Application of distributed optical fiber sensor technology for strain measurements in concrete structures

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Abstract

The outline as well as the basic results of a pilot research carried out in the Institute of Building Materials and Structures of Cracow University of Technology are presented and discussed in detail. These studies were devoted to the application of distributed optical fibre sensor technology for measuring strain distribution within cylindrical concrete specimen. The optical fibre was glued to concrete surface in such way, that allows to obtain five measurement sections: two circumferential (tensile) and three longitudinal (compressive). The specimen was compressed at the beginning to the level of 40 MPa and then unloaded, and, in the second part of the experiment, this specimen was compressed until destruction. The process was controlled by three reference mechanical sensors. As a result of the experiment the plot of strain distribution along the length of optical fibre was obtained. Basing on measurement data it is possible to calculate elastic modulus of concrete, estimate material homogeneity and analyse many other aspects such as crack condition and relation between longitudinal and transverse strains. It is important that this approach gives us much more comprehensive information about structural element behaviour than in the case of the traditional, spot measurements. Taking all this into consideration it seems that distributed optical fibre sensor technology could be used in the near future for applications within structural health monitoring of real engineering structures. In the paper the list of suggested further research activities is presented as well.

1 Introduction

Structural monitoring systems represent a branch of civil engineering undergoing a very rapid development nowadays [1]. Increase in safety constitutes one of the basic objectives behind this development, leading to the installation of devices measuring selected physical quantities related directly to the effort of structural elements [2]. Interpretation of the measurement data related to the work of building structures, with respect to the well-defined mechanical systems, is a complex problem, especially when related to the structures made of concrete. Concrete is a heterogeneous material, its internal effort is strongly affected by the qualitative and quantitative composition of the concrete mix, age during the loading, magnitude of the applied load, influence of time (rheology) [3] as well as many other factors. Damage detection in concrete structures, including the quantitative estimation, i.e. for instance the measurement of the crack width, so far remained rather a theoretical request instead of practical capability. This is mostly due to the fact, that the long term strain evolution measurements are performed usually point-wise, the most often with application of the string sensors [4].

Development of the fibre optics measurement technique during recent years allowed for the application of the so called quasi-continuous measurements, relying upon the distribution of several measurement points along the length of a single fibre optic filament. This approach may yield a much more complete information on the deformation of the monitored structural component, than the data gathered through the sensors located at only a few discrete points of the structure. Quasi-continuous fibre optic measurements are accomplished, based on several optical phenomena (i.e. Bragg grating or Fabry – Perot interferometers [5]). But only the application of the light dispersion phenomenon (Rayleigh, Raman or Brillouin dispersion) allowed for the execution of measurements continuously (from the practical engineering point of view) along the length of a fiber optic cable fastened to the structural component or embedded in such a component. Those measurements allow for the so far unavailable analysis of structural behaviour in time. This measurement technique is developed around the world for the last few years only, and thus a lot of research work is still required in order to allow for the reliable application of such fiber optics to identify the crack nucleation points, i.e. the potential damage areas of the concrete and reinforced concrete structures.

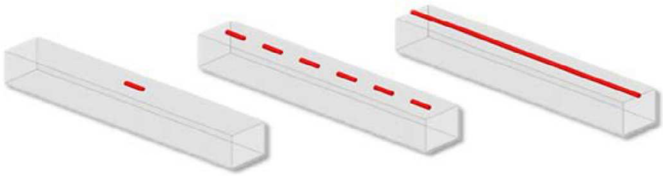

Fig. 1. Point-wise, quasi-continuous and continuous measurement schemes (own work)

