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Crack monitoring capability of plastic optical fibers for concrete structures

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ABSTRACT

Optical fibers have been widely used in structural health monitoring. Traditional silica fibers are easy to break in field applications due to their brittleness. Thus, silica fibers are proposed to be replaced by plastic optical fibers (POFs) in crack monitoring in this study. Moreover, considering the uncertainty of crack propagation direction in composite materials, the influence of the angles between fibers and cracks on the monitoring capability of plastic optical fibers is studied. A POF sensing device was designed and the relationship between light intensity loss and crack width under different fiber/crack angles was first measured through the device. Then, three-point bend tests were conducted on concrete beams. POFs were glued to the bottom surfaces of the beams and light intensity loss with crack width was measured. Experimental results showed that light intensity loss in plastic optical fibers increased with crack width increase. Therefore, application of plastic optical fibers in crack monitoring is feasible. Moreover, the results also showed that the sensitivity of the POF crack sensor decreased with the increase of angles between fibers and cracks.

1. Introduction

Cracks are signs of aging and damage of structures, which shorten the integrity and service life of structures. For example, cracks increase the permeability of concrete structures, permitting the infiltration of erosive materials such as chloride and sulfate into the structures and thereby accelerating the aging process. Therefore, crack monitoring is important to guarantee the safety of structures. Currently, a number of techniques have been proposed for crack monitoring, such as ultrasonic method [1], acoustic emission [2], impact-echo [3], infrared thermograph [4], ground penetrating radar [5], etc. However, all have restrictions when applied in real projects. All the above-mentioned techniques can only detect the pre-existing cracks in a structure and cannot provide information about the development of the cracks.

In recent years, fiber optic sensors have been widely used in the health monitoring of large structures because of their abilities to perform distributed and continuous monitoring of cracks, light weight and small size, resistance to electromagnetic interference, anti-lightning, corrosion resistance, etc. For example, Rossi et al. [6] embedded optical fibers in concrete to detect cracks based on the idea that signal can be interrupted by fiber breakage due to advance of the cracks. Ansari et al. [7] developed a ring fiber optic sensor to monitor cracks based on the finding that macro-bend optical loss in fibers increases due to the increase of crack width. Li et al. [8] developed a fiber optic sensor based on Michelson white light interferometer to monitor the crack tip width displacement. Shi et al. [9] measured the distribution of strain on the surface of concrete structures by Brillouin optical fiber both on transverse and vertical direction to monitor damage fields. Bao et al. [10] proved the fiber Bragg grating (FBG) is feasible in crack monitoring and FBG can serve as a quasi-distributed crack sensor. Leung et al. [11] worked on a distributed crack sensor which can detect and monitor a large number of cracks with a small number of fibers and a priori knowledge of crack locations is not required. The researches above applied optical fibers in crack monitoring and results showed that optical fibers have potential in crack monitoring. However, all the fibers in the above researches are silica fibers which are brittle (their elongation rates only about 1%) [12], so they are easy to break in real applications and only small cracks can be monitored. Therefore, the brittleness of silica fibers limits the application of above researches.

To overcome this disadvantage, researchers attempted to use plastic optical fibers (POFs) in place of silica fibers [13–15]. POFs

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have a high elongation rate (more than 40%) because they are made of high performance polymer material [16,17]. POFs have many excellent properties, such as uneasy to break, low cost, easy to be cut and connected, simple to be applied, etc. POFs were first widely used in local-area-network and automotive electronics. In recent years, POFs have been used in engineering fields. For example, Babchenko et al. [18] developed a POF sensor with multi-structural imperfections on it to measure the displacement of structures. Takeda et al. [19] embedded POFs in FRP laminates to detect transverse cracks. Husdi et al. [16] and Nakamura et al. [20] studied the sensing characteristics of POFs by optical time-domain reflectometry technique. Krebber et al. [21] and Liehr et al. [22] combined POFs with textiles and developed a type of geotextile with distributed strain measurement capability, which can be used for health monitoring of earthwork structures. Liehr et al. [22] also studied the sensing characteristics of POFs when crack increased. Kuang et al. [23] developed a POF sensor by abrading the surface of POFs and the sensor was attached to concrete specimens and the concrete specimens were conducted in three- and four-point bend tests. The possibility of POF sensors for detecting crack initiation and post-crack vertical deflection was evaluated. Kuang et al. [24] also developed a surface-attached optical fiber sensor using POFs and applied the sensor in structure health monitoring.

