

NDT-Based Characterization of Timber and Vulcanized Fiber for Civil Infrastructure

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Abstract

The paper addresses beech wood as well as vulcanized fiber and discusses the results obtained when using acoustic emission and thermography as non-destructive testing techniques along tensile and load increase fatigue tests to characterize the wooden material's behavior under increasing fatigue loads to get enhanced information regarding the fatigue behavior of both materials. Reference is mainly made to the materials' anisotropic and microstructural behavior and what implications this has with respect to the materials' strength. The influence of moisture is discussed, as well as parameters that may deserve monitoring in the sense of structural health monitoring to be applied in timber structures in general.

Keywords: Fatigue, load increase test, thermography, non-destructive testing, acoustic emission, wood, timber, vulcanized fiber

1. Introduction

Timber and vulcanized fiber are materials in civil engineering used to a limited extent but with an increasing demand and structural challenges with respect to its environmental friendliness, sustainability and ability to be recycled. Wood is also a structural material that has been widely used in existing civil infrastructure of considerable age and can therefore be found in a variety of listed buildings of significant age. Wood is an anisotropic material and as such not easy to characterize. Vulcanized fiber is a modified natural product, which is manufactured from cellulose in the form of special paper layers produced by parchmentizing which also shows a strong anisotropic dependence of the mechanical properties. The density (approx. 1.2-1.4 g/cm³) is comparable to wood and the mechanical properties are at the level of some engineering plastics (thermoplastics). In fact, wood and vulcanized fiber can be described as orthotropic, by having three main axes which remain the same by rotation of 180°.

For reasons of anisotropy and comparatively less knowledge of damage mechanisms in timber and vulcanized fiber, materials safety factors have been relatively high, or in other words, applied loads low such that structural integrity has not been compromised. The use of non-destructive testing (NDT) is common in the field of wood and timber. Vulcanized fiber on the other hand is a less well-characterized material in research and using NDT is a new aspect. The 'wood-like' constitution of vulcanized fiber led to the benchmark of the materials presented in this paper.

Enhanced characterization using NDT does allow the potential of timber, vulcanized fiber material and even other material and the structures made of it to be determined, would this be for new as well as for old infrastructure. The characterization of wood properties is critical for

the understanding of material behavior and performance under operating conditions. The large number of potential methods for non-destructive evaluation of wood requires a sufficient understanding of the different NDT techniques applicable to wood and associated materials where a good overview can be obtained from [1]. Passive thermography has a large field of applications for knot detection, slope of grain, imaging of moisture content distribution, wood rupture phenomena and imaging of cavities in trees. An advantage of passive over active thermography is its ability to record temperature distributions without resorting to mechanical loading of the material. The thermal stress is relatively low and does not damage the material [1]. Acoustic emission (AE) and acousto-ultrasonic (AU) are non-destructive techniques, of which the wave signal depends on the character of the wave source and wood grain angle. Longitudinal components of AU waves arrive first followed by transverse-wave components and attenuation is greater for transverse than for longitudinal waves. AU waves propagate longitudinally along the grain and tangentially along the annual growth rings. It has been observed that attenuation of the longitudinally propagating waves is high near intergrown knots [2].

Vulcanized fiber shows a linear-elastic deformation behavior under quasi-static mechanical loading until reaching the yield stress σ_y . After that plastic deformation occurs in the material leading to a sudden and brittle failure. From that point stress is still rising in a linear behavior until reaching its maximum [3]. The stress at failure σ_f is equal to the ultimate stress σ_{ut} of the material. Similar to investigations with wood there is no visible reduction in the cross-section area of the specimen. The specimen just becomes longer [3].

The ultimate resistance and elastic behavior are characteristics of each material and, in wood, it varies not only between species, but as for individuals of the same species and also in the same individual, depends on the position the sample has been taken out of the bulk material. Combining elastic and plastic properties, wood and its derivatives can be considered visco-elastic. When subjected to permanent loads, static as well as mean loads around cyclic loading, even within the proportional limit, wooden structures may present a residual and irreversible deformation, causing the material to withstand load at reduced level over time. Beyond this point wood as well as vulcanized fiber materials show a rheological behavior with a permanent deformation for a constant tension. When subjected to traction, wood has a small plastic deformation. These effects are complex with respect to load distribution and related to physical, mechanical and anatomical characteristics of the materials. Initially they are caused by alterations in cellular organization of wood polymers, with influences of adhesives and other additives used in the materials' and structures' manufacture [4]. As for other materials, under fatigue loading, a reduction of stiffness due to cracking and strength of wood occurs due to damage accumulation. As is known for fatigue damage accumulation in general each cycle accumulates damage and after a specific number of cycles, fatigue failure occurs [5]. So far fatigue in structural timber structures has been covered by comparatively high safety factors [6]. However, this may get those structures to become costly and therefore interesting in terms of better understanding their true structural potential to which NDT may contribute.

