FIBRE OPTIC MEASUREMENT SYSTEMS FOR BUILDING MONITORING

FASEROPTISCHE MESSSYSTEME ZUR BAUWERKS-ÜBERWACHUNG

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SUMMARY

Fibre optic sensing is a fairly new technology in building monitoring. We present in this paper an overview of the different sub-types and explain the underlying physical principles. The article concludes with an exemplary laboratory measurement and the instrumentation of a reinforced concrete bridge.

ZUSAMMENFASSUNG

Faseroptische Sensoren sind eine vergleichbar neue Technologie in der Bauwerksüberwachung. Wir geben in dieser Veröffentlichung einen Überblick über die verschiedenen Unterarten und erläutern die zugrunde liegenden physikalischen Prinzipien. Der Beitrag schließt mit einer exemplarischen Labormessung und der Instrumentierung einer Stahlbetonbrücke.

KEYWORDS: Fibre optic sensing; building monitoring; SHM

1. BUILDING MONITORING

Civil engineering structures are a vital component of our economy and to the civil society in the whole. This is especially true for infrastructure buildings, and of those first and foremost for bridges, as fundamental links for goods and people. However, numerous of these structures are faced with decay; a challenge for society that has to carry the expense in terms of finance, downtime during repair and rehabilitation but also the generalisation of risk of failure to the public users. The question that has to be answered by engineers is that of how to keep the structures in service, despite their ageing. One major aspect in this respect is the regular inspection, with comprehensive visual testing in the immediate vicinity being the mainstay, and supplemented with various methods of the non-destructive testing portfolio. However, such time-discrete inspections are not fully suitable to dependably detect all faults that may only be visible under certain circumstances, i.e. the ever-changing boundary conditions though traffic loads, temperature, humidity and precipitation, etc. Even more, most structures are not designed in a way to make regular inspection of every critical component feasible; take as example prestressing steel embedded in a concrete girder or bridge bearings closely wedged between the abutment and the superstructure such that access is strongly limited or impossible. It appears only logical that engineers and public agencies increasingly turn to instrumented building monitoring as additional tool, particularly in the light of decreasing financial expense and increasing informative value of such systems. Although building monitoring can certainly never completely replace visual testing, it can, if carried out correctly, bridge the time between inspection intervals by being on-site 24/7, capturing all major events, influences to the structure, and changes in its structural system, and therefore increase the structural and traffic safety as well as its usability.

The concept of instrumented monitoring, i.e. the quasi-permanent surveillance of a structure, is nothing out of the ordinary anymore and has found its recommendation as a supplementary measure for the maintenance of civil engineering structures in many research papers, action reports and official documents. Yet, what is missing so far is a comprehensive, generally accepted, normative or normative-like approach for meaningful instrumentation, although several guidelines for partial aspects have been developed [3], [4], [5], [6]. One reason for this absence is, of course, the essential uniqueness of every civil engineering structure that prevents definitive answers to the questions of sensor quantity, type, placement and measuring interval, how to interpret the data and many more.

For the instrumentation of a structure, a “meaningful” amount of sensors is installed to capture expected changes of the structural behaviour or building materials under the given influences. The choice of sensors and their quantity strongly depend on the selected mechanisms under observation, e.g. crack width, bearing displacement, global eigenmodes, actual loads, etc. The fundamental restriction of all of them is the opposite dependency of spatial resolution and sensitivity. The opening and closing of cracks in concrete, for instance, can be accurately measured to the micrometre. Yet, if a new crack forms just outside the measurement area of the sensor, it may not be captured, no matter its size. An example on the other side of the spectrum is vibration measurements with the determination of eigenmodes. Although this enables the detection of changes in the entire structure with only a few sensors, the extent of the damage must already be quite severe to reflect in the data. This limitation may be overcome to some extent by increasing the number of sensors. Yet, this is usually bought at the cost of a complex and expensive system, which implicates a high wiring effort, vulnerability through the sheer amount of components and therefore costly installation and maintenance.

