REALISTIC MODELLING AND REPAIR OF ANCIENT AUSTRIAN ROOF STRUCTURES WITH WOOD-BASED PANELS, PART II

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Abstract

The erection of ancient roof structures was based on the experience, tradition and the courage of their constructors instead of a structural analysis. A realistic model requires the consideration of the spatial load-bearing behaviour, as well as the flexibilities and the eccentricities of carpentry joints. However, the utilization ratios of roof structures yield high values, so no meaningful statement about the load-bearing capacity of these structures can be made. By using the "Grazer Dachstuhl" as an example, changes of the utilization ratios as a consequence resulting from the consideration of the capacity of the roof battens are pointed out. In the beginning, some theoretical background on the load-bearing capacity of roof battens is presented. This is followed by a report of some structural tests and the documentation of a model calculation.

Based on the findings of the analysis of ancient roof structures, a protecting repair-concept using wood-based panels will be developed. This integral structure comprises the improvement of the rafter roof, a strengthening of the rafters themselves and their bases and an in plane-bracing of the roof. Additionally, this concept is characterised by economical, constructural and building-physical advantages.

INTRODUCTION

In the context of a structural analysis, the mechanical behaviour of an existing structure is represented by a simplified structural model. In some cases these computations result in extremely high utilization ratios (see [1], [3], [4]), so that no meaningful statement about the load-bearing capacity of these structures is possible. The fact that, although calculated utilization ratios are high, joints, beams or structural elements did not fail, can be justified as follows:

- The local material strengths are higher.
- The calculated loads did not occur during the existence of the building.
- The safety level does not meet the current requirements of the standards
- The analytic model and the design concept is unable to represent the real structural behaviour

As illustrated in [4], the beams and joints in the influence area of the dormer and the hip area yield very high utilization ratios in the *„Grazer Dachstuhl"* (see [1]) of the real estate Mandellstraße 9 (see Fig. 1). The calculated capacity of rafter #12' is exceeded by the factor of 5 in the area of its cantilever which supports the valley rafters of the dormer. This paper deals with changes of the utilization ratios of rafter #12', due to taking into account the load-bearing capacity of the roofing lath.

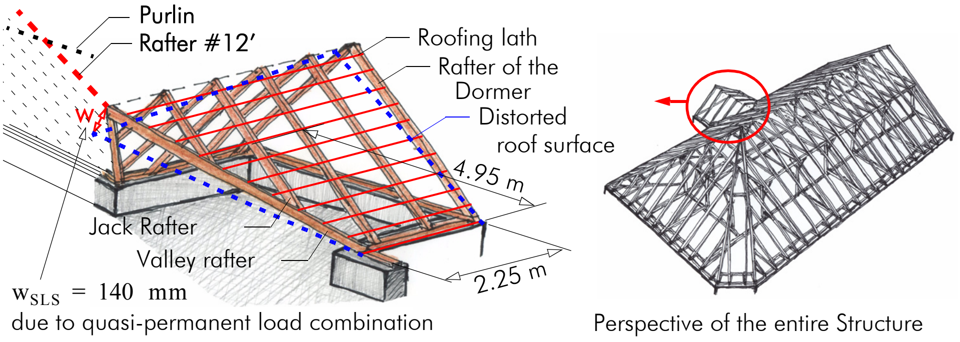


Fig. 1. Spatial illustration of the dormer and the entire structure (see [4]).

Numerous surveys of ancient roof structures showed, that the load-bearing capacity of roof battens significantly influences the global load distribution. For instance, the global bracing disregarding the roof battens is often inadequate to non-existent (see [4], [6]).

TYPES OF LOAD-BEARING BEHAVIOUR

The load-bearing behaviour can be divided in load-bearing behaviour due to loading *in* the X_L–Y_L–plane and *perpendicular* to the X_L–Y_L–plane.

