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A PROMISING APPROACH OF LINEAR TIMBER STRUCTURAL HEALTH MONITORING

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ABSTRACT: Structural monitoring of timber bridges includes the moisture monitoring as well as strain and crack monitoring of critical parts, especially when considering new construction methods. Currently, single-point sensors are used for moisture monitoring on timber bridges. However, the parts of the structural components which are not being measured may be moist. The lack of monitoring can result in wet areas not being detected. This could result in major damage, e.g. due to fungal decay. A higher degree of protection can be achieved with linear or area sensors. The same applies for strain monitoring using electrical strain gauges. The possibility of monitoring larger areas using new measurement methods like distributed fibre-optical sensors and technologies may help to promote new construction methods and structural health monitoring (SHM) of timber bridges.
This paper presents a literature survey of moisture monitoring and fibre optical measurement techniques, own studies on moisture monitoring on timber bridges and the strain analysis in mechanical load tests on timber-concrete composite beams. Finally, an overview of the combination of moisture monitoring and fibre-optical measurement techniques is given.

KEYWORDS: structural health monitoring, fibre-optical sensors, FBG, distributed sensing, moisture monitoring

1 INTRODUCTION

A high timber moisture content is a problem for timber bridges as well as it is for any timber structure. This is associated with a high risk of insect infestation and infestation by wood-destroying fungi. Wood moisture contents of more than 20 mass-% over a longer period of time are considered as a potential problem.[1, 2].
Bridges must be regularly inspected in Germany [3]. However, this only offers a limited possibility to monitor the long-term development of the timber moisture content of a bridge. Therefore, monitoring concepts can help to ensure that the timber moisture content is kept within acceptable limits. If timber moisture levels higher than 20 mass-% are measured, it is possible to detect and remedy the problem before major economic damage occurs. For this purpose, new sensors, measurement methods and technologies are required that allow reliable monitoring of the structures.
High-performance fibre-optical measurement techniques allow accurate and distributed or closely spaced linear measurements of strain and temperature changes in large structures such as bridges. If it were possible to use distributed fibre-optical sensors to measure the timber moisture content in addition to strain and temperature changes, it would be a major step forward in structural health monitoring (SHM) of timber bridges.
On the one hand in this paper, the different measuring methods for determining the timber moisture content are presented. It is explained which measurement methods are used in practice and which current developments are known. On the other hand, fibre-optical measurement methods and the usage of these methods for strain and temperature measuring of structures are described. Finally, an outline of the combination of these two methods and new concepts is presented.

2 TIMBER MOISTURE MONITORING

2.1 OPPORTUNITIES OF TIMBER MOISTURE MEASUREMENT

Different methods are available to determine the timber moisture content. An overview is provided in Table 1, according to [4].
The direct measurement of the timber moisture content is possible in two ways. The first possibility is the measurement of the mass of water of a material sample by using the kiln-dry method or the distillation/extraction method. The kiln-dry method is standardised in Germany [5]. It is necessary to take a sample from the building

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components. Temperatures above the boiling point or solvents are used to extract the water from the sample. The moisture content is calculated by dividing the mass of the water by the mass of the dry sample. These methods are destructive but very accurate and therefore used as reference measurement methods.
The other possibility is the measurement of physical or chemical properties which correlate with the moisture content. Several methods are available, see Table 1. For these methods the dependency on moisture content of the electrical resistance (electrical resistance method), the dielectrical constant (dielectrical method), the energy absorption (microwave method), the braking process of neutrons (radiometrical method), the reflection of light waves (spectrometrical method) and the colour reaction of chemicals (chemical method) is used.

Table 1: *Timber moisture measurement methods*

Method	Measured parameters
Kiln-dry method	Direct measurement of the mass of water in the timber
Distillation/extraction method	
Electrical resistance method	Measurement of physical or chemical properties which correlate with the timber moisture content
Dielectrical method	
Microwave method	
Radiometrical method	
Spectrometrical method	
Chemical method	
Sorption method	Measurement of the relative humidity and air temperature close to a timber surface which correlate with the timber moisture content

An indirect way to determine the timber moisture content is the sorption method, which uses the hygroscopicity of the wood. For this method, a borehole is made in a structural timber component, into which a climate sensor is inserted and sealed off from the outside. The climate sensor is then positioned in an enclosed air volume that constantly changes its humidity due to the timber moisture of the walls of the borehole. The relative humidity and air temperature is measured and then converted into the material humidity.

2.2 MOISTURE MONITORING OF TIMBER BRIDGES IN PRACTICE

Not all of the methods described above are appropriate for monitoring timber structures. Only methods used for monitoring purposes are discussed below.
Timber moisture monitoring is often carried out using the electrical resistance measuring method. This method is standardised for sawn timber in DIN EN 13183-2 [6]. The measurement method is based on the correlation between electrical resistance and timber moisture content. The electrical resistance increases as the timber moisture content decreases. In particular, the type of wood has a considerable influence on the electrical resistance to be determined. Therefore, wood species-specific calibration curves must be used to determine the wood moisture content when using this method. Timber temperature has also a relevant influence on the electrical resistance. Therefore, a temperature compensation is necessary.