A relatively new approach in civil engineering is fibre optic sensing. The development is strongly connected to advances in telecommunication, where fibre optic data transmission has become the definite choice for long-distance and high-speed connections. Classical monitoring solutions are based on the translation of sensor data to electric signals, which are then transferred to a data recorder by wire. The disadvantage of this solution is the limitation of the distance between the sensors and the reading unit due to increasing loss of the signal strength, increasing signal-to-noise ratio through electromagnetic interference, and increasingly difficult power supply of the sensors. Some monitoring cases can benefit from a wireless solution, which reduces the need for wiring but comes at the expense of needing a long-lasting local power supply, which in turn limits the data acquisition rate and the number of sensors at each node. In contrast, fibre optic sensing solutions use light to transfer the data between the sensors and the recorder. This approach facilitates, amongst others, a vastly increased transmission range at high data acquisition rates and eliminates the need for power supply at the sensor locations.

2. FIBRE OPTIC SENSING

Fibre optics allow for sensing systems that inhabit low attenuation, high data security, that are small in diameter and weight, are immune to electromagnetic interference and are electrically non-conductive. They are durable and heat and water-resistant and thus suitable for harsh environments. This comes at the cost of not having the possibilities of traditional circuitry without electro-optical conversion and vice versa. Furthermore, the sensing scope in civil and structural engineering is still very limited (mostly to strain and temperature, to some extent also vibration) and costly in comparison to traditional building monitoring.

Measurement systems for fibre optic sensing are composed of four main parts: the light source, the light-transmitting fibre optic cable, the sensor(s) and the light detector. Both the sender and receiver are in the vast majority of cases integrated into one optoelectronic device, the interrogator.

2.1. LIGHT SOURCE

The light source launches an infrared optical signal into the fibre. It is usually a broadband light-emitting diode (LED) or narrowband laser diode (LD) in a spectrum between 780 and 1675 nm wavelength. That is, LEDs emit a whole range of light wavelengths, whereas LDs emit monochromatic, coherent, directional light. The laser is usually operated in a frequency sweep to control the employed wavelengths systematically. The usage and exact characteristics depend on the type of measurement (see section 2.4).

2.2. LIGHT DETECTOR

The light returning through the fibre optic cable is converted into an electrical signal for further digital processing by a photodiode or photodiode array, which is a semiconductor that creates a voltage or current when light falls on it. Analysed are typically the wavelength of the returning light or its intensity distribution over time.

2.3. FIBRE OPTIC CABLE

Attached to the transmitter and receiver is the fibre optic cable, usually made of silica, in rare cases out of plastic. Its function is to guide the light to the optical sensor(s) within or at the end of the cable and back to the receiver.

The underlying physical principle for the guided transmission along the fibre is the total reflection of the light within the core. This requires the cable to have a concentric decrease of its refractive index, which is in the simplest case fibre realised by two distinct layers, the core and the enclosing cladding. The refractive index hereby describes the ratio of the speed of light in vacuum to the speed of light in the optical medium. Therefore, a refractive index of one corresponds to vacuum, whereas higher indices to materials with increasingly higher optical densities. Total reflection of a light beam in the fibre occurs, if the calculative transmission angle Φ_2 in equation (1) is equal to or larger than 90°.

$$\frac{\sin \Phi_1}{\sin \Phi_2} = \frac{n_2}{n_1} \quad (1)$$

For an exemplary fibre with a refractive index of the core of 1,45, and 1,48 of the cladding, the critical incident angle is 11,6° parallel to the main fibre axis.

The light at the source is emitted, simply viewed, in a cone-shaped distribution. That is, it enters the cable not only parallel to the main fibre axis but also in infinite divergent angles within certain acceptance limits. Considering this distribution as bundle of beams, each of them is reflected down the fibre, if the incident angle allows it. However, the light undergoes a phase shift at every reflection. Only some of these phase shifts lead to a constructive superposition, but most of them cancel out over time and distance. The wavelengths of the few remaining beams are a function of the core diameter and the refractive indices of core and cladding and are defined as “propagation modes”. Typical multimode fibres inhabit a diameter of 50 or 62,5 µm, which support about 300 and 1100 discrete modes, respectively [7].

