Reliability modelling and testing of optical fiber Bragg sensors for strain measurements

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ABSTRACT

Surveillance of facilities and critical structures by monitoring mechanical strength and integrity is necessary for safety in use. Fiber-optic sensors still have poor industrial acceptance due to their lack of demonstrated reliability and long-term stability. Reliability testing for objects with expected lifetimes of 10 to 100 years has to rely on accelerated ageing procedures. We report on a series of ageing tests of optical fibers and Bragg gratings at elevated temperature, humidity and mechanical stress performed in regard to field applications. Tensile and climate tests were performed with optical fibers embedded in glass fiber reinforced polymers (GFRP) and surface attached to carbon fiber reinforced polymers (CFRP). For surface attached fiber sensors relative humidity was found to be a critical parameter with strong influence on lifetime. A cable-stayed bridge (Storchenbrücke in Winterthur, CH, still under construction) where for the first time two steel cables are replaced by CFRP cables were equipped with optical-fiber Bragg gratings and standard resistance strain sensors.

keywords: optical fiber, Bragg grating, sensor, reliability, testing

1. INTRODUCTION

Strain and displacement are principal quantities of measurement for surveying materials and structures in civil and mechanical engineering. Standard sensing techniques include measurement systems with electrical resistance strain gages, inductive displacement transducers and interferometric and non-interferometric optical sensors. Fiber optic sensors are in principle well suited to complement or even replace some of these methods. Adequate performance with respect to accuracy, measurement range and speed as well as demonstrated reliability and stability over a long lifetime are most important requirements for their broad industrial acceptance. In contrast to some aerospace applications low costs and easiness of use are equally important. Fiber optic Bragg gratings are potential candidates to fulfill all essential requirements.

Several research groups in the US and Europe have successfully applied optical-fiber sensors in civil structures [1-10] (refs. [1, 2] are reviews). Various coatings such as acrylates, polyimides, carbon and metals as well as special mounting schemes [3], have been considered in order to increase lifetime. Many reliability and fatigue problems are the same as already investigated for telecom fibers. Additionally, in strain sensor applications fiber coating and protection must not exclude requirements of adhesion, negligible creep and non-disturbance of the specimen to be measured.

2. RELIABILITY MODELS AND ACCELERATED AGEING TESTS

2.1 Optical Properties

Several techniques are used to produce the periodic index of refraction variations in optical fibers required for Bragg gratings. Current technology favours side writing with UV-radiation using masks or holographic methods. To increase sensitivity and stability either optical fibers are doped with different amounts of Germanium sometimes supplemented with Boron or they are hydrogen loaded before irradiation permitting high reflectivities even with standard fibers. With the presently limited understanding of the microscopic structure (e.g. color center or photodensification models) and the physical
properties of these gratings the different production modes as well as the wavelengths and the range of reflectivity of interest have to be considered in order to obtain a consistent data set for modelling reliability and determining ageing parameters.

The decay of grating strength can be approximated with a power law, which is explainable by a sum of (exponential) Arrhenius decays. A distribution of activation energies with a central value of 2.8 eV and a FWHM of 1.6 eV has been reported for germanium-doped silica fiber [11]. Since the population density in activation energy space is not constant during ageing due to different decay times, data not corrected for preannealing or not considering density of states for different fiber types are not consistent.

For most commonly used production techniques decay has been shown to be small up to 300 °C and for some fibers up to 600 °C after a burn in phase of a fraction of an hour [12]. If properly preannealed, decay of reflectivity over an expected lifetime of 20-50 years is negligible for most applications in telecommunications and civil engineering where temperature is below 80 °C unless influence of humidity and chemical environment (pH-value and cation diffusion rate) drastically would change relevant activation energies through a catalytic effect. Since the strength of gratings is given by a change of index of refraction of $10^{-3}$ to $10^{-5}$ substantial decay may cause an offset drift in strain sensors typically sensitive to 1 µm/m.

2.2 Mechanical Properties

Mechanical strength and fatigue through stress-enhanced crack corrosion has been investigated extensively for telecom fibers [13] without achieving full agreement or understanding of the long term time dependence of the residual strength [14] although there is a broad agreement on the fracture mechanical model to be used. Fiber core and cladding is treated like ceramic brittle material. Degradation from intrinsic strength is explained by surface flaws introduced before coating. Relatively small differences in the n-value cause a large effect in lifetime predictions based on accelerated testing [14].

