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An Optical Fiber Sensor for Measurement of Dynamic Structural Response

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ABSTRACT: This paper reports the development of and an experimental study on an optical fiber sensor for monitoring civil infrastructure systems. This optical sensor employs a vibrating wire whose tension can be modulated by external force, strain, or vibration and transformed into the change of frequency of wire vibration. The frequency of wire is detected by light sent to and reflected from the wire through an optical fiber cable. Compared to other optical fiber sensors developed so far, the proposed sensor has two significant advantages: one is that the sensing head is a vibrating wire (rather than an optical fiber), which can sense a specific physical quantity without being interfered by miscellaneous effects; the other is that the wire vibration is a well understood and reliable physical phenomenon and its frequency is optically measured and transmitted without attenuation or distortion through the optical fiber to recording and other devices. These advantages make the sensor extremely simple, reliable and robust, and hence more readily deployable in civil infrastructure applications. Three prototypes have been developed and their static and dynamic characteristics have been experimentally tested. One of the prototypes was embedded into a concrete specimen to measure its strain and the result agrees with that from a conventional strain gauge. The experimental study with prototypes demonstrates the high performance of the developed optical sensor in terms of accuracy, high frequency range, and other characteristics.

INTRODUCTION

An advanced civil infrastructure system requires sensor technology to monitor the surrounding environment and integrity of the system itself. The conventional sensor technology, however, has a number of difficulties associated with its utilization for this purpose. Civil infrastructure systems, particularly advanced ones, perform complex functions which may generate significantly strong electromagnetic fields that interfere with the conventional sensors and drive them reckless. The long cables required for the use of conventional sensors can act as large antennae and thus they may pick up all kinds of noise, create ground loops, and are susceptible to lightning strikes. Careful and heavy shielding could, in principle, eliminate electric interference, but not magnetic one. Almost all the sensors currently used for monitoring civil structures such as strain gauges and accelerometers are electric or magnetic, and hence the interference by electromagnetic fields are unavoidable. Also, civil infrastructure systems need a large number of sensors for monitoring purpose due primarily to its usually large physical size, which can be the source of many problems. One of these problems is the cabling. A conventional sensing system which usually comes with more than one hundred data channels obviously requires a large number of long cables for signal transmission, power supply, and shielding which need to be heavily waterproofed in order to prevent electric short due to moisture. The installment of such a large number of long cables creates all types of practical complications. Another problem is that the conventional sensors and attendant cables are too expensive to install at all the necessary locations. Civil infrastructure systems are usually exposed to harsh environments, such as corrosive surroundings, high or low temperature and external loads causing severe shock and vibration. This requires ruggedness and durability of the sensors. However, the conventional sensors do not always demonstrate these desirable characteristics. Moreover, an advanced civil infrastructure system should have a self health monitoring function which examines, for example, the existence and severity of fatigue crack and other damage, ideally throughout the three-dimensional body of the structure for the ultimate purpose of ensuring structural safety and integrity. For this reason, a sensor system with a distributed sensing capability is required. Unfortunately, the conventional sensors cannot be easily used for this purpose.

An emerging sensing technology, optical fiber sensing, has shown great potential to overcome these difficulties associated with conventional sensors. In general, optical fiber sensors demonstrate the following superior performance:

1. Immunity to electromagnetic interference
   Since an optical fiber sensor is dielectric, it will not suffer from interference by electromagnetic fields.
2. Lightweight, compact size, low power, and reduced cable requirement
   Optical fiber sensors and cables are lightweight, carry light for excitation and sensed signal simultaneously

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through the same line and can be multiplexed. Electric short due to moisture does not happen to optical fiber cables, and hence they do not need to be heavily waterproofed. Therefore, many of the cabling problems observed in the conventional sensor system do not exist in the optical fiber sensor system.

3. Distributed property

   Optical fiber sensors in certain configurations can sense quantities distributed over a linear distance and in principle even in two- and three-dimensional arrays.

4. Ruggedness and durability

   Optical fiber sensors are reliable under various adverse environmental conditions including high temperature. Also, their all-solid-state configurations are capable of withstanding extremely high levels of vibration and shock.

