Development of an optical fiber sensor to monitoring the formation of cracks in concrete structures

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Abstract

Many times when a fissure in a concrete structure is discovered, it is too late because the fissure has already propagated. Because of this, a fiber optic sensor for detecting fissures at their origin was sought to be developed. The goal of developing such a sensor was to monitor the formation of fissures in their initial stages before they propagate and, in this way, avoid the failure of a structure. The functionality of such a sensor was shown and was able to detect fissures early (from their origin) in any part of the structure. This sensor is innovative due to the fact that it can monitor the condition of a structure in a distributed way and not at points. The possibility exists that, through special calibration, certain information about the deformation of structures can be obtained.

Introduction

Interest in the supervision of structures in civil engineering has been growing constantly in order to improve the durability and safety of structures (Zhijun and Farhad [11]). Because of this, development of fiber optic sensors has been researched for a number of engineering applications (Grattan and Meggitt [3], Hecht [4] and Buck [1]). One of these applications is the continuous supervision of concrete structures (Kin-Tak [7]).

This type of continuous supervision has many advantages when compared to visual inspection. This is because visual inspections sometimes cannot detect fissures inside a structure unless these fissures propagate to the surface, which many times cause irreparable damage. The continuous supervision of optical sensors allows the permanent monitoring of the condition of a structure. These sensors are recommended for structures that have variable loads such as bridges and dams. In Mexico, this technology is still being developed. The ability to permanently monitor a structure has been recognized as an important development in the supervision of civil infrastructure. At the same time, it is important to mention that other authors have developed sensors based on optical fibers for monitoring concrete structures (Yoji [10] and Davis et al. [2]).

Experimental

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Experimental

Preparation beams

Concrete beams which were 36 cm long by 3 cm wide by 3 cm high were made (Instituto Americano del Concreto [5]). The concrete mixture was carried out according to the 211.1-70 ACI standard (William [9] and Steven [8]). Weights for each component of the beams (water, cement, fine aggregate and course aggregate) were calculated from the same standard. A wooden mold was used to make the beams. The mold was 40 cm wide by 37 cm long and had 7 cavities with 5 holes on each side, with 4 of these oriented towards the corners of the faces. Four copper wires were placed through these 4 holes to increase the strength of the beam. The fifth hole, at the center of the cavities, contained the optical fiber.

Techniques

Optical module. The optical module has basic components which function in the following way: a light emission device (LED) whose wavelength is 850 to 950nm. A female fiber optic connector is coupled with the LED in order to allow the light emitted from LED enter the optical fiber. Then there is the receptor. This is a wide-spectrum phototransistor which covers the infrared spectrum. The output signal of this phototransistor is proportional to the light which comes in contact with it. Figure 1 shows the main components of the optical module.

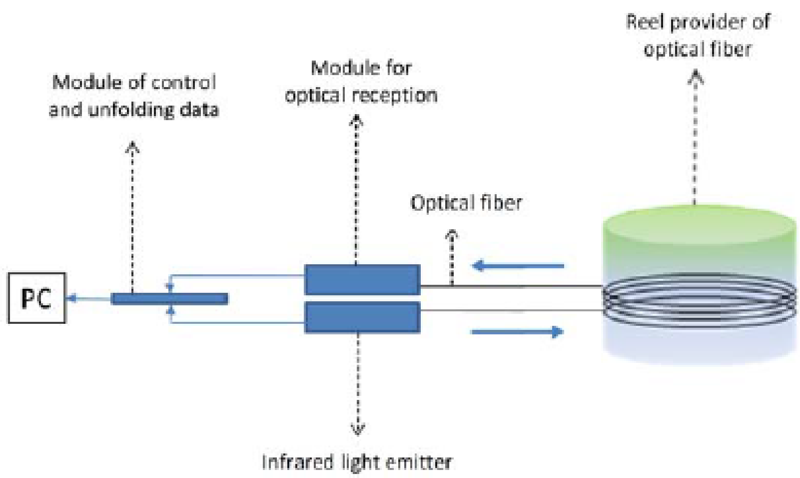

Figure 1. Basic components of the optical module.

Mechanical testing

All the tests carried out in this work were flexion tests at three points and were carried out in an Instron universal testing machine (UTM) with a 5 ton capacity. These tests were performed in accordance to the ASTM ACI 318-95 standard (Instituto Mexicano del Cemento y del Concreto [6]).

