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MEASUREMENT OF RESIDUAL STRESSES USING THE HOLE-DRILLING METHOD AND STRAIN GAUGES ON TIMBER MATERIALS

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ABSTRACT: Internal stresses are of great importance in the design of modern machine parts. This applies to metal components in mechanical engineering as well as to wood products. The state of the art is to measure internal stresses in metallic alloys using the hole-drilling method. Wood products, too, are highly stressed components. Therefore, the aim here is to determine the stresses in wood samples using the hole-drilling method. Two types of wood materials are tested for their internal stresses, the first being natural laminated birch wood with up to 3 layers per millimetre. The second material is press laminated beech wood with a layer thickness of 5 mm. The laminated birch wood has a very thin structure and is therefore considered to be quasi-isotropic in an exceptional way. With the help of the hole-drilling method, the stress in the wood can be approximately determined. Wood is not isotropic, but the results show an interesting correlation.

KEYWORDS: residual stress, hole-drilling method, fatigue life

1 – INTRODUCTION

Determining the service life of highly stressed components requires an understanding of residual stresses. Crystalline materials, such as metallic alloys, can be evaluated for these stresses using advanced and standardised methods like X-ray and borehole techniques.

However, the direction-dependent elastic properties of wood material make measuring their residual stresses a greater challenge. This article aims to fill this gap by adapting established techniques used for metallic alloys to measure wood-based materials. In a first step, natural laminated wood and densified solid wood will be analysed.

2 – BACKGROUND

The measurement of internal stresses in metal components is widely used in lightweight design. In the case of aluminium alloys, it has been shown that the stresses introduced during production significantly influence mechanical strength [1], [2], [3]. The effect can easily be 10 to 20%. This has been demonstrated for aluminium and ferrous alloys. By knowing the internal stresses, it is possible to reduce the weight of the components.

X-rays are not suitable for wood materials, so the hole-drilling method is the best way to inspect the component's localised areas. Of course, there are other methods, such as measuring specimens in grips (e.g., the tensile test tractor). However, these studies only provide information about the entire cross-section and cannot measure local stresses.

2.1 EXTERNAL AND INTERNAL STRESSES

Components comprise two types of stresses that are of interest to mechanical engineers. A vital issue for the lifetime of machine components and products is the external loads.

These external loads can be in-service loads, assembly loads or loads from the gravity of the machine component itself. Otherwise, there are the internal stresses or residual stresses that have no external cause. These stresses result from the manufacturing process, such as casting, heat treatment or welding. The residual stresses are not visible from the outside; they invisibly exist in the component

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itself. However, these stresses are important for service strength, as they can lead to the component's early destruction.

There are a number of methods for measuring residual stresses, as shown in Table 1. The two most common methods are X-ray diffraction and the hole-drilling method. A crystalline structure (such as metal components) is necessary for X-ray examinations.

Table 1. Typical residual stress measuring methods.

Common residual stress methods	
Destructive and quasi-destructive methods	**Non-destructive methods**
- Hole drilling method - Bending method - Toroidal core method - Sectioning method	- X-ray diffraction - Neutron diffractometry - Ultrasound method

2.2 MEASUREMENT OF RESIDUAL STRESSES IN METAL PARTS

The crystalline structure of metal alloys means that both X-ray methods and drilling methods are used for this type of material.

The X-ray method examines the internal stress through the physical effect of 'diffraction' on the metallic lattice. Interference measurements of X-rays are used to measure the tension in the atomic lattice, which is then used to calculate the internal stresses. The technology achieves penetration depths of 10 to 30 µm and is non-destructive. Deeper measurements usually require the sample surface to be carefully removed, e.g., by erosion, without introducing new internal stresses.

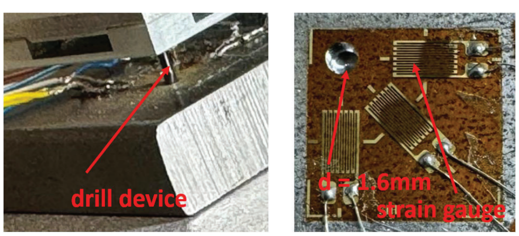

Figure 1. Internal stress measurement with hole-drilling method. Drill in action (left) and drill hole scheme with strain gauges (right).

