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Analysis of the temperature distribution in an insulated reinforced-concrete building envelope using FBG sensors

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Abstract: The progressive climate change caused by anthropological factors has led EU member states to set themselves a very ambitious goal of achieving climate neutrality by 2050. Within the *Fit for 55* packages and regulations, a CO_2 emissions system (EU ETS) has already been in place since 2005, affecting energy-intensive industries, energy producers and airlines. It is planned that from 2027 the ETS2 system will apply, which will cover CO_2 emissions from burning fuels in buildings and road transport. The ETS2 means that gas, coal and fuel oil, i.e. fossil fuels used to heat households, will be subject to taxation. The most effective way to reduce the consumption of these fuels is to reduce the energy intensity of buildings. This can be achieved using appropriate thermal insulation of building envelopes/partitions. Knowledge of the temperature distribution inside a partition can significantly improve the process of thermo-modernization in existing buildings. The paper presents the method and results of the measurement of the thermal distribution inside a reinforced-concrete building wall using FBG sensors.

Keywords: FBG temperature sensors, temperature distribution, thermo-modernization

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Introduction

FBG (fiber Bragg grating) sensors are modern fiber optic sensors that can be used to measure the distribution of strain, temperature and humidity (Bhaskar et al., 2021). They are characterized by very high sensitivity, resolution, linear dependence of the wavelength shift, and immediate reaction to the application of force or a temperature change. The fundamentals of the method of strain and temperature measurements

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based on FBG sensors are presented in (Bao & Liang, 2012; Kersey et al., 1996; Othonos & Kyriacos, 1999).

The sensor measuring element is a Bragg grating applied to the inner surface of the fiber core. The most important advantage of the method is the possibility of creating Bragg gratings with high repeatability and continuity.

The idea of measurements using FBG sensors is based on the use of Bragg's law. It consists of measuring the wavelength of light reflected by the diffraction grating due to the Frensel effect. The reflected wavelength λ_B is referred to as the Bragg wavelength and expressed as:

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

where:
λ_B – wavelength,
n_{eff} – effective refractive index of the grating in the fiber core,
Λ – grating constant.

Bragg wavelength λ_B is essentially determined by the Bragg grating constant Λ and the core refractive index n_{eff}. The optical fiber deformation due to tension or compression leads to a change in the grating constant, and consequently to a change in the Bragg wavelength. The temperature sensitivity of the Bragg optic fiber grating is a result of a change in the refractive index of silica caused by the thermooptic effect (Fig. 1).

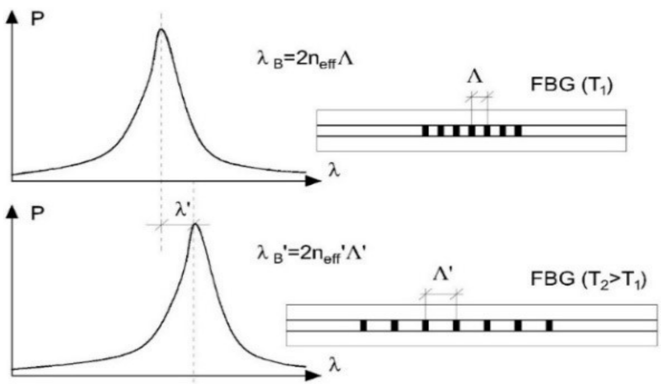

Fig. 1. Change in the Bragg wavelength due to the FBG sensor thermal load (*own research*)

The dependence of the Bragg fiber optic grating deformation on temperature can be defined by differentiating the wavelength according to the following relation:

$$\frac{\Delta\lambda}{\lambda_0} = (\alpha + \zeta)\Delta T \tag{2}$$

where:
ΔT – temperature change,
α – thermal expansion coefficient of the core,
ζ – thermooptic coefficient.

