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Development of FBGS-systems for Monitoring Purposes of large Timber Structures

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ABSTRACT: Wood is used nowadays as structural load bearing material for large audacious structures. Only the use of the most recent advances in computer technologies combined with exceptional production quality enabled the achievement of such structures. The creation of such structures nowadays, even though possible, still demands a strong personal commitment of the all parties involved and require exceptional regulations which are accompanied by large safety factors. Application of Fiber Bragg Grating Sensors in monitoring methods for timber structures are not used yet although they are applied already in many other fields of civil engineering for instance. Measurement of two important parameters for timber engineers is investigated in the presented feasibility study: moisture content of the wood and strain. In conventional methods, these two parameters can often not be measured simultaneously and two separate systems need to be used. The study presented here shows that although not many sensors are available on the current market, solutions were found to enable continuous measurement of these two parameters using one single instrumentation system, i.e. Fiber Bragg Grating Sensors.

Keywords: Fibre Bragg Grating Sensor, Timber Engineering, Structural Monitoring, Moisture Content, Strain, Temperature.

1 INTRODUCTION

1.1 Timber in modern day architecture

Through engineering and innovation, wood is used as the main load-bearing material in audacious structures nowadays. Timber elements are used in multi-story buildings across the world such as the H8-building in Bad Aibling, Germany, the 84-meter high HoHo Wien under construction in Austria, and the 18-story Brock Commons building finished recently in Vancouver, Canada. Three dimensional beam or shell structures such as the ones of the Elephant house in Zürich (Switzerland) or of the Pyramidenkogel in Austria, see Figure 1, are currently made out of wood, too. Only the use of the most recent advances in computer technologies combined with exceptional production quality enable the achievement of such structures. Moreover, the use of the latest innovations from the wood industry such as the cross laminated timber or the combination of hardwoods and softwoods lead to structures in which efficiency of material use is continuously improved.

These type of structures push timber engineers, architects and designers, and national authorities to the very edge of the building standards. The achievement of such structures nowadays, even though possible, still requires a strong personal commitment all parties involved. They usually require exceptional regulations which are accompanied by large safety measures including strict inspection procedures.

Figure 1: Elephant house, Zurich zoo, Switzerland (left, foto: Walt+Galmarini) and the Pyramidenkogel, Wörtherlake, Austria (right)

1.2 Monitoring timber structures

In the early years of the new millennium, and especially during the winter 2005-2006, numerous failures of timber structures occurred in Scandinavian countries, Germany, Austria or Poland. These failures could not solely be explained by exceptional climate conditions. They triggered a global awareness of public authorities of the timber construction community, but also of the general public regarding safety of timber, steel, and concrete structures. The reaction came through the European COST Action E55 (2010). Major results of research into structural failure were published in several research reports such as the ones of Frühwald et al. (2007), Blass and Frese (2009) or Dietsch (2009).

Monitoring timber structures is an important method to ensure structural health for the following reasons: a reduction of risk levels associated with the design, ensuring the quality of the construction, increasing the operational safety of the building, reduction of the cost of construction and repair, and optimization of the use of timber. Reliable methods to perform structural monitoring of timber structures are available. Amongst them, the monitoring of the timber's moisture content like in Franke et al. (2012).

In conventional monitoring methods, separate sensors and measuring equipment are needed to measure climate, moisture content, strain, and temperature. Different systems have to be bought, requiring different operating equipment and analysis software. Furthermore, the data synchronization requires an extra step in the analysis. It was expected that that through fiber-optics, these values could all be obtained with one unit and even combined in one sensor. An additional advantage of optical measurement techniques is that data of several gauges along the glass fiber can be transferred through only one cable by multiplexing over long distances without much loss of signal power.

1.3 Development of a hybrid sensor

The concept of the hybrid sensor developed in this project was using the current Fiber Bragg Grating (FBG) technology. This development was conducted aiming at creating a sensor optimized for monitoring the moisture content of timber and its related effects. The project was carried out with the objective to monitor three quantities: moisture content, temperature and moisture content-related strains in wood. The main obstacle was expected to be the measurement of the large moisture content related strains (up to 14%) that wood can induce.