In addition to X-ray methods, the hole-drilling method is very popular for metal components. There's a reason for that - the process can penetrate a few millimetres into the component. Another advantage is that it is easier to install the measurement equipment outside the laboratory (in the factory or outdoors) compared to X-ray technologies. All that is needed is to attach a strain gauge the size of a postage stamp and drill a small hole (see Figure 1). When the hole is drilled, the residual stresses are released. It is this relaxation that is measured by the strain gauges. A complex linear elastic back-calculation is done to calculate the stresses at the borehole location (before drilling).

2.3 RESIDUAL STRESS MEASUREMENT USING THE HOLE-DRILLING METHOD

The theoretical basis for this method is old and goes back to *KIRSCH* in 1898 [4]. Figure 2 shows the distribution of stresses around a borehole found by *KIRSCH*. It is an analytical description of the distribution of stresses in a flat bar tension specimen. The hole acts as a notch. High radial and tangential stresses occur near the hole and decrease with distance from the hole. This makes it possible to use measured strains next to the hole to determine the stresses in the hole.

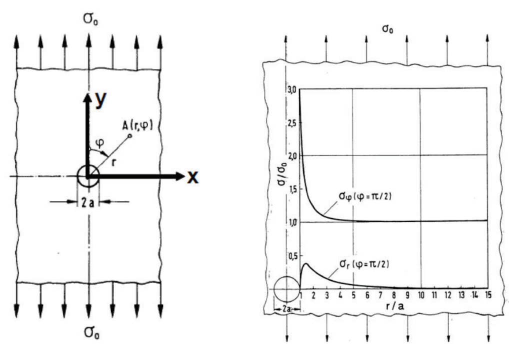

Figure 2. Stress distribution around a circular hole according to KIRSCH [4].

Various scientists have developed the connections found by *KIRSCH*. This has led to the measurement of residual stresses using the hole-drilling method. A state of development is shown by the work of [5] and the ASTM standard [6].

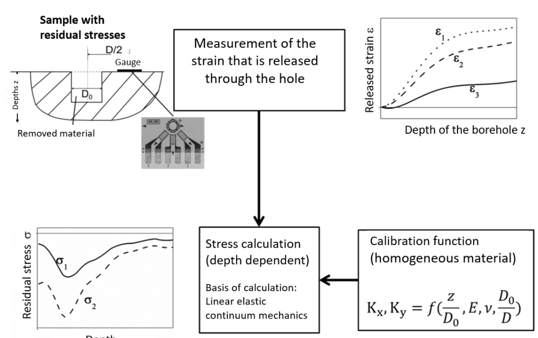

Figure 3. Computer-assisted calculation of the residual stresses. [7] translated from original German.

Today, it is possible to determine the internal stresses as a function of depth. A depth evaluation of the two main stresses and their angular position is possible. Figure 3 gives an overview of the process. Calibration functions

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can be used to improve the results for a variety of component conditions.

The procedure illustrated in Figure 3 is complex. This chapter presents a simplified calculation with easy-to-understand formulas, one that can be especially used for homogeneous internal stresses. This means that the internal stress will remain constant regardless of the hole's depth.

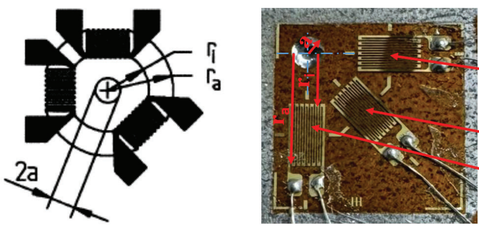

Figure 4. Borehole grid geometry with strain gauge rosette. Drawing (left) [8] and picture of laboratory rosette (right).

