Moisture content and its influence on glued timber structures

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Abstract. The glued timber structure is well-known worldwide engineering product nowadays. Extensive knowledge of wood structure behavior has been as important basic to create new design projects. This paper presents the issue of determining moisture content (MC) in load-bearing glued wood structures, depending on a value of indoor relative humidity and temperature. There are two ways to study timber moisture content – calculation (manual or in programs) and measurement methods. This ways complement each other. Each of methods is more or less suitable for monitoring of structural elements or not suitable at all. Graphs, tables or 3D models of timber moisture content distribution in structure are can received using these methods. Two simple equations to determine timber moisture content are given in the paper. Besides, effect of timber moisture content on durability properties of wood structure is describes there.

1. Introduction

Traditionally, wood has always used as the most common building material in Russia (figure 1). The research in production, design and application of glued timber constructions have carried out in Russia and foreign countries since the beginning glued wood technology. However, because of the new trend towards concrete and metal structures, number of timber developments and research have decreased significantly in my country nowadays. Many objects with using glued timber have been built. These are sports buildings, aqua parks, swimming pools, storage, hangars, residential, and other public and industrial buildings. Despite the extensive database has been obtained during XX – beginning of XXI centuries, the glued timber is still not fully understood. Glued wood constructions are composite technological engineering product which is being improved by scientists and engineers. Such studies should go on in Russia along with like research in other countries.

Glued timber structures are developing and gaining more popularity in the world. The wood timber production was more that 1 million m$^3$ in Germany in some years, according to [1]. About 66% of sports buildings and 25% of pavilions was built with using glued timber structures in Germany and in Switzerland as of 2006 [2]. The building projects with glued timber are implemented or plans for low-rise and high-rise residential, public and industrial construction in Canada, the USA, Australia, Japan, Scandinavia and Europe countries.

Analysis of some building accidents [3, 4, 5] demonstrated that the most common reason for a glued wood structures collapse is human factor in design, construction, choosing materials and operation. Shortage of knowledge about glued timber structures is more often cause of human errors.
The Structural Health Monitoring (SHM) is one of the modern and sensitive methods to studying and predicting structure behavior. SHM system is usually installed for the operation and management phase and sometimes for the construction phase. SHM system requires theoretical and practical knowledge about a monitoring object to obtain necessary and sufficient dates. Timber structure moisture content is the important physical property which influence on structure durability properties. The most common reasons for cracks in structural timber elements associate with shrinkage (low timber moisture content), swelling (high timber moisture content) and wood MC fluctuation (changing surrounding climate) [3, 4]. That is why moisture content is included in a monitoring program for timber structures [6].

![Figure 1. Church of the Transfiguration, Kizhi Island, 1714. Part of the World Cultural Heritage UNESCO “Kizhi Pogost”. Photo: kizhi.karelia.ru](image)

There are some methods to determine wood moisture content: measurements with using sensors and devices and calculation methods. Destructive methods, such as the oven-drying (kiln-drying) method, is not suitable for monitoring on the operation phase.

Limit values of each controlled parameters are created for automated SHM system. It may be boundary values of loads, structure deformations or physical parameters. As a boundary value of timber MC can be considered 20%-30%. If moisture content is permanently higher than 20% MC, fungal growth and organic destruction cannot be ruled out. This rule is true for structures are located in heated rooms. Timber moisture content can also be used to correct boundary values of structure reliability parameters.

2. Calculation methods to determinate timber moisture content
When timber construction keeps long enough in a room with constant combination of air temperature and relative humidity, the timber MC become a constant. So, this value is named Equilibrium Moisture Content (EMC). That is, structure moisture content has come into equilibrium with heat and humidity parameters of the environment.

There are handbooks and normative documents which contain EMC diagrams for practical use. Such diagrams obtained from studies of small wood samples by prof. Franz F. P. Kollmann (Germany), prof. Pavel S. Sergovsky (Russia) and others. For example, figure 2 demonstrated two diagrams, one of them (figure 2, b) is taken from Russian Set of Rules “Timber Structures” (SP 64.13330.2017).
Figure 2. Equilibrium moisture content of wood. a) from Wood handbook [7], b) diagram of prof. Pavel S. Sergovsky

The following equation (1) determines EMC [7]:

\[
EMC = \frac{1800}{W} \left( \frac{Kh}{1 - Kh} + \frac{K_1 Kh + 2K_1 K_2 K^2 h^2}{1 + K_1 Kh + K_2 K^2 h^2} \right)
\]

where \(h\) is relative humidity (decimal) and factors \(W, K, K_1, K_2\) depend on air temperature:

\[
W = 349 + 1.29T + 0.0135T^2;
\]

\[
K = 0.805 + 0.000736T - 0.0000273T^2;
\]

\[
K_1 = 6.27 - 0.00938T - 0.000303T^2;
\]

\[
K_2 = 1.91 + 0.0407T - 0.0000292T^2;
\]

\(T\) is air temperature, °C.