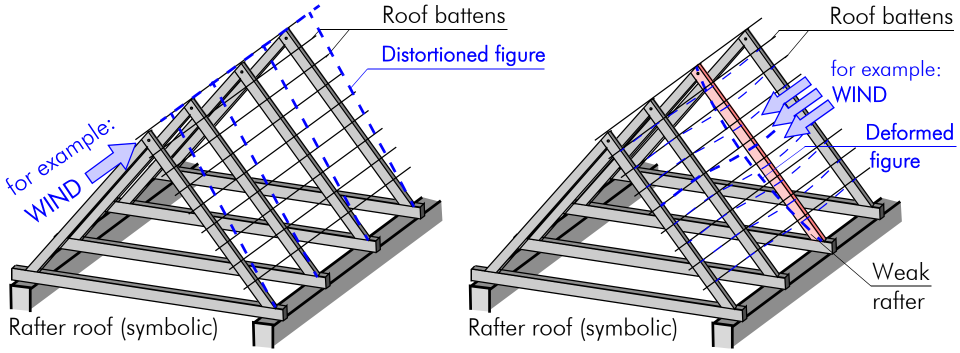


Fig. 2. Types of load-bearing behaviour, Left: loading *in* the X_L–Y_L–plane,
Right: loading *perpendicular* to the X_L–Y_L–plane.

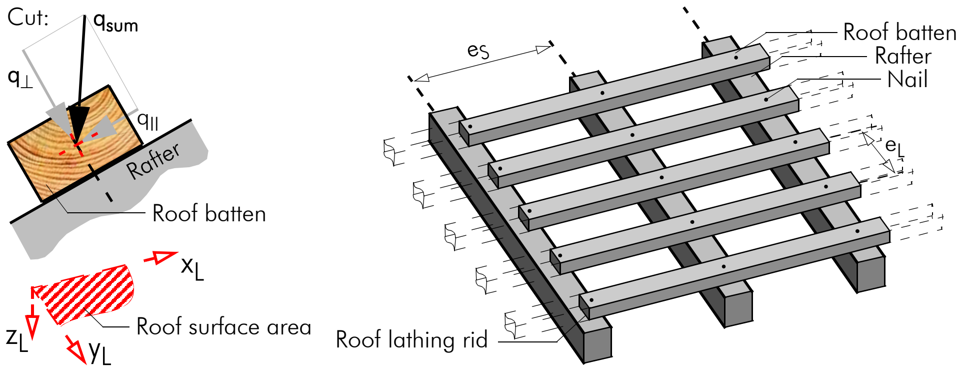


Fig. 3. System of rafters and roof battens (not according to scale).

Load-bearing behaviour due to loading *in* the X_L–Y_L–plane

Longitudinal bearing behaviour (in X_L-direction)

Valley and hip rafters, together with the jack rafters and roof battens form many *triangles in the roof surface area*. As a result of deformations in the roof surface area axial forces are evoked in these triangles, that depend on the axial stiffness of the battens, the stiffness of the nail joints between battens and rafters and the roof lathing rids.

Furthermore, the roof battens support oppositely placed hip rafters in hip areas for instance. The longitudinal capacity of the rafters is also important for the spatial bracing of the rafters perpendicular to the frame plane.

Shear bearing behaviour

Distortions of the roof surfaces result from deformations perpendicular to the frame plane. These distortions cause changing angles between rafters and roof battens, whereby small equivalent torsion spring stiffnesses in the nodes can arise (*flexible vierendeel girder system*).

Furthermore, the spatial stability of numerous ancient rafter and collar beam roofs is only possible due to the shear bearing capacity and the longitudinal bearing capacity of the roofing lath (see for example [4], [6]).

In the case of relative deformations of adjacent rafters in the roof surface, the bending stiffness of numerous, flexibly joined roof battens is raised (*system effect in the roof surface*).

Load-bearing behaviour due to loading *perpendicular* to the X_L–Y_L–plane

In case of differential deformations of adjacent rafters, load restributions due to bending can be enabled by the roof battens (*system effect*). See Fig. 4 and Fig. 5.

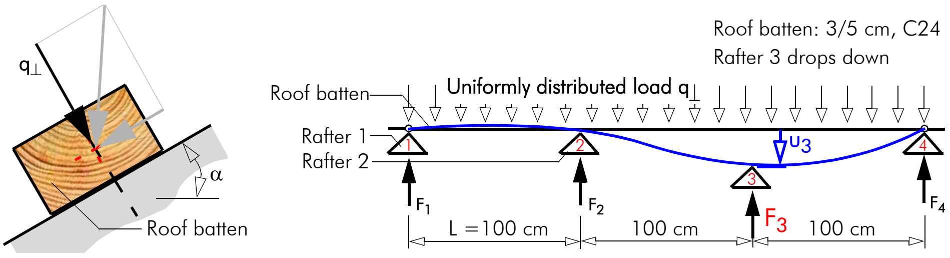


Fig. 4. Structural system and assumptions for the model calculation.