The light in each mode is reflected at a certain angle with respect to the main fibre axis and therefore has to travel different lengths through the cable. Consequently, they arrive at the receiver at different times. This effect is called “modal dispersion”. In addition, the speed of light differs for different wavelengths, and hence also for each mode. The smaller the wavelength, the higher the interaction of the light with the transmitting medium and thus the slower its velocity. This is known as “chromatic dispersion” (in reference to the prismatic dispersion of light into a spectrum of colours). The influence of chromatic dispersion compared to modal dispersion is generally low. Both time-dispersive effects superimpose each other constructively. A short impulse of light, that is sent into the fibre, therefore spreads out with time and distance. This is unfavourable in terms of data transmission, since tight sequential light pulses may overlap due to spreading and in consequence lose their information.

There are several mitigation approaches for this constraint. The simplest are to increase the spacing between consecutive pulses to prevent overlapping or to use LDs with a narrow spectral output instead of LEDs as light source, which decreases the number of modes with the introduced limited spectrum. Both propositions decrease the bandwidth for data transfer by downgrading the time or frequency resolution. A technical improvement tackles the fibre design. To mitigate the effect of modal dispersion, the simple cable structure with two concentric layers and a sharp discontinuity in the refractive index can be replaced by a gradual index reduction within the core from the core axis outward. This kind of optical cable is called “graded-index fibre” in contrast to the so far considered “step-index fibre”. The effects of the variable refractive index in the core are that the additional distance to be travelled by higher modes is decreased, as it is guided on a rather curved instead of a triangular route, and that the light travels at increasingly higher speeds the farther it departs from the core axis. An intelligent fibre index design can therefore very accurately compensate for the slower advance of higher mode light. Additionally, the attenuation due to dispersion out of the core is reduced in graded-index fibres.

Another approach involving the fibre design is the maximum reduction of the core diameter, such that only the fundamental mode can propagate. Typical diameters are around 8 to 10 µm. This kind of fibre is called “single-mode fibre”, in contrast to the so far considered “multi-mode fibres”. With only one mode travelling the cable, none of the mentioned dispersion effects can take place, which allows a very high bandwidth over great distances.

In summary, there are three different types of fibre optic cable in use: the single-mode step-index fibre, the multi-mode step-index fibre and the multi-mode graded-index fibre. Their deployment depends on the type of measurement (see section 2.4).

2.4. FIBRE OPTIC SENSORS

Specific applications in civil engineering require specific sensors and sensor types with certain requirements. The temperature and strain measurement along a pipeline, for example, demands extremely great measurement lengths at rather low sampling rates, whereas the focus on a reinforced concrete bridge might lie on the opening of a particular crack with a required resolution in the µm-range, or the vibration of the bridge deck with a sampling rate of 100 Hz. All of those demands can be met if the right sensor and measurement type is selected.

There are three main sensor type categories, which are not based on their measurement parameters (e.g. strain, temperature), but rather the exploited physical principles, which influence the attainable spatial coverage and resolution with a single fibre.

2.4.1. Local sensors

Local sensors are based on optical interferometry at the end of a fibre. This implies that only a single sensor can be used per cable, which justifies the given designation. It is necessary to use dedicated channels for measuring more than one sensor (“space-division multiplexing”).

Optical interferometry is the superposition of two light beams from a common source that causes typical intensity patterns at some point of observation in dependence on their phase difference. Analysis of these fringe patterns can be performed to determine the relative phase mismatch between the beams and therefore the difference in their travelled distances. Several different interferometer architectures may be applied in fibre optic sensing. Out of those, the Fabry-Pérot and the Michelson interferometers are mainly reported for use in civil and structural engineering [1].

The Fabry-Pérot interferometer is an optical resonator that basically consists of two parallel, semipermeable mirrors in the fibre. An incident light beam is repeatedly reflected in the cavity in-between. Each time, a small fraction of the light exits through the first mirror. All of the outbound beams interfere together and produce a pattern with constructive superpositions that correspond to multiples of the resonant wavelength. This means in reverse consideration that an analysis of the signal amplitude allows a calculation of the cavity length. A variation of the distance between the mirrors, caused for instance by a change in temperature or strain, can thus be measured. Typical cavity lengths are up to the mm-range.

