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ANALYSIS OF THE ACCURACY OF FIBRE-OPTIC STRAIN GAUGES

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Abstract. In recent years, the field of structure monitoring has been making increasing use of systems based on fiber-optic technologies. Fiber-optic technology offers many advantages, including higher quality measurements, greater reliability, easier installation and maintenance, insensitivity to the environment (mainly to the electromagnetic field), corrosion resistance, safety in explosive and flammable environments, the possibility of long-term monitoring and lower cost per lifetime. We have used SOFO fibre-optic strain gauges to perform measurements to check the overall relative deformation of a real reinforced concrete structure. Long-term monitoring of the structure revealed that the measurement readings obtained from these fibre-optic strain gauges differed from each other. Greater attention was therefore paid to the calibration of the fibre-optic strain gauges, and to determining their measurement accuracy. The experimental results show that it is necessary to calibrate SOFO strain gauges before they are used, and to determine their calibration constant.

Keywords: fibre-optic strain gauge; SOFO system; calibration; accuracy.

1. Introduction

During the lifespan of building structures, changes take place in the volume of the structure due to the effects of external loads from the surrounding environment. A whole range of sensors, working on various physical principles, are used for monitoring these changes. The most widely used deformation sensors include resistance strain gauges, capacity and induction displacement sensors, and video strain gauges. A disadvantage of these standard displacement sensors is that they cannot be integrated into the internal part of the structure or into fresh concrete structures. These sensors therefore cannot be used to monitor the behaviour of building structures during the concrete casting process or immediately after the casting operation. In recent years, fibre-optic measuring methods have been introduced for monitoring the behaviour of concrete structures. Strain gauges of this type use the capability of optical fibres to transmit optical radiation in the direction of their centreline. The radiation is transmitted by means of the reflection of light at an interface between two environments with a different reflection index [1]. The principle of fibre-optic sensors is derived from various physical phenomena. An example is the Fibre Bragg Grating (FBG) reflector,or sensors on the basis of the Fabry-Perot or Michelson interferometer etc. The main advantage of fibre-optic strain gauges is that they can be installed directly on the reinforcement steel of the structure. This enables deformations in the structure to be monitored right from the concrete casting operation. Other advantages of these sensors are their higher quality, reliability and measurement accuracy, easier installation and maintenance, electromagnetic resistance, resistance against corrosion, and the opportunity to carry out long-term monitoring of the structure. Strain gauges of this type can be used for monitoring the behaviour of a whole range of building structures, e.g. bridges, tunnels, dams, power stations, buildings, piping systems, interactions between old and new concrete, etc. [2].

In 2008, the Klokner Institute of the Czech Technical University in Prague acquired a SOFO measuring system for measuring static quantities, with SBD ver. 6.3.53 measuring software and SOFO fibre-optic strain gauges of various active lengths, produced by SMARTEC S.A. Four of the fibre-optic strain gauges, together with the measuring system, were used to perform measurements to check the overall relative deformation of a real reinforced concrete structure. Long-term monitoring of the structure revealed that the measurement readings obtained from these fibre-optic strain gauges differed from each other. Greater attention was therefore paid to the calibration of these fibre-optic strain gauges, and to determining their measurement accuracy.

2. Description of the experimental equipment

In the experimental part of our work, we analysed the measurement accuracy of SOFO long-fibre strain gauges, produced by SMARTEC S.A. Fibre-optic strain gauges of this type works on the principle of the Michelson interferometer. The SOFO measuring system for static quantities with SBD ver. 6.3.53 software from SMARTEC S.A. was used to record the measurement readings. The SOFO measuring system comprises a SOFO long-fibre sensor and a