With respect to fatigue loading, vulcanized fiber shows a strong material reaction from the very beginning which can be detected by NDT techniques e.g. thermography or acoustic emission through high-frequency impulse measurements (HFIM). The results of such investigations will provide a relationship between cumulated damage and the change of temperature in the specimen comparable to delamination processes in composite materials in general resulting from fatigue loading. In that case the stress amplitude at failure $\sigma_{f, LIT}$ may be higher than the ultimate strength σ_{ut} [3].

Woehler ($S-N$ or σ_a-N) curves describe the relationship between applied load σ_a and the

related numbers of cycles to failure N_f . The diagrams are derived from a huge number of constant amplitude tests (CAT) within an adequate range of stress amplitudes. The stress amplitude is reduced until no fracture occurs for a defined number of loading cycles being traditionally called fatigue or endurance limit. The fatigue limit evaluated depends on different parameters such as the load/stress ratio R , moisture, gross density and loading frequency [7,8]. Axial tests performed show that stress ratio $R = -1$ is the most severe loading mode. In [7], the hysteresis was measured for CATs and the accumulated creep, work, strain and stiffness were suggested as damage measurements during fatigue tests.

Going beyond CATs, load increase tests (LIT) are able to provide information regarding the stress-strain material behavior due to different load levels with one single specimen [9-11]. In that case the material reaction is measured during a stepwise or continuous increase of the stress amplitude from a quasi damage-free (non-critical) starting amplitude up to failure. The number of load cycles in each load level should be chosen large enough such that material changes can develop and stabilize, but they should be held to a minimum for the benefit of a reasonable testing time. This approach has already been validated with success for metals, polymer- and paper-based materials [9,10]. Different measurable signals as cycle- and loading-dependent material reactions could be correlated to damage, including plastic strain amplitude and deformation-induced temperature increase and, in case of metals, the change in electrical resistance due to increasing defect density in the specimen [9-11].

This paper aims to present this LIT-based advanced short-time fatigue testing procedure for timber and vulcanized fiber material. As shown further below, LIT allowed a good estimation of the fatigue strength to be obtained. The main advantages of this resource- and energy-efficient procedure described above are the need of relatively few tests. Because of numerous factors influencing the behavior of those materials and hence to be considered in testing, a reliable short-time procedure could enable involving these influencing factors in a time- and cost-acceptable way.

2. Experimental setup

Stress-controlled load increase tests were carried out at ambient temperature with a frequency of 5 Hz on a servohydraulic testing system with a maximum load of 63 kN using a triangular load-time function at a load ratio of $R = 0.1$.

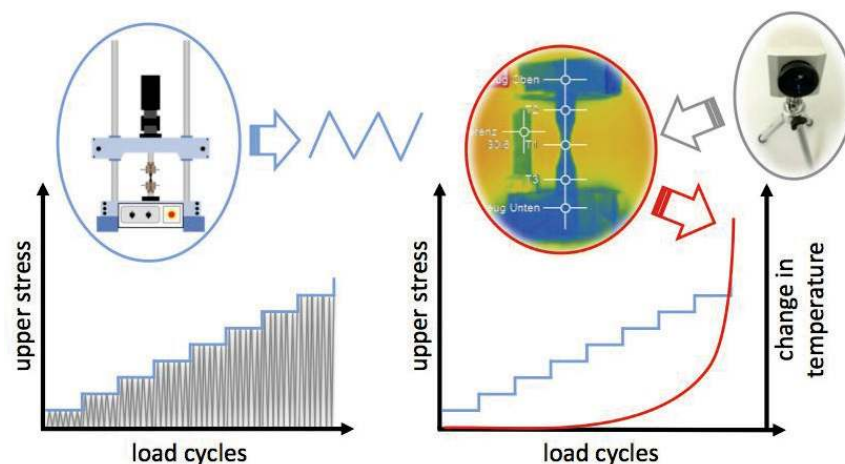


Figure 1: Procedure of stepwise load increase test and temperature measurement by means of thermography, schematically

Fig. 1 shows the schematic procedure for a stepwise LIT and the temperature measurement by

means of an infrared camera system. For the LITs, the upper stress σ_u was stepwise increased from $\sigma_{u,start} = 5$ MPa by 5 MPa each 10^2 cycles until specimen failure. During the LITs the change in temperature ΔT was measured by an infrared camera allowing the microstructure-related fatigue behavior of the wood and vulcanized fiber material to be characterized.