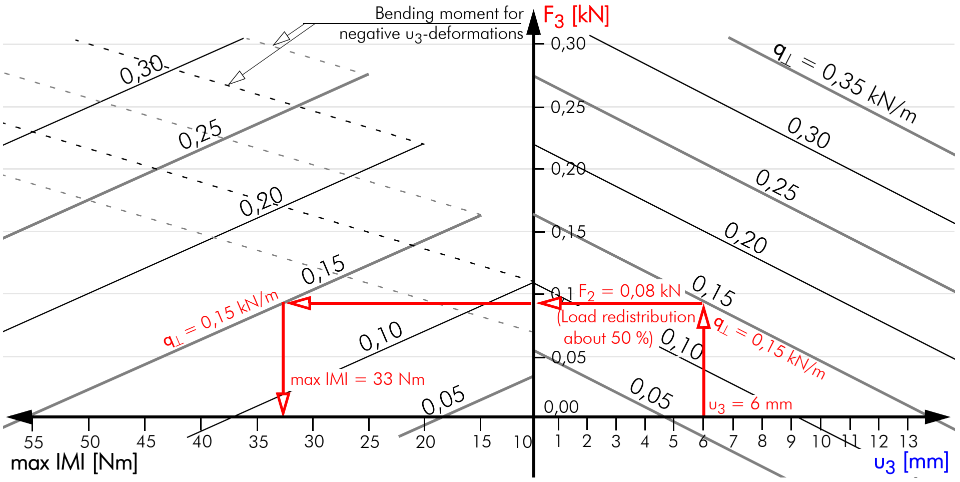


Fig. 5. Load redistribution (Changes in the reaction force F_3 = load of the rafter) and bending moment of the roof batten for different $q_\perp$ per batten (example for u_3 = 6 mm and $q_\perp$ = 0,15 kN/m in red).

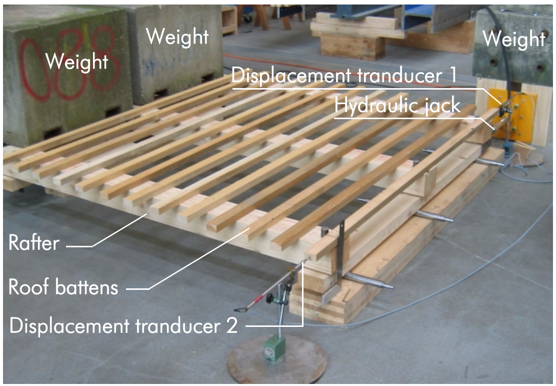
DETERMINATION OF THE SHEAR STIFFNESS IN THE ROOF SURFACE AREA BY TESTS

Currently the calculation of the shear stiffness in the roof surface area seems to be nearly impossible, therefore several tests were performed. As 39 nodes were simultaneously tested in this case, at least fundamental findings may be gained.

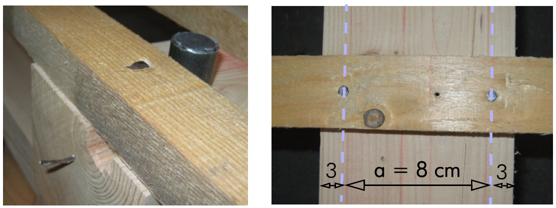
Friction forces between the roof tiles appears to be statically not useable, because the magnitude of these forces depends on further effects such as roughness as well as geometric influences. Therefore no roof tiles have been applied in the tests.

Construction at the building site

In many cases the roof battens of ancient roofs tiled with plain tiles are 30/50 mm in cross-section at a distance of 150 mm. In accordance with investigations on ancient roof structures [4] only one nail per roof batten-rafter-node exists. In former times forged nails were used (see Fig. 6). Due to the fact that the roof battens are often less durable than the timber of the roof structure, today the battens are mostly fixed with wire nails instead of forged nails.