2 MONITORING THROUGH FIBER OPTIC SENSOR TECHNIQUES

2.1 Fibre Bragg Grating Sensor

Like in other sectors dealing with cutting edge materials or high load bearing requirements, long-term monitoring techniques have been developed in the timber industry. The FBG sensor technology is available for use in many industries, however has not yet found its way to dedicated applications in the timber industry.

A FBG is a type of distributed Bragg reflector constructed on a short segment of optical fiber to reflect particular wavelengths of light and transmit all others. The distributed Bragg reflector is a multi-layered structure of material in which each layer has alternating refractive indices. Inscription with an Excimer UV-Laser is used to obtain this short segment of optical fiber which shows alternating refractive indices, see Figure 2.

When a broadband light source is transmitted into an optical fiber containing an FBG, the specific wavelength which meets the Bragg condition is reflected at each grating plane while the rest of the light beam propagates through the grating without optical loss. This Bragg condition can be expressed as such:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

In which

$\lambda_B [nm]$	The Bragg wavelength or the central wavelength of the Bragg grating
n_{eff} [-]	The effective refractive index of the fibre core
Λ $[nm]$	The grating period

The period of the refractive structure is a function of its strain and thermal expansion. To obtain these measurements, the reflected light spectrum is analysed using a spectrometer after which measured peak frequencies are logged.

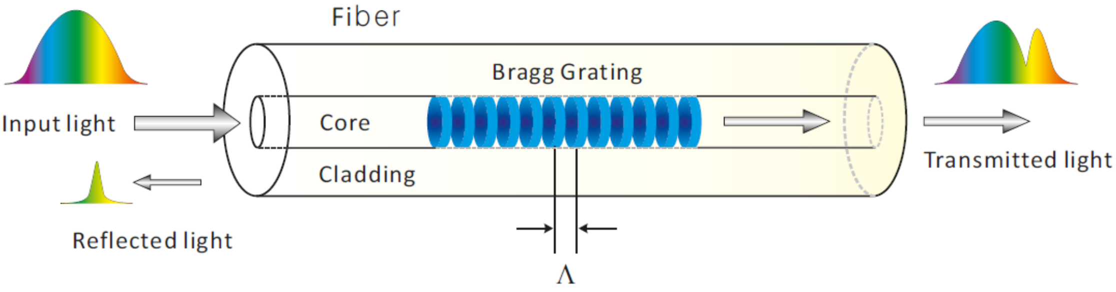

Figure 2: Structure and principle of a Fiber Bragg Grating (Wang et al. (2012)

The following advantages of the FBG-systems are of special interest to the timber industry: FBG sensors do not need calibration and are easy to install, they support multiplexing, they have low transmission loss enabling remote sensing and long line transmission, they are wavelength encoded which means they do not require electricity, their operation does not depend on power fluctuations, and FBG sensors are mass producible and therefore available at reasonable cost. Apart from that, there are disadvantages of which the main is that the sensor is sensitive to temperature variations, i.e. FBG sensors measures have to be corrected for temperature variations.

2.2 Sensor requirements

An analysis of different structures that were to be monitored was made to identify the sensor requirements. Amongst the 26 structures analyzed were four ice rinks, three swimming pools, three sports halls, two production halls, three agricultural buildings and three warehouses, three riding halls, and five bridges, see Franke et al. (2012), Gamper et al. (2013), Franke et al. (2016). The range that needs to be covered by the sensors is given in Table 1. The table gives the needed working, operating, and accuracy values for the temperature, moisture content, and strain measurements.

Table 1: Specification of measuring range, working range and accuracy of the needed sensor

Specification	Relative humidity *%RH*	Temperature *°C*	Moisture content *%*	Strain *%*
Working range	50 to 95	-10 to 50	3.4 to 25.5	± 3.5
Operating range	0 to 100	-10 to 50	0 to 30	± 7.0
Accuracy	0.2	0.1	0.1	0.01

2.3 Measurement of moisture content

The most reliable and accurate method to measure wood MC is the oven-dry method, described in the EN 13183-1:2002. The disadvantage is that the method is slow and destructive. Other methods classified as indirect methods determine the MC by measuring the evolution of other physical properties, such as electrical resistance or capacitance, or from the climate in which the moisture content of the wood piece is in equilibrium. Measurement of moisture content, which can directly be done by measuring electrical resistance between two metal pins, is not possible through fiber-optic measurements. Temperature and humidity are though, and these can be measured in a small void in the wood.

