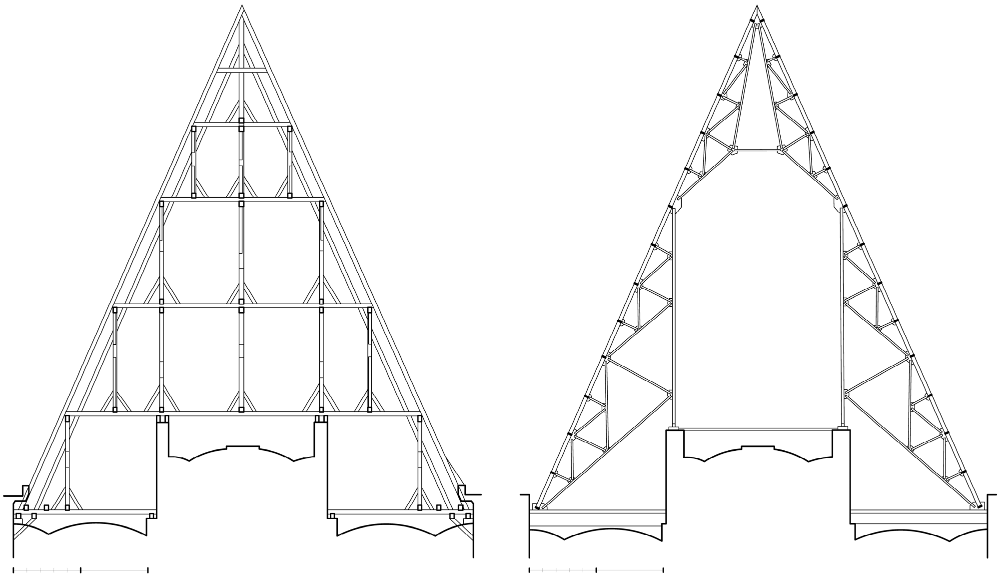


Figure 7. Lübeck cathedral roof structure: (**a**–**h**) reconstruction variants; (**i**) built version.

Therefore, for the selection process, structural compliance—including the composition of the frames and the implementation of longitudinal stiffening—was thoroughly analysed. The comparison involved the consumption of raw materials such as wood, metal, and cement, considering both the cost per square meter and the overall weight of the structure, including roofing.

The selected solution considered factors such as minimal wood consumption, cost-effectiveness, and durability. It prioritized the implementation of materials with fire resistance and low maintenance costs. The final solution (Figure 7i) used precast reinforced concrete elements of 1.25 m, which were monolithic in a transverse and longitudinal direction, as well as reinforced concrete beams instead of a tie beam and upper collar. Wood was only used for roofing support and the maintenance platform. In the case of other churches destroyed during the Second World War, the well-documented historic medieval roofs were replaced by metal structures, with or without wooden structural elements, focusing on the preservation of the roof shape. This reconstructed solution was chosen for St. Stephen's Cathedral in Vienna, Cologne Cathedral, and Nuremberg. In case of Vienna's Dome, the 34.20 m span roof, dating to 1440, covered all three naves in one roof structure (Figure 8).



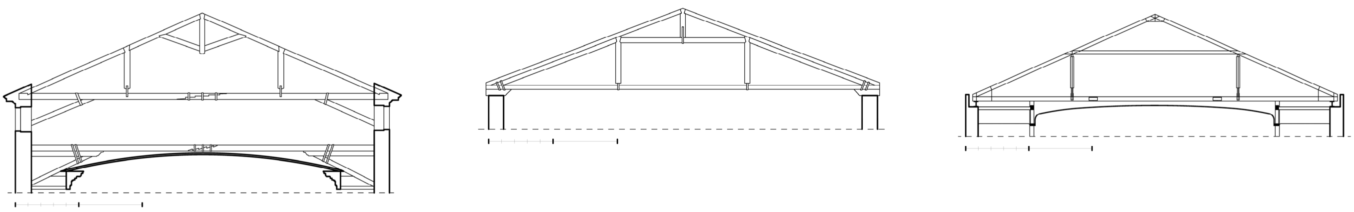
(**a**) (**b**)

Figure 8. St. Stephen's Cathedral: (**a**) original roof structure; (**b**) structure after reconstruction.

3.2.4. La Fenice Theatre Roof Structure

La Fenice Theatre in Venice was built during 1791–1792. From a total of 29 projects, the one by Giovanni Antonio Selva was chosen [23].

The roof had a lead and tile cover supported by a timber structure (Figure 9a), which can be studied from a set of drawings preserved in the Cooper Hewitt, Smithsonian Design Museum, New York and also on the original wooden scale model, displayed in a restored state in Sale Apollinee.



(**a**) (**b**) (**c**)

Figure 9. La Fenice theatre. Roof structure above auditorium: (**a**) original structure; (**b**) reconstruction after the 1836 fire; (**c**) reconstruction after the 1996 fire.

In December 1836, after the installation of new stoves, a devastating fire destroyed most of the building. The rebuilding work was entrusted to a team formed by architect Giambattista Meduna, along with engineer Tomaso Meduna and architect Tranquillo Orsi, who was in charge of decoration reconstruction [24]. The chosen solution for recreating the roof structure above the main auditorium consisted of pairs of rafters, a tie-beam, a collar-beam, compound rafters, and king/queen posts (Figure 9b) [25].