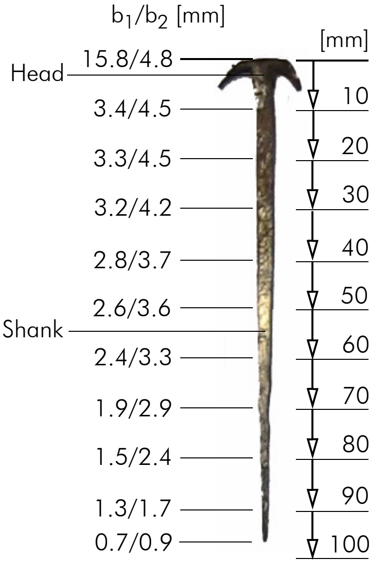


(a) Overview of the test configuration



(b) Curved forged nail

(c) Node (1): rafter-roof batten



(d) Typical forged nail

Fig. 6. Test configuration including node details and a typical forged nail.

Test configurations

A rafter-roof batten-field, consisting of 13 battens on three rafters was assembled on the floor (see Fig. 6 and Fig. 7). The shear distortion of this shear field was applied by a hydraulic jack. The maximum displacement *u* of the field was set to 100 mm. The lateral forces were uniformly transferred into the rafters by a roller-supported load transfer beam. Two Teflon disks were placed in between the rafters and the load transfer beam or the anchor beam in order to reduce the frictional resistance in the rotation center.

A total of four test configurations was tested:

1) Two wire nails (3.1/80) for each roof batten-rafter-joint at a distance of 8 cm
2) One forged nail (dimension comparable with the wire nail) for each roof batten-rafter-joint
3) One wire nail (3.1/80) for each roof batten-rafter-joint
4) No connection between battens and rafters in order to investigate unintentional frictional resistances in the steel pin joints.

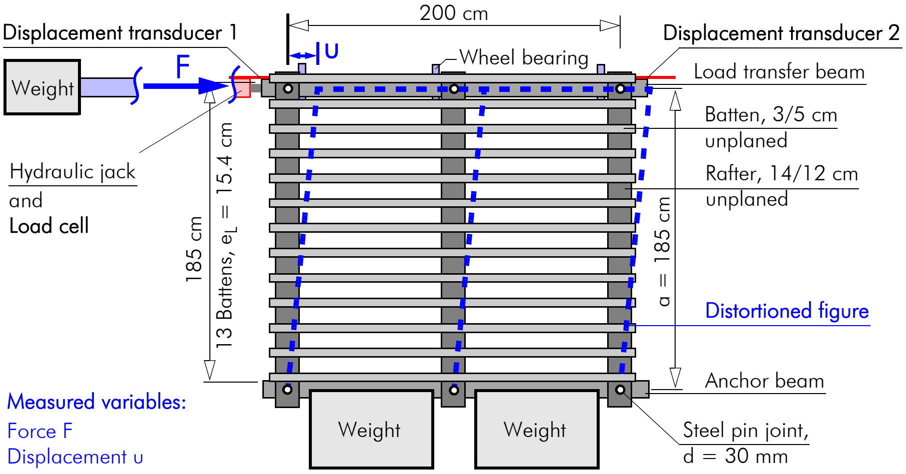


Fig. 7. Sketch of the test configuration in top view.

Test results

Fig. 8 illustrates the results of the four tests. In each case multiple hystereses were passed through, in order to simulate varying stresses and stress directions and their effects. It can be assumed that in ancient roof structures at least the first hysteresis was passed through completely. Therefore, the diagram always illustrates the second hysteresis. All other hystereses differ only insignificantly from these.