For these investigations an infrared camera type thermoIMAGER TIM 160 from Micro-Epsilon was used. The camera system provides a spectral range of 7.5-13 μm , an optical resolution of 160×120 pixels, a $23^\circ \times 17^\circ$ objective and a thermal resolution of 0.04 K. The related data acquisition software was programmed on National Instruments LabVIEW 2011. The software allows relevant thermographs to be extracted as well as point/field temperatures to be measured. Compared to conventional testing techniques the use of thermography, which is well known within the context of NDT, results in a gain of information with respect to the characterization of the cyclic deformation behavior of timber and vulcanized fiber material. To analyze the character of the wave sound generated by failure through AE a HFIM sensor from Qass was used. In HFIM a curve which shows the development of acoustic energy during the test and the signal path of the process topography during fracture has been used to compare the possible result presentations from an acoustic sensor [12]. With HFIM the signals are calculated using a Fast Fourier Transformation (FFT) by fragmentation of the individual signals in the spectra and visualizes them in the process topography. The process topography shows the acoustic signals detected by HFIM in real time. For signal detection, the piezo-sensor of the HFIM was fixed on the clamping system [12]. In this way first cracks of (wood) fibers or concerning vulcanized fiber material the sound of delamination of the paper-layers can be obtained. Focus of the research presented here is the resource-efficient determination of fatigue performance based on damage detection and evolution in multiple step fatigue tests. Fig. 2 shows the experimental setup for tensile as well as fatigue tests for wood and vulcanized fiber material.

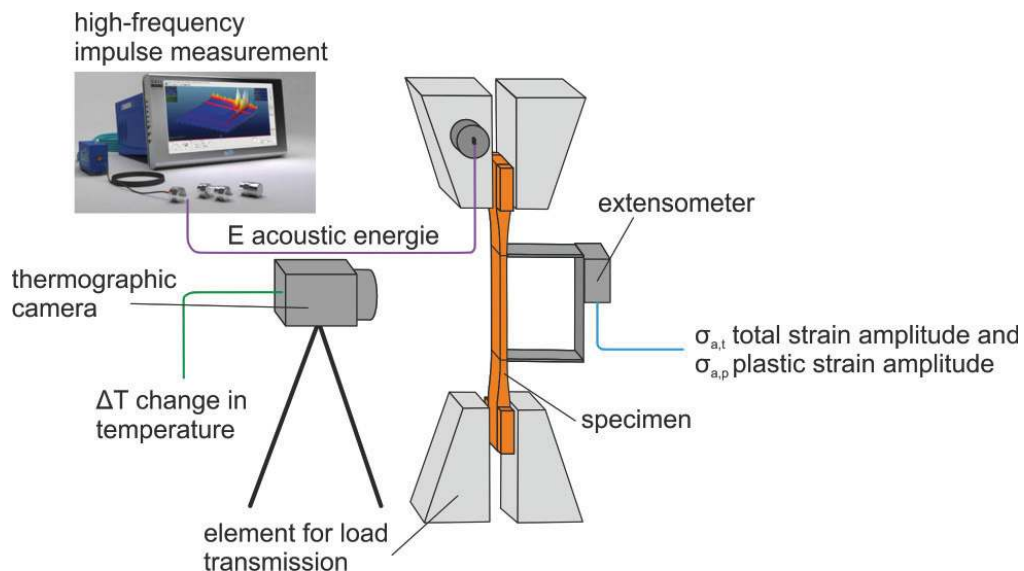


Figure 2: Schematic of test setup

3. Material and specimen geometry

In order to investigate the deformation behavior of wood and vulcanized fiber material, tensile and fatigue tests on dog-bone specimens were carried out. The wood species used was beech (*fagus sylvatica*) cut from high quality defect-free boards. For samples cut far from the tree center and small in size in relation to the distance to the pith, the growth ring curvature can be ignored and properties are regarded as orthotropic with three orthogonal planes of material

symmetry: longitudinal, radial, and tangential. At structural dimensions and for simplicity in modelling, wood is mostly considered transverse isotropic, assuming identical properties in the radial and tangential directions [13].

Consequently, and in accordance with previously validated practice [14] the material was characterized with regard to orthotropy using off-axis tests, in which specimens were cut from timber boards with $t = 4$ mm thickness to obtain dog-bone shaped specimens (Fig. 3a). In these samples the angle of the specimen with regard to the timber fiber was set to 0° , 45° and 90° in the longitudinal-tangential (x-y) plane. Timber loaded at 0° fiber orientation is well known to have the best mechanical properties. All tests on timber presented in this paper were carried out with 0° specimens.