Other restoration works were carried out in 1854, 1937–1938, and 1996. During the last ones mentioned, the building was destroyed again by a second fire, which was caused by arson. The team of architect Aldo Rossi won the design competition for rebuilding the theatre. The restoration concept had, as a starting point, the motto "how it was, where it was", implementing conservative interventions where it was still possible; some elements and parts of the building were recreated using traditional materials and techniques, but others were built according to contemporary conditions and exigencies. Speaking in terms of roof structure, the solution varied depending on the particularities of the space that needed to be covered. Thus, for Sale Apollinee, where the roof structure was left visible, the solution necessitated using timber girders on one direction, acting as supports for the timber rafters. A specific request was that the species used be the same as the original one (larice). For the auditorium space, a steel truss structure was used (Figure 9c), which was completely concealed from view. The tie-beam, hanged by means of queen posts, was used to support a new steel–concrete composite slab. Two longitudinal bracing frames were placed in vertical planes, containing the queen posts. Technical equipment like the one for ventilation was housed in this newly created attic space. Measures were taken in order to protect all structural elements against fire [26].

4. Current Reconstructions

4.1. Bistrița Evangelical Church Roof Structure

The church dedicated to Saint Nicholas dates back to the 14th century, with a further late Gothic stage. Significant works start in 1559 when numerous donations were recorded. On December 16, stonemason Petrus Italus de Lugano was hired for conservation work on the Saint Nicholas Church, and carpenter Andreas Faysel was hired to build the roof [27]. First, the old roof to the naves was removed, as well as the upper part of the south tower, parts of the west elevation until the small tower stairs, and finally, the vaults of the three naves. The Renaissance phase of the building consisted of reshaping the church interior by placing the gallery at a walking level below the Gothic circuit towards the staircase tower, the new tower, the sacristy area, and the chancel area of the time. While the piers were continued with columns starting at the level of the railing and up to the vault.

Other occasional interventions were conducted over time, but they did not significantly change the exterior design. After the 1857 fire, the upper part of the destroyed tower was rebuilt. In 1897, according to an inscription on the beam, the pier was heightened in the loft, and overlapped timber beams were inserted to ensure intermediary support for the roof structure, which dated back to 1563. The interior layout was changed in 1925 according to Phleps's design. Conservation works were resumed in the beginning of the 1990s, the west elevation was consolidated, and metal consolidation elements were inserted in the roof structures [28]. The Gothic church attracted the attention of specialists, not only because of the 2008 fire but also due to its significant size, i.e., 42 m length of the ground plan, 32 m span at the nave level, 18 m span at the chancel level, and the 72 m height of the masonry tower at the ornament level.

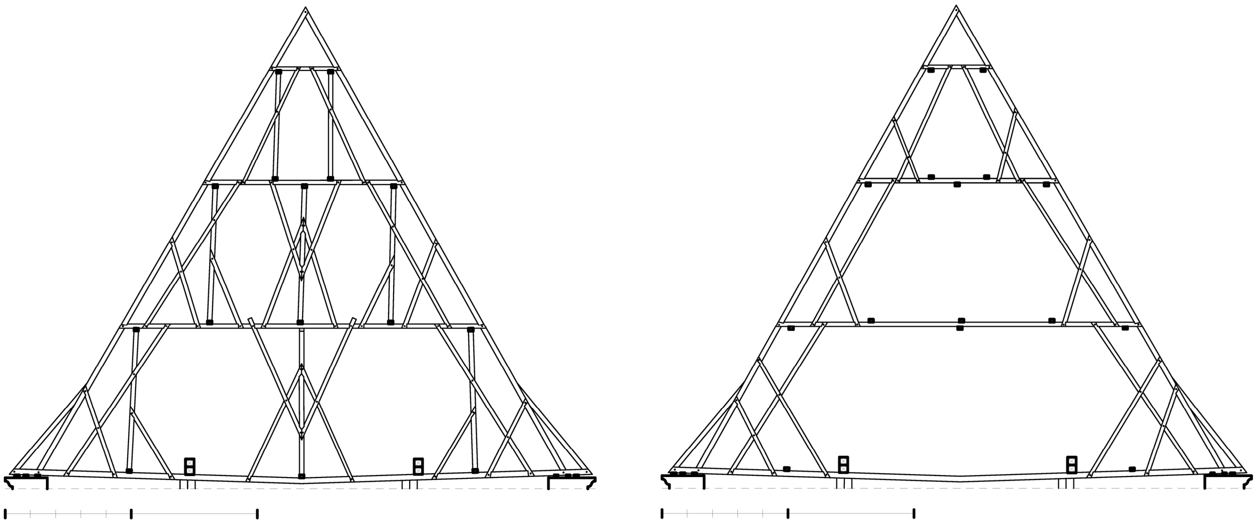
On 11 June 2008, a destructive fire swept through the timber structure of the Lutheran Church in Bistrița (Romania). The tower had already been destroyed by fire in 1857 and had been subject to a large intervention. After the Romanian Revolution in 1989, a large conservation project was launched, starting with the consolidation of the roof structures and of the western elevation. The restoration started timidly, with little funding. The tower of the church, undergoing restoration works between 2006 and 2008, was covered by wooden scaffolding. The fire in 2008 was noticed around 19:40, announced at 19:43, localised at 21:00, and put out at 00:35. Lightning was dismissed as the fire source due to the lack of unfavourable weather conditions. The construction site electrical panel inside the church, powered by a general electrical panel located outside the church, had some deficiencies, but the fire also affected the insulation of the power cables. Viable hypotheses are the use of matches or a lighter, with likely circumstances pointing to children playing with fire under the scaffolding or a lit cigarette thrown negligently onto combustible materials.

