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CONSERVATION OF WOODEN CHURCH IN THE VILLAGE TRNOVE

Katarína Zgútová[1], Martin Pitoňák[2], Juraj Šrámek[1], Dominika Ďureková[1(*)]

[1]Department of Construction Management and Technologies, Faculty of Civil Engineering, University of Zilina
[2] Centre of Excellence in Transport Engineering, Faculty of Civil Engineering, University of Zilina
[(*)]*Email:* dominika.durekova@fstav.uniza.sk

ABSTRACT

Culturally, it is important to upkeep national monuments and to preserve them for future generations as historic heritage. In the process of preserving historic sites it is very important to choose an appropriate method of remediation, which will conserve the authenticity of the object to the greatest extent. Determination of appropriate method of remediation is essential to the object period of life and its serviceability. The presented paper describes the diagnostics, remedial design and successful reconstruction of the wooden church of St. George in the village Trnove. This church is the westernmost located wooden church in Slovakia. It is a national historic landmark and the first information about the church dates back to1583.

Keywords: wooden objects remediation, biotic factors, diagnostics, reversibility principle, the principle of authenticity, the principle of moderation, replacement of damaged wooden elements, grouting

INTRODUCTION

Church presented in Fig. 1 is a single nave church built of logs. Short nave facing east has almost a square ground plan. It accommodates sanctuary, presbytery and later built tower of a frame structure filled with wooden plates. The tower finished by a pavilion roof is only slightly higher than the nave. The roof is saddle shaped, covered with wooden shingles. The church is built of wooden beams, precisely deposited, so there are nearly no voids between them [1].

Fig. 1 Church of St. George in Zilina prior to reconstruction works

Year of construction of the church is unknown and all its history is shrouded in mystery. Nevertheless, there are many rumours regarding the age of the building. According to the oldest written record, the church already existed in 1583. However, dendrochronological dating of wooden elements carried out in 2010 specified these conjectures. Samples were taken from logs in walls, roof and tower structure. Standard chronology methods were applied:

- measuring tree ring widths
- relative synchronization of the obtained tree ring genera
- standardization of tree-ring series
- attempted absolute chronology compared to a standard chronology of trees.

Examination clearly determined that walls and roof of the church were made of fir and spruce truncated in the period from 1610 to 1614. Tower supporting columns were carved of fir truncated at the turn of 1768/1769 [2].

DIAGNOSTICS AND REMEDIAL DESIGN

Proposing a suitable way to address remediation of damaged wooden structures based on accurate analysis. Inputs for analysis can be obtained by a detailed direct examination on the object.

Examination by:

- destructive methods
- non-destructive methods

Examination of conditions of wooden elements included the following:

- Humidity of wooden elements
- Biological and other damage to wooden elements
- Deformation, cracks and other abiotic defects in the wooden elements

Survey also evaluated the extent of damage [3].

HUMIDITY OF WOODEN ELEMENTS

According to [3] the humidity of wooden elements in the church was determined by a portable hygrometer - Profimeter Mini C. Measurements were carried out on random samples, and also on elements in critical condition, exposed and damaged by precipitation (bottom annular beams, elements under the damaged shingle).

Results:

- absolute humidity of selected wooden beams from log work walls, without visible damage by water leakage, ranged in most cases from 15% to 21%
- absolute humidity of selected elements from the timber of roof and bell-tower, without visible damage by water leakage, ranged in most cases from 15% to 21%
- absolute humidity of threshold girders of log walls was usually above 30% and often even above 60%

- in local areas of the framework and bell tower under the damaged shingle roofing was identified even higher moisture content from 30% to over 60%.