Before calculating the stresses, it is helpful to consider the measurement system's geometry. Figure 4 shows the geometric conditions of the borehole rosette with the following parameters:

- hole diameter = *2 a*
- position of strain gauges: ε_c, ε_b and ε_a
- distance of hole to strain gauge r_i and r_a

According to [8], the following equations (1) and (2) can be used to estimate the principle normal stresses σ_1 and σ_2:

$$\sigma_1 = -E\frac{\varepsilon_a + \varepsilon_c}{4A} + \frac{E}{4B}\sqrt{(\varepsilon_c - \varepsilon_a)^2 + (\varepsilon_a + \varepsilon_c - 2\varepsilon_b)^2} \quad (1)$$

$$\sigma_2 = -E\frac{\varepsilon_a + \varepsilon_c}{4A} - \frac{E}{4B}\sqrt{(\varepsilon_c - \varepsilon_a)^2 + (\varepsilon_a + \varepsilon_c - 2\varepsilon_b)^2} \quad (2)$$

Equation (1) and (2) use the coefficients *A* and *B* to consider the material properties (Poisson's ratio ν, Young's modulus *E*) and the geometry of the strain gauge configuration; see Figure 4:

$$A = -\frac{(1+\nu)}{2E} * \frac{a^2}{r_a r_i} \quad (3)$$

$$B = -\frac{2a^2}{E r_a r_i} * \left(1 - \frac{a^2(1+\nu)(r_a^2 + r_a r_i + r_i^2)}{4{r_a}^2{r_i}^2}\right) \quad (4)$$

3 – TYPICAL RESIDUAL STRESSES OF METALLIC PARTS

In the case of metallic components, the measurement of residual stress is often carried out using the hole-drilling method. This is especially so if the results have to consider an over-the-depth gradient to interpret the consequences of the measured stresses correctly. This method is defined in the ASTM 837-20 [6], particularly for metals. Nonetheless, many applications require some flexibility from that norm, e.g., when measuring in-depth of the specimen. The norm states that for a correct use of the incremental 'non-uniform' measurement the thickness of the specimen must be at least 0.6 d, considering d as the effective diameter of a round strain gauge rosette. In practical research, it is possible that not all ASTM standard conditions can be realised, as is the case with the sample thickness in this example. The results must then be checked for plausibility.

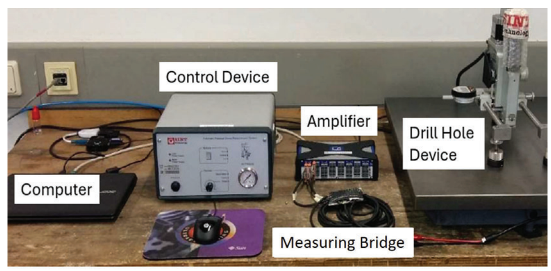

Figure 5. Experimental setup for residual stress measurement with components from SINT.

The measurements in this chapter use the hole-drilling method performed with the SINT MTS-3000 setup. It is a semi-automatic, all-in-one solution for measuring residual stresses in all materials with a homogenous behaviour with respect to their modulus of elasticity. Figure 5 shows the components of this system. The hole-drilling device can perform up to 400,000 rpm using an air turbine combined with a 1.6 mm flat head drill. This combination combined with a very low feed rate of 0.2 mm/min ensures that the process of drilling does not impact the specimen with new stresses. The sensory part of the setup contains a carrier frequency measurement amplifier and measuring bridges for every single strain gauge on the rosette. A rosette with the designation HBM 1-RY61-1.5/120S is utilised. The software is able to perform the calculations for the in-depth steps to produce a typical stress-depth graph, like in Figures 6 and 7. The plausibility of the measurement results was demonstrated in a current research project at Ostfalia University.

These graphs are results of an exemplary measurement on a 2" by 2" Al-6063 T6 square aluminium profile with a material thickness of 10SWG (3.25 mm). The graphics

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illustrate two types of residual stress measurements: first, the 'low' residual stresses resulting from the production of the profile (unloaded); second, the residual stress introduced by plastic deformation (bending). Figure 8 presents a geometric overview of the sample and the measurement setting.