2 State of the art

The potential application of fibre optic cables to measure the strains in reinforced concrete structures was analysed in many papers, for instance in [6,7,8]. Very promising results, with respect to crack analysis, were presented in the paper [9], where reinforced concrete beams were subjected to four-point bending. The fibre optic strands were embedded within the beams as well as glued to the bottom (extended) and top (compressed) surfaces. The measurements were made using the Rayleigh dispersion phenomenon. The profile of this phenomenon was measured at the beginning of the experiment at the ambient temperature and saved as the reference before the loading process begun. Fibre optic strands polarized in two planes, having different refractive indexes, were applied. Thus the reflection of the light beam from a single fibre optic strand segment had two different wave numbers, corresponding to the polarization planes. The general idea of such measurements is based upon the transformation of the light dispersion data to the frequency domain by the Fast Fourier Transform (FFT). Thus an amplitude profile is created. When the temperature ΔT or strain $\Delta\varepsilon$ acts upon the fibre optic strand, the reflected spectra are shifted with respect to each other. The magnitudes of these shifts ($\Delta v_a, \Delta v_c$) may be calibrated directly as the changes in temperature or strains through the determination of the autocorrelation coefficients ($\chi_{Ta}(z)$, $\chi_{\varepsilon a}(z)$) and the cross correlation coefficients ($\chi_{Tc}(z)$, $\chi_{\varepsilon c}(z)$) for each fibre optic strand segment according to the following formula [9]:

$$\begin{bmatrix} \Delta v_a \\ \Delta v_c \end{bmatrix} = \begin{bmatrix} \chi_{Ta}(z) & \chi_{\varepsilon a}(z) \\ \chi_{Tc}(z) & \chi_{\varepsilon c}(z) \end{bmatrix} \cdot \begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} \quad (1)$$

The coefficients present in this system of linear algebraic equations may be determined by the calibration process, consisting of several measurements executed at the known external temperature and strains in fibre optic strand.

During the experiment described here the load was applied to the beam gradually, and the observed distribution of strains agreed with the expected trapezoidal distribution of bending moments at the bottom as well as at the top surface. During subsequent steps the development of strains was observed. The extreme value of these strains at the tensile side, approximately in mid span of the beam, corresponded to the location of the first crack, which had the largest opening width. It is worth to notice, that the shape of the recorded diagrams remained unchanged from the beginning of the experiment. This indicates, that the measurements of the type considered are justified in the context of discovering potential locations of concrete damage at the higher load levels. The strain distribution graphs along the length of a single fiber optic strand during subsequent load stages are depicted below.

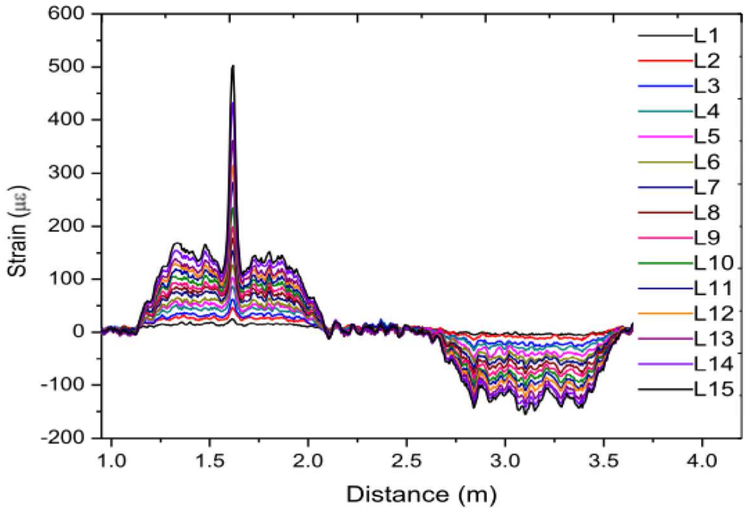

Fig. 2. Distribution of strains along the fibre optic strand glued at the compressed and the tensioned side of a reinforced concrete sample subjected to bending [9].

The peculiar shape of the graph at the crack nucleation point is related to the mechanical response of the glue-strand system during transfer of the crack from concrete to the measuring filament. This phenomenon depends above all on the geometry and mechanical properties of the filament material and glue. It is noteworthy, that the width of the strain extreme registered on the graph at the averaged value level, during the last stages of the experiment, is equal to approximately 15 mm, and is by far larger than the observed crack width equal to 0.2 mm. This indicates, that further research on the better recognition of the concrete-glue-fibre optic filament interface is necessary, followed by development of numerical algorithms allowing for quantitative estimation of inflicted damage. However, even the measurements reported here may be successfully applied to discover and locate the cracks at the early stage of the loading process, when the concrete deforms within the elastic regimen envelope, and the possible micro-cracks invisible to the naked eye do not affect the material behaviour in an important manner. The beam damage due to the increasing loads will develop in the future in the zones where the micro-cracks originated.

