Wood science approach for the preservation of historic timber structures

Margarita Kisternaya[1], *Valery Kozlov*[2]

[1] "Kizhi" State Open-Air museum of architecture, history and ethnography, Petrozavodsk, Russia
[2] Forest Research Institute, Karelian Research Centre RAS, Petrozavodsk, Russia

Abstract

Authenticity of wooden architectural monuments is determined by original building material – timber.

The report presents the results of the investigation of XVIII cc. historic timber structures in the Republic of Karelia carried out in 1998-2008. The data obtained indicate that the chemical composition of Scots pine (*Pinus sylvestris* (L)) changes as the timber ages. Cellulose molecules are destroyed and water-soluble extractives – acids, sugars, appear. Nevertheless, the timber not damaged by biological agents preserves its strength properties. Biological agents – brown rot fungi (*Serpula lacrimans* (L.), *Coniophora puteana* (Fr.), *Coriolellus sinuosus* (Fr.), *Fibuloporia vaillantii* (Fr.), *Paxillus panuoides (*Fr), soft rot, and wood borers (*Hadrobregmus pertinax* (L.), *Anobium confuses (Fr.)*) are the most common destructors of historic timber in this region.

The proposed coherent strategy of regular monitoring aims to prevent biodeterioration of timber structures. It consists of several related levels and includes regular inspections; temperature and air humidity measurements, as well as control of wood moisture content, fungal and insect activity.

The procedure of historic structure inspection is described. It includes: visual inspection of structural elements to reveal the zones with high wood moisture content and those damaged by fungi and insects; sampling for mycological analysis in the zones damaged by fungi and insects; detection of wood-destroying insects and investigation of timber integrity using special equipment.

The main efforts are focused on detection the zones where the fungi and insects are active. At the first stage the fungal activity is predicted by wood moisture content. Continuous measurements allowed determining saprogenic zones. At the second stage small wooden samples (30-40 mm long, 5 mm in diameter, referred to below as "witness" samples) are exposed in the zones under investigation for estimation of fungal activity *in situ*. Their weight loss is considered an indicator of fungal activity.

Detecting wood- destroying insects includes light traps monitoring, visual inspections and acoustic detection. Audio sensors used by the authors proved to be quite efficient in detecting insects even if visual signs – flight holes, were not obvious. The best periods for the detection of *Anobiidae* are May-June and September.

The system of monitoring biodeterioration has been established in the State Open-Air Museum "Kizhi" since 1998. As a result, zones damaged by wood-destroying fungi and insects were revealed, their activity was assessed: microclimate of the structure was studied, and the sources and distribution of moisture within timber were determined. The results were used as the basis for timely maintenance of the monuments.

As a result roof leakages were located and eliminated, although it was a rather difficult task given the complicated structure of the multi-domed churches. It decreased wood moisture content considerably, and the fungi development ceased. The absence of fungal activity was proved by experiments with "witness"-samples.

Disinfection is more problematic than control of the activity of wood-destroying fungi: the pests develop at relatively low wood moisture content and nearly all stages in their life are hidden inside the timber.

The report presents the technique for eradication of wood-destroying insects by means of local-scope microwave treatment developed by the authors and protected by Russian Federation copyright law. The obtained within the framework of the research temperatures and the exposure times lethal for the insects and larvae of borers are discussed. It is shown that the heating modes with slow increase in temperature at low wood moisture content provide the low temperature gradient and preserve the integrity of the timber.

The "Kizhi" museum experience proved the idea that preventive conservation principles can be applied to historic timber structures. Regular monitoring, integrated pest management, in-time maintenance are the best approaches for preservation of wooden monument. The proposed monitoring system can be easily adapted to a wide spectrum of historic timber structures. In the long term, it would increase the service life of the wooden architectural monuments preserving their authenticity.

1. INTRODUCTION

Wood has been the main building material in the northern part of Europe since prehistoric times. Its workability and versatility as well as exceptional impact strength, effective thermal insulating properties are well known. Among the major construction materials, wood uses the least amount of energy to process and manufacture, it is a renewable resource.

Longevity of timber structures is determined by a number of factors: environmental impact, timber quality, protective treatment, quality of maintenance. Environmental factors may be divided according to ISO 8241 standard into thermal, mechanical, chemical, biological and electromagnetic ones.

