
DEFECTS AND FAILURES OF JOINTS OF HISTORIC ROOF TRUSSES AND POSSIBILITIES OF USING FRP MATERIALS IN THEIR REHABILITATION AND STABILIZATION

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ABSTRACT

The survey of selected historic roof trusses performed within the NAKI DF12P01OVV037project revealed numerous failures and defects of joints of roof truss elements of historic and listed buildings. Based on the results of the survey, the article outlines potential rehabilitation and reinforcement techniques of joints of roof truss elements in which the most frequent defects and failures were found using composite fabrics based on high-strength carbon fibres and epoxy resin (CFRP).

KEYWORDS

historic roof trusses, rehabilitation, stabilization, high-strength carbon fibres

STRENGTHENING OF TIMBER CONSTRUCTION WITH FRP MATERIALS

Composites based on high-strength fibres and epoxy resin are currently most commonly used for strengthening beams in timber structures. The bulk of scientific studies carried out since the second half of the 1960s has focused on the application of these materials for strengthening timber elements under flexural loading or for their local reinforcement under shear loading or increasing locally their tensile/compressive strength in bending [2, 3, 4, 7, 9, 10, 11, 12]. The research manifested that even low level reinforcement with high-strength fibres leads to a significant increase in the load-bearing capacity and rigidity of a timber element. According to Andre [1], reinforcing fabrics have a prominent effect on enhancing the resistance of dynamically loaded structures. Research into the strengthening of historic timber beams with carbon strips [8] pointed out the fact that the preparation of the surface for gluing had an important role in the mutual interaction of wood and the carbon strip. The strengthening of carpentry joints of wooden elements with composite materials has been outside the main stream of research so far; the preferred procedures are mostly based on cutting holes or grooves for mounting composite rods. The issues of strengthening timber joints with metal connectors by means of technical textiles were investigated by [5]. The behaviour of joints of historic structures was analysed and their rehabilitation solved by [6]. The design procedures and the assessment of structures - elements and joints - reinforced with composite materials based on high-strength fibres and epoxy resin have not been integrated into technical standards yet.

STRUCTURAL DESIGN OF ROOF TRUSSES, THEIR MOST FREQUENT DEFECTS AND FAILURES

Roof trusses belong to outstanding technical and construction monuments documenting the high workmanship level of builders of the past and representing, in many cases, complex spatial constructions. While evaluating the structural function of individual elements of historic roofs it is often not easy to determine the function of some roof truss elements in connection with the overall design of the roof truss and its joints. The oldest historic trusses were designed based on the intuition and experience of builders and carpenters of that time.

The structural design of roofs has created a series of unique roof truss constructions over the historical evolution of architectural styles and construction practices differing mainly by the type of supporting rafters and securing the transfer of the effects of vertical and horizontal loads into the masonry structure. The basic roof truss systems with a number of transitional versions are a rafter system, strutting beam system, and purlin system.

The joints of individual elements of trusses are crucial for their mutual interaction, for securing the structural function, spatial rigidity and dimensional stability of roof trusses. The most commonly used carpentry joints of wood trusses (scarf joints and lap joints, halving joints, mortise and tenon joints, single or multiple dovetail joints, bird's mouth joints and cogged joints complemented by wooden pegs, corner beads, iron angles and special elements, nail or bolt connections) may be classified as non-rigid, yielding joints, considered as articulated joints if the appropriate adjustment prevents the displacement of an element in the joint. In cases where it cannot be reliably assumed that there is no displacement in the joint, the joint is considered as simply supported (running in a straight line in the direction of the anticipated displacement - so-called "linear joint"). Articulated joints of roof truss elements – e.g. rafters at the apex, a strut and a strutting beam, a strutting beam and a rafter, etc. - complemented by a brace in the immediate vicinity already have a nature of an unyielding joint in bending, which can be classified as a rigid joint. The spatial rigidity of the roof truss construction in the longitudinal direction generally depends on the mutual connection (coupling) of principal or common rafters. In roof truss systems with standing or lying trusses, braces, struts, seats, St Andrew's crosses, etc. the above elements secure the distribution of the horizontal load onto individual roof trusses in the proportion to their rigidity.

