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Sensing Applications for Plastic Optical Fibres in Civil Engineering

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1. Introduction

Monitoring of the performance and integrity of structures using sensors attached or embedded to them has been of great interest in view of the possibility of predicting potential structural failures, optimising the operational efficiency of the structure, extending the useful lifespan of the host structure as well as tracking the propagation of cracks, amongst other benefits. Indeed, the field of structural health monitoring has received considerable attention and investments from private and public institutions including academia, professional institutes, industrial research laboratories, government agencies as well as the industry. A wide range of companies involved in the designing, fabrication, integration, usage, servicing and maintenance of structural components, assemblies and systems have a common need to monitor, understand and manage the performance and integrity of the structures in their possession. These companies hail from industries such as the offshore, oil-and-gas, power generation, building construction, marine, aerospace, civil and environmental.

Monitoring the performance and integrity of a host structure is often translated into the measurement of key parameters or health signatures of the structure as indicator of the integrity and level of performance of the host. Common parameters of interest include strain, load, deflection, displacement, pH-level, temperature, pressure, vibration frequency, liquid level, detection of cracks and monitoring of their rates of propagation, moisture, detection of events such as impact, overload, fracture and others. Several review papers are available in the open literature outlining various examples of optical fibre sensor applications [1-3].

In recent years, optical fibre sensor technology has gained significant attraction as the sensor of choice in many structural health-monitoring applications. Several optical fibre sensing techniques have been commercialised whilst others are being developed. These sensors in general, offer several distinctive benefits and advantages over conventional sensors - these include their insensitivity to electromagnetic and microwave radiation (occurring near power-generating equipment), being spark-free (hence suitable for use in areas where risk of explosion is a concern), the fact that they are intrinsically safe (inert and passive), non-conductive, lightweight and potentially suitable for embedding into structures such as fibre composite laminates during the fabrication stage.

There are several unique features associated with optical fibre sensors. Certain types of optical fibre sensors (e.g. fibre Bragg gratings) possess the possibility of having multiple sensing regions in a single strand of fibre - this capability where multiple sensors could be interrogated simultaneously in quasi-real time using a single channel is a significant advantage over conventional sensors such as strain gauges where a single channel monitors only a single sensor. In addition, recent advancement in the development of interrogators based on optical time-domain reflectometry (OTDR) principle has opened up the possibility of performing distributed monitoring of strain and temperature along a single fibre sensor. Also, although optical fibre sensing techniques, in general, are known to be capable of obtaining high measurement resolution (e.g. sub-microstrain measurement is possible with fibre Bragg grating sensor), their ability to monitor large strains (e.g. 40% strain or more) has also been reported [4]. In applications requiring the measurement of parameters that modulate over time (e.g. as in fluctuating liquid level [5]), optical fibre sensors offer a range of dynamic characteristics or responses which could be tailored to suit specific needs.

There are two main types of optical fibres based on the material from which they are made and these can be classified as either glass-type optical fibres (GOFs) or polymer-type optical fibres (POFs). Within each class of fibres, a variety of materials have been used, developed, doped and purified to achieve low transmission attenuation. Historically, optical fibre sensors were developed using GOFs due to their availability, excellent transmission properties, and other optical characteristics which make them amendable to sensor fabrication – e.g. the ease of changing the refractive-index of a section of a specially-doped glass fibres via light radiation has led to the development of fibre Bragg grating sensors. In recent years, however, interest in the use of POFs for short distance networking (e.g. local area networking), significant improvements in transmission properties, lower cost and various practical advantages of POFs over GOFs have spurred intense research and development in sensor technologies based on polymer fibres. Whilst many of the sensing methodologies developed based on GOFs could also be applied to POFs, the unique features and advantages of POFs opened up new possibilities and opportunities for its applications in the field of civil engineering.

Plastic optical fibres usually come with core sizes ranging from diameters of 0.25mm to 1mm although fibres of larger diameters could also be purchased - a search on the Internet will reveal many suppliers of POFs. The core of the fibre could be made from poly-methymethacyrlate (PMMA), polycarbonate (PC), polystyrene (PS) and cyclic-transparent optical polymer (CYTOP), this being a recent addition to the list. Although the transmission attenuation of POF based on PMMA (160 dB/km) is inferior to the CYTOP-type fibre, it is the most readily available POF. Being inexpensive, many cost-effective sensors have been developed based on PMMA step-index fibre for a variety of applications in civil engineering.

POF sensors have attracted increasing interest for use in health-monitoring of civil structures due to a number of advantages over their silica counterpart. These include their lower cost (the fibre itself and the associated accessories and hardware), less susceptible to fracture and flexibility compared to bare GOFs. They also offer ease of termination (i.e. cleaving can be done with a razor blade and connected easily to the ferrule), safe disposability and ease of handling during sensor fabrication and installation to the host structure. Compared to GOFs of the same diameter, POFs are lighter, cheaper and less prone to flexural damage. In addition, POF has an elastic limit of an order higher than GOF [6,7] and it has been shown that standard step-index PMMA POF can be integrated into geotextile materials to measure strains up to 40%. When it is desirable to embed sensors within concrete structures, POF sensors offer a possible solution since the extremely alkaline (pH 12) environment of the concrete mixture is known to be corrosive to standard glass fibres [8]. Furthermore, the presence of moisture can weaken the glass core and accelerates crack growth in the fibre. Although a polymer coating may be applied in order to protect the glass fibre from the corrosive environment, this will incur additional cost and change the sensing properties of the sensor.

The brief introduction above serves as the background information to the following examples of applications encountered in civil engineering. Initially, examples of POF sensors based on intensiometric principles will be highlighted, followed by techniques based on OTDR. This chapter will focus on these two particular techniques in view of the author's experience in working with these in many projects over the last ten years. The principle of operation of each technique will be outlined in each category prior to a showcase of some examples to assist the reader in appreciating the subject matter.

The aim of this chapter is to present to the reader the potential of POF sensing technique as an attractive option for various applications in civil engineering and is not intended to be a comprehensive review of the various studies published in the literature in the area of POF sensor. Through illustrative examples of applications, it will be shown that POF sensors are ideal candidates in numerous civil engineering projects, either complementing or replacing conventional sensors. In some cases, POF sensors will be shown to offer a solution not possible with existing commercial sensors in the same class. With further development aimed at exploiting the unique features of POF-based sensors they may well prevail as the sensor of choice in many civil engineering applications where their cost-effectiveness, reliability, simplicity in design and ability to perform under demanding conditions are the key considerations in the sensor selection process.

2. POF sensors for civil engineering applications

To date, there are several sensing methodologies developed for the POF. These techniques differ in the way which the optical signal (which contains information on the measured quantity) is interrogated. Depending on which optical characteristic was monitored, the technique could be classified as intensity-based, interference-based, polarisation-based, wavelength-based or OTDR-based.

Of the various types listed, intensity-based sensing technique represents one of the earliest and perhaps the most direct and inexpensive way of interrogating optical fibre sensors for structural health monitoring applications. The sensing principle is straightforward and relies on the monitoring of the intensity level of the optical signal as it modulates in response to the measured quantity. Although intensity fluctuation in the optical signal due to possible power variation at the source as well as influence of external parameters unrelated to the measured quantity (e.g. micro- and macro-bending along the fibre length) can occur, these could be overcome. For example, with the availability of stable and inexpensive light sources and low bend-sensitivity fibres, the intensity-based approach offers excellent technical and commercial prospects for high volume, large-scale applications from a cost-effectiveness point of view.

Intensity-based technique is also well-suited for vibration measurement since absolute strain values are not required for this quantity – provided that the oscillation is within the sensitivity of the sensor. In recent years, POF-based accelerometers have been developed with vibration monitoring capability and it has been demonstrated that these optical fibre-based vibration sensors compare well with conventional capacitive accelerometers for vibration up to 1 kHz.

In addition, intensity-based technique can be integrated to wireless modules with ease for monitoring of static and dynamic loads. This can be carried out at a low-cost and with ease in view of the availability of miniaturised solid-state devices which could be used as light sources and detectors for the POF sensor. An example of this concept has been demonstrated for a flood monitoring application [5]. These features highlight the potential of intensity-based technique for field deployment where their sensing capabilities could be exploited whilst achieving cost-effectiveness. Instead of the common approach which is to use an optical fibre technology based on best-in-class for their measurement needs (e.g. high strain resolution of fibre Bragg grating sensors, which often entails a high up-front cost) potential users need to be clear in their requirements and be open to evaluate intensity-based optical techniques which to provide a more cost-effective solution.

In this section, the principle of operation of each type of interrogation method covered in this chapter will be outlined accordingly. The two main types considered in this chapter are (1) Intensity-based sensing and (2) OTDR-based sensing.

