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The safety of Gothic roof structures

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ABSTRACT: The safety of the Gothic roof structures is ensured by the quality of the geometrical-mechanical empirical-intuitive concept, and the traditional technologies, through which the historic materials were put in operation. The safety during use can become questionable due to factors that determine the relation between the corresponding design resistance (reduction of the geometric dimensions in cross and longitudinal sections being partially out of use, reduction of resistance under different actions), corresponding design value of internal force or moment (increased by the functional demands, the change of the environment, or the more and more exacting technical regulations). The interventions carried out to improve the safety of the roof structures – conservation, restoration, retrofitting or reconstruction – are used from case to case according to the way, in which the relation between the design stress and the corresponding design resistance can be provided by preserving the extant situation or returning to a former situation.

1 PREAMBLE – INTERVENTION WORKS ON HISTORIC ROOF STRUCTURES

1.1 *The conservation of historic roof structures*

The conservation of the historic roof structures is linked with: (i) the totality of the technological phases, through which the technical state of the load-bearing structure is maintained after the intervention (including the introduction of temporary props), (ii) the checking of the state of preservation of the sub-units of the load-bearing structures (e.g. renewal of the protection against corrosion, biological decay or fires), (iii) works related to the building construction sub-units, which protect the load-bearing structures.

1.2 *The restoration of historic roof structures*

The restoration of the historic roof structures allows the load-bearing structural unit to return to the initial concept, using materials, which are close in quality to the original ones and applying traditional technologies similar to the initial ones (possibly useful contemporary technologies).

At this intervention category, the correct initial mechanical concept is worth emphasizing (during the technical survey on the load-bearing structure it was discovered that the historic load-bearing structural unit meets the present performance requirements), in the case of which local replacement of materials, every time these materials got damaged because of local overloading or extraordinary actions (such as fires, explosions etc.). Restoration does not require the return to initial geometry and dimensions compulsorily, if the deformations during use do not endanger the resistance and stability of the ensemble – even if the initial load-bearing capacity was reduced.

Of course the load-bearing capacity of the unit and/or of the sub-units or of the load-bearing structural elements is increased considering the existing situation in the moment of the intervention and it does not necessarily reach the initial performance of the load-bearing structures.

It is the ideal intervention category from certain points of view, but it needs qualified specialists and requires a correct initial mechanical concept. The maximum preservation of the historic material is recommended, the replacement of parts of certain elements is preferred, if the damages are not of a nature that compels us to replace complete elements or sub-units.

1.3 *The retrofitting of historic roof structures*

The retrofitting of the historic load-bearing structures is the intervention category, through which the initial load-bearing capacity of the load-bearing structure is increased. This increase may be justified by the

improper initial mechanical concept regarding the initial loading, the damages being also the result of a wrong mechanical concept.

Retrofitting is also needed when the correct initial concept is not suitable for the structure, because the initial loading alters due to changes made to certain building construction details or because of the repurposing of the construction.

Special attention is paid to the retrofitting works necessary after the increase of the safety level during the use of the constructions, required by the contemporary technical legislation. The decisions are always debatable, especially if the load-bearing structural degradations are not significant.

Retrofitting is carried out with different methods, the most successful being those, through which the historic load-bearing structure is completely preserved, introducing certain consolidation elements or sub-units, which help the structure to meet the present-day usage requirements through the modification of the initial mechanical behaviour (initial static schemes) – (this demand can contrast with the functional-aesthetic requirements of the interventions and is linked with the protection of the intrinsic values of the structural heritage).

1.4 *The reconstruction of historic roof structures*

The (partial or total) reconstruction of the historic roof structures is a less frequently applied method, which can be made possible with or without the re-use of certain preserved historic elements or sub-units, or material. Reconstruction can be used – for example – at a quite damaged, relatively independent sub-unit, and the reusable material is applied in reconstructions. In other cases the historic condition of the preserved sub-units compels us to create other historic versions, even if there is no certainty about the reconstruction of some structures, which do not exist anymore and the amount of information gathered is not enough.

