APPLICATION AND DEVELOPMENT OF FIBER OPTIC SENSORS IN CIVIL ENGINEERING

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ABSTRACT :

In recent years, fiber optic sensors have been deployed successfully in the supervision of structures. Mainly due to their small size they are enable to be widely used in structural elements. In facts, advances in the production of optical fibers made possible the recent development of innovative sensing systems for the health monitoring of civil structures. An overview is presented of our research towards the development of structurally fiber optic sensors. This demonstrates that fiber optic sensors show high sensitivity and accuracy in strain, stress, temperature measurement in several structures. In this research, several examples have been shown in which strain, stress and temperature have been determined for structural elements.

KEYWORDS: Fiber Optic Sensor, Smart Structures, Monitoring, Stress, Strain, Temperature.

1. Introduction

Nowadays, the monitoring and control of civil infrastructure systems are subjects that have received increasing attention. This is due to the recognition by engineers of the great potential of "smart-structures" concepts to improve the efficiency and reliability of civil structures. The generation of smart structures will be capable of through use of automatic instruments, which rely on sensors that are incorporated in the structures. Indicative of the extent of interest in these related fields are several recent workshops. The proceedings of these workshops include long lists of research topics that require further investigation and development. Among the key research topics that require further study are fiber optic sensors that can be used to quantify various structural parameters.

2. Optical Fibers

Optical fibers (or optical fibres) are transparent fibers, usually made of glass or plastic, for transmitting light. They are flexible strands roughly the diameter of a human hair. With the use of this latest technology, large amounts of data can be transmitted over long distances. During several years the optical fibers are used to broadcast light signals and audio signals, producing distortion-free sound. In addition, fiber optics is useful in medical procedures (for internal inspection of the body), automobiles, and aircraft.

Though fiber optics was first invented in the 1930s, the use of this technology barely started in the late 1960s. A serious momentum occurred in the 1980s when the phone companies started to replace their long distance copper cables with fiber cable. Gradually, all transmission systems and networks started using fiber cables.

Although fibers can be made out of either transparent plastic or glass, the fibers used in long-distance telecommunications applications are always glass, because of the lower optical attenuation. Both multi-mode and single-mode fibers are used in communications, with multi-mode fiber used mostly for short distances (up to 500 m), and single-mode fiber used for longer distance links. Because of the tighter tolerances required to couple light into and between single-mode fibers, single-mode transmitters, receivers, amplifiers and other components are generally more expensive than multi-mode components. A fiber-optic relay system contains a transmitter that produces and encodes the signals, an optical fiber that transmits the signals over a distance, an optical regenerator that is essential to boost the signal for long distances, and an optical receiver, which receives and decodes the signals. Optical fibers are generally arranged in bundles known as optical cables. Each bundle is protected by a jacket, the cable's outer covering. A single optical fiber consists of core (the central part where the light travels), cladding (special additives surrounding the core), and buffer coating (plastic coating that guards the fiber from break and moisture). The cladding has a high index of refraction so that the light is internally reflected and zigzags through the fiber instead of leaking out.

Optical fibers are classified into two types, single-mode fibers and multi-mode fibers. Single-mode fibers feature small cores (around 3.5 x 10-4 inches or 9 microns in diameter) and broadcast infrared laser light of wavelength 1,300 to 1,550nm. Multi-mode fibers have larger cores (2.5 x 10-3 inches or 62.5 microns in diameter), transmitting infrared light (wavelength ranges from 850 to 1,300nm) from LEDs. There are a few optical fibers, which are made from plastic, having a large core (0.04 inches or 1 mm diameter) and send visible red light of wavelength 650 nm from LEDs.