2.1 Intensity-based POF sensors

2.1.1 Operating principles and background of intensity-based POF sensors

The ease of monitoring the intensity of the optical signal in POF naturally leads to the investigation of their potential as intensity-based sensors. Light sources are easily available and inexpensive and could come in the form of high-intensity light-emitting diodes (LEDs), typically those operating at the red region (centred at 625 nm) region of the visible light spectrum. Light detectors are also widely availably and those that are commonly used in association with POF are light-dependant resistors (LDRs) or solid-state photodetectors. The interrogation technique is straightforward and involves monitoring the modulation of the light intensity as a function of an external perturbation of interest which include strain, displacement, load, pressure and others. Indeed the simplicity in design of the sensor as well as the low cost of the light source and detector associated with intensity-based technique have led to numerous applications not just for civil engineering but also for many other fields where detection and monitoring are required.

In general there are two categories of intensity-based POF sensors and these are classified as either (a) intrinsic or (b) extrinsic sensors. In the former category, the modulation of the intensity of the optical signal in the fibre is a result of the physical change in the optical fibre due to an external perturbation, such as load, strain or pressure acting on the fibre itself. This phenomenon can be observed when a sensitised region of the POF is bent resulting in the modulation of the light intensity. In the latter category of sensor, the modulation of the optical signal in the fibre is a result of a change in the physical-optic state of a transducer attached to the fibre resulting in the modulation of light intensity.

The optical fibre in this case serves as a light conduit and is not physically affected by the external perturbation itself. An example of this effect is when the light intensity modulates as a result of a change in the distance between two cleaved fibres resulting from an external perturbation.

2.1.2 Applications of intensity-based POF sensors

Intensity-based POF sensors have been demonstrated for a number of structural applications ranging from monitoring of flexural loading to detection of cracks in concrete specimens. In one of their earlier works, Kuang et al. [9] investigated the use of such type of POF sensor to monitor the mechanical response of a number of plastic specimens. The POF utilised in their studies was a step-index 1mm diameter PMMA POF supplied by Mitsubishi Rayon Co. Ltd. The flexural sensitivity of the fibre used (ESKA CK40) was enhanced by removing the cladding layer of a segment of the POF over a pre-determined length, the aim being to promote light loss in this region due to the reduction in the number of modes undergoing total internal reflection when the fibre was bent. In their studies, the sensitised regions reported range from 70mm for smaller specimens to 300mm for larger specimens were shown to be appropriate although it may be postulated that the length of choice will depend largely on the sensitivity required and the size of the host structure of the actual application. The study also demonstrated that the POF sensor based on the removal of cladding layer possess directional sensitivity in that highest flexural sensitivity could be achieved when the plane of cut resulting from the removal procedure was perpendicular to the direction of flex. The flexural strain-optic coefficient was reported to be approximately $1.8 \times 10^{-5}/\mu\varepsilon$, implying that at 1% flexural strain, a normalised loss of 18% in light intensity could be expected.

Since the removal of the cladding layer was done manually by scrapping the POF with a razor blade, the light intensity transmitted through to the fibre end would have decreased considerable with each subsequent scrapping process since with each cut, more of the POF core was removed. To achieve consistency in the amount of material removed, the procedure should be done with the POF placed in grooves machined to specific depths. The scrapping of the POF material would then be carried out in steps of decreasing groove depth as desired. A photograph showing the cross-section of the sensitised POF is given in Figure 1.

To test the response of the POF sensor under flexural load and tensile load, the authors mounted the POF onto its respective specimen using an acrylate-based adhesive. For the flexural load condition, a section of a straight fibre was aligned along the longitudinal axis of the specimen and attached to the bottom surface of the plastic specimen. The specimen was tested under a three-point bend set-up to evaluate the response of the sensor. To sensitise the POF to the flexural load, a segment of the fibre attached to the specimen was removed as described above. To test the POF response to tensile loading, the sensing region of the POF was curved slightly such that the fibre would tend to straighten out as the tensile load was applied.

Figure 2(a) shows the repeatability of the POF sensor response under a cyclic flexural loading, demonstrating the potential of the sensor to monitor the flexural displacement of the specimen reliably. The response of the POF sensor when tested in the tensile direction is

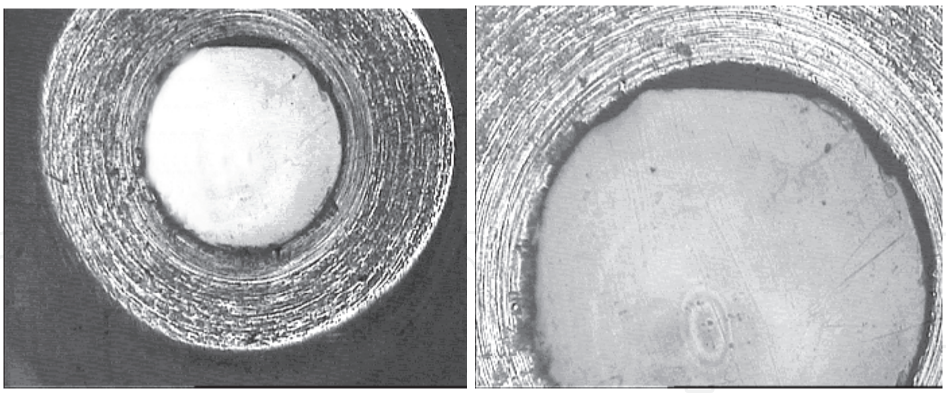
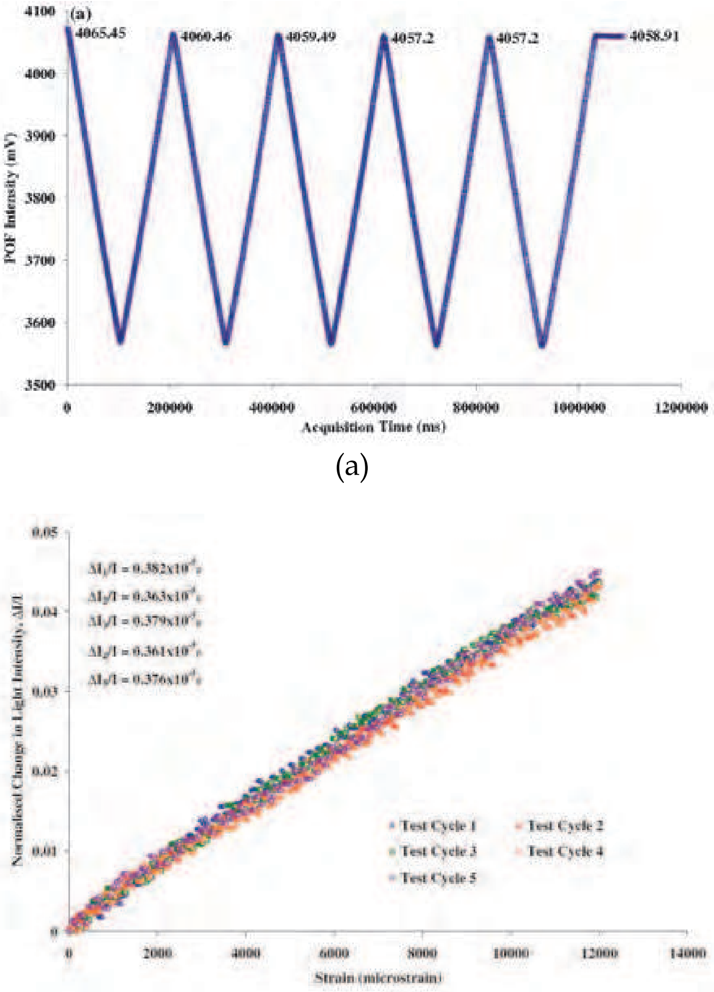


Fig. 1. Photograph showing the cross-sectional view of the sensitised POF where a segment of the POF (cladding and core) was removed (after [9]).



(a)

(b)

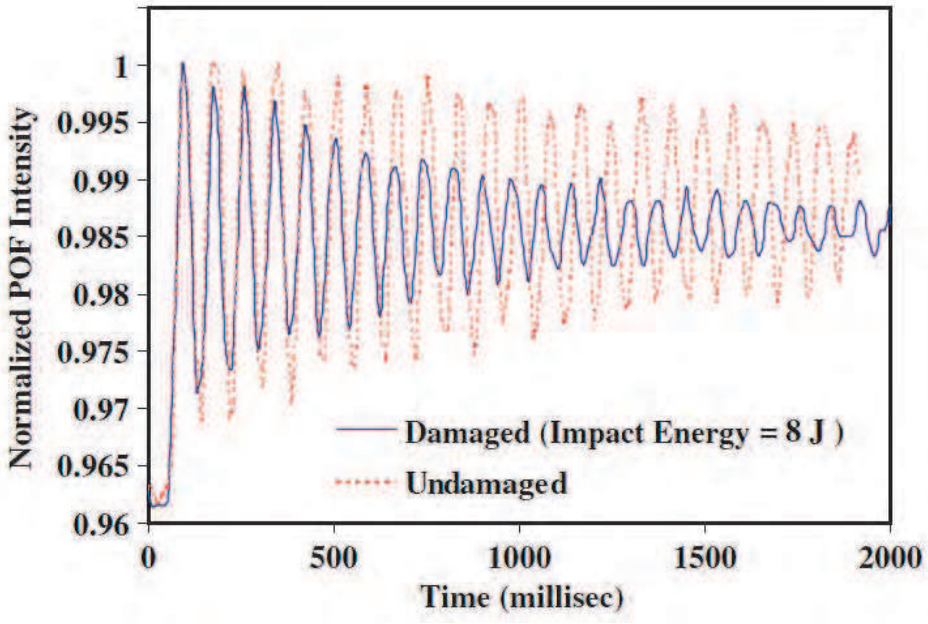
Fig. 2. Plot showing the response of the POF sensor during (a) cyclic flexural loading, (b) tensile loading (after [9]).

shown in Figure 2(b). Here the result also illustrates the high degree of repeatability of the response of the POF. It was highlighted that although the tests stopped at flexural and tensile strains of 0.7% and 1.2% respectively, the ability of the POF sensor design used in this study to measure strain values higher than that observed in the tests can be achieved. This may be supported by the fact that at those levels of strain observed in the study, the loss of intensity in each case did not show evidence of a plateau. In addition, studies conducted by other workers up to 45% [6,7] can be expected while other studies have shown that POF could endure stretching of more than 80% strain under certain conditions [10].