The combined action of light and water makes wood surface darker and leads to the formation of macro-and microscopic inter- and intracellular cracks and checks. The strength of cell wall bonds near the wood surface decreases. As weathering continues, rainwater washes degraded portions out and further erosion takes place. Erosion correlates directly with wood quality: the higher the density, the slower the erosion.

As a result of wood ageing, cell walls degrade starting from the lumen toward middle lamellae. Cellulose molecules degrade and water-soluble extractives – acids, sugars, appear. Lignin proved to be a more stable component of wood. Changes in timber properties due to ageing are rather slow (decades or even centuries). Numerous investigations proved the idea that timber unaffected by biological organisms has preserved its strength properties [1,2,3,4,5].

At the same time, if the conditions are favorable for wood-destroying fungi and insects, wood can be destroyed within several years.

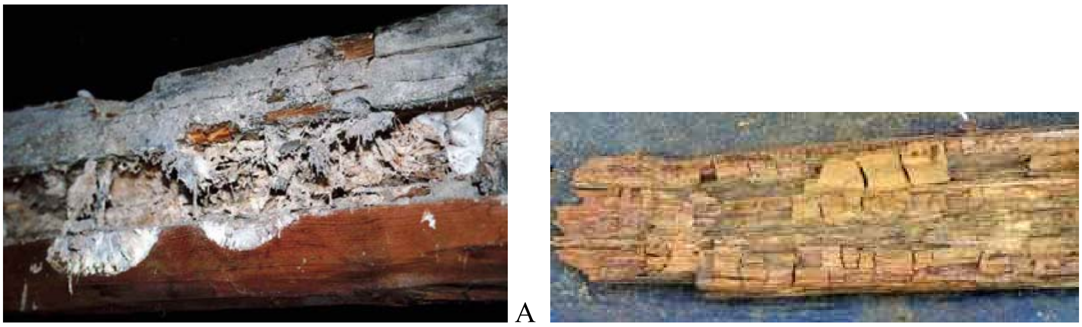
1. Biological agents destroying wooden architectural monuments

Brown rot fungi are the most common destructors of historic timber in the north of Europe. In our region insects are the secondary destructors [3].

Wood-destroying insects and fungi are described in monographs and guidelines [3,6,7,8]. The short description of typical for Russian North destructors is given below.

Wood-destroying fungi

Brown rot fungi: *Serpula lacrymans* (L.), *Coniophora puteana* (Fr.), *Coriolellus sinuosus* (Fr.), *Fibuloporia vaillantii* (Fr.) and *Paxillus panuoides* (Fr.) are the most common destructors of historic timber. They break the cellulose part of the wood by means of several enzyme systems down into smaller particles, namely water soluble sugars (glucose) [6, 7, 9]. At the final stages of the attack, wood grows brown in color and breaks apart into cube-shaped pieces (Fig. 1).



A B

Figure 1 – Timber damaged by wood-destroying fungi A – mycelium, B – destroyed wood

By far the most important fungus destructive to wood in buildings is the "dry-rot fungus" *Serpula lacrymans* (L.). Decay caused by this fungus occurs quite frequently in poorly ventilated spaces: on the reverse of floorboards or ceiling, in basements, more seldom – in the attic. The fungus prefers a wood moisture content of 20 to 30 %; it can transport water through vessels in the strands and is able of moistening dry wood.

For optimum growth of other brown rot fungi, the moisture content of wood should be between 35 and 50 %. The high wood moisture content determines the occurrence of the white polypore fungi (*Coriolellus sinuosus* (Fr.)) in unventilated roof spaces of buildings. The cellar fungus *Coniophora puteana* (Fr.) very often occurs where there is continuous water leakage or condensation. *Gloephyllum sepiarium* ((Fr.) Karst) occurs on external surfaces where temperature and wood moisture content vary considerably.

Another common defect of moistened structures is soft rot damage. High moisture results in the development of imperfect and ascomycetous fungi causing soft rot. Wood-rotting microfungi (*Coniothecium, Stysanus)* destroy the S_2 layer or middle lamella; the wood surface darkens and this superficial layer, up to 3-4 mm deep, becomes very soft. Wood below decayed surfaces is usually sound, but the water-absorbing ability of the wood increases greatly (Fig. 2).

