Biodegradation and Treatment of Ancient Wood in Slovakia

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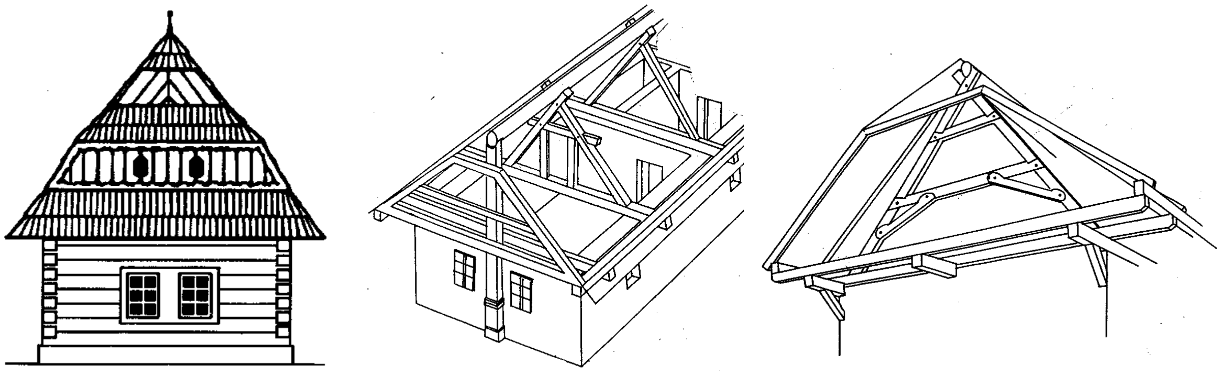
1. Introduction

Ancient wooden structures form a separate group in the history of architecture in Slovakia. For example, the roof constructions reached technical peak in the sacral buildings, especially in the gothic wooden and stone churches and articulate churches. Interesting roof constructions are also on country residential houses (Fig. 1).



A B C

Figure 1: Typical country residential house (A), which roof construction has one top purlin supported by a shield stud (B), or has a collar accouplement support (C)

Some of them are in a critical state and have to be renovated (Fig. 2).

Figure 2: Wooden church in Hunkovce during and after renovation

The presented paper deals with investigation of wooden structures in Slovakia, their typical failures caused mainly by wood destroying fungi and insects, and also with their maintenance and renovation.

In our laboratories we also made some experiments aimed at:

- model damaging of wooden elements with wood destroying fungi or with a mechanical boring (analogy of insect galleries),

- subsequent renovation of these elements with various reinforcing and conservation methods,

and on a basis of achieved results we can give expert recommendations for the restored practice.

2. Investigation, failures and maintenance of ancient wooden structures

2.1 Investigation

Over the last years we investigated more wooden structures (roof trusses, ceilings, log-cabins, etc.), for example in several wooden churches in eastern Slovakia (Reinprecht 1995), in three articulated wooden churches (Štefko 1995), in several old buildings in the historical town of Banská Štiavnica (Reinprecht 1999), in the capital town of Bratislava, and also in other towns and villages (e.g. Cebecauerová and Stillhammerová 1999, Hazucha et. al. 1999, Jochim and Svocák 1999, Draškovič 2000, Ďurica 2000, Reinprecht - internal reports).

Investigations of roof, ceiling, log-cabin or other wooden structures were aimed at:

- documentation of architectural details,
- detection of failure types, ranges and degrees,
- determination of failure causes,
- elaboration of suitable renovation methods.

2.2 Failures

Failures in the inspected wooden structures we investigated either by the sensual methods (visual, tactile, aural - using simple tools as chisel, hand magnifier, etc.), and also by the instrumental ones (Tree-vitality meter, moisture meter, Fractometer, microscopes, devices in a mycological laboratory).