SURVEY OF SELECTED ROOF TRUSSES OF HISTORIC BUILDINGS

The NAKI DF12P01OVV037 research project included the visual survey of roof trusses of selected historic buildings of the Premonstrate Monastery at Teplá (Fig. 1a), Hájčí Court in Prague (Fig.1b), a sheep shed of Lužany Castle (Fig. 1c) and Litovice Stronghold (Fig. 1d). The historic masonry buildings selected for the survey come from different regions of the Czech Republic differing by their type of use, maintenance quality or rehabilitation measures performed (protection against biological degradation).

Due to the fact that the issues of strengthening timber elements, mainly beams, with composite materials based on high-strength fibres and epoxy resin are the subject of long-term research, the survey of the above structures was primarily focused on the defects and failures of joints of truss elements with the objective of verifying the applicability of composite materials for their rehabilitation and strengthening.

The survey dealt with the frequency of the failures of carpentry joints used in the roof truss construction (100% = total number of a respective type of carpentry joint in the construction). Tab. 1 to Tab 4 present relative proportions [%] of the above carpentry joints revealed during the visual survey of defects and failures, e.g. slippage of an element from a joint, pin deformation, etc.

Tab. 1 Roof truss survey evaluation – frequency of failures – Premonstrate Monastery at Teplá

CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS	CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS	CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS
Miltre joint	2%	Butt joints	35%	Tenon joints	55%
Halving joints	2%	Dado joints	45%	Bird´s mouth joints	25%
Cogged joints	15%				

Tab. 2 Roof truss survey evaluation – frequency of failures – Hájčí Court

CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS	CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS	CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS
Miltre joint	5%	Butt joints	45%	Tenon joints	60%
Halving joints	4%	Dado joints	55%	Bird´s mouth joints	30%
Cogged joints	10%				