2 THE GEOMETRICAL MECHANICAL EMPIRICAL-INTUITIVE CONCEPT AND SAFETY

The roof structures are load-bearing structural sub-units placed in order to sustain the roofing. They constitute a spatial network of lineal load-bearing elements, arranged in cross- and longitudinal bracing frames or built as (radial and annular) spatial systems.

Historic roof structures are built of timber, based on an empirical-intuitive load-bearing structural concept, without any engineered theoretic support, characterized by their resting exclusively on load-bearing sub-units (load-bearing walls, pillars, columns), usually placed on the external outline of the buildings, without leaning on slab sub-units (vaulted or plane, moreover, timber attic slabs are often hanging from historic roof structures). According to their mechanical behavior, the historic roof structures are classified into roof structures on beams and roof structures on common rafters and tie beams.

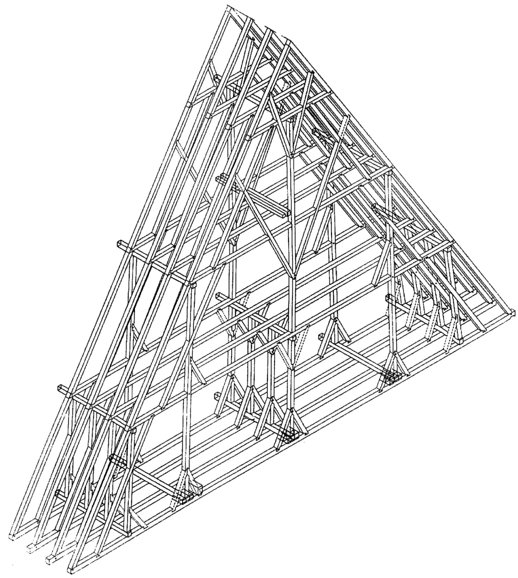

Figure 1. Axonometric view – Gothic roof structures with longitudinal bracing frame at three levels.

Historic roof structures are – in order of their appearance – Romanesque, Gothic, Baroque, or eclectic, each having several sub-types marked by a different concept.

Gothic roof structures are widely spread "continental"-type roof structures, including in Romania, where they were built until the 18th century, and were mostly made from hardwood. Each truss of roof has a tie-beam, upper collar, collar beams and angle braces; main trusses possess hanging truss(es) [built of king or queen posts (possibly including pairs of slanted struts and compound rafters)], while longitudinal bracing frames are (only) vertical.

The stiffness to gravity actions is ensured by compressed upper collars and collar beams placed between eccentrically compressed common rafters, balanced horizontally by tensioned tie-beams, which hang in their turn from a special hanging truss (made up of king or queen posts in tension – maybe slanted posts in tension – and passing braces). Secondary trusses also have tie-beams, and thus all trusses are self-bearing.

The stiffness to non-gravitational actions:

(i) transversal rigidity is ensured by: (sometimes) doubled angle braces (also connecting the king or queen post in tension with horizontal elements),

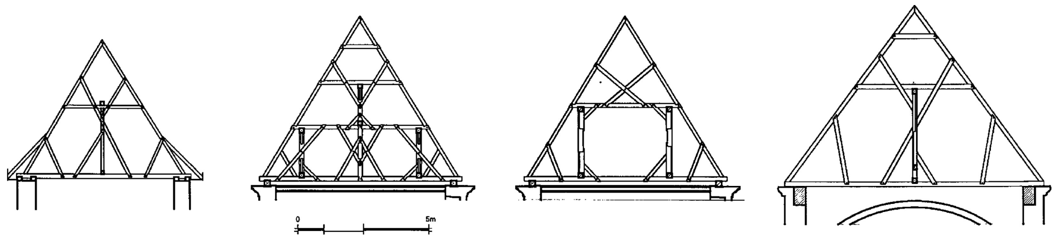

Figure 2. Gothic main frames.

Figure 3. Gothic roof structure from a dwelling house in Sibiu.

passing braces (that intersect the king or queen posts in tension) and – if provided – slanted struts;

(ii) longitudinal stiffness is ensured by longitudinal frames, sometimes placed on two levels (or more), and even in several always vertical planes, placed symmetrically to the vertical symmetry axis.

