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# The Role of the Structural Model in Monument Value Preservation

## Failure Mechanisms and Restoration Options from a Heritage Conservation Perspective

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**Abstract**

The separation of engineering and architectural perspectives in the 20th century led to the delegation of different aspects of building design to specialized professionals. Consequently, structural, architectural, and heritage preservation tasks were handled independently, creating diverse prioritization orders in the evaluation of the buildings. One of the greatest victims of this approach are heritage buildings, as less constructive collaborations can result in lasting damages, leading to the loss of certain values.

In heritage preservation projects the structural model is typically less regarded as a value, often leading to a reconstruction without consideration of the original state. This significantly impacts the timber roofs, which are one of the most vulnerable building structures and their deformations can affect the entire building, underscoring the critical importance of preserving the original structural model and raising awareness of its significance as a heritage value.

This research examines roof structure damages, their categorization from a structural perspective, and possible restoration options considering heritage preservation criteria. Through the examples presented, it becomes evident that the roof structures can only be understood as parts of a complex system. It also becomes apparent that due to this complexity, categorizing structural damages in heritage buildings does not help in making schematic solutions.

For every heritage building a thorough investigation and understanding of the historical structural model, the examination of building structures and their interconnections, and the preparation of a reconstruction plan are essential. This process must acknowledge that both the building and its structural model require a unique approach.

**Keywords**

historical roof structures, structural analysis of roof structure failures, structural model as value, heritage protection, value preservation

## 1 Introduction

### 1.1 The evolution of structural approaches in architectural restoration

The use of traditional load-bearing structures remained prevalent in architectural restoration practices until the 20th century. Over time, historical structural systems, often developed through empirical methods, were increasingly replaced by engineered structures. These newer structures, enabled by industrial advancements, prioritized material efficiency and extended the limits of traditional designs, allowing for greater spans, slimmer profiles, and faster production. Initially, such innovations aimed to surpass the capabilities of historical systems but later became essential for their repairs and replacements. The theoretical foundations of an approach radically different from the practice of historicism were laid by the engineering perspective as early as the early 19th century, particularly in the field of heritage preservation. One of the most intriguing examples of this is the multi-phase restoration of the Roman Colosseum in the first half of the 19th century (Jokilehto, 1999).

These interventions, however, can be considered post-traumatic; they aimed not to restore the exact forms of partially ruined structural elements but to evoke their original appearance while taking over their structural role.

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At that time foresight and prevention were not yet emphasized. The anticipated deterioration of structures did not become a central concern until their continuous replacement or reconstruction following the structure's original logic got to be part of everyday practice. The construction methods of historicism did not differ significantly from traditional approaches, and design in this style often reflected a holistic perspective, using not only historical forms but also historical structural models.

However, the new industrial construction methods and faster constructions introduced conceptual errors into roof structures based on historical traditions even though these roofs were often the most vulnerable parts of buildings. The systematic omission of ridge beams and the material-saving design of specific types of roof structures have led to damages that, in many cases, have been left to modern construction industry to correct.

The real paradigm shift occurred in the early 20$^{th}$ century when modern conservation principles broke with the restoration practices of historicism, redefining the concept of restoration itself. The stylistic unity sought in historicist restorations was seen by conservation movements as a falsification of historical authenticity. The key to ensuring authenticity became the clear and relevant distinction between newly added structures and the original ones. This principle found fertile ground in modern architecture, which developed from an engineering perspective and significantly diverged from historical forms. Consequently, authentic interventions increasingly relied on visible structural reinforcements and auxiliary structures distinguishable from the original structural model. This shift had two significant consequences. First, restoration practices began to separate architectural and engineering tasks, with the latter emerging as an independent discipline. Second, the original structural model was no longer treated as a critical input in restoration research. Efforts to fully understand it were often replaced by symptomatic solutions. Importantly, this approach differed from historical architectural practices, which incorporated new discoveries into the logic of the original structure. Instead, the fragmentation of the original became a marker of authenticity, requiring retention and distinguishable supplementation.

