Estimation of wooden coefficient of expansion due to temperature and moisture with geodetic sensors

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Abstract

At the University of Stuttgart an adaptive shell structure, called Stuttgart SmartShell, was developed to investigate the behaviour of adaptive shell structure due to the load-bearing. This shell structure is made out of timber and its shape varies due to swelling and shrinkage phenomena. Some reasons for shrinkage and swelling are the influence of the meteorological effects. Changes of shape or isolated part changes may lead to a variation of the structural behaviour. The factors should be considered during the calculation of load-bearing. That means, with a precise knowledge of the influence of meteorological effects, the load on each support could be calculated and minimized by moving the adaptive supports to the position with minimal load.

In a first investigation, the behaviour of timber, here spruce, determined by temperature and humidity is investigated in laboratory conditions. The first step is the investigation due to temperature. According to the literature this influence is very small, so a laser tracker is used. A wooden plate is measured six times while the temperature varies between -20°C and +40°C. The results of the test show that no shrinkage and swelling due to the temperature is detectable in a tangential, parallel or radial direction to the fibre.

The influence of humidity is, on the other hand, much stronger. For that reason the laser scanner can be used additionally. The shape of the plate is measured while the plate's moisture changes from 1% to 8%.

The next step will be testing the influence of shrinkage and swelling due to the structural behaviour of wooden plates during load tests. With the result of that test, the changes of the E-Modulus of wood caused by meteorological effects should be detectable.

Key words: laser scanner, laser tracker, timber, expansion coefficient

1 INTRODUCTION

The construction industry, as well as all other kinds of industries, is searching for renewable and eco-friendly materials. Since a long time, wood is used as a renewable and eco-friendly material in the construction industry. Due to the fact that wood grows over a long time, the resources of wood have to be treated gently. For that reason lightweight building methods are developed and investigated. At the University of Stuttgart different research groups are working on this topic. One result of this work is a wooden ultra-lightweight shell structure, the Stuttgart SmartShell, developed by the Institute for Lightweight Structures and Conceptual Design and its partners. The special property of this shell structure is its adaptivity. Due to the adaptivity it is possible to homogenize stress distribution, reduce peak stresses and damp vibration actively (Neuhaeuser et al., 2013). This leads to an increase of the life span of the system. The Stuttgart SmartShell is a 10 m x 10 m double-curved prototype of an adaptive shell structure, shown in Fig. 1. Three of its four support are adaptive and it is made of spruce and fir multilayer laminate.

Due to the behaviour of wood, which is a living material, the structure and also the loads of Stuttgart SmartShell are changing over the time. The reasons for the changes are environmental influences as well as aging. In former investigation the current shape of the Stuttgart SmartShell was compared with the CAD models (Poptean et al., 2016). Not yet published investigations show the changes of the shape of Stuttgart SmartShell over three years. This paper shows a method of how geodetic sensors like laser scanner and laser tracker could be used to observe the impact of environmental influences on wood. Several spruce plates of about 15 cm x 40 cm x 1-2 cm are used in this study. In the future, the environmental influences due to loads on wood should be investigated and the Stuttgart SmartShell support position given by the behaviour of wood, according to climate influences like moisture and temperature should be optimized.

Fig. 1 Stuttgart SmartShell ©Bosch Rexroth

2 PROPERTIES OF WOOD

As already mentioned, wood is a traditional building material. Due to the fact that it is an organic material it has several properties which have to be considered while building with wood. Wood is anisotropic, that means that influences on the wood have different effects on each individual axis of the structure. The axes of wood are defined in dependence of the fibre of wood. In

Fig. 2, the three directions are shown. Besides, earlywood and latewood bands do have their influences to the material properties of wood. Earlywood cells arise in springtime, when the trees are growing fast. They have a lower density and thinner walls, compared to the latewood cells, which are growing slower and later the year (Hunt & Gu, 2006).

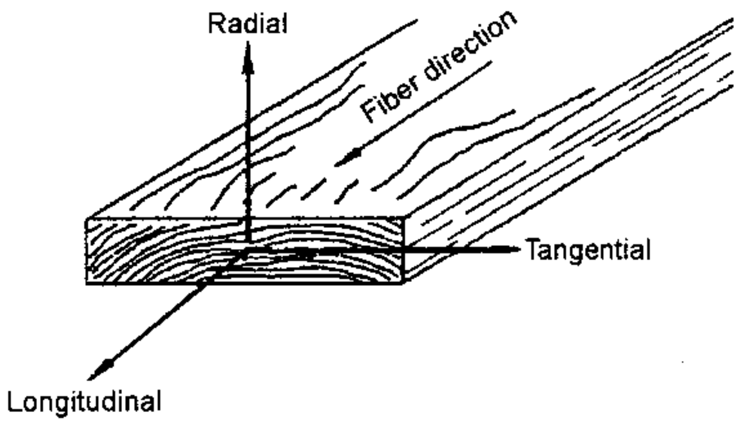

Fig. 2 Axes of wood (Hunt & Gu, 2006)