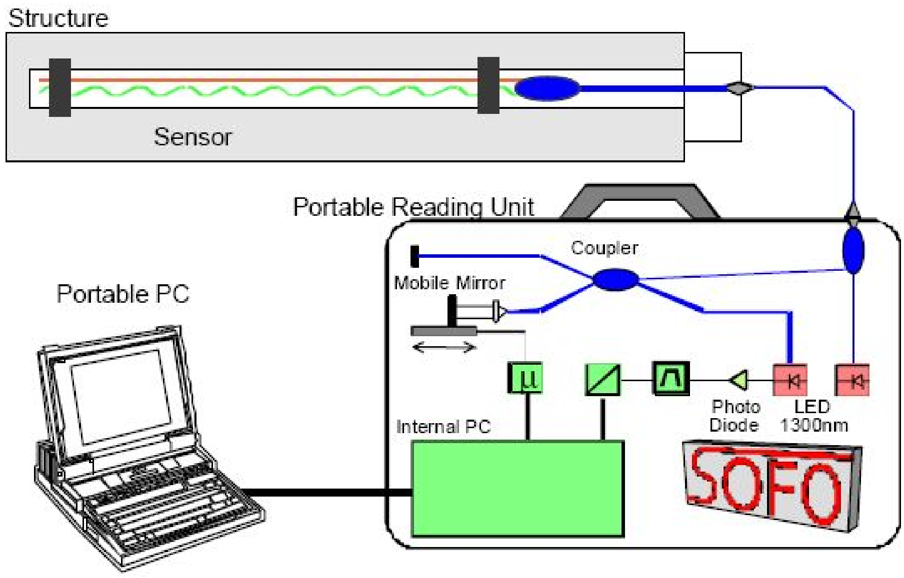

Figure 1. Configuration of the SOFO system for measuring static quantities [3].

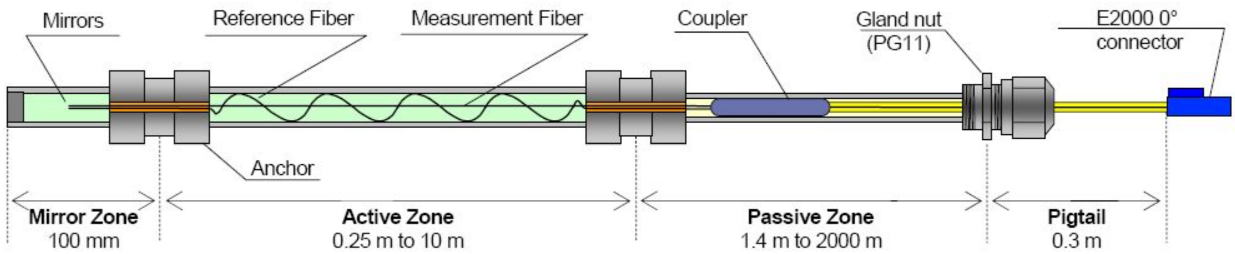

Figure 2. Design of the SOFO long-fibre strain gauge [5].

portable reading unit, and this whole system can be connected to a control computer with software. A schematic drawing of the configuration of the SOFO measurement system for measuring static quantities is illustrated in Figure 1.

The SOFO fibre-optic strain gauge comprises two parts — the active part and the passive part. The active part is formed by a polyamide tube, inside which a measuring and reference optical fibre is installed. The active part is available in the length range from 0.25 to 10 m. This part of the system is a so-called Michelson interferometer. The passive part is composed of a fibre-optic connection cable, which is available in lengths up to 50 m. The cable connection ends are fitted with E-2000 optical connectors (Figure 2). The measurement range of this strain gauge is 0.5 % of the active length when shortened, and 1 % when extended. The working temperature range of the passive part is −40 °C to +80 °C, and the range of the active part is −50 °C to +110 °C. The SOFO fibre-optic strain gauge is connected by the optical connection cable to the measuring unit containing a Michelson interferometer, which is referred to as the reference interferometer. This measurement system provides deformations in absolute values by comparing data from the measuring unit and the reference Michelson interferometer. The measuring unit also contains an internal memory. This measuring unit uses SOFO SBD (version 6.3.53) software, which can establish a database of the configurations of the connected sensors and a database of measuring project configurations, in order to control the SOFO measuring system for static measurements and to administer the measurement readings data [4]. The control computer with the software has two roles. Firstly, it saves the data, and, secondly, it controls the system.

3. Calibrating the experimental equipment

Calibration was carried out on a total of six SOFO long-fibre strain gauges of varying active length — 0.5 m, 1.0 m and 2.0 m. The specification of the standard SOFO strain gauges used in our work is presented in Table 1. These standard fibre-optic strain gauges were calibrated under identical ambient conditions in the laboratory of the Klokner Institute. The air temperature was 22 ± 1 °C and the humidity was 45 ÷ 50 %.

For the actual calibration of the SOFO fibre-optic strain gauges, a jig device was designed to hold the strain gauges and to set their initial stress length — see Figure 3. The jig device was made from stainless

Sensor's serial number Number SN	**Active length** LA [m]	**Passive length** PL [m]	**Initial stress length** DL [mm]
7063	0.5	5	37.127
7064	0.5	5	37.488
9490	1.0	5	38.623
9491	1.0	5	36.498
7076	2.0	10	36.358
7077	2.0	10	35.645

TABLE 1. Specification of the calibrated standard SOFO fibre-optic strain gauges.