For nearly a century, supplementation replaced maintenance as the dominant practice. The degradation of structures was further exacerbated in Hungary after World War II, when neither economic resources nor professional demand supported knowledgeable, value-based maintenance.

This study aims to analyze the failure mechanisms characteristic of wooden roof structures, one of the most vulnerable structural elements of buildings, using the failure categories defined by Eurocode (MSZ EN 1990:2024, 2024), illustrated with examples. In this context, we aim to identify among the optional heritage conservation and restoration methods those that best preserve the original structural model as a core value.

## 2 Roof structures as the most vulnerable building structures

Among building structures, wooden constructions – particularly roof structures – are unequivocally the most vulnerable. These elements are designed to be the most economical to construct while bearing the greatest loads, and they form an integral part of the building superstructures. Consequently, even in the case of independent roof structures, structural failure significantly impacts the stability of the supporting framework. In many cases, defects in the roof structures not only cause but also indicate other stability issues.

These deformations can be examined from several perspectives:

- Materials;
- Structural solutions;
- Construction sequence and logic;
- Connections with supporting structures.

## 3 Durability of timber

The assessment of wood durability can be approached from multiple perspectives. For wood materials, a distinction is often made between natural (theoretical) lifespan and practical lifespan (Bálint, 1956). The theoretical lifespan is generally longer, as it is not influenced by factors that significantly affect practical lifespan, such as the design of joints or the physical and chemical impacts of the built environment. Consequently, durability can be evaluated separately for theoretical and practical lifespan.

Kollmann (1951) categorized the theoretical lifespan of wood species as follows:

- Highly durable: oak, larch, elm, black locust, sweet chestnut, black walnut;
- Moderately durable: beech, ash, spruce, fir, Scots pine, hornbeam;
- Less durable: maple, birch, poplar, alder, linden, willow, horse chestnut.

Conversely, Lámfalussy (1951) focused on practical lifespan, paying particular attention to wood species found in Hungary:

- Durable: black pine, Scots pine, elm, juniper;
- Less durable: spruce, fir, ash;
- Not durable: beech, hornbeam, maple, turkey oak, alder, birch, cherry, poplar, linden.

These comparisons reveal that durability is not a universally defined concept but is influenced by numerous factors. However, the two classifications show correspondence despite their differing focuses.

Historically, particularly durable wood species were selected for construction based on empirical knowledge. Larch was the most commonly used material for roof structures, although other coniferous species were also applied. Hardwood species were also often applied for heavily loaded elements, posts and hardwood pegs (Andorné Tóbiás, 1974).

## 4 Structural failures

According to the Eurocode (MSZ EN 1990:2024, 2024) structural failures are categorized into the following two main groups:

1. Ultimate Limit State (ULS):
   - Loss of equilibrium (EQU);
   - Internal failure and excessive structural deformation (STR);
   - Fatigue failure (FAT);
   - Subsoil failure or excessive deformation (GEO).
2. Serviceability Limit State (SLS):
   - Deformations and displacements;
   - Vibrations and oscillations;
   - Cracks;
   - Other damages affecting external appearance;
   - Internal forces (in specific cases).