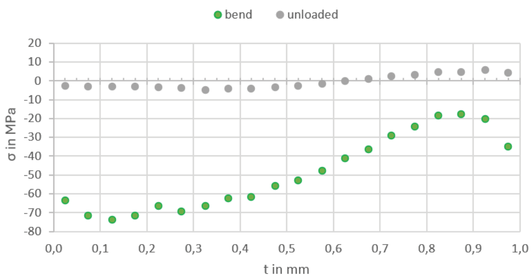

Figure 6. Manufacturing residual stresses (grey values) and residual stresses after plasticisation (green values). t indicates borehole depth.

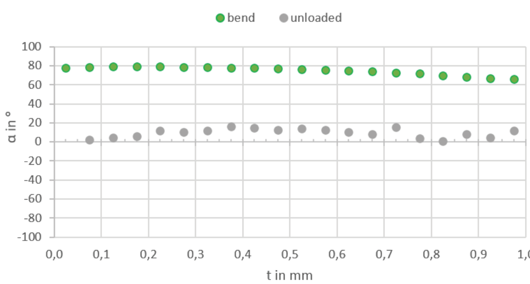

Figure 7. Angular position of the stresses shown in Figure 6.

The typical stresses in such a specimen, if left in their original state, are quite low and lie in the pressing direction. Here, the stress of the unloaded profile is in the single digits, while the angle of the stress vector is coherent with the pressing direction. On the other hand, the bending inflicted stresses around -70 MPa in the direction of the bending force. The convention of the interpretation of positive and negative values results from the strain gauge behaviour, meaning negative stresses are compressive, while positive stresses are tensile. It has to be said that the angle is not to be taken too exactly, since a variation of a few degrees can be the result of a small variation while using the formula containing $\tan^{-1}$.

Measurements on metal parts are state of the art and lead to plausible results. Therefore, stress measurements on wood samples will be performed in the following chapters. The authors are aware that the hole-drilling method is not designed for the anisotropy of wood; nevertheless, they will attempt to use it in this manner.

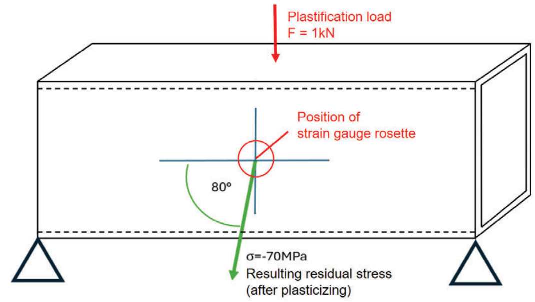

Figure 8. Al-6063 T6 Aluminium profile 50.8x50.8x150mmm (sickness 3.25 mm) with plastification load and resulting residual stress.

4 – RESIDUAL STRESS MEASUREMENTS ON WOOD SAMPLES

In the following chapter, the authors perform residual stress measurements on wood samples and evaluate the results. The use of the hole-drilling method is a typical manner of residual stress measurement in mechanical engineering. The measurements are carried out on the basis of a quasi-isotropic and linear elastic material behaviour.

Wood is an interesting anisotropic material and cannot be compared to steel, for example. It should be investigated whether the findings from the metallic studies can be transferred, at least in part, to wood materials.

4.1 INVESTIGATION OF THIN LAMINATED WOOD

Due to its layered structure, aircraft plywood is considered quasi-isotropic and will be used in the following investigation. Figure 9 shows the specimen preparation tool and the types of specimens. The specimen type b) is utilised to calculate E and ν, as the small cross-section generates higher stresses. The strain gauge rosettes are applied using sample form d).