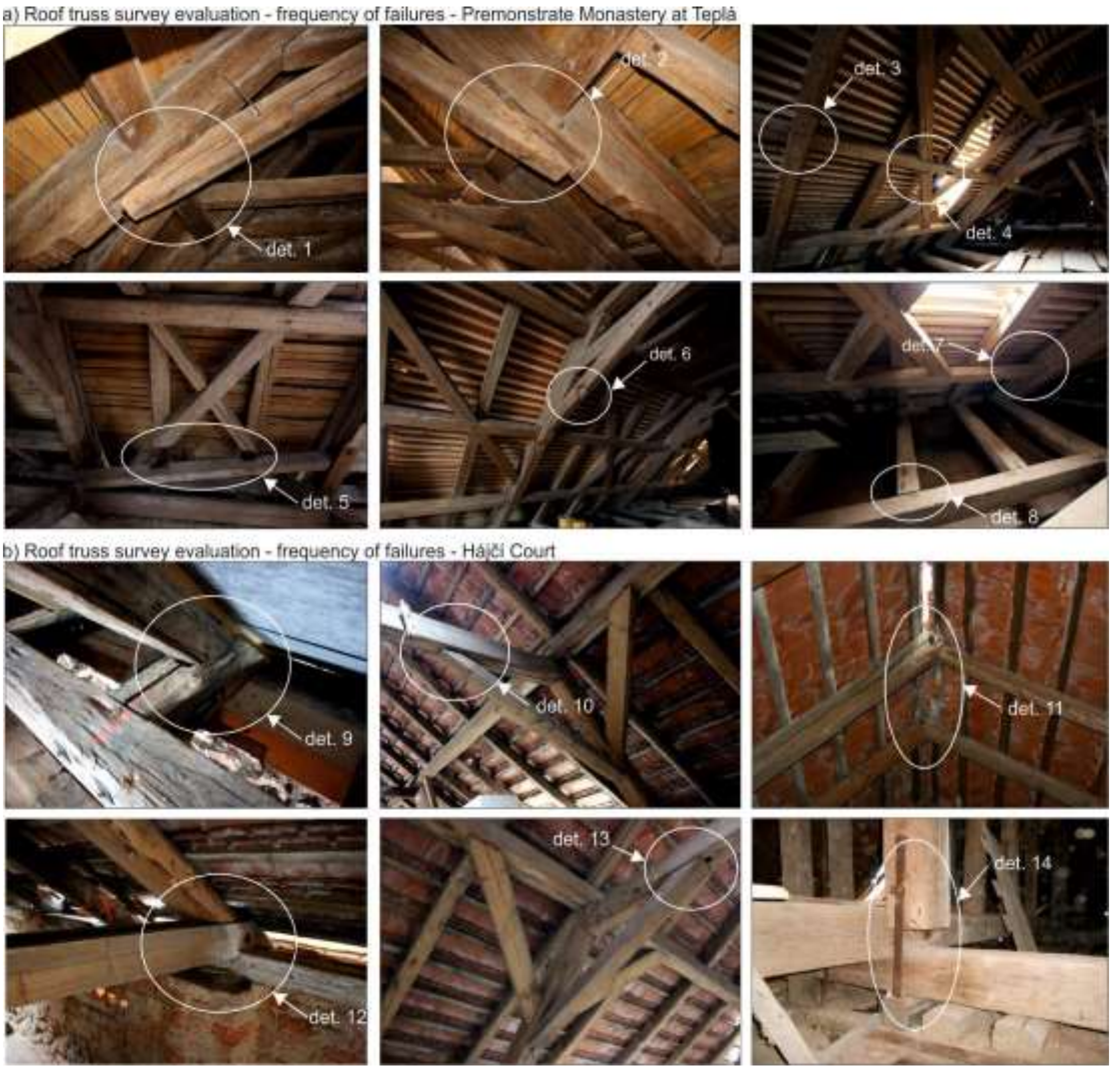

Fig 1. Roof truss survey evaluation – frequency of failures

Tab. 3 Roof truss survey evaluation – frequency of failures – Lužany sheep shed

CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS	CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS	CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS
Miltre joint	3%	Butt joints	45%	Tenon joints	60%
Halving joints	10%	Dado joints	65%	Bird´s mouth joints	25%
Cogged joints	15%				

Tab. 4 Roof truss survey evaluation – frequency of failures – Litovice Stronghold

CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS	CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS	CARPENTRY JOINTS	THE HIGHEST FREQUENCY OF DEFECTS
Miltre joint	8%	Butt joints	48%	Tenon joints	60%
Halving joints	1%	Dado joints	36%	Bird´s mouth joints	45%
Cogged joints	20%				