After the fire, it was found that the timber structures inside the tower were completely destroyed, along with the spatial roof structure, and that the fire had spread to the first eight Gothic trusses of the roof structure over the nave. The vaults were also weakened (by the fire and water used for extinguishing it).

This unfortunate event led to a different approach to the life of the building. After the fire, a re-evaluation of the methods and types of intervention of the previous decades was carried out. Although the value of church was multi-fold—providing artistic, aesthetic, technical value, etc.—we will focus on the valuable timber structures and the interventions thereof.

- Value record. The roof structures;

The church nave roof structure has a Gothic character and is made of 20 main and 19 secondary trusses (Figure 10), interlaced, as well as eight vertical longitudinal bracing systems. The span of the trusses is approximately 21.60 m. It can be dated between 1559 and 1563, according to the general contractor agreement, the inscription discovered during the conservation works, and dendrochronological research carried out in 2009. There have been at least two major interventions in the nave roof structure, which altered the roof structure's static model. In 1897, two longitudinal compound beams (a) were mounted, resting on the heightened intermediary columns, as well as the straining systems in the main trusses (Figure 11a) up to truss no. 23; in 1926, straining systems were mounted in some of the secondary trusses (Figure 11b), starting with truss no. 26. The 1897 intervention loosened the longitudinal bracing system by removing the first level's passing braces.

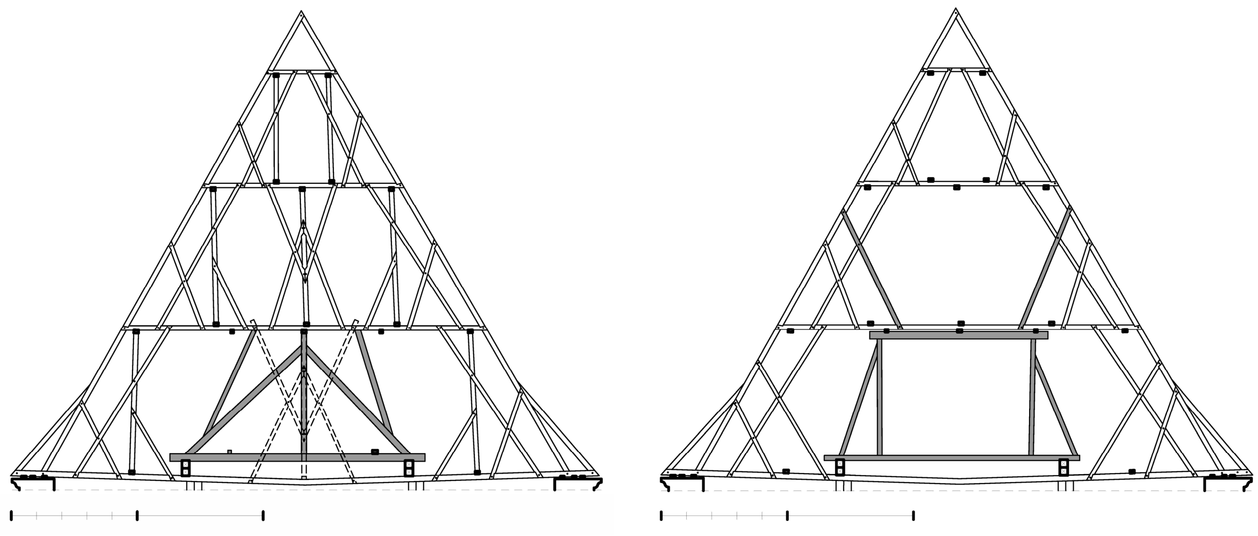


(**a**) (**b**)

Figure 10. Bistrița church original roof trusses: (**a**) main truss; (**b**) secondary truss.

The chancel roof structure has a Gothic character as well and is made of five main trusses and four secondary trusses, interlaced, of the semi-trusses of the apse, and of three longitudinal frames. The span is 8.50 m; it can also be dated between 1559 and 1563. The interventions on this roof structure aimed to partially or completely replace the elements (without altering the initial static scheme).

The church tower roof structure, built after the 1857 fire, has an Eclectic character and is 21.60 m tall. It was a spatial structure made of (radial and annular) spatial systems, which could not be divided into frames, and it was destroyed by the fire on 11 June 2008, along with the timber spatial structures inside the tower.



(**a**) (**b**)

Figure 11. Bistrița church roof trusses. The 1897 interventions: (**a**) main truss; (**b**) 1926 interventions, secondary truss.