Compared to the copper wires, optical fibers are less expensive, thinner, have higher carrying capacity, less signal degradation, carry digital signals, and are non-flammable, lightweight, and flexible. Since signals degrade less, lower-power transmitters are used instead of the high-voltage electrical transmitters required for copper wires. The signal coming out of a fiber wire possesses the same quality and intensity as when it was first entered into the cable. An optical cable is resistant to electromagnetic interference, as well as to crosstalk from adjoining wires. Fiber Optics provides detailed information on Fiber Optics, Fiber Optic Transmitters, Fiber Optics Training, Fiber Optics Receivers and more. Fiber Optics is affiliated with CCNA Exams.

3. Fiber Optic Sensors

Optical fibers can be used as sensors to measure strain, temperature, pressure and other parameters. The small size and the fact that no electrical power is needed at the remote location gives the fiber optic sensor advantages to conventional electrical sensor in certain applications. Optical fiber sensors for temperature and pressure have been developed for down-hole measurement in oil wells. The fiber optic sensor is well suited for this environment as it is functioning at temperatures too high for semiconductor sensors (Distributed Temperature Sensing). Another use of the optical fiber as a sensor is the optical gyroscope which is in use in the Boeing 767 and in some car models (for navigation purposes) and the use in Hydrogen microsensors.

Fibers are widely used in illumination applications. They are used as light guides in medical and other applications where bright light needs to be brought to bear on a target without a clear line-of-sight path. In some buildings, optical fibers are used to route sunlight from the roof to other parts of the building (see non-imaging optics). Optical fiber illumination is also used for decorative applications, including signs, art, and artificial Christmas trees. Swarovski boutiques use optical fibers to illuminate their crystal showcases from many different angles while only employing one light source. Optical fiber is an intrinsic part of the light-transmitting concrete building product, LiTraCon. Optical fiber is also used in imaging optics. A coherent bundle of fibers is used, sometimes along with lenses, for a long, thin imaging device called an endoscope, which is used to view objects through a small hole. Medical endoscopes are used for minimally invasive exploratory or surgical procedures (endoscopy). Industrial endoscopes (see fiberscope or borescope) are used for inspecting anything hard to reach, such as jet engine interiors. An optical fiber doped with certain rare-earth elements such as erbium can be used as the gain medium of a laser or optical amplifier. Rare-earth doped optical fibers can be used to provide signal amplification by splicing a short section of doped fibre into a regular (undoped) optical fiber line. The doped fiber is optically pumped with a second laser wavelength that is coupled into the line in addition to the signal wave. Both wavelengths of light are transmitted through the doped fiber, which transfers energy from the second pump wavelength to the signal wave. The process that causes the amplification is stimulated emission. Optical fibers doped with a wavelength shifter are used to collect scintillation light in physics experiments. Optical fiber can be used to supply a low level of power (around one watt) to electronics situated in a difficult electrical environment. Examples of this are electronics in high-powered antenna elements and measurement devices used in high voltage transmission equipment.

4 Types of Fiber Optic Sensors

Fiber optic stress sensors can be classified into two major categories: intension-metric and interfero-metric. An intension-metric sensor relies on variations of the radiant power transmitted through an optical fiber, whereas an interfero-metric sensor relies on measured induced phase change in light propagating through the optical fiber. External forces (such as compressive stress) can introduce small bends in an optical fiber which couples light out of the fiber, thereby varying the intensity of light transmitted through the fiber. A micro-bend sensor is a common intension-metric sensor. Two interfero-metric type sensors are Fabry-Perot and Bragg grating. The Fabry-Perot sensor consists of two mirrors placed in line with the optical fiber. Strain induced changes in the longitudinal mirror spacing produces a measurable phase change in the light frequency. Two samples of these sensors are shown in Figure 1.