Generally, all found failures have been generated by more expected and unexpected factors:

1) Additional effect of input faults existing in wooden elements or in surrounding materials which were not observed or considered during the building works
   - input material faults (presence of bark, knots too large and frequent, reaction wood, rot and/or wormholes descended from a forest, large cracks and/or deformations as a result of cutting and seasoning defects, etc.).
2) Projection and technological defects
   - structural defects (possibilities for wood moisture increasing by rain, condensed or capillary water, unsatisfactory ventilating, poor by designed or sloppy joints, etc.),
   - undersized wood elements,
   - using of wet wood with a moisture content of above 20 %,
   - no or inadequate chemical protection (previously there were no binding criteria, however now criteria of the EN 351-1 standard [coming out from EN 335-1, EN 350-2, EN 460, EN 599-1] should be observed for wood protection in constructions against wood-destroying fungi, moulds and insects).
3) Increased loading on the structure or its individual elements
   - excessive load and stress (e.g. replacement of wooden shingles for heavier tiles),
   - unsuitable re-constructive actions (e.g. removal of important bearing elements at attic rebuilding), extraordinary effects (gale, etc.).

4) Decrease of mechanical properties (stiffness, strength) of wood as a consequence of changes in its structural levels - molecular, anatomical, morphological and geometric
   - damage of wood by wood-destroying fungi, insects, aggressive chemicals, fire or weather effects,
   - rheological distortion of wood by cyclical or durable mechanical and moisture stresses.

A majority of the failures in the inspected ancient wooden structures resulted from the damage of wood elements by biotic agents:

- wood-destroying insects (Hylotrupes bajulus, Callidium violaceum, Anobium punctatum, Hadrobregmus pertinax),
- wood-destroying fungi (Coniophora puteana, Serpula lacrymans, Poria vaillantii, Gloeophyllum sp.).

The types, ranges and degrees of biodegradation of individual wooden elements have been significantly dependent:

- on their location in the ancient wooden structure (Tab. 1),
- on a location of wooden structure in the Slovak region (Tab. 2).

Table 1: Critical places of failures in inspected wooden structures due to fungal attack and insect galleries

DAMAGE BY FUNGI AND INSECTS:

- Wooden elements situated near to roof gutters:
  - contact of elements with external walls (platts, header of ribbons, ceiling beams, etc.),
  - small distance of elements to external walls (basis of rafters, rakers, etc.)
- Wooden elements under/near to the untight or damaged roofing material, mainly:
  - in nook of two roof planes (valley rafters, etc.),
  - at chimneys (rafters, columns, ribbons, etc).
- Wooden elements under opened skylights.
- Wooden elements near to ground or in contact with ground:
  - lower beams in log-cabins,
  - doors, etc.

DAMAGE BY INSECTS:

- Damage by insect galleries non-rarely also in other wooden elements, because the minimal moisture content of wood for activity of *H.bajulus* and *A.punctatum* is only 10 %.

2.3 Maintenance

Maintenance of ancient wooden structures is generally connected:

1) with repairing of roofs and keeping of suitable inside moisture conditions (wooden elements are isolated from rain and other sources of water, with the aim to keep their moisture content under 20 %, or less),

2) simultaneously, coming out from their historical value and financial conditions, with:

- regular checking of wooden structures and evaluation of respective states (1 or 2 times a year),
- if needed, according to the moisture conditions of wood (hazard classes: EN 335-1) and also to the wood species (class of durability: EN 350-2), performing the chemical protection of wooden elements with suitable preservatives (EN 351-1, EN 460, EN 599-1), e.g. with insecticides or with insecticides and fungicides,
- detection of all failures at their beginning and prompt removal of failure causes,
- detailed investigation of observed failures,
- renovation, i.e. repair or replacement of damaged wooden elements and/or (in accordance with the respective demands) a larger re-constructive operation.