The Michelson interferometer uses a beam splitter to guide incoming light into two separate fibres, one under test and one reference. The light is reflected by a mirror at the end of each arm and recombined in the beam splitter, where the amplitudes superimpose and form a distinctive fringe pattern in dependence on the path difference. The measurement hence always represents the relative change between both beam branches. The advantage over a Fabry-Pérot interferometer is the possibility of a greatly increased (integral) measurement range up to 20 m [1]. Strain measurements on civil engineering structures with Michelson interferometers are per se temperature compensated, since both the stressed and unstressed arms are subject to the same temperature change, which therefore cancels out in the data.

2.4.2. Quasi-distributed sensors

Several sensors of the quasi-distributed type can be placed one after another within a single optical fibre at pre-defined positions. The differentiation between the sensors in a measurement is achieved by tuning their sensitivity to different wavelengths of the incoming light (“wavelength-division multiplexing”).

The by far most common representative of this type is Fibre-Bragg-Grating (FBG). To manufacture an FBG-fibre, a sequence of reflective markers is inscribed in the core at the designated sensor position with an ultraviolet laser. These markers are simply a periodic perturbation pattern of the fibre’s refractive index in the order of 10^{-3} to 10^{-5} within a section of a few millimetres in length.

This index modulation acts as a wavelength-sensitive mirror, on the physical principle of distributed Bragg reflection. That is, incident light with a broadband spectrum is partially reflected at the sensor location. The peak reflected wavelength λ_{Bragg} corresponds to twice the grating period Λ, multiplied by the effective refractive index n_{eff} (the mean – increased – refractive index within the sensor area).

$$\lambda_{\mathrm{Bragg}} = 2\Lambda \cdot n_{\mathrm{eff}} \tag{2}$$

All other parts of the spectrum are transmitted without disturbance and hence available for measurement with other sensors within the fibre.

When an FBG-sensor is subjected to stress that causes elongation or shortening of the fibre, e.g. strain or temperature, the grating period changes and with it the peak reflected wavelength. The observed change in the reflection spectrum can be quantitatively mapped to the desired stress-related variable.

As monitoring with FBGs is based on the shift of wavelengths, it is necessary to leave sufficient spacing between neighbouring reflection peaks in the spectrum, such that overlapping in expectable load combinations is prevented. Typical safe spacing for strain measurements on civil engineering structures would range between 5 to 10 nm, and around 2 nm for temperature. The typical width of a peak lies at about 0,1 to 1 nm.

2.4.3. Distributed sensors

Measurements with distributed sensors exploit the light scattering at the natural small impurities and the constituent silica molecules of the fibre-optic cable. It is not necessary to explicitly introduce individual sensors, since the fibre itself constitutes the sensor. The spatial resolution along the cable is achieved by measuring the travel-time between the transmission of a light pulse and reception of the reflections (“time-division multiplexing”).

Rayleigh scattering is the most commonly known type of scattering, for example as a cause for the blue colour of the sky during daytime and the shift towards red during sunrise and sunset. It accounts for the by far greatest part of attenuation in an optical fibre [7]. Rayleigh scattering describes the elastic interaction of light with the electric charges within the molecules or atoms of the transmitting medium. The passing electromagnetic wave, i.e. the light, oscillates with frequencies f according to the wavelengths λ of the contained spectrum and the specific speed of light c in the medium (equation 3).

$$f = \frac{c}{\lambda} \tag{3}$$

This stimulates the particles to oscillate at the same frequency, which are hereby themselves caused to emit radiation at the same frequency in the manner of electric dipoles. The part of the generated light, which is send back towards the source, is “backscattered” and used for the distributed sensing. The reflections are of incoherent, random nature.

Brillouin and Raman scattering are, in contrast to Rayleigh scattering, inelastic interactions between the electromagnetic wave and the elastic vibrational excitation of the wave carrier’s crystal lattice, i.e. the silica fibre. A typical reason for such periodic lattice deformation is temperature, but it may also be induced by an interaction between the electromagnetic field of a strong incoming light and the dielectric medium. The effect of the lattice excitation is a density variation on a microscopic scale, which is equivalent to a variation in the fibre’s refractive index and hence causes a Bragg-type reflection of light [8].

