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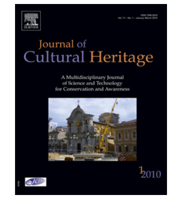

Original article

Comparative evaluation of acoustic techniques for detection of damages in historical wood

Michal Kloiber [a], Ladislav Reinprecht [b,*], Jaroslav Hrivnák [a], Jan Tippner [c]

[a] *Czech Academy of Sciences, Institute of Theoretical and Applied Mechanics, v. v. i., Centre of Excellence ARCchip Telč, 588 56 Telč, Czech Republic*
[b] *Technical University of Zvolen, Faculty of Wood Sciences and Technology, 960 53 Zvolen, Slovak Republic*
[c] *Mendel University in Brno, Faculty of Forestry and Wood Technology, Department of Wood Science, 613 00 Brno, Czech Republic*

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ABSTRACT

This study assesses the suitability and sensitivity of select acoustic devices (Arborsonic Decay Detector, Fakopp Ultrasonic Timer with two types of sensors–TD45 and US10, and Fakopp 2D) for identification of damage in seven approximately 315 year old fir joining beams acquired during the reconstruction of the Baroque truss in the St. Mary of the Assumption Church in Vranov nad Dyjí, Czech Republic. The particular acoustic devices did not always provide similar results. However, brown rot and other inner damages in fir beams, located closer to their endings situated on masonry and connected with rafters, were determined with all acoustic devices. The possibility of indirect prediction of the strength, elasticity and hardness of the historical wood by means of the acoustic method was verified by correlation analyses, however, not seldom without higher significance. Generally, the results obtained indicate that it is not possible to fully rely on in situ acoustic methods for inspection of defects in wooden elements of historical structures, and therefore they should be combined with visual inspection and some other instrumental method(s).

1. Research aims

Detection of inner decay and other damage in wooden elements of historical structures is an important task to enable their reconstruction. Study of the sensitivity of selected acoustic nondestructive techniques (NDT) in localization of damage in old joining beams at various distances from their visually damaged ends and correlation of these in situ analyses with mechanical properties of wood determined in vitro should give a realistic view on the use of acoustic techniques for inspection of wooden monuments.

2. Introduction

Historical timber structures are frequently exposed to environmental conditions which result in their damage by abiotic and biological agents–temperature and moisture gradients, water with aggressive chemicals, sunlight, insects, wood-destroying fungi, moulds, etc. [1–3]. Some types of damage are detectable and quantifiable in extent and degree through preliminary visual survey by the naked eye using only simple instruments [4,5]. These results can be classified by convenient ratings, e.g. by Italian standard UNI 11119: 2004 [6]. The findings achieved at preliminary inspections are important to evaluate the integrity and mechanical performance of the historical timber structures needed for their stabilization, and also before their detailed survey and the complex restoration [5].

During visual inspections of timber structures, there some types of rot, insect damages or other failures in the inner parts of wood elements that can remain more or less hidden. Therefore, in practice, the in situ diagnoses of biodamages, cracks, or other defects in roofs, ceilings and other wooden structures are preferentially performed by a combination of visual methods [7,8] with selected instrumental nondestructive (NDT) or semi-destructive (SDT) techniques [4,9–15]. When carrying out the assessment of historical wooden elements, their surfaces and inner parts should not be injured (convenient are NDT), or the injuries should be reduced to a minimum (convenient are also SDT–e.g. the resistance drilling or pin penetration devices [16]).

From among the NDT, usually the ultrasonic and other acoustic methods are used for the analysis of timber structures [17–21]. By Marčok et al. [22] or Raczkowski et al. [23], they are also able to determine early stages of wood damage. Acoustic methods are simpler, quicker and cheaper in comparison with other NDT, e.g. the radiographic, microwave, thermographic, molecular or computer-tomographic ones [15]. The ultrasonic measurements can on the whole detect the location and degree of failures in the ends and

* Corresponding author.
E-mail address: reinprecht@tuzvo.sk (L. Reinprecht).

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Table 1
Basic visual characteristics of the old fir beams I–VII (see Figs. 1 and 2).