While monitoring five timber bridges in Norway, Dyken and Kepp (2010) developed a method using the development of temperature and relative humidity in a small cavity. They concluded however, that existing methods to calculate moisture content using these two parameters, such as the model by Simpson (1998), could not be applied in this situation. A new model describing the evolution of the MC based on the air temperature and relative humidity in a small cavity was developed, which was also validated experimentally by Pence (2013). It is suggested that these techniques are to be used in a new sensor. Temperature and relative humidity sensors were tested in climate chambers, see chapter 3.

2.4 Measurement of strain

Measuring strains with fiber-optic sensors is currently possible up to 2% strain. This range is too low for most applications in timber, so a new sensor had to be developed to transfer a strain of 7% and 14% to a measurable range. This was achieved by integrating the sensor into a portal, see Figure 3, designed through simple beam elements in Finite Element Methods, that would

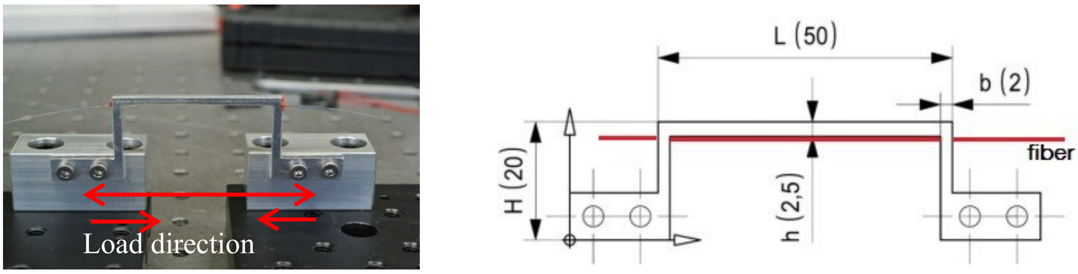

Figure 3: Picture (left) and illustration (right) of the developed sensor bridge with fiber

shift the strain to a measurable range. The figure shows the actual sensor (left) and the schematised representation (right).

The strains measured by the FBG prototype can be calculated from the wavelength shift. The strain sensing unit behaviour is described by the following equation:

$$\Delta\lambda_B\, 10^3 = (\lambda_B - CWL)\, 10^3 = \alpha_{proto}\, \Delta L + \beta\theta + cst \tag{2}$$

With

λ_B [nm]	The wavelength measured through the FBG interrogator
CWL [nm]	The central wavelength of the prototype
α_{proto} [pm/µm]	The sensitivity of the prototype to mechanical strains
ΔL [µm]	The displacement of the base of the prototype
β [pm/°C]	The thermal sensitivity of the prototype
θ [°C]	The temperature of the air
cst [nm]	The internal constant of the prototype

In this equation, the value β represents a thermal expansion factor of the aluminium bridge and the fiberglass sensor.

3 TESTING THE CAPABILITIES OF THE SENSORS

3.1 *Measurement of moisture content and temperature*

Two separate tests were set up to measure relative humidity and temperature. These were both set up in climate chambers of the laboratories of the Bern University of Applied Sciences using sensors produced by Hottinger Baldwin Messtechnik. Along with the sensors being tested separately in climate chambers with different constant environmental conditions, also some measurements were made in realistic ambient climates. The results are observed in Figure 4. The top figure shows the measurement of relative humidity in ambient conditions and temperature measured in a climate chamber on the lower figure. Elprolog© loggers were used with which much experience was gained in earlier monitoring campaigns.

As is seen on the top figure, satisfactory results are obtained within the working range defined in Table 1, although it could be argued that accuracy could be improved with respect to the comparison with the Elprolog.

The temperature sensor also showed a good ability to accurately monitor the temperature of air within the range of -10 °C to +40 °C. Finally, this sensor will be used for multiple functions in the final hybrid FBG sensor developed in this project, these are: the measurement of temperature, and for the correction of measurement of relative humidity and strain. Measurements of temperature and relative humidity will then be used to calculate the moisture content.