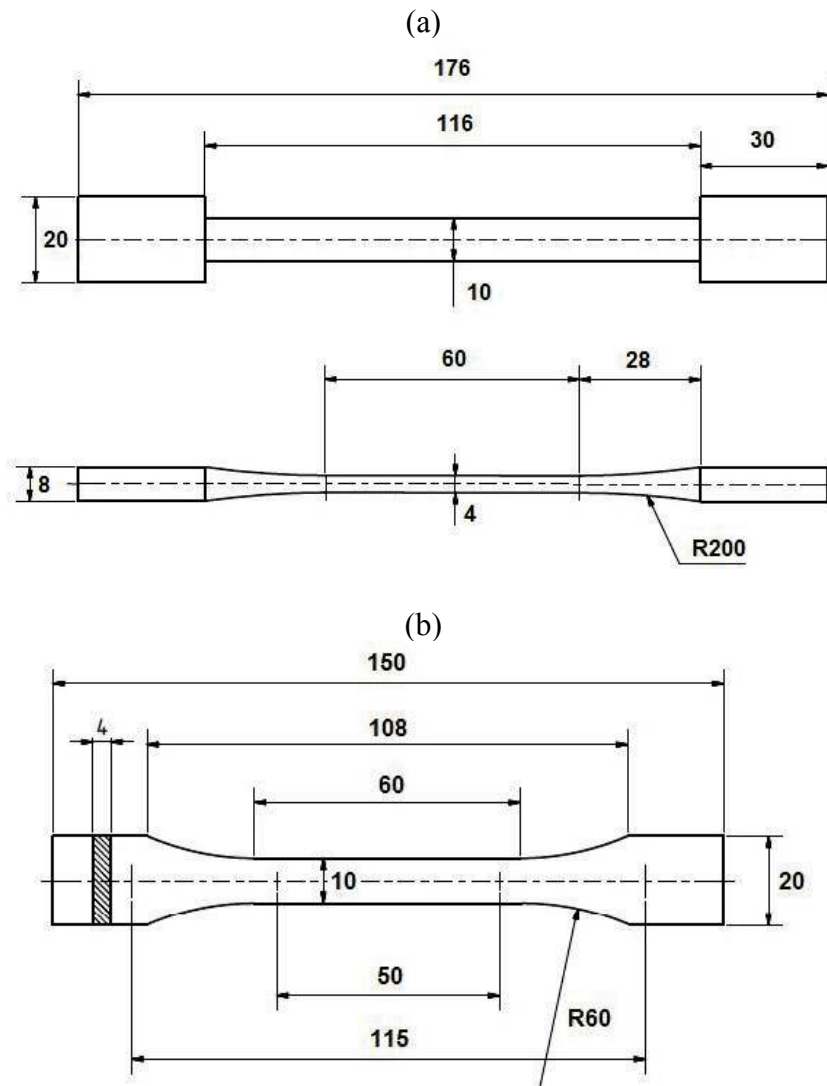


Figure 3: Specimen geometry for timber (a) and vulcanized fiber (b) materials

According to the manufacturing direction of vulcanized fiber material [17,18] specimens of three different predominated fiber orientations (0° , 45° , 90°) were cut out from boards with a thickness of $t = 4$ mm comparable to the timber specimens (Fig. 3 b). Due to the orthotropy the behavior of vulcanized fiber material in 0° orientation is expected to be much better as well which marks the comparability of the two structured materials. The investigations shown in this paper will also concentrate on 0° orientation.

Within the investigations performed, the influence of the moisture content on the mechanical

properties was observed for the two materials. The moisture content has been increased through an aging process in a climate chamber with a relative humidity r.H. up to 70% and a constant temperature of 20°C. The aging duration from one test interval to the next was 30 days to simulate different seasoning stages of the material. As being typical for natural products wood and vulcanized fiber material both are hygroscopic. To date, the investigations of the initial state and the first aging step have been completed. Three other aging steps are to follow with respect to the current work plan.

4. Results

4.1 Tensile tests

Prior to the fatigue tests, tensile tests (universal testing system type AGX, $F_{max} = \pm 100$ kN, Shimadzu) have been performed for both materials at ambient temperatures with a constant strain-rate of $2 \cdot 10^{-3} \text{ s}^{-1}$ (6 mm/min). The strain was measured contact-free by means of a video extensometer (Type: TRViewX, Shimadzu). In addition to strain measurement the change in temperature was measured by an infrared camera and the acoustic energy AE signal was detected by the HFIM sensor mentioned before. Fig. 4 shows the results for timber in both seasoning stages. For the change in temperature, initial state timber has a low material reaction with regard to temperature before reaching its limit at $\sigma_{f, tens}$ whereas the material which is one month seasoned shows a reaction at a stress of $\sigma = 100$ MPa already, which is nearly 50% lower than $\sigma_{f, tens}$. An increase of the AE signal is observed for $\sigma = 150$ -175 MPa, which has to be considered as a more conservative signal than the change in temperature obtained.

