WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.140652
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVIII ISSUE 2 2022

pp. 445 –460

Research paper

Fibre optic system based on FBG sensors for the monitoring of modern structures

Janusz Juraszek[1]

Abstract: The aim of the research was implementation of fibre Bragg grating sensors and the Aramis system to monitor strain, displacement and stress values in new materials used in the building industry. Selected elements of a residential building made of the Polytech material with a 60% content of the EPS granulate from recycling were tested: a prefabricated wall with a lintel, a reinforced concrete floor slab, a lintel, a reinforced concrete column and a wall. Long-term testing was also carried out taking account of changes in environmental conditions. The methodology of the research was based on the development of purpose-made dedicated FBG strain sensors, laboratory calibration and the embedding of the sensors in the tested element structure. The proposed system of continuous measurements made it possible to determine real strain, displacement and stress values in selected elements of the Polytech structure for a facility founded in a difficult geotechnical terrain (subsoil).

Keywords: fibre optic FBG, monitoring, modern materials

---

[1] Prof., DSc., PhD., Eng., University of Bielsko-Biała, Departament of Civil Engineering, Willowa 2 Street, 43-300 Bielsko-Biała, Poland, e-mail: jjuraszek@ath.bielsko.pl, ORCID: 0000-0003-3771-2776

1. Introduction

The implementation of strain measurement techniques using Fibre Bragg Grating (FBG) sensors in a residential building was the main research topic of this work. FBG sensors are a promising alternative to classical strain measurement systems. They are created in a laboratory by applying a Bragg grating to the inner surface of an optical fibre using UV radiation. The keen interest in this technique is mainly due to the fact that it is free of the drawbacks typical of electroresistive systems (time and temperature drift, need for periodic calibration, short operational life in conditions of a building construction). Fibre optic systems are characterized by high reliability, measurement accuracy of ±1 µstrain, small dimensions (the fibre diameter of 125 µm, the sensor can be embedded without compromising the material resistance), long service life and high resistance to deformation up to 5%. Because the working medium is light, the information is encoded as its resonant wavelength, which creates unique properties of the system, great multiplexing possibilities, resistance to electrical and electromagnetic interference, intrinsic safety (sparkless operation), significant fatigue life. The limitations of this method are the expensive measuring equipment (optical interrogator), the strain measurement range of up to 5000 µstrain and the fact that the sensor only works if it is properly stretched, so it requires appropriate pre-tension to measure compression. Reducing the consumption of natural resources implies the development of new materials derived from recycling. An example of such a material is the Polytech polystyrene concrete, which contains 60% of recycled expanded polystyrene (EPS) and appropriately modified cement mortar. This is important because European analyses indicate that EPS accounts for as much as 7% of total waste and is classified as non-biodegradable material. In this context, the recycling of EPS is of great significance [1–5]. The proposed solution contributes to a reduction in the consumption of natural resources and in EPS waste. The material was used in a prefabrication system intended for construction of residential building elements. Considering the current difficult situation in the labour market and the deepening lack of workers, an obvious need arises for the development of modern prefabricated technologies. It should also be noted that without the results of laboratory testing of samples and of the lintel element, the behaviour of a residential building made of the material would be unknown. The building was founded in a difficult geotechnical terrain. The purpose of the research described herein was to present a fibre optic system based on FBG sensors to monitor selected elements of a residential building made of the Polytech prefabricated elements. The fibre optic technique was also used to determine the values of Young's modulus of Polytech material samples reinforced using wool fibres (fibre reinforcement) and strips of wool. The lintel surface strains were analysed using the ARAMIS optical system. The system also made it possible to identify the areas affected by the highest stresses and strains, where the monitoring sensors should be placed. In this way, optical techniques assist in the engineering of new construction projects together with the process of implementing new materials. The research presented herein is a part of multi-year studies on FBG-based structural monitoring of civil engineering structures which involved the testing of supporting structures of high-voltage power lines [6], geogrids intended for subsoil reinforcement, especially in areas affected by the mining activity [7], strains in footbridges or the monitoring of the temperature distribution in the building envelope and walls [8] , industrial overhead cranes and machines [9]. Other implementations of monitoring the aforementioned building structures are presented in [10–15]. No attempt to monitor a residential building using an FBG system was found in the available literature databases.

The system of the POLYTECH MS prefabricated elements was developed in response to the needs of low-energy building construction. The insulating panels are manufactured as two-layer elements with a 30-cm-thick layer of polystyrene concrete and 17-cm-thick EPS thermal insulation. The innovative solution is the combination of the construction layer with thermal insulation with a hexagonal element connecting the panels during production. The assembly is carried out at the construction site. The system characteristics are as follows:

- panel height 1 storey (max. 3.0 m);
- panel width from 0.3 m to 3.6 m;
- panel thickness 47 cm (load-bearing wall 30 cm + EPS 17 cm);
- compressive strength 2.5 MPa;
- heat transfer coefficient (wall U) 0.12–0.15 W/($m^2 \cdot$K);
- no mechanical connectors of thermal insulation (no thermal bridges);
- joining of panels using reinforced concrete cores (poured at the construction site);
- no construction waste when laying the panels.