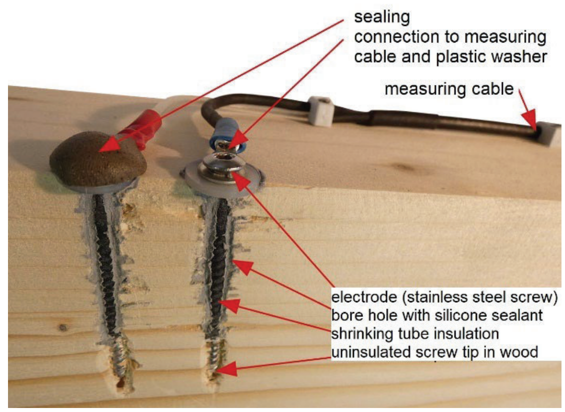

Figure 1: *Model of electrodes in a test specimen*

In a monitoring programme at the University of Applied Sciences Erfurt the following measurement setup was used [7], [8]: Stainless steel screws were used as electrodes, inserted into a pre-drilled hole and insulated with shrinking tube to the specified measurement depth. The exposed part of the thread was screwed into the wood without pre-drilling and the holes were sealed with silicone to prevent water and air ingress. Plastic washers and insulating putty were used to decouple the screw heads from the wood to prevent creepage currents on the wood surface (see Figure 1). The measuring equipment used was from the company Scanntronik Mugrauer GmbH. A similar measurement setup has been used in several other studies [9, 10, 11].
The sorption method has been used in a monitoring programme on several bridges in Norway [12]. Sensors were placed at different depths in the cross section of the main components of the bridges. The boreholes were sealed from the outside. The sensors measure air temperature and relative humidity in a small cavity. The moisture content was initially calculated using Simpson's equation for equilibrium moisture content [13]. However, a more accurate equation was found.

2.3 CURRENT DEVELOPMENTS

New sensors are currently being developed by several institutions. At the Bern University of Applied Sciences, a single-point sensor has been developed that also uses the sorption method. The advantages are the low costs and wireless data transmission of each sensor. This simplifies the application of this system. A gateway close to the sensors can transmit data to a server or send alerts to mobile phones [14].
Another approach is the usage of Radio Frequency Identification (RFID)-tags. An RFID-tag is a small device that uses radio waves to receive, store, and transmit data

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to a reader. The capacitive measurement method is used. The water in the wood affects an RFID-tag antenna and causes its impedance to deviate from its intended design value. This effect becomes stronger as the moisture content of the surrounding medium increases. Therefore, it is possible to determine the moisture content. Tags are available which get their energy by electromagnetic transmission from the reader. Wires and an energy supply are not necessary, only a reader is required. The tags can be applied to the surface or inserted into the timber components. The disadvantages of this method are its low level of accuracy and the fact that it is a single-point sensor, as it is the case with many other techniques described before [14, 15, 16].

Single point sensor measurements only give information about the moisture content at the measurement points. It is not possible to detect potentially high moisture levels next to the measurement points. This disadvantage of single-point measurement is overcome by linear or area sensors. Such sensors are currently being developed as described in the following.

In [17] the development of a 'sensor lamella' is described, which can be used as a linear or area sensor. The measurement principle is based on the determination of the specific resistance of the wood volume between two plate electrodes. The system is suitable in the range of 10 mass-% to 20 mass-% but not for the detection of locally increased moisture content above the critical value of 20 mass-%.

Kühne et al. [18] describe linear sensors using dielectric measurement techniques such as Time Domain Reflectometry (TDR) and Damping and Phase Shift in the Alternating Voltage Field of Electrical Conductors (DPW). They allow local estimation of wood moisture, but require calibration for each application.

Research at the University of Applied Sciences Eberswalde is taking a different approach. In his dissertation [19], Winkler describes the use of piezoresistive wood adhesives. In [20] it was already shown that it is in principle possible to use such electrically conductive adhesives for timber moisture detection. In addition, strain can also be determined. It is therefore a technology that can be used in many ways to analyse timber structures. The measured resistance depends on the load, temperature change, moisture and the associated swelling and shrinking of the material. The task at hand is therefore to distinguish between the causes of this 'sum signal'.

Although commercially available linear and area moisture sensors are used to monitor bridges, they are used in particular for flat roofs. However, these sensors are not used to measure the timber moisture content, but only as a continuous check on the integrity of the waterproofing layer. These systems usually include a leak detection option. However, as the timber moisture content is not measured, these systems are not included in the following discussion.