Effect of coating is usually not considered. Most fiber Bragg gratings are produced by de- and re-coating either mechanically with a large reduction in fiber strength or chemically with a lesser effect. By surface melting and reflow a periodic structure is induced at the surface depending on thermal load during writing [15]. In strain sensor applications not only strength of pristine fiber is of importance but even more adhesion of coating to cladding as well as surrounding glue or specimen. Due to permeability, cation mobility, inhomogenous stress distribution, properties of core, cladding, coating and specimen cannot be treated separately, it also has to be considered that in low cost applications exotic solutions for expensive coatings, Bragg grating production methods or time consuming application procedures are excluded.

3. EXPERIMENTS AND RESULTS

3.1 Experimental Set-up and Data Analysis

We used optical-fiber Bragg grating arrays with 7 elements for distributed sensing of strain and temperature. The sensor arrays were either adhered to the surface or embedded in materials. The arrays of wavelength-stepped Bragg gratings (BGs) used in this work were written into the fiber with a single laser pulse while it was fabricated on an conventional draw tower [16]. The breaking strength of the sensor fibers exceeds 4.8 GPa.

Equations 1 - 3 summarize the sensitivities of optical-fiber Bragg gratings for strain and temperature sensing [17]. A uniform fiber optic Bragg grating (BG) with a grating period of $\Lambda$ and a mean refractive index of $n$ reflects at a Bragg wavelength of $\lambda_B$. The axial strain sensitivity depends on the effective elasto-optic coefficient $P_E = 0.204$ which includes the geometrical length change and the elasto-optic effect of the fiber. For the temperature sensitivity the thermo-elastic coefficient $\alpha = 0.55 \cdot 10^{-6}/K$ and the thermo-optic coefficient $\xi = 8.3 \cdot 10^{-6}/K$ of the fiber have to be considered.

\[
\lambda_B = 2n\Lambda \quad (1)
\]
\[
\frac{\Delta \lambda_B}{\lambda_B} = (1-P_E)\Delta \varepsilon \quad (2)
\]
\[
\frac{\Delta \lambda_B}{\lambda_B} = (\alpha+\xi)\Delta T \quad (3)
\]
Figure 1 shows the detection scheme used for the measurements of the temperature or strain induced Bragg wavelength changes. The light of a superluminescence diode (SLD, $\lambda = 830 \text{ nm}$) is coupled into one arm of a fiber optic 3dB coupler and passes to the optical-fiber Bragg grating array from which only light corresponding to the individual Bragg wavelengths is reflected. Wavelength read-out was performed with a 0.5m-spectrometer equipped with a CCD-array as detector. For absolute wavelength calibration a spectral lamp was used. By measuring simultaneously the wavelengths of the spectral lamp and of the Bragg gratings first the absolute wavelength of the Bragg grating can be regained at any time and second any temperature drifts of the spectrometer can be compensated. The spectrometer was designed to have a wavelength step per CCD-pixel of $\Delta \lambda = 36 \text{ pm} / \text{pixel}$. The Bragg reflection curves were further processed and this resulted in a wavelength resolution of $\Delta \lambda = 1 \text{ pm}$, which corresponds to a strain resolution of about $\Delta \varepsilon = 1 \mu \text{m/m}$ or a resolution in temperature of $\Delta T = 0.1 \text{ °C}$ in the free fiber.

3.2 Storchenbrücke Winterthur

In Winterthur, Switzerland, a cable-stayed and suspension road bridge (Storchenbrücke) is currently under construction. For the first time one pair of the twelve traditional steel cables was replaced by two carbon-fiber-reinforced polymer (CFRP) cables [18]. The properties of CFRP include excellent corrosion resistance, high specific strength and equivalent modulus, and outstanding fatigue behaviour. It is necessary to monitor the behaviour of such new structures during installation and lifetime.
Both CFRP cables on the bridge were equipped with optical-fiber Bragg grating strain and temperature sensors to monitor the loading of the cables during construction of the bridge and to surveille its behaviour during traffic load and seasonal fluctuations (see Fig. 2.). We also installed standard electrical resistance strain gauges and temperature and humidity sensors for comparison. A laboratory CFRP cable set-up was built and equipped with identical sensors to simulate load state and climatic environment on the bridge.

Tensile and climatic tests with embedded and surface attached optical-fiber Bragg grating sensors were performed to test lifetime and reliability of the sensor fibers, the epoxy bondings, and the protection of the sensors against environmental influence. Preliminary results are presented in section 3.3 and 3.4.