The versatile applications of FBG sensors and the possibilities of comprehensive measurements of deformation and temperature distribution are presented in (Liao et al., 2020; Loizos et al.,2013; Wang et al., 2006; Weng et al., 2014). Practical implementation of FBG sensors for long-term measurements of temperature distributions in multilayer external walls of buildings is presented in (Ahola & Lahdensivu, 2017; Marino et al., 2018; Minardo et al., 2014). In the years 2020-2021 comparative tests of the two-layer wall were carried out using fiber Bragg grating sensors and equivalent classic temperature sensors (Juraszek & Antonik-Popiołek, 2021; Juraszek, 2022). FBG sensors were also implemented for the analysis of strain in power transmission towers, strain analysis of the hoisting machine brake linkage and strain monitoring of residential buildings (Juraszek, 2018; 2020).

The requirements for building materials and elements as well as for the building thermal calculations are specified in relevant standards (PN-EN ISO 12524; PN-EN ISO 6946).

1. Measuring probe structure

In order to investigate the real temperature distribution, a measuring probe was designed and made in the cross-section of the partition using a fiber optic Bragg grating sensor.

The tests to measure the temperature distribution inside an insulated reinforced-concrete partition were carried out using a measurement system supplied by the FiSense company. The system consisted of the following elements:

- a fiber-optic chain of sensors with four Bragg gratings with a reference wavelength of 850 nm,
- a FiSpec FBG X100 interrogator (spectrometer),
- FiSens BraggSens 1.88 software.

The measuring probe design was adapted to the dimensions of the FiSens FBG sensor and to the partition thickness, taking into account the dimensions of the layer of reinforced concrete and polystyrene. A schematic diagram of the design solutions adopted for the measuring probe is presented in Figure 2. The built-in sensor makes it possible to embed it in the existing reinforced concrete wall.

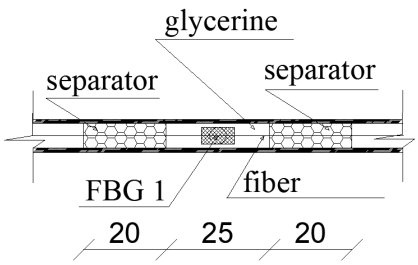

Fig. 2. Measuring probe design details (*own research*)

Before the probe was mounted on the test stand, the measurement path of the FBG sensor was calibrated. During calibration, the real value of the temperature sensitivity of the FBG sensors was determined and the coefficients of the linear approximation function were calculated (Table 1).

Table 1. Comparison of theoretical and measured temperature sensitivity of FBG sensors (*own research*)

FBG	FBG sensor reference wavelength λ	Theoretical sensitivity	Measured sensitivity
	nm	pm/°C	pm/°C
FBG 1	850	7.65	6.18
FBG 2	860	7.74	5.99
FBG 3	870	7.83	6.06

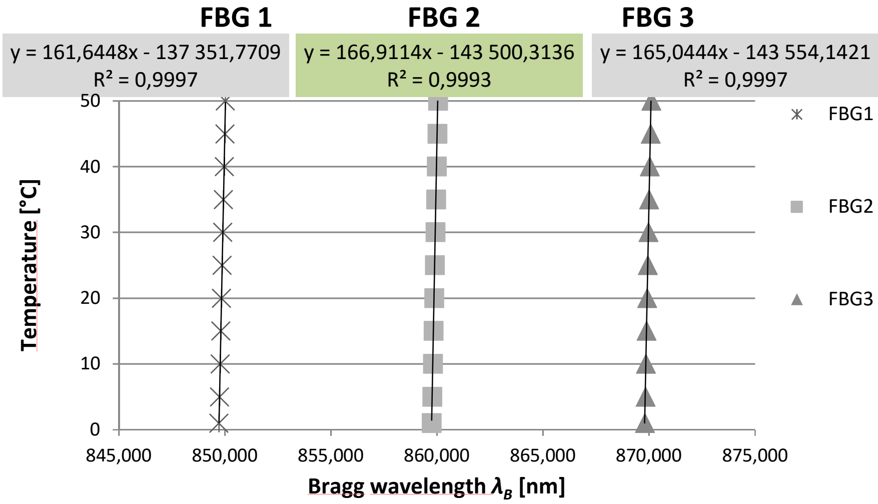

Fig. 3. Approximation equations of the temperature dependence on the Bragg wavelength (*own research*)

The calibration of the FBG sensors showed a linear dependence of the recorded wavelength on temperature. The approximation polynomials determined based on the calibration results for the calculation of temperature guaranteed a measurement accuracy with a maximum error of 0.3 °C (Fig. 3).