3 THE USE OF A FIBRE-OPTICAL MEASUREMENT METHOD FOR THE ANALYSIS OF TIMBER STRUCTURES

3.1 FIBRE-OPTICAL MEASUREMENT METHODS

3.1.1 Principles

Fibre-optical sensors and measurement methods provide another approach for the analysis of timber structures. In principle, the sensor technology is based on passing a light wave through the core of an optical fibre and measuring the reflected and/or the transmitted light wave properties. External influences such as temperature changes and mechanical strains in the direction of the fibres cause them to stretch or compress and affect the light properties. This method may also be suitable for determining the timber moisture content i.e., by measurement of hygric strains of the timber or analysis of the relative humidity of the air close to wood using a fibre-optical sensor with humidity sensitive coating.

Fibre-optical sensors are divided into single-point, semi-distributed and distributed sensors. Single-point measurement systems and sensors are not part of the present discussion.

3.1.2 Fibre Bragg Grating (FBG) Sensors (semi-distributed measurement)

Very thin fibre-optical sensors, such as fibre Bragg grating sensors (FBGS), allow the measurement of changes caused by temperature and mechanical strain. Due to their insensitivity to electromagnetic interference, corrosion resistance and long-term stability, FBGS are widely used for structural monitoring in various applications [21], [22].

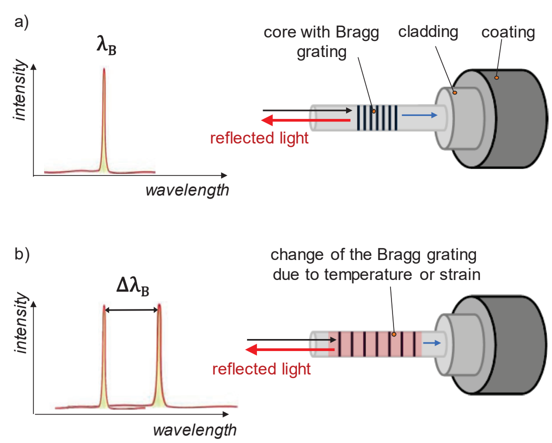

Figure 2: *Schematic representation of the principle of fibre Bragg grating sensors (a) FBGS with the reflected light spectra (wavelength at the maximum of the peak is the Bragg wavelength λ_B) and (b) shift of the Bragg wavelength ($\Delta\lambda_B$) due to changes in temperature and/or mechanical strain*

FBGS are light guiding optical fibres with zones where the refractive index in the fibre core is periodically modulated. The zones with modified optical properties are

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called Bragg gratings [23]. When broadband light is passed through the fibre Bragg grating, a wavelength-selective reflection of the light occurs as schematically shown in Figure 2. The light is reflected at the Bragg wavelength λ_B [23].
If temperature or mechanical strain is applied to the fibre Bragg grating along the fibre axis, the Bragg wavelength is shifted to lower or higher wavelengths depending on the situation. The Bragg wavelength shift is given by Equation (1) below:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi) \cdot \Delta T + (1 - \rho e) \cdot \varepsilon \qquad (1)$$

with $\Delta\lambda_B$ = change in the Bragg wavelength, ρe = photoelastic constant, α = thermoelastic coefficient, ξ = thermo-optic coefficient, ΔT = change in temperature and ε = strain.
For more information on the relationship between the change in optical properties with temperature and strain see [23]. The Bragg wavelength shift depends on both temperature and mechanical strain. For strain measurements at constant temperature, the peak shift of the Bragg wavelength is typically converted into a measurement of strain along the axis of the optical fibre. If the temperature is not constant, temperature effects must be separated from mechanical strain effects using temperature compensation techniques. For strain measurements, the FBGS are normally attached to the surfaces of the structure of interest using structural adhesives. It has been shown that FBGS can also be used as embedded sensors in laminated composite structures [24] as well as in adhesive layers of structural joints [25]. Embedded FBGS can therefore provide detailed information on strain or temperature at different points in a structure [26].

3.1.3 Distributed Fibre Sensing

In recent years, distributed measuring fibre-optical systems have also become established. These measurement techniques use the light scattered back from ‘defects’ and inhomogeneities in the optical glass fibre itself. The optical fibres contain a characteristic reflection signal whose defined changes under the influence of temperature and mechanical force are analysed to determine temperature and strain. Special interferometer measurement techniques and defined tunable laser light sources are used to evaluate the light scattered back into the fibre.
Optical frequency domain reflectometry, which uses frequency analysis to evaluate the Rayleigh components in the backscattered light, is well established for applications requiring high spatial resolution in the millimetre range over the entire fibre. The measurement systems consist of a tunable narrow-band laser and a Mach-Zehnder interferometer, with one arm used as a sensor and the other as a reference. By using special analysis techniques and algorithms strains and/or temperatures can thus be continuously recorded over the entire optical fibre (over a length of up to 100 m) with high spatial resolution in the lower millimetre range. Usual optical fibres and optical fibre cables can be used for this measurement technique [27].
Other measurement techniques are used to analyse the Raman and Brillouin components in the backscattered light. These techniques can measure over distances of tens of kilometres, but their spatial resolution is limited [27].
A new technique of interest for spatially resolved strain monitoring is the combination of FBG technology and frequency domain reflectometry. By inscribing a large number of low reflective Bragg gratings of the same output wavelength into the fibre, a better backscatter signal is obtained. Strains of up to 30,000 µm/m can be measured with spatial resolution along a fibre length using frequency domain reflectometry [28].

