APPLICATION OF DIGITAL REFLECTION PHOTOELASTICITY METHOD FOR EARLY DETECTION OF CRACKS IN CONCRETE ELEMENTS

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ABSTRACT
Concrete is a material of diverse structure, for which it is usually impossible to predict a certain behaviour. Of course, there are well developed methods used for engineering calculation of concrete or RC elements. However none of the so far known models provides the possibility to predict the exact location and propagation of cracks in concrete elements. Obviously, once a crack appears it is fairly easy to detect it; however, its appearance makes a permanent change in the material structure. So there is the fundamental question that instantly arises: is it possible to find weak spots in the concrete element before a permanent change actually happens?

This article describes the preliminary results of ongoing research aimed at the development of a method for early detection of cracks in concrete elements. The conducted experiment shows that by using special materials of photoelastic properties it is possible to observe local concentration of strain on an element’s surface. Those spots can be considered as the weakest, most likely locations for the cracks to form. The method gives a unique possibility to detect locations that are mostly eligible for the appearance of cracks in concrete elements. In order to conduct the experiment a test station, including custom-made equipment and custom-developed image-processing software, had to be prepared. This setup allowed the researchers to register, process and analyse collected image data in real time.

This article consists of three main parts. Firstly, some background information regarding the methods is provided, including a short literature review. Secondly, the test station is described. In the final section, the results are presented and conclusions are drawn.

Key words: digital reflection photoelasticity method, early detection of crack, concrete

INTRODUCTION
Photoelasticity methods belong to the oldest and most commonly used empirical techniques used for the measurement of deformation propagation and, eventually, for the determination of stress in structures with the use of mathematical dependencies. A synthesis of these and other contemporary laboratory methods of deformation analysis is presented in the work by Szala (Szala et al., 2007). Photoelasticity can be used in cases when difficulties in calculations are encountered in the analysis of designed or tested structural elements. It is widely used in the mechanical industry, where the degree of complexity of the designed elements is the highest. Boeing has been successfully using the photoelastic coating method, which is one of variations of the discussed techniques, for years, for the analysis of the manner of stress propagation and to identify the locations most exposed to stress in the landing gear elements of designed aircrafts.

Photoelastic tests are conducted on structural elements or two- or three-dimensional models of such elements made from materials characterized by birefringent properties. The photoelastic method is a visual method and the image obtained in the course of tests is directly visible to the human eye. This is particularly important, as it appeals to the human imagination, being both convincing and suggestive. Additionally, the form and colour scheme of the emerging images is very similar to those of deformation or stress maps obtained in FEM analyses. This enables one to find direct analogies between the images obtained in experiments on models and the results of computer analyses.

In the era of dynamic development of software and information technology, empirical methods such as the photoelastic method continue to play an important role, as they allow for the observation and verification of assumptions and results obtained in the course of theoretical analyses of complex design and research issues.
BASIC PRINCIPLES OF PHOTOELASTIC TESTS

For a typical model photoelastic method, tests are carried out on models of actual structural elements made from birefringent materials, characterised by high uniformity, isotropy and elasticity. Test results obtained on the model are then translated to the actual structural element in compliance with the model similarity principle. This method is suitable for structural elements made from uniform, isotropic materials such as metals.

In the case of anisotropic or heterogeneous materials such as concrete, it is not always possible to transfer the results from the model to the actual element. In such cases another experimental method is used, i.e. the photoelastic coating method, pursuant to which tests are conducted directly on the structural element made from the actual material and a photosensitive coating is applied directly onto the surface of the element. It is essential to provide a very good bond between the photoelastic coating and structural element, as the deformations of the structural element have to be transferred 1:1 to the photoelastic coating. The photoelastic effect resultant in the tests reflects the propagation of deformations and stress on the surface of the analysed element.

The photosensitive materials commonly used in both methods are epoxy resins, used for the first time by Fleury and Zandman in the 1950s. After a certain decrease in the popularity of photoelastic methods, they have become increasingly popular in recent years, mainly due to the development of digital image recording and analysis techniques (Remesh, 2000, Chang at al. 2008). They are used both in photoelastic tests on two- and three-dimensional models and in the photoelastic coating method.