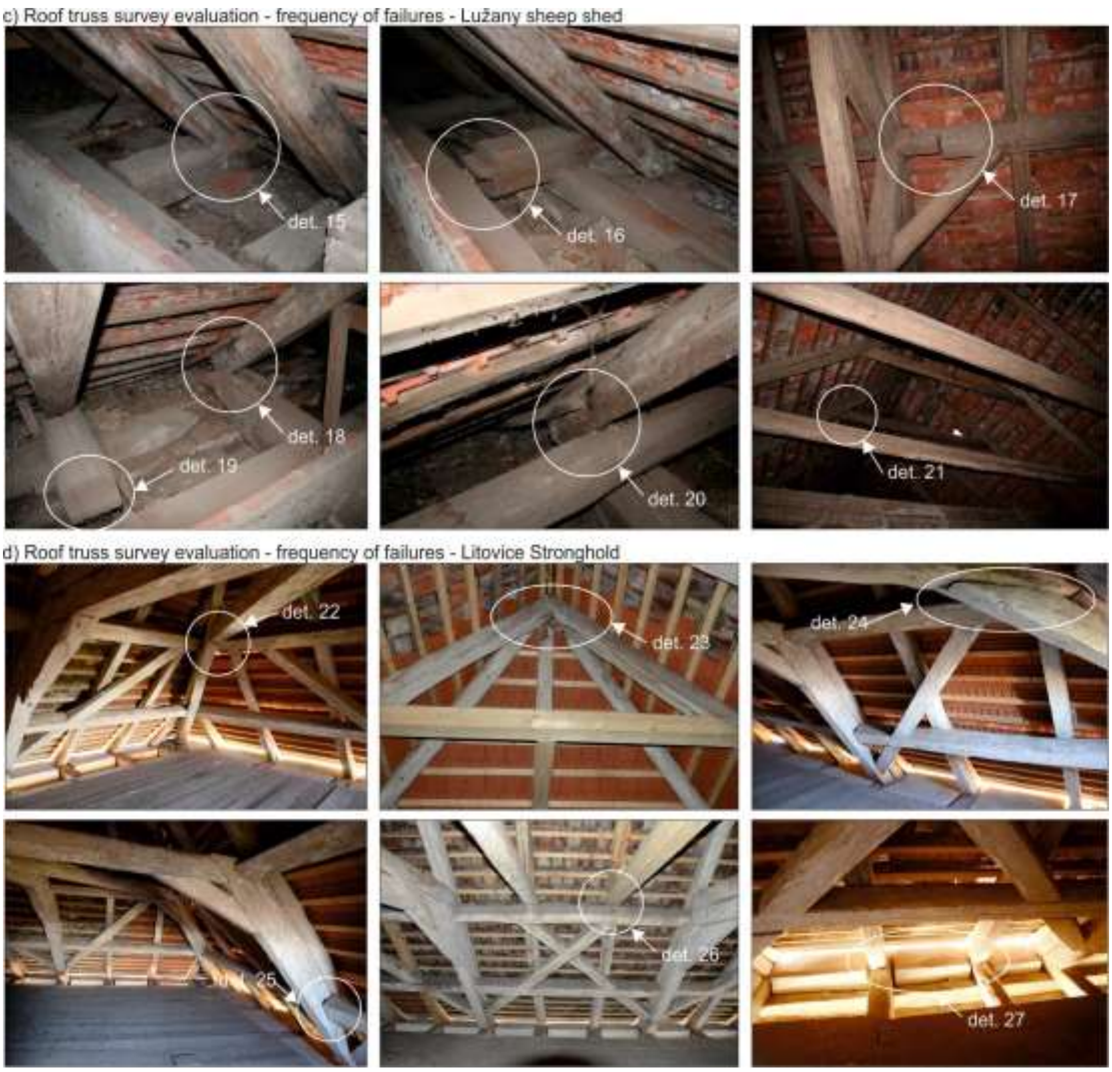

Fig 2. Roof truss survey evaluation – frequency of failures

The evaluation of the visual survey of roof trusses of selected historic buildings pointed out that the highest frequency of defects and failures have been found in the following carpentry joints: dado 36 – 60% of degraded joints, bird's mouth 25 – 45% of degraded joints, mortise and tenon 55 – 60% of degraded joints and butt 35 – 45% of degraded joints.