In the case of missing, removed elements in cross or longitudinal frames, the spatial safety of the gothic structures cannot be provided. The preservation condition of the Gothic structures is directly connected to the use of the building.

The dwelling house suffered a large number of interventions compromising its safety requirements.

3 HISTORIC MATERIALS AND SAFETY

The structural performance of the timber – used initially and for conservation – is affected by specific and growth characteristics. The widespread oak or the larch (depending on the area) belongs to durable species, and is less vulnerable to attacks.

The compatibility of the interventions also implies the compatibility of the timber newly inserted. New inserted timber used for replacement, extension in an existing structure, which was built centuries ago, where rheological deformations have already occurred, must correspond in species, resistance, technological criteria etc. – especially related to moisture content. The major problems refer to the co-working of the old timber with the newly inserted one, and formulating the compatibility criteria when choosing the new material.

The timber used in conservation works can be "produced" like this: (i) using old material resulting from demolitions, (ii) improving the newly inserted timber quality up to the performances of the old one, taking into account criteria related to:

– moisture content;
– resistances;
– number of annual rings per cm;
– exhaustion of the rheological deformations through specific treatments or the use of special species resulting from special plantations.

4 TRADITIONAL TECHNOLOGIES AND SAFETY

The technological aspects are equally important in the conception/ implementation phases and in those related to the interventions (of any kind). The technological characteristics in the building of historic roofs are linked to the technical and technological conditions of the roof elements (including the carpenter's assembling and continuation joints), of the frames (if it's necessary), as well as of the sub-unit of the historic roof structure.

The traditional construction technologies of historic structures imply technologies related to (i) the exploitation of the natural resources in order to obtain historic materials of load-bearing structures, (ii) the horizontal and vertical transportation of historic materials of load-bearing structures before building them in, and (iii) the processes by which the load-bearing structural elements, sub-units or units are built on site. Each development stage of the construction industry has its own particularly diversified technologies, being influenced by the technological development level of the society, the geographic and climatic conditions etc.

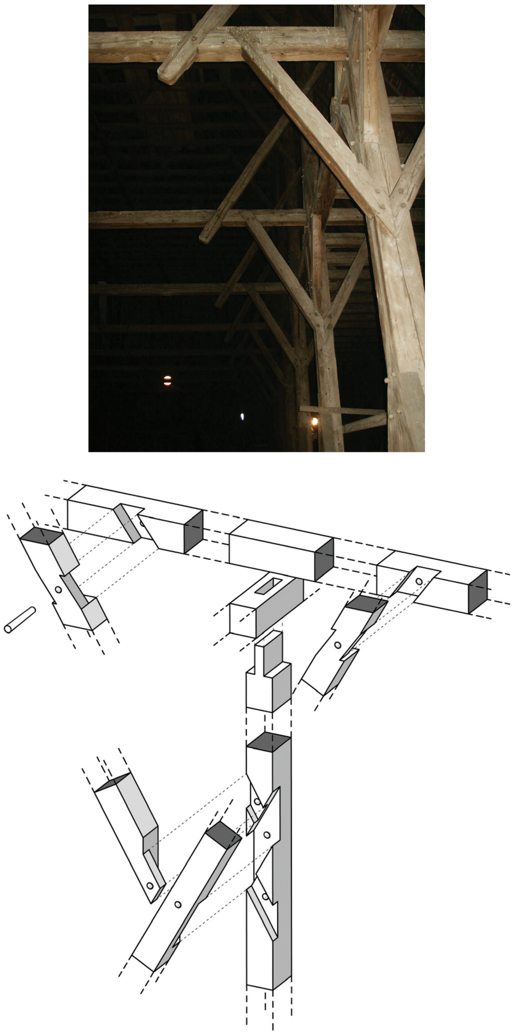

Figure 4. Gothic roof structure node, up photo, scheme of joint, below.