- Post-fire interventions

Following the extinguishing of the fire, the subsequent measures included securing the detached elements, stabilizing the remaining areas, and formulating a strategy for their protection. Due to the church's configuration and span, installing a protective roof over the nave was not feasible. Ultimately, the safeguarding of the building was accomplished at the extrados level of the vaults, employing a layer of bituminous cloth, and implementing a system for collecting and draining rainwater.

The owner's first natural question was how the roof structure would be reconstructed. Although the original elements were of considerable lengths, single pieces over 20 m long, the major issue was where to buy quality wood and labour. Could it be replaced by metal or glued timber? Should a witness—a truss with burnt areas, reinforced by an additional structure to ensure the required stability and strength—be preserved or not?

Due to the absence of a protective roof, time constraints prevented a more thorough and extended analysis of potential intervention options. Like historical examples, various intervention possibilities were taken into consideration.

The conservation principles (the principles for the conservation of wooden heritage, 2017 and principles for the preservation of historic timber structures, 1999) also considered sustainability principles, such as the maximum preservation of the appropriate wood, exclusive removal of elements affected by fire, and use of traditional wood-processing, lengthening, and jointing techniques.

The roof structure of the nave was conserved pursuant to the principles of minimal intervention, preserving the historical material to the greatest extent possible, using traditional techniques. The destroyed trusses were replicated in their original shape (Figure 10a,b) The spruce wood, similar to the original structure, was carved, and the jointing was made using only wooden elements, i.e., hardwood nails and wedges. Based on the traditional surveys of the tower structure from the early 2000s, a decision was made to build a replica. This roof structure was built on the ground in a carpentry workshop close to the restoration site; the elements and joints were marked, after which it was completely dismantled, lifted, and remounted on the reinforced cornice of the tower. Instead of the wooden beam slabs in the tower, a metal structure was introduced to facilitate vertical circulation, incorporating metal stairs and an elevator.

Since 2008, a reassessment of the nave's roof structure has been conducted; an analysis of the carpenters' marks and assembly marks was carried out, along with detailed dendrochronological research into the nave and chancel. This initiative aimed to underscore the significance of compensatory measures in restoring wooden structures, document historical wooden constructions—particularly roof structures—and integrate complementary sciences. This included 3D scanning, structural modelling, dendrochronology, and the extension of art history research to the attic.

The conservation works were completed in 2023. The roof structure has been restored and is planned to be integrated into a visitable historic roof structure circuit, which includes visiting platforms at all levels and stairs, as well as architectural lighting. Additionally, it incorporates all the necessary fire safety measures related to detection and alarm systems.

- Analysis of the roof structure over the nave

Following re-restoration, a comprehensive re-examination of the entire structure was undertaken, including the structural modelling, considering the possibility of discarding the interventions from 1897 and 1926, as well as the fire verification of the roof structure [29].

4.2. Structural Analysis of the Nave's Roof Structure

Specialists' perspectives on intervention principles have undergone a significant transformation. Instead of introducing secondary engineered structures, the focus has shifted towards meticulous preservation, retaining visible processing tool traces, assembly marks, and traditional carpentry joints. The effect of previous interventions was also analysed—in particular, the 1897 and 1926 interventions when, instead of frame bearing directly on the exterior longitudinal walls, intermediary supports were used, as well as pier extension in the attic.

Structural modelling was carried out in several circumstances and combinations, including accidental fire. The model only included the roof structure, supported by the three wall plates, which were modelled as articulations/simple supports. Calculations were carried out by linear and non-linear analysis, checking the efficiency of specific elements of the medieval roof structure (rafter, tie-beam, collar beams)—and their degree of use in the case of 3D modelling. The load was calculated in accordance with the Eurocode 1, CR-0-2012, SR EN 1991-1-3:2005/NA: 2006 CR-1-1-3/2012, CR-1-1-4/2012. All effects were considered, such as load/m, net weight (in case of wood corresponding to strength class C24, ceramic tile roofing), and wind load generated by a program. The computational model was created using Axis VM X6 software as a spatial model (Figure 12).