The production technology makes it possible to obtain any required length of the wall panel within the range from 0.30 m to 3.60 m (preferable dimension: in a 30 cm module).

The maximum height is 3.00 m, also adaptable to project requirements.

The POLYTECH MS system has ready-made corners, facilitating fast and precise assembly. Construction using all POLYTECH MS prefabricated elements is carried out using fixed or self-propelled cranes. Corners and panels are joined to each other using specially shaped reinforced concrete cores placed on vertical edges of all elements. Joints made in this way significantly contribute to almost complete elimination of linear thermal bridges. They are made in a production plant, from where they are transported to the construction site. One storey is erected in 1 day. As a result, the construction time and costs are substantially reduced. The production technology is environment-friendly – it meets the requirements of sustainable construction.

2. Tested structure and method

The tested structure was a residential building made of the Polytech prefabricated elements in the town of Zabrzeg located near a large water reservoir of Lake Goczałkowice. The area is boggy and geotechnically difficult. The building parameters are as follows:

- Floor space: 219.8 m^2
- Footprint: 146.1 m^2
- Cubic volume: 632.32 m^3
- Total consumption of electricity: EP = 57 kWh/m^2/year.

The building has a mechanical ventilation system with the central unit located in the gas boiler room on the ground floor. The ventilation system is equipped with a system of two independent heaters that heat the house by distributing warm air generated by the gas boiler through the mechanical ventilation ducts. The building is equipped with a heat recuperation system. The tested elements were a lintel (both at the manufacturing stage and after it was installed in the building), load-carrying reinforced concrete columns, a prefabricated wall and a floor slab. Purpose-designed fibre Bragg grating sensors were embedded in the elements. The sensors were connected to the FBG-800 optical interrogator and to a computer recorder using a telecommunication fibre. The FGB-800 interrogator enables both static and dynamic measurements. The deformability of Polytech samples was also examined using three-point bending tests. The lintel surface strains were analysed in a laboratory using the ARAMIS optical system. The building elements in which FBG-based monitoring was implemented are shown in the ground floor plan in Fig. 1. The figure illustrates the distribution of FBG sensors.

Fig. 1. Distribution of FBG sensors in the residential building

Two types of FBG sensors were applied: the strain sensor and the displacement sensor. Due to high values of deflection angles, the displacement sensor proved useless and was no longer used in further stages of the research. On a single measuring line, the strain sensor may have 10 sensors with the wavelength difference of 5 nm with temperature compensation. A special technology of gluing the sensor into the monitored element in the middle of its span was developed. The sensor and its parameters are presented in Figure 2.

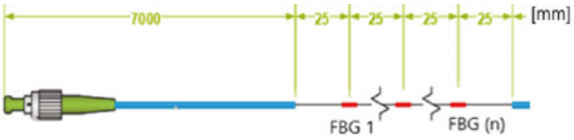


Fig. 2. Diagram of a fibre Bragg grating sensor

As mentioned above, the Bragg grating is produced in the fibre core in a laboratory using UV radiation. The wavelength reflected on the grating satisfies the Bragg condition:

$$\lambda b = 2n\Lambda \tag{2.1}$$

where: λb is the Bragg wavelength, $n$is the effective refractive index and Λ is the grating period.

Strain (ε) and temperature (T) occurring in a tested element equipped with an FBG sensor will change the effective refractive index and the grating period. This in turn will change the Bragg wavelength. A change in the Bragg wavelength due to strain and temperature is defined as:

$$\Delta\lambda b = 2n\Lambda(1 + Pe)\varepsilon + 2n\Lambda(\alpha + \xi)\Delta T \tag{2.2}$$

where: Pe is the strain optic coefficient, α is the thermal expansion coefficient and ξ is the thermo optic coefficient.

In order to compensate for the effect of the temperature change, an additional, passive, fibre sensor is introduced ($\varepsilon = 0$), which is not associated with the tested element but is located in the same place. As a result, the change in the length of the wave reflected on the Bragg grating is directly proportional to the change in the strain value. Subsequent sensors in this optical fibre should differ in the reference wavelength by 5 nm. In practice, this limits the number of sensors placed in the same optical fibre to 20. Appropriate pre-tension of the sensors should be selected experimentally to ensure that they are always stretched. The optical fibre fixing and stretching systems applied in this work have been filed for patent protection.