Figure 2 shows how the mechanical tests were carried out. Both ends of the optical fiber that were embedded in the concrete are connected to the optical module. A beam of light is sent to one end of the optical fiber and then the beam arrives to the other end, then to the detector. The optical module then sends the information after being processed in a computer. A video camera is also connected to the same computer. As seen, there are three points where the Instron machine performs flexion tests (two in order to support the beam, and another point for applying load). The UTM then sends the data to a computer.

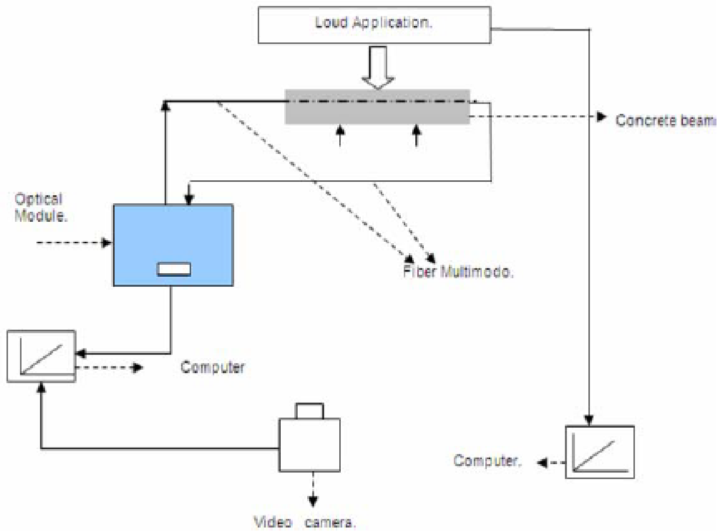

Figure 2. Mechanical testing at three points.

Experimental stages

First stage

Linear fiber optic sensor in the middle of beams. The first part of the work consisted of carrying out flexion mechanical testing at three points of the concrete beam. The optical fiber was placed inside the beams in a line which was centered within the beam.

Second stage

Fiber optic sensor in cyclical configuration at center of beams. The sensor was embedded in the concrete in a circle and was in the center of the beams. The geometric change in sensor configuration was done in order to find a mechanical assembly for the fiber and concrete. The reason for finding the mechanical assembly was to achieve the appropriate union of the fiber with the concrete.

Results

Results of the first experimental stage. Linear centered placement of fiber optic sensor inside beams. The experimental results of the mechanical flexion tests at three points using the ASTM E290-97A in which the optical fiber is in a centered linear configuration inside the beams are shown in Figure 3.

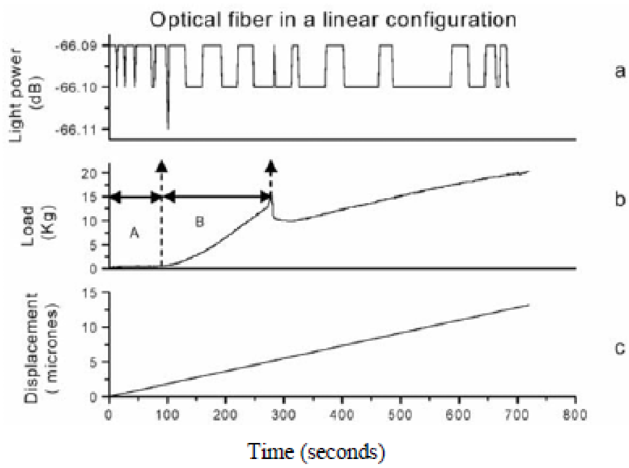

Figure 3. Results of the first experimental stage.

There were many variations in light potential (Figure 3(a)) during the application of load onto the beam. These variations were due to the fact that the fiber did not have good connection with the concrete and was sliding on several occasions.

In the loading graph (Figure 3(b)), there are two load areas: load area A is the beam that was fitted into the UTM and, therefore, not partial load was directly applied to it. At this stage, small edges came off the surface of the beams. In the B load area, the load is directly applied to the concrete. In the section B, the concrete was able to support the forces applied onto it from the start of the application of the load until the maximum point. Beginning at the maximum point, the concrete could not support the pressure and a fissure appears. After the maximum point, a minimum point appears again in the graph. During this time, the fissure propagates through the beam. After the minimum point, the load increased. This was due to the strength of the copper. During the increase, the fissure continued propagating. The displacement that the beam underwent was constant and uniform (Figure 3(c)). The tests were repeated four times without any difference in the results.