2. Testing facility – measuring stand

The two-layer wall consisted of a reinforced concrete column (48 cm thick) with a calculated heat transfer coefficient $\lambda = 1.7$ W/m·K and Swisspor EPS UNI fasada_045 facade polystyrene with the thickness of 12 cm and heat transfer coefficient $\lambda = 0.045$ W/m·K. The positioning of the measuring probe inside the partition is presented in Figure 4. In addition, DS18B20 temperature sensors were installed at the partition outer ends. The reflected Bragg wavelength was measured using the FiSpec FBG X100 interrogator (optical spectrometer).

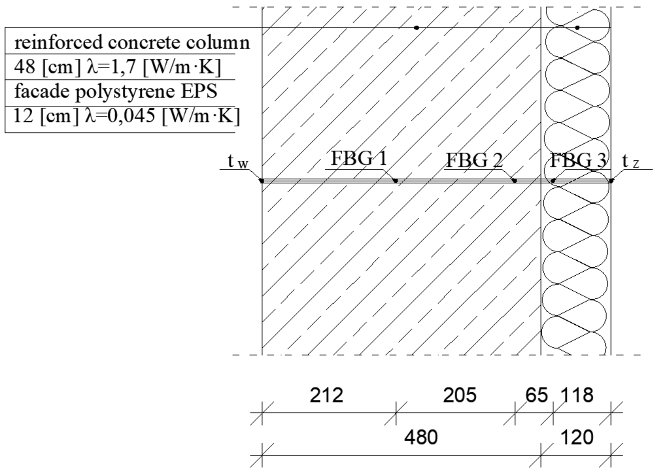

Fig. 4. Arrangement of the sensors in the tested partition (*own research*)

3. Results of temperature measurements in the partition

The example results of the testing of the temperature distribution in the reinforced-concrete partition in the winter period (2.12.2022-31.12.2022) were recorded using a measuring system based on the FBG sensor discussed in section 2. At the same time, the temperatures on the outer and inner surfaces of the wall were measured (DS18 B20 sensor). Based on the collected results, graphs were prepared to illustrate temperature changes over the analyzed period (Figs. 5-7).

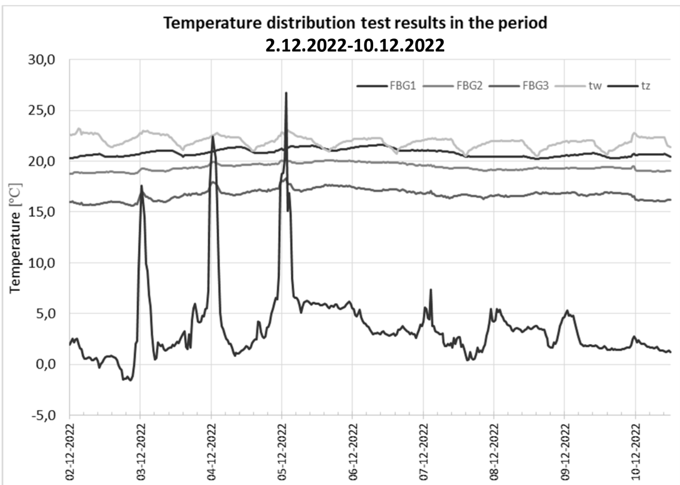

Fig. 5. Periodic changes in temperature inside the partition (*own research*)

During the testing the temperatures recorded on the outer side of the wall, despite the winter period, demonstrated considerable fluctuations, ranging from about –15 °C to about 30 °C. The highest variations in temperature were recorded on sunny days, in the early hours of the afternoon. During that time the outer layer of the wall heated to temperatures much higher than the air, due to the absorption of thermal energy through radiation (Antonik-Popiołek, 2021).

