Sustainable Bridges

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A new sensor for crack detection in concrete structures

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The condition of many important concrete structures can be partially assessed through the detection and monitoring of cracking. Crack detection in bridges is usually based on visual inspection. This procedure is time consuming, expensive, and unreliable; therefore, the use of cracking sensors is highly recommended. Nevertheless, most existing sensors are quite limited in their ability to detect and monitor cracks. This paper reports the development and applications of a distributed optical fibre crack sensor. This sensor does not require prior knowledge of the crack locations, which is a significant advance over existing crack monitoring techniques. Moreover, several cracks can be detected, located and monitored with a single fibre.

1. INTRODUCTION

The appearance of widespread failures in bridges has highlighted the importance of effective monitoring systems which are able to identify structural problems at an early stage. The potential of monitoring systems to reduce operational maintenance costs by identifying problems at an early stage is clearly significant (Casas and Cruz, 2003).

This paper presents a new fibre optic sensor for crack monitoring. The sensor simply consists of a polymeric plate with an embedded optical fibre that can be glued or embedded in a structural element. The principle is that, once a crack forms in a structural element, the bonded polymeric plate will crack in the same location and direction and a fibre intersecting the crack at an angle other than 90º has to bend to stay continuous (Figure 1). This perturbation in the fibre is very abrupt, and thus it can be considered a micro bending. This micro bending results in a sharp drop in the optical signal. From the magnitude of the drop the crack opening can be obtained if a calibration model is available. This technique was initially proposed by Leung and Elvin (1997). A method for applying the sensor to existing structures was recently proposed and it involves the use of a Sensor Plate (Olson, 2002).

To achieve the requirements in the monitoring of cracks on bridges a new sensor plate was developed by the authors within the aim of the Sustainable Bridges Project. The challenges in

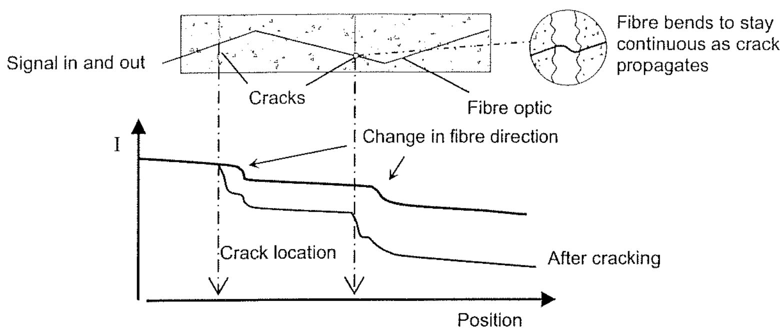

Figure 1. Principle of operation of the sensor

performing the new sensor to attain the necessary mechanical properties requirements to be feasible in practice are discussed in the present paper.

In this research, the plate sensor was made from a thermosetting polyester resin. The resin curing was studied and different additives were added to the polymer to obtain different grades of resistance and brittle mechanical behaviour of the sensor. The results obtained provide guidelines for modifying the polymeric material to assure that the plate breaks for thinner or wider cracks. The choice of polyester for making the sensor plate is based on its high performance and competitive price. Polyester is durable and capable of withstanding environmental attacks including chemical attack from pollution, severe cold and ice, or desert heat.

To gather the necessary parameters and to characterize the mechanical behaviour of the polymeric plate, several tension tests were carried out using a servo-controlled test machine, following the recommendations of ISO 527-1 (1993). The influence of the environmental temperature on variations in tensile properties was analysed (Cruz et al., 2003). The ductile behaviour of polyester observed in the tension tests can be useful to ensure that the sensor only detects cracks with a considerable width. On the other hand, to assure that the sensor detects thin cracks, it is important to assure that the plate is brittle.

The failure behaviour of the polymeric plate can be controlled by the incorporation of fine particles (granite, calcareous, metakaolin, quartz, river sand, and abrasives) and measured with a direct tensile test. The results of the tension tests, carried out in specimens with different particle size distribution, geometry and density of the materials added, demonstrate that it is possible to increase the sensitivity of the sensor effectively (Cruz et al., 2004).