Due to the fact that the optical fiber was sliding during the tests, it is evident that under these conditions, it was not possible to obtain information about the formation of a fissure or the evolution of deformation before calibrating.

In order to solve this problem, two alternatives exist which could function correctly:

(a) The surface of the fiber can be chemically treated in order to increase its adherence to the concrete. This solution is interesting, but requires the development of a resin with hydrophobic properties and, at the same time, the resin must be made compatible with the concrete. Currently, there is no resin that has these characteristics and, therefore, will be left for a subsequent investigation.

(b) A second alternative is to place the fiber in a geometric form so that sliding is prevented, i.e., make a mechanical assembly between the fiber and concrete. This geometry can be cyclical. This alternative was carried out in the next stage of this work. Figure 4 shows the mold cavity with the embedded sensor in this configuration.

Figure 4. Cyclical fiber optic sensor.

Before testing the second alternative, the appropriate radii of the curves necessary for preventing excessive attenuation of the light signal were explored. Figure

5 shows the influence of curvature radius on the attenuation of the fiber. It is interesting to note that, in this test, the attenuation intensity by the first 360° folds (one twist) does not increase when the fiber is folded more times. This is mainly due to the fact that, in the first fold, there was a complete loss of light and not increase with the next twist. This behavior is more noticeable in curvature radii of 20mm to 10mm.

Results of the second experimental stage (placement of optical fiber in cyclical configuration in central location inside beams).

In order to determine the optimal curvature radii for the cyclical sensor, a test to see how the curvature radii effect attenuation was carried out.

Nineteen cylinders with different curvature radii from 2mm to 20mm were obtained. The fiber was wrapped around each cylinder four times. The attenuation for each turn was measured. The results of these tests are shown in Figure 5.

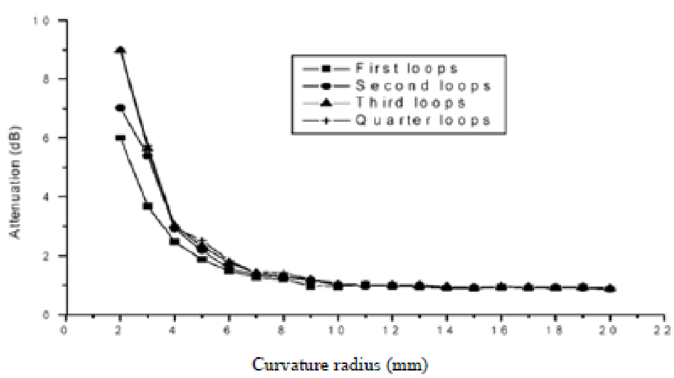

Figure 5. Influence of curvature radii against attenuation.

As expected, the smaller the curvature radii, the higher the attenuation was. With curvature radii from 20mm to 10mm, the attenuation level does not vary with the number of turns of the fiber. With the radius of curvature of 10mm or less, the attenuation level does vary. The curvature radius of the sensor was varied, with the first radius being 14mm to 12mm. The results of the tests for these two radii were very similar. Figure 6 shows the results of the tests.

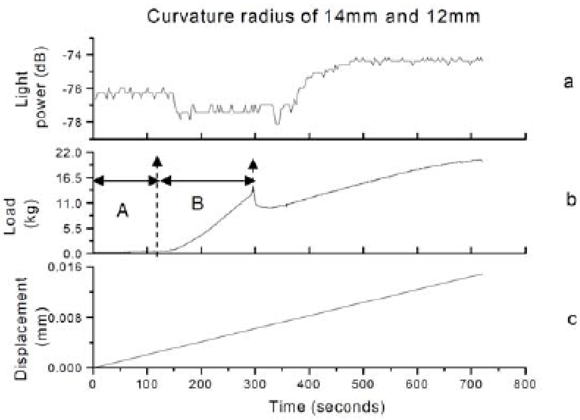

Figure 6. Results of sensor with curvature radius of 14mm and 12mm.

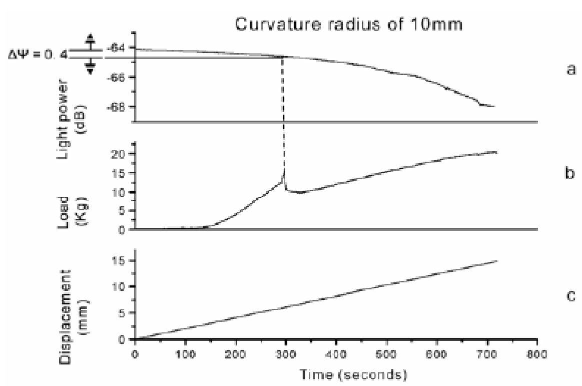

Figure 7. Results of sensor with a curvature radius of 10mm.