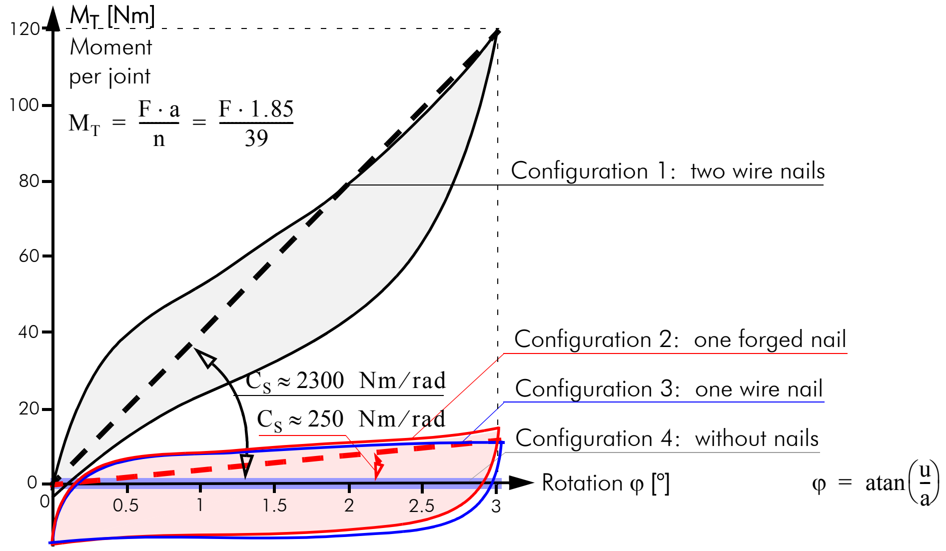


Fig. 8. Moment-rotation-diagram for all test configurations and illustration of the calculation values of the equivalent torsion spring stiffness.

For configuration 1 (two wire nails at a distances of 8 cm) the approximation by a linear-elastic moment-rotation-trend seems to be suitable for the engineering practice.

The results of both configurations with only one nail show a significantly different behaviour. Starting from a rotation φ of about 0.5°, no considerably higher forces can be transferred (plastic behaviour). The transfer of the moments is mainly carried out by sliding friction. The maximum moments are in the range of 10 % compared to configuration 1.

The maximum achieved moments for the joint with one wire nail are about 15 % lower than for a forged nail. Two reasons for this may be the lower pull-out resistance (and therefore contact pressure) and the lower shaft friction of the wire nails.

The test without connectors between roof battens and rafters (configuration 4) demonstrates that the undesired frictional resistances in steel pin joints have only insignificant effects on the test results with nails.

Calculated value of the equivalent torsion spring stiffness

Due to the following facts, it is problematic to define a calculated value of the equivalent torsion spring stiffness:

- Only few test results are available.
- High variations are expected.
- High shear distortions of the roof surfaces up to 3° were found in ancient roof structures (see example in "Introduction").
- Besides plain shear behaviour, an additional bending behaviour of the roof battens could be observed in the test. This fact leads to a falsification of the calculated torsional moments.

Because of these facts, the calculated value of equivalent torsion spring stiffness is defined as a secant modulus for joints with two nails at a distances of 8 cm and a maximum displacement of 3° as follows:

$$C_{S,\,ser} = C_{S,\,u} = \mathbf{C_S} = \frac{M_{T,\,max}}{\varphi} = \frac{120}{0.0524} \cong 2300 \;\; Nm/rad \qquad \varphi = 0.0524 \;\; rad = 3.0°$$

Without considering friction, the value of the equivalent torsion spring stiffness can be calculated for two nails:

$$C_{S,\,ser} = J_P \cdot K_{ser} = 2 \cdot r^2 \cdot K_{ser} = 2 \cdot \left(\frac{a}{2}\right)^2 \cdot K_{ser} = 2 \cdot \left(\frac{0.08}{2}\right)^2 \cdot 710 \cdot 10^3 \cong 2272 \;\; Nm/rad$$

The flexibility of one wire nail due to shear is calculated according to EN 1995-1-1 [5]:

$$K_{ser} = \frac{\rho_m^{\,1.5} \cdot d^{0.8}}{30} = \frac{420^{1.5} \cdot 3.1^{0.8}}{30} = 709.32 \;\; N/mm \approx 710 \;\; kN/m$$

$$\rho_{mean,\,C24} = 420 \;\; kg/m^3 \qquad d = 3.1 \;\; mm$$

The test configurations were modelled to gain test results independent from the bending stiffness of the battens. It was found that the bending stiffness of battens is only important in tests with two nails per joint. Therefore the calculated value of the equivalent torsion spring stiffness is approximately *2500 Nm/rad* (see Fig. 8).

The design value of the equivalent torsion spring stiffness for joints with only one nail is defined with approximately 10 % of the stiffness for joints with two nails (250 Nm/rad). Due to the small differences between forged and wire nails, the same value is used for both. The calculation values for one or two nails provide conservative results for rotations less than 3° (corresponding to a displacement/inclination of L/19).