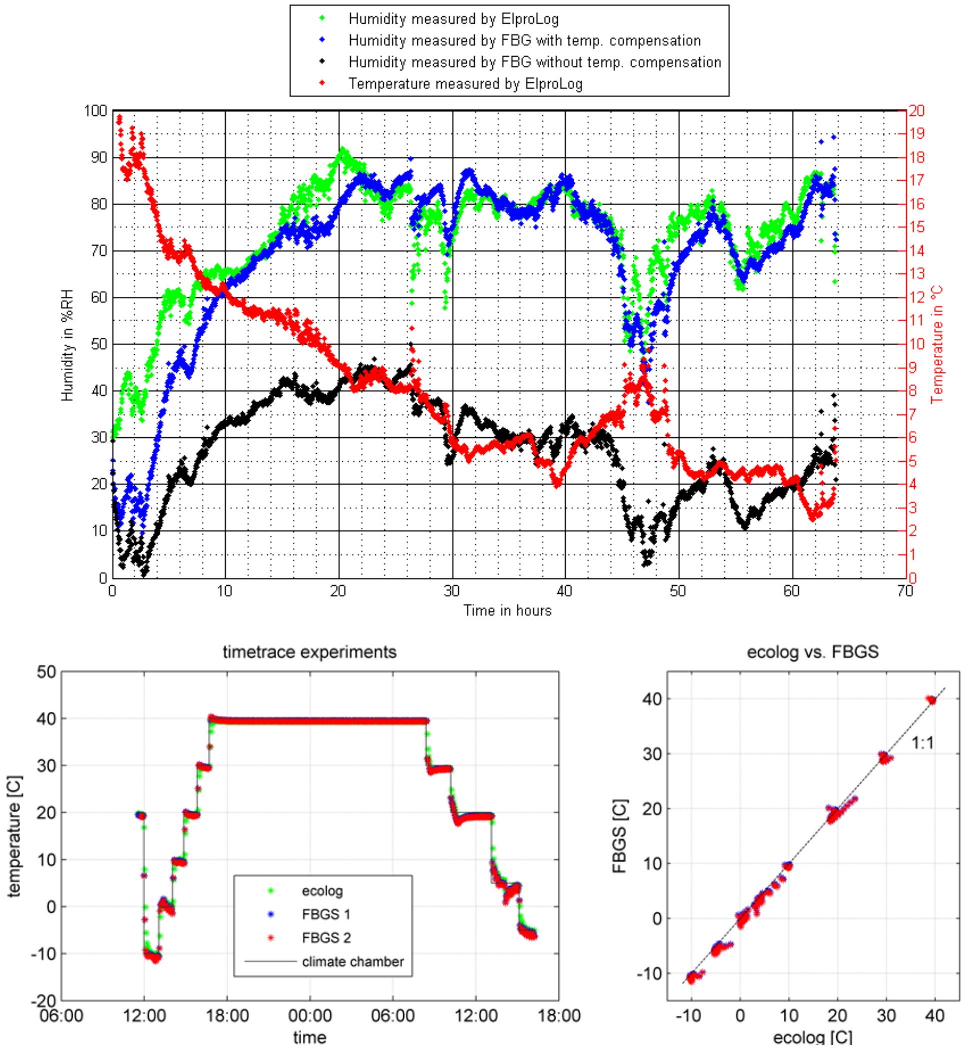

Figure 4: Measurement of the relative humidity (top) and temperature (bottom) with the FBG sensors

3.2 *Measurement of strain*

A bare FBG glass fibre was glued to the bottom of the top beam of the strain sensor bridge. The top beam could stretch and bend freely while the base of the portal was fixed to the timber element. During deformation, the grating of the glass fibre resulted in a shift of the reflecting wavelength. After a prototype was fabricated, laboratory tests were conducted to prove the concept. Where a dampening of a factor 5.3 was expected, a value of only 3.7 was achieved. However, it is expected that this can be improved through modifications in design.