Based on identified humidity of wooden support elements of the church was conclude that:

- generally there was a potential danger of wood-boring larvae activities of wood-destroying insects:

$$w_{\text{crit.minimal (wood-destroying insects)}} = 10\ \%$$

$$w_{\text{optimum (longhorn beetle, Anobium punctatum)}} = \text{approx. } 30\ \%$$

- in local areas (low beams in contact with concrete) show humidity conditions even for rotting due to wood decaying fungi:

$$w_{\text{crit.minimal (wood decaying fungi)}} = 20\ \%$$

$$w_{\text{optimálna ((serpula lacrymans, cellar fungus, gleophylum)}} = 30\text{-}80\ \%.$$

BIOLOGICAL AND OTHER DAMAGE TO WOODEN ELEMENTS

Examination of wooden elements found the following types of biological damage:

Wood decay caused by fungi:

- Older rotting, both local and current rotting in the elements that were in the past, or are even today exposed to precipitation. Their moisture content was or is even today consistently above 20-40%. This is especially the rot in the bottom threshold girders in the log walls and several following logs of the wall. The rotting is present also in several wall beams and in some other elements of roof and bell tower. Wooden struts supporting log walls from outside, which were applied at the last reconstruction of the church, are heavily damaged by the rotting. Moreover, the rot has significantly impaired also the wooden shingles.
- Identified was wood decaying fungi gloeophyllum trabeum.

Tunnelling by larvae of wood destroying insects (Entomology survey):

- Tunnelling - in various elements of the wooden church, i.e. log walls beams, roof frame
- Significant tunnelling damage to the wood was identified as caused by the following types of wood-destroying insects:
- longhorn beetle - oval holes with cross-section of about 7x12 mm
- wood worm - round holes and exit holes diameter 1-3 mm.
- Minor and only scattered damage identified as caused by callidium violaceum - oval holes under the remains of bark on rafters [4].

DEFORMATION, CRACKS AND OTHER ABIOTIC DEFECTS

According to [3], due to biological damage to the wood and due to other factors acting since incorporation of wooden parts (compression wood, spiral growth of wood, or even very high moisture content of the incorporated wood) in the wooden church were found in some wooden elements:

- significant cracks
- deformations
- released jointing.

REMEDIAL DESIGN AND PROGRESS

The method of remediation is subject to respect the historical value of the building. Priority is to save maximum of the original building material. Replacements of elements or partial replacements are proposed only to the necessary extent.

1. Numbering of all the logs and wooden elements according to their location
2. Dismantling the object according to beams and wooden elements and storing them in a suitable dry place
3. Detailed diagnostics of elements and assigning them suitable remedial repairs
4. Removing the first two rows of the lower perimeter beams and replacing them with new healthy beams which are of the same material and shape as the original
5. Workshop treatment to the elements, replacement of partially damaged part, grouting, replacement of the whole element
6. Assembling the church according to the numbered logs and wooden elements
7. Application of wood preserving chemicals to all wooden components.

During remediation process were applied several methods:

Replacement of wooden elements

This technology involves removal of unsuitable elements and replacing them by new, healthy ones. Replacement of the whole element is decided only if there is no possibility to save the original. It means that the particular element is damaged 70% or more.

Damaged part replacement

Damaged part of supporting element is replaced or supplemented by a new part – by the so called prosthesis which is to restore original strength and stiffness of the element. Prosthesis has the same shape as the removed or missing part.

Grouting

Grouting technology is used to fill the caverns and cracks in wooden elements. Cracks are filled with polyurethane resin which, after reacting with the wood obtains strength similar to wood.