Brillouin scattering arises from the interaction of the incident light with low-frequency collective lattice oscillations (“acoustic phonons”) with wavelengths larger than the distance between neighbouring atoms. It is therefore dependent on the elastic properties of the transmitting medium. Raman scattering describes the interaction with high-frequency elastic vibrations on an atomic level (“optical phonons”) and is thus influenced by the fibre’s molecular structure.

A characteristic feature of both Brillouin and Raman scattering is a frequency shift of the scattered light, which is caused by the exchange of photons with the fibre. The incident light can dissipate a photon towards a lattice atom, which therefore enters an unbalanced excited state that resolves by reemission of a photon. The emitted photon may be in a higher (“Anti-Stokes process”) or lower energy state (“Stokes process”). This corresponds to an interaction with an elastic wave moving towards or away from the light source, respectively, and alike, to negative and positive wavelength shifts, respectively, according to the Planck-Einstein relation for photon energy (equation 4), with h being the Planck constant.

$$E = \frac{h \cdot c}{\lambda} = h \cdot f \tag{4}$$

The caused shift in the wavelength $\Delta f_{\text{Brillouin}}$ is dependent on the specific lattice (and with it the refractive index) of the wave carrier n_{optical} and the wavelength λ and speed v of the elastic lattice wave (equation 5).

$$\Delta f_{\text{Brillouin}} = \pm 2 n_{\text{optical}} \cdot \left[\frac{v}{\lambda}\right]_{\text{elastic}} \tag{5}$$

The respective shares of Stokes- and Anti-Stokes component intensities are quantitatively correlated with the material temperature. Brillouin and Raman scattering can thus be used for distributed temperature sensing. The dependence of Brillouin scattering on the elastic properties of the fibre furthermore allows a determination of strain along the fibre.

3. LABORATORY TESTING

In a recently conducted 4-point bending test on thin basalt-fibre reinforced concrete slabs (50 x 300 x 1200 mm^3) at the MPA University of Stuttgart, FBG-strain-sensors were applied to monitor the formation of cracks and the mechanical strain. An additional FBG-sensor was used to compensate the temperature changes. Due to the experimental setup, ten sensors with a gauge length of 100 mm each could be mounted to the lower surface of the slab. A 780 mm long section in the middle of the slab could be monitored during the testing by overlapping the measurement areas of the single sensors. The sensors were screwed to 40 x 60 mm large metal plates, which were then glued to the concrete surface with an epoxy resin adhesive. Fig. 1 shows the basalt-fibre reinforced concrete slab in the test setup with all applied sensors. In addition to the fibre optic strain sensors, the deflection in the middle and above the supports was measured with inductive displacement transducers. Due to the FBG's limited measuring range of 5000 µm/m, the sensors were only used until the machine reached 10 mm deflection. At this point in the experiment, several cracks inside the strain-monitored area were visually detected.

In Fig. 2, the measured strain in sections of 100 mm is displayed over the measurement duration. The sensors are according to their specific Bragg-wavelength. The corresponding machine loading is given in kN. The graph of the applied load shows a number of sudden drops while the deflection in the path-controlled test was constantly increased. This suggests that the resistance against the imposed deformation swiftly decreases due to a weakening of the cross-section. This indicates that a new crack has formed.

