WOOD RESEARCH
59 (3): 2014
411-420

VARIOUS NON-DESTRUCTIVE METHODS FOR INVESTIGATION OF TIMBER MEMBERS FROM A HISTORICAL STRUCTURE

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(Received April 2014)

ABSTRACT

The article introduces the non-destructive methods and devices that are used within the research project of Department of Steel and Timber Structures, CTU in Prague. Non-destructive techniques are appropriate for building-historical inspection because the historically valuable material is not damaged by investigation. Some of the laboratory and in situ measurements are described in details. The timber members from the Masaryk Railway Station were used for the tests.

KEYWORDS: Non-destructive testing, historical structure, timber, ultrasonic wave, crack.

INTRODUCTION

Timber, as a structural material, has been used for hundreds years and recently has became popular again, because it is the only real renewable material. It is necessary to assess and monitor its condition as a part of maintenance in old buildings, without any obvious damage because of the cultural value of historical buildings. Timber structures are parts of the whole building and their form was changing within the time and life of the building according to external conditions. Monitoring and assessment of structure condition are an integral part of building-historical inspection (Razím and Macek 2011).

Standardized testing, that defines material properties reliably is unfortunately destructive. Non-destructive testing is more suitable for using in-situ and does not break the compactness of structural components, but it is not covered by standards. The procedure and precision of the results depends also on the person doing the tests because some of the methods are device-dependent and evaluation needs awider overview of the topic. Non-destructive methods are popular for initial diagnosis because historically valuable material is not damaged by the measurement and they provide sufficiently precise information about the material quality at the moment. The results can also reveal hidden defects, cracks and areas of biotic damage. Devices used for non-destructive investigation have generally a few advantages; they are light in weight, easy to transport and handle. Eyesight is the only necessary tool for the use of the basic and oldest method, visual assessment. However, to do it properly the evaluator needs to have years of practice. Non-destructive testing has been used at the Department of Steel and Timber Structures for many years. It has been studied in association with Eurocodes being implemented into system of Czech technical standards. The devices based on sonic and stress waves are the most popular, but also Pilodyn 6J, a device working with material resistance, is very often employed (Dolejš 1998; Kuklíková 2004; Hasníková and Kuklík 2013). Nowadays the possibility of using radiometry for mass density determination is also studied (Pošta et al. 2013).

MATERIAL AND METHODS

Wood has very good acoustic properties and sonic wave propagates well in the material. In fact, sound is a mechanical wave that causes oscillation of material particles. The deformation is elastic and there are no changes in the material structure after the wave passes. Tools based on sonic and stress waves are very popular for the investigation of historical structures.A few tools for in-situ investigation are presented below.

Sylvatest device operates with ultrasonic waves and can determine dynamic modulus of elasticity as one of the mechanical characteristics. The device evaluates the quality of the wood by measuring the velocity of the wave passaging through a structural member. The device is composed of a control box, two conical transducers (a transmitting one and a receiving one) especially designed for timber and a probe for humidity measurement. The source of the ultrasonic wave is an oscillating piezoelectric core in a transmitting transducer. The contact between the transducers and the wood does not imply any transfer viscous medium, but the conical shape allows installing them directly into the mass of the wood. The wave propagates along the element directly from the transmitting to the receiving probe. A surface wave is produced in case of indirect measurements when the transducers are placed on the same element surface. The device records the time t required for the transmission, and knowing the density ρ and the moisture content of timber w it directly determines the mechanical properties of the wood. However, this applies only if the timber is of good quality. If it is not, only the velocity of the ultrasonic waves is the output and mechanical properties have to be calculated manually.

The most important mechanical property, which represents the quality of the material, is modulus of elasticity, the elastic modulus along the longitudinal axis. Static modulus of elasticity is determined from bending tests and is 10 - 15 % lower than dynamic modulus of elasticity obtained from non-destructive testing. Dynamic modulus of elasticity E_d is calculated as shown below in Eq.1, where represents the velocity of the wave. It is established simply according to Eq.2, where L is the distance between transducers.

$$Ed = \rho c^2 \quad (1)$$

$$c = L/t \quad (2)$$

Dynamic, another portable device, uses an acoustic wave to assess the material quality. The stress wave is excited by a hammer blow, which should have a weight of about 1 % by weight of the tested element, on one side and a sensitive microphone records the wave on the opposite side.

The balance is used as one of the supports, so that the element can be weighted. See Fig. 1 for the measurement set up.

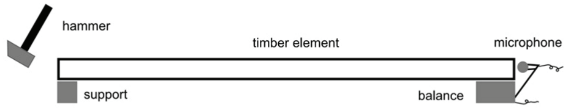

Fig. 1: The scheme of dynamic set up. (Portable lumber grader).