Table 2: Types of wood biodegradation in selected structures located in the region of Eastern Slovakia, in historical town of Banská Štiavnica, and in capital town of Bratislava

Object	Wood Species	Actual moisture %	Elements expressively biodegraded with:		
			Brown-rot	Insect galleries *Anobiidae*	*H.bajulus*
1) Sacral wooden structures "churches" in Eastern Slovakia (investigation of 15 from 29 – Reinprecht 1995)					
Inovce (1836)	s, x		lower beams	beams	beams
Hrabová Roztoka (18th century)	s, x		-	-	rafters
Uličné Krivé (1718)	s, f, x		-	-	beams ceiling beams icons, benches, windows, doors
Ruský Potok (18th c.)	s, f, o, x		-	-	beams ceiling beams icons, benches, windows, doors
Jedlinka (1763)	s, f, o, x		lower beams	beams	beams, icons
Ladomírová (1742)	s, x		(restored – open for tourists)		
Nižný Komárnik (old from 18th c. was destroyed - new copy build in 20th c.)	s, x		floor	beams	benches, doors
Vyšný Komárnik (1924)	s, x				
Krajné Čierno (18th c.)	s, x		lower beams	beams	beams
Bodružal (1658)	s, f, x		-	beams	beams, icons
Miroľa (1770)	s, f		-	beams, rafters, etc.	beams, rafters, etc. floor, icons
Topoľa (18th c.)	s, f, x			beams, ceiling beams	beams, floor, icons
Brežany (1727)	s, f, o		interior boards	beams, ceiling beams	beams, c. beams, icons, windows
Korejovce (1761)	f, x		ceiling beam	rafters, etc.	beams, icons, windows
Hunkovce (18th c.)	s, f		beams, ceiling beams rafters, etc.	beams, ceiling rafters, etc. beams,	beams, c.beams, rafters, etc.

Note to wood species: s = spruce, f = fir, o = oak , x = others (e.g. beech, lime, poplar, ...)

Table 2 (continued)

Object	Wood Species	Actual moisture %	Elements expressively biodegraded with: Brown-rot	Insect galleries *Anobiidae*	*H.bajulus*
2) Banská Štiavnica – historical town, in 1993 stated by UNESCO us world cultural heritage					
Tower on old castle (gothic/baroque)	s, f, o	14-30	platts, ribbons, etc.	columns, studs	-
Evangelic church (18^{th} - century)	s, o	12-16 (28)	ribbons, rafters, stud	-	rafters
Bourgeois house (D.Resla 2, 17^{th} c.)	12-25 (>60)		platts, rafters, header of ribbons	rafters studs	platts, rafters
Bourgeois house (Sladkovič 8, 16^{th} c.)	s, f	12-19 (>60)	top of rafters, header of ceiling beams	ribbons, rafters	studs, ceiling beams
Bourgeois house (D.Ružová 2, 18^{th} c.)	s, f, o	11-14 (>60)	ceiling beams	platts, rafters, etc.	ceiling beams
Bourgeois house (Radničné 2, 16^{th} c.)	s, f	15-19	ribbons, shingles	rafters	ribbons, rafters, etc.
Old hospital (A.Pécha 5, 16^{th} c.)	s, f	11-17	platts, ribbons, rafters, etc., header of ceiling beams	plats, ribbons rafters	platts, ribbons, rafters header of c. beams
Manor-house in Antol (1744)	s, f	11-14	header of ceiling beams (4 %)	header of ceiling (15 %)	beams (2 %)
3) Bratislava – capital town of Slovakia					
Desseffy palace (Nám. Ľ.Štúra 2)	s, f	15-20 (>60)	platts, rafters, ceiling beams	platts, rafters	platts, c. beams
Tower on St. Michal church	o, s	8-14	chair of beels	steps	chair of beels
<u>Roof trusses:</u>					
Grammar school A.Markuša, (ČA 18)	s, f	8-17 (>60)	P.sp., C.puteana S.lacrymans		
Klariska 5	s, f	12-17 (>60)	G.sp., P.sp.	yes	yes
Michalska 1	s	12-17 (>60)	G.sp., P.sp.	yes	no
Venturska 13	s	11-17 (>30)	G.sp.	yes	no
Štefániková 1	s, f	11-19 (>60)	P.sp., S.lacrymans	yes	yes
<u>Ceilings:</u>					
Panská 7	s, f	9-14	S.lacrymans	no	yes
Michalská 26	s, f	6-11 (>60)	S.lacrymans	no	yes

Note to wood species: s = spruce, f = fir, o = oak , x = others (e.g. beech, lime, poplar, ...)
Note to brown-rot fungi: G.sp. = Gloeophyllum species, P.sp. = Poria species