5. Potential low costs

   Due to the large commercial telecommunication market, the costs of key optical elements have been falling steadily. An optical fiber sensing system will be significantly cheaper than a conventional counterparts when it is commercialized.

These advantages of optical fiber sensors meet exactly the requirements demanded for civil infrastructure applications. Unfortunately, only a limited number of attempts has been made to apply optical fiber sensors to civil infrastructure systems. Among them, most of the research performed to date has focused on obtaining qualitative measurements such as detecting cracks within a concrete block. The research on quantitative measurements includes: measurement of strains in concrete beams using embedded fiber optic Fabry-Perot sensors [1,2] in laboratory [3]; installation of multimode interferometric sensors to a building, a highway pavement system, and a bridge to measure vibrations, concrete curing, and other parameters [4–6].

These exploratory studies have demonstrated the applicability of optical fiber sensors and provided basic knowledge specifically related to the installation or embedment techniques. However, these sensors are not originally developed for monitoring civil infrastructure systems, and hence have some difficulties in their direct applications to this field. For example, (1) these sensors usually detect the change in light intensity, phase delay, wave length, or interfered light mode pattern, and therefore they are too sensitive to measure response parameters (e.g., strain) of civil structures which usually require a large measurement range; (2) they register the combined effect of changes in several quantities such as strain and temperature, and thus it is difficult to single out and measure a specific quantity; and (3) the sensing heads of these sensors are optical fibers whose maximum capacities for sensing such quantities as strain and temperature are limited due to the fiber's physical strength. These problems prevented easy applications of these sensors to actual civil infrastructure systems. Therefore, the development of optical fiber sensors more suitable for civil infrastructure applications is urgently needed.

This paper proposes an innovative optical sensing system to bridge this gap and reports on the prototype development and preliminary experimental results.

CONCEPT

The proposed optical sensor is based on a completely different concept from those mentioned above. The sensor contains a transversely-vibrating wire, the resonant frequency of which is proportional to the square root of the tension in the wire. The tension may be modulated by, for example, external force, or more indirectly, by strain or acceleration which may be converted into the change in the wire tension. The wire is constantly oscillated by a series of laser pulses whose frequency is automatically and instantaneously adjusted to the resonant frequency of wire which varies due to the change in the wire tension. The vibrating frequency of the wire is sensed by a simple proximity optical sensor, in which light is sent to the wire from a light source and reflected from the wire into a return fiber.

Based on this concept, design of an optical sensing system has been made. As shown in Figure 1, the sensor system consists of the following parts: (1) a vibrating wire stretched between top and bottom portions of a frame through which the external force (force, strain, pressure, vibration, etc.) is

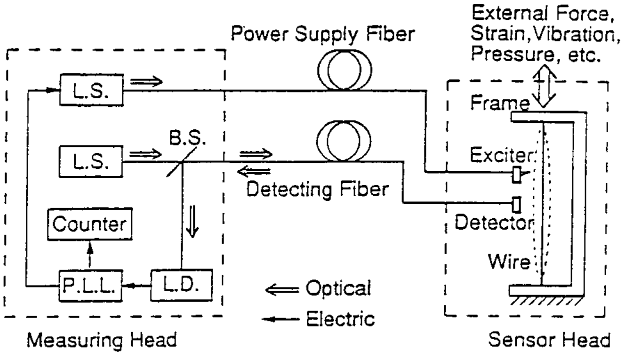


Figure 1. Conceptual configuration of proposed optical sensor.

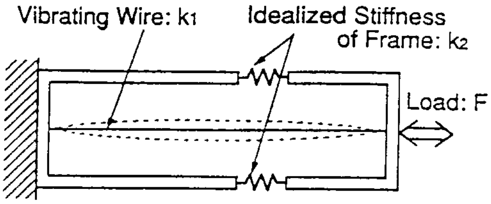


Figure 2. *Vibrating wire and its supporting frame.*

transformed into the change in tension of the wire, (2) an exciter to keep the wire vibrating, whose energy comes from an L.S. (light source), (3) an optical detector to measure the frequency of the wire vibration in which light from an L.S. is sent to and reflected from the wire through an optical fiber to an L.D. (light detector), and (4) a frequency adusting circuit called P.L.L. (phase lock loop) that ensures the exciting frequency to instantaneously match the resonant frequency of the wire varying with the external force.