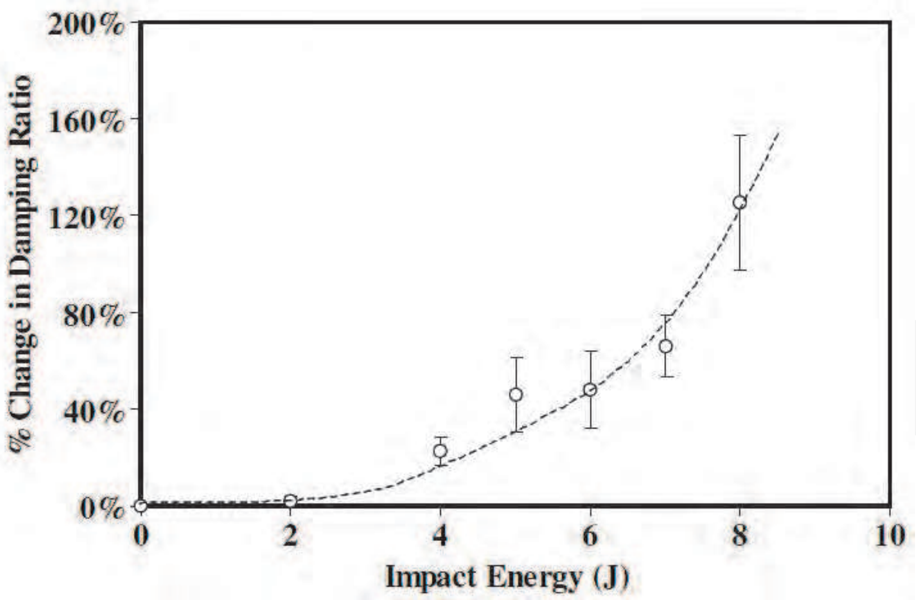
The performance of the POF was also investigated under dynamic loading conditions to assess their potential for vibration measurement, a technique frequently employed in health monitoring of civil engineering structures. Here, Kuang et al. [11] used the same POF sensor design described above in a set-up involving monitoring the natural frequencies of a series of increasingly damaged composite beams subjected to various degrees of damaged induced by low-velocity impact. The ability to detect the change in the frequency response of the host beam as a result of impact-induced damage is shown in Figure 3(a). In addition, the damping ratio of the cantilever set-up was also monitored. The ability of the sensor to monitor the damping ratio as a function of impact energy (inferring degree of damage) is shown in Figure 3(b). The changes in natural frequency and the decrease in the damping ratio were used to characterise the reduction in the post-impact flexural stiffnesses and the residual strengths of the composite beams with increasing level of impact damage. The study showed that the POF sensor was evidently able to detect a change in the damping ratio as small as 2.5%. The natural frequencies of the beams at various stages of damage based on the results of the POF sensor were found to compare well with the predicted theoretical values as well as the readings obtained from an electrical strain gauge. The authors also discovered in their study that impact tests on simply supported carbon-fibre reinforced beams also showed that the sensor was able to monitor out-of-plane deflections during the impact event. A laser Doppler velocimeter was also used in conjunction with a piezoelectric load cell as a means to validate the results of the POF sensor.

The ability to monitor the dynamic response of the host beam encouraged the authors to further apply the technique to monitor the morphing response of a nickel-titanium fibre- metal laminate [12]. A collocated electrical strain gauge provided a reference measurement to compare the response of the POF sensor. It was reported that following activation of the smart fibre metal laminate using a heat gun, the nickel-titanium deformed as predicted and the POF sensor was found to monitor the flexural response of the smart composite accurately. The response of the POF was compared to the electrical strain gauge and this is summarised in Figure 4 showing the high degree of similarity in the responses of both sensors.

This type of intensity-based POF sensor also found applications in crack detection and monitoring of deflection of civil structures. Kuang et al. [13] conducted a series of flexural tests on scaled-specimens where the POF sensor was attached to the bottom surface of the concrete beams and demonstrated in their study that the POF sensor design used were of sufficient sensitivity to detect the presence of hair-line cracks. Figure 5 shows photomicrographs of the size of the cracks in the concrete relative to the POF. The smallest crack width measured approximately 0.04 mm was successfully detected using the POF sensor. In order to improve the sensitivity of the POF to the beam deflection and crack initiation, a segment of the POF was



(a)



(b)

Fig. 3. Plots showing (a) a comparison of the dynamic response of undamaged and damaged specimen as measured by the POF sensor, (b) the ability of the POF sensor to monitor the change in the damping ratio response for an increasingly damaged specimen (after [11]).

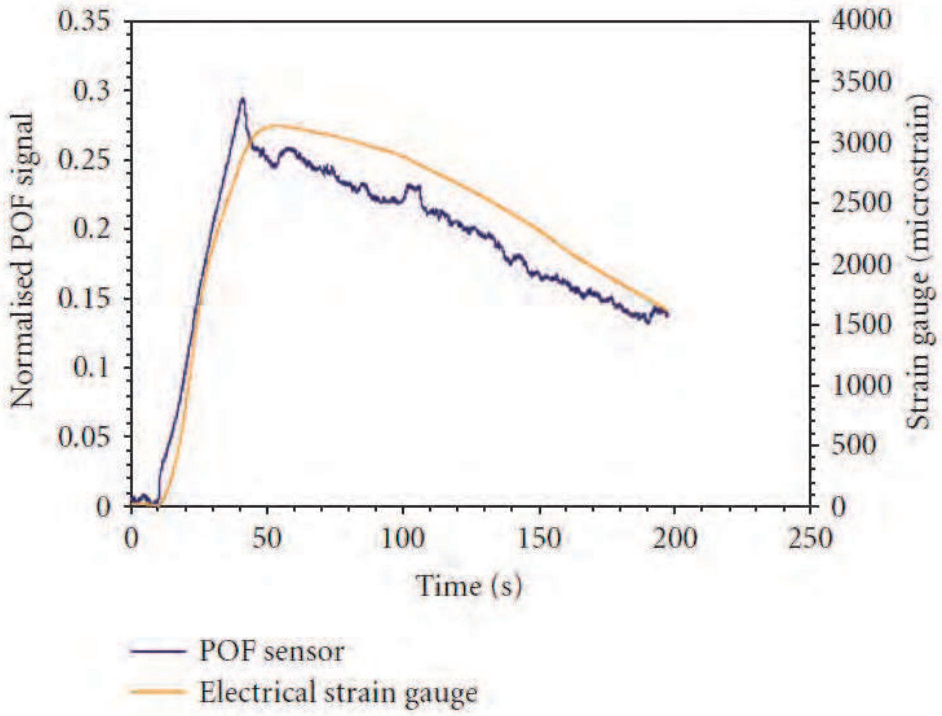


Fig. 4. Plots showing response of the POF in monitoring the fibre metal laminate upon activation of the nickel-titanium (after [12]).