The strain of the optical fibre sensor is the function of the wavelength (1) measured by the optical FBG-800 interrogator enabling dynamic measurements. The sampling frequency is 2000 Hz.

$$\Delta\varepsilon = \frac{\dfrac{\lambda_{\text{act, strain}} - \lambda_{0,\text{inst, strain}}}{\lambda_{0,\text{inst, strain}}} - B \cdot \left(T_{\text{act}} - T_{0,\text{inst}}\right)}{A} \tag{2.3}$$

where:

$\Delta\varepsilon$ – strain shift (με),

$\lambda_{0,\text{inst, strain}}$ – initial strain wavelength (nm),

$T_{0,\text{inst}}$ – initial temperature (°C),

T_{act} – actual temperature (°C),

$\lambda_{\text{act, strain}}$ – actual strain wavelength (nm),

A and B are constant:

$A = 7.758423 \cdot 10^{-7}$ ($\mu\varepsilon^{-1}$),

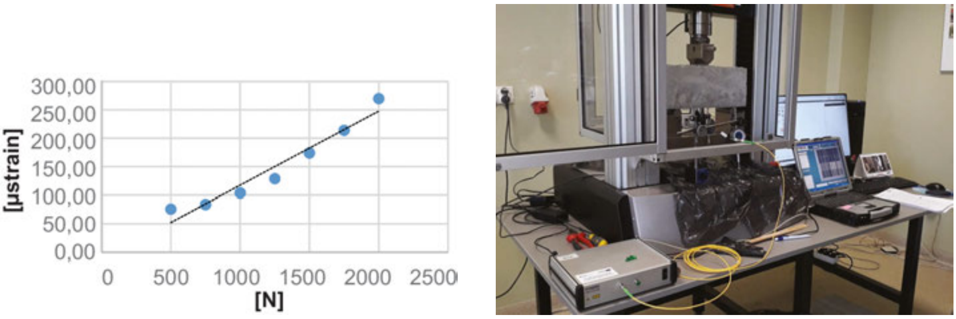
$B = 5.892923 \cdot 10^{-6}$ ($^\circ$C^{-1}).

3. Testing results

This section presents the results of strain testing performed using the optical system based on FBG-sensors of beams and selected elements of the residential building under consideration, such as: a lintel module, a column, a floor slab and a wall module. Strain levels were analysed both during successive stages of construction and during the building operation.

3.1. Deformability testing of beams made of the Polytech material

The testing included classical three-point bending tests of beams. The beam was loaded with a concentrated force located halfway through the beam span, on the element top surface. The strain tests were carried out using optical fibre strain sensors with Bragg gratings glued halfway through the beam length, on the beam bottom surface. The strain testing results and the test stand are shown in Fig. 3a and 3b respectively. The tested specimen had the cross-section of 100 × 100 mm, and the spacing between the supports totalled 600 mm. The load was applied at the mid-length of the specimen.In the linear range of the load-strain relation, the strain value totalled about 270 µstrain at the load of 2000 N.



(a) (b)

Fig. 3. (a) Deformability of the Polytech beam, (b) 3-point-bending test rig

Due to the significant content of the recycled EPS granulate reaching up to 60%, the Polytech material is characterized by high deformability. In essential places of the building the material requires reinforcement in a form causing no damage to the EPS granulate. The dimensions of the wool-reinforced specimens and the spacing between the supports of the strength testing machine were the same as for the specimens with no reinforcement. A proposal was made to modify the Polytech material by adding sheep wool as reinforcement. The parameters of the wool used during the testing are as follows: fibre thickness – 33 µm; fibre length – 68 mm; fibre strength – 15 cN/tex;

The results of the deformability testing of beams reinforced with wool fibres are presented in Fig. 4. The strain values of the beam made of the WOOLPOLYTECH material with fibre reinforcement are presented in the chart in red. They range from 160 to 170 strain. The strains obtained for the beam reinforced with strips of wool are marked in blue (cf. Fig. 4) and total 90–100 strain. The figure also shows the difference between the strain values. It totals 66 to 69 strain.

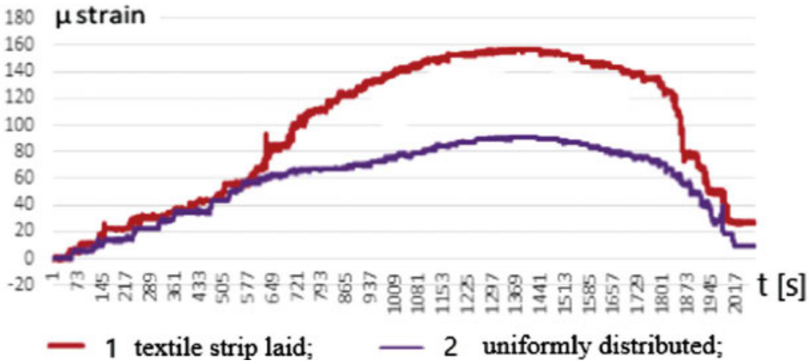


Fig. 4. Strain values obtained for beams reinforced with wool during the loading

It was observed during the testing that the beam reinforced with wool in the form of a textile strip laid (1) in the region subjected to tension was much less deformed compared to the beam reinforced with wool with fibres uniformly distributed (2) across the entire cross section. The differences are significant and total 160%. The value of Young's modulus determined from physical relations for the beam reinforced with a wool strip totalled 3564.16 MPa. This means a significant increase in the material rigidity considered to beams with no reinforcement.