In bird's mouth joints, non-precise shaping of the "cog" appeared most frequently, its excessive length and different planeness of contact surfaces (the element does not fit in the entire area of the joint). In the case of mortise and tenon joints, the most common failure was partial or total slippage of the tenon from the mortise, tenon deformation or large tolerances and the ability of tenon "movement" in the mortise. In the case of butt joints, the most frequently occurring defect was different planeness of contact surfaces, in dado joints large tolerances and also different quality of the bearing surfaces. Some of the above defects are, to some extent, affected by volume changes of wood. Based on the survey of selected historic buildings, we may summarize that the most common defects of selected historical roof trusses from the perspective of joints of truss elements are poor quality or loosened joints, their insufficient rigidity and bearing capacity, inappropriate joint design, insufficient spatial rigidity of the truss system in the transverse and longitudinal direction (faulty, loosened connections). The most common failures of joints according to the research are the loosening or damage of joints, loosening of nails, bolts, loosening of carpentry joints, etc., nail corrosion in wood (using wet thin wood), loosening of anchoring iron ties (straps) of eaves plates, excessive deformations of the roof truss due to insufficient rigidity of principal trusses or loose or unsecured joints, degradation of the roof truss due to unqualified interventions (removal or damage of e.g. tie beams, purlin posts, etc.), initial deformations of built-in elements or their excessive shrinkage. The prevailing part of the above failures is caused by the properties of wood (shrinkage or swelling, biological degradation, poor quality of wood), while failures caused by the overloading of the construction, excessive deformations or insufficient dimensions of some elements are represented to a lesser extent.

REHABILITATION AND STRENGTHENING OF SELECTED JOINTS OF TIMBER ROOD TRUSS ELEMENTS

To ensure a long service life and functional reliability of historic roofs we must, above all, provide conditions that minimize the risk of biological degradation of wooden elements and their joints i.e. prevent the penetration of elevated moisture levels into the roof truss construction. At the same time, it is also necessary to secure sufficient strength and rigidity of the roof truss construction, both of its individual elements and their joints. The methods used presently for the rehabilitation of joints and increasing their load bearing capacity are invasive methods (e.g. inserting steel plates and bolts). They reduce, to some extent, the historical value of the roof truss and are not reversible (Fig. 2).

Fig 3. Traditional strengthening and stiffening of joints of roof truss members – using steel bolts and plates

The application of composites based on high-strength fibres and epoxy resin for the rehabilitation and strengthening of joints of roof truss members is advisable in terms of the minimum additional loading of the construction and the minimum dimensional changes of the connected elements. Fig.3 shows reinforcement and bracing options for the most frequently damaged joints of roof truss elements selected on the basis of the survey. Apart from the low weight and width (thickness) of the reinforcing layer of a composite based on high-strength fibres and epoxy resin, another important characteristic, from the perspective of current heritage conservation, is the non-invasiveness of these materials in surface applications and a possibility of their later removal.

The proposed rehabilitation and strengthening techniques of joints of timber truss elements are designed for surface applications of composite strips of fabrics of high-strength fibres and epoxy resin: surface applications reduce further weakening of stressed joints which would otherwise require the execution of holes or grooves for inserting bars or lamellae. The disadvantage of surface reinforcement is the necessity of ensuring adequate anchorage lengths of reinforcing strips and the necessity of previous surface treatment of wooden elements to secure the highest quality of the contact between the reinforcing layer and the elements of the reinforced joint.