3. Renovation of ancient wood

Renovation of the ancient roof trusses, ceilings, log-cabins, windows, icons, etc. (with smaller or larger failures in wooden elements or in structural sections) is solved with the following methods:

- Reinforcing of damaged elements
- Stiffening of weakened structural sections, or indirect reinforcing of damaged elements

- propping (e.g. of ribbons, if situated above load bearing walls),
- unloading (e.g. of ribbon which is situated between two undamaged ribbons, using transverse beam - transom),
- trussing,
- coupling of weakened structural sections with an additional one(s),
- insertion of new elements.

• Replacement of damaged elements with new ones.

3.1 Reinforcing of damaged wooden elements

Reinforcing of damaged ancient wooden elements in various historical structures of Slovakia is solved mainly by the following methods (Fig. 3)

- extension method, using either natural wood and carpentry joints (mostly scarf joints), or polymer-concrete material in combination with linking rods - the “Beta method” (e.g. in Banská Štiavnica – Cebecauer 1991),
- scab method (stiffening with plates),
- anchoring of damaged elements into steel supporting flitch plates “arms or consoles”,
- sealing (filling – up reintegrating), using either solid wood or binding agents (mixture of natural agents and/or synthetic polymers with suitable fillers – sawdust, glass microballoon, etc),
- treatment of deteriorated wood with natural agents and/or synthetic polymers (e.g. epoxy resins) – see point 3.2.

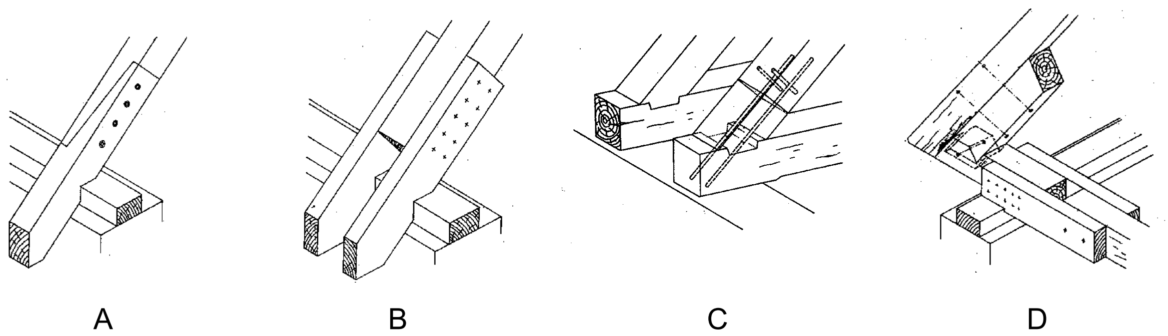


Figure 3: Repair of rafters, which were damaged at base A) using scarf joints, B) using scabs, C) using the Beta method, D) reinforcing with a new insert element

In our laboratories have been carried out some experiments aimed on testing the effectiveness of these methods:

• Influence of the type and length of carpentry joints (unglued or glued with epoxy resin) on the deflection and bending strength of wood elements reinforced by the extension method (Reinprecht and Joščák 1996).

• Influence of the length and diameter of steel linking rods in wood elements restored by the “Beta method” on their deflection and bending strength (Reinprecht and Joščák 1993).

• Influence of various distances of the top and bottom plates in steel consoles on the deflection of repaired wooden elements loaded in a bend (Reinprecht and Grec 1999).

- Influence of the binding agents (mixture of epoxy or phenol-formaldehyde resins with sawdust) on bending properties of the primary perforated spruce and lime elements (Reinprecht and Joščák 1994).

The experimental results corresponded on the whole with theoretical assumptions.