Figure 2 – Soft rot development in poor-ventilated space of wooden structure.

Wood-destroying insects

Important pests of timber in monuments in the North of Europe are beetles belong to the family *Anobiidae*. The most frequent species found in our region are *Hadrobregmus pertinax (L.)* and *Anobium confuses (Kr.) [4, 8]*.

Hadrobregmus pertinax (L) attack usually occurs in timber which has been in service for several years. Structural elements such as moistened lower timber sets, attic beams, corners, elements below windows are mainly damaged. Certain moisture level (18%) and frosts in winter are the prerequisites for infestation. Insects complete their life cycle in a year or two, but it may be extended under unfavorable conditions.

The presence of attack may remain unnoticed for several years because its only signs are flight holes approximately 1 mm in diameter, and in many cases, sufficient sapwood is present (Fig. 3). Timber is damaged by larvae which hatch from eggs laid in cracks in the wood or in old flight holes. Adults do not feed. Our results show that in our region wood-borer adults emerge in late May and June.

A

B

Figure 3. A – Flight holes of *Hadrobregmus pertinax (L)*. B – timber destroyed by *H. pertinax (L)* larvae.

Anobium confuses (Kr.) damages only softwood. It can be found in any part of buildings (cellar, attic). Wood borers may complete their life cycle in two or three years depending on climatic conditions. The flight holes are 1,9 -2,1 mm in diameter.

Cossoninae (*Curculionidae* spp) destroys wet timber structures damaged by brown rot.

Cerambycidae can be introduced to wooden architectural monuments with infected soft wood. The insects are bigger than *Anobiidae*. Their oval flight holes are 3-5 times larger and their sizes vary from 3x6 to 5x12 мм for *Hylotrupes bajulus* (L.) and approximately ~2x5 мм for *Callidium violaceum* (L.). The last pest is quite common destructor of the interior objects in Russian North.

2. Biological control of wooden architectural monuments

2.1. Prevention technique

A coherent strategy of regular monitoring and maintenance is very important for preservation of historic timber structures. A system of monitoring can be defined as a sustainable approach to pest management in a way that minimizes economic, health and environmental risks and extends the monuments' service life [10, 11, 12].

The system for monitoring wooden architectural monuments was developed by the authors of the paper [5]. The proposed procedure for monitoring wood condition is based on preventive conservation approach and includes regular inspections; temperature and air humidity measurements, as well as control of wood moisture content, fungal and insect activity.

It is very difficult to reveal the initial stages of fungi development. As a rule the mycelium and fruit bodies of the fungi indicate the severe damage of the element of construction. It is known that the most serious and extensive damage is connected with high wood moisture content. It is the main limited factors for fungi development. Therefore during the survey, special attention is paid to the constructions or the building elements with a high wood moisture content (> 30%).

Continuous measurements allowed determining saprogenic zones. All elements of the structure can be divided into three groups (zones) by moisture content (MC): those with MC never exceeding 20%, those with MC around 20%; and those with MC above 20%. The first zone can be considered as a safe one. Development of the true dry rot fungus is possible in zones belonging to the second group when the temperature is above 15 ^{o}C. Moisture content in the third zone is sufficient for the development of the majority of brown rot fungi if the temperature is above 20 ^{o}C. In this case it is very important to find and eliminate the source of water.

At the same time, estimation of fungal activity *in situ* is of great importance. It is known that during degradation, cellulose molecules are decomposed into water soluble compounds. Therefore, weight loss can be considered an indicator of fungal activity.

We suggest exposing small wooden samples (30-40 mm long, 5 mm in diameter) in the zones under investigation. Analysis of the samples, referred to below as "witness" samples, after the exposure indicates fungal activity [5]. Weight loss is accepted as an indicator of the biodestruction. Microscopic analysis reveals hyphae of brown rot fungi in samples with a weight loss higher than 1%. Changes are observed also in the structure of tracheid secondary cell walls: they became thinner compared to the control sample.