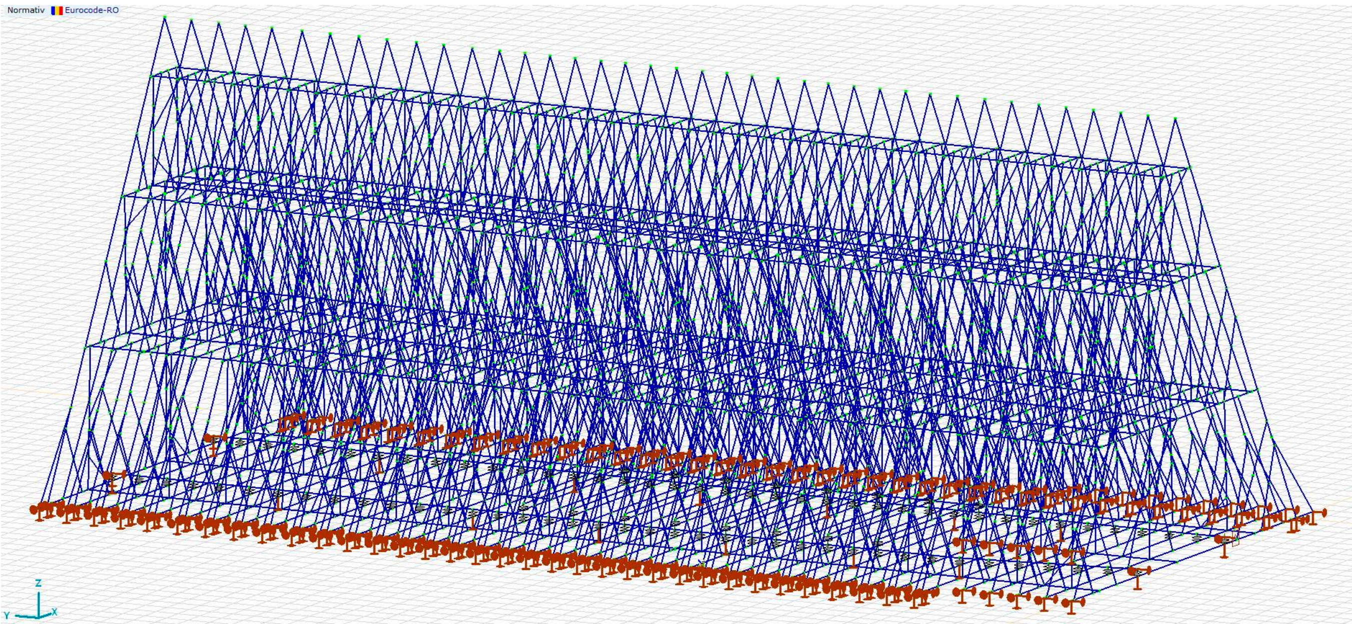


Figure 12. Roof structure 3D modelling (wireframes).

The reconstruction of the damaged trusses—the first eight trusses—intended to restore the initial shape, without intermediary supports, using axe-hewn timber, and joints with fixtures made exclusively of wood.

Using the experience of our Czeck colleagues [30], lengthening was made using vertical wedges, shear dowels, and wooden pegs without the insertion of bolts or other metal parts. In addition to local materials (*Abies Alba*), the local labour force implemented local techniques, and local technologies were used. Beyond fulfilling mechanical structural requirements and adhering to principles specific to wooden heritage, interventions in historic structures must also address sustainability criteria.

In some trusses (trusses no. 9, 11, 13, 15, 17, 19, 21, and 23), the additional straining systems (Figure 11a) from the 1897 interventions were preserved, as witnesses of a stage in the history of the building. The analysis showed that these trusses were subjected to the highest loads (Figures 13 and 14).

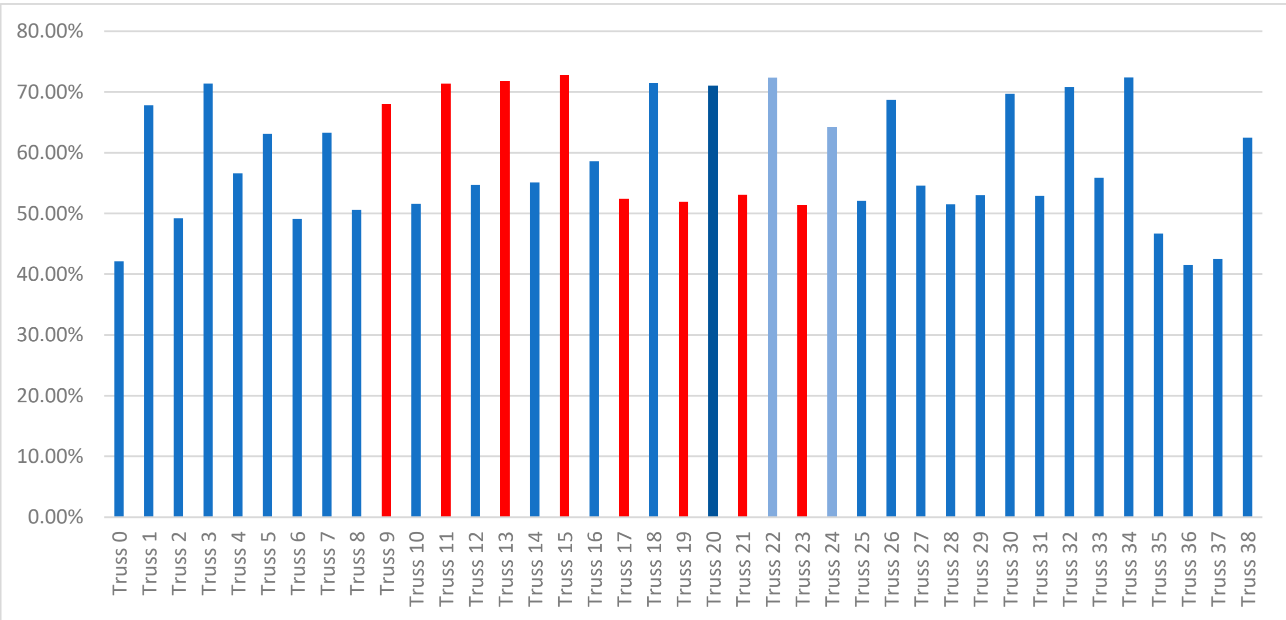


Figure 13. Trusses' level of use. In red, trusses with straining systems preserved. Linear static analysis.