3.2 Treatment of biodegraded wood with natural agents and synthetic polymers

The integrity, strength and dimensional stability of biodegraded wood can be improved more or less successfully by means of various conservation methods:

- coating,
- cell wall bulking,
- lumen filling,

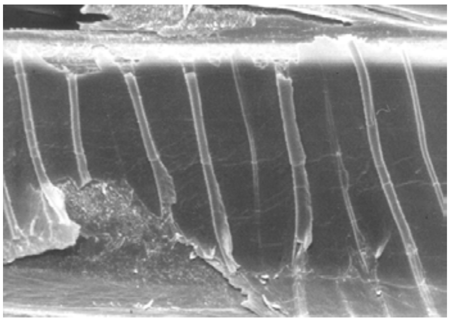
applying various modification substances.

From our laboratory experiments resulted these conclusions:

- Hydrophilic reactive thermosetting resins (urea-, melamine, and phenol-formaldehyde), non-reactive polyethylene-glycoles and some other substances can penetrate into wood lumens and also into cell walls. However, degree of their penetration into cell walls depends on:

  a) the steric factor of individual molecules:

    - for the reactive thermosetting resins is a very important the type and amount of catalytic agent (e.g. NH_4Cl) used for their condensation (Fig. 4), and also the method of their curing in impregnated wood (without or with thermal heating, dielectric or convention thermal heating, etc.), at which this factor is changed more or less quickly during the curing process (Reinprecht and Makovíny 1987),
    - for the polyethylene-glycoles is a very important their degree of polymerisation (Reinprecht and Hudec 1995, Reinprecht 1995-a).



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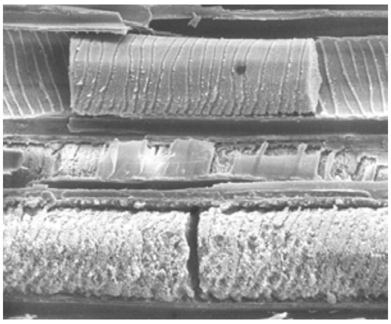

B

Figure 4: Influence of the steric factor of urea-formaldehyde resins on their possibility to penetrate also into cell walls

A ⇒ non-catalysed UF resin penetrate into cell walls

B ⇒ catalysed UF resin (with NH_4Cl) was not able to penetrate into cell walls

  b) the character and degree of wood biodegradation:

    - e.g. connected with the enzymatic dissolving of polysaccharides in cell walls.

- Improving of the mechanical properties of biodegraded wood with modification substances depends on:

  a) the type of natural agents or synthetic polymers ⇒ their chemical structure, physical-chemical properties and own mechanical properties:

  - on their ability to penetrate either only into wood lumens or also into cell walls,
  - on their ability to create covalent, hydrogen or other bonds with polysaccharides and lignin directly in wood cell walls,
  - on their own modulus of rupture, modulus of elasticity, hardness, etc.

    For example:

    i) The brittle urea-formaldehyde UF-resins or melamine-formaldehyde MF-resins, with capability to penetrate into cell walls and in cured state having a very hard but also a very brittle consistency, are able expressively improve the hardness of rotten woods, their compression strength or modulus of elasticity in bending, but on the other hand the bending strength can improve only negligibly and on the impact bending strength did not have any influence (Horský and Reinprecht 1986, Reinprecht and Varínska 1998, 1999).

    ii) The polyethylene-glycol "PEG 1000", with capability to penetrate into cell walls and having constantly wax-thermoplastic consistency, had an apparently negative effect on all mechanical properties of biodegraded woods (Reinprecht and Varínska 1998, 1999).

    iii) The polybutylmethacrylate "Solakryl BT 55", without possibility to penetrate into cell walls and having constantly thermoplastic consistency, had a slightly positive effect on the hardness, compression strength and bending properties of biodegraded woods (Reinprecht and Varínska 1998, 1999).

  b) the amount of modification substance in a biodegraded wood:

  - e.g. increase or decrease of the modulus of elasticity in bending (ΔMOE) was proportional to the density increase of biodegraded wood (biodegradation in laboratory conditions with *C.puteana*) after its conservation (Δρ)

Modification substance:		Shellac	Epoxy 510	MF resin	Solakryl 55	PEG 1000
ΔMOE / Δρ	Spruce:	0.92	0.59	0.75	067	-0.39
	Beech:	0.33	0.22	0.52	0.30	-1.07

  c) the character and degree of wood biodegradation:

  - e.g. various modification substances (UF and MF – resins, epoxy resin, shellac, etc.) had a more positive effect on wood strength and stiffness just at those situations when wood samples were in a higher degree of rot (Horský and Reinprecht 1986, Reinprecht and Varínska 1998, 1999).