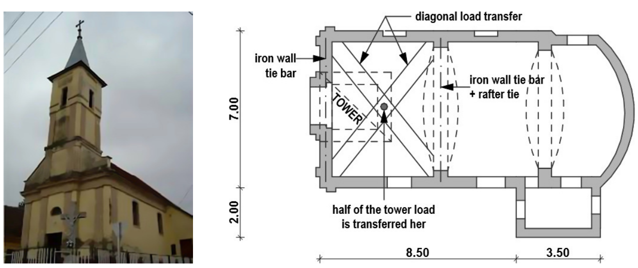
## 5 Details of failures

The analysis of failures in historical roof structures can be approached in two ways. The failure of the roof structure can be assessed independently, but in historical buildings it is also crucial to examine the failures of connected structures, as their force interactions are interdependent. This necessitates the examination of supporting walls, which bear the load of the roof structures. Vaults are often constructed beneath roof structures, typically after the roof covering is completed, to allow the following construction works to proceed in covered conditions and to use the roof structures loads' vertical force during the building of the vaults (Andorné Tóbiás, 1974). The lateral forces of the vaults impact the supporting walls of the roof structure. It is also common to find buttresses, tension beams and iron tie rods incorporated to counteract the lateral forces. These elements influence the force dynamics of the roof structure, often making independent calculation of its forces either impossible or incomplete. Due to the sensitivity of connected structures, the failure of the whole structural system is more common than the failure of just the roof structure. Similarly, damage of the roof structure can lead to the failure of other interconnected structural elements, making their separation from the roof truss problematic in the context of structural modeling.

In many cases, signs of failure become apparent in connected structures before they are evident in the roof structure itself. A typical example of this is the cracking of vaults. Vaults are highly sensitive to changes in force dynamics, and even minor displacements can cause visible cracks, which often indicate a more significant, less visually apparent problem in the overall force dynamics.

A striking example of the need to consider roof structures and connected elements as a complex system is the collapse of the church in Belvárdgyula in May 2006, analyzed by Dulácska and Dulácska (2010). In this case, the church tower applied direct loads on the vaults (Fig. 1), increasing lateral forces. The roof had a collar-beam structure without a ceiling joist, which also applied lateral forces on the sidewalls, amplifying the effects of the tower's loads. The combination of these forces led to the collapse of the tower, which then fell onto the nave, causing the whole church to collapse. While other contributing factors, including construction errors, were also involved, these forces were likely the decisive ones.

In the following I will analyze the different types of failures using a systematization based on the Eurocode (MSZ EN 1990:2024, 2024) limit states, to categorize the failures from a structural point of view, illustrated with examples from Hungarian reconstruction projects.




(a) (b)

**Fig. 1** The picture (a) and the floor plan (b) of the church in Belvárdgyula with the marked position of the tower and the vault (Source: Dulácska and Dulácska, 2010)

### 5.1 Ultimate Limit State (ULS)

#### 5.1.1 Loss of equilibrium (EQU)

This failure mode typically occurs in structures that shift due to environmental effects, such as uplifting, sliding, or overturning. In the case of roof structures, such failures are not common under normal circumstances. Such stability issues in the case of roofs primarily arise when there are changes in the force interactions provided by supporting structures, though these are typically related to the subsoil (GEO) or problems with the supporting structure itself. Stability concerns may arise, for example, under wind loads, but these are generally resolved with bracing systems. This study focuses on damages arising from static, non-dynamic forces, therefore this category is not relevant here.

#### 5.1.2 Internal failure and excessive structural deformation (STR)

Strength-related failures are not typical in Baroque-era structures, as these were generally overdesigned (Andorné Tóbiás, 1974). The undersized cross sections became more characteristic in the Classical period, and the structures built during that time with this problem have already deteriorated. In the current stock of historic roof structures, due to their age, new strength-related failure issues are unlikely unless additional loads are imposed, such as during the installation of a new roof covering.

An example of this occurred in the case of the Reformed Church in Szamostatárfalva (Czeglédy and Mendele, 1972) (Fig. 2). During renovations in 1935, a ceramic tile roof replaced the original wooden shingle covering. The additional load, combined with prior water damage to the old roof structure, led to severe deterioration.

**Fig. 2** Reformed church and wooden bell-tower in Szamostatárfalva (Source: Czeglédy and Mendele, 1972)

Strength failures can also include decay (for example lignin decomposition causing white rot or cellulose decomposition causing brown rot), caused by wood-damaging fungi and insects (Bálint, 1956). These degrade the cross-section of the wood, reducing its load-bearing capacity, leading to STR-type failures. These issues can also influence other load-bearing limit states. Numerous solutions and treatments exist to prevent or fix fungal damage, insect infestation, or internal decay, including chemical and biological treatments, paints, or fumigation, though these are not covered in detail in this study.