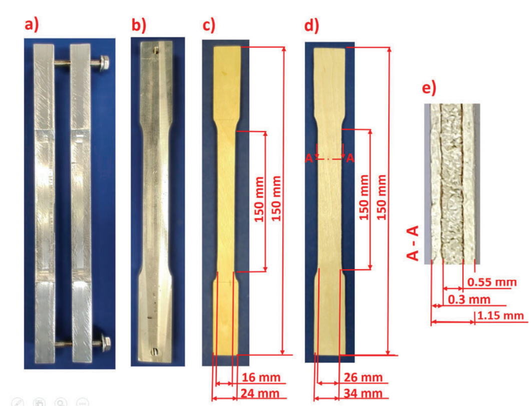

Figure 9. a) and b) specimen preparation tool; c) specimen for E-modulus and ν testing; d) specimen for borehole testing; e) specimen cross-section.

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To validate the drilling method, an external load is applied to the specimen. In a static tensile test, a 10 kg / 25 kg weight is attached to the specimen. The external load produces a tensile stress of σ_0 = 3.21 N / 8.05 N in the specimen, type d). This stress simulates the residual stress and is measured by the hole-drilling method. In order to eliminate the specimen's original residual stresses, a manipulation of the original hole-drilling method is performed. The strains of the specimen (ε_c, ε_b, ε_a) are measured twice. First, the deformation under σ_0 without hole is determined. The next step is to measure the strain with a drill hole and also under load with σ_0. According to [5], the difference between these stresses (drilled and undrilled) results in the stress in the sample that would be released by the original drilling method. This procedure allows the external stress σ_0 to be measured using the hole-drilling method.

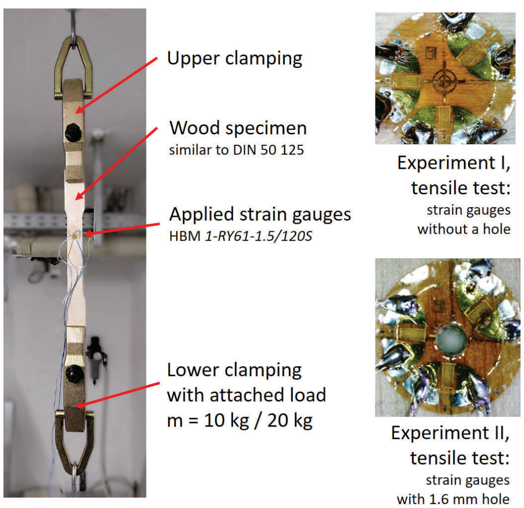


Figure 10. a) Clamped sample with rosette (left); b) rosette before and after drilling (right).

Figure 10 shows the plywood probe applied with a 3-strain gauge (rosette). The same rosette is measured once without drilling and then drilled. A 1/4 Wheatstone bridge (3-wire technology) and an HMB QuantumX MX1616B amplifier are used for the measurements.

The result of the measurements of sample P1 can be seen in Figures 11 and 12. As it is typical for 1/4 bridge measurements to have a slight drift, the readings have been averaged across the red lines in the graph. The oscillation of ε_b results from the attachment of the weight m. The next step is to calculate the differential strains:

$\Delta\sigma_c$= - 105 µm/m; $\Delta\sigma_b$= - 14 µm/m; $\Delta\sigma_a$= 43 µm/m

The strains calculated in this way are inserted into the formulas (1), (2) to calculate the principal normal stress $\sigma_{1/2}$. The stress σ_1 should be close to the 'simulated' residual stress σ_0 and the stress σ_2 should be approximately 0.

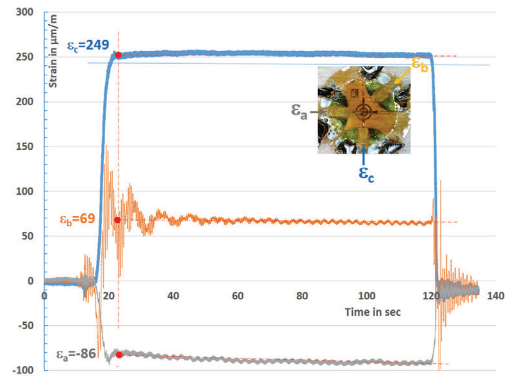


Figure 11. a) Determined elongations of specimen P1 (Experiment I, not drilled). Strain ε_c is in load (m= 10 kg) direction.