SPATIAL MODEL OF A ROOF STRUCTURE WITH DORMER

In the spatial structural model (including the consideration of the flexibilities and eccentricities of joints) of the "Grazer Dachstuhl" of Mandellstraße 9 all roof battens in the area of the dormer and the adjacent ridge roof surface are implemented as mentioned in the introduction (see Fig. 1). The flexibilities of nail joints in direction of the roof battens and rafters are taken into account according to Fig. 9. The shear stiffness of batten-rafter-joints is considered as mentioned above. The slip modulus K_{ser} of a wire nail is included in accordance with EN 1995-1-1 [5].

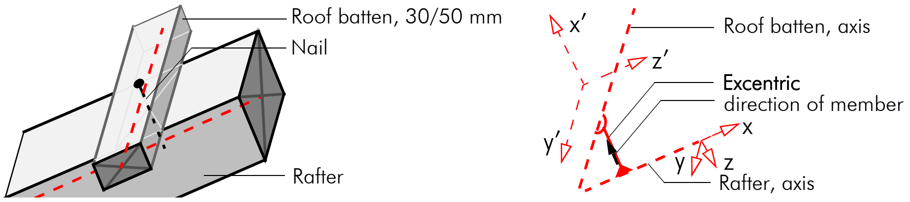


Fig. 9. Modelling of the roof batten-rafter-joint connection.

Table 1: Degrees of freedom and spring stiffnesses of the excentric-end.

deformations in direction of axis			rotations around axis		
$u_{x'}$	$u_{y'}$	$u_{z'}$	j_T	$j_{y'}$	$j_{z'}$
rigid	$K_{ser,}$ K_u	$K_{ser,}$ K_u	$\mathbf{C_s}$	flexible	flexible

Results of the implementation

The effects of the consideration of the roof battens on internal forces and utilization ratios of rafter #12’ are investigated exemplarily (see Fig. 1). By approximation all roof battens in the area of the dormer and the adjacent ridge roof surface are implemented into the spatial structural model M1 (details see [1], [4]). The input- and computational effort increases considerably. In this first approximation are neglected the rides of the roof battens.

As demonstrated in Tab. 2, utilization ratios decrease significantly in models considering the capacity of the roof battens. The determination of the buckling lenght (for buckling out of the roof surface) is not specified for the rafter, that is elastically supported by the battens (* see Tab. 2). This results in conservative axial design forces. Taking into account the shear stiffness in the roof surface for one nail shows hardly influences the results of the present example (Tab. 2).

Table 2: Design values of the internal forces and controlling net section design (according to EN 1995-1-1 [5]) for rafter #12’ (Cross section: 15/15 cm with tenon hole 5/5 cm, C24, $k_{mod} = 0.90$).

	$M_{y,max}$	$M_{z,max}$	N_{max}	Buckling length		Utilization ratios		
Model	[kNm]	[kNm]	[kN]	$L_{k,y}$ [m]	$L_{k,z}$ [m]	Bending	Stability	[-]
M1 ([4] page 336), without roofing lath	-29.39	0.57	-53.85	6.10	3.10	4.20	5.35	100 %
with roofing lath, without C_S	-19.48	2.54	-37.74	6.10*	0	2.94	3.75	70 %
with roofing lath, C_S for one nail	-19.23	2.53	-37.51	6.10*	0	2.91	3.71	69 %
with roofing lath, C_S for two nails	-13.10	2.26	-31.28	6.10*	0	2.02	2.69	50 %

Furthermore by taking into account the roof battens deformations are decreased. Under quasi-permanent loading, the cantilever of rafter #12’ deforms 140 mm in model M1 without battens (see Fig. 1). In the model with battens, under the same loading deformation is calculated to only 95 mm and to 94 mm without and with equivalent torsion spring stiffness respectively. This represents a decrease of 33 %. These results coincide very well with the measurements in situ (approximately 90 mm).

Due to the participation of roof battens in the global load transfer, their design stresses exceed the design values of strength. The computed stresses are in a range, where the capacity can be explained by a reduction of the level of safety.