Due to the cell structure, wood may absorb water and the cell walls grow according to the influence of temperature. The behaviour of wood is investigated since a long time therefore expectancy values for the moisture and thermal expansion are available (Kollmann, 1951). The differential shrinkage values are given as relative change in length per 1% moisture change and the thermal expansion coefficient is defined as the relative change in length per 1°K. They are shown in Table 1 for spruce.

Table 1 Thermal expansion coefficient and differential shrinkage values for spruce (Weatherwax & Stamm (1956), Gesamtverband Deutscher Holzhandel e.V.(2017))

	Radial	Tangential	Longitudinal
thermal expansion coefficient (tec)	$23.8 \cdot 10^{-6}\,K^{-1}$	$32.3 \cdot 10^{-6}\,K^{-1}$	$3.15 \cdot 10^{-6}\,K^{-1}$
differential shrinkage value (dsv)	$0.16 \cdot 10^{-3}\%^{-1}$	$0.33 \cdot 10^{-3}\%^{-1}$	$0.01 \cdot 10^{-3}\%^{-1}$

3 TEMPERATURE INVESTIGATION

The behaviour of wood caused by temperature is investigated with the help of a Heraeus Vötsch VM08/500 Climate Chamber. The tested spruce plate has a size of about 15 cm (radial) to 40 cm (longitudinal) to 2 cm (tangential), with respect to the coordinate system showed in Fig. 3. The wooden piece is cooled down to -20°C and then heated to +40°C in three circles. Each circle takes about 48 h. Firstly the piece is cooled for 24 h, followed by a heating period of 24 h. For the measurements with the laser tracker, the wooden piece is removed from the climate chamber for about 15 to 20 min. Before the measurement starts, the wooden piece was weighed, to check if the moisture content is stable.

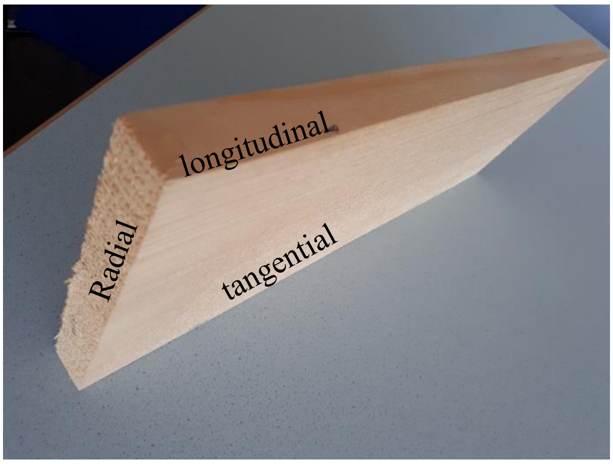

Fig. 3 Example of the used wooden plates

For these measurements, the laser tracker API Radian is used together with a spherical mounted reflector (SMR) in the scanning mode. Each side of the wooden piece is scanned. The data is processed in the software CloudCompare. First of all, outliers are deleted manually and a statistical outlier filter (SOF) is used to delete the outliers which are not detectable manually. From the cleaned point clouds, Delaunay 2.5D (best fitting plane) meshes are calculated and compared with a Cloud to Mesh – Comparison (C2M) tool. To determine the average deformation between the two epochs the average distances between the sides are subtracted.

Referred to the literature, for example Kollmann (1951), the expectancy values in all three directions of wood could be calculated and compared. On basis of the thermal expansion coefficient α_{tec}, given in Table 1, the expected expansion could be calculated according to Kollmann (1951) as followes:

Radial: $$dl_r = l_r \cdot \alpha_{tec_r} \cdot d\vartheta = 0.214 \text{ mm} \quad (1)$$

Tangential: $$dl_t = l_t \cdot \alpha_{tec_t} \cdot d\vartheta = 0.039 \text{ mm} \quad (2)$$

Longitudinal: $$dl_l = l_l \cdot \alpha_{tec_l} \cdot d\vartheta = 0.076 \text{ mm} \quad (3)$$

where the difference in temperature is $d\vartheta = 60°C$ and l is the length of the corresponding plate side. It is expected that for an increase of temperature, the wood will expand and for a decrease of temperature the wood will shrink.

