ABSTRACT

Fibre reinforced polymer (FRP) composites have become gradually accepted by the civil engineering industry for the repair and rehabilitation of concrete structures in recent years. Extensive research on the use of a host of different forms of FRP forms, such as rods, plates, grids and jackets, has led to confidence in their design for strengthening work. It is however extremely difficult so assess the structural performance of a strengthened structure using conventional non-destructive evaluation (NDE) technologies such as strain gauges, dye-penetrant, x-ray, radiography and acoustic emission. One form of NDE which has attracted research attention of late is the use of optical fibre sensors as they have the potential of providing real-time structural health monitoring. The sensors, which are typically embedded into the strengthening work, are capable of being used to assess damage and warn of impending weakness in the structural integrity of the structures at any marginal situations. The development of distributed fibre-optic sensors, which provide a large number of continuously distributed parameters such as strain, temperature and vibration profile due to traffic loading, is also of great interest in most engineering applications. In this paper, the use of glass fibre composites and embedded fibre-optic Bragg grating strain sensors as external reinforcement and structural health monitoring devices, respectively, for concrete structures are introduced. The potential applications of FRP reinforcing bars with integrated fibre-optic sensors, for new structures and known as a “Smart Composite”, is another real-time structural health monitoring application discussed in this paper.

INTRODUCTION

The high strength-weight ratio as well as the corrosion resistance of fibre-reinforced polymer (FRP) composites has made them a particularly attractive solution for strengthening existing civil engineering infrastructure. Research on the characterisation and quantification of the behaviour of reinforced concrete (RC) structural elements strengthened with FRP composites has surged ahead for over a decade now. Such research has led to the publication of several design guidelines and approaches (Teng et al. 2002, ACI 2006) and subsequently many practical applications (Nanni and Rizkalla 2003). The externally bonded FRP in essence however ‘hides’ the existing structure from view this making monitoring or a structural evaluation of the system post-strengthening extremely difficult throughout the remaining life of the structure. The mechanical properties of the concrete in service may not be measured or detected easily through conventional non-destructive evaluation (NDE) methods such as strain measurements using surface mounted strain gauges or extensometers, radiography, thermography and acoustic emission methods, particularly at a region with micro-cracks and debonding underneath the externally-bonded composite. Besides, these structural inspection technologies, in certain cases, require special surface preparations or a high degree of flatness on the concrete surface. These requirements may be hard to achieve, particularly for an area that is exposed to a harsh environment. Reinforced concrete structures can also be reinforced with FRP reinforcing bars. The monitoring of the FRP bars is also extremely difficult. The demand for finding suitable means to monitor the structural health condition of RC structures reinforced or strengthened with FRP is therefore of utmost importance.

In the past decade, a multi-disciplinary field of engineering known as “Smart Structures” has emerged (see Figure 1). Smart structures are capable of assessing damage and providing warning of impending weakness in the structural integrity of the structure. Such structures have the potential to revolutionize the building industry and create a new generation of civil infrastructure. A Smart Structure is formed by combining a structure with structurally-integrated sensor systems. Fibre-optic sensor technology is most attractive and is currently being developed in the aerospace industry for on-line monitoring of large-scale airplanes made of FRP polymers. Such technology has tremendous potential for use in Smart Structures as distributed fibre-optic sensors can provide a
large number of continuously distributed parameters such as strain and temperature of the surface of the structure (Doyle et al. 1998, Padula and Kincaid 1999).

Typically, the sensors are embedded into a structure to form a novel self-strain-monitoring system, i.e., the system can self-detect its health status and response signals to operators at any marginal situations during service. The embedded sensor, due to its extremely small physical size, can provide the information with high accuracy and resolution without significantly influencing the dimensions and mechanical properties of the structure. In Figure 2, an embedded optical fibre into a glass fibre reinforced composite is shown. There are a number of distinguishing advantages over conventional strain measuring devices associated with the use of embedded fibre-optic sensors for infrastructure applications, namely (i) ability to provide an absolute measurement that is insensitive to fluctuations in irradiance of the illuminating source; (ii) enable the measurement of strains in different locations with only one single optical fibre by using multiplexing techniques; (iii) having a low manufacturing cost for mass production; and (iv) enabling embedded sensors inside a structure without influencing the mechanical properties of the host material. In this paper, an introduction to the principles of fibre-optic strain sensing technologies for civil engineering infrastructure, in particular the combination of RC and FRP composites. Successful as well as potential applications of fibre-optic sensors and FRP materials with integrated optical fibre sensors, known as a “Smart Composite”, for civil infrastructure elements are also discussed.