3.2 EXPERIMENTAL STUDIES USING FIBRE-OPTICAL MEASUREMENT METHODS

3.2.1 Strain Measurement along the Joint of Adhesively Bonded Timber-Concrete Composite Beams for Bridge Construction

A research project [29] carried out at the Bauhaus-University Weimar included component tests on timber-concrete composite beams. The subject of the research project was the investigation of new types of composite joint configurations for timber-concrete composite road bridges with continuous bond between the concrete deck slab and the main timber girders. One of the composite variants investigated was the adhesive connection of the components using tolerance-compensating polymer mortar with mineral fillers. Together with the Materials Research and Testing Institute at the Bauhaus-University Weimar, a fibre-optical measurement system was used in two bending tests (beams HBV-11 and HBV-12), which allowed a nearly continuous measurement of the strains over the entire length of the adhesive joint. Detailed information on the investigated composite system and the results concerning deformation, load-bearing and failure behaviour of the components are documented in [29, 30, 31]. An overview of the fibre-optical measurements of the strains is given below. Further information can be found in [32].

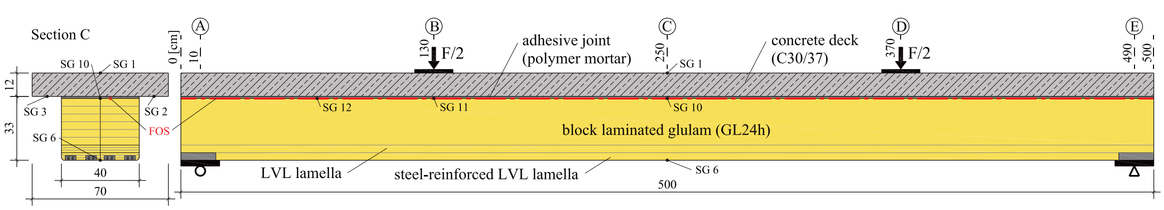

__Figure 3:__ Specimen dimensions of the four-point bending tests with fibre-optical strain measurement along the adhesive joint of the timber-concrete composite beams HBV-11 and HBV-12

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General information on the test specimens and boundary conditions are given in Figure 3. To prevent sudden failure of the wood, the glulam beams were reinforced with both tensile and shear reinforcements. Details can be found in [30]. The adhesive was applied to the full surface on top of the glulam beam over its whole length. The average thickness of the adhesive joint was approximately 13 mm (± 3 mm). The optical sensor fibre was previously applied over a length of 5 m in the area of the composite joint on the timber surface (see FOS in Figure 3) and, in the case of the HBV-12 beam, also in the bending tension zone. Strains along the sensor fibre were already measured using an optical frequency domain reflectometer during the production of the adhesive joint and during the short-term bending test. The global and local deflections were measured according to the relevant standard [33], as well as the relative displacement between timber and concrete components using inductive displacement transducers at different points on the composite beam. In addition, local measurement of longitudinal strains was carried out using electrical strain gauges in the following areas of the composite beam (see Figure 3):

- in the middle of the composite beam at the top and bottom surface of the concrete deck slab (SG 1, SG 2 and SG 3)
- in the middle of the composite beam at the top and bottom surface of the block laminated glulam (SG 10 and SG 6)
- in axis B at the top surface of the block laminated glulam (SG 11)
- in the middle between axis A and B at the top surface of the block laminated glulam (SG 12)

In the four-point bending tests the load was applied displacement controlled in four consecutive load cycles (see Figure 5) until failure at the end of the fourth cycle. Strain changes were detected along the whole length of the fibres during the production of the adhesive joint. Events such as loading due to the application of the concrete deck and strain reduction due to the hardening of the polymer mortar (reaction and cooling shrinkage) were identified.

Figure 4: *Deformed timber-concrete composite beam HBV-12 at the end of the bending test; cracks in the LVL and in the glulam are marked in red*

Figure 4 shows the significantly deformed HBV-12 test specimen. Figure 5 shows the strain distribution determined by fibre-optical sensing in the adhesive layer along the whole specimen for five load levels. Using the optical frequency domain reflectometer, strains between -400 and +700 µm/m were determined up to final bending tensile failure at t = 2442 seconds. The maximum load was 1221 kN.