Pilodyn, a device with a steel stick, can assess the material quality using correlation between the depth of stick indentation tp and material strength. The strength is evaluated on the basis of material resistance against penetration indenter (Bláha and Kloiber 2008). The method is semi-destructive, the damage after the measurement is small, visible by the naked eye, but does not impair the function and is still acceptable by officers from National Heritage Institute. The steel pin is pushed against an element surface by defined energy (thanks to a spring with defined stiffness). Timber strength calculation is based on the reading of the penetration depth. The method is local, and therefore it is necessary to do more tests. The relationships are created to evaluate the measurements, taking into account the number and location of holes (Tannert and Kasal 2010). Long experience shows high compliance, using the strength determined by Pilodyn with values determined by standardized destructive mechanical tests. Depth of indentation $t_{p,12}$ (moisture content of 12 %) is a default variable for further evaluation and is calculated according to Eq. 3 Kuklíková (2004).

$$t_{p,12} = t_p(1-0.007\Delta w). \tag{3}$$

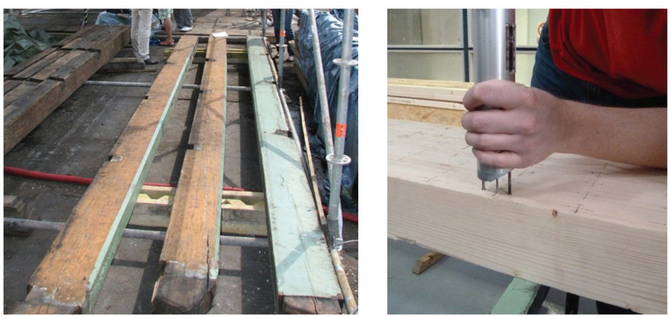

Fig. 2: a) situation on site during in-situ investigation, b) Pilodyn measurement.

Aspecial laboratory experiment was designed to confirm the theory that the presence of surface cracks with transducers installed indirectly significantly prolongs the time of flight of the ultrasonic wave because of longer path. The beams were investigated on both intact surfaces A and B in different distances LI and LII from the intended future crack at first, see Fig.3a. Then the artificial crack was produced gradually with increment of 20 mm and after each step the time was measured in both positions. The maximum depth of crack was 180 mm from surface A. Observation of changes on both surfaces was important from the practical point of view. Sometimes it is not possible to access the bottom surface of the beam in the structure (e.g. it is part of the ceiling). The test should show if the damage of bottom surface is perceptible by ultrasonic testing from the opposite surface. In the experiment the bottom surface was simulated through surface A and the accessible surface was stimulated through surface B.

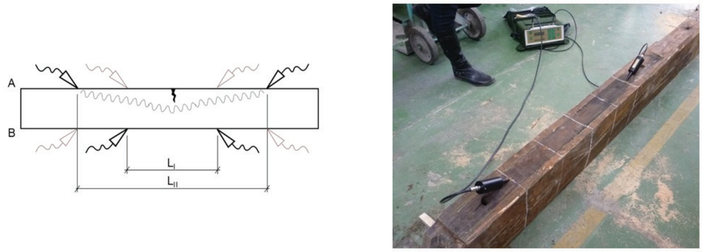

Fig. 3:a) Scheme of the concept of the experiment, b) set up of the experiment.

All the samples both for in-situ and laboratory investigation were originally built-in in the historical structure of a railway station from 19^{th} century. Within the construction the local timber, typical for the Central Europe region, was used – a spruce and a fir. The species of laboratory samples were determined by their microstructure with the help of an optical microscope. The main identification key is the resin canal, which is present in the spruce wood whilst it is not in the firwood, see Fig. 4.

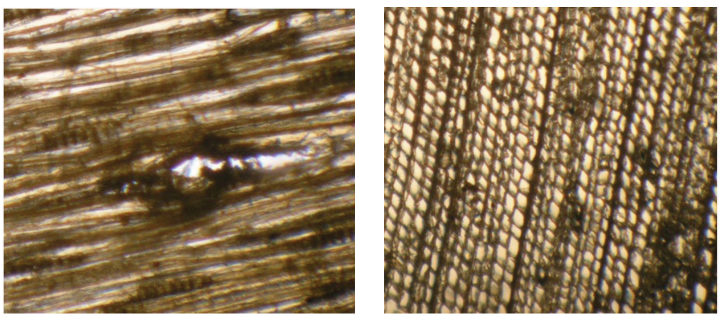

Fig. 4: Wood anatomy of the investigated structural elements; a) detail of a resin canal of spruce (Picea), b) cross section of fir (Abies), © ITAM AS CR.