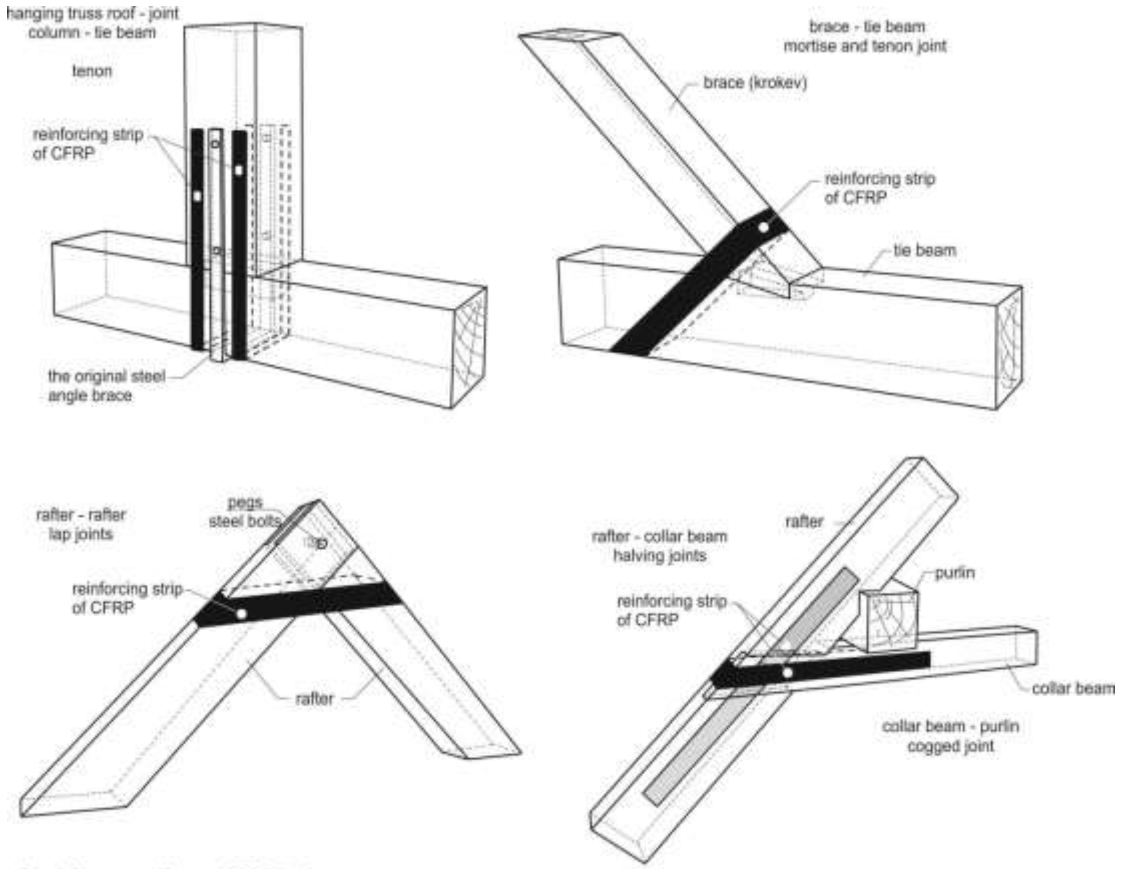

Fig 4. Rehabilitation of selected joints by means of surface application of CFRP composite fabrics and epoxy resin

The disadvantage of surface applications is the high diffusion resistance of the composite. The prevention or limitation of natural drying (non-uniform shrinkage) of parts of the element around the joint may set off the development of biodegradation processes and subsequent destruction of parts or entire roof truss elements. For this reason, the reinforcement of joints should not be carried out on the overall surface basis, but should be limited to strips with a required width. For the above reasons, but also to protect wood, it is necessary to minimize or completely eliminate the sources of moisture (leakage, condensation, capillary action, etc.), especially in places of the masonry contact with wood.

The application of a composite based on high-strength fibres and epoxy resin is also limited by the low fire resistance of this material, where most epoxy resins already start melting at 80 °C and the reinforcement loses its structural effectiveness. For this reason, the completed reinforcement must be properly protected from the effects of high temperatures.

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CONCLUSION

The above survey has manifested that regardless of the locality where a building is situated and the building's purpose, the carpentry joints with the most frequent occurrence of defects and failures are butt joints, dado joints, bird's mouth joints and mortise and tenon joints. On average, 40 – 50% of these joints currently show some defect or failure.

The application of composites based on high-strength fibres and epoxy resin is a non-invasive, reversible rehabilitation option for joints of roof truss elements. It is a surface application using strips of fabrics based on high-strength fibres applied onto clean and solid wood surfaces which may be completely removed without any major consequences in the future and replaced with a new technology. The possibility of using composites based on high-strength fibres and epoxy resin for the reinforcement of carpentry joints is a progressive technique, which, however, requires the performance of comprehensive experimental and theoretical research to identify the design and calculation procedures.

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