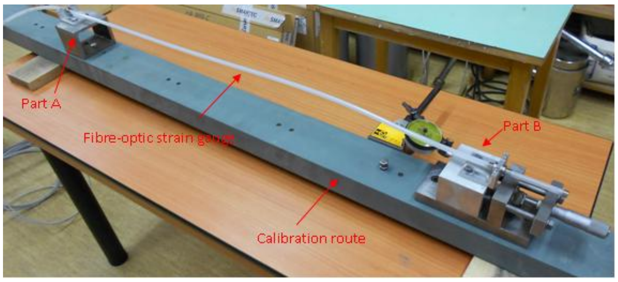

FIGURE 3. Calibration of SOFO fibre-optic strain gauges of active length LA 1 m.

steel and had two main parts (A and B). The function of these parts was to fasten the fibre-optic strain gauge that was being calibrated. Part A could be moved along the calibration route, depending on the active length of the sensor. Part B allowed deformation changes to be continuously set. A Somet inclinometer with a range of 1 mm and accuracy of 0.001 mm was used for setting the changes in deformation.

4. EXPERIMENTAL WORKS

The manufacturer of SOFO fibre-optic strain gauges provides the value for initial stress length DL in the Technical Sheet of each sensor. The sensor should be stressed to this value during installation. In the course of the experimental works, calibration constants were derived and the measurement accuracy was determined as a function of the initial stress length.

Calibration of the SOFO fibre-optic strain gauges commenced by setting the strain gauge to the initial stress length declared by the manufacturer (value DL). The initial stress length set in this way was recorded by the SOFO portable reading unit, and a zero value was set on a Somet inclinometer, and was also entered into the measuring application. From this initial state, the SOFO fibre-optic strain gauge was then stretched and compressed by ±0.5 mm in steps of 0.01 mm. The displacement values were checked on the inclinometer. After each step, a reading was taken of the stress length of the fibre-optic strain gauge, and the set real value of the displacement was read off the inclinometer. This process was repeated five times for each initial stress length. An example of a recording is presented in Figure 4. After five repetitions, the initial stress length was changed, and the stressing process was repeated five times. For each fibre-optic strain gauge, the calibration was carried out for the declared initial stress length (DL) and for at least five other stress length values.

The displacements as a function of time obtained from the inclinometer, ΔL_{H}, were then plotted against the displacements obtained from the SOFO fibre-optic strain gauge, ΔL_{SOFO}, for the repeated measurements of ±0.5 mm displacement in 0.1 mm steps for each initial stress length. A linear regression curve was then fitted through the measurement readings, and the calibration constant k_i (see Figure 5) was determined from the regression equation

$$\Delta L_{\mathrm{H}} = k_i \cdot \Delta L_{\mathrm{SOFO}}.$$

For the five repeated measurements of a single initial stress length, the calibration constants k_i in equation 1 were then obtained by means of the least square method. An example of the five calibration constants k_i obtained in this way for a fibre-optic strain gauge of active length 1 m is presented in Figure 5. For each value of the initial stress length, the calibration constants k_i determined in this way were used to derive the value of the resultant calibration constant k, described by an average value $\overline{k}$ and the limits of a 95% reliability interval [6]

$$k = \overline{k} \pm \frac{s \cdot t_{(m-1);0.05}}{\sqrt{m}},$$

where $t_{(m-1);0.05}$ is a coefficient of Student's t-distribution for a 5 % level of significance, m is the number of repeated measurements for each initial stress length, and s is a standard deviation.

5. MEASUREMENT RESULTS

The calibration procedure and the calculations to determine the limits of a 95 % reliability interval have been described above. The values obtained in the calibration of six fibre-optic strain gauges of varying active lengths (0.5 m, 1 m and 2 m) have been plotted as graphs depicting the spread of calibration constants together with a 95 % reliability interval as a function