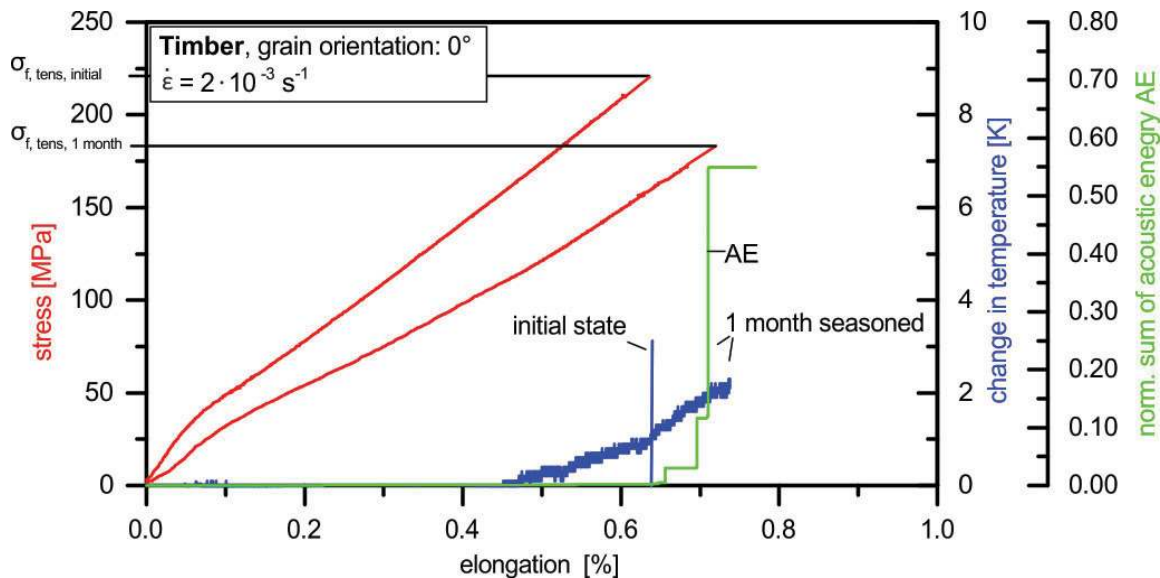


Figure 4: Tensile test on timber for the initial state and 1 month seasoned

In contrast to timber, vulcanized fiber material shows a distinct change in temperature in both the initial and seasoning stage (Fig. 5). The change in temperature shows for vulcanized fiber material a very slight increase near to zero followed by a change in the slope with increasing temperature values at a stress of $\sigma = 60$ MPa (initial state) and 50 MPa (1 month seasoning). The AE signal shown here for the 1 month seasoned specimen already increases at $\sigma = 35$ MPa, which is much earlier than the change in temperature.

It has to be noted that these are first single experiments performed which require a further statistical basis being currently established. What can however already be concluded is the

fact that the cellular structure of those materials significantly changes due to the materials' humidity content (and possibly other environmental factors) and that this influence can be seen in the different stress-strain-diagrams performed. A first obvious effect is the difference in non-linearity versus tensile strength. While timber exhibits less of non-linearity (or more of hardening) and higher tensile strength the vulcanized fiber material is explicitly non-linear and has a much lower tensile strength. Seasoning of the two materials leads to little difference in tensile strain but significant difference in tensile strength in the case of timber while for the vulcanized fiber material more the opposite can be seen. The answers from the thermographic as well as AE measurements can be concluded in a way that they are correlated to the behavior of the respective materials under higher strain. However due to the limited number of experiments so far not more conclusions should be made at this stage.

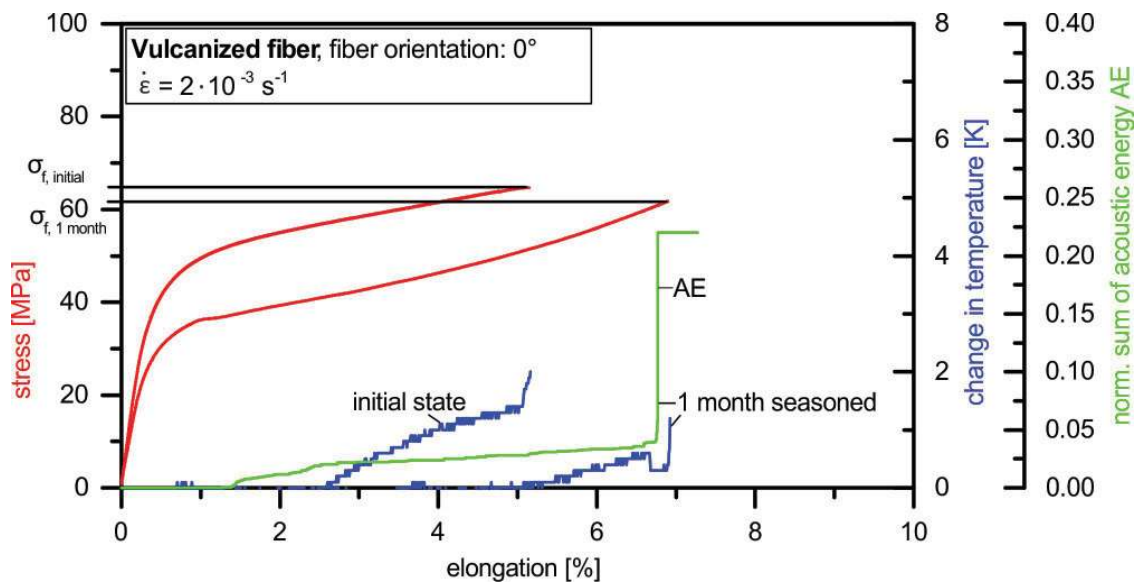


Figure 5: Tensile test on vulcanized fiber material for the initial state and 1 month seasoned

4.2 Load increase tests

The load increase tests (LIT) were performed on a servo-hydraulic testing system (type PC63M, $F_{max} = \pm 63$ kN, Schenck/Instron). For the characterization of the material behavior under cyclic loading an extensometer, thermography by means of an infrared camera as well as a HFIM sensor was used.