Beam I (Fig. 2a)
Length of 75 cm–7 measuring positions
Outside: brown rot and network of woodworm holes. Brown rot located in the lower side to a depth of 3–6 cm and length of 0–18 cm from the end
Inside after splitting: brown rot near the mortise made near the rafter fit from positions 1 to 2–3, reaching up to position 4
Beam II (Fig. 2b)
Length of 130 cm–12 measuring positions
Outside: minor decay damage and a network of woodworm holes
Inside after splitting: severe inner brown rot and insect galleries between positions 1–7
Beam III (Fig. 2c)
Length of 100 cm–9 measuring positions
Outside: slight brown rot to a depth of 0.5–2 cm, located in the lower side to a length of 15 cm from the end, and also woodworm holes
Inside after splitting: less serious local inner rot around the position 1, near the mortise for the rafter
Beam IV (Fig. 2d)
Length of 80 cm–7 measuring positions
Outside: brown rot to a depth of maximally 2 cm, located in its lower side near the position 1 end, and in addition, woodworm holes
Inside after splitting: Mild inner rot at position 1
Beam V (Fig. 2e)
Length of 130 cm–12 measuring positions
Outside: severe rot from the lower side (i.e., where it was fitted to the masonry) at positions 1–4, and also woodworm holes
Inside after splitting: severe inner brown rot and insect galleries between the positions 1–6
Beam VI (Fig. 2f)
Length of 130 cm–12 measuring positions
Outside: a strong rot from the lower side (i.e., where it was fitted to the masonry) in the positions 1–4, and also woodworm holes
Inside after splitting: a significant brown rot and also insect galleries between the positions 1–5
Beam VII (Fig. 2g)
Length of 80 cm–7 measuring positions
Outside: signs of damage by a brown rot and woodworm holes between positions 1 and 4
Inside after splitting: Considerable brown rot and also insect galleries between positions 1–6

The opposite cut ends of beams showed cracks, but usually no signs of rot or insect attack. The drying cracks going to the pith were visible usually across the entire length of beams.

other parts of rafters, jointing beams and other timber members well [24–26]. For example, according to Pellerin and Ross [19], a 30% decrease in the velocity of ultrasonic waves indicates severely decayed wood with an approximately 50% loss in strength. These authors also reported that to find nonhomogenous decay in beams or other structural elements it is better to conduct the ultrasonic measurements in the transversal directions than in the longitudinal one, because parallel-to-grain travel paths of waves can bypass regions of *decay*. The effect of the anatomical orientation, and the type and degree of decay in spruce wood in its air-conditioned state has been studied by Reinprecht and Hibký (2011) [27]. Results of acoustic methods can be used also for an indirect determination of mechanical properties of inspected wood [26,28–30].

However, the classic one-dimensional (1D) acoustic methods are less sensitive in the determination of the type of damage (e.g. are not able distinguish the brown-rot, white-rot, or cracks) and for internal localization of damage in the timber between transducers [31]. When such questions should be answered, a 1D acoustic technique can be combined with the drilling resistance method, i.e., the measurement with the ultrasonic transducers is performed in the centre of the input and output of the Resistograph drill with a diameter of 3 mm [32]. Nowadays, the two-dimensional (2D) and three-dimensional (3D) acoustic devices are used for inspection of historical wooden structures as well, but their application means a prolonged inspection time.

3. Materials and methods

3.1. Fir beams

Seven joining beams (No. I to VII) with a cross-section of 20 × 24 cm and with damaged ends have undergone to visual and acoustic analyses (Table 1, Figs. 1 and 2). These beams, made approximately 315 years ago from silver fir (*Abies alba* Mill.) wood, were taken out in the 2011 year from the Baroque truss in the St. Mary of the Assumption Church in Vranov nad Dyjí, Czech Republic, during its reconstruction. Trees used for beams manufacture were felled between 1696 and 1697, as established with dendrochronological method [33].

Qualitative assessments of beams: (1) in situ preliminary visual, (2) in situ acoustic, (3) in vitro visual for longitudinal cuts, and (4) in vitro of mechanical properties for small samples, were performed for their end parts having lengths of 0.75–1.3 m (Figs. 1 and 2).

3.2. Visual assessment of fir beams

The ends of beams I–VII were more or less damaged by:

- brown rot, e.g., dried-out mycelia of fungus *Antrodia vaillantii* DC. Ryvarden were found in two mortises of beam VII;
- insect galleries caused by woodworms *Anobium punctatum* De Geer and *Hadrobregmus pertinax* L.;
- cracks.

The most important biological damages were located near the ends of beams situated on masonry and connected with rafters (Table 1, Figs. 1A and 2).

3.3. Acoustic measurements of fir beams

The following ultrasound and stress wave devices were used in this study: (1) Arborsonic Decay Detector (ADD), (2 and 3) Fakopp Ultrasonic Timer with triangular (UST$\hat{}$) or cylindrical piezoelectric transducers (UST•), and (4) Fakopp 2D (FAKOPP) (Table 2).

Firstly the end parts of the historical fir beams were conditioned to a moisture content level of 12 ± 1%. The passage of the acoustic waves in beams was established in their radial direction, using 10 cm distance between the measuring positions–from 7 to 12 positions in one beam, i.e., in total in 66 positions–performing four measurements in each position by one acoustic device (Fig. 1B,