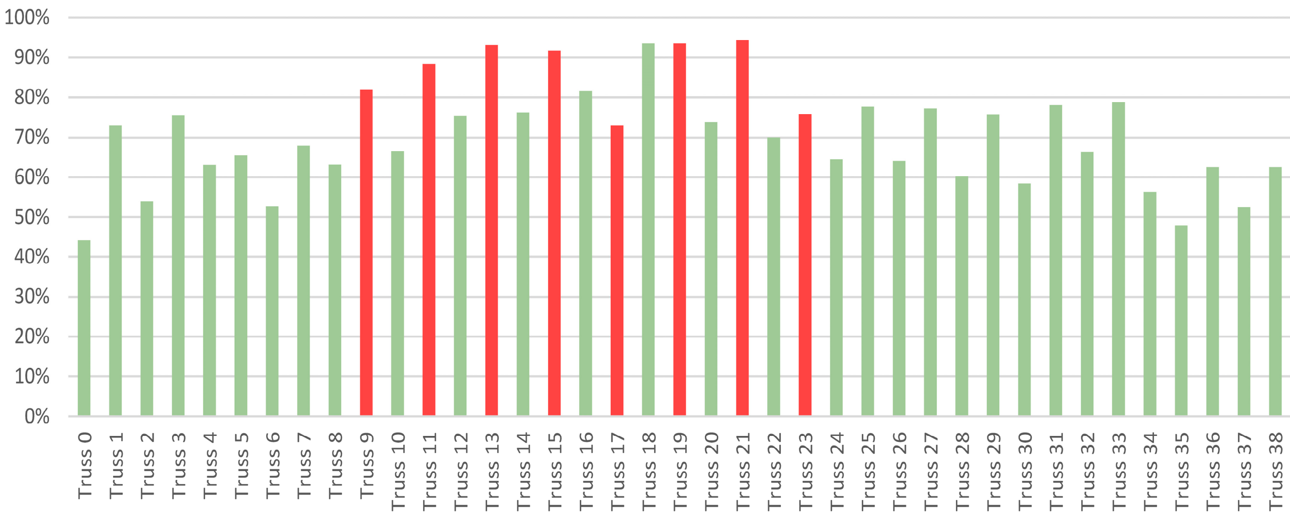


Figure 14. Trusses' level of use. In red, trusses with straining systems preserved. Nonlinear static analysis.

4.3. Monastery Complex in Vințu de Jos, Romania

Even though the principle of minimal interventions is adopted, in many situations, the complete or partial replacement of the roof structure is necessary due to the initial flawed design or advanced degradation. Such a situation occurred in the case of the monastery church, where the wood degraded due to the connection between the roof structure above the choir and the monastery. The reconstruction aimed to return it to the original form with minor corrections (Figure 15), using raw wood.