4.1 *Carpenter's joint in a Gothic roof structure*

Carpenter's joints in a historic roof structure are connections between load-bearing structural elements; (Fig. 3) they can take over and transmit mechanical stresses; they are built according to requirements, by processing the timber in their joining areas; they transmit (compression, tension, or shear) stresses directly from one load-bearing element to the other; they are built intuitively on the basis of century-long experience and used without specific resistance calculations; the elements are lapped, notched, grooved, with mortise and tenon, discussed in details in the technical literature [2].

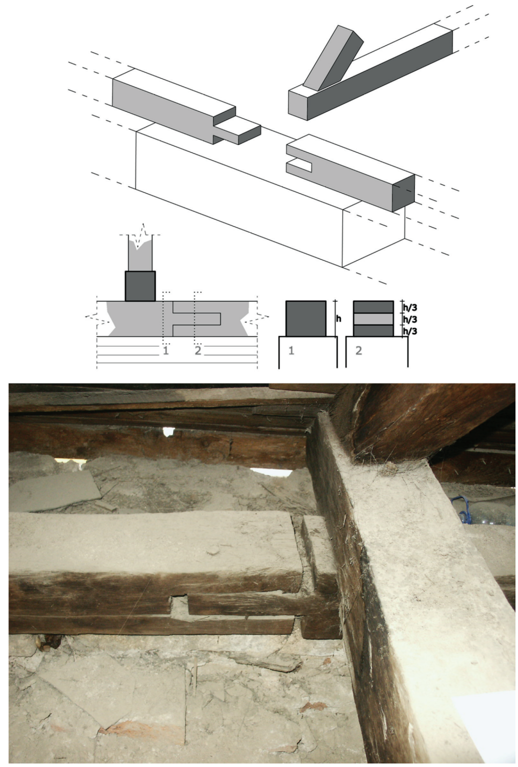

Figure 5. Carpenter joints used for the extension in length of the wall plates, up – joint scheme, below – photo.

4.2 *The carpenter's continuation joints used in historic roofs*

The carpenter's continuation joints are used in Gothic roofs each and every time the timber does not have the necessary size. Continuation was needed in length, but the carpenter's joints were also used for the lengthening of the cross-sections of the elements (not used for Gothic structures).

Lapping and notching are used more often.

The joints used for the continuation in length are applied mainly at longitudinal roof elements (wall plates, longitudinal upper or lower plates from the bracing system), as well as at tie-beams, the complexity of the joints being in direct proportion to the size of the transmitted stresses. The wall plates have a major constructive role, ensuring the transmission of the stresses from the roof to the supporting sub-unit. The joints usually transmit only insignificant shear stresses, thus the joint elements are less carefully built.

The longitudinal plates – elements of the Gothic roof bracing frames – not being challenged by gravitational loads, only occasionally in the II-rate theory, are subject to relatively reduced compression and tension

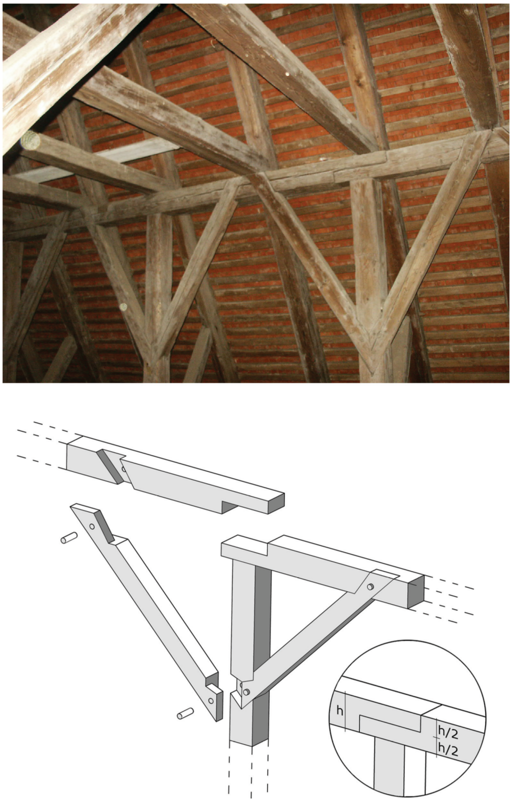

Figure 6. Carpenter's joints used for the continuation of the longitudinal plates in length, up – details, below – joint scheme.

stresses of small eccentricity, with a strong intermittent character (resulting from the longitudinal non-gravitational actions). The joints are mainly lapped, which are usually placed along the main trusses.