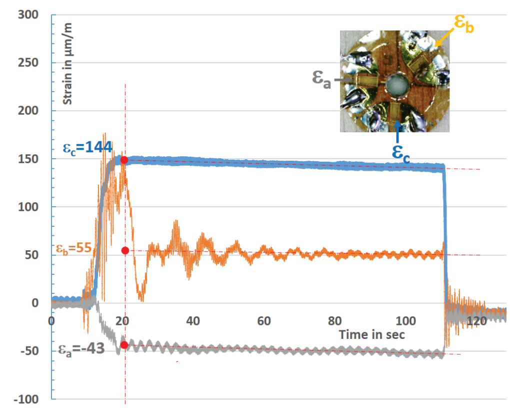


Figure 12. a) Determined elongations of specimen P1 (Experiment II, drilled). Strain ε_c is in load (m= 10 kg) direction.

It is possible to execute one final operation to obtain a more precise result. The centre position of the hole is important for the calculation. For this reason, the hole's offset from the centre of the rosette is accomplished using the following approach. Taking into account the eccentricity, the geometry coefficients A and B are changed to A_a, A_c, B_a, B_b and B_c. Equations (5) and (6) are used to achieve this. The results of the adjusted radius r_i and r_a are then inserted into equations (3) and (4). Hereby the eccentricity of each of the three strain gauges is taken into account.

$r_{i,n}' = r_i + e_n$ (5) and $r_{a,n}' = r_a + e_n$ (6) using $n = [a, b, c]$

The equations (1) and (2) are calculated with the new coefficients A_n and B_n. The result is:

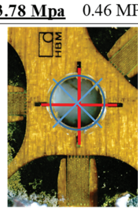
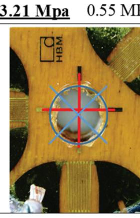
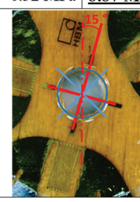
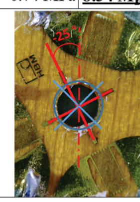
$$\sigma_1' = \frac{-E\varepsilon_a}{4A_a} - \frac{-E\varepsilon_c}{4A_c} + \frac{E}{4}\sqrt{\frac{2\varepsilon_a^2}{B_a^2} + \frac{2\varepsilon_c^2}{B_c^2} + \frac{4\varepsilon_b^2}{B_b^2} - \frac{4\varepsilon_a\varepsilon_b}{B_aB_b} - \frac{4\varepsilon_b\varepsilon_c}{B_bB_c}} \quad (7)$$

$$\sigma_2' = \frac{-E\varepsilon_a}{4A_a} - \frac{-E\varepsilon_c}{4A_c} - \frac{E}{4}\sqrt{\frac{2\varepsilon_a^2}{B_a^2} + \frac{2\varepsilon_c^2}{B_c^2} + \frac{4\varepsilon_b^2}{B_b^2} - \frac{4\varepsilon_a\varepsilon_b}{B_aB_b} - \frac{4\varepsilon_b\varepsilon_c}{B_bB_c}} \quad (8)$$

The results of a series of measurements are illustrated in Table 2. Two specimens are strained with a force in the axial direction (ε_c parallel to σ_o), while two others are investigated with a deviation of 15° and -25°. This procedure verifies the independence of the method with respect to the load direction. In addition, two distinct loads of 10 kg and 25 kg are examined. For the measurements P1, P2, P3 and P4, different samples, i.e. 4 pieces, are used.

As can be seen in Table 2, the six variants demonstrate a high degree of correlation between the applied load σ_o and the determined load σ'_1. Therefore, residual stress measurements on thin laminated plywood can be considered as a feasible measurement technique.