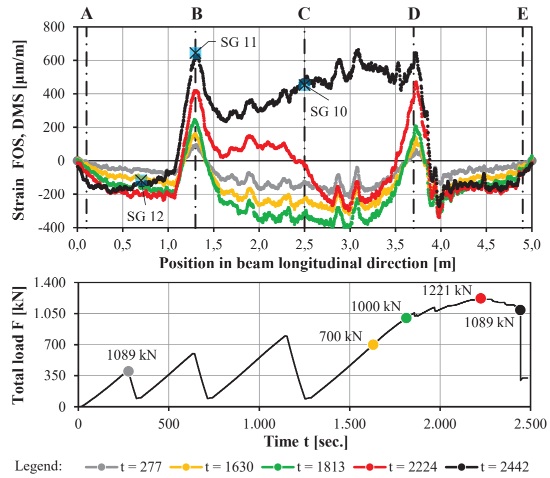

Figure 5: *Strain distribution along the fibre-optical sensor within the adhesive joint of the timber-concrete composite beam HBV-12 for five specific test times (above) and associated load levels (below)*

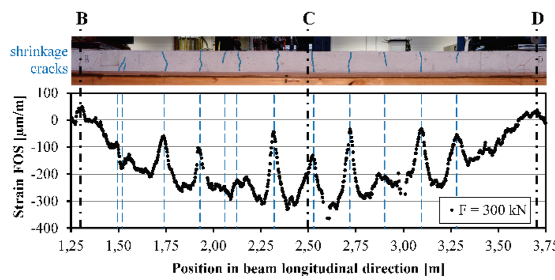

Figure 6: *Correlation between the location of shrinkage cracks within the concrete slab and local peaks in the strain distribution measured with the fibre-optical sensor along the adhesive joint of timber-concrete composite beam HBV-11*

The results of the strain measurements using strain gauges on the one hand and the fibre-optical measurement method on the other showed a high level of correlation (see Figure 5, for t = 2442 seconds). Due to the stiffness of the rigid-bonded timber-concrete composite beam, the sensor fibre is largely within the bending compression area of the undamaged test specimen (negative strains). Local influences, such as the concentrated load application in axes B and D, can be seen as peaks in the strain distribution. Below the load application points, local tensile strains of more than 600 µm/m were measured within the adhesive joint. The location of previously detected shrinkage cracks in the concrete slab correlates with the location of smaller strain peaks along the sensor fibre (see Figure 6). The theoretically

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continuous force transmission is locally interrupted by the existing crack structure, which is clearly demonstrated by the measurement results.
The results of the studies presented here show that it is possible to measure strain values in the adhesive joint over the whole length with a high spatial resolution by using distributed fibre-optical sensors. If the data is correctly analysed and interpreted, it can be used to gain a lot of information. This allows the detection of local events as well as influencing factors from the production process and during the service life.

3.2.2 Optical Fibre Sensors for Strain Monitoring on Bridges

Fibre-optical sensor solutions have sporadically been used for the strain monitoring of bridges. In particular, fibre-optical displacement transducers and FBG sensors have successfully been used to monitor some bridges. In 2016, Roßteutscher et al. showed in the research project ‘i.bridge’ [34] that the deflection and vibration of a concrete bridge in need of repair can be measured using a fibre-optical measurement system based on optical frequency domain reflectometry and Rayleigh backscattering. Optical fibres were applied to the concrete surface, vehicle overpasses were analysed and correlated with sensor data [34]. Distribution measuring sensor systems based on Brillioun scattering have also been used [35, 36]. With this measurement technique, spatially resolved sensor data can be recorded at a distance of approximately 0.50 m. In the investigations by Wosniok et al. [37], the fibre-optical sensors were applied to the surface of the concrete structure of a bridge in Amsterdam. Static loads were induced by controlled truck overpasses, which were detected by the fibre-optical sensors with a spatial resolution of 0.20 m. The temperature compensation was done using unloaded areas of the sensor fibres [37].

3.3 CONCEPTS OF TIMBER MOISTURE MEASUREMENT USING FIBRE-OPTICAL SENSORS

3.3.1 Using the Sorption Method

As shown above, fibre-optical measurement methods are in principle very powerful technologies. They are particularly well-suited to monitoring long structures such as bridges. So far, the technology described has been used to measure strain and temperature in this field of application. It would be a major step forward in structural health monitoring if these methods could be used to measure the timber moisture content. There are different suitable possibilities.
One option is the combination of the sorption method and the fibre-optical measurement method. A humidity-sensitive fibre-optical sensor is required to calculate the timber moisture content from the relative humidity and temperature of a small cavity in the wood. The FBG technology is suitable to make this possible. The cavity could be a notch. The usage of a perforated stainless-steel capillary around the fibre might also be an option.
Normally FBGS are used to measure both temperature and longitudinal strain. To make the FBG sensitive to the relative humidity of the surrounding air a hygroscopic coating of this part of the fibre is necessary. Polyimide [38, 39] or ORMOCER® (organically modified ceramics) [40] are suitable coating materials. The coating induces strains in the FBG structure by hygroscopic expansion if the relative humidity is changing as given by Equation (2) below:

$$\varepsilon_{RH} = \beta \cdot \Delta\mathrm{RH} \tag{2}$$

with ε_{RH} = hygroscopic strain, β = humidity-induced expansion coefficient and ΔRH = change in relative humidity.
The strain ε in Equation (1) could be replaced with the hygroscopic strain ε_{RH}. The result is given in Equation (3) below:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi) \cdot \Delta T + (1 - \rho e) \cdot \beta \cdot \Delta\mathrm{RH} \tag{3}$$

