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Analysis characteristics embedded plastic optical fiber sensors for crack detection in concrete structures

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Abstract. Plastic optical fiber (POF) used as sensors to detect cracks in concrete structures. Sensors made using straight, sinusoidal, loop, and triangle configurations. The POF connected to LED light source and photodetector. The light from LED will propagate along the embedded POF in the concrete then received by the photodetector and measured using by Optical Power Meter in the form of output power displayed on the computer. Sensor testing is done by putting pressure on the concrete using the Ultimate Testing Machine until a crack occurs causing the POF in the concrete to experience strain. The strain of the POF sensor will cause power losses, so the light intensity received by the photodetector will be decreased. The best measurements obtained at triangle configuration sensors 60° have characteristics with a range value of 1.975 μW , the sensitivity of 0.790 $\mu\text{W}/\text{cm}$ and a resolution of 0.001 cm. Sensors based on POF for measurement of cracks in concrete structures have the advantages like easy fabrication, low cost, simple measurement system, and high sensitivity.

1. Introductions

In recent years, research about monitoring of damage detection on building structures has been developed and attracted the attention of many researchers in various fields of science. This was done to prevent and detect early structural damage to buildings that may endanger public safety. Damage of structures in buildings occurs due to natural factors such as landslides, floods, and earthquakes. One of the damage in building structures is crack in the concrete. Cracks in the concrete consist of two types of cracks, i.e. small cracks and large cracks. A small break has a crack opening spacing of 0.2 to 0.4 cm, while a crack opening spacing above 0.4 cm includes a large crack which is a sign of severe degradation [1, 2]. Damage of the concrete structure can be detected using fiber optic sensors. Based on the type of material, the optical fiber consists of two, namely plastic optical fiber (POF) and glass optical fiber (GOF). Compared with glass optical fibers, plastic optical fibers are cheaper, resistant to electromagnetic intervention, and suitable for use as sensing devices [3].

Fiber optic sensors as sensing devices have been widely applied to monitor infrastructure especially in the field of civil engineering [4, 5, 6]. In this field, POF sensor applications have been widely studied such as detecting cracks in concrete structures using Brillouin optical correlation domain analysis system [7], measurement of displacement concrete cracked shifts using POF sensors [1, 4, 5], as well as measurements crack concrete based on POF using a straight angle variation change configuration [8, 9]. The weakness of these studies elaborate fabrication, high cost, and low sensor sensitivity.

In this research, we will develop crack concrete sensor based on POF without coat embedded in concrete. The novelty of this research is used straight, sinusoidal, loop, and triangular configurations.



This method utilizes the power losses that occur in the bending of the POF and expected to produce higher sensor sensitivity. The advantages of the crack concrete sensors based on POF are having simple measurement and easy fabrication processes, small size and light in weight, low cost, and can be connected with other measurement system devices.

2. Method

The optical fiber used in this research is POF made from polymethyl methacrylate (PMMA) material with a core refractive index and the refractive index of 1.492 and 1.402 respectively. POF has a numeric overture value of 0.5 with the coat, cladding, and core diameters of 2.2 mm, 1 mm and 0.98 mm respectively. Crack concrete sensors based on POF connected to the IF-E91A infrared type LED as light source and the S120C type photodetector. The light from the LED will propagate along the POF embedded in the concrete then received by the photodetector and measured on the Thorlabs PM100D type Optical Power Meter (OPM) in the form of output power displayed on the computer. The sensor testing is done by putting pressure on the concrete using the Ultimate Testing Machine (UTM) until a crack occurs causing the POF embedded in the concrete to be a strain. The strain of the POF sensor will cause power losses, so the intensity of light received by the photodetector decreases.

The scheme of the concrete crack sensor based on POF circuit shown in figure 1. The sensor testing performed using various indentations on the POF and angle change variations as shown in figure 2. The created sensor is the POF embedded in the concrete.