To guarantee the accurate behaviour of the sensor, it is important to establish a correct bonding procedure. Consequently, the bond between the plate and the concrete was evaluated through pull-off tests. In this work, the use of two adhesives was studied: polyester and epoxy resin. In this work, a bonding procedure involving the pre-treatment of the sensor plate for a strong bond to the concrete surface was established. To measure and to improve the adhesion of the sensor plate to the concrete, pull-off tests were performed.

A detailed description of the sensing principles, the thermal and mechanical properties of the polyester, the mechanical properties of modified polymeric materials, and the experimental analysis of the bond properties, can be found in (Cruz et al., 2006).

The present paper gives an insight to the most important aspects of the sensor fabrication, of the calibration tests and of the procedures to apply the sensor. Furthermore the use of the sensor in the multiple cracks monitoring on RC beams and the field implementation of the sensor in the Övik Bridge, in the north of Sweden, is described with detail.

2. SENSOR FABRICATION

Instead of pour the polymer with the fibre placed inside a 254 μm diameter steel wire, coated with releasing agent, it is placed in the mould at the desired angle. Next polymer is cast into the mould and allowed to cure. Once the polymer is fully cured it is removed from the mould. Then the steel wire is also removed and the optical fibre can be placed into the hole left by the steel wire. This way the inopportune break of the optic fibre related with a possible adherence between the optical fibre and the surrounding polymeric matrix is avoided.

3. SENSOR CALIBRATION

There are different ways in which the calibration of prototypes of crack sensor can be made. In this study, instead of using an Optical Time Domain Reflectometer (OTDR) a power meter to measure the loss in forward power transmission was used. The reasons for this choice were: the simplicity and accuracy of the power meter and the fact that the location of the crack was known in advance.

Several calibrations were performed to understand and to predict the behaviour of the sensor under different operating conditions. The calibration tests were done using the mechanical simulator of cracking developed by Olson (2003). This simulator was designed so that the crack opening could be measured using a Linear Variable Differential Transformer (LVDT). The testing stage has a fixed part and a moving part. The moving part rests on two hardened steel rods and has four precision ball bearings to keep it aligned and moving with very little friction. The specimen is clamped onto the stage by tightening the screws. The engine turns the reaction nut that moves against the reaction block and therefore pulls the main rod that opens the testing stage.

4. PROCEDURES FOR SENSOR APPLICATION

The establishment of a strong bond of the plate to the concrete surface is an important prerequisite for the successful performance of the sensor. For a successful bonding application, the strength of the substrate surface is equally as important as a clean and dry surface, the absence of contaminants, and the best profile that can be achieved. Surface blasting with hand held mechanical equipment can be used to attain a uniform surface texture and to remove the laitance (the weak alkaline surface residue), dirt, and dust until coarse aggregates are exposed (Figure 2, left part). Any oil and/or grease contamination on the concrete must also be removed prior to bonding (Figure 2, right part).

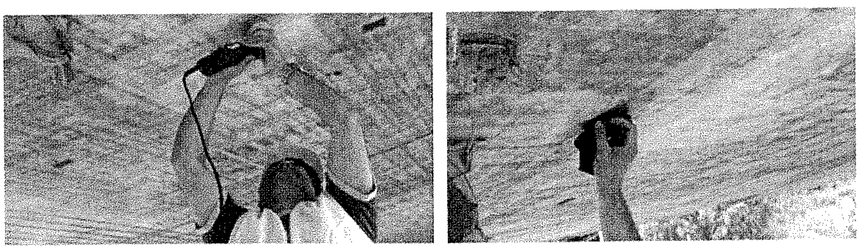

Figure 2. Surface blasting and cleaning

Moreover, to have better compatibility with the adhesive surface pre-treatment of the sensor plate is recommended. An effective pre-treatment of the plate includes a fine blasting with sand paper and cleaning with pure acetone, to remove any contaminant like oils, dirt, and release agents.