Chemical treatment of wood

Proposed remediation of particular parts of the church are listed in Tab. 1

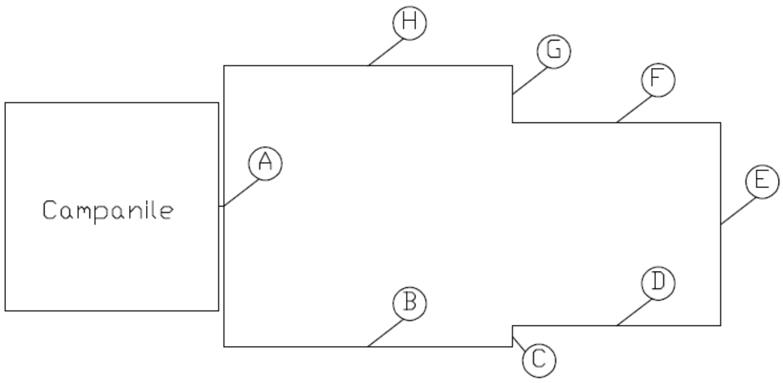

Fig. 2 Church ground plan scheme with identification of walls

Tab. 1 Remedying proposal

Part:	Replacement	Damaged part replacement	Grouting	Chemical wood protection *
Wall A	5 beams	2 beams	2 beams	4 beams
Wall B	6 beams	3 beams	1 beam	3 beams
Wall C	4 beams	1 beam	2 beams	6 beams
Wall D	6 beams	2 beams	3 beams	2 beams
Wall E	4 beams	1 beam	5 beams	3 beams
Wall F	7 beams	2 beams	4 beams	0
Wall G	3 beams	0	1 beam	8 beams
Wall H	6 beams	2 beams	3 beams	2 beams
Bell tower	6 spurs, 40 m^2 shingle and 72 wooden boards	4 spurs, 4 columns, 70 ceiling wooden plates		80 wooden boards, 2 spurs
Roof frame	8 rafters	23pillars,8 tie beams, 6 bonding ties, 18 rafters	4 wall beams	12 pillars, 4 tie beams , 5 bonding ties
Shingle	128 m^2			
Ceiling boarding	198 wooden boards			

*Note. * Apart from the above listed parts were chemically treated all new (replaced) parts, prosthesis and grouted parts.*

TRANSPORTATING THE CHURCH

Before the church was dismantled it was measured, documented and each part was marked. On 25th of November 2010 began the dismantling of the church (Fig. 3). Parts of the church were transported to the Eastern part of Slovakia, where was performed remediation. Companies from Eastern Slovakia which specialize in remediation of wooden structures have many experiences with repairs of historical objects. Therefore it was decided to transport the church.

Fig. 3 Dismantling the wooden church

Following successful remediation process the church was transported back to its original location and built up (Fig. 4). Opening ceremony of the church was held on 29th of April 2012. Total reconstruction took about 17 months.

Fig. 4 Assembling the church

SAFETY

Safety of the project is defined as a safety and protection of people, property and surrounding area. It is the result of the risk assessment, justification of the solution in terms of risks, fire safety, and impact on environment, protection of cultural heritage, nature and landscape. Safety protocol of the church is subject to continuous update even after the building is in service. At buildings that are classified as cultural heritage we do not consider the service life of the building, but the aim is to preserve it for future generations - continuously. Moreover, it is required to preserve the authenticity of construction, which is sometimes in conflict with safety.

The primary objectives that investors, designers and operators of such buildings seek to ensure are:

- prevent critical events that threaten human lives and cause damage to property or environment,
- in case of critical event, it is necessary to prevent its consequences as much as possible.

Safety of wooden building can be achieved by selecting the appropriate material (spruce, acacia, oak or pine), but also by continuous adequate wood protection.

PROTECTION OF WOODEN OBJECTS

Wood is natural material. It is composed of three basic organic polymers - cellulose, hemicellulose, lignin. These organic compounds are susceptible to damage by abiotic agents (UV radiation, fire, water, oxygen, emissions) and biological pests (wood decaying fungi and insects). [4].

Wood protection basic rules:

- selection of appropriate wood material,
- use of structural wood preservation,
- chemical preservation of wooden objects,
- static assessment of wooden structure.

Selection of appropriate wooden material means selection of durable woods used for construction or parts, which are exposed to outdoor climate conditions. For building front face, pergolas, playgrounds and the like is recommended to use wood which contains in addition to the basic polysaccharides and lignin also relatively large proportion of extractives (i.e. tannins, quinones, flavonoids, terpenoids, ...). These substances make wood more resistant to rot, wood decaying insects or emissions. Slovak wood species in this category include larch, acacia, oak or pine. So-called modified wood belongs to wooden materials with perspective. Chemically treated wood (i.e. acetylated wood) or thermally modified wood (thermo wood) has higher resistance against fungi, insects and is less hygroscopic.