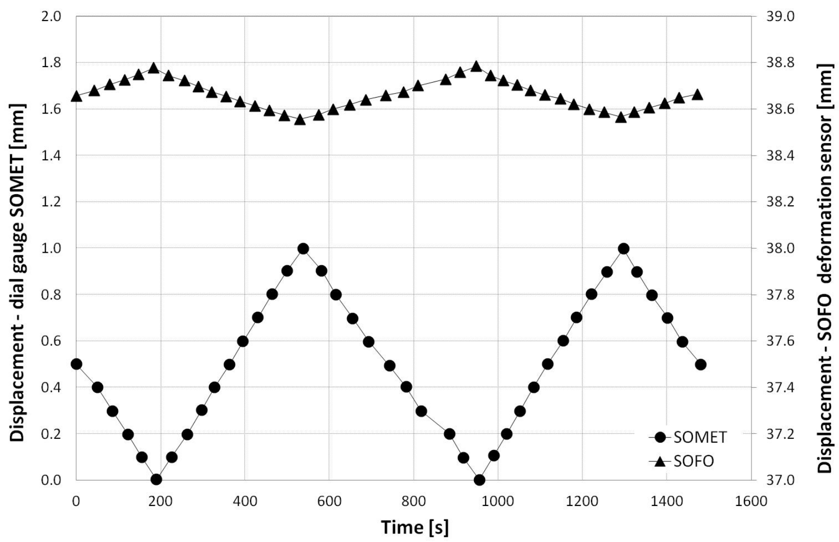

Figure 4. An example of displacements obtained from the Somet inclinometer and the initial stress length of the SOFO fibre-optic strain gauge with a 0.1 step obtained during calibration, as a function of time (SN 9490; LA 1.0 m; DL 36.623 mm; initial stress 38.657 mm).

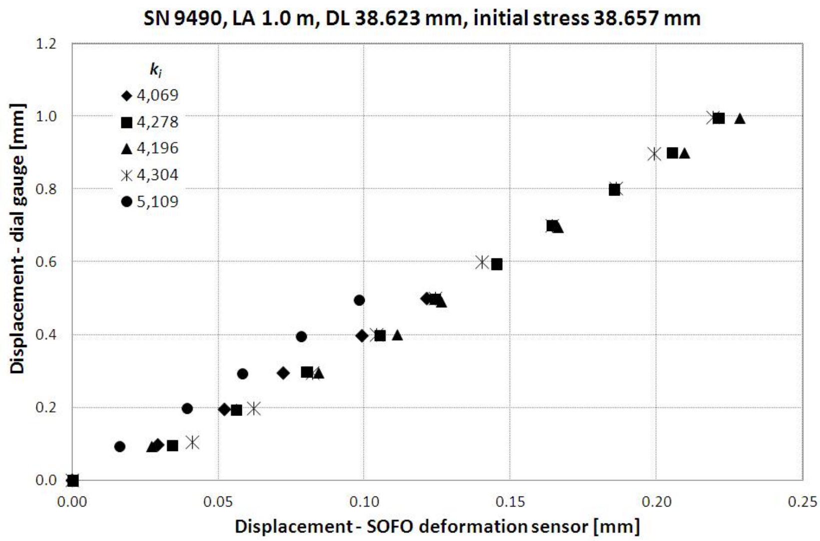

Figure 5. An example of displacements determined by the inclinometer and by the SOFO fibre-optic strain gauge for five repeated measurements with a fitted regression curve and calibration constants for the given initial stress value.

of the initial stress length — see Figures 6 to 8. Each graph depicts the functions for two strain gauges of identical active length. In addition, the initial stress length recommended by the manufacturer (DL) is shown for each function.

6. Conclusion

Calibrations of six SOFO sensors showed that the spread of calibration constants as a function of the initial stress length is similar for sensors of identical active length. However, this does not apply to strain gauges of other active lengths. For example, Figure 7 shows that the calibration constant k of a SOFO strain gauge of active length 1.0 m changes considerably with the value of the initial stress length, whereas for a SOFO strain gauge of active length 2.0 m the value of the calibration constant is almost independent of the initial stress length (Figure 8). The graphs also show that the greater the value of the initial stress length of the SOFO strain gauge, the closer the calibration constant is to the limiting value, and the dispersion is reduced.

The spreads of the calibration constants show that it is necessary to calibrate SOFO strain gauges, and to determine their calibration constant, before they are used. When the sensors are being installed in the structure, it is necessary to achieve the highest possible initial stress length value, as this will guarantee that the constant will be close to the limiting value, and that the highest possible accuracy will be achieved.