Regarding geometric stability failures, deformation in wooden roof structures typically develops gradually. Initially, it may cause only aesthetic or usability issues, but as deformation increases, it can lead to full stability failure. Consequently, issues stemming from deformation are discussed in the SLS failure mode section under Section 5.2.1.

#### 5.1.3 Fatigue (FAT)

Fatigue is not a common phenomenon in wooden structures. It typically occurs under cyclic loads. Since this study does not analyze dynamic loads, and roof structures are not generally exposed to significant cyclic loading, fatigue failure is not considered here.

#### 5.1.4 Subsoil failure or excessive deformation (GEO)

Subsoil failure can cause the building to settle, leading to movement in the walls or columns supporting the roof structure. This demonstrates that the roof structures cannot be examined separately, as the damage or movement of connected structures can also significantly impact the roof.

For example, it was common in church architecture to build new churches on the ruins of earlier ones. This often resulted in uneven foundations, as parts of the new structure rested on remains of the old building or on different subsoils. One such example is the Saint Michael Church in Érd (Fig. 3), which was built on the ruins of an earlier church (Gyetvainé Balogh et al., 2016). Due to the uneven subsoil and inadequate drainage, which led to the saturation of the subsoil near the foundations, the building began to settle. Over time, this caused cracking in the walls (Fig. 4) and additional damage to the vaults and roof structure (Krähling, 2016).

In this case, the primary goal was to stabilize the supporting structures before restoring the roof, as further movement of the supporting elements would have caused new damage to the superstructure (Armuth et al., 2016).

**Fig. 3** Southern façade of Saint Michael Church in Érd (Source: Krähling, 2016)

**Fig. 4** The cracks on the southern facade of the Saint Michael Church before the restoration (Source: Armuth et al., 2016)

### 5.2 Serviceability Limit State (SLS)

#### 5.2.1 Deformations and displacements

A common issue is the creep of wood, where deformation increases over a long period. Initially, this may result in usability problems, but significant displacements can eventually lead to stability issues.

For example time-dependent excessive deflection of wooden members can damage connected or even originally non-connected structures. A typical case is when a rafter tie deflects above a vault, transferring loads to the vault, increasing lateral pressure on the walls. This destabilizes the roof's support system, creating a self-perpetuating structural issues.

In the Capuchin Church in Máriabesnyő[1], deflection was the root cause of structural issues. The deflection of a wooden rafter tie caused loosening in the strut beams, reducing their support for the central post. As a result, the central post transferred more load onto the rafter tie, causing further deflection. The rafter tie, positioned above a vault, eventually began exerting force on the vault, altering its force distribution, leading to more significant structural issues. The solution involved repositioning the strut beams, moving them closer to the central post, and connecting them with a tensioned U100 profile (Fig. 5). This lifted the central post, preventing further deflection in the rafter tie. Additionally, secondary rafts were tensioned underneath.

In the church of Héreg[2], the creep of the timber material caused the primary problem (structural engineer: László Besey). The transverse floor beams rested on a suspended beam spanning an oval space. The suspension system's pillars holding the beam were subjected to compression due to the forces from the two side struts and the intermediate beam. The perpendicular compression of the pillars caused creep, thereby altering the entire structural model. As a result, the struts failed to transfer adequate vertical force to the posts, which slipped downward and began loading the originally suspended beam. This led to significant deflection of the beam.

The solution, considering both economic and structural aspects, was to underpin the rafter tie and the posts with a tensioned rod, thereby elevating the posts and reducing the deflection (Fig. 6).

#### 5.2.2 Vibrations and oscillations

Vibrations and oscillations resulting from dynamic loading can also cause damage. This is a special case, depending on environmental factors such as construction work in the vicinity of the building. These scenarios are not included in the general failure modes examined in this study.