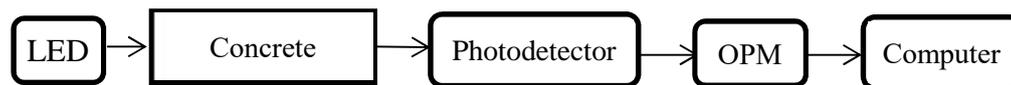


Figure 1. Schematic of concrete crack sensor based on POF

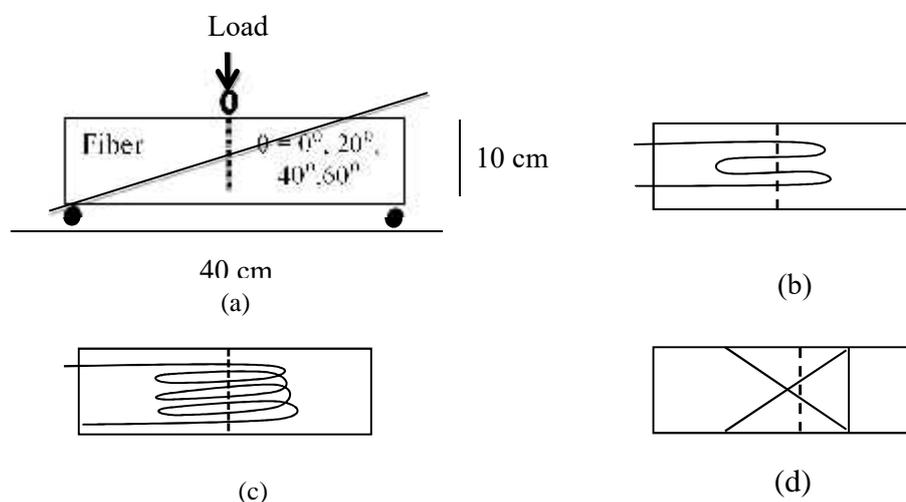


Figure 2. Design of crack concrete sensor configuration (a) straight, (b) sinusoidal, (c) loop, and (d) triangle.

3. Result and Discussion

The testing of crack concrete sensors using 4 configurations i.e. straight configuration of angle change variation ($0^\circ, 20^\circ, 40^\circ, 60^\circ$), sinusoidal shape (0.5x, 1x and 1.5x), loop configuration (1x, 2x, 3x), and triangle configuration of angle change variations ($20^\circ, 40^\circ, 60^\circ$). In this measurement, each configuration is given different loads to obtain a displacement of the crack concrete. The sensor output data is measured at each movement of crack concrete of 0.1 cm from 0 cm to 2.5 cm. The measurement results are output power then read on OPM and computer.

The result of the measurement of sensor output power toward concrete crack opening used to calculate characteristics value of the sensor. Characteristics of the sensor include range, sensitivity, and resolution. Range is the difference of maximum output to minimum output, and sensor sensitivity is the sensitivity level of the sensor to the measured quantity. While the resolution is the value of the smallest quantity that can be measured by the sensor. The range (ΔP), sensitivity (S), and resolution (R) can be determined using equations (1), (2), and (3) below [10, 11]:

$$\Delta P = P_{m \max} - P_{m \min} \tag{1}$$

$$S = \frac{P_{m \max} - P_{m \min}}{L_{m \max} - L_{m \min}} \tag{2}$$

$$R = \frac{N}{S} \tag{3}$$

Where P_{\max} as the maximum output power and P_{\min} as the minimum output power. L_{\max} as the maximum crack opening and L_{\min} as the minimum crack opening. While N is the smallest scale value of OPM is $0.001 \mu\text{W}$. The result of measuring the sensor output power toward the crack opening on the concrete crack sensor based on POF is shown in figure 3 below:

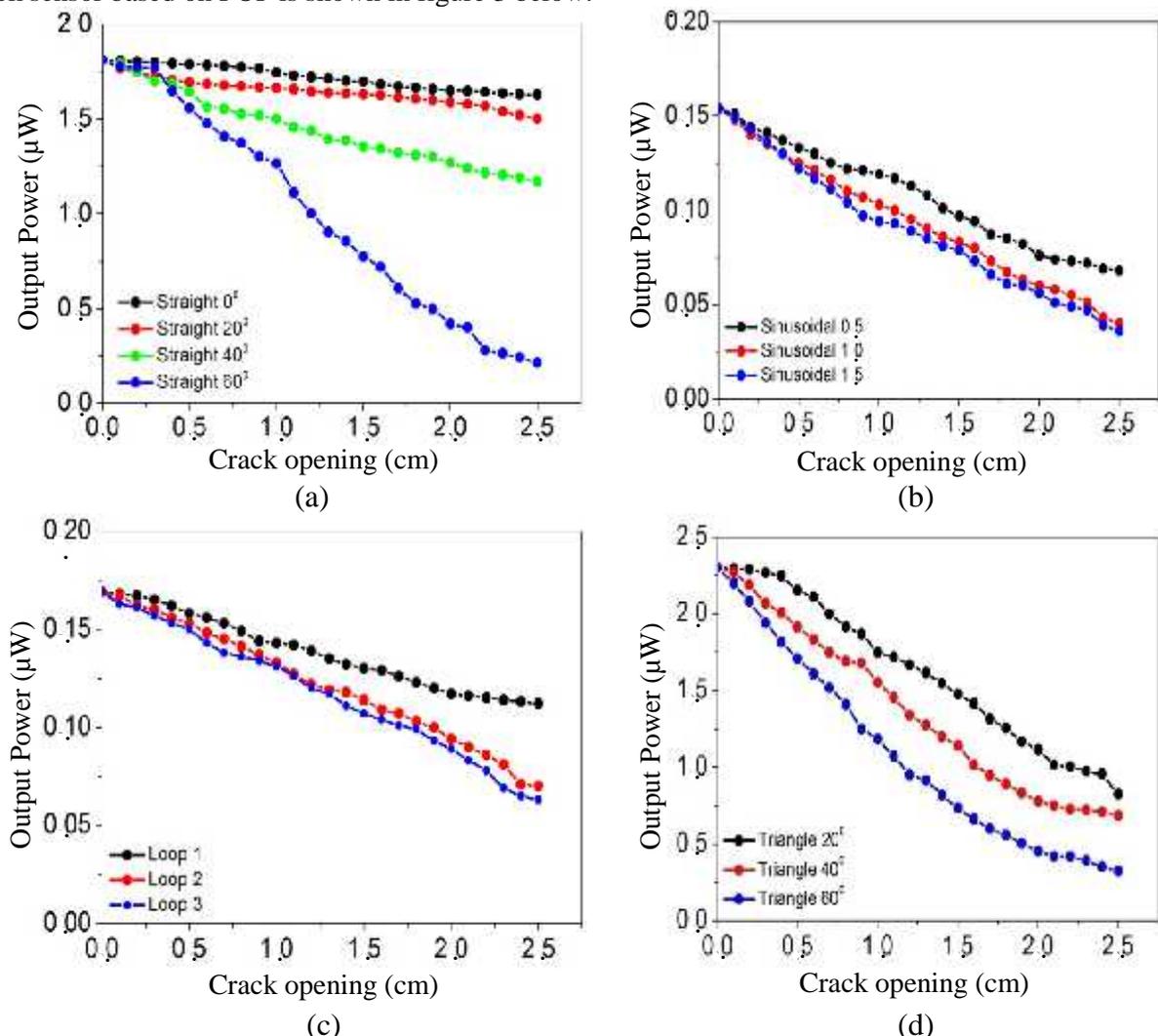


Figure 3. Graph of output power changes toward the crack opening in the concrete configuration (a) straight, (b) sinusoidal, (c) loop, and (d) triangle.