The LITs result in a significant change in temperature for specimens of both materials due to the stepwise increased load. The change in temperature shows for timber a very slight increase near to zero followed by a change in the slope with increasing temperature values at an upper stress of $\sigma_u = 30$ - 35 MPa (initial state) and 25 MPa (1 month seasoning), respectively (Fig. 6). The upper stress at failure $\sigma_{f, LIT}$ occurred at 75 MPa (initial state) and 45 MPa (1 month seasoning) respectively, which is a reduction by 47% . In the case of timber the change in the slope of the temperature occurs at 50% of the lifetime, which is in accordance with previous investigations [17]. Three specimens with grain orientation of 0° were tested for each seasoning stage.

The LIT of vulcanized fiber is given in Fig. 7. In accordance to the LIT on timber, temperature measurements were used to characterize the cyclic deformation behavior. A change in the slope can be observed at $\sigma_u = 45$ MPa (initial state) and 35 MPa (1 month seasoning) and specimen failure occurred at $\sigma_{f, LIT} = 65$ MPa (initial state) and 50 MPa (1

month seasoning), which is a significant smaller difference between the two seasoning stages by at least 28 %. For the initial state the change in temperature goes up to 25 K.

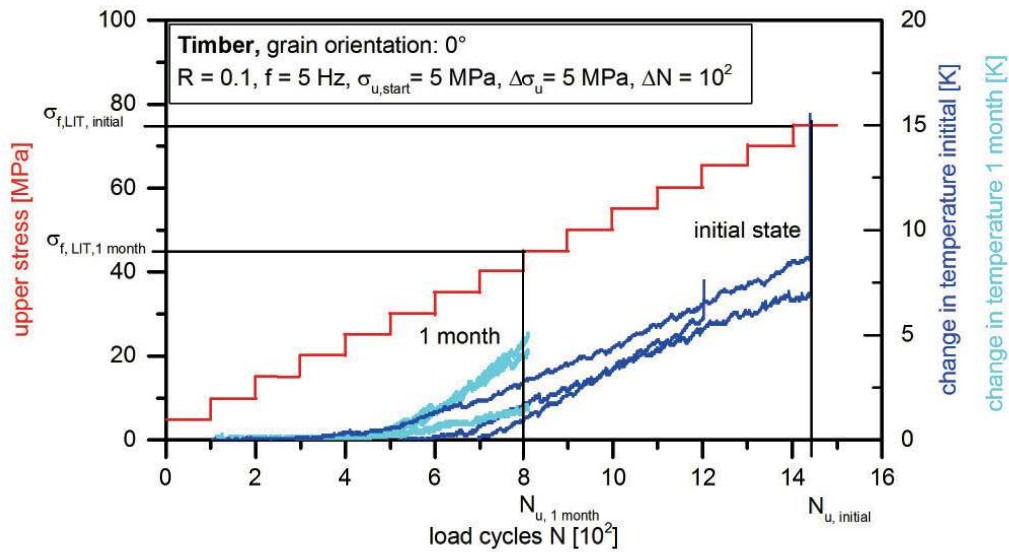


Figure 6: Load increase test on timber for the initial state and 1 month seasoned, (N_u = ultimate number of cycles)

In comparison to the LIT on vulcanized fiber material (Fig. 7), the LIT on timber (Fig. 6) shows a more linear increase of the change in temperature, which will be further investigated in a forthcoming work program.