#### 5.2.3 Cracks

The impact of cracks on the load-bearing capacity of timber is still a subject of research (Mergny et al., 2016). Depending on

[1] The details of the structure and its reconstruction were provided by the structural engineer of the reconstruction project, László Besey (Besey, 2024)

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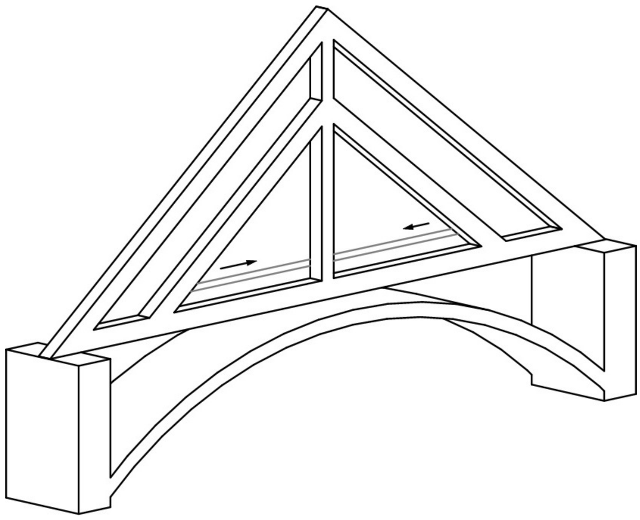


**Fig. 5** The schematic drawing of the roof structure reconstruction of the Capuchin Church in Máriabesnyő

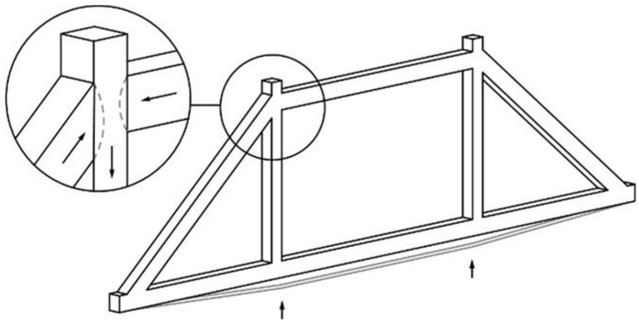


**Fig. 6** The failure of the joints in the Baroque church of Héreg and a schematic drawing of the structure's restoration

their orientation and depth, cracks can affect structural behavior in various ways. Larger cracks may lead to the splitting of the cross-section, altering its moment of inertia and reducing its load-bearing capacity. In such cases, the cross-section may no longer withstand the applied loads, resulting in the strength-related failure modes discussed earlier.

Longitudinal cracks can also alter the location of the torsional center of the cross-section. This can transform the originally bent beam into a bent-twisted beam, which can further influence the displacements.

### 5.2.4 Other damages affecting external appearance

A typical issue affecting aesthetics is the appearance of fungal decay and insect infestation However, since these can also lead to structural failure, they were discussed earlier under the relevant category (Section 5.1.2). Other factors influencing aesthetic appearance do not impact the stability of the structure.

## 6 Construction errors

In addition to the failure modes described above, a frequently occurring issue is the presence of construction errors in roof structures. These may arise either during the original construction or during later renovations. The reconstruction of such structures inherently involves correcting these conceptual errors, which may lead to changes in the structural model and redistribution of forces. In such cases, it is also advisable to examine the structural models of the connected components to avoid further damage. These errors must be resolved as part of any reconstruction project.

A fitting example of this is the Church of St. Stephen in Mecseknádasd (Schőnerné Pusztai, 1974), whose 1970–1971 restoration was designed by structural engineer András Vándor. After the Turkish occupation, the church was reconstructed with a roof structure built with structural deficiencies. Later, during the 1936 renovation, a partial restoration was carried out, where they created additional support for the existing roof structure, but the fundamental design flaws were overlooked. Additionally the original shingle covering was replaced with a significantly heavier ceramic tile roof. Given the numerous conceptual and structural flaws, the designers of the 1970–1971 reconstruction deemed it unfeasible to restore the existing roof, opting instead for a full reconstruction of the roof structure.