EMC can be calculated with one else equation (2) is taken from papers of Swedish university [8]:

\[
EMC = \frac{125}{5 + (t_1 + t_2)}
\]

where \(W_p\) is EMC (%), \(t_1\) is dry-bulb temperature and \(t_2\) is wet-bulb temperature.

3. Measuring methods to determinate timber moisture content

The device measuring electrical resistance – resistance moisture meter (resistance method) allows for determine timber MC without damaging timber structure. It may be useful if necessary to carry out a building operation or inspection. Wood electrical resistance decreases with increasing MC because water has electrical conductivity much more than wood conductivity. Destruct of the construction is slightly with using resistance method – two small electrodes are rammed into the timber construction to the defined depth of section (figure 3). Resistance moisture meter calculates the current MC based on correlation between electrical wood and water resistances. Timber density and temperature influence on measuring. This method provides an acceptable accuracy (1%) for timber MC from 6% to 20% and suits well for monitoring systems [6].
Another measuring instrument is based on the determination of wood dielectric constant using electromagnetic waves (dielectric/capacitive method). It determines only the average moisture content on the surface of structure, excluding the moisture gradient in the section unlike resistance method. Density, temperature of construction and voltage frequency are the main influences on measurements. This method provides accuracy of 1-2% for timber MC between 2% up to the fiber-saturation point (~30%). Dielectric method usually is used for monitoring of flat elements such as panels or boards.

4. Analyses of the methods
Equations (1) and (2) was created based on experimental measurements of selected wood samples. Moisture content gradient over a large cross section of timber structure element is not taken into account in equation (1). As practical experience shows, elements of wood structure seldom have equilibrium moisture content with ambient air parameters under real conditions of dynamic changes in temperature and relative humidity [8]. For example, if wood equilibrium MC at a given surrounding air temperature and RH will be reached by drying (in a heated room) but not by gaining moisture, maximum error in equation (1) is 3% [9].

Measuring methods are more accuracy for determination actual moisture content than calculated. But measuring methods also have a something error; temperature, structure density, voltage frequency, immersion depths in construction affect measurements. Besides the methods listed in Section 2 there are also microwave, sorption, spectrometric and others [6]. Each of them is more or less degree suitable for monitoring of structural elements or not suitable at all. When you plan monitoring system, it is necessary to provide suitable locations for installation of measuring sensors and correctly determine the minimum and sufficient number of sensors.

Results of the one and a half years period of the moisture content monitoring for law wood and glued laminated timber open structures are presented in [10]. The graphical results from [10] one else confirm there is the structure MC dependence on air temperature and relative humidity. Two values of moisture content were calculated according to equations (1) and (2) for the peak of RH and temperature (figure 9a [10]). Results equal 15, 45% and 14,26%, respectively. These results, determined by the calculation, are within between the values of moisture content for traditional wood building and moisture content for glued timber building (figure 8a [10]) and closer to the second value for glued timber structure (14%) than to the solid wood moisture content (18%).

So, any of the methods for determining MC has a certain error. It is better to use several methods to obtain the most reliable result.

5. Effect of timber moisture content on the reliability properties
Timber moisture content changing affects a change in majority of elastic and mechanical timber properties such as elastic modulus, spalling, tensile, compressive strength parallel or perpendicular to
grain and bending strength. The material elastic and mechanical properties, in turn, define safety of structure work.

Relationship between timber moisture content and reliability properties of wood has studied in laboratories on samples of pure wood. According to the results of researches graphs and equations were obtained, for example represented in [7, 11]. The same picture is observed in all studies, - timber MC has received the fiber-saturation point (25-30%, depending of wood species) with decrease of timber MC by kiln-drying. After this point timber reliability properties have increased in a curvilinear relation. Information about “MC-reliability properties relationship” is applied during lumber processing on timber factories included glued timber production. You can see clearly the dependence of basic reliability properties from wood moisture content on the graph below (figure 4) [7].

It will be reverse process of mechanical and elastic properties decreasing during water logging, accordingly. However, a strong water logging is unlikely for large cross section of structures which is located inside heated building. Humidity increasing above a design value may be result of fluid leaks, direct leaks or water evaporation as well as internal microclimate that differ from a project.

Another, more common hazard is emergence and crack propagation in structures. Appearance of cracks causes internal stress due to irregular distribution of moisture content in the cross section or due to ambient air temperature and relative humidity jumps.

![Figure 4. Effect of moisture content on wood strength properties. A, tension parallel to grain; B, bending; C, compression parallel to grain; D, compression perpendicular to grain; and E, tension perpendicular to grain](image)

To predict or determine the ambient properties of a timber structure the calculation methods, measuring methods, graphs or models which is described using finite element analysis software such as ANSYS, ABAQUS [12] and others can be used.

6. Conclusions

Thus, information about relationship timber moisture content, structural mechanical properties and environmental air properties can serve as a support for designing, construction management, production management (including drying process, storage, transportation to construction site). In addition, it promotes a better understanding of material (glued timber) behavior and importance of taking into account material physical properties when material is used for building.

For structure normal operation the limiting values of the structure deformation, for example, deflections, should be automatically changed depending on structure condition.
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