The system of monitoring biodeterioration has been established in the State Open-Air Museum "Kizhi" since 1998. Nowadays the "Kizhi" museum id one of the largest museums of wooden architecture in Russia. It's collection is presented by 82 monuments: houses, churches, chapels, house holding structures built in XIV-XIX cc. Among them there is the World Heritage Site "Kizhi Pogost". It is an enclosed architectural ensemble composed of two churches – the Church of the Transfiguration (1714) and the Church of the Intercession (1694-1765), the bell-tower (1862). A real masterpiece of log engineering it attracts many visitors (Fig. 4). In 2008, there came 200 000 people altogether.

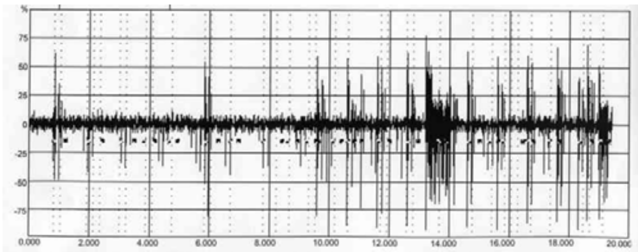
The museum activities focus on securing longevity of the wooden monuments. The system of monitoring timber structures aimed to prevent biodeterioration is operated in the museum under the supervision of the chief curator. Our experience testifies that it is quite effective for prevention of wood decay.

Wood-destroying insects play a significant role in the destruction of timber of wooden architectural monuments. Light traps installed from May to August in rooms give us information about the pest population.

Figure 4 - The Kizhi museum attracts many visitors of different age.
Traditional child’s festival on 12.06.09

Early detection of infestations has become increasingly important for preservation of historic timber structures. The most common method of detecting infestations with wood-destroying insects is visual inspection, but as a rule it reveals an infestation only in its later stages.

Visual inspection in the “Kizhi” museum is supplemented through the use of acoustic equipment. The AND-1 sensor (worked out for the State Hermitage) and audio sensors of the STG Stetographics Inc (USA) are used in the museum. The first model records the acoustic emissions generated by the larva and insects in an analog and the second one – in a digital format. Both models proved to be quite efficient in detecting insects even if visual signs – flight holes, were not obvious. The best period for the inspection is late May–June, when *Anobiidae* emerge from wood. The small size of the larvae hatched from eggs in July-August does not allow hearing the sounds (Fig. 5).


A


B

Figure 5 – A – acoustic detector STG. B – Sound record of borers activity

2.2. Eradication of wood-destroying insects

Disinfection is more problematic than control of the activity of wood-destroying fungi: the pests develop at relatively low wood moisture content and nearly all stages in their life are hidden inside the timber.

Heat treatment is one of the most promising techniques for eradication of pests. It is quite cheap, effective and environmentally friendly technology. Microwaves provide an effective heating of the timber. Lethal for pests’ temperatures can be easily reached. Slow increase in temperature at low wood moisture content created a low temperature gradient securing integrity of the object.

The problem of detection of the pests was one of the limiting factors for this local-scope treatment. It was solved by acoustic detection. Our research determined the temperatures (53-55 oC) and exposure periods (30 minutes) lethal for the insects and larvae of borers. The lethal temperatures were reached in 120-240 minutes depending on the element size.

The currently developed technique for the heat treatment was protected by Russian Federation copyright law (Fig.6) [13].

Figure 6 – Microwave treatment of the structure infected by borers

3. Conclusion

Preservation is a preferable approach to extending the service life of historic architectural monuments. Modern biological control takes into account the monuments features, their service life conditions and main destructors, up-to-date disinfection and disinfestations techniques.

Nowadays the museums have good facilities in choosing the strategies for prevention against biodeterioration. They include prevention (microclimate control, monitoring) as well as eradication techniques. The main idea in modern strategy of biological control is prevailing of prevention techniques, minimal intervention to the object and environmentally friendly approach.

The system of biological control of timber structures proposed by the authors aims to prevent biodeterioration. It consists of several related levels and includes regular inspection of structural elements to reveal zones damaged by fungi and insects; assessment of fungi activity, detection of wood-destroying insects. The results of the monitoring serve as the basis for the maintenance plan. Up-to date maintenance enables preservation of historic timber structures.

Modern technologies require high qualification of the museum staff and high-value and high-technology equipment. Specialists in biology, chemistry, climatology are employed nowadays in the museums all over the world. Integration of their efforts save our heritage for future generations,

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