3.2. Deformability testing of the prefabricated lintel made of the Polytech material

The testing of the lintel module was carried out both for laboratory and industrial conditions and for the conditions of the building construction and operation. A special stand was designed and made to enable the testing of the lintel loading. The lintel dimensions and the locations of the FBG sensors are presented in Fig. 5. The test rig for the prefabricated lintel was the same as the stand intended for testing using the ARAMIS system. A photograph is included in Section 4 (Fig. 14).

The top part of the lintel beam was loaded using a press with a single-acting cylinder. The biggest recorded strain value was −102.2 µstrain at the corresponding load of 122.84 kN. The deflection values of the lintel beam bottom strip were also measured. The strain testing results both for the loading and the unloading process ((b) and (od), respectively) are presented collectively in Fig. 6.

Further strain testing based on fibre optic techniques concerned a wall panel with a window opening and the window lintel made of the POLYTECH material. SG-01 optical fibres with the Bragg grating were used; they were terminated with single-mode FC/APC

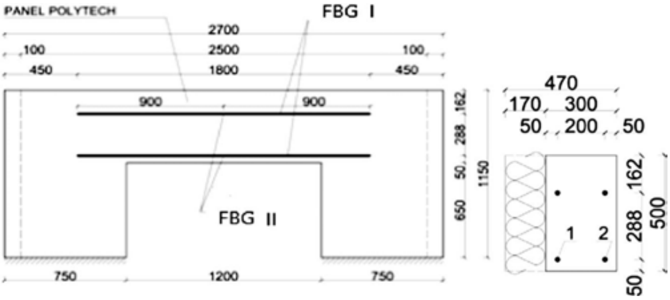


Fig. 5. Diagram of the prefabricated lintel and lintel cross-section I

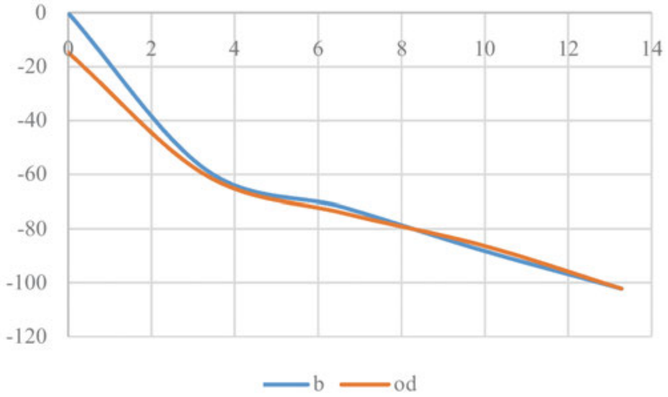


Fig. 6. Values of strain arising in the beam – laboratory conditions

connectors connected to the optical interrogator (measurements performed with the S-line 800D dynamic model with the timing frequency of 2 kHz). Two sensors were located in the bottom zone subjected to tension. As indicated by previous testing results, this particular zone is much more sensitive to loading. The FBG sensors were individually calibrated and the FBG sensor initial tension was selected based on a number of experimental tests to ensure the sensor appropriate tension. The optical fibre initial tension was adopted at the level of 540 µstrain. Next, specially prepared reinforcement bars with FBG sensors were covered with POLYTECH mortar. After 28 days of seasoning the ready-made panel was carried to the construction site, where it was installed on the residential building foundation. At individual stages of construction the window panel and especially the window lintel were loaded with subsequent elements of the building.

Lintel strain values in individual months of the building observation in the years 2018–2021 are presented in Figure 7.

The results of the testing of the lintel strain state indicate that the process of the lintel loading with subsequent elements of the building structure involves a rise in strain values. Up to the value of about –20 µstrain, the process runs similarly in the 6 months. After this value is exceeded and after the timber-framed roof is mounted, the strains of the FBGC2

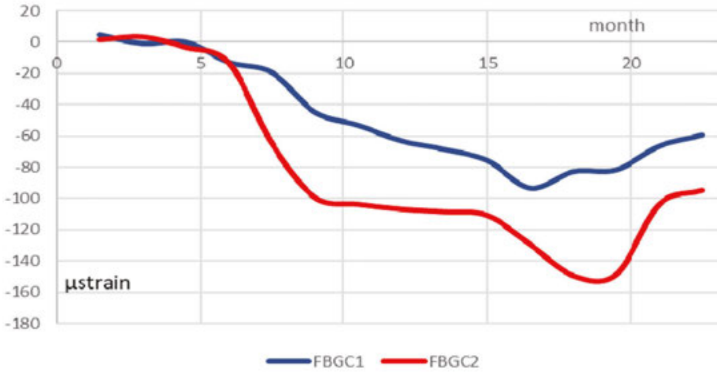


Fig. 7. Lintel strain values in individual months of the building observation

measuring path continue rising to the value of –100 µstrain, whereas the strains of the FBGC1 path increase more slowly to stabilize at the level of –50 µstrain. This means that the mounting of the timber-framed roof and then the laying of ceramic roof tiles caused non-uniform deformation of the lintel beam. This may be due to a shift of the resultant load towards the inside of the building, which may produce a complex stress state in the form of bending with torsion and a rise in strains along the FBGC2 measuring path. After 18 months of operation, reaches the highest values. Later on, the strain values decrease slightly. Fibre optic measuring techniques enable detection of any assembly irregularities involving a change in the loading pattern. For this reason, this is a valuable new diagnostic method making it possible to prove the correctness of the construction of a building facility.