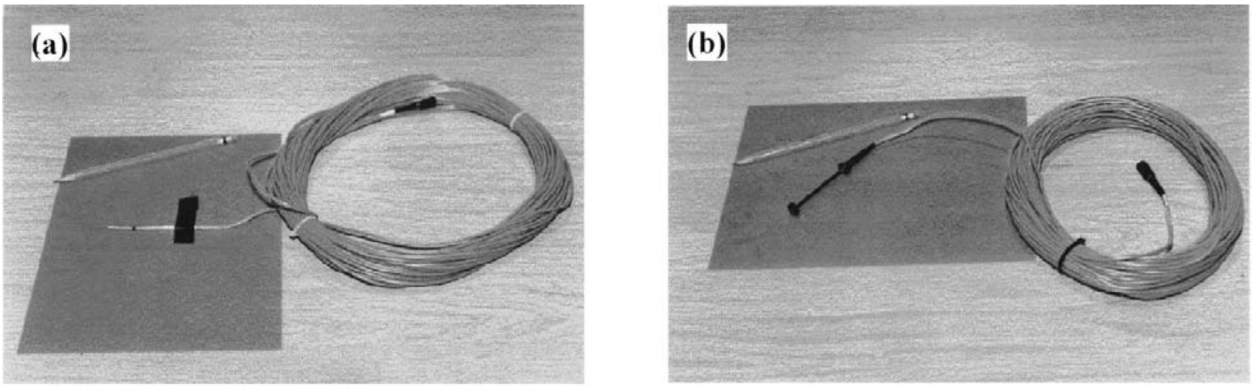


Figure 1. Two Types of Fabry-Perot Fiber Optic Sensors

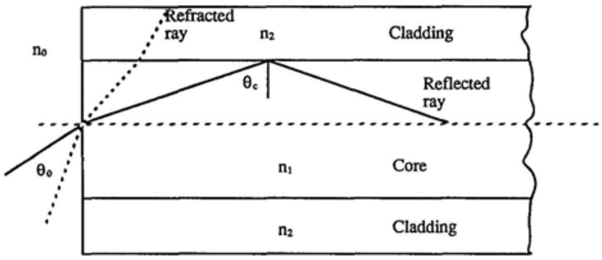


Figure 2. Basic Geometry of Optical Fiber Sensor

The Bragg grating sensor relies on the reflection of light from a region in the index of refraction of the optic fiber core. Longitudinal strain in the fiber changes the spacing of these periodic variations, thereby varying the wavelength of reflected light. (Figure 2)

5. Application of Fiber Optic Sensors

Over the past decades, a variety of fiber optic sensor configurations have been developed for measurement of several parameters in structures. Fiber optic sensors can be embedded in various kinds of structures such as buildings, roads, dams, and other concrete or steel structures. The optical fiber itself can be divided into two basic types: single mode and multimode fibers. Usually, the former can be used as localized or mechanical sensors, such as strain or force sensors, while the latter can be used as sensors in a more wide range such as distributed and thermal and other sensors. Several applications of fiber optics for monitoring of the most important parameters in structures have been developed. They are described in the following sections.

5.1. Applications to Stress Sensors

Structural monitoring is concerned with the safety of the users of a structure, especially for the case of building structures and infrastructures. When considering the safety of a structure, the maximum stress in a member due to live load, earthquake, wind, or other unexpected loadings must be checked not to exceed the allowable stress of a member. In allowable stress design of steel structures, if the maximum stress in a member reached the yield stress, the member is considered to be analogous to failure. Therefore, to guarantee the safety of a structure and its users, the maximum stress in a member must be monitored. Since the actual stress distribution induced in a beam by varying amounts and types of loads is non-uniform, many difficulties exist when determining the maximum stress in a beam with the point sensors. In this case, the reliability of the evaluated safety depends on the number and location of point sensors. Various fiber optic systems based on different mechanisms have been developed to assess the safety of structural members. One of these sensors is shown in Figure 4.