This optical sensor can provide superior performance over the usual optical fiber sensors as mentioned earlier: (1) the frequency of the wire vibration is a robust signal which is not attenuated or deformed through the optical fiber transmission, (2) the sensing head is a vibrating wire instead of an optical fiber, which greatly broadens the possible range of measurement, and (3) for all practical purposes, it is insensitive to temperature variation. These advantages will facilitate its civil infrastructure applications.

The relationship between the tension of the wire T and frequency of wire vibration f can be calculated by the following equation:

$$f = \frac{1}{nl}\sqrt{\frac{Tg}{\varrho}} = \alpha\sqrt{T} \qquad (1)$$

where l is length, ϱ is weight per unit length of wire, g is the gravitational acceleration, and n represents vibration mode of wire with $n = 2,1,2/3,\ldots$ respectively for the lst, 2nd, 3rd. . .mode.

Since the wire is supported by a frame where the external load is applied to, as shown in Figure 2, the tension of the wire T and the external load F has the following relationship:

$$\frac{T_0 - T}{k_1} = \frac{F}{k_1 + k_2} \qquad (2)$$

where T_0 is the initial tension of the wire, k_2 is the stiffness of the supporting frame, and k_1 is the stiffness of the wire which is calculated by

$$k_1 = \frac{EA}{l} \qquad (3)$$

where E is Young's modulus and A is area of cross section of wire.

The relationship between the load F and the wire frequency f is then derived from Equations (1) and (2) as

$$f = \alpha\sqrt{T_0 - \frac{k_1}{k_1 + k_2}F} \qquad (4)$$

PROTOTYPE DEVELOPMENT

Three prototypes have been developed. Figure 3 shows the prototype #1 developed to demonstrate the feasibility of the basic concept of the proposed sensor. The design is very simple following the basic principles of mechanics and optics. The wire is stretched between two flanges of a channel shape (]-shape) frame and is oscillated by a solenoid which is driven by a series of laser pulses from a light source. The following basic functions are confirmed through testing: (1) the external force applied to the two flanges of the sensor frame can be transformed into the change in the vibrating frequency of wire, (2) the wire can be excited at its resonant frequency of a certain mode through the P.L.L. circuit, (3) the vibration frequency of the wire can be detected accurately by the light sent to and reflected from the wire.

Figure 4 shows the prototype #2 developed to test its basic characteristics as a sensor. It has basically the same configuration as that of #1 except for the shape of the supporting frame. The wire is stretched between two relatively flexible end plates of a relatively rigid shell as shown in Figure 4. The relative flexibility of the end plates allows applied external force transformed into the change in the tension of the wire. Tests are performed to examine the static and dynamic characteristics of prototype #2.

Prototype #3 has the cylinder shape which is similar to prototype #2. It is carefully sealed to become water-proof in order to be embedded into a concrete specimen.

EXPERIMENTAL TESTING

Static Characteristics

The static relationship between external force and frequency of wire vibration is tested first using prototype #2.