The concept of the photoelastic coating method used in the tests presented herein has been widely discussed in literature (e.g. by Vishay, 2011). The image created in the course of photoelastic tests shows two types of interference stripes, which determine certain values characterising the state of strain and deformation. These stripes are called isochromes (fringes) and isoclines.

Fringes are the geometric positions of points characterised by constant differences between principal stress and maximum tangential stress. The relations between the fringe orders and the difference in deformations are expressed by the Wertheim law:

$$\varepsilon_1 - \varepsilon_2 = N \frac{\lambda}{2ch} = N f_c$$  \hspace{1cm} (1)

where:
- $\varepsilon_1, \varepsilon_2$ – values of principal deformations;
- $N$ – fringe order;
- $\lambda$ – length of light wave;
- $h$ – thickness of the photoelastic coating;
- $c$ – Strain-optical coefficient;
- $f_c$ – fringe value:

$$f_c = \frac{\lambda}{2ch}$$ \hspace{1cm} (2)

If monochromatic light is used for analysis, full fringes are visible in the form of dark lines. If white light is used, a multi-colour image emerges, with visible full and fraction fringes. Figure 1, presenting the sequence of colours to the third fringe order (Vishay, 2011), may be used for approximate identification of fringes.

![Figure 1. Sequence of fringe colours](image)

The image of higher order fringes becomes harder to identify, due to a similar repetitive colour sequence.

Isoclines are the second type of interference stripes. They are the geometrical loci of points of constant directions of principal stress. In white light, isoclines are dark lines visible on the background of coloured fringes. Each of the isoclines is described by the value of an angle called the "isocline parameter". This angle is measured in the counter clockwise direction, between the optical axis of the polariser and the axis of the assumed reference system. One of the features of isoclines is the fact that only one of them may cross a given point. Isoclines are possible to observe only in linearly polarised light. Circular polarisation enables to eliminate isoclines so that only fringes remain visible.
PHOTOELASTIC TESTS IN THE CONSTRUCTION INDUSTRY

Photoelastic methods are used in research in numerous areas of science, including also construction.

Jankowski (Jankowski et al. 2005) presents the results of tests of static work of selected carpentry joints used in historical roof trusses. Tests were conducted on models of such joints, made from epoxy resin. Results of laboratory tests were compared with the results of numerical analysis of the said joints carried out with use of the finite element method. One of the causes for the discrepancies in results obtained with use of these two methods that were pointed out in the conclusions of the study consists in the differences in material properties. The applied resin composition is an isotropic material, while timber is characterised by anisotropic properties. Significant approximation of the results of tests conducted with use of the photoelastic method to the actual behaviour of timber in carpentry joints may be obtained by carrying out experiments on wooden models covered with a photosensitive coating.

Jankowski (Jankowski et al. 2010) used the photoelastic coating method in the tests of wooden beams reinforced by carbon bands (CFRP). The deformation propagations obtained in photoelastic tests were compared to the deformations measured by electric resistance wire strain gauges. The values of deformations obtained with use of both techniques differed significantly, which results from the differences between the measurement techniques themselves. The photoelastic method enables one to observe the deformation propagation in the whole area covered by the photosensitive coating, while tensometric measurements provide only information about local deformations in the place where the wire strain gauge is installed. Another factor influencing the obtained results is the heterogeneity of the structure of the wood itself and local imperfections in the form of cracks or inclusions (knots). The photoelastic method makes it possible to analyse the influence of such defects and imperfections on the state of deformations and stress in the analysed element.

The photoelastic coating method was also used by Foust (Foust et al. 2014) for analysing stains in dowel connections of timber elements. Covering the whole surface of the element surrounding the opening with photoelastic coating enabled the researchers to obtain an image of the propagation of deformations throughout the connection. The obtained image differed from the theoretical distribution as a result of individual properties of the element, resulting from the heterogeneity of wood.