Each of the two CFRP cables has a length of 35 m and is assembled in a specific pattern of 241 individual 5 mm-diameter wires. Three Bragg gratings were installed on three of the outermost wires in a circle equally spaced. This arrangement tests the symmetry of the axial load on the cable as it is uniformly loaded by its own weight. For temperature compensation and monitoring of long term drifts four reference Bragg gratings were mounted in the vicinity of the measuring gratings on separate CFRP-wires. Two of these reference gratings were pre-strained to a level of 2500 µm/m which is the median strain the CFRP cables experience. With this approach information can be obtained about delamination of the fiber coating or the epoxy adhesive due to environmental influence leading to wrong strain measurements. The installation of the electrical strain gauges followed the same scheme. During transport and installation of the CFRP-cables neither an optical-fiber nor an electrical sensor failed.

![Graph of measurements during different construction stages of the bridge](image)

*Fig. 3. Overview of measurements during different construction stages of the bridge.*

In Fig. 3, first results are given for measurements made at different construction phases of the bridge. The measurement points correspond to the following events: after installation of gratings (with straight cables), after fixation of cables on bridge, after first load, after concreting the first section of the bridge. The agreement with the measurements of the electrical strain gauges is good.

Due to different thermal expansion of steel and CFRP the load on the CFRP-cables will increase during hot periods in summer and vice versa. This is demonstrated in Fig. 4 where the measurements during a three-hour period in the morning, i.e., with increasing temperature, are shown. The temperature starts to increase and consequently relative humidity in the cable decreases. The drift of the reference grating (BG2) was used to compensate for temperature drift therefore the indicated increase in strain (see active gratings BG1, 4, and 7) is due to the re-distribution of load between the steel-cables and the CRFP-cables. BG3 is another reference sensor while BG5 and 5 are the prestressed sensors.
3.3 Tensile Tests

We performed tensile tests with surface attached fibers on CFRP-wires and with fibers embedded in glass fiber reinforced polymer (GFRP) test specimens to simulate various parameters influencing measurements with embedded fiber-optical sensors in GFRP objects. From literature it is known that improperly embedded optical fibers may degrade the structural performance of composite materials [19, review]. Tensile tests at 25 °C and 50 % rh were performed. Similar tests under different environmental conditions are in progress. Some climate tests are described in chapter 3.4.

GFRP (0/90)_{12} specimens of 360 mm x 25 mm x 2 mm were fabricated. Between the 4th and 5th and the 8th and 9th laminate two fibers were embedded. Samples with multi-mode fibers, single-mode fibers, and with single-mode fibers containing Bragg gratings were investigated.

Curing was performed at a temperature of 120 °C and a pressure of 3 bars for 4 hours. By simply monitoring the signal intensity through the embedded fibers thermal deformation and the build up of residual stresses can be observed. Multi-mode fibers showed a transmission loss of 15 % during the first few minutes, afterwards the intensity remained constant. The transmission of single-mode fibers remained nearly constant during curing. Also the reflectivity of the embedded Bragg grating did not change. The failure strain of GFRP-specimens (without fibers) was determined to be 2 % (corresponding to a load of 29 kN) at a velocity of 1 mm/min and 1.8 % at 0.1 mm/min. Therefore the tensile tests were performed at strains up to 1 %.

Figure 5 shows the transmission of a multi- and single- mode fiber during a stair-step loading test from 0.1 % up to 1 % strain with release down to 0.1 % between each step. Transmission of the multi-mode fiber increased continuously. This indicates a re-arrangement of the GFRP fibers and of the optical fiber resulting in a smaller microbending effect and thus decreasing attenuation of the higher order modes. This re-arrangement was not observed in the transmission of the single-mode fibers due to their smaller microbending sensitivity but the attenuation of the single mode by the GFRP fibers resulted in a small decrease of transmission at higher load.

The transmission of the single-mode fibers decreased continuously during a constant load of 16 kN (1 % strain) indicating that at this strain level the GFRP material is not in a steady state. This was also observed with independent acoustic emission measurements which were made simultaneously.
Fig. 5. Transmission of a) multi- and b) single-mode fiber during increasing load.

Fig. 6. GFRP probe. Splitting of Bragg reflection peaks of embedded (left) and surface attached gratings (right).

The Bragg wavelength change of the embedded grating in GFRP test specimen indicated the curing state; the changes were predominantly due to the temperature changes during curing. After curing peak shape changed from a symmetric to a
slightly asymmetric form caused by handling of the test specimen. During the tensile tests up to 1% strain the asymmetry increased and the peak splitted into two (see Fig. 6) indicating a non-uniform strain distribution over the 7 mm long Bragg grating. We assume that the 90° crossed fibers induce this non-uniformity. The splitting of the peak was also observed for a surface attached grating, but it appeared at a higher strain level.