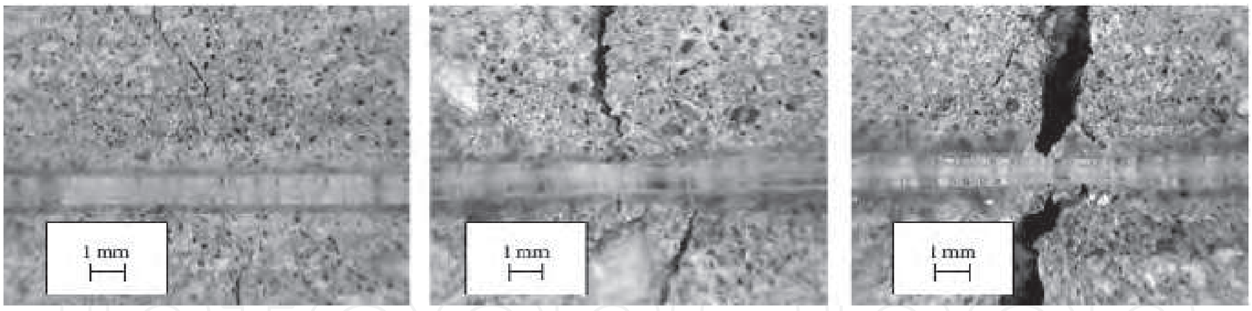


Fig. 5. Photographs showing intersection of the crack and the POF sensor for the concrete specimens at difference degrees of crack width (after [13]).

removed as described earlier over a predetermined length (70 mm for a series of scaled un-reinforced concrete specimens and 300 mm for full-scale reinforced concrete specimens). For the scaled specimens, the authors showed that under three-point bend loading, the POF sensor was able to detect the presence of crack once it intersected the sensor and this observation was repeatable for the entire series of specimens as shown in Figure 6. Similarly, for the full-size specimens the test results affirmed the potential of the POF sensor to monitor the response of the concrete beam under load. Initial cracks in the concrete beam were successfully detected and the POF continued to monitor the post-crack vertical deflection through to finally detecting the failure cracks in the specimen.

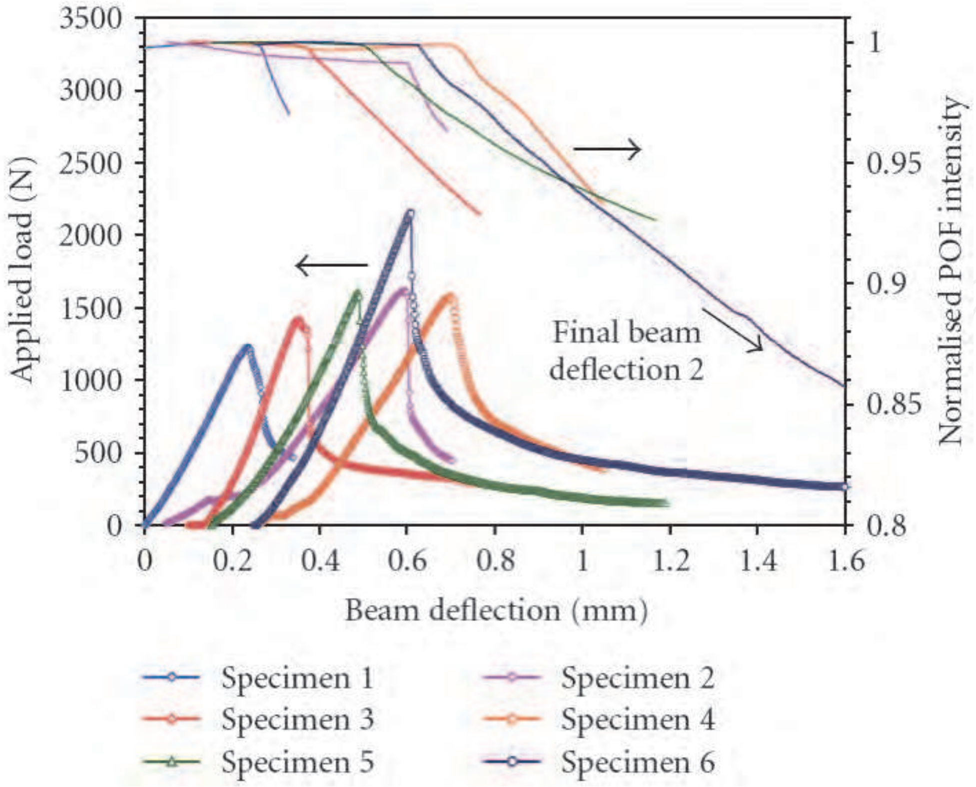


Fig. 6. Plots showing the ability of the POF sensors in detecting the crack for a series of six scaled concrete specimens (after [13]).

In a different area of application within the field of civil engineering, POF sensor has been demonstrated to have potential to be used as flood sensors. Monitoring of the water level in flood-prone areas could provide early warning of flash floods which devastated various regions in ASEAN (Association of the Southeast Asian Nations) in recent times, both in the urban and rural areas. The monitoring of liquid level is also an important activity in many industries and the special requirements to monitor a large number of multiple containers of volatile fluids demands the implementation of cost-effective and safe sensor systems. Other applications where liquid level monitoring is desirable include monitoring of the water level in catchment areas, monitoring of illegal dumping of trash and pollution in canals (which can be inferred by an unexpected rise of water level) and early warning of impending drought (when water levels drops to a minimum level). Information collected by a network of sensors could also be used to complement and update flood monitoring and prediction software models.

The intensity-based POF sensor proposed for flood monitoring by Kuang et al. [5] was simplified from earlier designs applied to glass-type fibres. In the simplified design, neither fusion-splicing nor heating were used in the sensor construction as the POF could be readily bent to shape without any risk of fracture. No prismatic element was used in the proposed design, thus rendering its construction significantly easier whilst exhibiting excellent optical response. It was argued that the simplicity in design of the proposed sensor could lead to an inexpensive, rugged, easy-to-use and effective optical fibre-based sensor for mass deployment in a flooding monitoring application. In addition, the authors demonstrated the ease of integrating the POF sensor to a commercial wireless mote, utilizing the on-board light dependent resistor to monitor the optical intensity transmitted through the fibre. Figure 7 shows the assembled unit consisting of the POF sensor and the wireless mote. The convenience and ease of integration the POF to off-the-shelve wireless motes would not be possible with other interrogation techniques, highlighting the unique advantage of intensity-based approach.

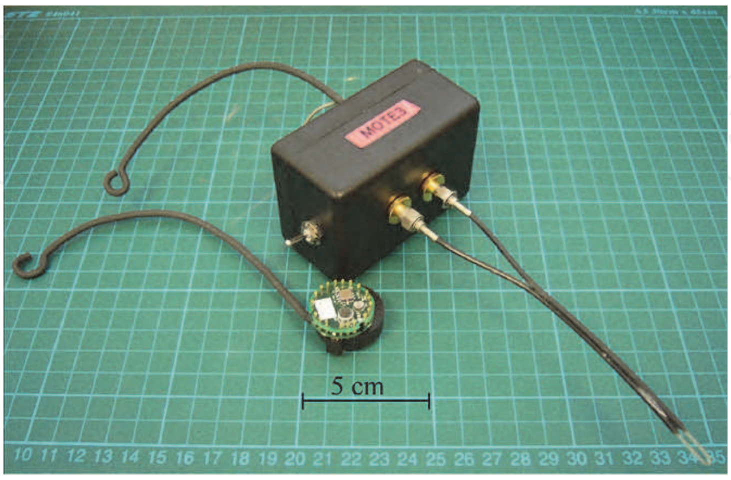


Fig. 7. Photograph of the wireless POF prototype and the MICA2DOT unit used in the flood monitoring experiment (after [5]).

The principle of operation of the POF sensor used in the flood monitoring study was based on the loss of total internal reflection or absorption of evanescence wave when the probe was immersed into the liquid medium. Before the sensitized probe was immersed into the liquid (i.e. in air which has a refractive index of ~1), the majority of the light ray will undergo total internal reflection and will be guided along the optical fibre to the output end of the fibre. However, when the probe was immersed into a liquid with a higher refractive index (e.g. water, which has a refractive index of 1.3), light traveling as cladding-mode will be absorbed by the liquid as the condition for total internal reflection could not be satisfied at the fibre–water interface. The intensity of the optical signal arriving at the output end of the fibre will correspondingly be reduced. It follows that when the probe was immersed in a liquid with higher refractive index, more light will be lost from the optical fibre into the liquid. This being a point sensing system, several such sensors may be deployed concurrently to achieve a multi-level discrete measurement of liquid level.

The response of the sensor was also tested and Figure 8 shows the repeatability of the liquid detection capability of the proposed sensor. From the sensor response, it is clear that it exhibits excellent repeatability showing no sign of hysteresis. At the circle marked A, corresponding to the moment the tip of the probe touched the surface of the liquid, the displacement transducer reading was initialized and set to zero. At that moment, the sensor signal decreased sharply as light escaped into the test liquid. When the probe was being drawn out, the sensor signal began increasing gradually starting from time B when the probe was beginning to leave the surface of the liquid. This occurred at approximately the same probe position corresponding to that of circle A. As a result of the surface tension of the liquid, a cusp formed at the tip of the probe as it past the zero position. The wetted area at the tip decreased gradually as the probe was being drawn out and this corresponds to the increasing signal reading as more light rays undergo total internal reflection. As the cusp broke at time corresponding to circle C, the sensor signal reaches maximum value at approximate probe position of 0.37mm. From the chart, the response of the sensor when withdrawn from the liquid lags behind the physical position of the probe as defined by the difference in the distance between positions A and C, this interval being approximately 0.37mm for the liquid used. Clearly, the value of this interval, which is a function of the surface tension, will vary accordingly with liquid used. However, level of accuracy better than 1mm may not be at all necessary for many applications in civil engineering such as flood monitoring or water level in reservoirs. This example provides further evidence of the cost-effectiveness of the intensity-based approach in meeting the sensing needs of an important area in civil engineering.