![Figure 1. Smart Structures](image1.png)

![Figure 2. An embedded optical fibre (the centre circular part) in the glass fibre composite](image2.png)

**FIBRE-OPTIC SENSORS**

**Background**

In fibre-optic sensors, external perturbations such as strain, pressure or temperature variations induce changes in the phase, intensity or wavelength of light waves propagating through the optical fibres. The changes in one or more of the properties of light can then be related to the parameters being measured. Optical fibres are
geometrically versatile and can be configured to arbitrary shapes. The smart structure concept takes advantage of the geometric adaptability of optical fibres. In this technology, fibre-optic sensors are embedded within the structural material or bonded on the structure surface for the purpose of real-time damage assessment. The most attractive feature of fibre optic sensors is their inherent ability to serve as both the sensing element and the signal transmission medium, allowing the electronic instrumentation to be located remotely from the measurement site. This is especially useful for remote monitoring of the condition of bridges.

Proper application of fibre-optic sensors to concrete structures requires understanding of certain fundamental methodologies pertaining to sensor mechanisms as well as sensor multiplexing strategies. Currently, three different types of fibre-optic sensor arrangements have been well-developed in real-life applications; they include localised, multiplexed and distributed sensor systems (Figure 3).

Concrete Applications

The use of fibre-optic sensors in civil engineering applications was first suggested by Méndez and Morse (1992). Subsequently, several research groups in North America and Europe have reported on a variety of fibre-optic sensors embedded in or attached on reinforced concrete (RC) structures. Most of the work has been mainly focused on the laboratory demonstration of their suitability for strain, vibration and temperature measurements. Until recent years, multiplexed grating sensors (more than one sensor can be written along in a single optical fibre) have been installed along a pre-stressed girder in the Taylor Bridge to monitor strain responses at different positions during service (Maaskant et al. 1997). Maaskant et al. (1997) have demonstrated the static strain measurements from the Beddington Trail Bridge sensor array. The sensor array was made by multiplexed grating...
sensors in one single-mode optical fibre. At that period, the accuracy of strain measurement was about ±40με by using the wavelength division multiplexing (WDM) technique. The sensors could also be used for cure monitoring of the concrete to monitor the temperature and stress variations during the curing process. Since the girders were post-tensioned, the strain measurements during the process revealed the conditions of stress relaxation in the tendons from the combined effects of de-stressing, concrete shrinkage and creep, the dead loading of the bridge deck, and the post-tensioning applied across the two spans. The sensors, however remain in the bridge as smart sensors for its health monitoring.

Advanced Composite Materials Applications

The advantages of using embedded optical fibre sensors in composite materials are dimensional and material compatibilities. The fibres do not degrade during curing, they do not corrode, and they bond strongly to the matrix. Incorporation of the fibres during the processing stage also offers the opportunity to monitor the condition of structural elements during fabrication. The success of fibre-optic sensor technology in the condition monitoring of composite materials has led to a limited number of research and development activities in the civil engineering discipline. Several researchers realised that this emerging field of technology could have impact on the condition monitoring of civil structures, so that durability, safety and efficiency of infrastructure systems can be improved.

Watking et al. (2007) embedded a fibre optic sensor network (Fabry-Perot interferometer sensors) prior to externally bonding FRP sheets for the strengthening of an existing RC bridge. The sensors displayed better performance than externally bonded strain gauges although several questions regarding practical issues were raised such as installation and environmental effects.

INTEGRATED FIBRE-OPTIC SENSORS SYSTEMS

Externally Bonded FRP Plates

The first use of FBG sensors as structural health monitoring devices in a bridge structure was demonstrated in 1994. An array of FBG sensors was adhered on the surface of a carbon fibre composite tendon to measure strain and deformation of the structure. Saouma et al. (1998) and Lau et al. (2001a, 2001b) have used embedded FBG sensors to monitor strains of laboratory sized concrete beams. They found that the results were in a good agreement with those measured by externally bonded electric strain gauges. The Naval Research Laboratory in the USA (Kersey et al. 1996) performed an experimental study for a bridge, which is a ¼ scale of a real structure with 60 FBG sensors embedded to measure strains. They found that the FBG sensors could measure the strains in real time. However, due to the limit of scanning speed of the Fabry-Perot tunable filter used for wavelength-shift measurement, only static strain could be measured.