A CFRP probe with 3 wires was specifically prepared for the simulation of the conditions on the Storchenrücke. We performed stair step tests, continuous cycling tests, and constant load tests at room temperature and 50% rh. In future tests the probe will be aged at higher temperature and relative humidity. Figure 7 shows the results of the stair step tests. Electrical and optical strain measurements are in good agreement. The main differences are due to the slightly asymmetric fastening of the three wires which were loaded simultaneously. A constant load of 25 kN (3000 µm/m) was applied during 5 days (see Fig. 8). The strain measurements of the optical-fiber Bragg gratings and of the electrical resistance gauges remained constant.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig7.png}
\caption{Stair step load test of CFRP probe (strain vs. load).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig8.png}
\caption{Constant load test of CFRP probe.}
\end{figure}

3.4 Climatic Tests

Many authors of optical-fiber sensors claim robustness and reliability without specifying the environmental conditions. Moreover, the sensors should not be considered alone but for each application test object and sensor have to be treated as a
system, e.g., the reliability will strongly depend on whether the sensors are surface attached or embedded, or on the type of fiber coating and protecting scheme, and the stress state.

One of our target applications is the measurement of strain distribution in steel tubes or vessels containing steam or hot water. The objects to be measured may be already manufactured so the sensors have to be surface attached. We tested several high temperature glues and epoxy adhesives in a pressure cooker test, i.e., the water temperature was increased from 25 °C to 120 °C and to a final pressure of 2 bars. Most of them failed, as expected, shortly after exposure to humidity, i.e., strain transfer from steel to a fiber sensor failed.

One of the tested high temperature epoxies worked in this temperature regime and was used to attach optical Bragg gratings to measure moderate strains up to 1000 µm/m. In Fig. 9 a) measurements of thermal strain of a steel bar in a dry oven are compared to those made in a pressure cooker. The agreement is very good. From a linear fit the thermal expansion coefficient of the tested steel was found to be \( \alpha = (9.55 \pm 0.15) \times 10^{-6} / \text{K} \) in both cases. From the measured Bragg wavelength changes \( \Delta \lambda / \lambda \) the thermal strain was calculated by taking into account the thermo-optic and thermo-elastic effect of the fiber and the strain sensitivity of the bonded Bragg grating sensor (see Eqs. 1-3). The experiment failed when a steel bar was first pre-strained to about 1300 µm/m. At a temperature of 100 °C the fiber slipped through the adhesive(Fig. 9 b)). The temperature was further increased up to 120 °C and then decreased. The adhesive partially recovered and could again hold the fiber at temperatures below 90 °C. When further decreasing the temperature the Bragg grating was now under compression.

Several adhesives have been tested in less harsh environments to simulate the conditions experienced at the Storchenbrücke in Winterthur. Technical reasons only allowed the installation of Bragg grating sensors before tensioning the carbon fiber cables. Therefore, the sensors will be under median tensile strain of about 2500 µm/m during their lifetime. The

\( \text{Fig. 9. Thermal strain of steel measured in dry oven and in a pressure cooker at 100 % rh a). Adhesion loss between epoxy adhesive and prestrained fiber(-coating) at elevated temperature b).} \)
environmental conditions in the cables are expected to be in the range of -40 °C up to 70 °C and 50 % - 70 % for relative humidity.

![Graph showing cumulative slippage of pre-strained fiber glued at a CFRP-wire through epoxy at 85 °C and 85 % rh.](image)

**Fig. 10. Cumulative slippage of pre-strained fiber glued at a CFRP-wire through epoxy at 85 °C and 85 % rh.**

Optical fibers with different coatings (acrylic, polyimid) were strained to a level of 5000 µm/m. The pre-strained fibers were glued to carbon fiber rods with nearly zero thermal expansion identical to those used in the Storchenbrücke. We always used pairs of 10 mm long glue lines separated by a region of 10 mm and a pre-strained fiber of length 360 mm in between. The fibers were cut in the separating regions after curing. The changes of the obtained gaps were used as measures of the remaining tension of the fibers, i.e., creeping of the glue or slipping through the adhesive would result in a wider gap which could be easily measured with a microscope.

A typical loss of tension during a climatic test is shown in Fig. 10. The tested epoxy adhesive is widely used in civil engineering for fixing carbon fiber materials. Four fibers with acrylic coating were prepared as explained above. In a first step after curing they were exposed to ambient air (T = 23 °C, 50 % rh) for a period of 24 h during which the initial gap width remained constant within the measurement resolution of 0.03 mm. Two of the prepared specimens were then exposed to a 85 °C / 85 % rh test whereas the two others were put into a dry oven of the same temperature for comparison. After 24 h of exposure the fibers in the climate chamber lost 60 % of their initial tension and came to nearly zero after 120 h. The residual tension at the end of the test cycle was obtained by cutting the strained fiber and measuring the width of the new gap. The samples in the oven lost about 17 % after the first 24 h hours but remained stable afterwards. However, putting them into the climate chamber showed that this dry heat curing process does not prevent the slippage of the fiber through the adhesive when exposed to a high relative humidity.