4.3 *The continuation/extension joints used in interventions on historic roofs*

The continuation (extension) joints used in interventions on historic roofs are the ones that partially remove original elements made of a single piece (where the local decay of the element requires the replacement of the timber) and change a part of the historic continuation element with traditional joints (in which case the historic continuation details are usually repeated). The carpenter's continuation joints are rarely in accordance with the present principles of built heritage protection – such as: minimal interventions, as complete a preservation of the historic material as possible – and they do not correspond to the modern mechanical indications (shearing lengths, resistance characteristics).

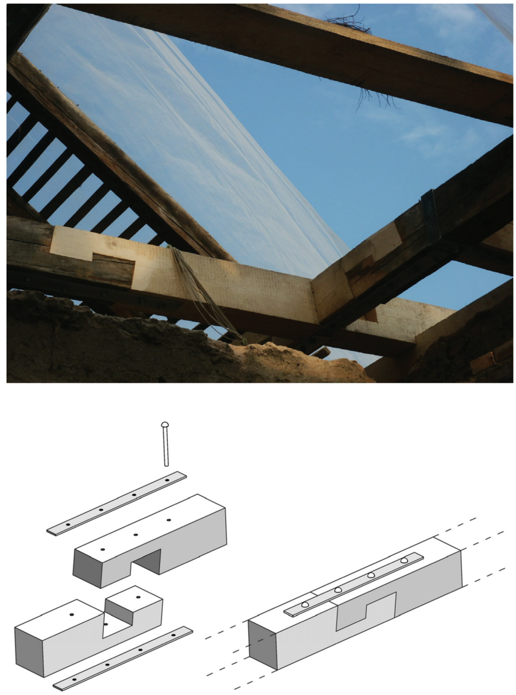

Figure 7. Engineered, tension continuation joints, up – joint scheme, below – details.

Moreover, there are situations, for which there are no historic joint details, because no parts of the elements were meant to be replaced in the past.

The use of the engineered continuation joints (built according to contemporary principles) is thus unavoidable, more and more wood can be used (possibly even exclusively) or a smaller amount of wood and more steel can be applied (the technological advantages are preferred to the incompatibility of the two materials). The continuation joints are of the engineered or of the carpenter's type, varying from case to case.

The engineered joints are classified in groups, which are subject to tension, compression or bending.

4.3.1 *Engineered, tension continuation joints used in historic roof structures*

The continuation joints subject to tension with small eccentricity, used in interventions on historic roofs usually require metallic parts, to which the tension is transmitted through sheared bolts.

4.3.2 *Engineered, compressed continuation joints used in historic roof structures*

The continuation joints subject to compression with small eccentricity, used in interventions on historic roofs are built in such a way, that the wood transmits

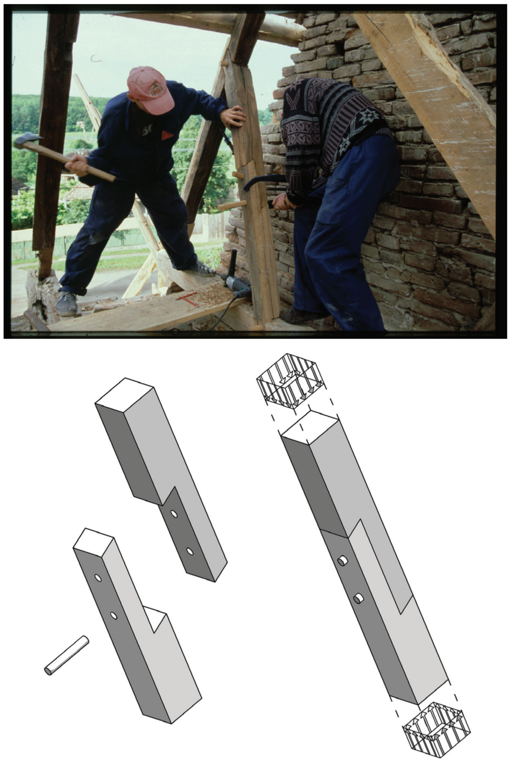

Figure 8. Engineered, compressed continuation Joints, up – implementation details, below – joint scheme.