## 7 Solutions considering heritage preservation principles

From the perspective of heritage preservation, there is no universal rule defining which values must be prioritized during restoration or reconstruction (Somorjay, 2011). However, there are typical key aspects that should be retained and protected, such as architectural aesthetics, historical significance, and material authenticity. In many cases, structural models are overlooked as heritage values since they are usually non-visible elements and are less frequently recognized as a relevant element on the "list" of heritage values. It is important to note that specific structural models often carry attributes characteristic to their historical period. Additionally, alterations to the structural load distribution can lead to long-term damage, even affecting adjacent structures, which can create additional challenges.

In case of executing a heritage reconstruction, the recreation of the original state is rarely comprehensive, with modifications often made where permitted. Structural stability is always paramount, often necessitating adjustments to the structural model. Modern load-bearing calculations have undergone substantial changes, introducing stricter safety factors. Consequently, many historical structures no longer meet current standards, and this cannot be ignored. As a result, structures, especially roof structures are often rebuilt using different structural models or materials to avoid the need for reinforcement of supporting structures. Economic and practical feasibility also play critical roles in decision-making. Furthermore, prioritizing values – such as preserving a valuable fresco over retaining the original structural model – may dictate the course of action.

The aforementioned cases clearly demonstrate that heritage protection projects involve numerous factors, requiring decisions that cannot treat all heritage values equally. Architects often face the challenge of prioritizing these values. This unequivocally shows that every heritage building is different, demanding a unique approach, that prioritizes finding the optimal solution.

During restorations, numerous reconstruction approaches can emerge, with particular emphasis on the need for unique solutions. Sections 7.1 to 7.6 outline some typical restoration methods without aiming for an exhaustive list.

### 7.1 Additive construction

This method involves supplementing the existing structure with a new element. For instance, the restoration of the Héreg Church (Section 5.2.1) applied steel cable tensioning to stabilize the structure. This approach aligns with the didactic principle (Zsembery, 2009a), using distinct materials to make the intervention visibly identifiable, even to laypersons. Additive restoration can also involve concealed elements, such as reinforcing a wooden beam against deflection using FRP fibers embedded in grooves within the timber.

### 7.2 Complete structural replacement while retaining the structural model

It is also a commonly used method, especially for overdesigned structures, such as Baroque-era designs, where original overdesigned cross-sections can only be replaced with similarly sized elements to maintain load distribution. In many cases, the cost difference between complementing the original structure and complete replacement with a new, thinner structure is negligible, leading designers to opt for total replacement (Andorné Tóbiás, 1974). As a drawback, this approach is against the principle of material authenticity, as the original material – often historically significant – is lost. Additionally in such cases they usually choose a cheaper, more simple structure since the roof structure is usually non-visible.

### 7.3 Partial replacement of structural elements

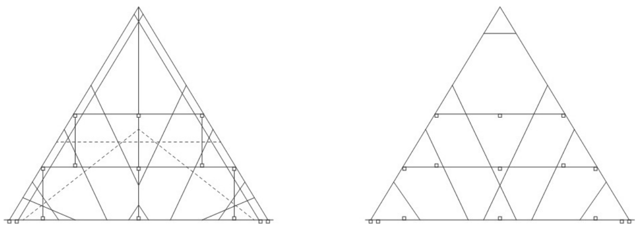
In timber roof structures specific elements can be replaced with creating appropriate connections. This can be done with either didactic or non-didactic solutions (Zsembery, 2009a). Roof structures are typically hidden structures, rarely accessible to visitors, which diminishes the necessity for didactic interventions. When applied, a didactic solution might involve replacing a wooden element with new wood distinguishable by color or finish to clarify the difference between old and new materials.

### 7.4 Modification of the structural model

In some cases, the structural model is altered. This can involve either a completely new structure or modifications to the existing one due to stability or functional requirements. For example, the reconstruction of the Reformed Church in Nyírbátor (Sarkadi, 2011) prioritized accessibility, which necessitated an intervention in the roof structure (Fig. 7). A steel staircase was added to facilitate visitor access to the attic, requiring the cutting and removal of a section of some rafter ties (Fig. 8). This demonstrates how certain values can conflict, requiring decisions from designers and clients about the final prioritization, not even mentioning the problem in certain cases of not paying attention on dealing with the additional forces appearing after the modification, which can affect the whole structure of the building.