3 Research performed at the Institute of Building Materials and Structures of Cracow University of Technology

Fibre optic measurements of strains and temperature within the pilot research conducted at the Institute of Building Materials and Structures of Cracow University of Technology (CUT), were performed using optical reflectometer OBR4600, courtesy of Interlabs company, an official Polish distributor of equipment made by Luna Technologies. The utilization of the Raileigh dispersion phenomenon and the fibre optic strands up to 70 m long with spatial resolution reaching several millimetres, allowed for the successful replacement of multiple single traditional strain sensors [10]. This research was conducted in cooperation with the SHM System company [11], currently working on the research project called "Development of the new fibre optic sensor allowing for the determination of the vertical and horizontal displacements of the studied objects at the distances of up to 120 km". This project is funded by the grant won at the National Center for Research and Development within the framework of Intelligent Development Operational Program 2014-2020.
A cylindrical concrete sample prepared according to the requirements of the Eurocode and having the height of 300 mm and diameter of 150 mm was subjected to the loading program applied by the testing machine. A standard telecommunications fibre optic single strand cable was glued to the sample at selected locations. Altogether five measuring sections were prepared: three longitudinal ones having the length of approximately 130 mm each and distributed symmetrically along the perimeter, every 120°, as well as two circumferential ones (having the length of

approximately 2πr = 470 mm), at the distance equal to the length of the longitudinal section. Additionally, in order to control and verify the obtained measurements, three extensometers having the measurement base equal to 170 mm were used during the experiment to measure the longitudinal strains. Each fibre optic strand was subdivided into measurement segments 5 mm long. The strains were averaged over these segments. The experiment was performed in two stages. During the first stage the sample was loaded until the compressive stresses in concrete reached the value of approximately 40 MPa, and subsequently gradually unloaded to 2 MPa. During the second stage the sample was loaded until destruction.

Before beginning of the experiment, the so called zero measurement level was set, which was subsequently treated as the reference for all the following measurements. The obtained strains $\Delta\varepsilon$ are analysed in two domains: time t and distance l measured from the end of the fibre optic strand (Eq. 2). In traditional experiments the analysis is simplified, as the measurement is a function of time only (Eq. 3):