5. MONITORING OF MULTIPLE CRACKS ON RC BEAMS SUBJECTED TO MONOTONIC AND CYCLIC LOADS

To assess the efficacy of the sensor to detect and localize the formation of simultaneous cracks in different locations a couple of tests on RC beams were performed (León et al., 2006). The beams have the following dimensions: 2.00 m length, 0.40 m depth and 0.20 m wide. Near the centre span of each beam, there were two pairs of 20 mm notches separated by 40 cm at both lateral faces. The purpose of notching the beams was to define the initial location of cracking. Two LVDT's were employed to monitor the crack openings. The LVDT's attachment was designed to monitor the opening of the crack at the level of the optical fibre sensor. The specimen loading was accomplished under displacement control at 0.5 mm/sec. Regarding the loading condition, the RC beams were given alphabetic designations A and B. Beam A was subjected to cyclic loading, while beam B was subjected to monotonic loading.

Table 1. Young's modulus and stress at maximum load

	E [GPa]	σ [MPa]
Sand 200	1.59	22.14
A1200	1.85	25.42
Pol2a1	0.81	41.00

To detect and compare the crack measurements in the same location two sensor plates made with different additives in the polymeric mixture were placed in series along the fibre, and they were strategically attached in parallel along the tension face at the centre span of the RC beams (Beam A: Plate made with Sand 200 at 20% in density volume and Abrasive A1200 at 20% in density volume with an embedded fibre at 30°; Beam B: Plate made with pure polyester (Pol2a1) and filler of Abrasive A1200 at 20% in density volume with an embedded fibre at 45°). Table 1 summarizes the mechanical properties of these materials.

Figure 3 shows the implemented configuration of installed sensors and overall connections for beam A.

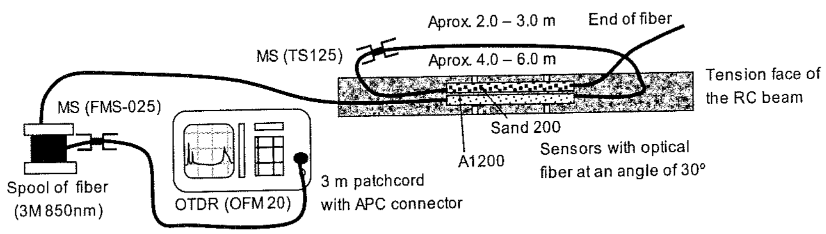

Figure 3. Configuration of installed sensors and overall connections on beam A

The configuration of beam A has included a reusable mechanical splice (TS125) between sensors. To eliminate the reflection induced by the Mechanical Splice (MS), beam B did not include any mechanical splice. 3M single-mode optical fibre was implemented in all configurations and sensors, with a High Resolution OTDR (OFM 20) using a wavelength at 850 nm in Rayleigh operation. The OTDR was linked to the sensors with a mechanical splice (FMS-025) through a spool of fibre, to avoid loss of crack signals due to the strong reflection created at the bulkhead connection, which was made using a fibre pigtail with an APC connector.

Figure 4 shows the initial screen of the OTDR for beam A and B, respectively. In both figures, the approximate location of the beams and sensors are indicated. Figure 4a highlights the insertion loss and Fresnel reflection of the reusable mechanical splice TS125. According to Figure 3, this event can be considered as a location reference between sensors. From Figure 4b it can be noted that the spool of optical fibre for the beam B is shorter.

a) b)

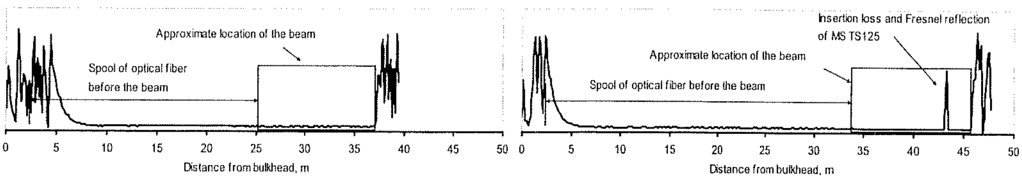

Figure 4. Entire OTDR screen capture showing no cracks: a) on beam A, b) on beam B

Three cycles of loading and unloading were performed. To assure proper data acquisition the maximum loading was maintained for intervals of 25 minutes, since the acquisition can be programmed with the OTDR to be executed in real time after locating the cracks.