The API Radian offers a 3D-point position accuracy of 0.05 mm. Consequently, the threshold from a two-sided test with $y_{0.975} = 1.96$ and for significant deviations between the point clouds is:

$$d = \sqrt{2} \cdot 0.05\, mm \cdot y_{0.975} = 0.139 \text{ mm} \tag{4}$$

considering that the deviations are normal distributed. That means that only the radial distortion is detectable. Table 2 shows the deformation of the plate in radial direction. Due to the measuring accuracy, all average deformations are significant. In a second statistical test, the significance of the deformation according to the standard deviation is calculated. The standard deviations are between 0.160 mm and 0.377 mm. The student distributed test quantile of the statistical test for the deformations is given by $y_{0.975} = 1.96$, that leads to the following equation:

$$u = \frac{d}{\sqrt{s_1^2 + s_2^2}} \tag{5}$$

In Table 2 the test qualities of the single tests are also given. None of the tests is significant, which leads to the conclusion that the deformation caused by temperature is theoretically detectable, but not by using this kind of measurements procedure.

Table 2 Radial deformation due to temperature

	-20°C to +41°C	+41°C to -20°C	-20°C to +41°C	+41°C to -19°C	-19°C to +40°C
Radial	-0.517 mm	-0.288 mm	0.239 mm	0.196 mm	-0.175 mm
Test size u	1.86	0.66	0.55	0.71	0.63

4 HUMIDITY INVESTIGATION

4.1 INVESTIGATION BY LASER TRACKER

The moisture content of wood is influenced by the humidity based on absorption. The humidity influence investigation is conducted in a self-made climate chamber of the Institute of Computational Design. This time, four different wooden plates are used. Two of the four plates have the same size like the one used for the temperature investigation. The other two have a tangential expansion of 11 mm. The first 65 hours, the wooden plates are stored in the climate chamber with a humidity of 92%. Their geometry is measured before the storage, after 22 hours and after 65 hours. After 65 hours of high moisture, the humidity in the climate chamber is decreased. After 27 hours the humidity declines to 26% and after 50 hours the humidity inside the climate chamber reaches 14%. Measurements are acquired after 27 hours and after 50 hours. During the measurements with the laser scanner and the laser tracker, the plates are outside of the climate chamber. The measurement takes about one and a half hour for each of them. The change of moisture content of the wood is documented by weighing the plates.

For the comparison based on laser tracker data, the same procedure described in section 3 is applied. Former investigations also offer expectancy values. The maximum expected shrinkage and swelling is calculated according to (Gesamtverband Deutscher Holzhandel e.V., 2017) as follows:

$$dl = l \cdot \alpha_{dsc} \cdot dm \tag{6}$$

where the length of the plate is l, the differential shrinkage values α from Table 1 and the difference in moisture in percentages, which is calculated from the weight of the plates. The expectancy values are given in Table 3. The maximum shrinkage is detected after changing the humidity from 92% to 26%. This decrease of humidity leads to a decrease of moisture content of the plates between 4% and 8%, which causes the minimization of the plates dimensions.

Table 3 Maximum expectancy values for humidity influences

	Plate 1	Plate 2	Plate 3	Plate 4
Max. moisture change	5.1 %	4.7%	7.0%	8.3%
Tangential	0.339 mm	0.309 mm	0.255 mm	0.300 mm
Radial	1.280 mm	1.168 mm	1.752 mm	2.062 mm
Longitudinal	0.235 mm	0.214 mm	0.322 mm	0.378 mm

The results from the evaluated laser tracker data illustrate very well the predicted behaviour of the wood, for example in radial direction, like shown in Fig. 4.