The presence of water does not only influence the adhesion properties of the epoxies but also of the fiber coatings. When using a relatively stable epoxy glue the acrylic fiber coating split in two parts and exposed the bare fiber (see Figs. 11 a, b). A possible reason is the diffusion of water through the coating and the build-up of a water layer at the interface between coating and fiber which is reducing the adhesion. In the two SEM-pictures the coating-fiber interface (Figs. 11 c, d) of a climate tested sample (85 °C / 85 % rh) is compared to a room-temperature sample. For polyimid coatings no splitting was found but at some locations the coating was slightly damaged.

The diffusion of water through the coating will certainly alter the ageing behaviour of the sensor fiber. Crack corrosion of glass cladding is accelerated by stress, elevated temperature and humidity. We performed preliminary tests with standard
telecom fibers to study the influence of these environmental parameters on life-time of fibers. Fibers wound around a drum of 200 mm in diameter experiencing a strain difference of about 300 μm/m from core to cladding surface were aged at a relative humidity of 85 % rh and a temperature of 85 °C, 110 °C, and 125 °C, respectively. Tensile strength was measured by a test apparatus which continuously measures force and displacement during pulling. For load introduction the fibers were fixed on wheels of 40 mm diameter; the tested length was 250 mm. Tensile strength of new fibers was found to be 4.6 GPa. They could be strained to about 6.6 %.

Figure 11. Deterioration of acrylic coating during accelerated ageing at a temperature of 85 °C and relative humidity of 85 % rh. SEM picture a) shows the exposed fiber, picture b) the fracture of the acrylic coating, c) the gap between coating and fiber of an aged fiber and d) the smooth transition for a non-aged fiber-coating interface.

Figure 12a shows the decrease of median tensile strength during the first 24 h. At each temperature the decrease reaches a plateau. At a temperature of 125 °C (85 % rh) a decrease of 24 % is reached already after 1 h of ageing time, a value reached after 6 h at 110 °C / 85 % rh. Modelling the influence of temperature on the time necessary to reach a certain loss of tensile strength with an Arrhenius equation, i.e., an exponential factor with the inverse temperature in the exponent, first rough estimates of acceleration factors and life times can be obtained. For a 12 % loss of tensile strength (still in the linear part of all three ageing curves) an acceleration factor of A = 2500 was obtained for ageing at 85 °C / 85 % rh compared to ageing at 25 °C / 85 % rh (see Fig. 12b). This means, that a fiber with a bending radius of 10 cm will experience a loss of 12 % in tensile strength in a time of about 7 years. At lower relative humidity, e.g., at 50 % rh, this time is expected to increase by a factor of 3, following the (rh)^-2-law for polymer coatings [20]. With the present preliminary and limited data set, these numbers have a large uncertainty.

A strain difference of 300 μm/m is however only 1/10th of the constant strain the sensor fibers installed in the Storchenbrücke experience. Experiments at 85 °C / 85 % rh with fibers loaded to 1 % strain showed that 85 % of the fibers broke in the first 12 h of the climate test. Time to failure is modelled by a power law in the applied stress.
More experiments have to be done in order to obtain more accurate data on the reliability of fibers and Bragg gratings under environmental conditions relevant to sensors. Especially adhesive problems and coating types (acrylic, polyimid, metallic or carbon coatings) have to be studied. Fibers and sensors should not only be treated separately, but have to be studied also as a system including the main parameters of the target application.

**Fig. 12. Loss of tensile strength during accelerated ageing at elevated temperature and humidity a) and estimated time for a loss of 12% in tensile strength at 25 °C b).**

4. CONCLUSIONS

Reliability and long term stability of optical fibers and Bragg gratings are of prime importance for their application as strain sensors used to surveille safety critical structures. Present data does not allow to safely predict expected lifetime. The many variables of fibers, coatings, Bragg grating types, preannealing and testing conditions employed and their expected non-linear dependence do not provide a consistent set of data. To enhance usefulness and comparability of results testing conditions and procedures have to be better harmonized. With today's limited physical understanding of the ageing process of fiber Bragg sensors lifetime testing has to be performed with a well defined parameter set relevant to the actual sensor application and environmental condition. Acceleration factors due to elevated temperature, humidity, cation concentration and mechanical stress level have to be considered.
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6. REFERENCES

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