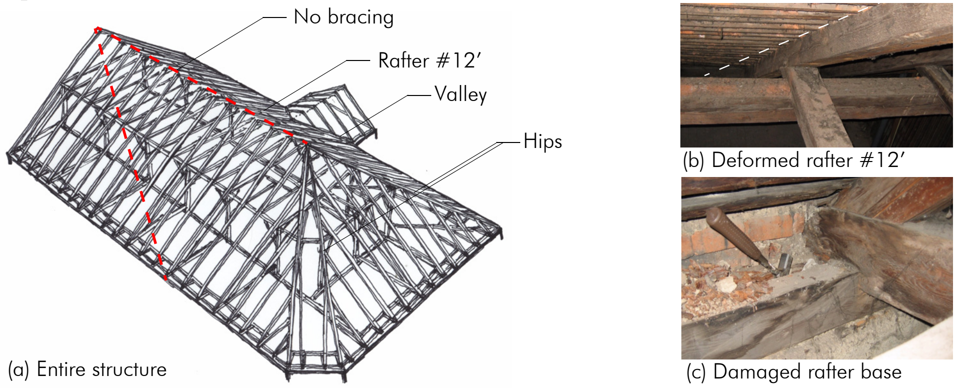
REPAIR OF ANCIENT ROOF STRUCTURES WITH WOOD-BASED PANELS

INTRODUCTION

The main structural vulnerabilities of the „Grazer Dachstuhl“ (see Fig. 10) are:

- The load-bearing capacity in hip- and valley areas does not meet the safety level of the current requirements of the standards (see Tab. 2)
- The bracing is inadequate
- The rafter bases are often inadequately designed and additionally weakend due to wood-destroying fungi and insects
- Especially in the case of additional loads (due to a loft conversion) the frame walls have to be reloaded

Therefore a repair concept that can solve all mentioned vulnerabilities without the usage of time-consuming reinforcements of single joints and beams should be developed.



(a) Entire structure

(b) Deformed rafter #12′

(c) Damaged rafter base

Fig. 10. Illustration of the main vulnerabilities (example see [1]).

BASIC CONCEPT

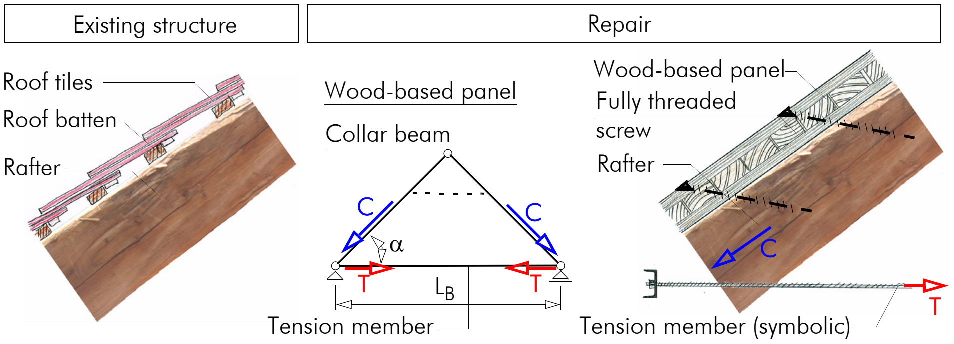


Fig. 11. Basic concept of the repair with wood-based panels.

Existing structure

At first a systematic survey, damage analysis and state-of-construction analysis is performed for an existing roof (see [1] and [4]). At the beginning of the repair, the attic is cleared from all built-ins, claddings, etc. Then the timber is cleaned and the roof tiles and roof battens are removed.

Repair

Subsequently, three layered panels or cross laminated timber panels (or other wood-based panels depending on their suitability) are applied and fixed. Their strong direction runs parallel to the rafters. Both legs of the formed triangle are connected with tension members (from existing tie-beams or new steel ties) in the level of the top floor to *a rafter roof*.

Depending on structural requirements and the condition of the old structure it can be used to variable degrees for the load transfer. The simplest option is to use the existing structure as a collar beam to support the new structure. Furthermore, a *flexible compound consisting of the old rafters and the wood-based panels* can be manufactured for example by means of self-tapping screws. Simultaneously, the wood-based panels are used as a bracing of the structure and as a load distributor for the rafters. Thus an integral structure is at hand, many different tasks will be performed by the element “wood-based panel“.