The control of the sensor's response could be observed when the plate made with Abrasive A1200 showed only two cracks. The third crack after the Fresnel reflection in Figure 5a corresponds to the cracking of plate made with Sand 200. After unloading and starting of the third cycle of loading the optical fibre was broken in the plate of Abrasive A1200. To continue monitoring the cracks the plate of Sand 200 was activated by linking the spool of fibre directly to the reusable mechanical splice (TS125). Figure 5b shows the enlarged OTDR screen showing four cracks in the beam location. The second and third drops of intensity are approximately 2.90 and 1.30 dB, corresponding to the 2.50 mm and 1.60 mm of crack opening measured by the LVDT's.

a) b)

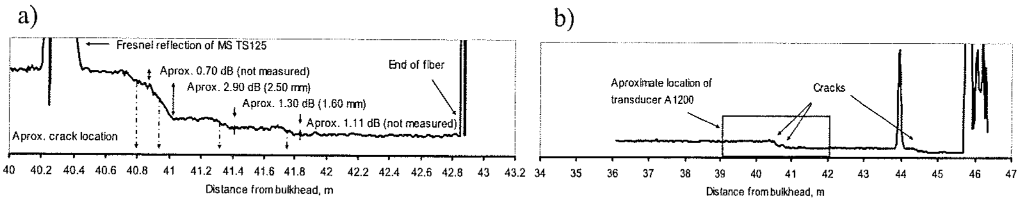

Figure 5. OTDR screen capture showing the location of cracks on beam A: a) general view, b) details

Based on examination of the results and visual observations throughout the test, the undesirable breakage of the optical fibre was developed by fatigue, when the crack was opened and closed by an opening bigger than 2.0 mm.

Figure 6a shows the final location and size of cracks on beam A. From this figure it can be concluded that the plate made with filler of Abrasive A1200 exhibit a better behaviour compared to the plate made with Sand 200 which presents more irregular failure planes.

a) b)

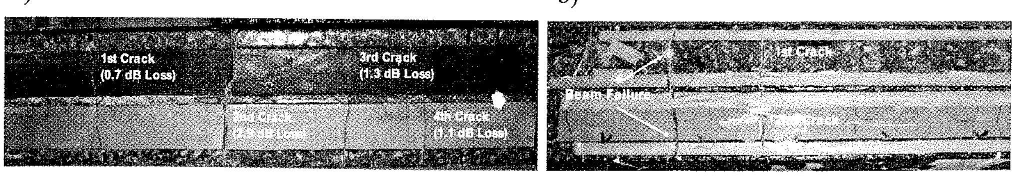

Figure 6. Final location and size of cracks: a) on beam A, b) on beam B

Experimentation on beam B corresponds to the opening of cracks under a monotonic loading until failure. Six consecutive increments of loading and final unloading were performed. Figure 7 shows the OTDR screen capture of cracking condition of the beam B after the third increment of loading.

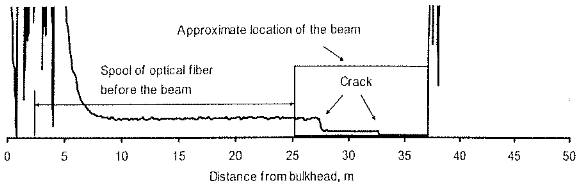

Figure 7. OTDR screen capture showing the location of cracks on beam B

By visual inspection (during test) it was found that there was only one opening crack at the bottom face. The location of the first and second intensity drops corresponded to the crack crossing the plate made with A1200 and pure Pol2a1, respectively. Notice that for beam B two different polymeric plates were placed in series along the fibre and attached in parallel along the centre span. Figure 6b shows the final location and size of cracks on beam B.