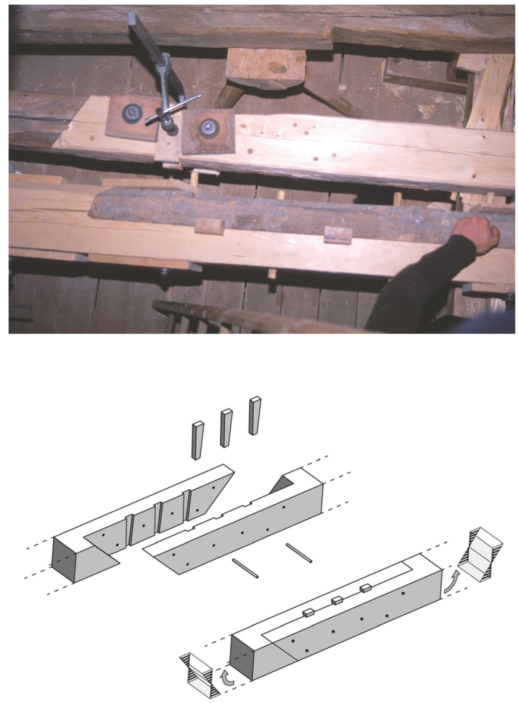

Figure 9. Engineered, bent continuation joints–joint scheme–model from the Czech Republic.

the compression stresses, while the metal parts have only a supplementary safety role. (Fig. 8).

4.3.3 *Engineered, bent continuation joints used in historic roof structures*

The engineered continuation joints subject to bending, stretching or compression with great eccentricity allow versions built exclusively of wood – model from the Czech Republic – or with strap-irons and steel bolts. (Fig 8).

4.4 *The implementation of the intervention works on historic roofs*

The implementation is completed according to the technical project and the details drawn up on the basis of the investigations, which were carried out prior to the actual interventions, and during the implementation (in the case of historic constructions the investigations usually cannot be finished in the elaboration phase of the conservation design; in most cases we do not have initial implementation projects or the projects of the subsequent interventions). During the works the building of a temporary roof is useful, which is supported by a scaffolding, that offers a work platform outside the roof structure (a platform useful even without the temporary roof).

The work is recommended to be completed in sections; the order and the position of the sections will be determined by the contractor, designer and scientific investigator depending on the proposed implementation technology. The work surface of a section will be given by the implementation period and the contractor's available funds, and for lack of a temporary roof the construction will be protected with tarpaulin in the area, where the covering is opened.

4.4.1 *Preliminary works in carrying out interventions on historic roofs*

These categories consist of: (a) the removing of the roof covering in sections, (b) ensuring the stability of the structure and safety during the interventions, (c) verification (reception) of the timber used for completion, (d) identifying the elements, which need interventions.

(a) – The removing of the covering in sections, ensuring simultaneously the temporary protection of the roof.

The removing of the covering (of the tile, shingle, tin, batten or boarding) is compulsory: restoring the roof to its initial form, as well as the interventions on the elements are more difficult in the presence of the roofing.

Carrying out the work in sections is also an administrative requirement – beside the major costs related to the temporary covering of the entire roof.

The temporary covering of the roof in rainy weather is a major self-evident requirement (even if only the load-bearing structure of the building gets wet from the rain, the damages are huge and cost much more than the temporary covering of the roof).

(b) – Ensuring the stability of the structure and safety during the interventions through supports, braces and wedges (general or special ones placed at certain work points).