This is only applicable if the fibre is not bonded to the wood and thus mechanical strain is excluded. To separate temperature and relative humidity temperature compensation techniques are necessary, e. g. an additionally temperature sensor close to the humidity sensor. Other techniques enable the separation within a single FBGS [40].
In [41] the development of a fibre-optical sensor is described that is suitable for measuring hygric induced strain, temperature and relative humidity. It is a combination of three FBGs. The humidity sensitive part is a commercially available polyimide coated FBG [42]. The timber moisture content was calculated according to [43]. The sensitivity of the sensor was customised and the temperature influence was compensated. Therefore, this measuring method seems to be a good alternative to established methods.

3.3.2 Using the Hygroscopic Strain of Wood

The other option is to use the hygric induced strain of the wood itself to determine the moisture content. The challenge in this case is to separate the measured signal into its component parts as there are:

- mechanical induced strains
- thermal induced strains
- hygric induced strains

The measured strain combines all of them in a ‘sum signal’. This is described in Equation (4) below:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi) \cdot \Delta T + (1 - \rho e) \cdot (\beta \cdot \Delta\mathrm{RH} + \varepsilon) \tag{4}$$

Using an additional fibre that is unloaded or unloaded parts of the same fibre offer the separation of the thermal induced strain.
The separation between mechanical and hygric induced strain is more difficult. A concept must be developed for the separation taking into account the following aspects:

- strain direction and maximum strain value (swelling and shrinking is much different between grain direction and perpendicular to grain; and also different between radial and tangential wood anatomic direction),
- influence of wood defects like knots, cracks etc.,

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- prevention of swelling and shrinking due to connected components like concrete slabs or perpendicular arranged timber layers.

One option is the definition of a ‘sensor lamella’. As part of the research project ‘HBVSens’ concepts of the described measurement method will be tested in TCC structures.

4 CONCLUSIONS

Structural health monitoring can help to detect potential damage of timber bridges at an early stage and thus to prevent major economic damage. As presented, semi-distributed and distributed fibre-optical sensor methods are good solutions for strain sensing including temperature measurement. At present, the moisture monitoring is often carried out using single-point sensors. The disadvantages associated with this can be overcome by using fibre-optical sensing not only for strain and temperature, but also for moisture. On the one hand, this is possible by combining the sorption method with the use of FGBS. On the other hand, the hygric induced strain of the wood itself could be used to measure the moisture content. Both proposals require further investigations.

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REFERENCES

[1] DIN 68800-1: Holzschutz – Teil 1: Allgemeines. Berlin: Beuth, June 2019.

[2] Willeitner, H.: Kommentar zur DIN 68800-1:2011-10 – Holzschutz – Teil 1: Allgemeines. in: Marutzky R. [Hrsg.] Holzschutz – Praxiskommentar zu DIN 68800 Teile 1 bis 4. 2. completely revised edition. Berlin: Beuth, pp. 9–76, 2013.

[3] DIN 1076: Ingenieurbauwerke im Zuge von Straßen und Wegen – Überwachung und Prüfung. Berlin: Beuth, November 1999.

[4] Niemz, P; Sonderegger, W. U.: Holzphysik – Eigenschaften, Prüfung und Kennwerte. 2. updated edition, München: Carl Hanser Verlag, 2021.

[5] DIN EN 13183-1: Feuchtegehalt eines Stückes Schnittholz - Teil 1: Bestimmung durch Darrverfahren. Berlin: Beuth, July 2002.

[6] DIN EN 13183-2: Feuchtegehalt eines Stückes Schnittholz - Teil 2: Schätzung durch elektrisches Widerstands-Messverfahren. Berlin: Beuth, July 2002.

[7] Koch, J., Simon, A., Arndt, R.W. and Jahreis, M.G.: Diskussion zum Erfordernis der jährlichen Hauptprüfung geschützter Holzbrücken. Bautechnik, 99, pp. 23-31, 2022. https://doi.org/10.1002/bate.202100104

[8] Koch, J.; Simon, A.; Jahreis, M.G.: Effectiveness of structural protection measures for timber bridges – results of long-term moisture monitoring. in: Conference Proceedings of the 4th International Conference on Timber Bridges, CH-Biel/Bienne, 2022.

