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MSc Eng. Marcin Knutelski

Faculty of Mechanical Engineering
Silesian University of Technology

Abstract of the doctoral dissertation

Composite sensing elements with integrated SHM manufactured in continuous processes

The dissertation deals with the manufacture of glass fibre-reinforced polymer (GFRP) rods which, apart from carrying mechanical loads, can also be used as distributed strain sensors. The sensing function was obtained by placing an optical fibre along the axis of the rod during composite forming. Pultrusion was selected from the integration methods considered because it allows the manufacturing process to be carried out continuously. The main aim of the work was to develop a repeatable method for producing such elements and to determine whether the optical fibre would retain its sensing capability without significantly reducing the mechanical properties of the rod. Another issue considered in the study was the transfer of strain from the composite to the optical fibre.

The literature review covered the principles of optical fibre strain measurement, including measurements based on Rayleigh scattering. Issues related to the integration of an optical fibre during pultrusion were also discussed. The review included methods of introducing the fibre into the composite and the influence of its position and thermomechanical interactions on strain measurement. The mechanism of strain transfer in the optical fibre–matrix system was described on the basis of adhesion theory and a three-phase shear-lag model.

The first stage of the experimental work involved the selection of an optical fibre suitable for integration with a GFRP rod. Its measurement parameters and the thermal and mechanical conditions of the pultrusion process were taken into account. Methods of preparing and joining the optical fibre were then established. The continuity of the optical path was checked at successive stages of the work. Rheological tests and differential scanning calorimetry provided information about changes in the viscosity of the resin mixture and the course of its curing. The results were used to select the processing parameters.

The production line was equipped with a separate optical fibre feeding path, a tension-control system and a guide system that kept the fibre along the axis of the glass roving bundle. A method of exposing the ends of the optical fibre embedded in the cured polymer matrix was also developed.

The location of the optical fibre inside the finished rods was checked using optical microscopy, scanning electron microscopy and computed tomography. In the section examined by computed tomography, the optical fibre was located close to the rod axis. The glass fibres were mainly aligned with the pultrusion direction. Local gaps and irregularities were observed at the optical fibre–matrix interface. Some of them may have been formed while the samples were being prepared for observation.

The influence of the optical fibre on the properties of the rods was assessed in tensile, three-point bending, short-beam and impact tests. The results depended on the type of loading. In the bending and impact tests, higher values were obtained for rods containing an optical fibre. In the tensile and short-beam tests, better results were recorded for the reference rods. The differences between the two

series were small and did not indicate that placing the optical fibre inside the rod caused its systematic weakening. The largest difference was found for the tensile modulus. The optical fibre therefore affected the axial stiffness to some extent, but no general deterioration in the mechanical properties under investigation was observed.

The next part of the work involved four-point bending tests of reinforced concrete beams. All beams contained primary steel reinforcement. Up to three additional GFRP rods with embedded optical fibres were placed in the beams of the test series. They were located at different positions within the cross-section, and each rod worked as a separate distributed sensor. Measurements were made by optical frequency-domain reflectometry based on Rayleigh backscattering. Unlike point sensors, this method provided a strain profile along the entire measured section of the rod.

The strain profiles were recorded at consecutive load levels. As the applied force increased, higher strains were measured in the bending zone. Local peaks and sudden changes in strain also appeared along the rods. Their positions were compared with cracks visible on the concrete surface. Changes in the strain profiles occurred in the regions where cracks started to form and continued to develop. The use of several rods in one beam allowed the responses of sensors placed at different positions to be compared. It was also possible to observe the redistribution of strain during loading.

A computer program was developed as part of the work to process the optical fibre data. It was used to synchronise the optical measurements with the loading history, select the load stages for analysis and compare spatial strain profiles.

The tests confirmed that GFRP rods with an optical fibre placed along their axis can be manufactured in a continuous process. The mechanical properties of the rods remained comparable to those of the reference elements. At the same time, the embedded optical fibre recorded the strain distribution in the loaded concrete beams. The changes observed in the strain profiles allowed the regions associated with crack initiation and further crack development to be identified.