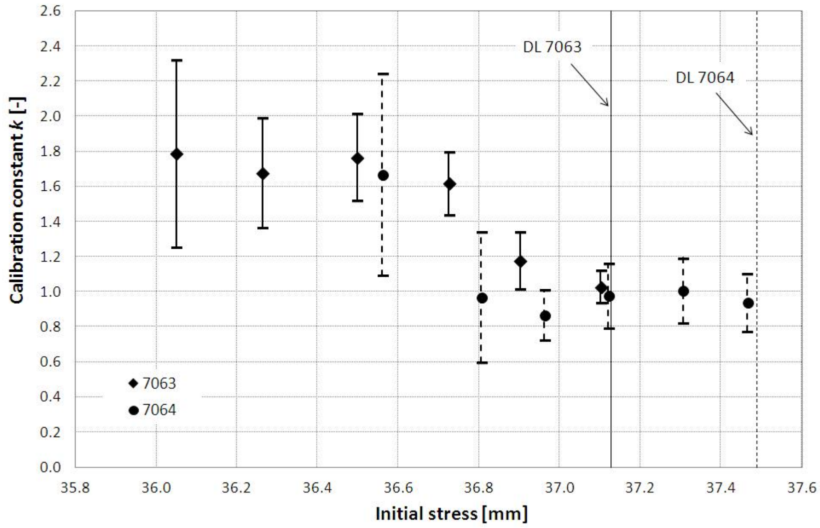

FIGURE 6. Calibration constants in a 95 % reliability interval of SOFO fibre-optic strain gauges of active length LA 0.5 m — SN 7063 (required stress length DL 37.127) and SN 7064 (required stress length DL 37.488).

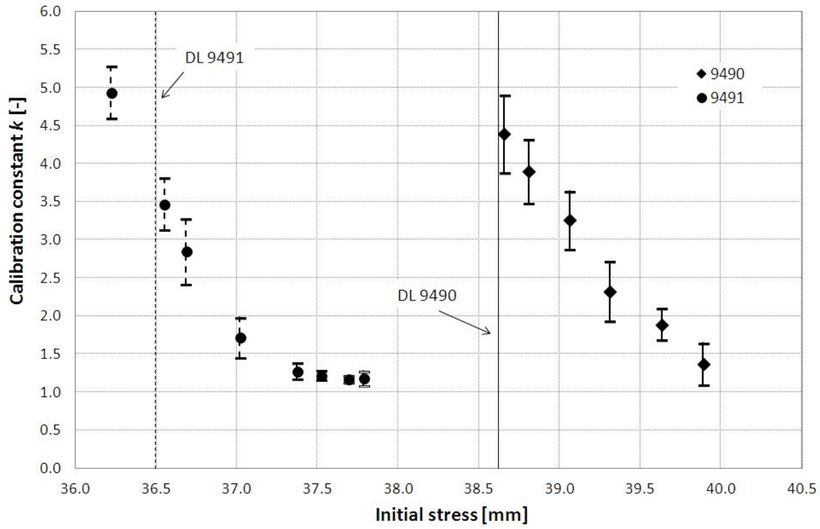

FIGURE 7. Calibration constants in a 95 % reliability interval of SOFO fibre-optic strain gauges of active length LA 1.0 m — SN 9490 (required stress length DL 38.623) and SN 9491 (required stress length DL 38.498).

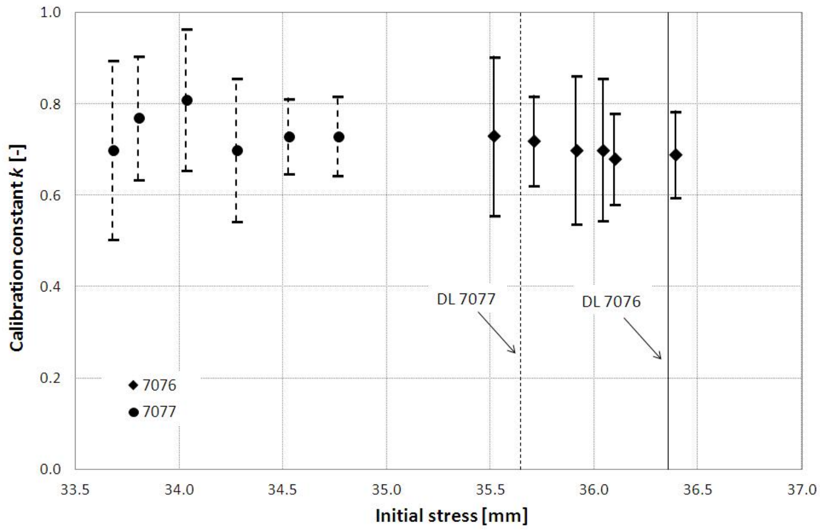

FIGURE 8. Calibration constants in a 95 % reliability interval of SOFO fibre-optic strain gauges of active length LA 2.0 m — SN 7076 (required stress length DL 36.358) and SN 7077 (required stress length DL 35.645).

When installing these sensors, it is recommended to attach the fibre-optic strain gauge as carefully and as rigidly as possible to the reinforcement of the structure, so that when the concrete is cast the fixing points are not moved along the steel and the initial stress length of the strain gauge is not changed.

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