$$\Delta\varepsilon_{distributed\ measurements} = f(t,l) \quad (2)$$

$$\Delta\varepsilon_{spot\ measurements} = f(t) \quad (3)$$

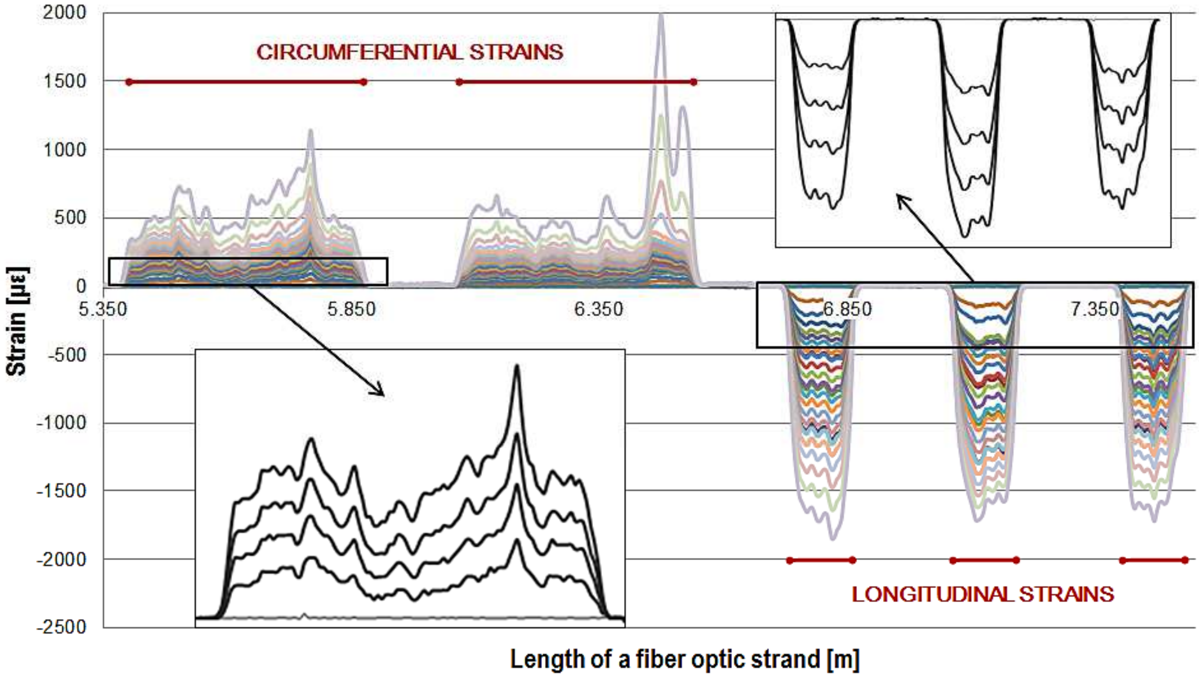

Fig. 3. Distribution (envelope) of strains along the length of a fibre optic strand in subsequent moments in time during the second stage of the experiment (own research).

The distribution of strains along the length of a single fibre optic strand in the subsequent moments in time is depicted in the following figure. One may clearly observe here the measurement sections (fibre optic strand sections glued to the concrete sample). These sections are symbolically denoted on the graph with thick horizontal black lines. The "+" sign is assigned to the tensile strains (two circumferential sections), while the "–" is assigned to the compressive strains (three longitudinal sections). The graph depicts the strains recorded during the second stage of the experiment up to the moment of sample failure. Analysis of the data recorded during the first stage yields similar results.

It is noteworthy, that the distribution (envelope) of strains along the measurement sections is remarkably stable with respect to the shape from the beginning of the experiment (close-up in Fig. 3) throughout all the following stages. Thus the weakest points (those, where the local concentrations of strains occur) may be identified in the early stage of load application, i.e. even then, when the concrete is not yet cracked, or when the micro-cracks invisible to the naked eye do not substantially affect the behaviour of the structure.

In the case of the longitudinal sections, along which the compressive strains are induced, the recorded graphs are by far smoother (i.e. the differences between the local extremes are much less pronounced) than in the case of the hoop strains, where tension occurs and induces the cracking of the analysed specimen. Thus the data derived from the measurements fully correspond to the reality. For additional mathematical confirmation one may calculate the averaged strain variation coefficient V along each measurement section according to the formula:

$$V = \frac{s_{\varepsilon}}{\varepsilon_{av}} = \frac{n \cdot \sqrt{\dfrac{\sum_{i=1}^{n}\left(\varepsilon_i - \varepsilon_{av}\right)^2}{n-1}}}{\sum_{i=1}^{n}\varepsilon_i} \tag{4}$$

where:

s_{ε} – standard deviation of the strain function along the considered measurement section,

ε_{av} – averaged strains along the length of the measurement section,

ε_i – subsequent strain values along the length of the measurement section,

n – number of measurements along the length of the analyzed section.