[9] Gamper, A.; Dietsch, P.; Merk, M.: Gebäudeklima - Langzeitmessung zur Bestimmung der Auswirkungen auf Feuchtegradienten in Holzbauteilen – Schlussbericht F 2962. Stuttgart: Fraunhofer-IRB-Verlag, 2015.

[10] Franke, B.; Müller, A.; Vogel, M.; Tannert, T.: Holzfeuchte-Langzeitmessung - Langzeitmessung der Holzfeuchte und Dimensionsänderung an Brücken aus blockverleimtem Brettschichtholz – Forschungsbericht 2775-SB-01. Biel: Fachhochschule Architektur, Holz und Bau, 2012.

[11] Brischke, C.: Untersuchung abbaubestimmender Faktoren zur Vorhersage der Gebrauchsdauer feuchtebeanspruchter Holzbauteile. Dissertation, University of Hamburg, 2007.

[12] Horn H.: Monitoring five timber bridges in Norway – result 2012. Oslo: Norsk Treteknisk Institutt, 2013.

[13] Simpson, W. T., Equilibrium Moisture Content of Wood in Outdoor Locations in the United States and Worldwide, Forest products Laboratory, Madison, WI, USA, 1998.

[14] Franke, S., Franke, B.; Schiere, M.; Bonifacio, S.; Müller, A.: Monitoring systems for quality assurance of timber bridges. in: Conference Proceedings of the 4th International Conference on Timber Bridges, CH-Biel/Bienne, 2022.

[15] Avery Dennison Corp.: Passive Sensors, A guide to the working principles and usage of our passive sensor products using Axzon Magnus® S2 and S3 ICs. 2021 (available under: https://rfid.averydennison.com/content/dam/rfid/en/products/rfid-products/product-guides/Passive-Sensors-Technical-Guide.pdf).

[16] Vogel, M.; Müller, A.; Andereggen, J.: Gebäudeerneuerung Oberwallis - Teil 3 Gebäudeanalyse und Dokumentation, 2022. https://doi.org/10.24451/t196-gb24

[17] Heite, D.; Englberger, A.; Osterloff, L.; Miebach, F.; Rödel, A.: H_2O-WoodController - Entwicklung eines sicherheitsrelevanten Überwachungssystems für feuchtetechnische Problemstellungen im Holzbau. Stuttgart: Fraunhofer IRB Verlag, 2018.

[18] Kühne, H.; Blüthgen, L.; Thiele, E.; Kuhne, M.; Döring, H.: Bautextilien für dauerhaftes Feuchtemonitoring. in: Holz- und Betonbauwerken, in: holztechnologie 55 (4), pp. 30–36, 2014.

[19] Winkler, C.: Process and material features influencing piezoresistive wood adhesives. Doctoral Dissertation, University of Natural Resources and Life Sciences, Vienna, Austria, October 2021.