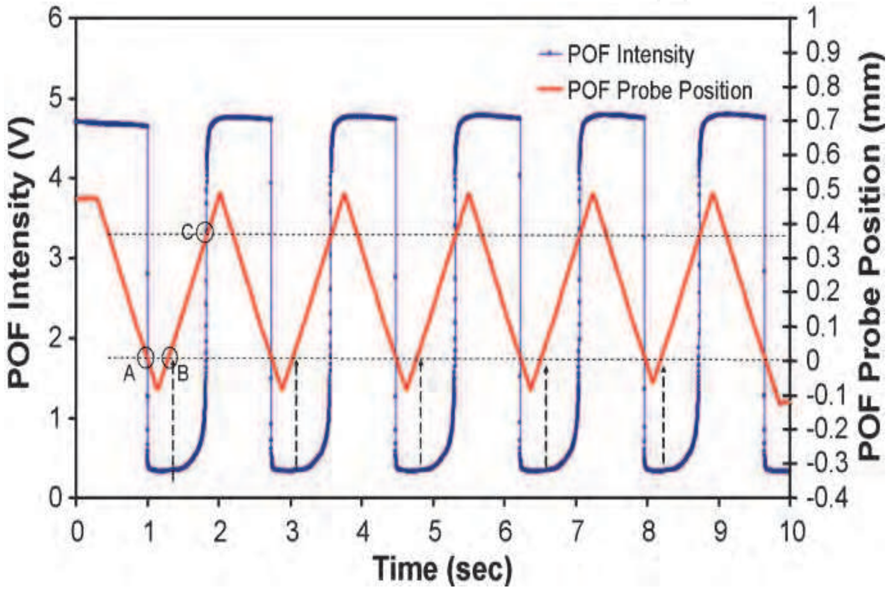


Fig. 8. Chart showing the repeatability of the POF sensor as the POF was immersed in and removed from water (after [5]).

Another significant design based on intensity sensing technique relies on the principle that a change in the gap between two cleaved POF surfaces resulting from an applied strain will leads to a corresponding chance in the light intensity of the sensor [14]. The operating principle of the POF sensor is straightforward- the sensor relies on the monitoring of the optical power transmitted through an air-gap between two cleaved optical fibre surfaces. The two fibres are aligned within a housing in which the fibre could slide smoothly. In this case, the housing itself is strain-free while the POFs are displaced relative to each other during the bending of the beam. It is important to note that the two fibres on either ends of the housing do not undergo any strain since they are free to slide relative to the housing. The gap changes in proportion to the applied strain leading to the modulation of the transmitted optical power.

Two versions of the sensor design are shown schematically in Figure 9. The authors showed that by adding a suitable opaque liquid, the strain sensitivity of the sensor could be improved significantly compared to one without the inclusion of the liquid. A comparison of the strain (or extension) sensitivity of the sensor is shown in Figure 10, highlighting the effect of different liquid opacity on its sensitivity. In the study, four POF sensors and an electrical strain gauge were attached to the bottom surface of a reinforced scaled concrete

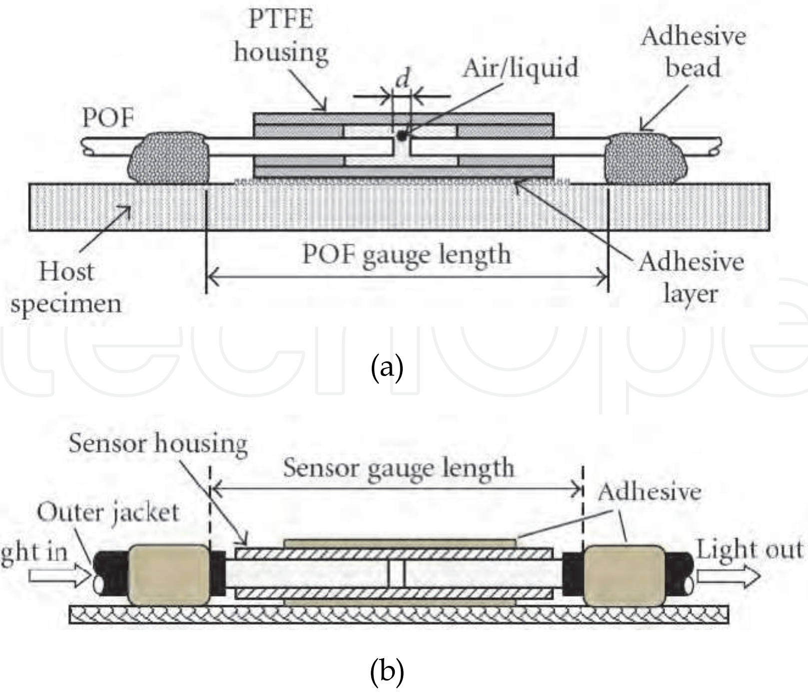


Fig. 9. Schematic showing the two versions of the POF sensor design based on changes in the gap between two cleaved fibres (a) (after [14]), (b)(after [4]).

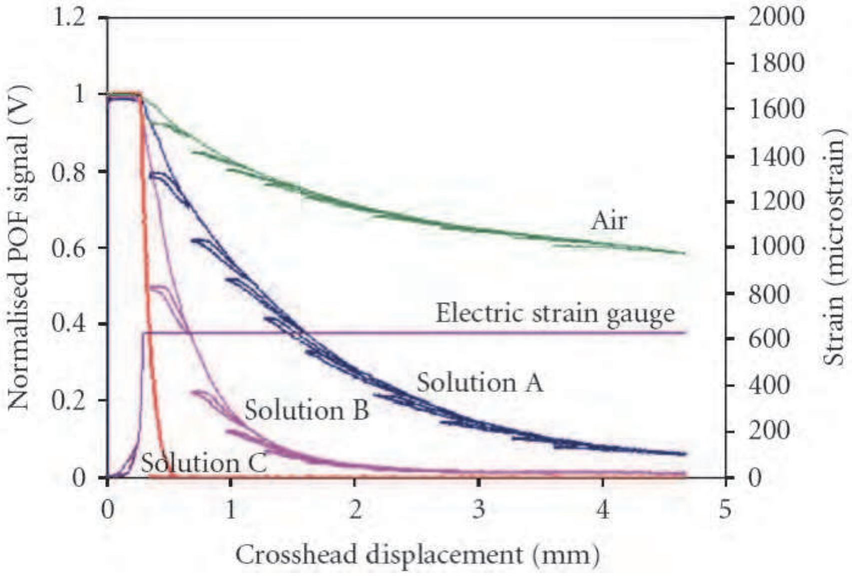


Fig. 10. Plot showing the different responses of the four POF sensors and the electrical strain gauge under a cyclic loading test (after [14]).

beam. The specimen was subjected to a flexural cyclic loading in a three-point bent set-up. When the failure load was reached, a crack developed across the beam which also damaged the electrical strain gauge. The four POF sensors were found to have survived and were able to continue monitoring the loading cycle as shown in Figure 11.

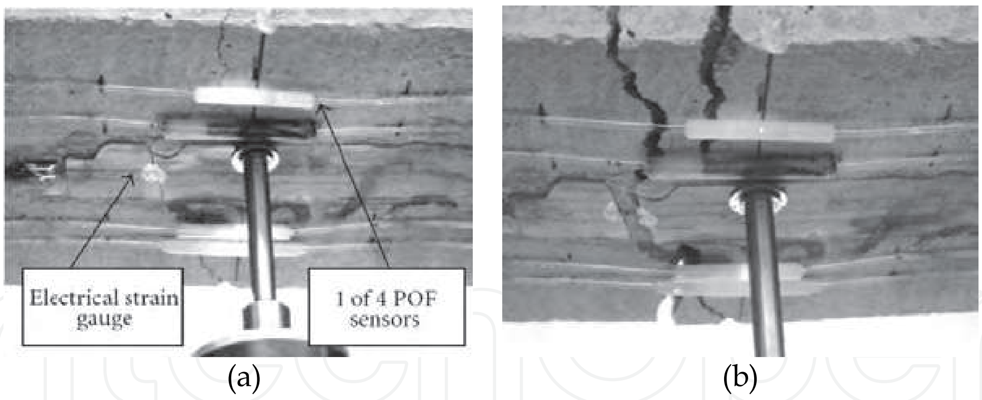


Fig. 11. Photos showing (a) the damage of the electrical strain gauge due to an intersecting crack (b) the relatively better survivability of the four POF sensors (no visible damage) even under severe crack (after [14]).

