

STATIC ANALYSIS OF SELECTED TYPES OF ROOF TRUSSES CONSIDERING THE WEAKENING OF THE STRUCTURAL ELEMENTS

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Abstract

Failures of structural elements in historical roof trusses pose a significant challenge in the preservation and restoration of a cultural heritage. These trusses, traditionally constructed from wood, are exposed to various factors that contribute to their degradation and damage. The most common factors include moisture, insect activity, fungal decay, and mechanical damage caused by geometric deformations or unprofessional alterations. These defects can compromise the structural integrity of an entire roof truss construction and jeopardize the stability of the building.

The restoration and conservation of historical roof trusses require a specialized approach involving detailed diagnostics, modern technologies, and the preservation of original construction elements. This paper focuses on identifying the most common structural defects in historical roof trusses, analysing their causes, and presenting possible repair methods aligned with the protection and care principles of a heritage.

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Key words

- Roof,
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1 INTRODUCTION

Historical roof trusses, particularly their structural systems from the Middle Ages to the early modern period, form an integral part of a cultural heritage (Jiří Bláha et al., 2020). Their durability and functionality are crucial for maintaining historical buildings in a good condition (Piotr Berkowski et al., 2015). Roof trusses not only provide the base for a roof structure but also protect buildings from weather conditions and ensure their long-term lifespan (Jerzy Jasieńko et al., 2014). Over time, roof trusses develop various defects that threaten their load-bearing capacity as well as the overall stability and functionality of the building. These defects may be caused by factors such as environmental conditions, inadequate maintenance, inappropriate renovations, and insufficient protective measures. Key factors contributing to gradual degradation are moisture, temperature fluctuations, and other biotic influences. Another factor impacting the structural

functionality of roof trusses is the unprofessional maintenance and reconstruction of historical buildings, which often leads to alterations in the original structure without respecting their historical values (Amir Causevic et al., 2008). These defects can seriously endanger not only the truss structure itself but also the safety of the entire building.

This paper identifies three main types of structural defects in historical roof trusses: the decay of structural elements, improper fabrication of components, and inappropriate interventions in the existing truss structure, these defects represent the most common causes of damage to these historical roof systems (Jerzy Jasieńko et al., 2014). The paper considers the causes, consequences and prevention options for these defects, while also addressing the static analysis of selected types of roof trusses, considering the aforementioned common defects (J. M. Branco et al., 2018).

2 STRUCTURAL DEFECTS OF HISTORICAL ROOF TRUSSES

As previously mentioned, structural defects in historical roof trusses represent a serious issue that requires thorough static analysis. The most common issues include wood decay caused by moisture and biological elements, poorly executed structural connections, and improper modifications during renovations. These problems can result in the uneven distribution of force within the roof truss structure, increased deformation, and failure or reduced durability of the structural elements. Each of the defects requires an individual approach to their diagnosis and subsequent repair to preserve the historical value and safety of the roof truss. When addressing these issues, it is crucial to consider not only technical but also historical aspects to minimize the risks of damaging the heritage of a structure while restoring its original function or designing a new out new function (J. M. Branco et al., 2018).

2.1 Decay of structural elements

The first category of defects, i.e., wood decay, is among the most common and, simultaneously, the most serious threats to historical roof trusses, as they significantly compromise their structural stability. Timber elements are frequently exposed to various sources of moisture originating from external factors (rain, snow) or internal condensation caused by differences in temperature within a roof. Persistent moisture leads to gradual wood decomposition and decay (Nathalie Van Roy et al., 2018)



Fig. 1 Impact of moisture on a beam in a roof truss structure

The structural elements most affected by moisture include rafters and tie beams, which play a crucial static role in a roof truss construction (Lubor Suchý et al., 2018). The most common visual indicator of decay is excessive deformation of the truss structure of the roof. The decay process can be very slow, and subsequent repairs must be handled by experts, they typically involve the thorough removal of damaged sections and their replacement with compatible, high-quality materials. Figures 1 and 2 illustrate typical examples of decayed load-bearing elements in roof truss structures (Jerzy Jasieńko et al., 2014).



Fig. 2 Damage to a Rafter's is Foot and Beam Due to Moisture and Wood-Decaying Fungi.