Table 2. Overview of the results and the rosettes of the drill holes

Specimen number	**P1**			**P2**			**P4 - 15°**			**P4 - 15°**			**P5 - 25°**			**P5 - 25°**		
Specimen profile	26.5x1.15 mm², three layer, birch																	
E, n	10.5 Gpa, 0.19																	
m_0, s_0	10 kg		**3.26 MPa**	10 kg		**3.26 MPa**	10 kg		**3.26 MPa**	25 kg		**8.05 MPa**	10 kg		**3.26 MPa**	25 kg		**8.05 MPa**
a [mm]	0.85			0.9			0.85			0.85			0.85			0.85		
$r_{i,}$ r_a [mm]	1.7																	
r_a [mm]	3.2																	
$e_{c/b/c}$ no hole [µm/m]	249	69	-86	225	75	-40	199	25	-17	530	-30	-25	218	170	-40	520	435	-71
$e_{c/b/a}$ with hole [µm/m]	144	55	-43	100	50	0	105	-12	19	295	12	65	150	75	-10	360	185	-10
$s_{1/2}$	3.79 MPa		0.32MPa	4.27 MPa		0.77MPa	3.42 MPa		0.43 MPa	9.36 MPa		0.28 MPa	3.33 MPa		-0.8 MPa	8.52 MPa		-1,94 MPa
deaxation, $e_{c/b/a}$ [mm]	-0.05	0	0	-0,2	0,1		-0.05	0	0	-0.05	0	0	0	-0,05	0	0	-0.05	0
$s'_{1/2}$ (incl. deaxation)	**3.78 Mpa**		0.46 MPa	**3.21 Mpa**		0.55 MPa	**3.25 Mpa**		0.32 MPa	**8.87 Mpa**		0.06 MPa	**3.26 Mpa**		-0.74 MPa	**8.34 Mpa**		-1.76 MPa
																		

4.2 – INVESTIGATION OF PRESS LAMINATED WOOD / MODIFIED BEECH WOOD

The solid beech wood (Fagus sylvatica) used in this chapter was densified by approx. 40% using the thermal-mechanical densification (TMD) method. Figure 13 shows the specimen pressing mould (left) and the shape of the finished specimen for residual stress measurement (right). For sample preparation, the wood was conditioned in a climate chamber to an equilibrium moisture content of approx. EMC = 10%. The samples were then heated to a core temperature of at least T = 80 °C in a pressing mould with subsequent compression. The wood structure compressed in this way shows a significant increase in strength and hardness. A disadvantageous property of such pressed wood is that humidification phases lead to decompression. As the moisture content increases, the wood is plasticised, releasing the energy stored in the microfibrils, which leads to increased swelling. The material swells in a limited area, but does not return to its previous compressed state without external influence. To reduce this effect, wood can be subjected to thermal treatment, which breaks down some of the hydrophilic components, but this is accompanied by embrittlement of the material. In order to be able to make a quick statement about the effect of temperature and holding time, residual stress measurements are to be carried out to provide direct results about the corresponding thermal treatment.

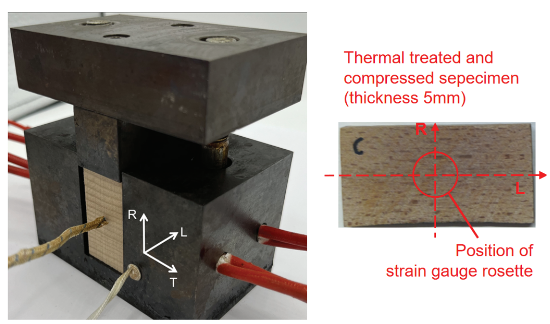


Figure 13. a) Heatable pressing tool with inserted sample. R: radial, T: tangential and L: longitudinal (for more information, see [9]); b) 5 mm compressed specimen.

For this study, the specimen shown in Figure 13 is measured using the hole-drilling method. The assumption with this specimen lies in relatively low residual stresses in grain direction (horizontal dashed line, Figure 13). The Young's modulus in the fibre

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direction is known from previous measurements of the university laboratory, with E = 14 GPa.