The species have been confirmed by dendrochronological dating when the age of the structural members used as laboratory samples was determined. Dendrochronology can, in specific cases, provide the year in which the tree was felled. It is the tool for investigation of a structure history and its evolution. Analysis is normally done by measuring tree-ring width on the cross section (end grain) of the timber. The width of the tree-ring depends on the climate and geology in the area. Therefore, an assumption that the same species growing in the same area during the same time period should produce similar sequence of tree-rings has been established (Pignatelli 2010). The width of ring is measured, chronologically, in the laboratory by using specialized equipment and the tree-ring curve is synchronized with standard tree-ring curve that is absolutely dated. Time Table device was used for tree-ring width measurement. Tree-ring curves were compared to each other and relatively synchronized, see Fig. 5. The final dating was made by the software PAST; standard tree-ring curve of fir in Bohemia (je-ce05 - 1131 – 1998) and standard tree-curve of spruce in Bohemia (sm-ce05 - 1151 - 2002) were used. Four structural members were tested and an average tree-ring chronology identified the year of the tree felling as 1866 for the fir and 1847+ for the spruce (Kyncl 2012).

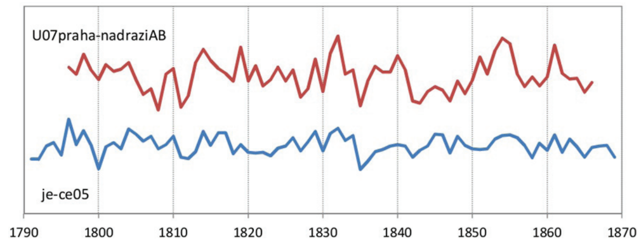

Fig. 5: The synchronization of the tree-ring curve of the fir from the Masaryk Railway Station with a standard tree-ring curve of fir in Bohemia (Kyncl 2012).

The original timber members used as samples served as timber trusses and subpurlins in the structure for more than a hundred years, see Fig. 6. The samples tested in-situ were chosen by the contractor company in advance according to the deformation. They were supposed to be the most preserved ones.

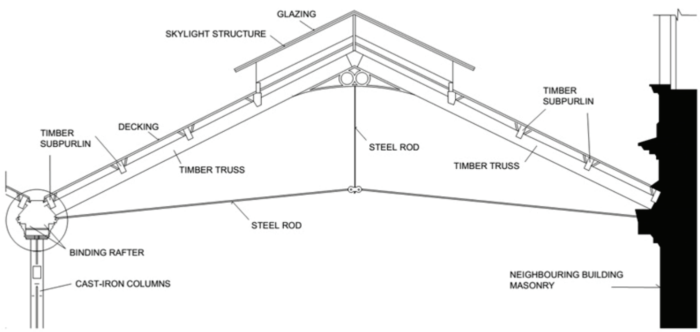

Fig. 6: Scheme of a vestibule roof structure of the Masaryk Railway Station in Prague.

The Masaryk Railway Station in Prague is the oldest still operating terminal railway station in Europe. Its origin is related to the expansion of the Emperor Ferdinand Northern Railway from Vienna via Přerov, with branches to Brno and Olomouc. The construction under the leadership of the engineer Jan Perner tooknine months in 1844-1845 and 4000 workers were involved in it. The architect Antonín Jüngling designed the railway station buildings in the classicist style. The area between the buildings was roofed in 1862 and its extension with cast-iron elements in 1879 (Zídková 2011). The structure endured a few difficult situations; the worst damage of departure hall roof was caused by massive fire at the end of World War II (Vašek and Šťastný 2011). The Masaryk Railway Station is a historically valuable, hence the condition of the structure was investigated in situ before the large-scale reconstruction of the vestibule in 2011. As a result of the testing, a recommendation was to be made whether or not it was desirable to re-use the historical material. Conservation of the original material was desirable from the cultural heritage point of view.

RESULTS AND DISCUSION

Dimensions of the tested structural members were 100 x 230 x 4000 mm, generally. The ends of the structural members were locally damaged but in general the timber along the beams was sound. The dimensions and the weight of the elements have been measured in order to calculate the bulk density ρ. Sylvatest was the most important device for the investigation. Tab. 1 below shows the procedure of the calculation of dynamic modulus of elasticity in-situ step by step. Tab. 2 shows how Pilodyn tests have been evaluated. Four tests were made on each sample, two holes on each end, and moisture content w was measured in those locations; the average value considering Sylvatest measurement was used. Formulas used for further calculations are described in detail in (Kuklíková 2004) and contain many special coefficients. The final modulus of elasticity is the result of statistical evaluation and represents the five percent quantile, i.e. it has to be much lower than the one from ultrasonic test.

Tab. 1: Procedure of Sylvatest measurement.