Figure 8 shows the comparison between experimental calibration curves of optical power loss versus crack opening obtained by Olson (2002) and results from the present experimental program. Regarding sensitivity the standard error for sensors with the optical fibre at an angle of 30° and 45° were 0.32 and 0.30 respectively. Based on the results, for quantitative measurements at high sensitivity it is recommended to use a fibre at an angle of 45° when 3M optical fibre operating wavelength of 850 nm is considered. Otherwise, the sensor at an angle of 30° can be used only to detect and locate the formation of cracks.

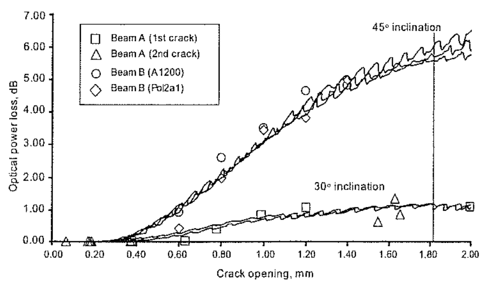

Figure 8. Comparison between experimental calibration curves of optical power loss versus crack opening and results from experimental program (Olson, 2002)

6. FIELD IMPLEMENTATION OF THE SENSOR PLATE

The field implementation of the sensor plate is the culmination and presentation of the research done to develop and test the novel technology for active monitoring of cracks in civil structures. The main purpose of this implementation is to demonstrate the capability of the sensor plate to detect cracks and measure the crack opening at the centre span of slabs and beams of concrete railway bridges.

The field implementation of the sensor plate was considered a success based on the experience and results achieved. It was demonstrated that the procedure proposed to install the sensor plate is easy and solves the problem of undesirable fibre loops bonding outside the plate. It was also observed that the transducer plate with Abrasive A1200 remains dormant if the cracks do not open by more than 75 microns. After concluding the destructive test, the proposed wiring configuration allowed the recovery of data acquisition when the fibre was broken by one of the cracks due to in-plane shear loads. The results demonstrated that it is possible to detect multiple cracks and measure their openings simultaneously using a conventional OTDR.

The Övik Bridge was built in 1955 in Örnsköldsvik, a city located in the north of Sweden. This bridge was part of an old railway line which has already been replaced by a new one. The bridge is a concrete frame structure with two spans of approximately 12 m. The cross sections consist of two lateral prestressed beams linked with the slab (Figure 9).

The destructive test on the Övik Bridge was coordinated by Luleå University Technology with the participation of several partners of the Sustainable Bridges Project involved in WP7. Demonstration of the sensor plate was carried out by University of Minho with the objective of detecting and measuring the opening of cracks.

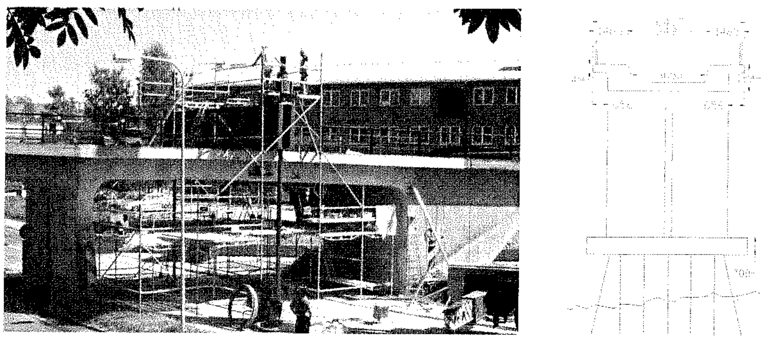

Figure 9. Load configuration of failure test over Övik Bridge: a) front view, b) cross section

The failure test of Övik Bridge was divided into two phases. Firstly, before any intervention, the general condition of the Övik Bridge was considered satisfactory without apparently severe damage. Some loss of concrete cover was detected in the bottom slab due to the impact of wood freight lorries. This kind of damage was not considered relevant. On the first phase, the bridge was loaded to reach the Serviceability Limit State. The test procedure consisted of placing a steel beam at the mid-length of one of the spans and loading the slab through the ballast as indicated in Figure 9. Tendons located at the two beam edges were loaded using two hydraulic jacks. A bending shear failure was expected in the joint between the slab and the longitudinal beams when the tendon load between 1 to 2 MN was applied.