In the vacuum-pressure impregnation device "Dreyer-Holand-Merten KG" we conserved also some ancient wooden elements, e.g.:

- Icons damaged by insect galleries and brown rot, using acrylic resins (Reinprecht 1991)
- Fragments from oak beams found under ground in the castle Slovenská Lupča (800-years-old waterlogged wood), in combination with a subsequent diffusion technique, using hot water solutions of polyethylene-glycoles PEG 600 / PEG 1500 and boric

acid with the aim to prevent cellular collapse and dimensional changes in these artefacts at their conditioning and also to prevent them before a next biodegradation (Reinprecht 1995-b).

4. References

[1] Cebecauerová,D., Stillhammerová,M. 1999: Prieskum drevených konštrukcií v kaštieli v Bytči. (Investigation of wooden structures in the Bytča manor-house.) In: Reconstruction and Conservation of Historical Wood 99, 2nd - International symposium, TU Zvolen, p. 89-91. (English abstract)

[2] Cebecauer,I. 1991: Sanácia drevených konštrukčných prvkov v objekte. In: Konzervovanie dreva poškodeného hubami a hmyzom, VŠLD Zvolen, p. 25-28.

[3] Draškovič,F. 2000: Príklady rekonštrukcií nosných sústav striech. In: Navrhovanie drevených konštrukcií, SKSI – SSS Kočovce, p. 87-90.

[4] Ďurica,J. 2000: Stabilita vežových krovov pamiatkových objektov. In: Navrhovanie drevených konštrukcií, SKSI – SSS Kočovce, p. 83-86.

[5] Hazucha,J., Pavlík,J., Langová,N., Sršeň,I. 1999: Rekonštrukcia krovu kostola v Dolných Rykynčiciach a Šipiciach. (Reconstruction of the church roof truss in Dolné Rykynčice and Šipice.) In: Reconstruction and Conservation of Historical Wood 99, 2nd - International symposium, TU Zvolen, p. 125-130. (English abstract)

[6] Horský,D., Reinprecht,L. 1986: Spevňovanie a rozmerová stabilizácia dreva degradovaného drevokaznými hubami. (Reinforcing and dimensional stabilization of wood degraded by wood-destroying fungi). In: Zborník vedeckých prác DF VŠLD Zvolen – 1985/86, Alfa Bratislava, p. 63-72. (English abstract)

[7] Jochim,S., Svocák,J. 1999: Analýza degradácie dreveného artikulárneho kostola v Hronseku. (Analysis of degradation of the articulate wooden church in Hronsek.) In: Reconstruction and Conservation of Historical Wood 99, 2nd - International symposium, TU Zvolen, p. 93-98. (English abstract)

[8] Reinprecht,L. - Makovíny,I. 1987: Hardening of aminoplasts in modificated wood with catalytic and thermic dielectric heating. In: Wood Modification, 6th Symposium, Poznaň, Poland, p. 288-298.

[9] Reinprecht,L. 1991: Reštaurovanie poškodeného dreva polyakrylátmi, epoxidmi, fenoplatmi a aminoplastmi. (Restoration of damaged wood with polyacrylates, epoxydes, phenoplasts and aminoplasts), In: Pokroky vo výrobe a použití lepidiel v drevopriemysle, 10th Symposium, VŠLD Zvolen, p. 312-325. (English abstract)

[10] Reinprecht,L., Joščák,P. 1993: Nadpájanie drevených prvkov metódami protéz a konštrukčných spojov s využitím lepidla Epoxy 1 200. (Wooden elements jointing with different constructional joints and aids by the application of Epoxy 1200 adhesive), In: Pokroky vo výrobe a použití lepidiel v drevopriemysle, 11th Symposium, TU Zvolen, p. 93-102. (English abstract)

[11] Reinprecht,L., Joščák,P. 1994: Reinforcement of model-damaged wooden elements. Part 1: Local perforation of wooden elements and their gap-filling treatment. Drevársky Výskum, 39, (4), p. 1-21.