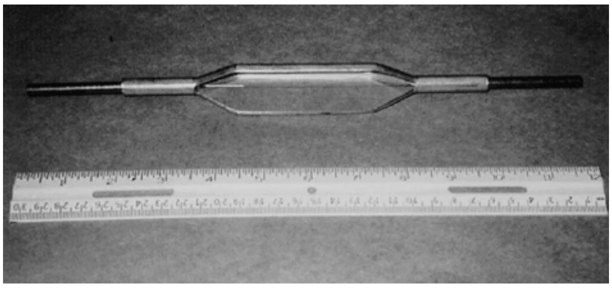


Figure 4. Photograph of a Stress Sensor

5.2. Applications to Strain Sensors

Strain sensors measure the relative displacement between two points in a structure. The distance between the two points along the fiber optic changes through various environmental effects. It is noticeable that due to the deformation measured is the average value measured, the strain variation or stress distribution of a beam can be considered by using several fiber optic sensors, and by means of these sensors the maximum strain or stress in a beam can be measured.

The strain sensors consist of a fiber Bragg grating sandwiched between layers of carbon composite material (Figure 5) and are about 50 mm long and 0.5 mm thick. The accuracy and sensitivity of the sensors are dependent upon the optical system. (Figure 6)

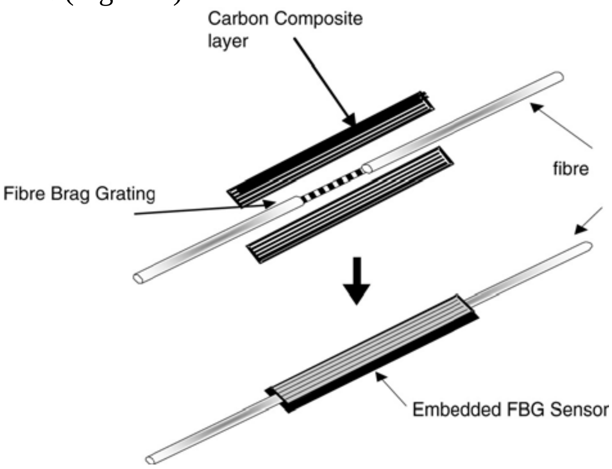


Figure 5. Strain Sensor Placed Between Layers of Composite Material.

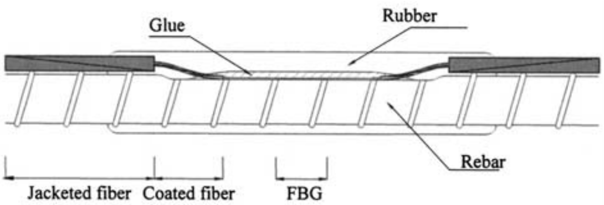


Figure 6. Scheme of the Strain Sensor

5.3. Applications to Temperature Sensors

Thermal expansion is an important factor in all types of structures where differential heating may occur, either from environmental effects, such as the solar heating of pavements and bridge decks, or from service conditions, such as in nuclear-reactor, pressure vessels or furnaces. The thermal expansion coefficient will be a variable quantity depending on materials. The Bragg wavelength λ_B, is related to the grating period, Δ, and the effective refractive index of the fiber n_{eff} by $\lambda_B = 2\Delta n_{eff}$. Subjecting the fiber to a change of temperature causes Δn_{eff} and therefore λ to change. By determining the wavelength of reflectivity, the temperature to which the fiber is subjected may be found. A scheme of the new temperature sensor is shown in Figure 7.

Typically, the temperature sensor is packaged into a 35 mm long metal tube (Fig. 8). The metal tubing protects the fiber Bragg grating from external stress and increases the temperature sensing range.