Building on the work conducted earlier, here the authors made further progress in demonstrating the ease of integrating the signal of the intensity-based POF sensor as a feedback to a control system to direct the amount of deflection in a smart fibre laminate beam [15]. Figure 12 shows a schematic of the set-up used in the experiment. Here, in order to activate the morphing of the smart beam, a thin-film heating source was attached to the beam. The POF sensor, attached to the opposite surface provided the feedback signal to the controller such that the appropriate amount of power was supplied to the heater to allow the smart beam to deflect to the desired position. The deflection of the beam was monitored continuously by the POF sensor and used as feedback to the controller to achieve the pre-set deflection position accurately. Figure 13 shows the POF sensor readings at three different beam deflections (A) to (C). The result illustrates that the POF-instrumented beam could be controlled accurately to within 3% of the desired deflection using the feedback data from the sensor with very little overshoot.

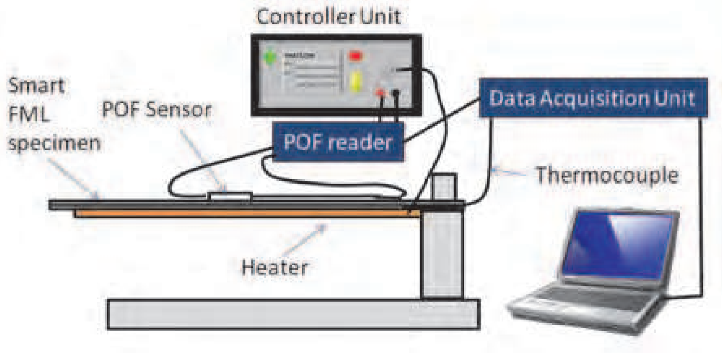


Fig. 12. Experimental set-up used to evaluate the potential use of the POF as feedback sensor to control amount of deflection of the smart composite beam (after [15]).

It was also of interest to gain an insight of the ability of the POF sensor to detect external disturbances acting on the beam and the ability of the control system to use the feedback data from the POF sensor to self-correct the amount of deflection of the smart beam. When a weight was added to the free end of the specimen after the smart beam had achieved steady-state, the POF immediately detected the change in the deflection of the beam which in turn resulted in a decrease in the POF sensor output triggering the controller to activate the

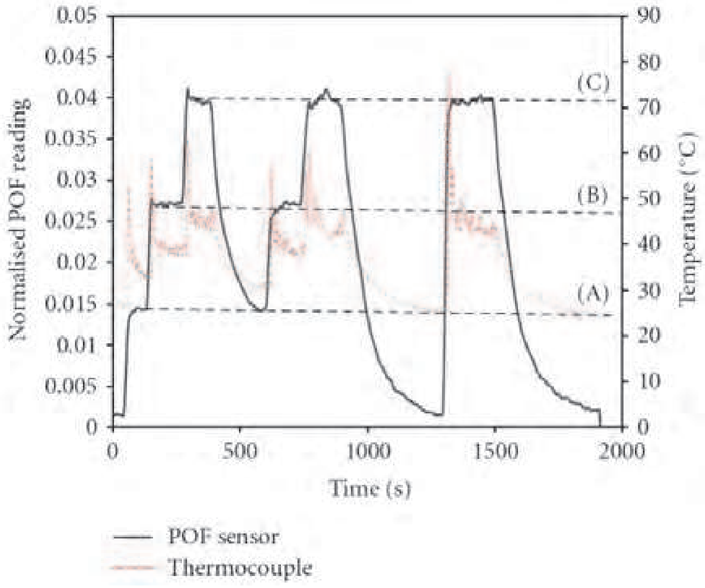


Fig. 13. Plot showing the response of the POF sensor demonstrating the potential of using the POF sensor to provide feedback signal achieve the amount of deflection desired in the smart composite beam (after [15]).

shape memory alloy via the heater. On heating to its activation temperature, the smart beam position was restored as evidenced by the steady state values of the POF sensor at the original controlled position. When the weight was removed, the position of the beam was again perturbed. Here the POF sensor triggered a corresponding series of action similar as before resulting in the beam settling to the controlled position as illustrated in the POF trace in Figure 14.

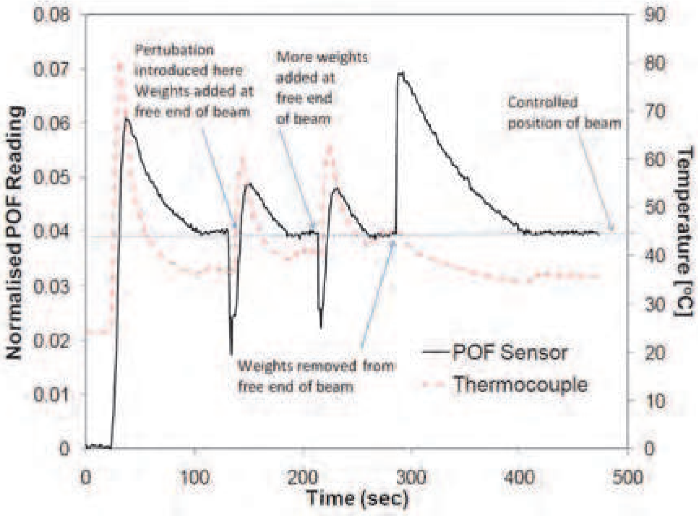


Fig. 14. Plot showing the self-correction capability of the control system based on the POF sensor output (after [15]).

The ability of the above POF sensor to monitor relatively large extension was further studied in a separate application [4, 16]. Here, the POF sensor based on Figure 9(b) was attached to two types of polypropylene geotextile specimens as shown in Figure 15, one being woven whilst the other being non-woven. A series of specimens, instrumented with

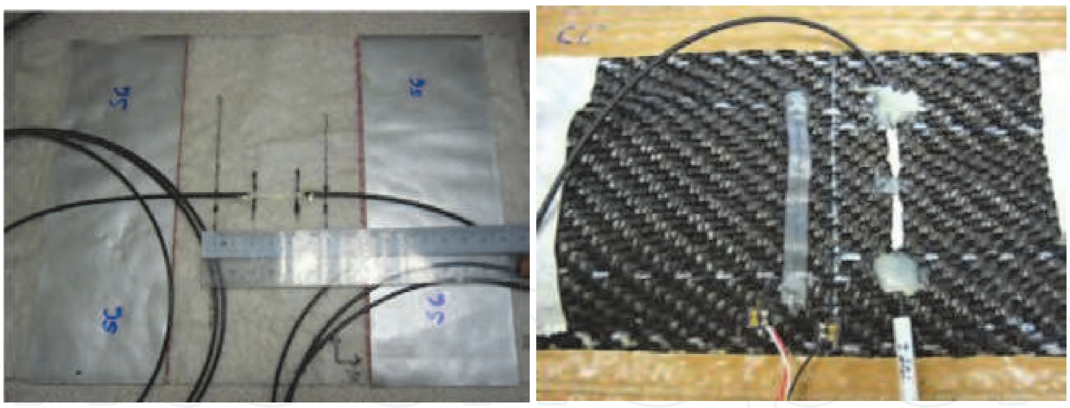
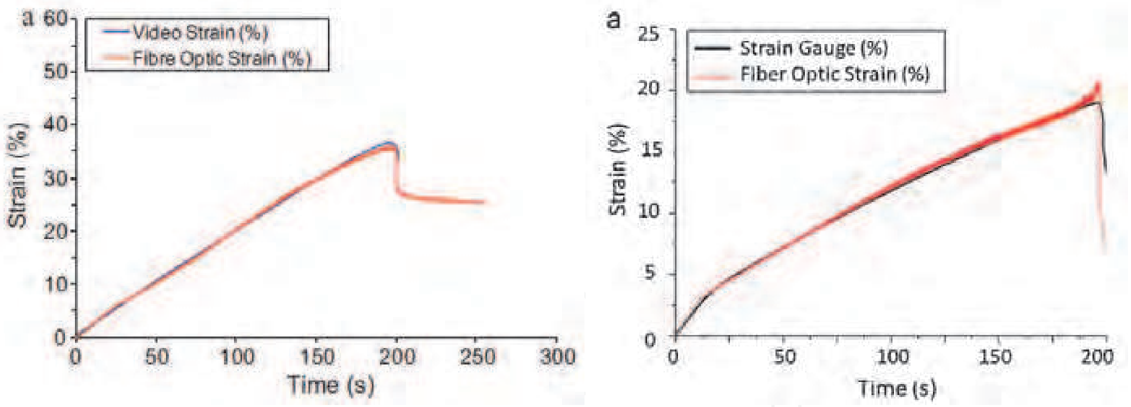


Fig. 15. Photographs showing the two types of POF-instrumented geotextile specimens (after [16]).

the POF sensor, were tested under quasi-static tensile load as well as being subjected to an acceleration field of 100g in a geotechnical centrifuge machine in a submerged condition.

In the quasi-static tensile test, the geotextile specimens were loaded to failure and the typical results are shown in Figure 16. The results show the ability of the POF sensor to monitor strains exceeding 35% for the non-woven specimens and approximately 20% for the woven specimens. The responses of the POF sensors in both cases compared very well with other reference measurement techniques. The POF sensor is expected to be able to monitor even higher strains since the fibre itself does not undergo any strain. It is noteworthy that the sensing principle relies on the changes in the distance of the gap between two fibres and the adhesive to attach the sensor to the host substrate was applied on the fibre, not on the housing itself, hence, neither the fibre nor the housing experience any significant strain, since the strain limit is a function of the gauge length (i.e. distance between the adhesives applied on both sides of the fibre) and the provision of sufficient fibre length within the housing is important such that at maximum extension, the fibre does not protrude from the housing.