[12] Reinprecht,L. 1995: Príklady poškodenia a rekonštrukcie drevených sakrálnych stavieb na východnom Slovensku. (Examples of damage and reconstruction of wooden sacral structures in eastern Slovakia.) In: Conservation of damaged wood. 2nd Workshop, TU Zvolen, p. 35-46. (English abstract)

[13] Reinprecht,L., Hudec,J. 1995: Tok a sorpcia roztokových systémov "voda-polyetylénglykol" v dreve. Časť 1. Permeabilita dreva a diferenčná sorpcia vody v dreve v závislosti na veľkosti makromolekúl polyetylénglykolu. (Flow and sorption of the solution systems „Water-polyethyleneglycol“ in wood. Part 1. Permeability of

wood and differential sorption of water in wood depending on greatnes of the polyethyleneglycol macromoleculs), In: Zborník vedeckých prác DF TU Zvolen 1995/1, TU Zvolen, p. 69-84. (English abstract)

[14] Reinprecht,L. 1995-a: Tok a sorpcia roztokových systémov "voda-polyetylénglykol" v dreve. Časť 2. Pomerné stredné polomery a početnosti aktívnych kapilár dreva - stanovené na základe parametrov toku a sorpcie. (Flow and sorption of the solution systems „Water-polyethyleneglycol“ in wood. Part 2. Relative middle radii and numbers of the wood active capillaries - determined on the basis of flow and sorption criteria), In: Zborník vedeckých prác DF TU Zvolen 1995/1, TU Zvolen, p. 85-98. (English abstract)

[15] Reinprecht,L. 1995-b: Konzervovanie dubových hrád zo zámku Slovenská Ľupča. (Conservation of oak beams from the Slovenská Ľupča castle), Rekonštrukcia a konzervácia historického dreva '95, Medzinárodné sympózium, TU Zvolen, p. 161-168. (English abstract)

[16] Reinprecht,L., Joščák,P. 1996: Reinforcement of model-damaged wooden elements. Part. 2: Restoration of wooden elements by the extension method using natural wood or epoxy-wood composite. Drevársky Výskum, 41, (2), p. 41-55.

[17] Reinprecht,L., Varínska,S. 1998: Bending properties, compression strength and hardness of wood modified with synthetic polymers. In: Wood Structure and Properties, 3rd International Symposium, Arbora Publishers Zvolen, p. 157-162.

[18] Reinprecht,L., Varínska,S. 1999: Bending properties of wood after its decay with *Coniophora puteana* and subsequent modification with selected chemicals. In: International Research Group on Wood Preservation, Section 4 – Wood Protecting Chemicals, 30th Annual Meeting Rosenheim – Germany, Document No. IRG/WP 99-40146 (11 p.)

[19] Reinprecht,L. 1999: Poruchy drevených stropov a krovov – príklady z regiónu Banská Štiavnica. (Failures of wooden ceiling and roof constructions – examples from region Banská Štiavnica.) In: Reconstruction and Conservation of Historical Wood 99, 2nd - International symposium, TU Zvolen, p. 81-88. (English abstract)

[20] Reinprecht,L. – Grec,M. 1999: Oprava drevených trámov s poškodeným záhlavím pomocou monolitných oceľových konzol – Modelové skúšky tuhosti a pevnosti v ohybe. (Repairing of wooden beams with damaged ends by using the monolithic stainless steel flitch paltes – Model tests of stiffness and strength in bending). In: Reconstruction and conservation of historical wood ’99, 2nd International Symposium, TU Zvolen, p. 117-123. (English abstract)

[21] Štefko,J. 1995: Drevené zrubové sakrálne stavby na Slovensku. (Sacral wood structures in Slovakia – architectural types.) In: Conservation of damaged wood. 2nd Workshop, TU Zvolen, p. 23-33. (English abstract)