2.2 Improper fabrication of structural elements and their joints

The second type of defect in roof trusses involves improperly fabricated structural components, which result from low-quality craftsmanship or errors during construction or renovation. Frequent issues include inaccurately designed or constructed joints. Improperly constructed joints or poorly secured components can result in uneven force distribution, which lead to failures such as bending or torsion. To preserve the structural integrity, long-term functionality and stability of an historic roof truss, the individual elements must match the original specifications. The use of inappropriately selected elements can compromise the integrity of the structure. Usage of replacement elements with different stiffness parameters can result in incorrect force distribution and lead to further defects. Such issues should be prevented by providing a thorough static analysis of the roof truss at issue. Typical examples of improper fabrication are shown in Figures 3 and 4 (C. B. Cestari et al., 2022).



Fig. 3 Element Tear-Out Due to Improperly Constructed Joint.



Fig. 4 *Twisting of a Rafter's Cross-Section*

2.3 Unprofessional intervention in the structure

A third type of defect arises from unprofessional roof truss modifications that have been executed without sufficient consideration of the original static and structural design. Common mistakes during the reconstruction or modernization of historical buildings include inappropriate removal of load-bearing components, changes to the original geometry of the roof trusses, or the installation of incompatible additional components. Such interventions can have serious consequences that can threaten the stability of the entire construction. Figure 5 shows an example of an unprofessional intervention in a roof truss structure involving the removal of a critical structural element.



Fig. 5 *Removal of an Original Structural Element*

3 STRUCTURAL ANALYSIS OF SELECTED ROOF TRUSS SYSTEMS

The impact of weakened or removed structural elements was carefully analysed in two selected roof truss constructions (typical historical roof trusses) (Stefan M. Holzer et al., 2009). The examples demonstrate the behaviour of roof trusses with weakened structural elements. In the first case, a roof truss without any longitudinal bracing was studied. An example of this type of roof truss can be found in Cheb (Czechia) in the roof truss of the presbytery of the Church of the Virgin Mary. The impact of the decay of the tie beam can be seen in Figures 6 and 7 (Magdalena Chylewska - Szabat et al., 2018). The decay is located over a length of 300 mm at the point where the roof is supported on a wall plate, as shown in Figure 7. It demonstrates how the decay of a beam can significantly affect the stability of the entire structure.

A detailed structural analysis accompanied by a parametric study was conducted to evaluate the effect of selected loads on various weakened versions of a roof truss. This analysis reveals weak points in the construction with the goal of assisting in the design of a reinforcement or in restoration measures for the structure.

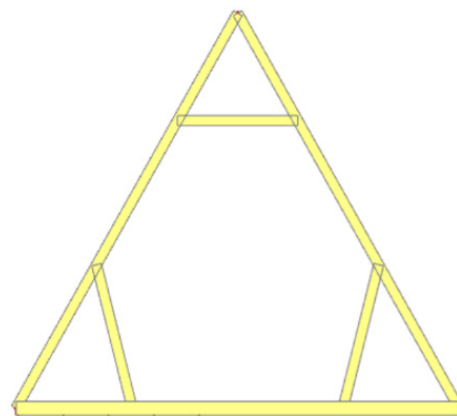


Fig. 6 *Diagram of a Roof Truss System Construction Without Longitudinal Bracing*

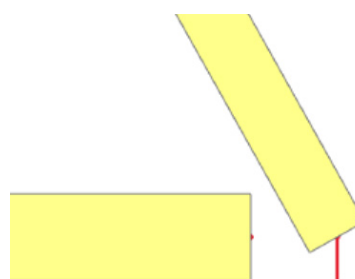


Fig. 7 *Diagram of the Critical Location of a Roof Truss with the Simulation of the Decay of an Element (Complete Decay of the Element)*

The second construction involved a truncated roof truss connected to a pentagonal still (Figs. 8 and 9), where an unprofessional intervention in the tie beam was simulated (Jiří Bláha et al., 2010). Some Baroque churches in Bavaria (Germany) have roof trusses built according to these principles of the collar beam, i.e. St. Michael in Münnerstadt. The simulation dealt with cutting the tie beam 300 mm behind the sill on each side of the main middle truss. This type of intervention was studied to determine the impact it could have on the overall redistribution of the internal forces in the structure. In cases where the roof is designed with a full tie on every fourth truss, an intervention in this critical area can significantly affect the distribution of force in the structure and cause overloading of the elements. As part of the analysis, the behaviour of the roof truss construction was examined due to the damage caused by the unprofessional intervention in terms of its load-bearing capacity and its overall resistance to external loading effects (Nela B. et al., 2018). The results of this simulation showed that even small changes in the critical points of the construction can have a significant impact on its long-term stability and safety. Based on these findings, specific measures can be proposed to reinforce the structure and minimize the risks associated with unprofessional interventions (Antonia Spano, 2015).