3.3. Testing the reinforced concrete column strain state

Another essential structural element of the residential building made in the POLYTECH system is the reinforced concrete load-carrying and connecting column. Two fibre optic lines – S1 and S2 – were installed in the column. The column location in the building walls is presented in Fig. 8.

Fig. 8. Reinforced concrete column location in the building erected in the POLYTECH system

The reinforced concrete column is located between two window walls. In Fig. 8 the column location is marked with the red line. The column plays two roles. Firstly, it serves the supporting function making it possible to transfer loads from the reinforced concrete tie beam through the column to the building foundation. Secondly, it serves the assembly-connecting function. During the assembly of window walls, the column cross section in the form of a hexagonal connector enables very easy and precise assembly of the structure.

The strain testing results of the reinforced concrete column during subsequent stages of the building construction and then operation are shown in Fig. 9. In the first 4 months of construction, i.e. construction of the gable walls and erection of the roof structure, the strain values are relatively small and vary within –26 µstrain. The strain analysis results indicate that the column has deformed slightly to the outside of the building. Further loading causes the column structure to return to its initial position and continue deforming, but to the inside of the building. The strain values for sensors FGBP2 and FBGP1 are –170 and –236 µstrain, respectively. Like before, a significant increment in strain occurs due to the last stage of construction – the laying of the ceramic tiles.

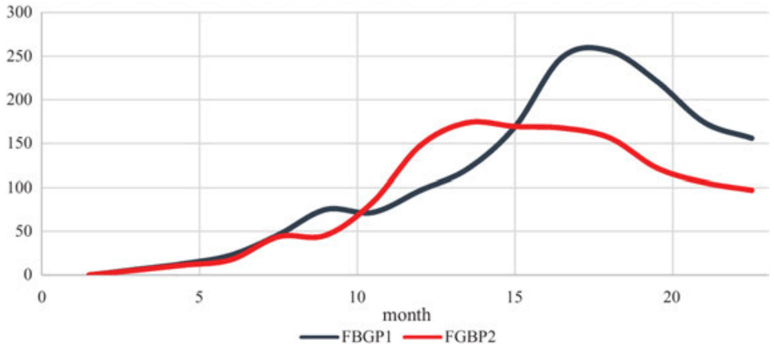


Fig. 9. Changes in strain of the reinforced concrete column in individual months of the building observation

After about 16–17 months observation periods, the deformation of the columns stabilizes. Later on, the strain values decrease slightly. Fibre optic measuring techniques enable detection of any assembly irregularities involving a change in the loading pattern. The presented method enables effective monitoring of strains in selected elements of the building.

3.4. Testing the floor slab deformability

The next tested element of the model building is the composite floor slab used in the POLYTECH prefabrication system. The 930 × 330 cm floor slab with the thickness of 14 cm was constructed using the stay-in-place formwork made of trapezoidal metal sheet (Cofraplus 60), ø8 rods and a 15 × 15 cm, ø 6 shrinkage-protection net; class C20/25 concrete was used. The whole structure rests on prefabricated walls made according to the POLYTECH system through a reinforced concrete tie beam [6, 8]. After 28 days of seasoning the floor slab reached appropriate strength. At the centre of the floor slab span in the room made available, a fibre Bragg grating sensor was attached to a trapezoidal metal sheet. Strain sensor location halfway along the slab span (in the middle of the slab) on the slab bottom part. The optical fibre was fixed in the external zone of the lost formwork (cf. Fig. 10).

Fig. 10. Composite floor slab at the construction stage – location of the FBG sensor installation on the slab bottom part

Strain measurements were performed of the floor slab during its seasoning. It turned out that the floor slab deformation had taken the form of convexity directed upwards. Such a form of deformation is favourable from the perspective of the floor slab load tests. The floor slab was loaded gradually to the force value of 11 kN. The history of changes in strain values is presented in Fig. 11. The rise in the floor slab strain with an increase in loads is quasi-linear from the value of the initial imperfection of –8 µstrain, being an effect of strains arising due to the floor slab seasoning, to 5 µstrain. This means the total strain of about 13 µstrain. After unloading proceeding along the black curve in the figure, the floor slab returns to the pre-loading strain state. Many more load tests were carried out. They confirmed the fact that the floor slab had been designed and made correctly, and the strain values obtained from the tests were very low.