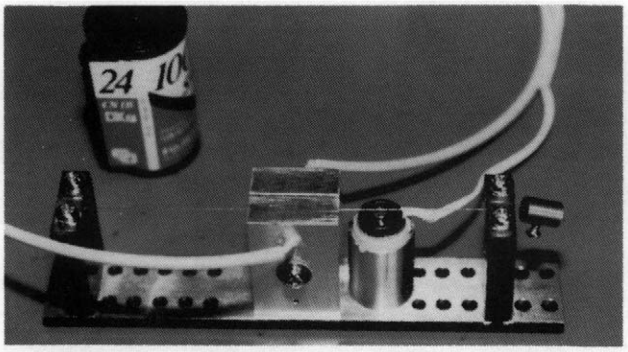
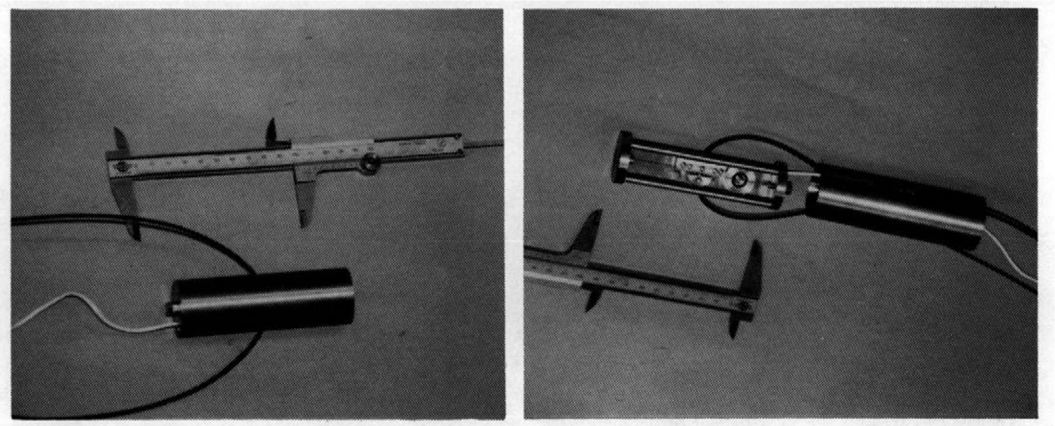


Figure 3. *Prototype #1.*



(a) Outside (b) Inside

Figure 4. *Prototype #2.*

One end of the optical sensor is attached to a conventional load cell, and axial the load is applied to the other end by a screw jack where the force is controlled by a handle. The conventional load cell is placed between the optical sensor and a fixed base.

In Figure 5, the voltage applied to the solenoid [Figure 5(a)] and the corresponding voltage detected by the L.D. (light detector) which transforms the light signal reflected from the vibrating wire into voltage [Figure 5(b)] are compared. It is observed that, (1) although the exciting signal is a severely distorted rectangular wave, the wire can be excited by this signal and vibrates in the form of a perfect sinusoidal wave. Therefore, it is confirmed that the vibration of wire is very robust and reliable. (2) Although the wire vibration is so small in its amplitude and so high in its frequency that it cannot be observed by human eyes (it can be slightly heard by human ears), it is accurately measurable by the proposed optical fiber sensor taking full advantage of the principle of optical fiber sensing.

The relationship between the applied external force (which is measured by the conventional load cell) and the corresponding vibration frequency of wire is shown in Figure 6. The open squares indicate the experimental data, and the solid line the theoretical result from Equation (4). It is observed that, (1) the experimental result perfectly agrees with the theoretical one. The theoretical relationship calculated according to Equation (4) is $f = 95.22\sqrt{216.0 - F}$, while the relationship from the regression analysis based on the experimental results is $f = 95.30\sqrt{215.8 - F}$ with a correlation coefficient as high as 0.99998. (2) Within the range of the force considered, the relationship can be in approximation modeled as linear in the form of $f = a - bF$ (where $a = 1401.5$ Hz, $b = 3.4551$ Hz/kgf with a high correlation coefficient of 0.99989).

Dynamic Characteristics

The dynamic characteristics of the developed sensor (prototype #2) is examined for the future applications in which the response of civil structures are to be measured under dynamic external loads such as winds and earthquakes.

The testing facilities are similar to the one used for static testing, except for the screw jack which is replaced by a hydraulic actuator as shown in Figure 7. Sweeping excitation tests are conducted in which the sinusoidal load applied by