### 7.5 Depriving the elements from their structural roles in order to be preserved and displayed

In cases of severe damage certain structures become incapable of fulfilling their original function. If preserving



(a) (b)

**Fig. 7** The main truss (a) and the secondary truss (b) of the roof structure of the Reformed Church in Nyírbátor (Source: Fátrai, 2008)

**Fig. 8** The cut rafter ties of the Reformed Church in Nyírbátor (Source: Sarkadi, 2011)

the structure remains a priority, additional elements can be introduced to protect and display the original ones. For example, a protective roof could be constructed to safeguard and exhibit a roof structure (or other structures) that can no longer serve its original purpose. This approach is less common for roof structures and more typically used for the preservation of walls or ruins, where protective roofing is implemented to ensure their longevity and visibility (Zsembery, 2009b).

### 7.6 Restoration of damaged supporting structures

In many cases, the primary damage is not in the structure itself (e.g., a roof structure) but in its supporting elements, such as foundations, walls, vaults, or buttresses. For instance, the previously discussed restoration of the St. Michael Church in Érd (Section 5.1.4) prioritized repairing the supporting structures, enabling subsequent roof structure rehabilitation.

## 8 Conclusion

From the previous analyses, it is evident that every building reconstruction project is unique, even if categorized under one specific failure mode according to Eurocode classifications (MSZ EN 1990:2024, 2024). This uniqueness becomes even more pronounced when considering the complexity introduced by adjoining structures for each building. Thus, it can be stated that traditional structural classifications are insufficient for providing a template solution in the reconstruction of heritage buildings and roof structures. Instead, it is necessary to thoroughly research and understand the historical structural model of the entire building – an approach already recommended by ICOMOS as early as 1999 (ICOMOS, 1999) – and to prepare a scientifically informed reconstruction plan.

These insights highlight that the structural model holds not only historical value but is also crucial for the stability of the load-bearing structure and the preservation of adjoining and other architectural elements. Therefore, preserving the structural model is of fundamental importance. Despite its current underrepresentation in value preservation, understanding and maintaining the structural model is essential, as alterations can lead to subsequent stability issues, which might result in the destruction of other heritage values.

Furthermore, engineering interventions, as demonstrated, are heavily influenced by principles of heritage preservation. Between the two World Wars, particularly with the spread of reinforced concrete, interventions often resulted in aesthetically questionable solutions. By the mid-1960s, the Italian critical conservation school emphasized the importance of aesthetic considerations. This approach did not advocate for a return to original forms or the complete reconstruction of historical structural models but rather sought to align the aesthetics and structural logic of new solutions more closely with the original structures.

The divergence of engineering practices from architectural art, coupled with the lack of holistic, constructivist perspectives among architects collaborating as specialized designers, and the quality of materials available at the time, contributed to the rapid obsolescence of these solutions. This situation also affected the building users and communities. For over a century, the social aspects of heritage conservation were largely ignored next to the professional aspects. This neglect led to a misinterpretation of modern architecture, where the "common taste" turned away from such engineering-aesthetic works, fostering a resurgence in the desire for original forms and structures.

Modern heritage interventions now tend to focus on reconstruction, which could potentially support the rediscovery of the values of structural models. However, this is precisely where the greatest uncertainties arise. For instance, the roofs of the Füzér Castle (Bereczki, 2016), the Nyírbátor Castle (Zsembery, 2009b), and the Visegrád Royal Palace (Zsembery, 2009b) still adhere to a didactic approach, making them visually distinct from the structures reconstructed with the "original form" below them. Often, these reconstructed parts incorporate hidden auxiliary structures, which introduces additional challenges. Without delving into the issues of heritage values and authenticity, this approach creates problems whose full impact yet remains uncertain. A significant question arises concerning the extensive use of reinforced concrete and hybrid contemporary solutions for historical structures, as seen in the Diósgyőr Castle. How these interventions will affect the upper structures remains to be seen.

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