Structural wood preservation means protection of natural durability of wood if it is not sufficient for particular exposure. These methods of protection are environment friendly and the wood remains wholesome. The main principle of structural preservation of wood is to ensure permanent low wood moisture content in the range between 6 to 15%. Such wood does not provide environment for existence of wood decaying fungi, mould or activity of larvae of wood-destroying insects. Moreover, it is necessary to resolve structural joints and links to avoid accumulation of moisture and condensation water (diffusion open structures), and to minimize the spreadng of fire. Isolation from any source of water (groundwater, rainwater, capillary, operational, condensation) is absolutely necessary, as well as securing the required initial moisture content of wood. Initial moisture and exposure moisture should be as close as possible. For example for roof frame it is 10 to 16%, external wood facing 12%, internal flooring 8%. At such conditions there is no deformation, cracks and pest activity. [4].

In relation to the structural wood preservation we speak of so-called optimization of the design and shape of wooden buildings. For example: design of the roof slope in relation to the roofing material, installation of wood in contact with the outside terrain etc.

Chemical preservation of wood belongs to special wood protection. Suitable certified chemical protection substances are applied to the wood (fungicides, insecticides, retardants). Special part of the chemical wood protection is protection against atmospheric exposure (UV radiation, moisture). Recently, diffusive, open, flexible and low molecular coating materials seem to be the most effective. Chemical protection of extreme exposures is provided by Vacuum pressure impregnation. [4].

STATIC ASSESMENT OF WOODEN STRUCTURE

The aim of static assessment calculation is to demonstrate the ability of the wooden building to withstand the load (Fig. 5 shows bending moments at the church choir) caused by its own weight, the random natural loads (snow, wind) and the load of people, equipment or special loads (seismic zone). Static assessment is necessary not only due to legislation requirements (Building Permit Design), but also due to the warranty. Static reliability of the structure recognizes two limit states:

- Ultimate Limit State - calculation proves that the proposed size and shape will transfer all types of loads without permanent deformation and destruction,
- Serviceability Limit State - calculation proves that the structure at the time of maximum load does not show illicit deflection and is not excessively deformed, which although does not affect the functionality of the structure, but certainly its appearance.

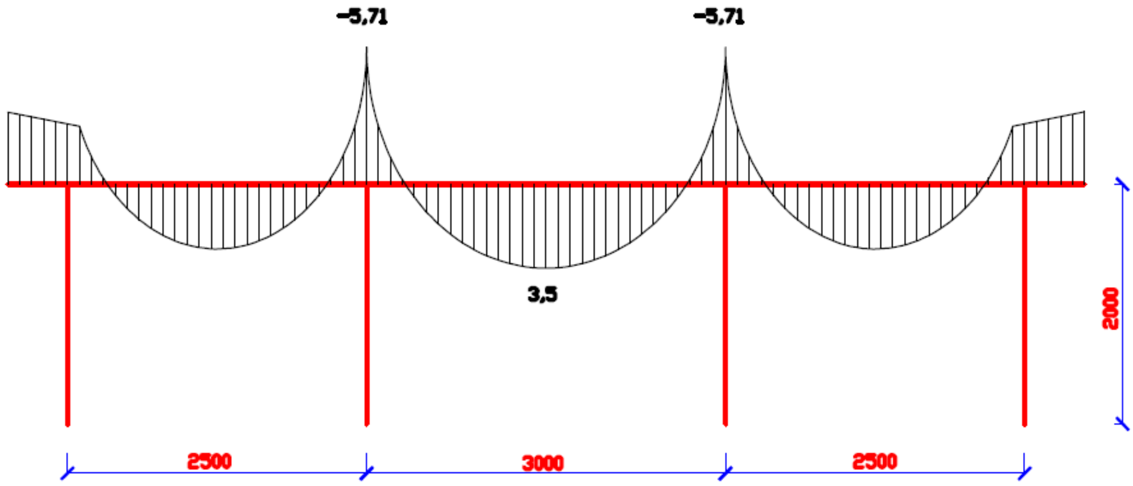

Fig. 5 Bending moments at the church choir

Static bending test - for this test were provided wood samples from the investigated object - 3 pieces of wood from the original samples and 3 pieces of grouted wood see Table No. 2 - Sample basic data. Static load test was performed on samples to determine the bending strength. Tests were carried out on standard samples in order to comply with the Standard EN 384 - Structural timber. Determination of characteristic values of mechanical properties and density [6]