(c) – Verification (reception) of the timber used for restoration

The timber used for completion is recommended to have rheological deformations (material received from demolitions, new material of an appropriate age), even if its processing is more difficult, because otherwise the compatibility of the original material with the newly inserted one is questionable. The moisture content of the two materials should also coincide during the interventions.

(d) – Identifying the elements, which need interventions (according to the project and the existing situation at the opening of the areas and joints mentioned earlier) – including the reception of the existing timber from a mechanical and biological point of view. Each and every joint is examined, while special attention is given to the walled-up areas and to those, which haven't been opened during the survey; these are generally: (d_1) the wall-plate; (d_2) the wall-plate – tie-beam and common rafter – common rafter joints; (d_3) the upper part of the common rafters.

Since the historic roofs show differences in trusses and the dimensions of the elements, it is necessary to check the dimensions given in the project, as well as the metal supporting and consolidation devices on site.

The length of the elements substituted because of biological degradation will be identified on site with the assistance of the expert in biology, in order to eliminate the possibility of a fungal contamination.

4.4.2 *Carrying out the interventions on historic roofs*

(a) – Removal of the deteriorated and unnecessary elements: (i) cutting and removing parts of elements and complete elements, which are biologically or structurally deteriorated; (ii) removing elements, which can be omitted according to the intervention (restoration) concept (which does not belong to the initial load-bearing structure etc.). Parts and ends of the existing and the newly inserted wood, as well as certain areas of the walled-up structures will be treated with fungicide substances in advance, in order to prevent contamination.

(b) – Replacement of the damaged/decayed elements and reinforcement of the unstable elements: (i) replacement of the ends of those elements, which were removed for biological reasons, especially at the walled-up joints; (ii) replacement of the wall-plate in the deteriorated areas, identified during the opening of the roof covering; (iii) replacement of the structurally damaged elements, especially of the distorted elements.

(c) – Replacement of the transformed, partially eliminated elements, as there is a series of transformed elements, which need to be restored.

(d) – Introducing elements, which completely disappeared – for example: (i) reconstruction of the tie-beams of the trusses, where these are missing; (ii) reconstruction of the compound rafters, angle braces and counterbraces.

(e) – The introduction of new elements, justified mechanically and supported through the intervention concept – for example: longitudinal elements to rigidify the straining beams horizontally.

(f) – The introduction of new sub-units, justified mechanically and supported through the intervention concept – for example: (i) steel trusses placed lengthways in a vertical line, to support the trusses of the roof, which were originally conceived in a wrong way; (ii) steel trusses placed crossways in a horizontal line, to support the semi-trusses of the roof in the lapped areas at the ends, which were originally conceived in a wrong way.

(g) – The reconstruction of some sub-units – for example: (i) the reconstruction of the parts of the roof, which were completely eliminated because of degradations and which formed the main elements of that portion (tie-beams, common rafters, compound rafters, collar beams etc.); (ii) reconstruction of the access areas supported by tie-beams.

5 CONCLUSIONS

(a) – These three features: (i) empirical-intuitive concept, (ii) historic materials, and (iii) traditional technologies, are intertwined, influencing each other (the processing technology depends on the quality of the materials and vice versa, the empirical-intuitive concept on the technological joining possibilities and vice versa etc.).

(b) – The safety of Gothic roof structures can become an issue of maximal importance any time these are exposed to exceptional actions (like storms), but especially if their maintenance during use is defective. The lack of maintenance can even cause collapse of the roof, or the attic slab, or modification of the load path in entire roof structure.

REFERENCES

[1] Szabó B. Gy. 2004. Illustrated dictionary of historic load-bearing structures. Cluj-N.: Kriterion & Utilitas. ISBN 973-9377-40-8.

[2] Gerner M. 1991. Handwerkliche Holzverbindungen der Zimmer. Stuttgart: Deutsche Verlags-Anstalt.

[3] Kirizsán I. 2005. Practice of historic roof structure conservation. Case studies: Gothic roof structures from Transylvania. In: Gennaro Tampone ed. *The Conservation of Historic Wooden Structures Proceedings of the International Conference Florence 22–27 February 2005.* Firenze, Collegio degli Ingegneri della Toscana.