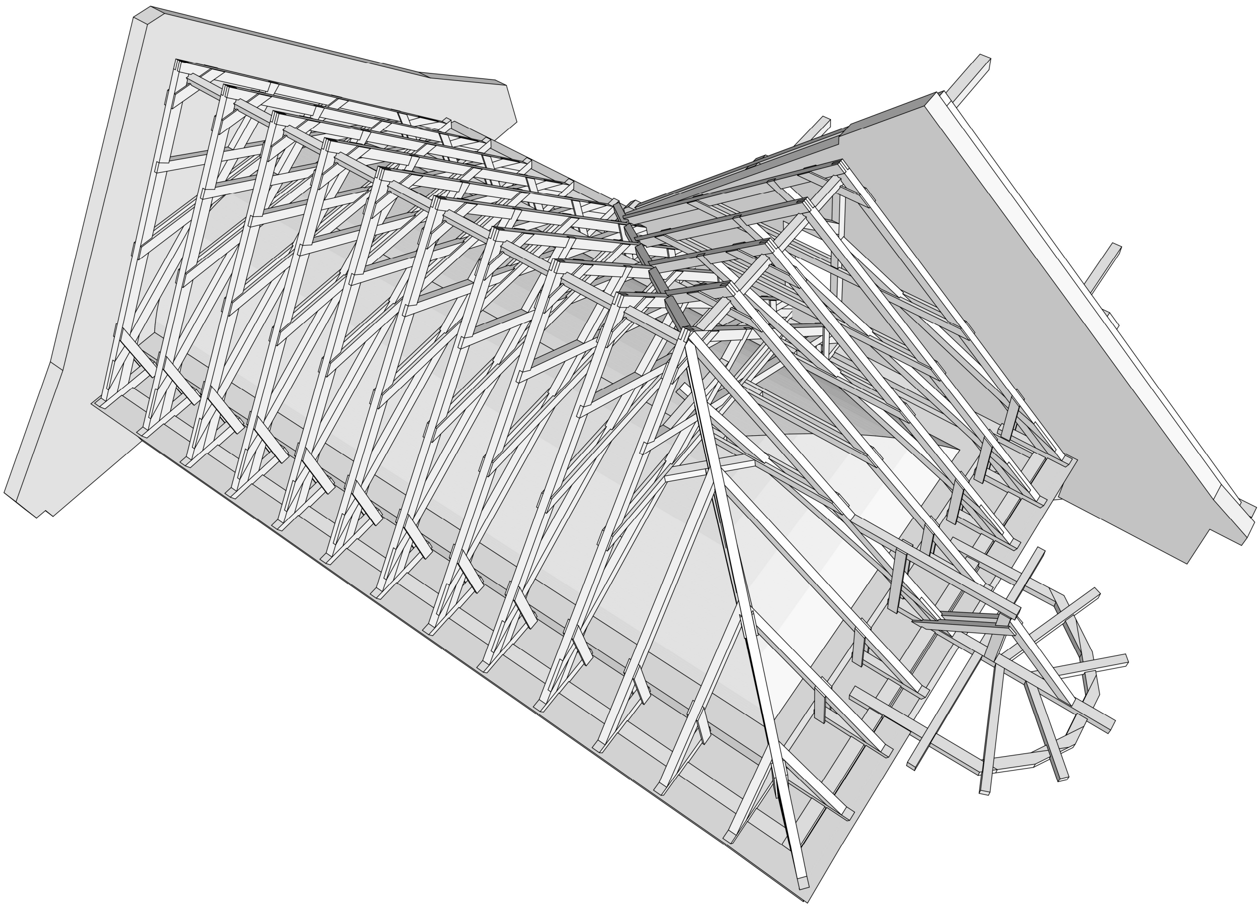


Figure 15. Vințu de Jos Franciscan church (monastery church). Proposal for the reconstruction of the roof structure over the choir.

5. Temporary Roofs above Ruined Buildings

5.1. Păuca: Ruined Reformed Church

A protective or temporary roof is a different matter. The emphasis is on the final shape without paying attention to replicating the structural concept. Using the example of colleagues from Mossfern and Planus Ltd., Cluj-Napoca, Romania, a reduction in consumption was analysed, indicating a reduction to half of that of a replicated historical structure. The structure is made of timber (5 cm × 20 cm) trusses spaced approximately 40–50 cm apart, with longitudinal stiffeners (Figure 16). In the case of constructing the final roof truss, these trusses can be reused for other protective roofs with a span of approximately 8–9 m.

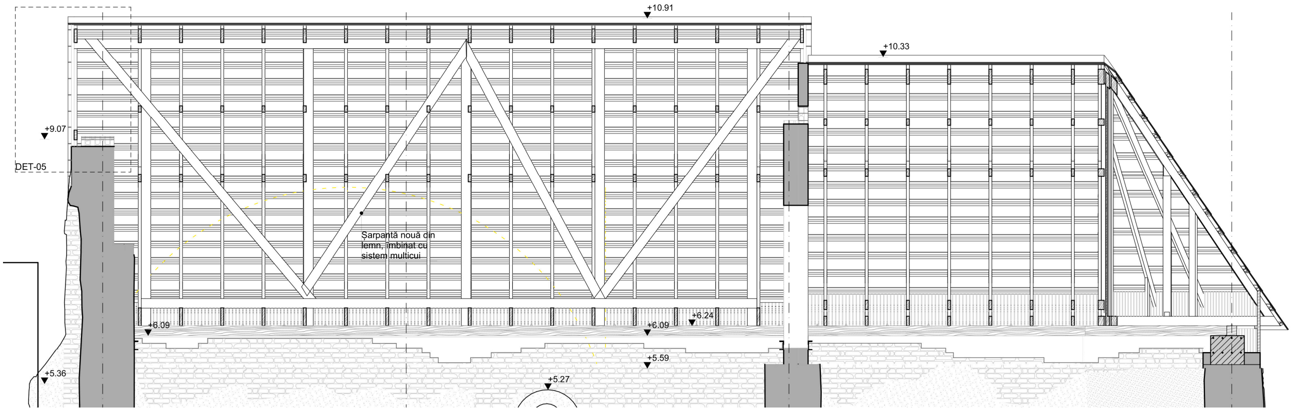
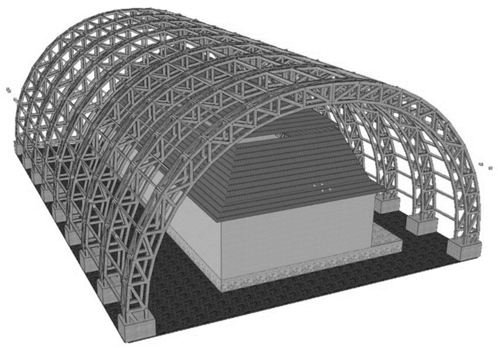


Figure 16. Păuca' reformed church. Proposal for the protective roof structure. Longitudinal section (courtesy of Planus BBM—Mossfern, arch. Macalik Arnold, arch. Szilágyi-Bartha József).

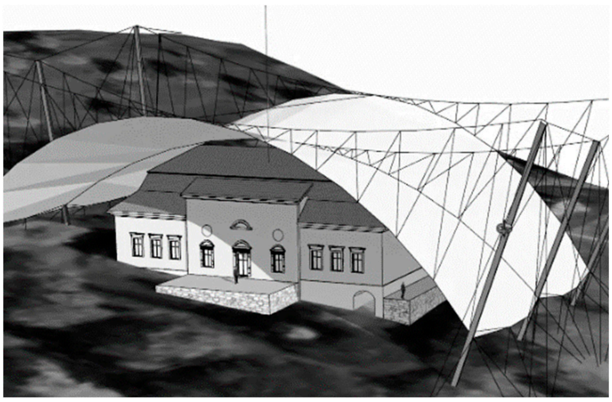
5.2. Comlod: Ruined Teleki Mansion

The protective roof over the ruins can also be structures built outside the building, without loading the bearing walls, as they are unable to bear the loads from the roofs without reinforcement.