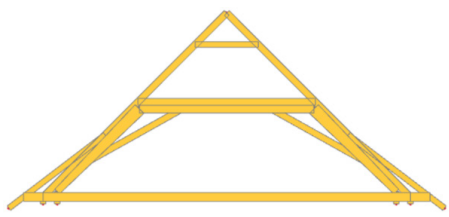


Fig. 8 Diagram of an intact main truss construction of a roof system with a truncated frame and a five-sided sill

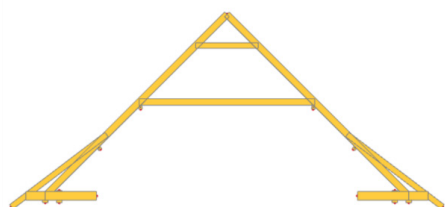


Fig. 9 Diagram of an intact main truss construction of a roof system with a truncated frame and a five-sided sill

3.1 Results from the analysis of Construction No.1 – a roof truss system without longitudinal bracing

The decay of the tie beam was subjected to a structural analysis, including the self-weight and permanent roofing load (clay tiles). Figs. 10-12 represent the diagrams of the internal forces, which include the axial forces N (kN), bending moments M_y (kNm), deformations (mm), and nodal displacements (mm) at the location of the failure caused by the decay. The images from the parametric study include only the diagrams of the original intact truss and the truss with the full decay of the tie beam element. The analysis revealed a significant change in the redistribution of the internal forces, with the largest change occurring at the damaged location of the tie beam, which is the key load-bearing element of the entire roof truss system. The change in the distribution of the internal forces is particularly evident in the bending moments (Fig. 11), while the change in the distribution of the axial forces is shown in Fig. 10.

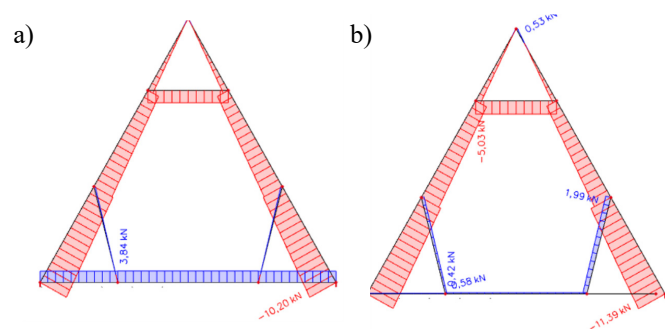


Fig. 10 Axial forces on a) the intact construction (Tie beam $N=3.84$ kN, Rafter $N=10.20$ kN), b) damaged construction (Tie beam $N=0.85$ kN, Rafter $N=11.39$ kN).

The diagram of the bending moment in the roof truss changes under the effect of decay. Previously, the maximum bending moment occurred at the centre of the tie beam, but after the damage, the maximum moment shifts position and

is found further from the point of failure, in a smaller single element, i.e., a rafter is a more subtle element than a truss which becomes overloaded. This leads to a change in the distribution of the forces within the entire main truss. This phenomenon indicates that the roof is no longer loaded uniformly but symmetrically (the load considered causes a symmetrical distribution of the internal forces in the construction). Additionally, the analysis of the nodal displacements showed that due to the decay of the tie beam and its detachment from the truss connection with the rafter, the tie beam experienced a vertical displacement of 11.2 mm (Fig. 12). As expected, the rafter stayed in its original location at that specific point.

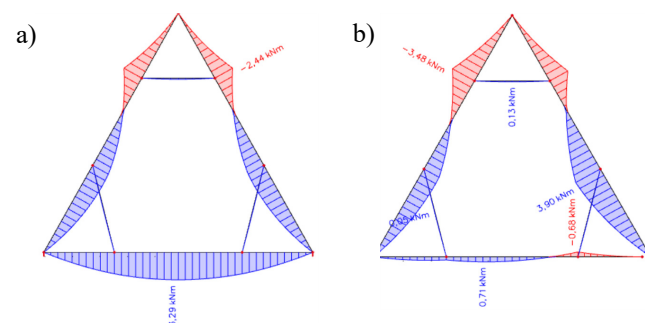


Fig. 11 Bending moments on a) the intact construction (Tie beam $M_y=3.29$ kNm, Rafter $M_y=2.44$ kNm), b) the damaged construction (tie beam $M_y=0.71$ kNm, Rafter $M_y=3.90$ kNm).