The graph in figure 3 shows the output power changes toward the crack opening in the concrete applied to the straight, sinusoidal, loop, and triangular configuration sensors. Based on the graph, each configuration shows that the change in the cracking opening of the concrete effects the sensor's output power. The greater the crack opening on the concrete, the smaller the output power of the sensor. When bending and lengthening occur in the optical fiber, the loss of power in the plastic optical fiber increases, causing the intensity of light to propagate in the POF sensor decreases. This results in the output power that read on the OPM and the computer is decreasing. Characteristics results of crack concrete sensors based on POF determined using equations (1), (2), and (3) shown in table 1 below:

Table 1. Characteristics of crack concrete sensor based on POF

Configuration	Variation	Range (μW)	Sensitivity ($\mu\text{W}/\text{cm}$)	Resolution (cm)
Straight	0^0	0.185	0.074	0.013
	20^0	0.311	0.124	0.008
	40^0	0.642	0.256	0.003
	60^0	1.600	0.640	0.002
Sinusoidal	0.5x	0.086	0.034	0.029
	1.0x	0.114	0.045	0.022
	1.5x	0.118	0.047	0.021
Loop	1x	0.057	0.023	0.043
	2x	0.099	0.039	0.022
	3x	0.106	0.042	0.021
Triangle	20^0	1.477	0.591	0.002
	40^0	1.616	0.646	0.002
	60^0	1.975	0.790	0.001

Based on table 1, the characteristics of concrete crack sensors based on POF using straight, sinusoidal, loop, and triangular configurations consist of output power range, sensitivity, and resolution values. Sensor characterization results with the best straight configuration at an angle of 60^0 . While the best sinusoidal configuration on sinusoidal 3x. The best loop configuration on loop 3x and best triangle configuration at angle 60^0 . The larger of the bending sensor then the sensitivity and resolution of the sensor the better. Comparison of the best test results of each configuration is shown in figure 4 below:

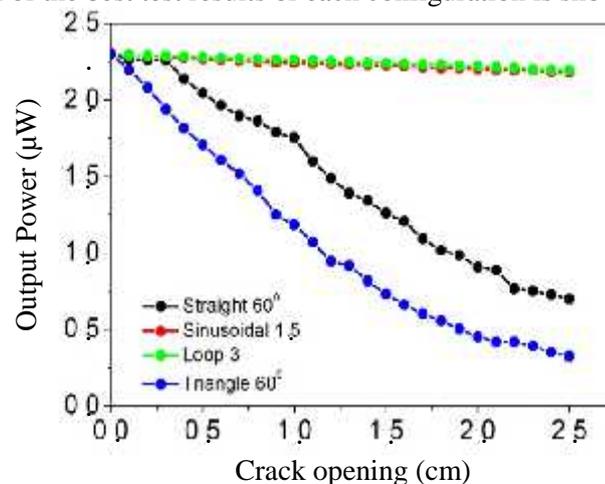


Figure 4. The best comparison of the test result graph for each configuration.

Based on figure 4 shows that the best result graphs of each configuration in the concrete crack sensor. The best result obtained in a triangle configuration with angle 60° has a value range of $1.975 \mu\text{W}$, the sensitivity of $0.790 \mu\text{W}/\text{cm}$, and a resolution of 0.001 cm . The large of the bending sensor, the sensor output power decreases. This is due to the large pressure applied to the concrete causing the crack opening in the concrete to increase, so the loss of power that occurs in the fiber optic sensor is greater. This study has suitability with previous research on optical fiber sensors embedded in concrete structures, that the greater of the cracking opening on concrete, the greater the loss of power [1] [8]. Based on the results of this research, the optical fiber sensor can be used to detect and monitor cracks of concrete structures effectively and efficiently on simple measurement systems with advantages easy fabrication, low cost, and can be connected with other measurement system devices.

4. Conclusion

In this research has successfully designed and made concrete crack sensors based on POF. The best sensor characteristics obtained in triangular configurations compared to straight, sinusoidal, and loop configurations. The crack opening of concrete increases with the increase of load. The increased crack opening of concrete affects bending on POF. The larger bending in the POF causes the loss of power is greater, so the sensor output power decreases. The best measurement results obtained in a triangle configuration with an angle 60° has a value range of $1.975 \mu\text{W}$, sensitivity of $0.790 \mu\text{W}/\text{cm}$ and a resolution of 0.001 cm .

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