In previous works, emphasis is put on FRP laminates (Takeda et al. [19]) and earthwork structures (Krebber et al. [21], Liehr et al. [22]) using POFs for structural health monitoring. To the best of our knowledge, only a few works about application of POFs in structural health monitoring of concrete structures have been reported, and researchers mainly used POFs with structural imperfections for structural health monitoring, for example, Kuang et al. [23] and Babchenko et al. [18] created the structural imperfections by abrading the surface of POFs as sensing area. The imperfections can increase the amount of light loss when bent in the sensors, and thus increase the sensibility of the sensors. However, the damage detection will be limited by the size of the imperfections.

In this paper, POFs without structural imperfections are used in crack monitoring for concrete structures. A simple and low-cost POF sensing device is designed and the sensing principle of the device is introduced. Then, the capability of bare POFs in crack monitoring will be investigated by two experiments. In the first experiment, the capability of POFs in crack monitoring is studied using a crack simulator that can provide well-controlled bending of the fibers. In the second experiment, the POFs are glued to the bottom of a series of concrete beams and three-point bend tests are conducted on the beams to assess the capability of POFs in crack monitoring. Moreover, POFs of different fiber diameters are used to study the crack monitoring capability for concrete structures under different fiber inclinations.

2. Structure of POFs and sensing principle

2.1. Structure of POFs

The POFs mainly consist of three layers, the protective layer, cladding and fiber core, as shown in Fig. 1. They are respectively made of polyurethane, fluorinated Polymer polymethyl methacrylate or polystyrene. Compared to the silica fibers, the diameter of the fiber core is bigger (up to 1 mm or even bigger) but the thickness of cladding is thinner, therefore the coupling efficiency of optical energy in POFs is higher.

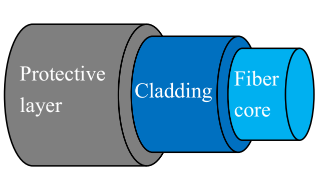

Fig. 1. Schematic diagram of plastic optical fiber structure.

The POFs used in this study are Mitsubishi Rayon ESKA SK10 and SK20. Details of the POFs used are given in Table 1.

2.2. Sensing principle

As shown in Fig. 2, two pieces of plexiglass plates (one fixed and the other can be moved freely) are placed together, the gap between which can be viewed as a crack. A POF is glued at the surfaces of the two plexiglass plates, crossing the crack. When the crack becomes bigger, the fiber intersecting the crack has to be bended to stay continuous, thus two micro bends will be formed on both sides of the crack. Bending loss in the fiber will occur at the curved portion, which can be monitored by an optical power meter on the left. Thereby, based on the change of bending loss, the increase of the crack can be continuously monitored.

The micro bend loss is mainly caused by spatial filtering, mode leakage, and mode coupling. The mode coupling plays a dominant role among them and there are four kinds of mode coupling: coupling from low order modes to high order modes, coupling from high order modes to low order modes, coupling from dissipative modes to transmission modes, and coupling from transmission modes to dissipative modes. Among the four, the coupling between low order modes and high order modes has no effect on the intensity change of optical in fiber. There is little coupling from dissipative modes to transmission modes. The coupling from transmission modes to dissipative modes is the main reason which leads to micro bend loss.

Assume the deformation function of micro bend as [25]:

$$f(z) = D(t)\ \sin qz \tag{1}$$

where $D(t)$ is the amplitude of micro bend; q is the spatial frequency of micro bend; z is the distance from deformation points to input terminal.

The period of the deformation function of micro bend is:

$$\Lambda = 2\pi/q \tag{2}$$

From the wave theory, the first order approximation of coefficient α of micro bend loss can be expressed as [25]:

$$\alpha = \frac{1}{4}KD^2(t)L\left|\frac{\sin[(q-\Delta\beta)L]/2}{(q-\Delta\beta)L/2}\right|^2 \tag{3}$$

where K is the proportional coefficient; L is the length of micro bend; $\Delta\beta$ is the constant difference of wave propagation in fibers. From Eq. (3), α is proportional to $D^2(t)$, indicating that the bigger the micro bend, the more bend loss is.

Table 1
Specification of SK10 and SK20.

Item	Unit	SK10	SK20
Core material	–	PMMA resin	PMMA resin
Cladding material	–	Fluorinated polymer	Fluorinated polymer
Core refractive index	–	1.49	1.49
Refractive index profile	–	Step-index	Step-index
Numerical aperture	–	0.5	0.5
Approximate weight	g/m	0.1	0.2
Max operating temperature	°C	70 Max	70 Max
Max transmission loss	dB/m	0.3 Max (at 650 nm)	0.18 Max (at 650 nm)

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