Internally Embedded FRP Reinforcing Bars

In Canada, multiplexing FBG sensors were embedded during construction along pre-stressed girders for a bridge, which was made of FRP to monitor strain response at different positions during service (Holton 1998). Lau et al. (2001c) and Davis et al. (1996) have installed multiplexed FBG sensors at the bond interface between the damaged concrete surface and externally-bonded FRP reinforcements for FRP-strengthened concrete structures. One sensor was attached on the concrete surface and just in front of a crack-tip to measure strain. An externally bonded strain gauge was also used on the surface of the reinforcement to compare strain measurements. The experimental results showed that the FBG sensor often gave high strain values compared with the strain gauge, particularly for a thick reinforcement. Since the sensor was located on the concrete surface and at the crack-tip, which was suspected as a high stress concentration region, the sensor was highly susceptible to micro-cracks on the concrete surface and the occurrence of debonding at the bond interface.

SMART COMPOSITE FOR INFRASTRUCTURE APPLICATIONS

The applications of fibre-optic sensors in the civil engineering industry have been discussed previously. However, smart composites in civil concrete structures have not yet been adopted in all real structures. It has been proven (Teng et al. 2002) that the use of FRP can substantially increase the strength of concrete structures by using simple composite plate bonding or hand lay-up techniques. Fibre-optic sensors, also present the ability to measure strain remotely and precisely without imposing any strength degradation to the structure. Thereby,
the use the smart composites for concrete strengthening as well as a structural health monitoring device can definitely improve the durability and safety of the structure.

The technology of smart composites, in which fibre-optic sensors are integrated into the composites to form a single part compound, has now matured. Smart composites are able to be used as reinforcement as well as sensors for repairing and strengthening damaged concrete structures as shown in Figure 4. The composite can be formed as a patch to bond on the concrete surface to improve the tension properties of the concrete structure. Since the sensors are integrated into the composite, the risk of damage of the fibre is reduced and patches can be manufactured in-house without being affected by the insitu-environment.

![Figure 4. The smart composite concept for concrete rehabilitation.](image)

A good Smart Composite example is the embedding of fibre optics into the centre of FRP reinforcing bars in the pultrusion stage (Kalarnkarov et al. 2005). Laboratory tests on small scale RC beams by Kalarnkarov et al. (2005) revealed the sensors performed well at low load ranges although were limited by their strain capacity. Lau and Zhou (2002) also revealed that the use of embedded FBG sensors can provide accurate strain measurement as compared with externally bonded strain gauges due to the shear effect in composite laminates of an FRP-strengthened concrete beam (Figure 5). The embedded FBG sensor can provide strain more sensitive to debonding at the interface between the composite and concrete surface. Strain variation due to the formation of micro-cracks on the concrete surface can also be indicated by the signal measured from the FBG sensor.

![Figure 5. Strain measured of an FRP-strengthened concrete structure by an embedded FBG sensor and an externally bonded strain gauge.](image)
PROBLEMS IN APPLICATIONS

Embedded fibre-optic sensors have been established as intrinsic strain and temperature measuring devices to assess structural conditions. However, the alkaline attack of the fibre core is still a problem for embedded strain sensors, since the coating at the measuring region is generally required to be removed, and this allows direct contact between bare fibre and surrounding materials.

The use of fibre-optic sensors in concrete has been demonstrated using a variety of measurements methodologies. The sensors can be attached on or embedded into existing concrete structures, even after being strengthening by FRP materials, and can evaluate the crack growth rate of damaged concrete structure. However, of more importance is that the measurement philosophy used in the laboratory and real-world applications are significantly different. In the factual environment, damage of the fibre may occur easily from weathering, rough handling by labourers and the concrete pouring process. In addition, the quality assurance of the sensor installation needs to be guaranteed.

Although many research achievements have been reported in recent years, the utilisation of the fibre-optic sensor technology in real-life civil engineering applications still needs more effort in solving several real practical problems.

CONCLUSION

Fibre-optic sensors exhibit considerable potential for real-life applications. Due to the physical size of the optical fibre sensors being relatively small compared with infrastructure elements, embedding fibre-optic sensors does not degrade the mechanical and geometrical properties of the structure. Smart composites have been adopted in some high-tech engineering applications such as in the aerospace industry. The results from most research have shown that smart composites could be used as primary structural members as well as sensors to monitor strain or temperature of structures. However, this innovative concept has not been popularly adopted in most infrastructure applications.

In the future, the development of smart materials and structures will pay a major role in all engineering disciplines. Fibre-optic sensors will be one of the structural health monitoring devices for achieving this goal. The use of a smart composite integrated into an externally-bonded strengthening scheme or internally embedded reinforcement as well as real-time structural health monitoring device can greatly improve durability and substantially improve safety of the structure.

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