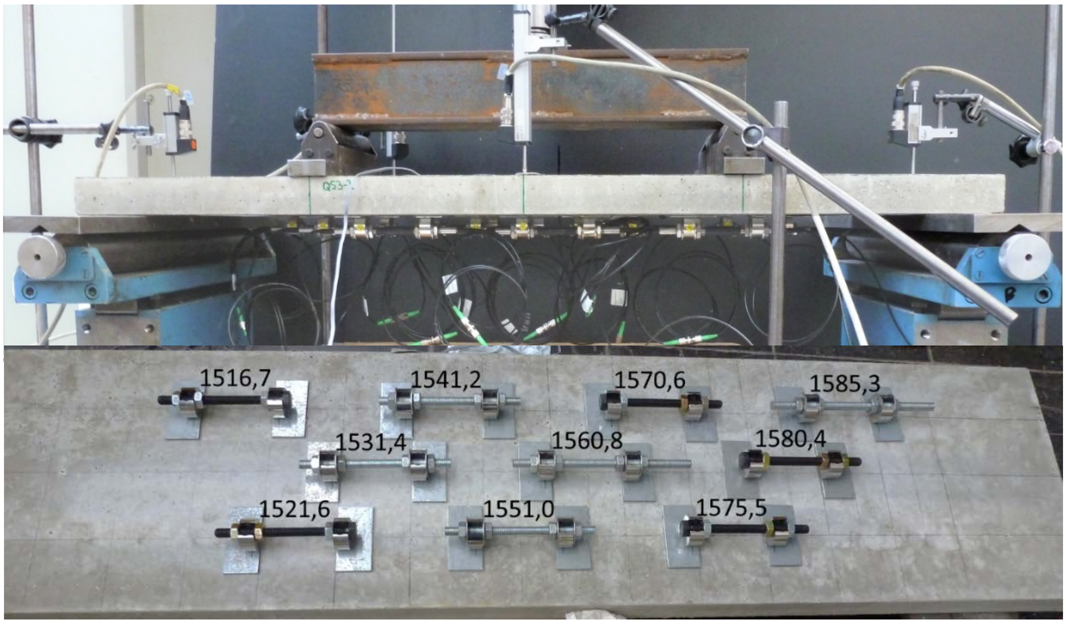

Fig. 1: Basalt-fibre reinforced concrete slab with fibre optic sensors

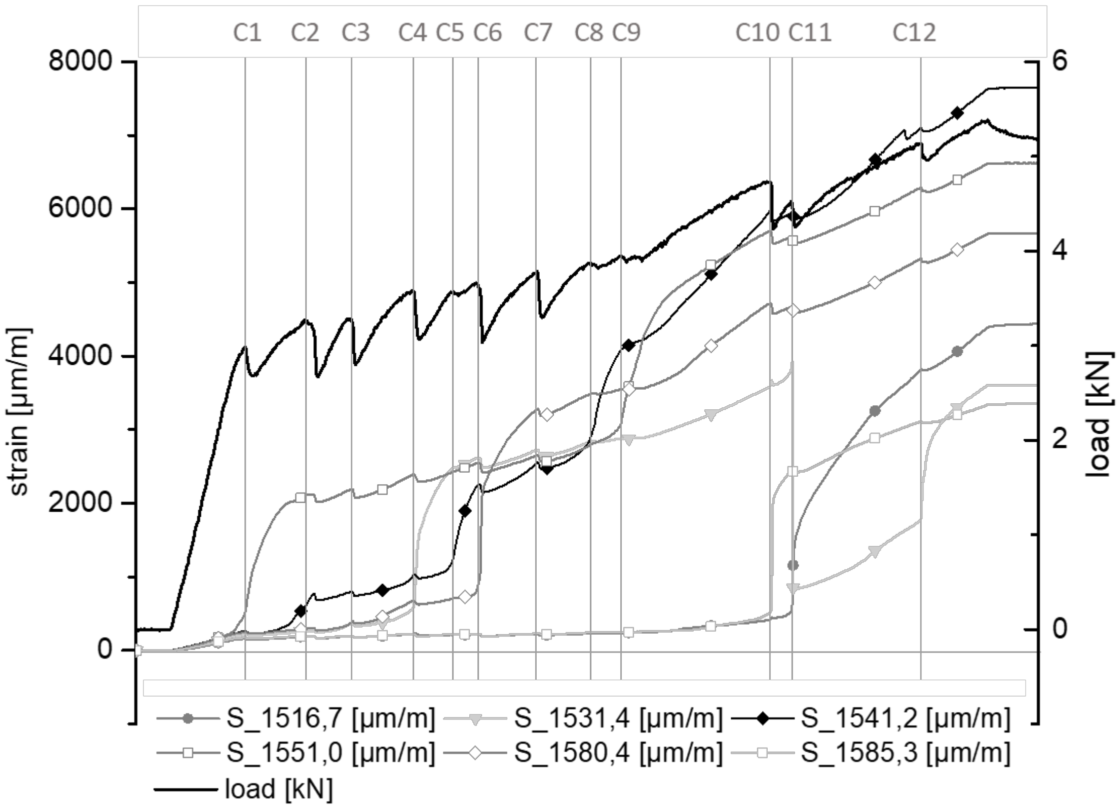

Fig. 2: Strain and load monitoring during the test. The vertical lines C1 to C12 mark the load drops and strain increases that indicate a crack initiation. Only six out of ten strain sensors are shown for better clarity

The monitored strain shows a rise in at least one sensor measurement when the load drops, indicating the crack formation within the gauge length of this specific sensor. Sensor “S_1551,0” shows two significant strain increases, which leads to the interpretation, that more than one crack initiation can be detected by one sensor.