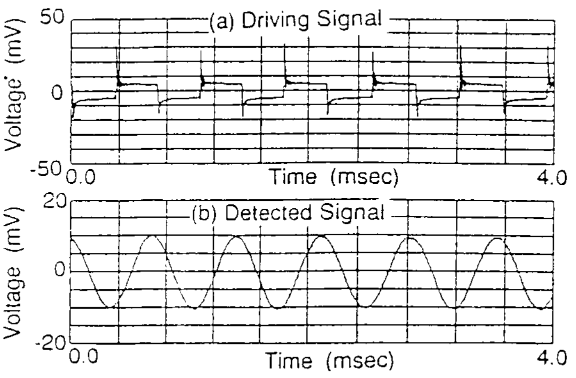


Figure 5. *Exciting signal and detected vibration signal.*

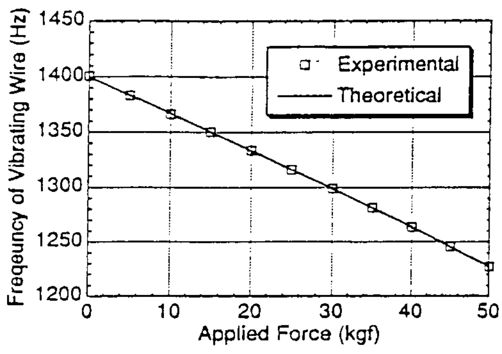


Figure 6. *Relationship between force and vibrating frequency of wire.*

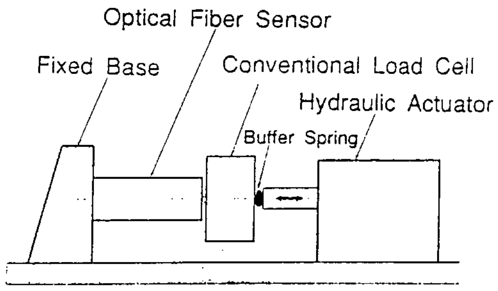


Figure 7. *Facility for testing dynamic characteristics.*

the actuator has a constant amplitude with the frequencies varied from 1 to 100 Hz within a time span of 10 seconds.

A typical set of signals measured by the load cell and by the optical sensor are compared in Figure 8, where the actuator excitation frequency is 10 Hz and the axial load is around ± 10 kgf. The signal from the optical sensor excellently agrees with that from the load cell, a conventional sensor. The accuracy of the optical sensor has thus been demonstrated.

The transfer function of the signal from the optical sensor over that from the load cell is shown in Figure 9. The magnitude remains to be approximately 1.0 up to $f = 25$ Hz where the discrepancy reaches a 10% level. The dynamic characteristics of the load cell used in this test is known to be adequate up to a 20 Hz range and therefore it is concluded that the prototype #2 can be used as a sensor to measure the dynamic response at least up to 20 Hz which represents a sufficient range for civil structures. Obviously, additional experiments using a load cell with a higher frequency range are necesary to test the dynamic range of the optical sensor over a higher frequency range.

Testing with Concrete Specimen

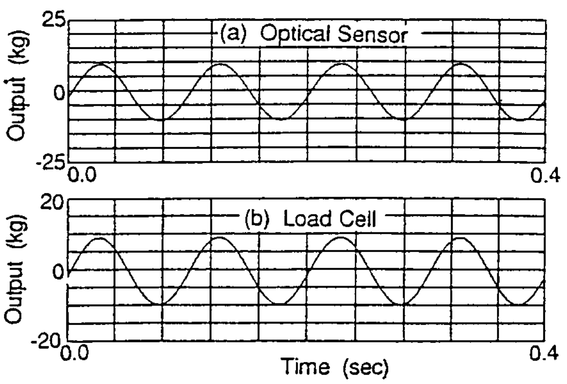


Figure 8. *Comparison of dynamic signals measured by optical sensor and load cell.*

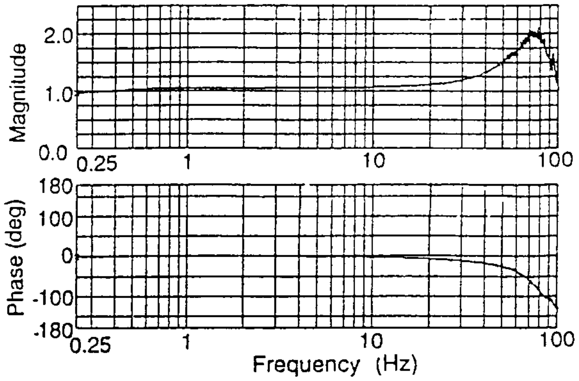


Figure 9. *Transfer function (optical/load-cell).*

Prototype #3 is embedded into a concrete specimen to measure the load and to compare the strain calculated from the load and measured from conventional strain gauges. The concrete specimen is made inside a mold with cylinder shape of $\phi 15$ cm × $l_C 30$ cm. The optical sensor has a cylinder shape of $\phi 3.2$ cm × $l_S 10.5$ cm and is placed in the center of the mold as shown in Figure 10(a). Concrete is then filled around the sensor. The complete concrete specimen with the sensor embedded is shown in Figure 10(b). Conventional strain gauges are also installed as indicated in Figure 11 to measure the strain at the surface of concrete cylinder.