Figure 5 shows the strain time traces obtained from a test in which the sensor bridge was mounted to a piece of spruce wood that was subsequently placed in a climate chamber. Relative humidity was then varied to induce the swelling and shrinkage of timber. The dark yellow line represents the hygro-expansion of the wood according to the equilibrium moisture content of the surrounding conditions, and the dark lines represent the measured strain in which different thermal corrections β were included. The thermal dependency of the FBG strain sensor and

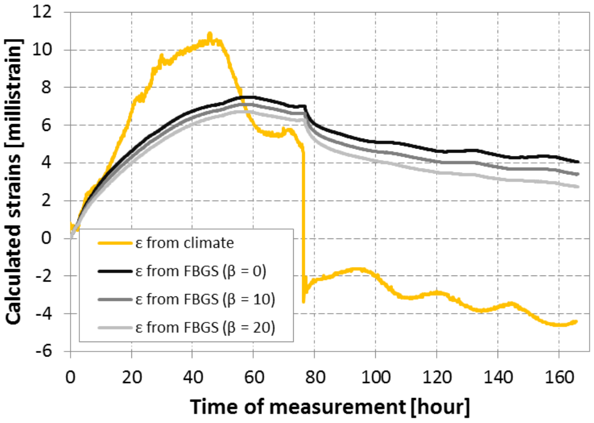

Figure 5: Real strain according to changes in humidity and measured strain

bridge was not measured, but it should be noted that this response is in line with expectations as the deformation of wood shows a delay with respect to its ambient loading.

3.3 Description of the final layout

The hybrid sensor to monitor wooden structures must consist of the following three sensors: a strain, a relative humidity, and a temperature sensor. Moisture content will be calculated from the latter two. Enabling this is possible through the concept shown in Figure 6. It consists of the temperature, humidity, and strain sensing units spliced together and mounted on a baseplate with a dilatation joint. The humidity- and temperature units are fixed on this baseplate, while the strain sensor is able to follow the deformation of the wooden structure. On the right, the integration of the sensor in the structural element is also visualized.

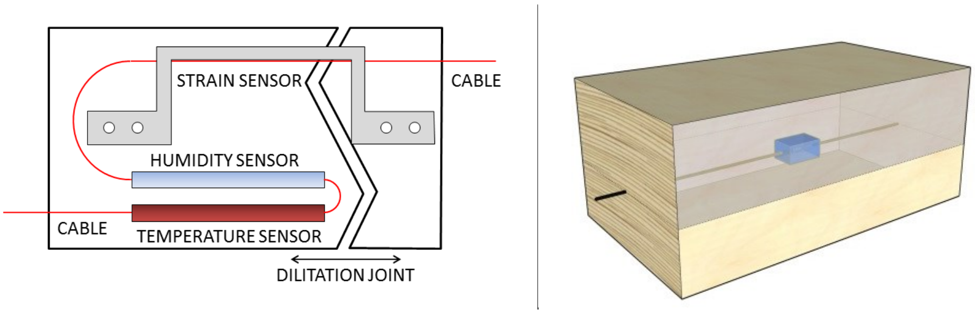

Figure 6: Possible setup for a hybrid sensor and the integration into a structural element

4 CONCLUSIONS AND OUTLOOK

This study showed that the development of a hybrid sensor based on the FBG technology and dedicated to the monitoring of timber elements is possible. Tests and thorough literature study validated the ability of these prototypes to reach the desired specifications. In addition, a concept was developed enabling to combine these three sensing units into a single hybrid sensor which could be used either embedded in the cross section or mounted to the surface of a timber element. Applications in laboratory environments could also be considered.

The FBG technology is currently at a turning point of its development. Positive experience is gained regarding its use in middle to long term performance. As this monitoring technology is already widely used in steel and concrete structures, the step to timber does not seem that large, however sensors are not always available. Dedicated applications of the FBG technology, such as for the measurement of relative humidity and large strains are still in the beginning of their development.

The development regarding the FBG technology itself should not necessarily stand alone, but should also include processing and implementation of the sensing systems into timber structures. The development of the FBG technology for timber should also be integrated to coordinated actions regarding the best-practice dealing with monitoring of timber structures.

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