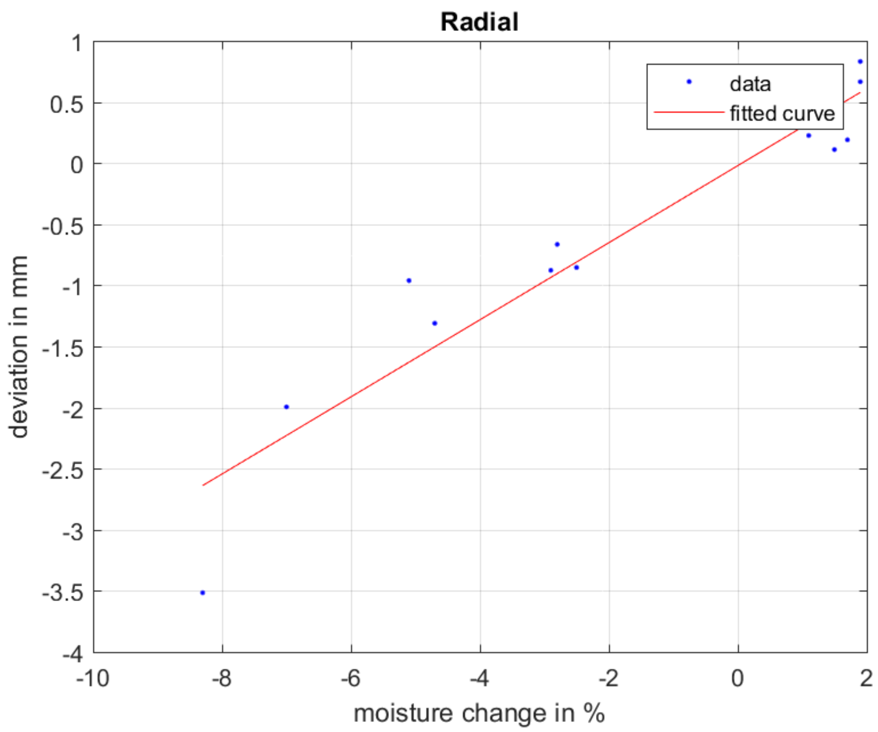

Fig. 4 Deformations due to moisture changes in radial direction

With these results the expansion coefficient of wood due to moisture could be calculated for each measurement as followed:

$$\alpha_{dsc} = \frac{dl}{l \cdot dm} \tag{7}$$

where the average deformation of the plate in each direction is dl and the change in moisture is dm. The average of these results can be used as a common expansion coefficient. The average expansion coefficients and their standard deviation are given in Table 4. In tangential and longitudinal direction, the calculated expansion coefficients are comparable to the ones given in literature. In tangential direction, the calculated coefficient is three times smaller compared to literature specifications. One reason for this difference could be that the expansion of the used plates in tangential direction is with 11 mm or rather 21 mm small.

Table 4 Average expansion coefficients and their standard deviations

	Radial	Tangential	Longitudinal
Average expansion coefficient	$0.110\ \%^{-1}$	$0.144\ \%^{-1}$	$0.011\%^{-1}$
Standard deviation	$0.039\%^{-1}$	$0.049\%^{-1}$	$0.006\%^{-1}$

4.2 INVESTIGATION BY LASER SCANNER

The Stuttgart SmartShell with a 10 m to 10 m ground area offers a perfect environment to monitor objects by laser scanners. For that reason the plates, which are measured by laser tracker are also scanned with the laser scanner LEICA HDS 7000. In this case only the radial deformation is investigated, because the laser scanner does not offer the necessary accuracy to detect the tangential and longitudinal deformation, compared to Table 1.

The two thicker plates used for laser tracking are scanned from two positions to get as much information as possible. The point clouds are registered with the software Leica Cyclone. For comparison, firstly the single sides of the plates are segmented and cleaned in the point cloud. Afterwards the planes of the single sides of the plates are calculated and prepared to be compared. These planes are sampled for the comparison. This time the average deformations are also compared. Table 5 shows the detected deformation due to moisture changes which are measured by the laser scanner. The results present deformations those are greater than expected.

Table 5 Deformation due to moisture change measured with laser scanner

Plate 1		Plate 2	
Moisture change	Deformation	Moisture change	Deformation
1,66 %	0,005 m	1,46 %	0,002 m
1,09 %	-0,010 m	1,44 %	-0,004 m
-5,13 %	0,007 m	-4,68 %	0,004 m
-2,84 %	-0,004 m	-2,53 %	0,001 m

5 SUMMARY AND OUTLOOK

The investigations presented in this paper show the possibilities to observe the impact of environmental influences like humidity and temperature on wood with geodetic sensors. As for the used geodetic sensors, a laser tracker and a laser scanner have been utilized. It has been presented that the influence of temperature is not detectable with these methods. The humidity, on the other side, is detectable with a laser tracker, but not with the laser scanner.

In future works a new measuring concept should be created to observe the temperature influence with the laser tracker. The investigation in relation to humidity shows that it is possible to estimate the expansion value using laser tracker data. To verify the detected values a larger sample of plates should be considered. The laser scanner might be able to detect the radial deformation for larger objects, e.g. the Stuttgart SmartShell.

The detected and verified expansion value for moisture influences has to be further investigated and also verified under loads. With the knowledge about the behavior of the expansion values under loads, the E-modulus and the position of the support of Stuttgart SmartShell could be optimized.

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