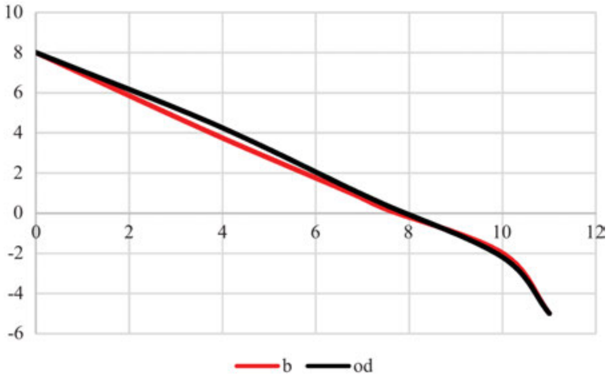


Fig. 11. Floor slab strain – load test

The last important element of the model building in which the strain level was analysed was a prefabricated wall made mainly of the Polytech material. The testing is important in view of the fact that the laboratory strength tests performed earlier showed a considerable scatter of strength parameters, compressive strength in particular. The wall was analysed using a specially designed displacement sensor with the measuring base $L = 300$ mm. The selection of such a big measuring base was due to the above-mentioned scatter of strength parameters.

At the beginning of the testing, a fibre Bragg grating sensor was installed on the reinforced concrete tie beam and the POLYTECH system wall. The sensor was fixed to the wall using specially designed system holders (cf. Fig. 12). The sensor pre-tension of about 900 μstrain was introduced. The floor slab was loaded with a force from 2 to 10 kN.

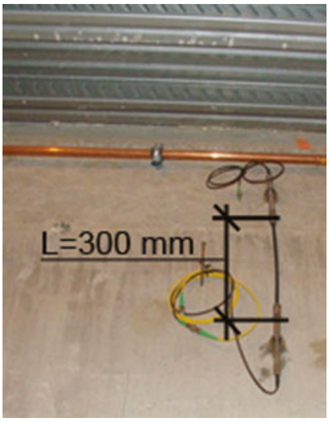


Fig. 12. Strain measurements – wall-optical fibre sensor

The wall displacement on the measuring base length of 300 mm was determined during the load test. The results are presented in Fig. 13.

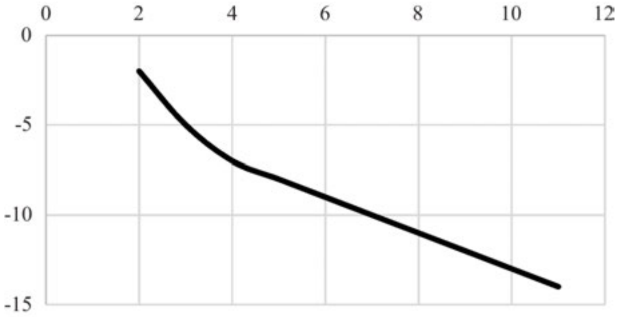


Fig. 13. Strain in the wall

The results of the analysis of the system wall strains point to a quasi-linear deformation of the wall due to the load test. The strains are very small. After unloading, the wall displacements return to the initial point. It may therefore be stated that the advanced fibre optic system made it possible to determine very low values of the wall displacement.

4. Surface strain testing using the ARAMIS system

The deformations of a lintel made of the Polytech material were analysed using the ARAMIS system. The basics of the Aramis system and the system application in the analysis of crack propagation in concrete was presented in [16]. For this purpose, the lintel face was prepared in the following way. First, it was covered with white paint. Then, in the areas where crack formation was anticipated, a uniform pattern was marked using black paint contrasting with the white background (cf. Fig. 14a). A special stand made of 4 columns and a horizontal traverse was constructed to enable the lintel load testing (cf. Fig. 14b). The load was applied using a hydraulic actuator.

(a)

(b)

Fig. 14. a) ARAMIS system – strain analysis of the lintel; b) test stand

The Aramis system utilized in the testing allowed taking 163 photographs per second, which in the case of testing where load is applied in a quasi-static manner is quite sufficient. The results of the analyses carried out with the Aramis optical system are presented in the form of summary reports for each of the recorded frames. They present coloured maps of major strains shown in the right segment of the report and charts with curves illustrating changes in major strains plotted along the section (Section 4) marked on the major strain map. The report presented in Fig. 15 relates to the initial phase of crack initiation for $T = 16.75$ s and Photo 337. The biggest deformations occur in the crack and total 1.33‰. The performed tests indicate the location of first cracks and, at the same time, the areas affected by the highest strains and stresses. The obtained information is utilized to determine where the FBG strain sensors should be placed.