From Figure 12, it is observed that the load detected by the optical fiber sensor is proportional to the total load on the concrete with the proportionality constant equal to 0.00797. Young's modulus of concrete is measured using a different concrete specimen which does not contain the optical sensor and is found to be $E_C = 1.77 * 10^5$ kgf/cm². The equivalent Young's modulus for the optical sensor can be calculated as $E_S = 2.987 * 10^4$ kgf/cm² through the following equations.

$$\frac{k_S}{k_S + k_C} = 0.00797 \tag{5}$$

$$k_C = \frac{A_C E_C}{l_C} \tag{6}$$

$$E_S = \frac{k_S l_S}{A_S} \tag{7}$$

where k_S, l_S, and A_S are the stiffness, length, and end plate's area of the optical sensor, and k_C, l_C, and A_C are those of the concrete specimen.

Therefore, the strain experienced by the optical sensor has the following relation with the load acting on the sensor F_S

$$\epsilon = \frac{\sigma}{E_S} = \frac{F_S}{A_S E_S} = 4.17 * 10^{-6} F_S \tag{8}$$

In Figure 13, the strain calculated by Equation (8) on the basis of the load measured by the optical sensor is compared with that measured by the conventional strain gauge. Excellent agreement is observed.

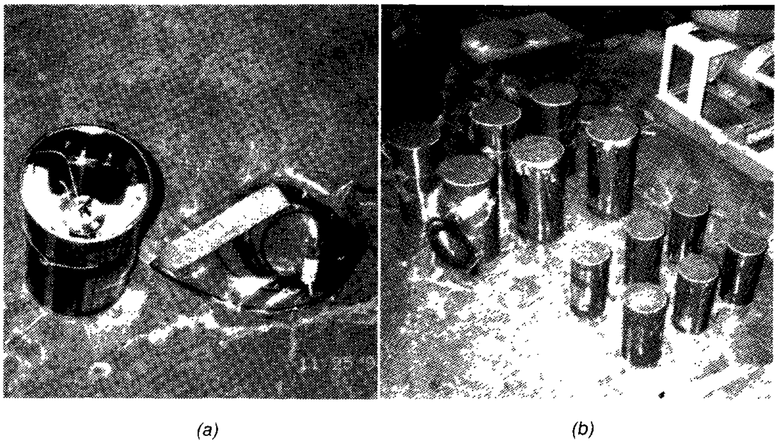


Figure 10. Prototype #3 embedded in concrete specimen: (a) before concrete filled in and (b) after concrete filled in.

FUTURE DEVELOPMENT AND APPLICATIONS

The optical sensor developed here has shown significant potential for applications to civil infrastructure systems because of its high accuracy and robustness in addition to the general advantages associated with optical fiber sensors. In fact, this sensor can also be easily modified to other sensor devices that measure strain acceleration, and pressure variation. To be specific, if the web of the frame (see Figure 3) in which the wire is stretched is made to be at most as stiff as the extension rigidity of the surface layer of concrete or steel members of civil structures, it can be attached to the surface or embedded to the surface layer of beams or columns of structures to measure strains; if a mass and a damper are attached, it can serve as an accelerometer; if a large plate with appropriate stiffness is installed to one of the end plates of the shell (see Figure 4), it can be used as an anemometer, soil or water pressure sensor. Such sensors will find wide applications in smart civil infrastructure systems.