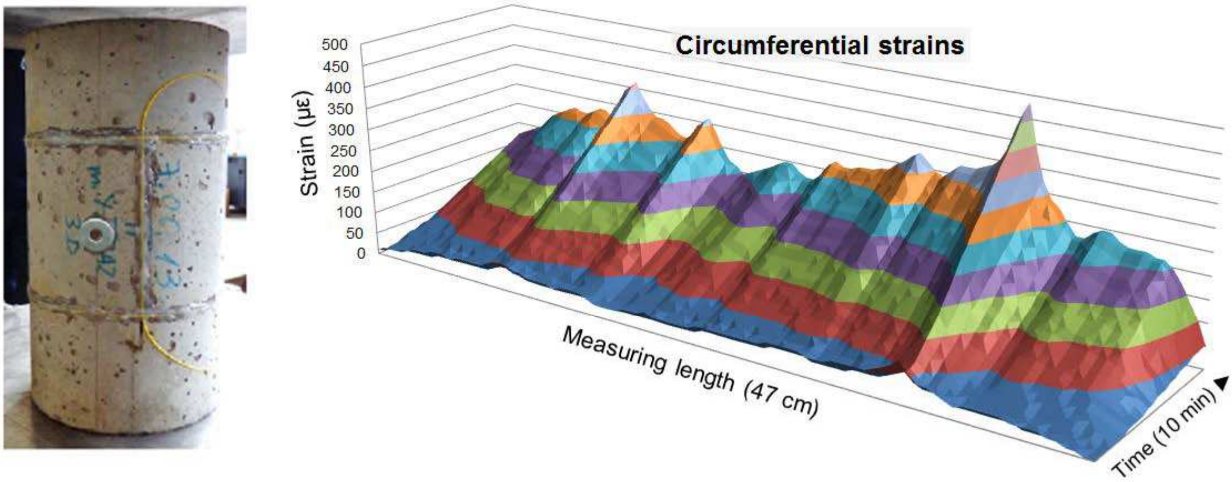

Fig. 4. View of the sample right before the experiment and a sample graph of the hoop strains in the time and distance domains

During the first stage of the experiment, the value of the strain variation coefficient for the longitudinal strains was equal to 36% (moderate variation) while for the circumferential strains was equal to 45% (strong variation). One should note however, that in the case of the classical or the numerical calculations, performed under the assumption of the concrete homogeneity and linearly elastic deformation regimen, one would obtain the variation coefficients for strains equal to 0% (constant values). The similar information is arrived at when the extensometers are applied, as these devices yield the data averaged over the measurement base. Thus once more it is confirmed, that even in the case of the very simple analyses the complexity of real life by far exceeds the models, but when the continuous fibre optic measurements are applied the reality may be examined much more thoroughly, than in the scenarios considered so far.

Since the results obtained are a function of two variables, they may be conveniently depicted on the 3D graphs, where the time and distance domains are assigned to the horizontal axes. A sample graph of the circumferential strains recorded during the loading process is depicted in the figure above accompanied by a photo of the sample prepared for the experiment.

4 Conclusions

As the advantages and capabilities of the fibre optic strand measurement technology were confirmed in numerous experiments ([6, 7, 8, 9]), it offers a significant potential for application in civil engineering problems, including the monitoring of cracks in reinforced concrete structures. One of the axioms of the structural health monitoring systems, set after many years of the experiments [12] stipulates that the sensors cannot measure the damage, which may be ascertained only via the analysis and statistical treatment of the measurement data. Application of the distributed measurement technology thus constitutes a new, much more effective approach.
The pilot research performed at the Institute of Building Materials and Structures of Cracow University of Technology and presented in this paper, consisting of distributed measurements made with fibre optic strand glued to the concrete cylinder subjected to compression in the testing machine, may not be used to derive the quantitative conclusions. These experiments were oriented on showing potential advantages of continuous measurements, when applied in the structural health monitoring systems, and especially on the capability to identify and evaluate the developing cracks. The further research may be oriented on, among others:

- definition of the computational algorithms to determine the crack width,
- determination of the accuracy and usable measurement range for the fibre optic sensors executing continuous measurements,
- investigation of the fibre optic strand mounting modes, depending on the analysed material,
- analysis of the “transmission” length, i.e. the length along which strains in the structural component are fully transferred to the fibre optic strand, depending on the analysed material and fibre optic sensor mounting mode,
- compensation of the experimental results to account for the thermal influences and other external factors,
- remote and automatic execution of measurements,
- simultaneous read out of several fibre optic strands,
- analysis of correlations between the longitudinal and transverse strains.

Fibre optic measurement technology requires continued research and development efforts, as many technical problems still await solution. For instance, the guidelines for system design, or procedures for sensor installation on various types of structures do not exist. Common experience gained through widespread application of these sensors is missing as well. Undoubtedly, the crack monitoring in reinforced concrete structures with new measurement technologies presents a complex task, but the potential gains offered by the proposed approach are worth the effort.

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