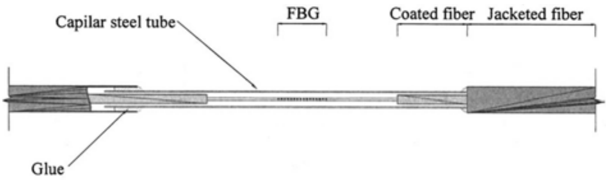


Figure 7. Scheme of the Temperature Sensor

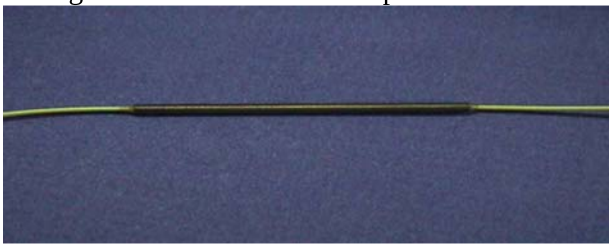


Figure 8. Photograph of the Temperature Sensor

5.4. Applications to Crack Monitoring

The existing condition of many important concrete structures can be accessed through the detection and monitoring of cracking. For example, in concrete bridge decks, crack openings beyond 0.15 to 0.2 mm will allow excessive penetration of water and chloride ions, leading to the corrosion of steel reinforcements. The crack opening of the order of millimeters, which may occur after a major earthquake, is a sign of severe structural damage.

Conventionally, crack detection and monitoring have been carried out by visual inspection. The procedure is time consuming, expensive, and yet unreliable. Recently, researchers developed sensors for the reliable detection and monitoring of cracks in concrete structure.

An optical fiber is embedded in the concrete element in a ‘‘zigzag’’ shape (Figure 9) and before the formation of cracks, the light intensity distribution along the fiber is measured. When a crack opens in the structure, fiber bend to stay continuous and consequently light intensity is changed.

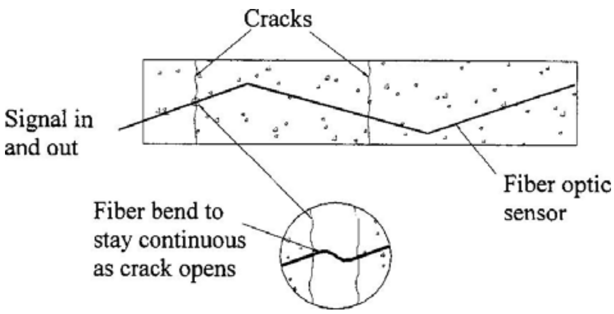


Figure 9. Principle of Operation of the Zigzag Sensor

5.5. Applications to Cable and FRP Monitoring

With the development of the fiber optic sensing techniques, the applications of fiber optic sensors have been extended from the laboratory test to in site experiments. Some kinds of fiber optic sensors have been applied to the health monitoring of FRP and cable structures in recent years. They employed fiber optic sensors to monitor the strains of steel, FRP (fiber reinforced polymer), pre-stressing tendons, post-tensioning cables and etc. They can measure strain and temperature in arbitrary regions. A photograph of test setup sensor is shown in Figure 10 and two other photograph show application of fiber optic sensors to cable and FRP Monitoring. (Figures 11,12)