Table No. 2 - Sample basic data

	sample	m (kg)	b (m)	h (m)	l (m)
1	A	0.1303	0.026	0.0260	0.545
	B	0.1409	0.026	0.0258	0.542
	C	0.1409	0.026	0.0259	0.542
2	A	0.1236	0.025	0.0250	0.545
	B	0.1316	0.025	0.0250	0.545
	C	0.1329	0.026	0.0250	0.545

Note. :
1 – samples without grouting
2 – samples with grouting

Weight of the spreading element – 11135.73 g
W = (b.h$_2$)/6

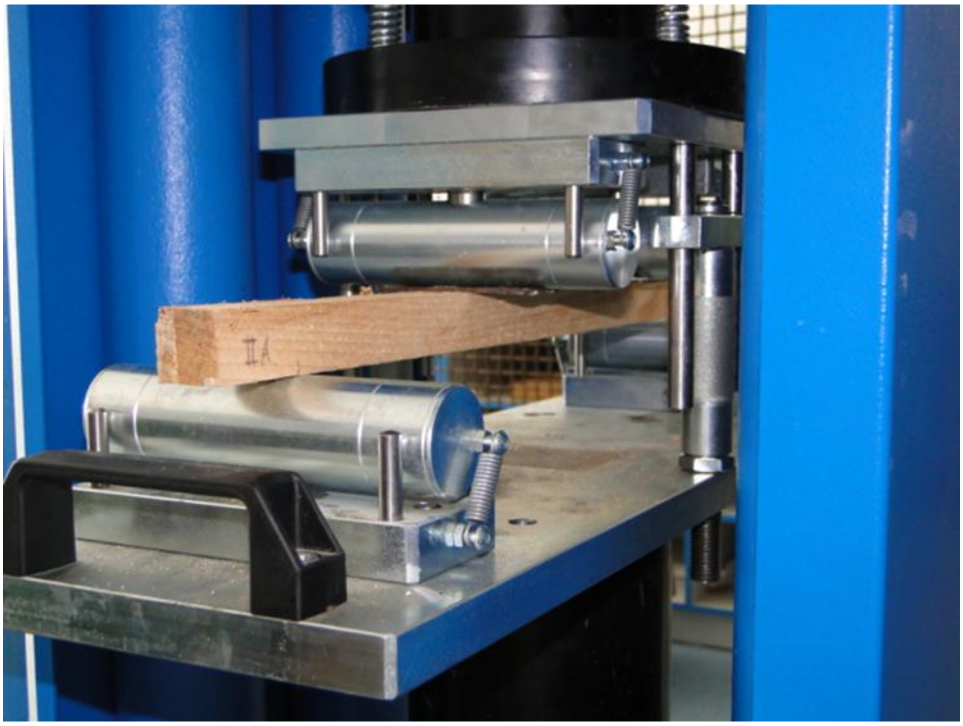

Figure 6 - Testing the bending strength

Table 3 - Results

	sample	F (KN)	m (kg)	F+m	a (m)	f_m (KN)	$F_{m,average}$ (KN)
1	A	1.560	0.111	1.671	0.182	51909.76	50820.64
	B	1.559	0.111	1.670	0.182	52686.14	
	C	1.418	0.111	1.529	0.182	47866.01	
2	A	1.913	0.111	2.024	0.182	70726.66	66708.10
	B	1.842	0.111	1.953	0.182	68245.63	
	C	1.702	0.111	1.813	0.182	61152.00	

The table shows that grouted wood has higher resistance (approximately by 31%) at the static bending than non-grouted wood.