The light potential signal (Figure 6(a)) stays almost constant in area A. The range corresponds to area B and a little after there is a fall in light potential which also stays almost constant. The light potential data is not completely continuous because the fiber still sliding, although much less than the previous tests.

Afterwards, a test was carried out with a curvature radius of 10mm. The results of this test are shown in Figure 7.

In this test, the light potential signal (Figure 7(a)) had a constant and uniform drop while the load was applied. This is due to the fact that the fiber in this test had good connection with the concrete. The value Δψ = 0.4dB means the difference of light potential that exists upon the application of load until the moment where it is at a maximum. With this value, the start of a fissure can be predicted because the fissure originates at this maximum point.

In this test, a mechanical assembly between the fiber and the concrete was achieved because the data obtained from the sensor are uniform and continuous.

The above test was satisfactory and was repeated in order to verify the results. The results from the second test were the same. In order to continue confirming the data, tests were carried out with curvature radii of 8, 6 and 4mm. The results of these tests were also satisfactory. Δψ kept a value of 0.4dB with a variation of ±0.1dB.

Discussion

In Figure 3(a), the fiber has many variations because it was sliding and it is evident that information about the formations of fissures could not be obtained.

From the theoretical point of view, a satisfactory explanation of the phenomena involved in Figure 6(a) is not known. First of all, it is difficult to explain the reason that the potential stays almost constant in area A, and even more so; why does the potential experiences a drop in the B area? The really intriguing thing is: why does the potential increases afterwards?

Evidently, the exact answers to these questions are beyond the scope of the present work; nevertheless, a few hypotheses can be made.

It is possible that the signal keeps its light potential before drastically increasing force due to the fact that the fiber still slides easily inside the concrete. Afterwards, the signal could have a drop in potential due to the deformations in the fiber due to the load applied. This is because the formations cause the light to escape and this is reflected in a drop in potential. The increase in potential could be due to the fact that the optical fiber is loose because, at that stage of the test, the action of the load was almost completely on the copper wires of the beam. These hypotheses will possibly be studied in future works.

In regards to radii less than or equal to 10mm, the results were satisfactory. With this configuration, a good mechanical assembly between the fiber and the concrete was achieved. The light signal had a continuous and uniform drop in potential. This means that the fiber did not slide during the test. With these results, the moment when a fissure starts to form can be known. With these results, one can carry out a calibration to obtain the percentages of deformation equivalent to the beam. This is due to the fact that this test was able to detect the start of a fissure and was repeated in order to verify its reliability and thus the data in this test was verified satisfactorily.

In order to continue corroborating these results, curvature radii of 8, 6 and 4mm were tested and had the same behavior. The value of $\Delta\psi$ is very important because it can determine with repetitivity when a fissure is going to begin to propagate. This critical value is when $\Delta\psi$ is approaching 0.4dB. This value is reliable because it was the same in the last five sensors that were tested, with a variation of ±0.1dB. The results of curvature radii less than 10mm are perfectly explained by the distortion of the fiber upon applying load. This explanation evidently must be confirmed by theoretical calculations which model fiber deformation.

The feasibility of designing a continuous sensor (distributed with one fiber) which is different than point-sensors and that uses a Bragg grill or an array of fibers has been demonstrated.

It is evident that this sensor is more evolved than previous sensors because it is able to monitor the behavior of the structure in its extension and with this can carry out early detection of fissures in any part when they are present.

The placement of the sensor in a linear configuration is not appropriate because this did not have a good connection with the concrete. The optimal curvature radii for the cyclic configuration for the sensor are when the attenuation levels vary according to the number of turns of the wire. The value of $\Delta\psi$ can be calculated for any value where the applied charge is at maximum because the light potential signal has a constant and uniform behavior. This sensor can monitor the condition of a concrete structure continuously due to the fact that it was able to carry out early detection of fissures in any area of the structure.

In a real structure, the optical fiber can be placed in the following ways:

It can be used in a beam design where the sensor is embedded during setting and, at the same time, does not produce a negative effect during setting. The optical fiber can be intertwined in rebar where the application of load is more critical.

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