On the second phase, the same load configuration shown in Figure 9 was adopted. Nevertheless the load was applied directly to the concrete beams after removing the supporters that were in contact with the ballast. A shearing failure in the beams was expected when the tendon load was between 6 to 10 MN, which corresponded to the Ultimate Limit State.

The wiring configuration was set for single crack monitoring in view of the spatial resolution of the available OTDR. Figure 10 shows the wiring configuration proposed for field test when the mini OTDR AQ7250 was implemented. To detect and compare the measurements of the sum of crack openings of several cracks in the same transducer plate, two plates with the optical fibre at an angle of 15° and 30° and 20% in density of Abrasive 1200 as additive in the polymer were placed in series along the fibre. They were strategically attached longitudinally along the tension surface at the centre span of the slab and one of the beams of the concrete bridge.

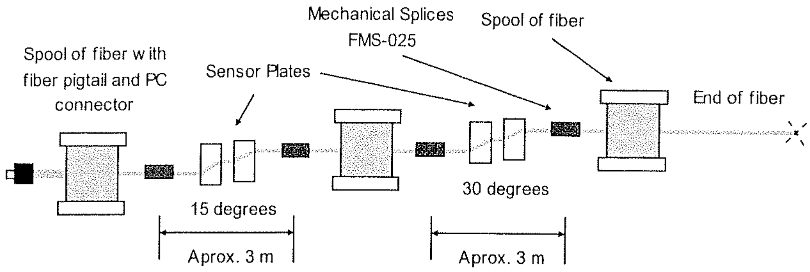

Figure 10. Wiring configuration proposed for field test using the mini OTDR AQ7250

In the wiring configuration proposed (Figure 10) the fibre was connected to the mini OTDR AQ7250 through a 3 m fibre pigtail with a PC connector. The wiring configuration includes three cylinders of 4 km. The purpose of the first and last cylinders are to isolate the back reflection of the connection with the OTDR and that of the end of the optical fibre. The third cylinder is to separate the back reflection and loss at the fibre ends of mechanical splices from the loss at different transducers.

The acquisition was done remotely from the site where the sensors were installed. Figure 11 shows the localization of sensor plates over expected failure regions of the slab and beam.

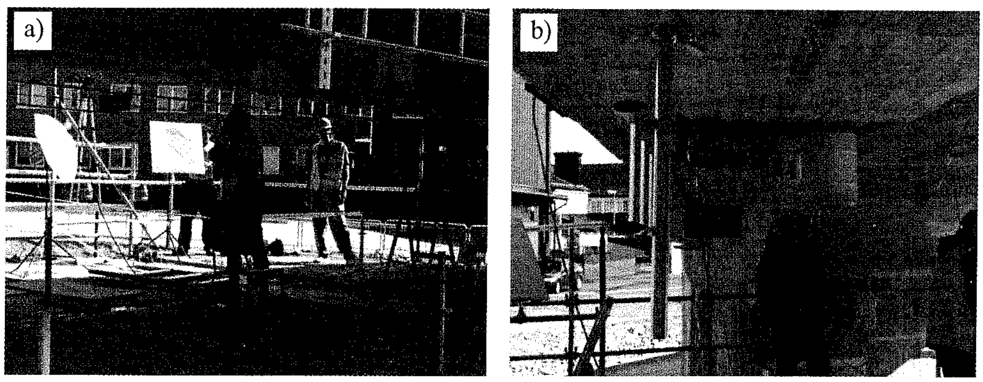

Figure 11. Localization of sensors on expected failure region at slab and beam: a) sensors under the slab, b) sensors under the beam

Through the first phase of the failure test of the Övik Bridge, the sensor plates were placed at the centre span of the slab. After loading the slab through the ballast a bending shear failure was expected to occur in the joint between the slab and the longitudinal beams. However, only narrow random cracks were found to spread on the bottom of the slab in the loading region. The types of cracks were predominantly mixed-mode resulting from combined flexure and shearing mode of loading. Since the sensor plates were located at the expected failure region, it was observed that the transducer plate with Abrasive 1200 could bridge the cracks and remain dormant if they did not open by more than 75 microns.