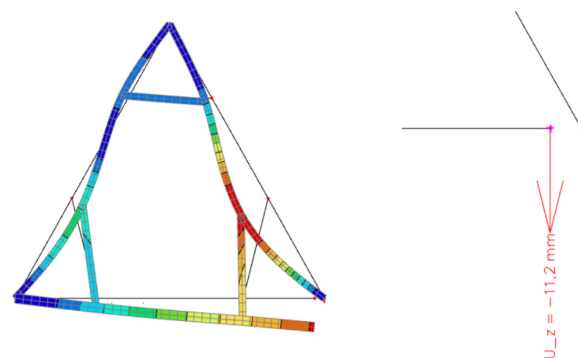


Fig. 12 Total deformation of the tie beam with the damage and nodal displacement at the support location.

3.2 Results from the analysis of construction No.2 – horizontal truss to a pentagonal sill

The static analysis of the horizontal truss for a pentagonal sill revealed significant consequences of an unprofessional intervention on the tie beam. This intervention involved cutting the tie beam, which had a substantial impact not only on the directly affected main truss but also on the intermediate barren truss. In the case of roof trusses containing a main truss followed by three empty bays, the simulated intervention in the structure initiates a "wave-like deformation" that propagates from one truss to the next. The intervention causes a gradual disruption to the stability of the structure, with the deformation transferring from one part of the truss system to another. This leads to changes in the overall distribution of the forces and deformations throughout the entire roof system. The intact and damaged main truss of the roof structure studied are shown in Figure 13.

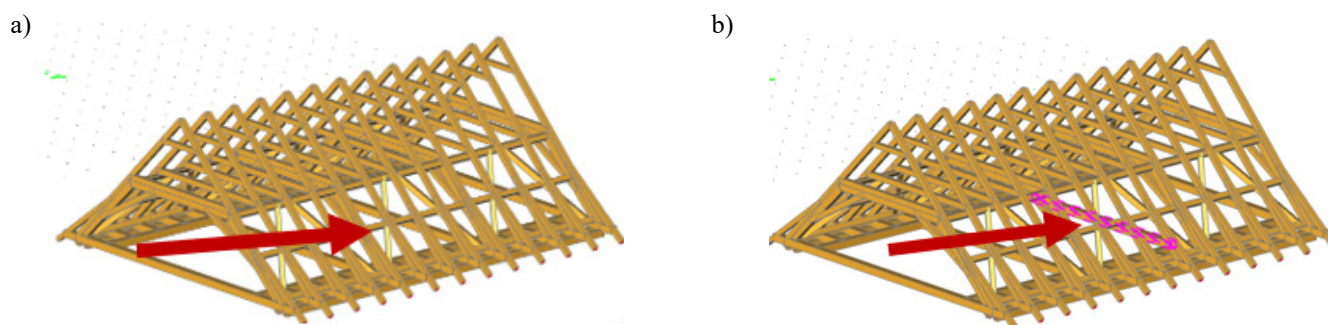


Fig. 13 The position of the complete a) intact and b) damaged joint of the roof structure.

The following diagrams show the internal forces: normal forces N (kN) in Figs. 14 and 15 and bending moments M_y (kNm) in Figs. 16 and 17. The descriptions of the figures

mentioned include the maximum internal forces in the main load-bearing elements of the structure.

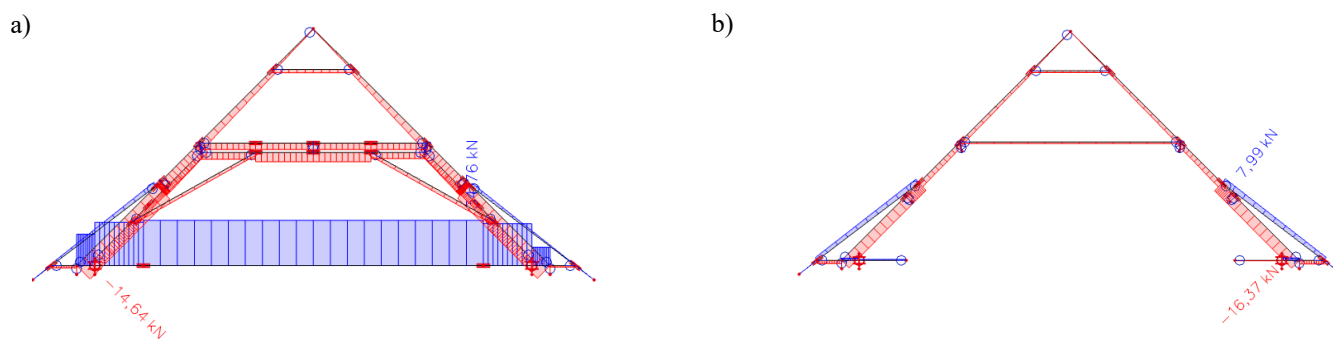


Fig. 14 Axial forces in the intact structure: a) complete joint (Tie beam $N=34.76$ kN, Rafter $N=14.64$ kN) b) empty bay (Sprocket $N=7.99$ kN, Rafter $N=16.37$ kN).