Other heterogeneous construction materials include concrete and reinforced concrete. However, there are relatively few contemporary photoelastic analyses of these materials. Chang et al. have successfully used the photoelastic coating method supported by digital image processing techniques to measure and analyse the propagation of stress in concrete around corroding reinforcement rods (Chang et al. 2007) or to develop the method of determining the value of compressive loads in concrete elements initially subjected to compressive forces (Chang et al. 2009).

To sum up, it should be emphasised that the photoelastic coating method can be successfully applied in tests of the properties of heterogeneous materials such as timber or concrete. Moreover, the possibility of a quick digital recording of high-resolution images and the application of adequate processing techniques makes it possible to obtain high accuracy and repeatability of the conducted analyses.

The objective of the pilot tests presented in this study is to develop preliminary assumptions of a test method for early detection of cracks in concrete elements.

TEST STATION

The tests were conducted with the use of custom-made equipment and software developed by the authors. The main element of the test station was a type V polariscope consisting of the following elements: source of white light (LED lamp), a system of polarising filters with quarter-waves (polariser and analyser) and a recording system – Internet camera Logitech C960 and a PC computer with custom-made software developed by the authors. The application of polarising filters with quarter-waves allowed the researchers to obtain circular polarisation of light, which in turn made it possible to eliminate the isoclines obscuring the fringes from the image.

The image captured by the camera was processed in real time by averaging five subsequently recorded frames. The analysed elements were subject to load in a compression testing machine ToniPrax 1540 of a maximum force of 10kN. The computer-controlled apparatus made it possible to load the tested elements in a repeated way, in quasi-static conditions (with a load rate of 0.005 kN/min). A mirror of the dimensions 3.5x8.0 cm, enabling to observe the cracks emerging on the bottom surface of the sample was placed underneath the specimen. Additionally, the image from the mirror was recorded by a digital camera for further analysis.

CONCRETE SAMPLES

Due to the pilot nature of the conducted tests, the authors decided to prepare small-size 40x40x160mm samples, used for the determination of strength parameters of concrete mortars. The composition of the mixture was based on standardised composition, characteristic for testing
concrete mortars. Additionally, each sample was reinforced with steel wire of a diameter of 1mm, with a characteristic strength of 250MPa, leaving 3mm of cover. All irregularities on the surface of samples in locations where the photoelastic coating was to be adhered were polished, cleaned and prepared for the installation of photoelastic sheet plates as recommended by the manufacturer. Two types of photoelastic plates (hereinafter referred to as Type A and Type B plates) manufactured by Vishay Micro-Measurements, made from epoxy resin and characterised by the same optical coefficient $k=0.15$ but of different thickness were used in the experiment. Type A plate (PS-1D) of a thickness of $0.508 \pm 0.0508$ mm, Type B plate (PS-1B) of a thickness of $2.0828 \pm 0.0508$ mm were used.

**Figure 2.** Samples with attached photoelastic plates

**Figure 3.** Sample B1 – element without applied load

**COURSE OF THE EXPERIMENT**

The course of the experiment has been analysed basing on sample B1. In the initial stage of the experiment, permanent photoelastic effects were recorded. The distortions visible in Figure 3 occurred during the cutting of the photoelastic plate. No other effects were observed. Figure 4 presents phase I of the work of a beam at the moment of occurrence of the photoelastic effect, but before the element cracked. This took place at a load of 1.72kN, in the 172nd second from the moment of application of load. Transition from phase I to phase II (cracked phase) occurred as late as in the 264th second. The crack on the bottom of the sample, visible in Figure 5 appeared at the load of 2.64 kN. Then, in seconds 240 and 333, cracks 2 and 3 appeared, subsequently (Figure 6).