In the centrifuge test, it was reported that the POF sensors survived the acceleration of 100g whilst submerged under water. Here, the instrumented geotextile tube was released from a hopper and dumped to the bottom of the centrifuge box to study the strain development of the geotextile tube throughout the whole of this process. A study of the sensors output showed that the POF sensor was able to monitor the strain experienced by the model geotextile tube reasonably well, following a similar trend and magnitude of measurement as obtained using the electrical strain gauge as illustrated in Figure 17. Towards the end of the test, it was noted that the two sensors gave different responses; the POF sensor indicated a sharp increase in strain while the strain gauge recorded a decrease. The resistance type strain gauge was deemed to have correctly recorded the decreasing strain trend. It is postulated that since the geotextile tube came to its resting position on the base of the strong box, without any external loading, the strain developed on the base centre portion of the geotextile would be insignificant, as registered by the strain gauge. On inspection of the POF sensor, it was noted that the fibre ends of POF sensor had protruded out of its housing which led to the sudden loss of intensity at model time 6 s as indicated in Figure 17. It was likely that the POF was tugged as the geotextile tube was being released resulting in the separation of the fibre from its housing. Although the POF sensor was damaged during the last phase of the test, the centrifuge experiment was encouraging, demonstrating the potential of the POF sensor for measuring large strains in geotextile tubes.



(a) (b)

Fig. 16. Plot showing the response of the POF sensor during a quasi-static tensile loading for (a) a non-woven specimen, (b) a woven specimen (after [16]).

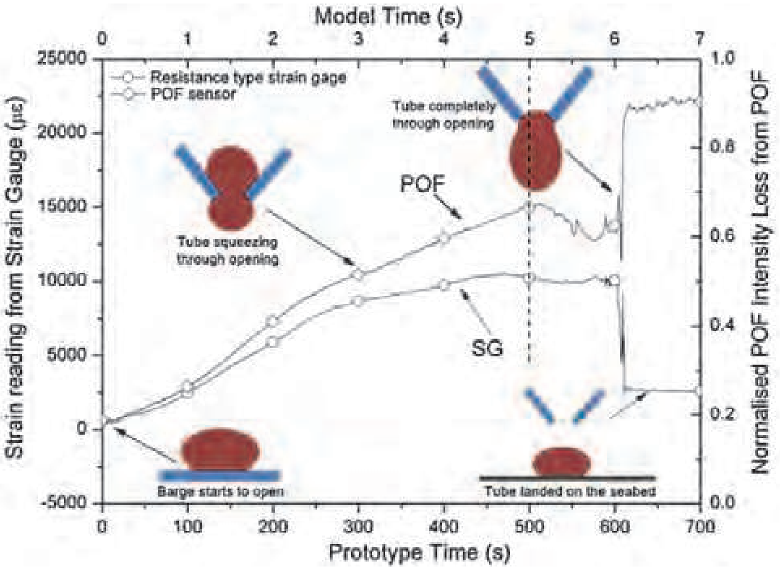


Fig. 17. Plot showing the excellent response of the POF sensor in the centrifuge test compared to the electrical strain gauge (after [16]).

2.2 OTDR-based POF sensors

OTDR-based POF sensors have received some attention recently partly in view of the recent advancement in the field of optical time-domain reflectrometry for POF. Developmental work in the area of the interrogator has resulted in the availability of high-resolution photon-counting systems allowing distributed monitoring along a single POF fibre. OTDR is a well-known technique in telecommunication for fault analysis and crack detection in silica fibres. The ability to detect the very low intensity light levels and high detection speed whilst achieving a high level of spatial resolution is not possible with standard OTDRs. The use of graded-index fibre in conjunction with v-OTDR also reduces the modal dispersion encountered in step-index PMMA fibres and hence graded index fibre is also used for monitoring of fibre over longer distances compared to step-index fibres. One of the most significant advantages of the OTDR technique is the possibility of distributed sensing, i.e. monitoring along the entire length of the fibre is in principle achievable.

2.2.1 Operating principles and background of OTDR-based POF sensors

OTDR sensing exploits the monitoring of the backscatter light in an optical fibre following the launched of a short optical pulse at one end of the fibre. The ability of the OTDR to detect the position of a defect along its length is based on the principle of time-of-flight. The time it takes for the pulse to be reflected back to the detector as backscatter signal is measured very precisely i.e. the backscatter signal is recorded as a function of time which is then converted to a distance measurement. Perturbations, such as strain or defects along the length of the fibre will result in either a peak Fresnel reflection or loss in the backscatter signal at the location of the perturbation. Specifically for POF use, a few companies have developed and commercialized v-OTDR to detect the very weak backscatter light signal due to the high attenuation and large dispersion in POFs. The photon-counting technology, based on an avalanche photodiode allows detection of very short optical pulses (~1 ns) necessary to resolve the location of defects accurately (to within 10 cm resolution).

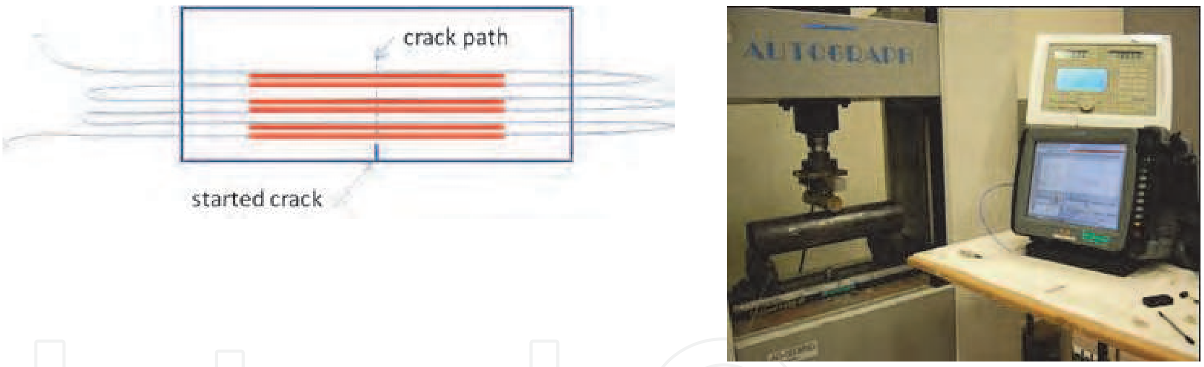
An OTDR trace consists of a number of reflection peaks corresponding to specific physical junctions along the fibre such as splices, connectors, fibre terminations or defects. The trace is typically plotted on an intensity-distance graph where the location of the peaks along the x-axis refers to their positions of the event or physical entity (splices, connectors, defects etc.) along the fibre. Hence the position of a crack along the fibre will be shown as a reflection peak on the OTDR trace. In order to match the peaks in the OTDR trace to their respective event, the position of a physical reference along the fibre such as a connector, should be defined. Unknown positions of defects or cracks anywhere along the fibre can then be determined accurately with reference to the pre-defined position.

When used to detect damage in structures, the POF should clearly be sufficiently sensitive to detect the parameter of interest. Since detection of cracks along the fibre is an inherent capability of the OTDR-technique, a possible application of the technique is to apply it for crack detection in structures such as steel tubes. Other applications, which will not be included in this chapter, include large strain measurement in geotextile, exploiting the high yield strain of the POF compared to its glass counterpart which has been reported elsewhere [10]. Here, the segment of the fibre where stress is concentrated will result in the formation of a growing peak in the OTDR trace as the fibre experienced increasing strain.

2.2.2 Applications of OTDR-based POF sensors

Graded-index POF sensors in conjunction with the v–OTDR could be used for detection of cracks in tubular steel specimens encountered in the offshore oil platform. Small hairline cracks along weld lines are frequently the precursor to structural failure under the cyclic loading condition in which the structure is subjected to. Typically, offshore platforms are constructed using steel jacket structures. The steel jacket or ‘substructure’ is fabricated by joined together tubular steel members using welding and pin-jointed to the seabed. The steel jacket is a massive structure which can weigh up to 20,000 tonnes. In a complex structure such as that of an offshore platform, potential failure hot spots are many which may result from fatigue due to cyclic stresses. Cracking in the steel tubular members may occur due to the high stress intensity experienced at the intersections of brace and chord members. At certain critical sections, stress concentration would be as high as 20 times that of continuous non-welded sections. The welded joints and the abrupt change in geometry are likely locations where cracks would initiate and grow. An array of conventional non-destructive techniques such as ultrasonic scanning, X-radiography and acoustic emission exists for damage detection purposes but these are not suitable for real-time monitoring of large structures since these techniques, in general, require an experienced personnel to conduct the assessment in a localized manner. Hence a distributed sensing based on optical fibre sensor technology for crack detection offers a potential solution for health monitoring of large structures.