On the second phase the load was applied directly to the concrete beams after removing the support in contact with the ballast. A shearing failure in the beams and deck occurred near the centre span when the loading reached the predicted Ultimate Limit State of the bridge (approximately at 10 MN). Expecting this failure, the sensor plates were placed close to the position where the load was applied, to detect the cracks that initially opened in a direction perpendicular to the crack plane. When the loading reached 4.5 MN cracks started to appear at arbitrary locations along the deck but essentially perpendicular to the spanning direction and close to the position where the loading was applied. After finishing the second phase six cracks between the sensors were formed and data acquisition was interrupted because fibre breakage occurred in the transducer with the 15° optical fibre due to in-plane shearing caused by the sliding of two crack surfaces on one another. Nevertheless, with the wiring configuration proposed, it was possible to recover the acquisition by focusing on the transducer plate with the optical fibre at an angle of 30°.

Figure 12 shows images of the screen using the emulation software AQ7931B to determine the reference and integrated loss in the post-processing of acquired data. Figure 12a shows the reference loss of 1.088 dB from the sensor at 30° before the second phase of the failure test was started. Figure 12b shows the interruption of the acquisition because of the rupture of the optical fibre in the sensor at 15°. Figure 12c shows the integrated loss of 11.403 dB from the sensor at 30° after completing the second phase.

a) b) c)

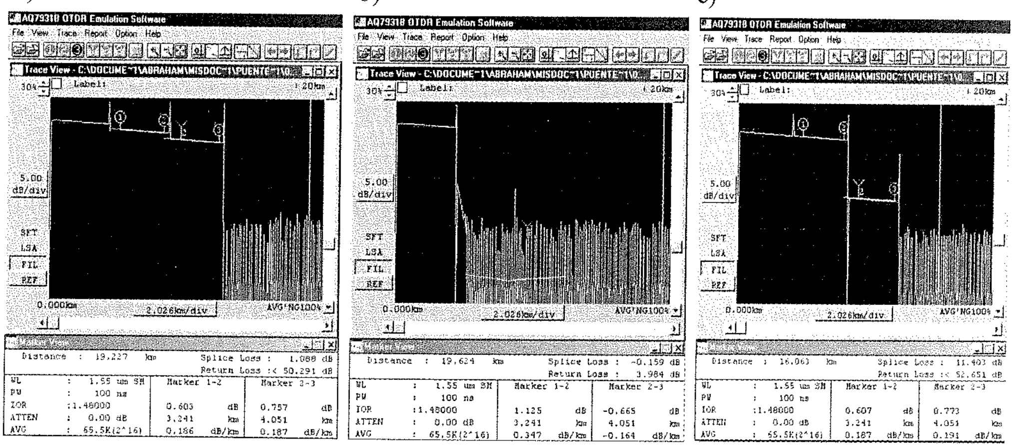

Figure 12. Images of the screen using the emulation software AQ7931B: a) reference loss, b) interruption of the acquisition, c) integrated loss

By a simple subtraction of the integrated and reference losses a net optical power loss of 10.315 dB is obtained. By knowing the mean theoretical calibration model for the implemented sensor and assuming the same angle of crack direction for all cracks, the measured value corresponding to the total optical power loss was 1.19 mm with an absolute and relative error of 1.053% and 0.833% regarding the input range and true integrated size of crack opening.

7. CONCLUSIONS

This paper provides an overview of the challenges in the development and improvement of a novel fibre optic sensor to monitor flexural and tensile cracks on concrete structures. The proposal and studies about new alternatives concerning the material to make the sensor plate, the fabrication process and the bonding procedures to attach the sensor to the concrete were presented.

The primary objectives of this paper were: to examine the methodology of the sensor in detecting and localizing the formation of cracks in various locations; and to demonstrate the implementation of the sensor in monitoring flexural cracks on RC beams subjected to sustained and repeated loading.

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