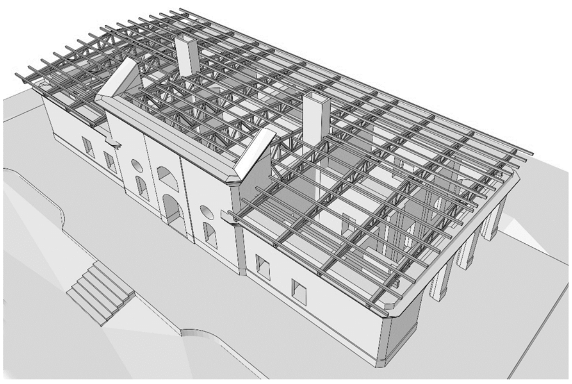
In the case of the ruined mansion (Figure 17), an analysis of options was conducted, taking into account the materials used—wood, wood derivatives, or lightweight timber trusses on internal structures—and, of course, the total cost (refer to Table 4)



(**a**)



(**b**)



(**c**)

(**d**)

Figure 17. Teleki mansion from Comlod. Proposals for the temporary roof structure. (**a**) Arched timber trusses; (**b**) Tensile structure; (**c**) Trusses timber structure resting on the original structure; (**d**) Timber trusses resting on additional supports.

Table 4. Comparison between studied examples. Timber consumption; price.

Location (Locality/County)	Reconstruction Variant	Timber Consumption Cubic Meters/Square Meters	Price Euro/Square Meters
Comlod/Romania	1	0.18	334
	2		399
	3		141
	4		225
Păuca/Romania		0.05	65

6. Conclusions

Historic buildings sometimes face destruction of building elements and parts by various types of disasters.

Disasters—whether fires, storms, earthquakes, or floods—destroy important values of historic buildings. The most exposed parts are those of the roof timbers that are made of wood, a combustible material. This even turns them into unstable structures or causes a potential loss of stability and a significant decrease in mechanical strength.

The relevance of this theme Is further underscored by the catastrophic fire at the Church of Notre-Dame in Paris in 2019, as well as the absence of clear legislation in the field [10,31].

This article analysed the damage caused by fire to churches where reconstruction was carried out in several variants—(a) either by rebuilding, (b) nearly rebuilding, and (c) implementing a contemporary design. The analysis of historical examples illustrates the changing attitude towards the rebuilding of roof structures. In maintaining the roof shape, considerations encompass criteria such as wood consumption, loads, ease of maintenance, and intervention sustainability.

One should utilize recycled materials whenever possible and prioritize the recovery of resources such as waste tiles, metals, or wood whenever necessary. Recovered resources typically have a significantly smaller embodied carbon footprint compared to newly manufactured materials because they have already utilized carbon during initial production. For instance, choosing recovered wood helps conserve energy that would have been consumed in the process of felling trees, transporting them to the mill, and processing them.

The analysed examples (except for temporary protection roofs) follow the principle of preserving the original image, which includes its shape, materials, textures, and colours. Recovered materials, whenever possible, implies saving historical values in many cases. From a sustainability point of view, it is also the better option when dealing with intervention in existing buildings. The fact that one does not have to spend valuable energy on producing new elements already constitues an advantage. While some materials can be reused as they are, others can only be recycled (wood shingles can be used for the production of wood fibres, and decayed clay tiles can be transformed into aggregates for infills).

The burning of churches led to a change in appearance after rebuilding, and this disaster is a benchmark for dating interventions. In the case of the Transylvanian examples studied (rebuilding efforts from the 17th–19th centuries show virtually similar roof structures, indicating the survival of the most efficient structural solutions) where the longitudinal braces are mounted in place of rafters, and because of the vault's extrados, the secondary trusses do not have tie-beams.

The Bistrița fire is an important milestone in the field of roof structure interventions in Romania. Since 2009, the use of wooden (combustible) scaffolding has been prohibited, and a dedicated chapter is under development for the fire protection of historic buildings [32]. This initiative aims to ensure the safety of users and the preservation of heritage values, as well as material and spatial authenticity.

Following the removal of the structure from immediate danger, a comprehensive review of prior interventions ensued, complemented by thorough research and calculation of the fire resistance requirements for the roof's structural elements. Since the building serves as both a place of worship and a venue for exhibitions and cultural events, a fire scenario was developed, considering the following design options to limit fire and smoke development and spread, install fire detection and alarm systems, include a dry column in the tower, install internal hydrant installations, and ensure the fire resistance of the structure.

In the case of protective or temporary roofs, the selection criteria are primarily sustainability [33], taking into account the connection to the structure, the material used for the structure, and the covering and the degree of reuse. Given the significant number of heritage buildings in a state of ruin, these temporary structures can be adjusted to fit the size and height of the remaining buildings in terms of plans and elevations.

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