Figure 10. Photograph of Test Setup

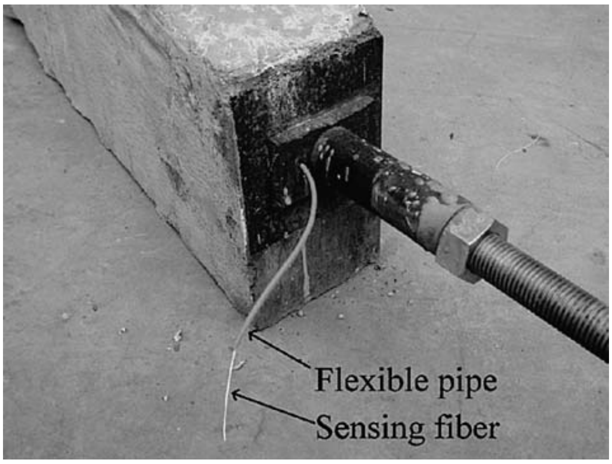


Figure 11. Photograph of a Beam Strengthened with FRP Cable

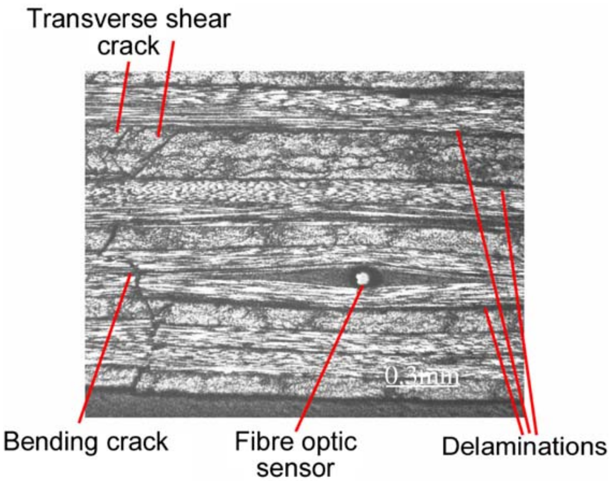


Figure 12. Section through Damaged Area of FRP Containing Fiber Optic

5.6. Applications to Bridge Monitoring

The applications of fiber optic sensors to bridge monitoring are focused in measurement of short and long-term parameters of bridges. One of these bridges is the Mjosundet Bridge (Fig. 13). This five-span bridge is located on the west coast of Norway. It is practically symmetrical with two end spans of 41 m, two intermediate spans of 82 m, and a center span of 100 m giving a total length of 346 m. Up to 100 fiber optic sensors were mounted inside the bridge and six locations were monitored in order to assess the strains at the center of the bridge and the shear strains close to one of the supports of bridge.

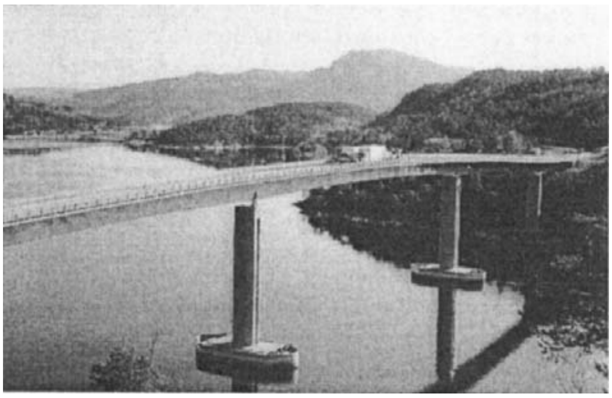
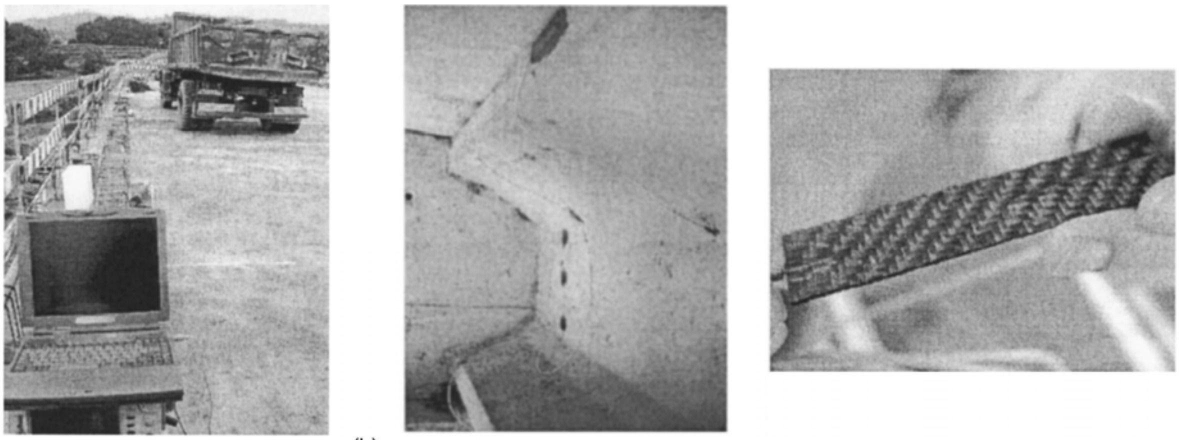