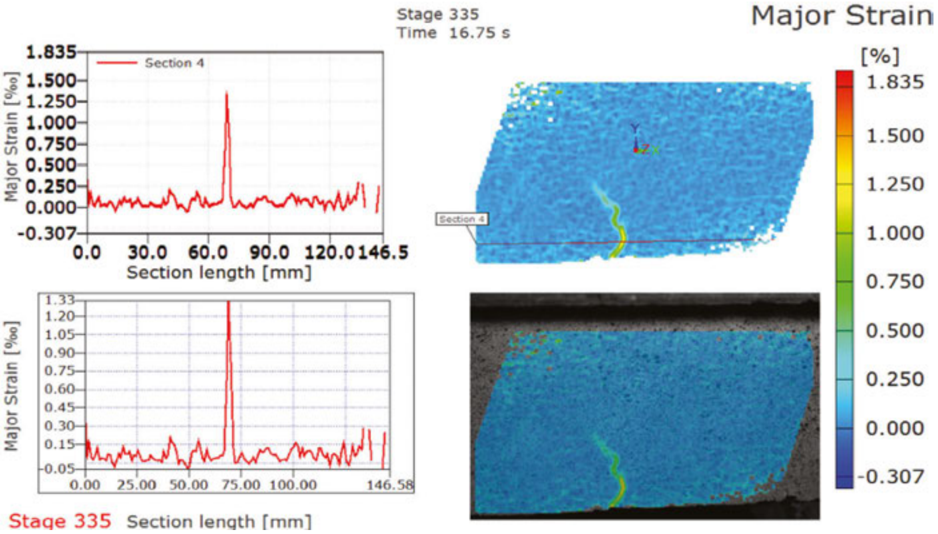


Fig. 15. Report for time step $T = 16.75$ s

5. Conclusions

Using the results of experimental strain testing performed by means of optical methods based on properly designed and selected fibre Bragg grating sensors, it is possible to determine the actual values of strains occurring in selected structural nodes of a building made of the new POLYTECH material. Long-term testing (1.5-year monitoring) pointed to an ongoing process of deformation of the lintel and the reinforced concrete column, which stabilized after a period of 1.5 years. The presented fibre optic monitoring system plays the role of a nervous system embedded in the residential building structure. Moreover, the fibre optic technique enables appropriate selection of places where elements made of the Polytech material should be reinforced with wool fibres or wool strips in the lintel part subjected to tension. Fibre Bragg grating strain sensors enable precise determination of the value of Young's modulus. The ARAMIS system of optical correlation of image made it possible to precisely localize first cracks in the prefabricated lintel, which is of great significance for determination of the lintel load-bearing capacity and identification of places where FBG sensors monitoring the lintel performance should be embedded.

Due to its universality, the presented fibre optic system of strain measurements based on FBG sensors can be used to measure any building facility. The universality results from the possibility of performing measurements both inside the tested element and on its surfaces.

In the next stage it is planned to extend the system of automatic measurements of strains and transmission of results via the Internet and create a measuring data base.

References

[1] B. Choi, S. Yoo, S. Park, "Carbon footprint of packaging films made from LDPE, PLA, and PLA/PBAT blends in South Korea", *Sustainability*, 2018, vol. 10, no. 7, pp. 1-13, DOI: 10.3390/su10072369.

[2] T. Cardinale, G. Arleo, F. Bernardo, A. Feo, P. De Fazio, "Thermal and mechanical characterization of panels made by cement mortar and sheep's wool fibres", *Energy Procedia*, 2017, vol. 140, pp. 159-169, DOI: 10.1016/j.egypro.2017.11.132.

[3] T. Cardinale, C. Sposato, M.B. Alba, A. Feo, F. Grandizio, G.F. Lista, G. Montesano, P. De Fazio, "Energy and mechanical characterization of composite materials for building with recycled PVC", *TECNICA ITALIANA-Italian Journal of Engineering Science*, 2019, vol. 63, no. 2-4, pp. 129-135.

[4] T. Bouagga, T. Harizi, F. Sakli, M. Zoccola, "Correlation between the mechanical behavior and chemical, physical and thermal characteristics of wool: a study on Tunisian wool", *Journal of Natural Fibers*, 2020, vol. 17, no. 1, pp. 28-40, DOI: 10.1080/15440478.2018.1461727.

[5] C. Piña Ramírez, A. VidalesBarriguete, R. Serrano Somolinos, M. del Río Merino, E. Atanes Sánchez, "Analysis of fire resistance of cement mortars with mineral wool from recycling", *Construction and Building Materials,* 2020, vol. 265, art. ID 120349, DOI: 10.1016/j.conbuildmat.2020.120349.

[6] J. Juraszek, "Fiber Bragg sensors on strain analysis of power transmission lines", *Materials,* 2020, vol. 13, no. 7, DOI: 10.3390/ma13071559.

[7] J. Juraszek, M. Gwóźdź-Lasoń, D. Logoń, "FBG strain monitoring of a road structure reinforced with a geosynthetic mattress in cases of subsoil deformation in mining activity area", *Materials*, 2021, vol. 14, no. 7, DOI: 10.3390/ma14071709.

[8] J. Juraszek, P. Antonik-Popiołek, "Fibre optic FBG sensors for monitoring of the temperature of the building envelope", *Materials*, 2021, vol. 14, no. 5, DOI: 10.3390/ma14051207.

[9] J. Juraszek, "Application of fiber optic FBG techniques in analysis of strain in engineering machines", *New Trends in Production Engineering*, 2019, vol. 2, no. 1, pp. 480-485, DOI: 10.2478/ntpe-2019-0051.

[10] W. Liao, Y. Zhuang, C. Zeng, W. Deng, J. Huang, H. Ma, " Fiber Optic Sensors Enabled Monitoring of Thermal Curling of Concrete Pavement Slab: Temperature, Strain and Inclination", *Measurement*, 2020, vol. 165, DOI: 10.1016/j.measurement.2020.108203.