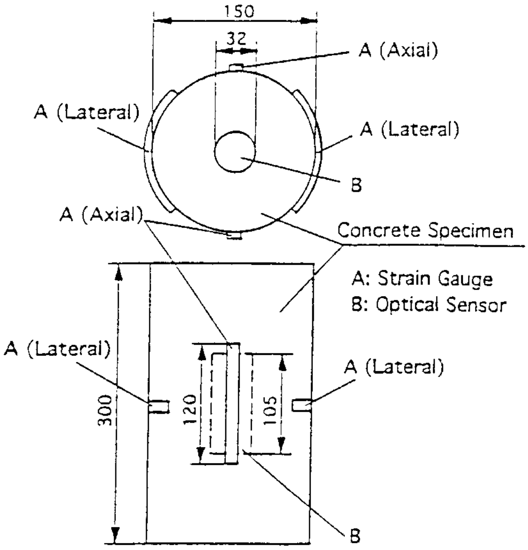


Figure 11. Installation of sensors in concrete specimen.

Another potential advantage of the proposed optical sensor is that possibly a large number of these units can be combined to form a distributed sensor network which has multiple sensor heads but uses only two light sources and only two optical fiber cables, just as demonstrated by a single sensor in Figure 1. One set of light source and optical fiber cable is for generating and transmitting the light pulse to excite the wires of all the sensor heads which have possibly all different frequencies, while the other set of light source and optical fiber cable is for sending the detecting light to and back from the wires, where signals with different frequencies are multiplexed into one cable. Since the light sources and optical fiber cables can be shared by multiple sensor heads, such a sensor network will significantly reduce the cost and eliminate cabling problems typically associated with conventional sensors.

CONCLUSIONS

An optical fiber sensor for civil infrastructure applications has been proposed. This sensor is based on an innova-

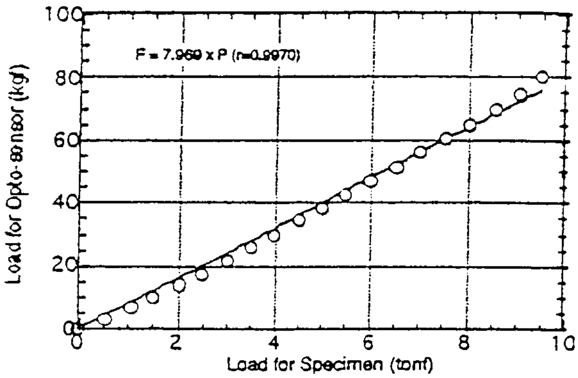


Figure 12. Loading on concrete specimen and on optical sensor.

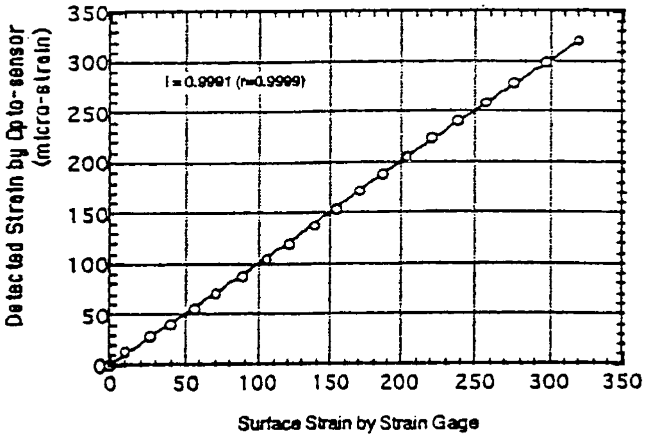


Figure 13. *Comparison of strains measured by optical sensor and strain gauge.*

tive concept of using a vibrating wire which is oscillated by a series of light pulses and whose vibration frequency is detected by optical fiber. Three prototypes have been developed, and experimental studies on their static and dynamic performances have been conducted. Experimental testing on the measurement of concrete strain has also been performed. It is demonstrated that

1. The wire vibration is a well known and reliable physical phenomenon, and it can be accurately detected by optical fiber. This makes the proposed sensor robust and reliable, and thus can be easily used in civil infrastructure applications.
2. The experimental results perfectly agree with theoretical ones. The sensing mechanism allows easy and accurate calibration.
3. The proposed optical sensor has high accuracy and a broad frequency range.
4. This sensor is easy to be embedded into concrete structural components and its high accuracy has been demonstrated.
4. The configuration of the sensor is very simple and the cost is highly competitive.

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