[20] Winkler C.; Schwarz U.: Characterization of adhesively bonded wood structures by electrical modification of the bonding system. In: Eberhardsteiner J.; Winter W.; Fadai A. (eds) World Conference on Timber Engineering, Vienna, Austria, 2016.
[21] Schroeder, K.; Ecke, W.; Apitz, J.; Lembke, E.; Lenschow, G.: Fibre Bragg Grating Sensor System Monitors Operational Load in a Wind Turbine Rotor Blade. in: Measurement Science and Technology 17 (5), pp. 1167-1172, 2006.
[22] Zhou Z.; Graver, T. W.; Hsu L.; Ou J. P.: Techniques of advanced FBG sensors: Fabrication, demodulation, encapsulation and their application in the structural health monitoring of bridges. in: Pacific Science Review 5(1): pp. 116–121, 2003.
[23] Peters, K.: Fibre Bragg Gratings Sensors, Chapter 61, p. 1103: in Boller, C.; Chang, F.-K.; Fujino, Y.: Encyclopedia of Structural Health Monitoring, Vol. 2, Wiley & Sons, 2009.
[24] Hadzic, R.; John, S.; Herszberg, I.: Structural integrity analysis of embedded optical fibres. in: composite structures. Compos Struct47(1–4), pp. 759–765, 1999.
[25] Ganß, M.; Barnickel, J.; Kuhne, M.; Beinersdorf, H.; Hildebrand, J.; Bergmann, J. P.; Könke, C.: Zustandserfassung von strukturellen Klebverbindungen mittels faseroptischer Sensoren: Untersuchungen an geklebten Stahl-CFK-Verbindungen. in: Smarte Strukturen und Systeme, p. 51, Tagungsband des 4Smarts-Symposium, ISBN: 978-3-8440-5083-7, 2017.
[26] Peters, K.; Studer, M.; Botsis, J.; Iocco, A.; Limberger; H.; Salathe; R.: Embedded optical fiber Bragg grating sensor in a nonuniform strainfield: Measurements and simulations. Experimental Mechanics 41(1) pp. 19–28, 2001.
[27] Samiec, D.: Verteilte faseroptische Temperatur- und Dehnungsmessung mit sehr hoher Ortsauflösung. in: Photonik (6), pp. 34-37, 2011.
[28] Vlachopoulos, N.; Forbes, B.; Cruz, D.: The use of Distributed Optical Sensing Techniques for Ground Support; Not all Fiber Optic Methods are Similar, Proceedings of the 70th Annual Conference of the Canadian Geotechnical Society Geo Ottawa, Ontario, October 2017.
[29] Rautenstrauch, K.; Kästner, M.: Entwicklung einer ökologischen Straßenbrückenbauweise aus Holz und Beton mit kontinuierlichem Klebeverbund auf Basis (bio-)polymerer Reaktionsharzsysteme – Ein Beitrag zum Einsatz nachwachsender Rohstoffe für Verkehrsbauten. Schlussbericht FNR-Forschungsvorhaben 22000612, Bauhaus-Universität Weimar, 2017.
[30] Kästner, M.: Zum Tragverhalten von Polymermörtel-Klebverbindungen für die Anwendung bei Straßenbrücken in Holz-Beton-Verbundbauweise (Dissertation). Bauhaus-Universität Weimar, 2019.
[31] Kästner, M.; Rautenstrauch, K.: Polymermörtel-Klebverbindungen für Holz-Beton-Verbundbrücken Teil 1+2. in: Bautechnik 98, SH Holzbau, Ausgabe 1, pp. 23–39, 2021.
[32] Ganß, M.; Hildebrand, J.; Beinersdorf, H.; Kuhne, M.; Könke, C.: Monitoring von Klebverbindungen mittels faseroptischem Messsystem – MOFAS. Schlussbericht IGF Vorhaben 17777 BR, Bauhaus-Universität Weimar, 2015.
[33] DIN EN 408: Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties; German version EN 408:2010+A1:2012, Berlin: Beuth, October 2012.
[34] Roßteutscher, I.; Wohlleben, P.; Waizenhöfer, U.: Intelligente Zustandsüberwachung von Brückenbauwerken mit Hilfe faseroptischer Sensoren basierend auf der Rayleigh-Rückstreuung, Fachbeitrag 18. GMA/ITG-Fachtagung Sensoren und Messsysteme 2016, Nürnberg, 10-11.05.2016.
[35] Grosso, A. D.; Inaudi, D.; Bergmeister, K.; Santa, U.: Monitoring of Bridges and Concrete Structures with Fibre Optic Sensors in Europe. in: IABSE Symposium Report, 2001.
[36] Inaudi, D.: Overview of Fiber Optic Sensing Technologies for Structural health Monitoring, Informacije MIDEM 40 4, pp. 265-274, Ljubljana, 2010.
[37] Wosniok, A.; Jansen, R.; Cheng, L.; Chruscicki, S.: Ortsaufgelöste Zustandsüberwachung von Brückenbauwerken mittels faseroptischer Sensoren. DGZfP-Jahrestagung, 2021.
[38] Wang L.; Fang, N.; Huang, Z.: Polyimide-coated fiber Bragg grating sensors for humidity measurements. in: High Performance Polymers—Polyimides Based—From Chemistry to Applications, Ch. 8, pp. 150-166, Ed.: M. J. M. Abadie, INTECH Open Access Publisher, Rijeka, Croatia, 2012.
[39] Makovec, A.; Berruti, G.; Consales, M.; Giordano, M.; Petagna, P.; Buontempo, S.; Breglio, G.; Szillasi, Z.; Benig, N.; Cusano, A.: Radiation hard polyimide-coated FBG optical sensors for relative humidity monitoring in the CMS experiment at CERN. in: Journal of Instrumentation, Vol. 9, p. C03040, 2014. http://iopscience.iop.org/1748-0221 /9/03/C03040
[40] Korenko, B.; Rothhardt, M.; Hartung, A.; Bartelt, H.: Novel Fiber-Optic Relative Humidity Sensor With Thermal Compensation. In: IEEE Sensors Journal 15(10), pp. 5450-5454, 2015. doi: 10.1109/JSEN.2015.2444100
[41] Franke S.; Magnière, N.; Schiere M.; Ferrazzini, T.; Meier, C.; Bossen A.: Einsatz von FBGS im Holzbau - Development and use of optimized Fibre Bragg Grating sensors for long term monitoring of timber components. Final Report No. 2838-PB-01. Bern University of Applied Sciences, Biel, 2016.
[42] Fiber Humidity Sensor. Ed.: O/E Land Inc., Canada, 2021. (available under: https://www.o-eland.com/SensorProducts/OEFHS-100-200%20Fiber%20Humidity%20Sensor.pdf)
[43] Dyken T.; Kepp, H.: Monitoring the Moisture Content of Timber Bridges. in: ICTB International Conference on Timber Bridges, Lillehammer, Norway, 2010.

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