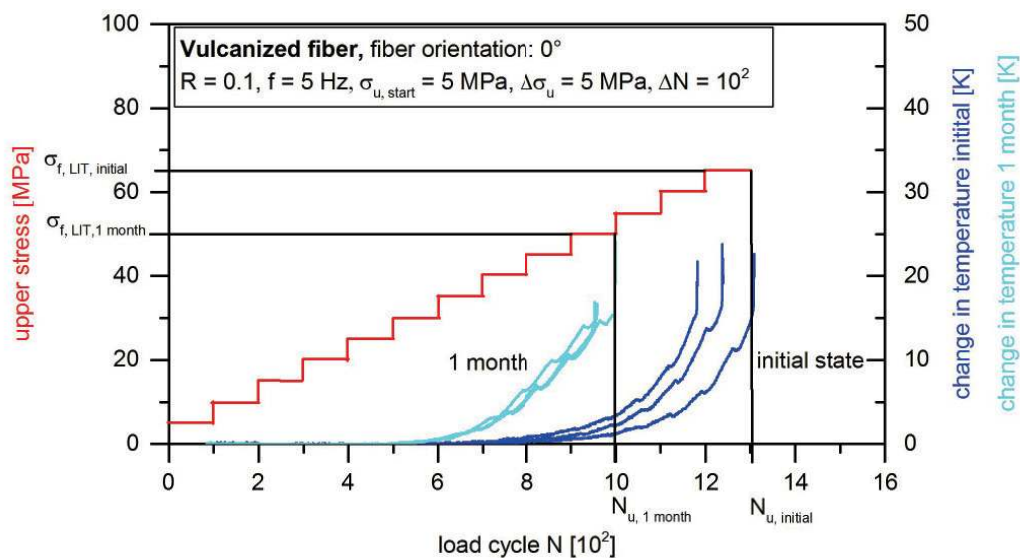


Figure 7: Load increase test on vulcanized fiber for the initial state and 1 month seasoned, (N_u = ultimate number of cycles)

With respect to the results of the quasi-static investigations $\sigma_{f, tens}$ for timber is 140 MPa higher than $\sigma_{f, LIT}$. In contrast, vulcanized fiber shows an inverse behavior whereas $\sigma_{f, tens}$ is 10 MPa lower than $\sigma_{f, LIT}$. The change in temperature reaches a value of 7.5 K and increases at fracture. Successive microscopic investigations of the different areas of fracture are due to follow. There were also three specimens with fiber orientation of 0° tested for each seasoning stage. Figures 6 and 7 show that temperature measurements are very well suited to

characterize the damage evaluation within fatigue tests.

The HFIM-sensor is used to evaluate the character of the cracking signal due to tensile as well as fatigue loading. Figures 8 a-d give the corresponding diagrams with the fracture's amplitude width as a fracture time frame t_b for the two materials in the 1 month seasoned stage. The width of the amplitude by fracture is in comparable ranges for tensile and load increase tests.

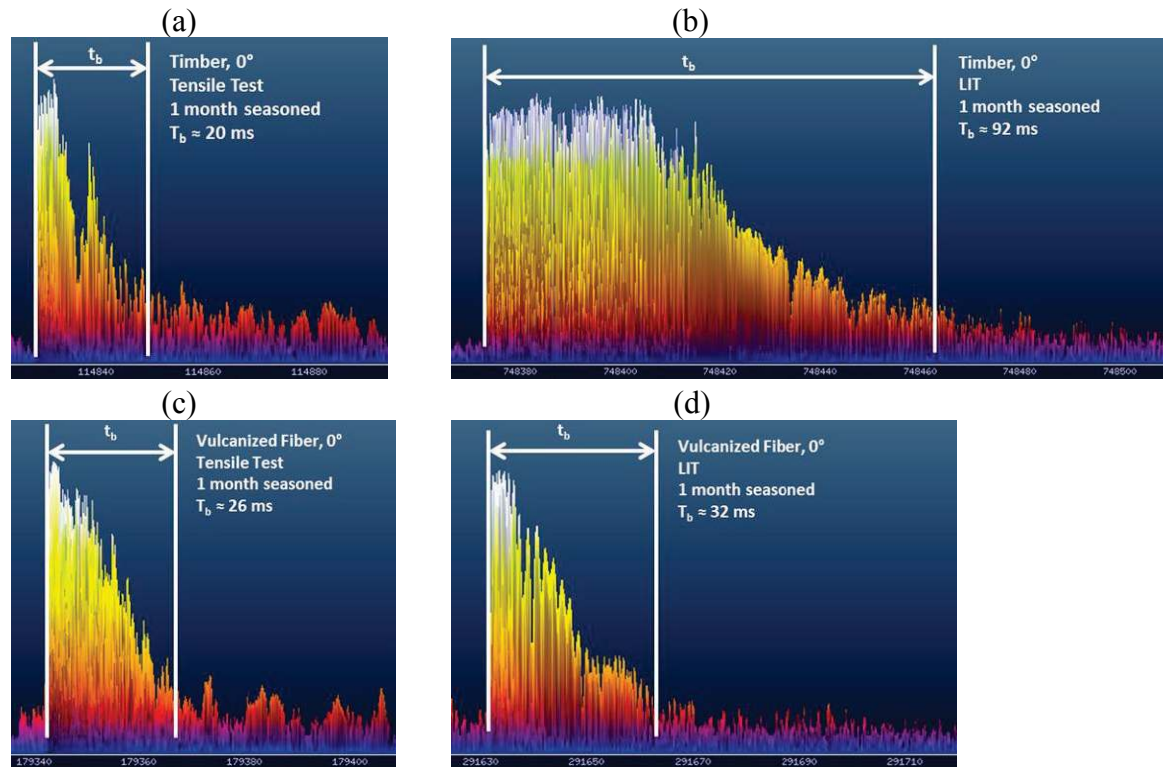


Figure 8: Acoustic signals detected by HFIM in real time: Comparison of the fracture's amplitude width t_b for wood (1 month seasoned) for tensile (a) and load increase test (b) and for vulcanized fiber (1 month seasoned) for tensile (c) and load increase test (d)