Structural member	Dimensions			SYLVATEST							E (GPa)
	b (m)	H (mm)	l (mm)	L (m)	T (°C)	w (%)	t (μs)	0.5*m (kg)	ρ (kg.m^{-3})	c (km.s^{-1})	
VK-1-3-P	98.3	232.0	3820	3.00	26.0	13.4	533	16.540	379.6	5.63	12.0
VK-4-6	147.3	240.0	3820	3.00	27.0	14.1	531	19.620	290.5	5.65	9.3
VK-9-6	100.0	229.7	3820	3.00	27.0	18.0	542	17.880	407.6	5.54	12.5
VK-15-5	103.0	235.3	4310	4.00	27.0	13.5	713	16.800	321.7	5.61	10.1
VK-19-6	97.7	233.3	3820	3.00	28.0	18.0	548	16.270	373.8	5.47	11.2

Tab. 2: In situ data from Pilodyn measurement and final result.

Structural member	Depth of indentation t_p (mm)			w (%)	$t_{p,12}$ (mm)	$E_{stat,05}$ (GPa)
VK-1-3-P	12.0	14.0	13.1	15.1	12.8	6.8
	10.0	16.5				
VK-4-6	17.0	15.0	15.5	13.9	15.3	3.1
	14.0	16.0				
VK-9-6	13.0	14.0	14.3	19.4	13.5	5.7
	15.0	15.0				
VK-15-5	14.0	14.5	14.1	15.5	13.8	5.3
	12.0	16.0				
VK-19-6	15.5	13.0	13.8	17.5	13.2	6.2
	15.5	11.0				

The experiment with the crack depth showed that the surface damage significantly influences the results of ultrasonic tests. With increasing depth of the crack, the time of flight of the wave extends, but only on the surface where the crack occurs (surface A). The time is an input for speed and the dynamic modulus of elasticity calculation. The measured data isin Tab. 3 and graphical confirmation of measurement on both surfaces is on Fig. 7.

Tab. 3: Record of the measurement during increase of the crack depth.

Depth of crack (mm)	t (μs) A	t (μs) B	c (km.s^{-1})	E_d (GPa)
0	106	103	5.660	11.214
20	108	103	5.556	10.802
40	123	103	4.878	8.328
60	143	104	4.196	6.162
80	178	104	3.371	3.977
100	195	103	3.077	3.314
120	294	103	2.041	1.458
140	314	103	1.911	1.278
160	342	103	1.754	1.077
180	380	101	1.579	0.873

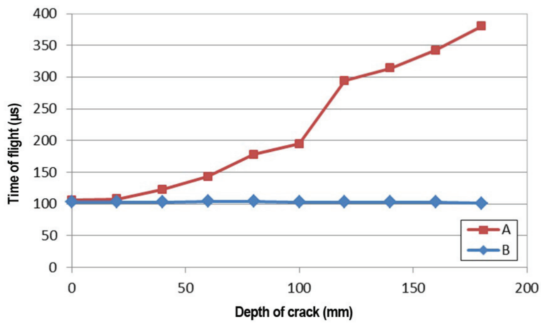

Fig. 7: Scheme of a vestibule roof structure of the Masaryk Railway Station in Prague.

The article shows the possibilities of some of the non-destructive testing that can be used for investigation of historical structures. Popular ultrasonic devices are very useful for in-situ preliminary measurements but it is important to do the measurement properly. Even the small crack influences the result of modulus of elasticity noticeably; the deeper crack is the more significant the decrease of mechanical property is. Not all the damages and heterogeneities can be detected; accuracy depends on the set up of the experiment as shown on Fig. 7. Pilodyn device gave the same results as the ultrasonic tool relatively; the less resistant beam was identified by both of them. The acquired data are valuable because of the material used for the beams.

CONCLUSIONS

The non-destructive testing methods are very useful for preliminary investigation as shown above. The received data can approximate the mechanical property quite well, but to evaluate it in the right way much experience is needed. Each device is unique so a comparison with the results of other researchers can be discussed further. However, long-term monitoring using the same device by one experienced team is very appropriate and the results are reliable.

One of the factors was shown in detail. A surface crack influences ultrasonic tests significantly when present on the same surface as the transducers. However, it is not detectable from the opposite surface of the beam. The other in-situ measurement results showed that some of timber structural members from the Masaryk Railway Station in Prague could no longer meet the requirements prescribed by current standards. They could not long erbea part of the structure, despite the wishes of the conservationists, and could not be re-used without additional and expensive reinforcement. Therefore, only the highest-quality elements were selected, which were re-used, and the rest of the elements were replaced by new elements of glued laminated timber.

ACKNOWLEDGEMENTS

The support of this research by the Czech Ministry of Culture (NAKI project No. DF12P01OVV004) is gratefully acknowledged. The authors would also like to thank the Institute of Theoretical and Applied Mechanics AS CR and DendroLab Brno for their help with species determination and dating.

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