**Figure 4.** Sample B1 – phase I, moment of occurrence of photoelastic effect in the tensile zone of the beam

**Figure 5.** Beam B1 – phase II – cracked beam

**Figure 6.** Beam B1 – phase II – beam with three cracks

Figure 6 shows fringes of the compressed zone (just under point where the load was applied) separated by a zone with zero stress, which allows for the determination of the location of the neutral axis of the cross-section. Additionally, in the tensile zone,
three overlapping zones of large-order fringes are visible. They appear in the places where the three cracks appeared. The beam was destroyed at a load of 6.48 kN in the 648 second of the experiment. The destroying crack was crack No. 1 (Figure 7), signalled by the photoelastic effect that occurred at the force of 1.72kN. After the end of the experiment, both parts of the beam were used to determine the compression strength of concrete. Tensile strength of concrete was determined during typical strength tests as in the case of mortars, carried out on non-reinforced beams the size of 40x40x160mm.

![Figure 7. Destroyed sample](image)

### ANALYSIS OF THE TEST RESULTS

Basing on the values of tensile strength of the concrete and the transverse dimensions of the elements, the theoretical cracking moment was determined, along with the theoretical cracking force for each of the beams, treated as working concrete elements in phase I (without cracks). The results of these calculations, together with the observed values of forces at which the photoelastic effects occurred and a crack on the bottom of the beam was noticed, are presented in Table 1.

#### Table 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of plate</th>
<th>Theoretical cracking force [kN]</th>
<th>Force at which photoelastic effect was noticed [kN]</th>
<th>Force at which a crack was noticed at the bottom of the beam [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>1.879</td>
<td>1.600</td>
<td>- *</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>1.879</td>
<td>1.500</td>
<td>- *</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>1.906</td>
<td>2.200</td>
<td>- *</td>
</tr>
<tr>
<td>1</td>
<td>B</td>
<td>2.103</td>
<td>1.720</td>
<td>2.640</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>1.985</td>
<td>1.780</td>
<td>2.840</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>1.934</td>
<td>1.880</td>
<td>2.420</td>
</tr>
</tbody>
</table>

* - value omitted due to very low resolution of photographic documentation, which made it impossible to read the moment of occurrence of the crack.

Two types of photoelastic plates of different thickness were used in the experiment. The aim of this procedure was to test the influence of plate thickness on the quality of the obtained interference images. The conducted tests confirmed the connection between the thickness of the plates of identical optical coefficient and the obtained images of the deformation state. During the experiment, the image on plates marked with letter A (0.5 mm thick) showed a less clear depiction of fringes in comparison to the image on B type plates (2.1 mm thick). On thinner plates a high-number fringes became visible nearly instantly after the occurrence of the photoelastic effect, which made it impossible to unambiguously determine the order of specific fringes. On the other hand, both types of plates made it possible to capture the moment of occurrence of the photoelastic effect in a similar way.

### CONCLUSIONS

The conducted tests demonstrated that the photoelastic coating method makes it possible to notice locations that are particularly vulnerable to structural changes in a material subjected to applied load. One may conclude that such spots are particularly prone to the occurrence of a stress concentration and thus, these are locations where the continuity of the material may be disrupted. The tests also confirmed that due to low values of concrete deformation the selection of thickness of the photosensitive coating is essential.

The result analysis showed, in five cases out of six, that the force at which the occurrence of photoelastic effect was noticed was significantly lower than the cracking force determined theoretically for a concrete element, pursuant to the principles of material strength. Thus, one can conclude that the photoelastic method provides the possibility to determine the location of the occurrence of a crack before it actually appears (mean percentage relation of force at which photoelastic effect was observed to the force at which a crack on the bottom of the beam was noticed equals 68.5%). This is interesting, because the use of suitable photosensitive materials and the application of an assumed, small load may make it possible to detect the weakest points in the cross-section and thus to determine which locations are particularly prone to damage.

It should be noted that the conducted tests are of a pilot nature and that they require additional laboratory experiments, in which the influence of external factors that may affect the presented results could be further limited. Currently, the authors are unable to determine the influence of effect of the adhesion of a photoelastic plate on the additional bearing capacity of the element. The plate adhered to the surface of the beam may carry some of the internal forces (here bending momentum), thus strengthening the cross-section of the tested element. Such strengthening might have delayed the moment of occurrence of the crack, resulting in incorrect outcomes. Further tests in this aspect are required.
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