As explained in [4], the rafter bases are the most common weak points in ancient roof structures. These areas will be strenghtend simultaneously due to the wood-based panels. The often poor longitudinal bracing is also improved by wood-based panels (racking resistance). Therfore, no work- and cost-intensive strengthenings of individual beams and joints are needed.

APPLICATION AREAS

The repair of ancient roof structures using wood-based panels on rafters is suitable for both, valuable ("monuments") as well as ordinary roof structures. The concept is ideal for slightly deformed, steep roofs on geometrically simple ground plans and few fixtures such as chimneys, etc. The majority of roofs erected in the period of promoterism meet these requirements.

Unique interiors can be developed with the illustrated repair concept. Their character is primarily determined by the numerous ancient timber elements. Small rooms, such as bathrooms, should be placed as an independent "box" in the loft, in order to avoid complex connections to the exisiting structure.

ADVANTAGES

General

- Short construction time, already under construction soon raintight
- Little or no time-consuming reinforcements of single joints or beams
- Favorable fire behaviour (depending on the wood-based panel)
- The ancient structure remains largely intact and visible.

- Robust and controlable construction (possibilities for load redistributions)
- The wood-based panel forms an underlay – this balances the temperature as well as the effects of moisture

Additional advantages in case of a conversion

- Unique appearance of the interior
- No complicated adjustment of the interior cladding needed
- relatively high thermal mass - high wood mass
- Insulation above the rafters guarantees economical and building-physical advantages and maximizes the interior cubature
- Simple and little error-prone construction of the roof because of relatively few layers

DISADVANTAGES

- Only suitable for simple geometries and slightly deformed roofs
- Roof covering needs to be removed in advance
- Heavy cranes are required because of the size and weight of the wood-based panels
- Slight rise of the roof surface
- Probably costl-intensive tailor-made solutions to preserve cornice and eaves edges
- Installation problems if the planned and actual geometry differ essentially

- For further information concerning problems, construction details and so on please see [4].

SUMMARY AND CONCLUSION

The proportion of the load-bearing capacity of the roofing lath from the global load transfer of roof structures

Especially in valley, hip and dormer areas and for the bracing in the roof surface, the roof battens can significantly influence the global load-bearing behaviour. The load-bearing capacity especially results from the *axial stiffness of the roof battens*. The valley rafters together with the jack rafters and roof battens form *triangles in the roof surface area*. Facing hip rafters support each other.

Shear stiffness in the roof surface area can also be relevant for the bracing of the structure. If the shear stiffness is considered in the structural model, there should be at least two nails available per joint. *Including the equivalent torison spring stiffness of a joint with only one nail does not significantly effect the global load-bearing behaviour.* In the case of serious, but locally limited damages, the load-bearing capacity of the whole structure can be illustrated with the system effect of the roof battens.

Although it is now possible to take into consideration the load-bearing capacity of the roofing lath, the structural analysis of ancient timber structures is still full of uncertainties. Especially the magnitude of flexibilities and excentricities of the carpentry joints is hardly investigated. Additionally timber possesses a distinctive creep behaviour depending on the level of moisture and quasi-permanent loads. In many European ancient roof structures green timber was installed and most carpentry joints transfer the forces via contact pressure perpendicular or at an angle to the grain. Therefore, the creep behaviour of timber will highly influence the final internal forces.

Repair with wood-based panels

The proposed repair concept is a robust alternative to conventional individual reinforcements (mostly carpentrys). It can be assumed that the repair of geometrically simple roofs with wood-based panels meets the economical requirements. The construction times are short, the level of prefabrication is relatively high and *multiple typical vulnerabilities of ancient roof structures can be strengthened simultaneousely in one step*. On the one hand the rafter bases are reinforced and on the other hand the bending stiffness and the bending capacity of the rafters is increased. The proportion of the rafter roof load-bearing on the global load transfer increases, with the consequence, that existing principal frames are unloaded. Wood-based panels are particularly advantageous in the area of ridges and valleys: Due to the high shear stiffness of the plates, all roof edges are semi-rigidly fixed. The interlock between the wood-based panels and the deformed rafters can be achieved labor-savingly by fixation of the components with screws.

Hopefully the described repair concept will be put into practice soon. Therefore, methods have to be developed in order to calculate such structures as simple and safety as possible.

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