In a recent study conducted by Kuang et al., [17] scaled-size tubular steel specimens loaded under flexure was tested with the intention of using POF to monitor the crack growth in the specimen. A pre-crack was initially introduced and subsequently propagated under a three-point bend set-up. Graded-index POF was attached to the steel tube with the aim to detect and monitor the crack propagation as the applied load was increased in a quasi-static manner. In order to achieve this aim, a single POF was attached to the specimen in a serpentine manner such that as the crack propagated, different segments along the length of the fibre will be affected and will be reflected in the OTDR trace. The schematic of the specimen and photo of the set-up are shown in Figure 18. The POF (GigaPOF-50SR) tested had core and cladding diameters of 50 µm and 490 µm respectively. A 5 m long fibre was prepared in addition to a spacer fibre of 2.3 m. A pre-determined segment of the 5 m fibre was attached onto the polished section of the tube using a cynoacrylate-based adhesive. The fibre length from one position of crack to the adjacent one was pre-determined to be approximately 0.5 m (i.e. distance for each bent segment mid-point to mid-point), hence if the POF was able to detect the crack, a peak should appear at intervals of 0.5 m sequentially as the crack propagated.



(a) (b)

Fig. 18. (a) Schematic of the specimen, the bold lines indicating the segment of the fibre attached to the specimen (b) Photo showing the three-point bend set-up and the OTDR used in the study (after [17]).

The specimen was loaded transversely to propagate the pre-crack until the crack front reaches the vicinity of the first segment of the POF fibre. Any degradation or fracture of the plastic fibre was noted and compared to the OTDR plot. The OTDR was set to monitor the POF sensor continuously and updates the OTDR. Initially the measurement time of the OTDR was set to a minimum of 1 sec without signal averaging to assess whether this setting is sufficient to detect and locate the crack accurately to within 10 cm. Following the fracture of the first segment of the POF (i.e. closest to the crack front), the loading was momentarily stopped to allow the OTDR data to be saved for further inspection. The loading was continued subsequently until the crack propagates through the entire segment of the POF sensor. The locations of the fracture where they were expected to occur along the fibre were recorded and then compared to the OTDR results. The objective of the mechanical test was to observe the response of the POF and its potential as crack sensors on pre-cracked tubular steel tubes under transverse loading.

A close-up shot of the specimen following fracture of the POF sensors in all segments is shown in Figure 19. The photo reveals that the POF sensor underwent brittle fracture with little signs of necking and stress whitening. The sensing fibre was also noted to experience damage at approximately the same instance as when the crack front intersected the fibre. The damage of the sensing fibre was corresponded to a new peak in the OTDR trace. All the traces were consolidated and presented in Figure 20.

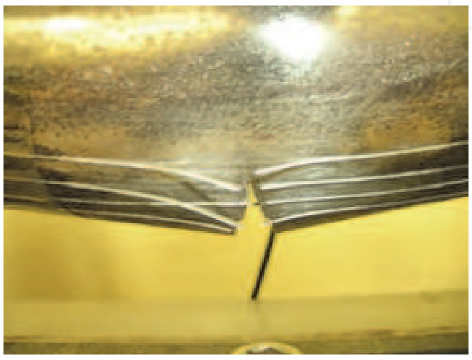


Fig. 19. Photo showing the fracture of the POF sensor along the crack path (after [17])

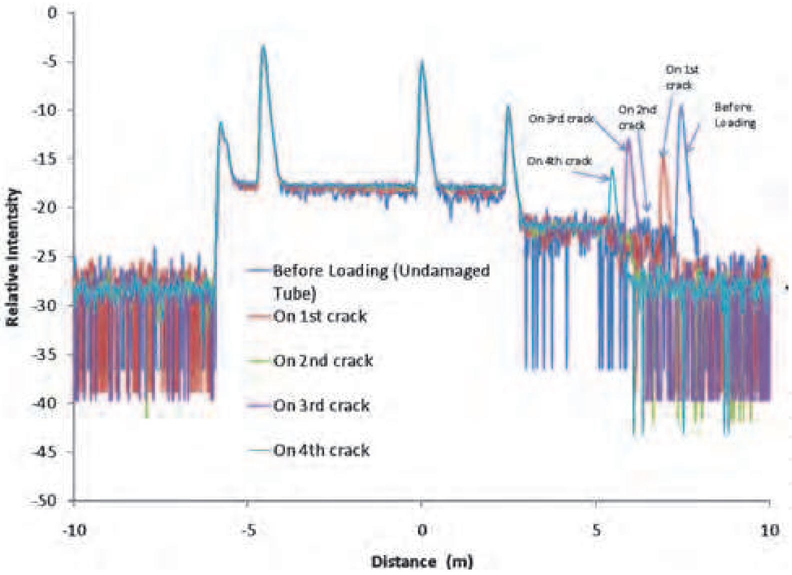
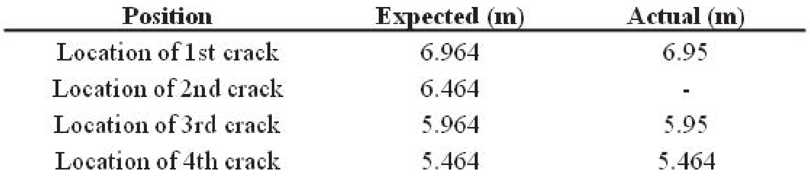


Fig. 20. Plot showing the consolidated OTDR traces highlighting the potential of the POF sensor in detecting and locating the position of the crack along the fibre (after [17]).

All the damage locations along the sensing fibre corresponding to the intersection of the crack front and the fibre were successfully located to within 20 mm by the v-OTDR except the second crack position. The authors argued that the POF segment at location 2 was not sufficiently sensitive i.e. the fibre at that particular location did not fracture when the crack intersected it. The sensitization of the fibre was clearly an important process to ensure that all cracks are detected. The adhesive used was also an important consideration as it is known that cynoacrylate-based adhesive embrittles the POF sensor and thereby improving its sensitivity to fracture.

Although the crack and location 2 was not detected in the particular test, it is evident that the technique shows excellent potential for detecting the location of cracks along the fibre and when configured in a serpentine shape, the sensor is capable of monitoring crack propagation accurately. From Table 1, it is clear that the v-OTDR possess the accuracy in determining the location of any crack along the POF given its high spatial resolution. The accuracy of locating the exact position of the crack along the fibre sensor relies on a proper calibration of the OTDR and determination of an accurate average refractive index of the graded-index POF. The results clearly showed that the calibration of the system was appropriate for the length of fibre used in the study.



Position	Expected (m)	Actual (m)
Location of 1st crack	6.964	6.95
Location of 2nd crack	6.464	-
Location of 3rd crack	5.964	5.95
Location of 4th crack	5.464	5.464

Table. 1. Accuracy of the crack locations detected by the OTDR versus actual positions (after [17]).

3. Conclusion

Plastic optical fibre sensors represent an emerging alternative for various applications in engineering. In this chapter, various examples of applications of POF sensors in civil engineering have been demonstrated e.g. for monitoring strain, deflection, liquid level, vibration, detection of cracks, and these have been applied to different materials including concrete, steel, geotextile and laminate composites. POF sensors offer many unique features that could be exploited to achieve a cost-effective sensing system. Potential users need to have an appreciation of these benefits and the capability of these sensors. Following an objective assessment of the capability of POF sensors together with a clear understanding of the sensing specification required in any particular project, POF sensors may proved to be the ideal candidate for the job.

4. Acknowledgment

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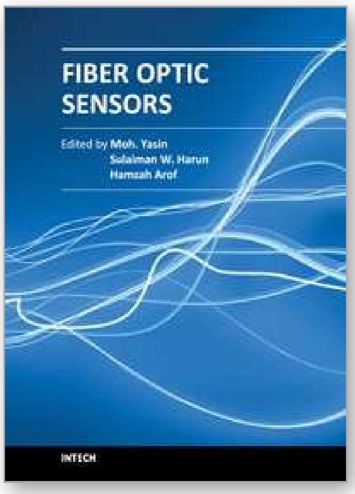

Fiber Optic Sensors

Edited by Dr Moh. Yasin

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This book presents a comprehensive account of recent advances and researches in fiber optic sensor technology. It consists of 21 chapters encompassing the recent progress in the subject, basic principles of various sensor types, their applications in structural health monitoring and the measurement of various physical, chemical and biological parameters. It also highlights the development of fiber optic sensors, their applications by providing various new methods for sensing and systems, and describing recent developments in fiber Bragg grating, tapered optical fiber, polymer optical fiber, long period fiber grating, reflectometry and interefometry based sensors. Edited by three scientists with a wide knowledge of the field and the community, the book brings together leading academics and practitioners in a comprehensive and incisive treatment of the subject. This is an essential reference for researchers working and teaching in optical fiber sensor technology, and for industrial users who need to be aware of current developments and new areas in optical fiber sensor devices.

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