At first the hole-drilling tests are done; the deformation results are similar to those of a typical metal measurement. Figure 14 shows the depth profile of the strains (ε_L, $\varepsilon_{45°}$ and ε_R) released by drilling. From a certain depth, an asymptotic course of the released strains can be observed. For metallic alloys, this is approximately 0.6 of the borehole diameter [7]. Stress relaxation at greater depths will be incorrectly reflected by the surface strain gauges. This means that the strains for the wood sample should be read at 1 mm depth.

Figure 14 also shows the released strain values at a depth of 1 mm for the specimen T1:

ε_L = 16.6 µm/m; $\varepsilon_{45°}$ = 16 µm/m; ε_R = 26.7 µm/m

In contrast to Young's modulus, the Poisson number of the sample is not known. Therefore, it is assumed to be 0.19, analogous to Chapter 4.1.

The strains in the example, Figure 14, are determined for 6 samples and converted to principal stresses using the formulas (1) and (2). Table 3 shows the result of the calculated principal normal stresses. An average is calculated even if the results vary significantly. As a result, the mean value of 1.65 MPa should be interpreted with caution. It is important to note that the formulas used are not designed for anisotropic materials.

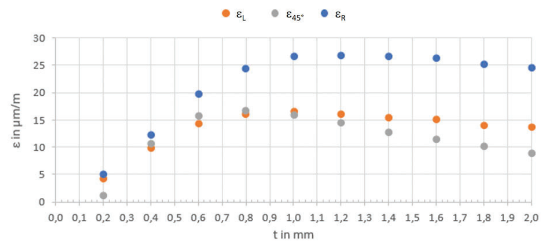

Figure 14. Measurement of the released strains (for directions, see Figure 13) using the hole-drilling method. Specimen T1.

For this reason, an attempt is made to validate the result. The sectioning method of metallic materials is also being investigated in a current research study at the university's laboratory. The method is known, for example, for measuring railway tracks and can only measure in one main direction. There are also reports of this method being used on wood [10]. Using the sectioning method, specimens T1 to T6 were examined orthogonally to the wood fibre direction (L). The result is an average residual stress of 2.03 MPa with a relatively small standard deviation of +/- 0.72 MPa.

The findings indicate that the two methods tend to produce similar results. Therefore, the hole-drilling method is also considered to be of interest for the analysis of wood. This must be done with the proper caution, as the theory of the hole-drilling method is not designed for anisotropic materials.

Table 3. Overview of the results and the rosettes of the drill holes.

Specimen number	T1			T2			T3			T4			T5	T6		
Specimen	Beech wood, treated with: thermal-mechanical densification, see [9]															
E, n	14 Gpa, 0.19															
$e_{L/45°/R}$ with hole [µm/m]	16.6	16	26.7	13.3	29	8.09	16.6	10.6	8.2	10.3	18.8	27.3	measurement error	11.6	9.9	7.6
$s_{1/2}$	1.91 MPa	1.54MPa		1.69 MPa	0.44MPa		1.4 MPa	1.09 MPa		2.17 MPa	1.6 MPa			1.03 MPa	0.89 MPa	
arithmetical mean s_1	1.65 MPa															

6 – RESULTS

Residual stress measurement on metallic specimens is state of the art. This results in improved part durability and lightweighting. It should be investigated whether the hole-drilling method can be applied to wood.

The results on thin plywood samples (birch) show a surprisingly interesting correlation. This may be due to the fact that the samples resemble quasi-isotropic behaviour. The numerical values of the residual stresses determined should not be used as exact values, but as tendencies.

In a further step, compressed wood was examined using the hole-drilling method. Although the formulas for the method were not developed for the tested anisotropic material, the results correlate principally with the disassembly method. These results indicate that the method is also interesting for anisotropic wood materials.

7 – CONCLUSION

The results were carried out on a small number of samples. Consequently, the measurements must be validated with additional samples. In addition, other types of samples (material, thickness, structure) will be investigated in the future. Including Young's modulus in its general form for anisotropic materials is a difficult but desirable task.

7 – REFERENCES

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