Ultrasound method - modulus of elasticity and modulus of rupture was determined by non-destructive method – ultrasound, which is based on ultrasonic waves between excitation probe and sensor. The shock wave is caused by hammer blows to the particular sensor. The advantage of this method is that it can be used not only to measure free resting timber, but also to measure wooden elements which are incorporated into the structure. In order to achieve precise measurements, the device shall be calibrated. Based on the distance between the two probes is determined the propagation velocity of ultrasonic wave. Dynamic modulus of elasticity is than determined according to the formula:

$E_{dyn} = v_2.\rho$ [Mpa]

where E_{dyn} is the dynamic modulus of elasticity

v – wave propagation velocity

ρ - wood density.

It is not possible to determine the wood density of incorporated elements by weighing and measuring, therefore are used values according to the density of each wood species [7].

For this test were available 2 samples of non-grouted wood and 2 samples of grouted wood. Data about samples and measurements results are listed in Table 4.

Table No. 4 Ultrasound method

	sample	**s (mm)**	**t (ms)**	**v (m/s)**	**m (kg)**	**ρ (kg/m^3)**	**E_{dyn} (Mpa)**	**$E_{dyn,average}$**
1	A	110	61.4	1.792	0.1303	353.59	1135.47	1407.37
	B	112	53.8	2.082	0.1409	387.40	1679.27	
2	A	145	81.7	1.775	0.1236	362.86	1143.24	1252.31
	B	143	76.2	1.877	0.1316	386.41	1361.37	

Note. :
1 – samples without grouting
2 – samples with grouting
$v = s/t$
$\rho = m/V$
$V = b.\ h.\ l$

FIRE SAFETY OF WOODEN BUILDINGS

Wooden buildings, similar as any other building are subjects to fire protection according to the procedures indicated in the Decree of the Ministry of Interior of the Slovak Republic no. 94/2004 Coll. which stipulates required fire resistance of buildings according to the building structure and in accordance with Technical Standards, particularly set of standards STN 92 0201-1 to 4. [4]

Within the Fire Safety Design shall be also demonstrated specified fire resistance of designed structural components (trusses, beams, columns, etc.) and assemblies (walls, cross walls, ceiling, roof ...).

Fire resistance of building structures in accordance with the Section 8 of the Decree of the Ministry of Interior of the Slovak Republic no. 94/2004 Coll. which stipulates technical requirements for fire safety during construction and use of buildings is determined:

- according to the initial type testing (Act No. 90/1998 Coll. on Building Products as amended),
- by calculation according to the technical standard (in cases where all the relevant coefficients can be expressed by calculation, for example, according to the Euro codes for structural fire design),
- by testing and calculation (in those cases where it is not possible to express the test and demonstrate all the relevant coefficients affecting the fire resistance of tested structures). [4]

In Slovakia was issued Technical Standard STN EN 1990 (Euro code - Basis of structural design) together with the National Annex STN EN 1990/NA in October 2004 and is valid as a primary standard for the Euro codes in Slovakia.

Euro codes provide common methods in the design, specification and demonstration of functional properties of structural components and assemblies (building structures) for designers - civil engineers, structural engineers, architects in the system of European standards. Moreover, are the instrument and the template for:

- demonstration of compliance of objects of civil engineering works with essential requirements of the Directive 89/106/EEC, in particular with the basic requirement No. 1 - Mechanical resistance and stability, and the basic requirement No. 2 - Fire safety (can be understood as the resistance to fire),
- signing of civil works contracts and related engineering services. [4]

PROTECTING THE WOOD AGAINST FIRE – FIRE RETARDANTS

Combustion process reduces the strength of all building materials. In case of fire, the building materials shall resist the increased stress for a while, to allow evacuation of people. Fig. 6 shows the comparison of the strength reduction of materials (aluminium, steel, wood) depending on the duration of fire.