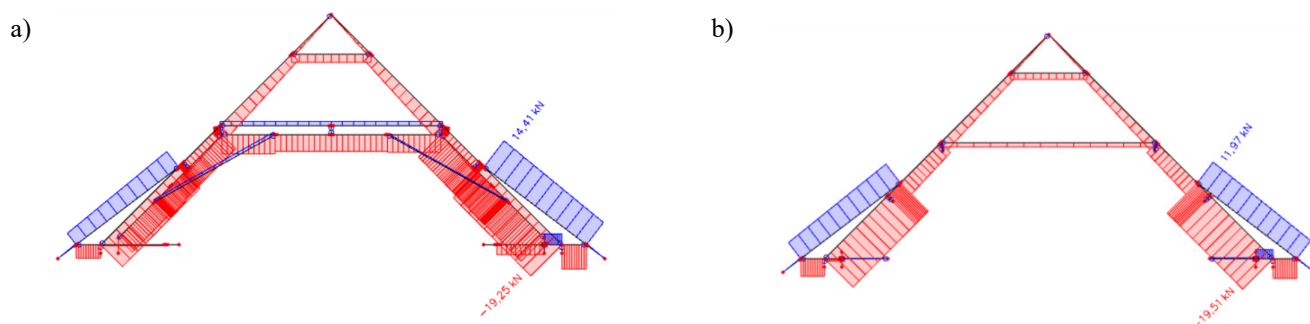


Fig. 15 Axial forces in the damaged structure: a) complete joint (Sprocket $N=14.41$ kN, Rafter $N=19.25$ kN) b) empty bay (Sprocket $N=11.97$ kN, Rafter $N=19.51$ kN).

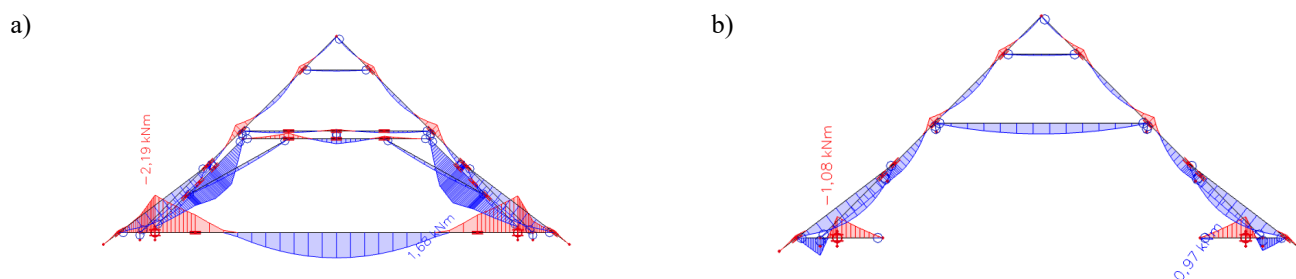


Fig. 16 Bending moments in the intact structure: a) complete joint (Tie beam $M_y=2.19$ kNm, Truncated principal $M=1.68$ kNm) b) empty bay (Tie beam $M_y=1.08$ kNm, Truncated principal $M_y=0.97$ kNm).