Figure 13. Photograph of Mjosundet Bridge

Another monitoring is presently being used in the construction of the bridge over River Ave, in Portugal. In this bridge, besides the Bragg grating sensors, conventional resistive strain gauges in concrete, reinforcing and pre-stressing steel and etc. were added to acquire complete information on strain and deformation all over the structure. (Figure 14)



(a) (b) (c)

Figure 14. (a) Static Loading Test; (b) Sensors Applied in a Beam;
(c) Strain and Temperature Sensor Protected by a Thin Laminate

5.7. Applications to Moisture Monitoring

Due to the nature of concrete structures and their exposed environmental conditions, corrosion can occur internally without this being evident from the outside. This is often due to the ingress of water corroding the reinforcements, which is hastened by the salts and chloride ions dissolved in it. At the moment, fiber optic based humidity sensor has been developed and used for the measurement of moisture absorption in concrete. The sensor was fabricated using a fiber Bragg grating coated with a moisture sensitive polymer. The sensor itself exploits the inherent characteristics of the fiber Bragg grating. It was found that optical fiber based humidity sensors form a basis for determining the changes in the moisture content in different concrete samples, indicating new applications of the sensors to ensure the integrity of structures.

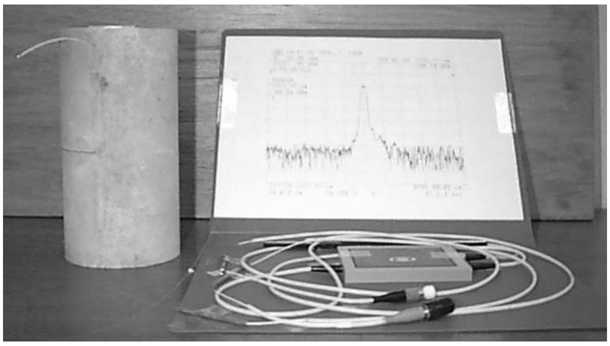


Fig. 15. A Concrete Cylinder with an Embedment of FBG Sensor (left)
Connection to Cable and Terminal (right)

5.8. Applications to Welding Residual Stresses Monitoring

Optical fiber sensors due to their small size are becoming to be widely used in high electromagnetic fields. This feature is combined with excellent stability and also with the possibility of having several optical fibers. As result of their features, a kind of sensors constitutes a very powerful tool for the analysis of welding transient and residual stresses. Under the assumption of a perfect bonding between the plate and the sensor, we are actually measuring transient and residual strains in the material being welded. Optical fiber sensors have been already used to detect welding transient and residual stresses in several kinds of structures. A scheme of test disposal is shown in Figure 16.

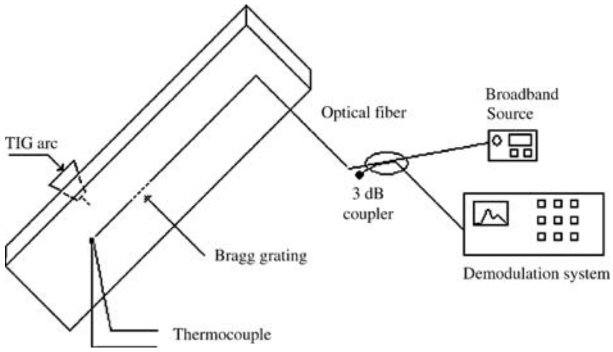


Figure 16. General Test Disposal

6. Conclusions

Lastly, it can be concluded that the fiber optic sensors can be successfully used for accuracy of structures and determination of quantity of parameters. At the same time, nondestructive tests of the members under long-term service loads, with the ability to warn against impending failure are other applications of fiber optic sensors. In general, fiber optic sensors show high sensitivity and accuracy in average strain, stress, temperature measurement in several structures. Also, the fiber optic sensors are flexible and adjustable and can be set to any desired direction. Yet, further studies involving laboratory and in site tests are necessary.

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