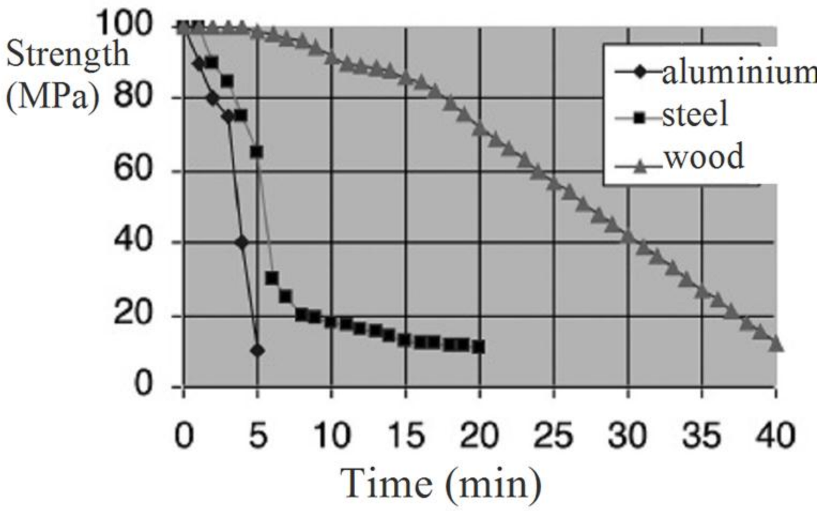

Fig. 7 Graph of burning beams: aluminium, steel and wood [5]

Fire retardants are chemicals that prevent rapid ignition and combustion by their chemical and/or physical action. Retarding new materials is relatively simple. We can only envy scientists in the field of plastics, how they are able to judge the tying of the retardation group to the particular element, the impact of its position in the molecule etc. Retardation of natural materials such as wood is more complicated. [5]

Fire retardants for wood can be divided into four groups [8]

- The first group consists of retardants, which emit nonflammable gases at the temperature range at which are formed flammable gases, such as products of wood degradation. This dilutes flammable gases, reduces their concentration and decreases the risk of combustion.

- The second group consists of retardants that accumulate the heat from the heat source, and thus "cool" the source down. Such retardants are currently not used very often due to their early deterioration which decreases their effectiveness.
- The third group of retardants consists of foaming intumescent flame retardants. Their efficiency is the highest, thus they are the most widely used flame retardants. They have two-stage effectiveness - physical and chemical. In the first stage of the action of the heat acts one component of the retardant by creating foam. This actually delays the wood surface from the heat source. This is the first method of physical retardation. The second method of physical retardation is based on the fact that the foam is a very poor conductor of heat and the wood is delayed from heating up. The next stage is chemical retardation. Further heating up causes chemical reactions which significantly retard the fire.
- There are also mechanical retarders, such as foil and various sheeting made of nonflamable material. Application of such retardants to wood is effective, however not risk free. [5]

Apart from selecting flame retardants mentioned above, is also very important to properly evaluate conditions to which will be retarded wood exposed. Correct choice of retardant, professional application and assessment of conditions in which will be retarded material exposed guarantees quality retardation. Important is also the cost of retardation and the volume of retardant required to achieve effectiveness. [5]

Fig. 8 Discoloration of wood and estimated thermal degradation
(After removal of the char layer were made 1mm thick cuts) [9]

Method of chemical protection application of the wooden church depended on a number of criteria. This mainly involved which part of the church is being chemically treated and how it will be stressed. The method of application also depended on the retardant - e.g. intumescent flame retardants can be applied only by coating. Retardants of the first group, which are based on water-soluble inorganic salt solutions, can be applied by coating, dipping or impregnation. [5]

CONCLUSION AND RESULTS

Based on the detailed survey and definition of the damage, the remedying works have been proposed. The main task of remedial was to preserve as much as possible of the original building material as the object under consideration is unique historical monument in the given region.

Wooden buildings of similar character as the church in Trnove are mainly located in the eastern part of Slovakia. Because restorers in Eastern Slovakia have a lot of experience with the preservation of such historic sites and also have the necessary technology available, it was decided to take the church into parts and transfer it to Eastern Slovakia. There was performed a successful reconstruction, which is evident from Figure 7.

As at all human activities also at looking for safety in buildings built of combustible material is possible to find a solution. Proper evaluation of the risk, its deep understanding and its elimination by the application of an adequate number of safety features leads to the aim. This brings benefits of other positive qualities of wood, which could not have been utilized because of its flammability.

Fig. 9 Wooden church in Trnove On the left prior to reconstruction, on the right after reconstruction

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