4. APPLICATION ON A REINFORCED CONCRETE BRIDGE

The B27 bridge over the Spitalstraße in Neckarsulm was built in 1964. The concrete hollow cavity plate bridge has three continuous prestressed concrete spans with a total length of 57 metres and a constant height and width of 1,10 and 11,1 metres, respectively, with prestressed cables in both the longitudinal and transverse direction. The two middle supports are singular circular concrete columns. The bridge is crossed on two lanes by around 50 thousand vehicles per day (figure from 2015).

This type of bridge was widely built until the 80’s within Germany’s highway infrastructure. After being subject to numerous inspections and, in some cases, to recalculation procedures throughout the years, this type of structure was found to be susceptible to the following critical aspects:

- The hollow cavities cannot be assessed during visual inspection.
- The actual position of the hollow cavities could have been altered in the construction phase, especially during the concrete pouring and compaction.
- The structures erected before 1967 are critical with regard to shear strength.
- The temperature load case was not fully considered during the design process until 1979, which can be critical to statically indeterminate structures, especially in combination with narrow webs and high slab slenderness.
- Until 1978, the prestressed steel type St 145/160 was broadly used, which is highly susceptible to stress corrosion cracking.

Since these aspects are often not known from plans and hardly inspectable, the deployment of a SHM system to acquire more in-deep knowledge of the structure’s behaviour and its actual damage state is desirable. The SHM of reinforced concrete structures relies typically on strain measurement to assess not only mechanical processes – i.e. deformation, tension distribution, crack formation and opening, and fatigue life of a measured point – but also correlate physical and chemical degradation phenomena. However, the concrete nonlinearity and the unknown location of crack formation, given the brittle behaviour, make it challenging to evaluate these processes using traditional strain gauges that can only measure the exact point where they are placed. Furthermore, a few additional operational problems may arise for electrical sensors, such as the excessive amount of sensors and cables needed to capture the crack development or the delamination of strain gauges from rebars. [1]

On the other hand, systems based on fibre optic technology can provide integrated, quasi-distributed, and truly distributed measurements on or even embedded into the structure, along with extensive measurement lengths [9]. A long-gauge FBG, for example, combined with in-line multiplexing and a high sampling rate provides a full strain history, which can for instance be used to monitor crack formation, prestressing losses or for fatigue analysis.

In this sense, a real-time fibre-optic SHM system composed of strain and temperature sensors was design to continuously monitor the B27 bridge in Neckarsulm. The chosen strain sensor was a long-gauge FBG that can measure the average strain between two fix points with an integrated FBG temperature sensor for temperature compensation. The bridge length was divided into 27 sections of two metres, where one FBG strain sensor with a gauge length of 2,05 m was surfaced mounted on the lower bottom of the bridge at each side, forming two lines of quasi-distributed strain measurement. Additionally, five lines of FBG strain sensors, with seven 1,35 m long sensors each, were mounted at the columns and the midspans.

Considering that each FBG strain sensor has its own FBG temperature sensor, 178 sensors – 89 for strain and 89 for temperature – were mounted. Given the multiplexing characteristics of the FBG technology, the sensors could be divided into eight arrays, each with 16 to 24 sensors connected in series to an eight-channel dynamic reading unit.

With this SHM system, it is expected to acquire a detailed strain and temperature profile of the bridge in order to detect crack formation and track the development of existing cracks; to create alarms in case of extreme events, such as the rupture of prestressed cables; comprehend the influence of the temperature variation in the structure performance; and estimate, with the aid of numerical models, the actual structure damage level and its residual life.

The monitoring is currently under development and it is planned to start the measurements by the end of September 2019.

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