[11] H. Weng, H. Zhu, J. Chen, D. Liang, B. Shi, C. Zhang, "Experimental investigation of pavement behavior after embankment widening using a fiber optic sensor network", *Structural Health Monitoring*, 2014, vol. 15, pp. 46–56, DOI: 10.1177/1475921714548935.

[12] A. Loizos, C. Plati, V. Papavasiliou, "Fiber optic sensors for assessing strains in cold in-place recycled pavements", *International Journal of Pavement Engineering*, 2013, vol. 14, no. 2, pp. 125–133, DOI: 10.1080/10298436.2011.614691.

[13] J. Wang, J. Tang, H. Chang, "Fiber Bragg grating sensors for use in pavement structural strain-temperature monitoring", presented at Proceedings of the SPIE 6174, Smart Structures and Materials 2006: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, San Diego, CA, USA, 27–28 February 2006.

[14] N. Hirayama, Y. Sano, "Fiber Bragg grating temperature sensor for practical use", *ISA Transactions*, 2000, vol. 39, no. 2, pp. 169–173, DOI: 10.1016/S0019-0578(00)00012-4.

[15] G. Ma, "A passive optical fibre anemometr for wind Speed measurement on high-voltage overhead transmissionlines", *IEEE Transactions on Instrumentation and Measurement*, 2012, vol. 61, no. 2, pp. 539–544, DOI: 10.1109/TIM.2011.2164837.

[16] G. Golewski, "Zastosowanie systemu Aramis do analizy propagacji rys pierwotnych w betonach z dodatkiem z dodatkiem popiołów lotnych", *Przegląd Budowlany*, 2011, no. 11, pp. 30-35.

Światłowodowy system FBG do monitoringu nowoczesnych materiałów

Słowa kluczowe: światłowodowe czujniki FBG, monitoring, nowoczesne materiały

Streszczenie:

Celem prowadzonych badań była implementacja światłowodowych systemów optycznych oraz systemu Aramis do monitorowania odkształceń, przemieszczeń, naprężeń występujących w nowych materiałach stosowanych w budownictwie. Badania prowadzono na wybranych elementach budynku mieszkalnego wykonanego z materiału Polytech składającego się w 60% z granulatu EPS pochodzącego z recklingu. Wybranymi elementami była prefabrykowana ściana z nadprożem, strop żelbetowy, nadproże w budynku, słup żelbetowy, ściana. Przeprowadzono również badania długookresowe uwzględniające zmiany warunków środowiskowych.

Metodyka prowadzonych badań polegała na opracowaniu specjalnie dedykowanych czujników światłowodowych odkształceń z siatkami Bragga FBG, kalibracji w laboratorium, wprowadzeniu czujników do struktury badanego elementu. Istota pomiaru polega na wyznaczeniu zmiany długości fali świetlnej rozproszonej na siatce Bragga która odkształca się dokładnie tak samo jak analizowany element konstrukcji. Wprowadzone w strukturę budynku czujniki światłowodowe spełniają role systemu "nerwowego". Zmiana długości fali jest proporcjonalna do zmiany wartości odkształcenia. Światłowodowy sensor odkształceń w jednej linii pomiarowej może mieć 10 czujników odkształceń przy czym długość fali każdego z czujników musi się różnić o co najmniej 5 nm.

Wyniki badań zawierają pomiary odkształcalności wybranych elementów budynku mieszkalnego. Przykładowo dla nadproża proces jego obciążania poszczególnymi elementami konstrukcji budynku powoduje wzrost wartości odkształceń. Do wartości ok. –20 µstrain przebiega on podobnie w dwóch torach pomiarowych. Po przekroczeniu tej wartości i po zamontowaniu konstrukcji drewnianej dachu odkształcenia toru FBGC2 dalej rosną (co do wartości bezwzględnej 100 µstrain) natomiast odkształcenia toru FBGC1 rosną w mniejszym tempie stabilizują się na poziomie –50 µstrain. Oznacza to, że konstrukcja drewniana dachu a następnie położenie dachówki ceramicznej spowodowało nierównomierne odkształcenie belki nadproża. Może to być spowodowane przesunięciem wypadkowej obciążenia do wewnątrz budynku. Nadproże jest w złożonym stanie naprężenia w postaci zginania ze skręcaniem. Po 18 miesiącach eksploatacji odkształcenia nadproża osiągają największe wartości ok. 150 µstrain. W dalszym okresie obserwacji ulegają one nieznacznemu zmniejszeniu. Światłowodowe techniki pomiarowe umożliwiają wykrywanie wszelkich niedokładności montażowych polegających oraz zmianę schematu obciążenia. Jest to zatem nowa cenna metoda diagnostyczna poprawności wykonania obiektu budowlanego.

Zaproponowany system ciągłych pomiarów umożliwił wyznaczenie rzeczywistych wartości odkształceń, w wybranych elementach struktury budynku Polytech dla obiektu posadowionego w trudnym geotechnicznie terenie.

Received: 29.09.2021, Revised: 05.10.2021