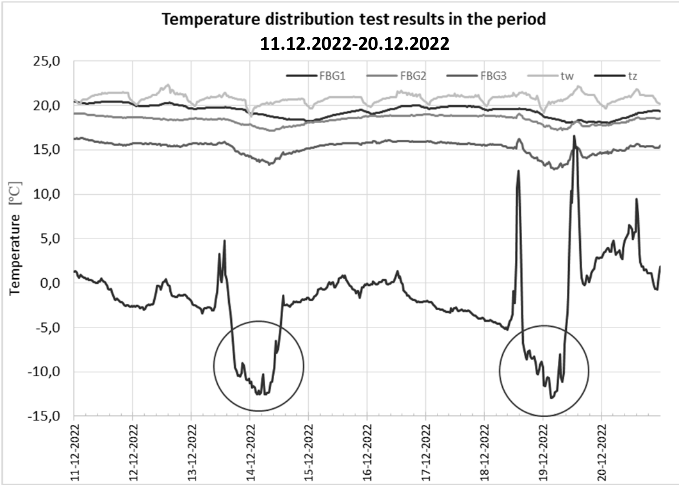

Fig. 6. Periodic changes in temperature inside the partition (*own research*)

The graphs show that the amount of energy supplied during this period is dissipated mainly in the wall insulating layer. Only a small, short-term increase in temperature was observed, recorded by FBG sensor 3 located in the inner layer of polystyrene, two centimeters from the border with the layer of reinforced concrete. Noticeable changes in temperature inside the partition occur only after several hours of the wall exposure to a drop in ambient temperature. This situation is particularly evident on the graph covering the period from 11.12.2022 to 20.12.2022 on the 14th and the 19th day of December (Fig. 6).

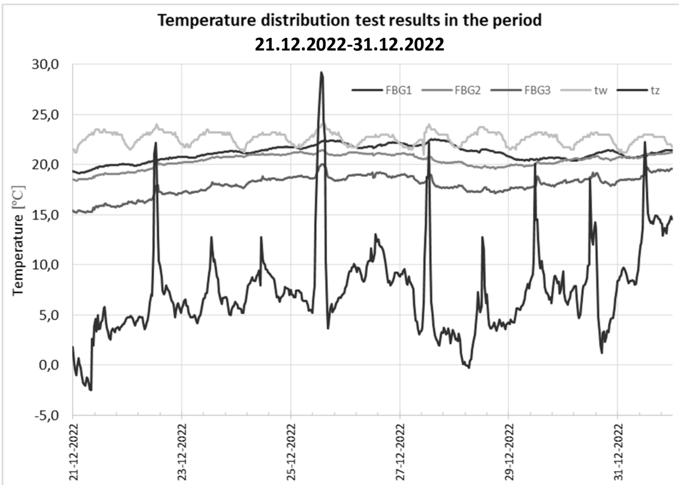

Fig. 7. Periodic changes in temperature inside the partition (*own research*)

Temperature changes in the inner reinforced-concrete layer of the external wall insulated with polystyrene occur mainly due to the energy supplied from the inside of the building, due to the transfer of a constant flux of energy to the outer layer. This is illustrated in the graphs by periodic, daily fluctuations in the temperature of the partition internal layer related to the building heating cycle. Despite the high temperature amplitude outside the external wall, the temperature values recorded by sensors FBG1 and FBG2 were subject to slight changes, which additionally were of a long-term nature. For sensors FBG1 and FBG2 the amplitude of the changes totaled ± 1.5 °C and ± 2 °C, respectively. This indicates that the heating system can be controlled.

Conclusions

Measurements of the real temperature distribution inside a building wall belong to the group of invasive testing. The use of measuring probes using FBG sensors makes it possible to significantly reduce the invasiveness of such tests. The possibility of applying Bragg gratings in an optic fiber at distances of up to 10 mm results in a very precise temperature measurement in the entire section of the partition. The data collected in this way enable accurate calculation of the heat flux conducted through the partition material. The usefulness of this information can be used both to calculate the partition insulation parameters and to identify structural defects (e.g. the partition dampness). In the context of testing existing building envelopes/ partitions, the ease of the measuring probe implementation for various wall structures, including multi-layer ones, is of great importance. As indicated by the testing results, FBG sensors are characterized by a linear dependence of the reflected Bragg wavelength on the thermal load. FBG sensors ensure high reliability in long-term testing and ease of collecting measurement data.

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