5. Conclusions

Within tensile and load increase tests thermography and high frequency impulse measurements were used to characterize the material behavior of timber and vulcanized fiber material with respect to the ageing stage. Both materials show a completely different relationship between the characteristic values of quasistatic and cyclic loading. The seasoning stage (moisture content) of natural products has a substantial influence on the materials reaction due to loading. After one month seasoning, decreasing values of the lower stress at failure come along with a decrease of the lower stress resulting in first plastic deformations in general for both materials.

In the load increase tests the sound wave characters of the fracture induced high frequency impulse measurements were compared, detecting a huge difference between the fracture processes of timber under quasi-static and cyclic loading. The results for vulcanized fiber material give a first impression with respect to the material behavior under quasistatic and cyclic loading leading to the assumptions for using this resource efficient material in civil engineering applications.

The non-destructive characterization of timber and vulcanized fiber material results in the conclusion, that temperature and high frequency impulse measurement techniques are very well suited for characterizing the damaging behavior of those giving rise to potential options for structural health monitoring applications.

6. Outlook

This research is ongoing and more seasoning stages will be applied on the timber as well as vulcanized fiber samples. The influence of the ageing process on the material's strength due to quasi-static as well as cyclic loading will be continuously observed. Therefore thermography and acoustic emission techniques will be used for the characterization of the microstructure and at least failure detection. These non-destructive testing methods are important allies for monitoring structures, because they allow failures to be predicted well before they can be seen by the naked eye. This ability of prediction results from the material sending signals as a consequence of internal modification and rearrangement in an efficient way well before rupture. Those modifications and rearrangements are the incubators of micro-cracks and the change in the internal temperature, which with time and without load removal leads to damage progression.

The results presented in this paper are just considering the 0° orientation. Successive investigations for the radial and tangential fiber and grain orientation are expected to provide further insight. As an outlook, the HFIM results for timber in Fig. 9 show that the wave sound characteristics of a fracture very much depends on the timber's orientation and hence anisotropy. The sum of acoustic sum energy shows how much energy is released. The 0° orientation shows the highest amplitudes and frequency range. Orientations in 45° and 90° show no significant difference and the resulting sums of energy are hence much lower than for 0° .

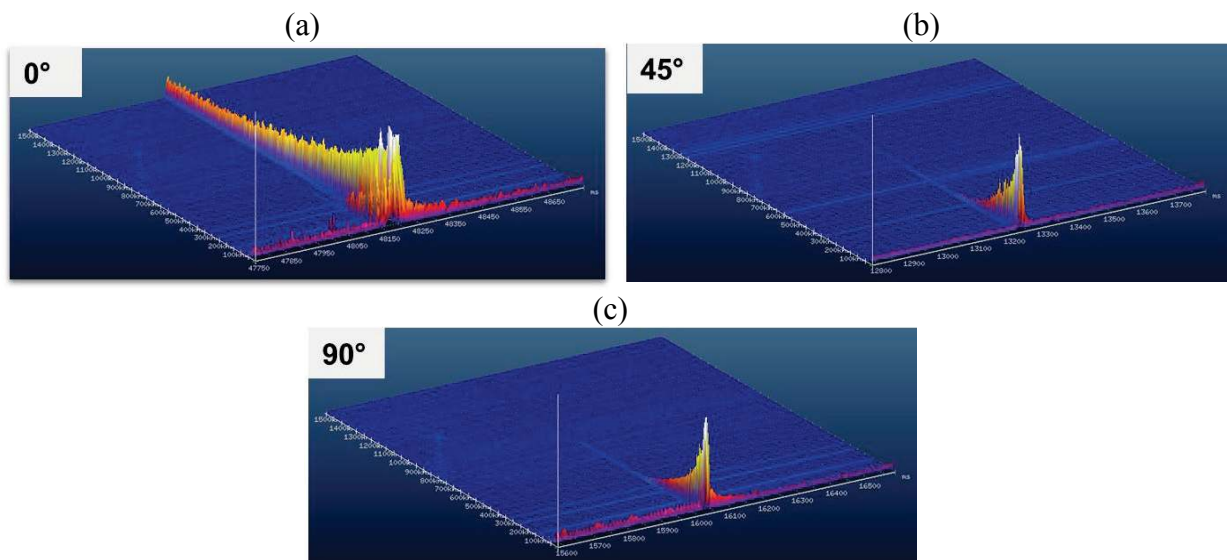


Figure 9: Timber: Comparison of the difference in wave sound by fracture for 0° (a), 45° (b), 90° (c) grain orientation

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