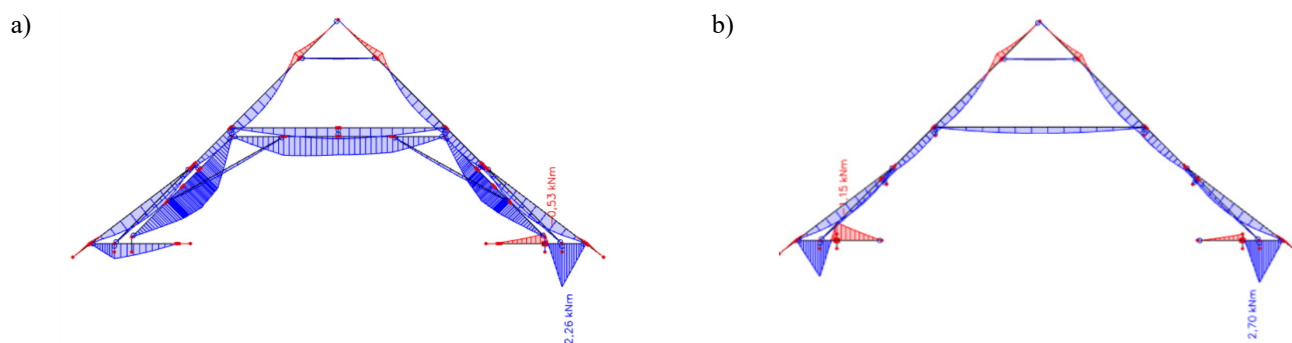


Fig. 17 Bending moments in the intact structure: a) complete joint (Tie beam $M_y = 2.26 \text{ kNm}$, b) empty bay (Tie beam $M_y = 2.70 \text{ kNm}$).

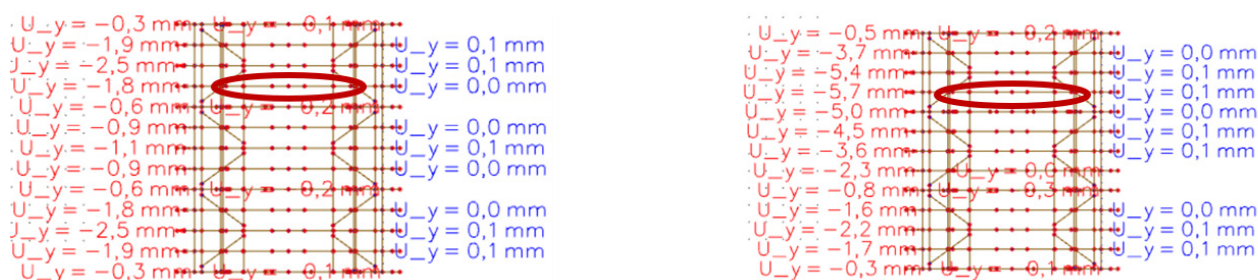


Fig. 18 Horizontal displacement in the roof structure: a) intact structure b) damaged structure, with the location of the damage marked.

The effect of the removal of the tie beam can also be noticed within the horizontally deformed structures with a damaged tie beam. Figure 18 shows a comparison of the horizontal displacement between the intact and damaged structures.

The analysis shows that in the case of the damaged complete truss bay, the largest deformations specifically occurred on the horizontal posts and rafters, that ensure the load-bearing capacity of this type of roof structure. Moreover, when comparing the horizontal node displacements between the intact and damaged truss bays, a significant difference is evident. The node displacement in the damaged complete truss bay increased from 1.8 mm to 5.7 mm due to the unprofessional intervention, thereby indicating a significant change in the behaviour of the entire structure. The most prominent change, which could lead to a critical failure of the roof, is the overloading of the adjacent empty bays in the damaged structure.

4 CONCLUSIONS

The analysis presented, which was carried out on two the roof truss structures selected, clearly demonstrates how the decay of the tie beam or unprofessional intervention in a structure can seriously affect the overall structural integrity of a roof system. The decay or cutting of a tie beam causes an uneven distribution of forces, which leads to the overloading of the adjacent load-bearing elements. In types of structures where the roof framework consists of both complete and empty truss bays, deformations may occur that negatively impact the structural properties of the neighbouring empty bays. These deformations gradually propagate from one truss bay to the next, which can lead to the failure of the structural integrity of the entire system.

As a result, the loads are distributed unevenly, which may cause failures at critical points in the structure. The historical and typological context of the roof systems analysed relates to their significance within a cultural heritage, as these structures represent specific construction techniques and the architectural development of their respective periods. Highlighting these aspects allows for a better understanding of the heritage value of these structures and the importance of their proper protection and restoration. No field measurements or other verification tests were carried out because this study addresses a hypothetical case and models potential situations, such as the cutting of a beam or its decay due to rot. Although the numerical models are based on measurements from real existing structures, the absence of certain elements in this case is simulated and documented purely hypothetically. The analysis also showed that such interventions can have long-term negative impacts on the functionality of a roof. This requires immediate measures to reinforce and stabilize the damaged parts. Without a professionally designed repair plan, the safety of a roof truss structure may gradually deteriorate. Unprofessional interventions or decay due to improper roof maintenance will ultimately necessitate further measures, such as stabilization and reinforcement, to ensure the long-term durability and functionality of the structure.

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