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Strain monitoring of RC members strengthened with smart NSM FRP bars

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ABSTRACT

Fiber-reinforced polymer (FRP) bars can be used as internal reinforcement for new reinforced concrete (RC) structures and as near-surface mounted (NSM) reinforcement for the strengthening of RC structures. The NSM method is an emerging strengthening technique for RC structures, where FRP bars are embedded into grooves cut in the cover of RC members. In both cases, strain monitoring of the FRP bars is desirable either for the investigation of the structural behavior or for the long-term health monitoring of the structure. This paper presents a study in which fiber-optic sensors were embedded into glass FRP (GFRP) bars to produce smart GFRP bars for NSM applications. The manufacturing process of the smart FRP bars is illustrated and their performance in tensile, bond and beam flexural tests is examined to assess the effectiveness of these smart FRP bars for achieving the dual purpose of structural strengthening and strain monitoring. On the basis of the test results, the advantages and limitations of fiber-optic sensors compared to electrical strain gages in the strain monitoring of NSM FRP bars are discussed. The bond and beam test results also confirm the effectiveness of the NSM method for the strengthening of RC structures.

1. Introduction

A significant recent development in structural engineering is the increasingly wide use of fiber-reinforced polymer (FRP) composites in the civil infrastructure, as a result of their high strength-to-weight ratio and excellent corrosion resistance. In particular, strengthening of reinforced concrete (RC) structures using externally bonded FRP systems has become very popular over the past decade [29]. Over the last few years, a new strengthening technique for RC structures based on FRP composites has emerged as a valid alternative to externally bonded FRP laminates. In this new technique, FRP bars or strips are embedded using a suitable binding agent (epoxy paste or cement grout) in grooves cut in the cover of a concrete member, as near-surfaced mounted (NSM) reinforcement for flexural or shear strengthening purposes. NSM FRP reinforcement has a number of advantages over externally bonded FRP reinforcement, including reduced risks of debonding and damage due to accidental impact and vandalism, and, in certain cases, can be more convenient to install than externally bonded FRP laminates [9]. A detailed review of the available research on the NSM method can be found in De Lorenzis and Teng [11].

Another recent development in structural engineering has been the use of the fiber-optic sensing technique for strain measurement in both destructive tests in the laboratory and long-term structural health monitoring in the field. Fiber-optic sensors are characterized by small dimensions, good resolution and accuracy, excellent durability, a wide range of operating temperature, and good signal transmission over long distances [3,31]. They are immune to electromagnetic fields or radio signals. Since optical fibers are extremely small compared with other strain measuring devices, they can be embedded into structural elements without influencing the mechanical properties and stress conditions of the host material [19].

The use of different types of fiber-optic sensors allows the measurement of localized, long-gauged or distributed strains, providing both local and global information about the structure [13]. These sensors also allow the detection of concrete cracks and the measurement of crack widths at multiple locations along a single optical fiber. This possibility makes them superior to the traditional electrical strain gages, as the latter give a point-based measurement and hence a large number of gages are required if the strain distribution in a structural member is of interest [31].

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Among the different types of fiber-optic sensors, fiber-optic Bragg grating (FBG) sensors have been shown to possess some unequaled characteristics which are important to strain-sensing applications [26]. The FBG sensors are intrinsic to the optical fiber, i.e. they are physically part of the optical fiber itself, and the sensor relies on the spectral content of the optical signal. These features provide high durability, the potential for inexpensive mass production, serial multiplexing of many sensors along a single optical fiber, and enhanced long-term measurement stability. They also allow strain measurements to be made in situations where strain measurements were previously impossible, or at best problematic for conventional strain-sensing techniques [26].

The development of fiber-optic sensors started at the end of the 1970s, prompted by the increased use of advanced composites in the aeronautical industry and by the consequent need for new damage detection techniques. Fiber-optic sensors are able to monitor the integrity of structural components during their service periods [3]. The interest in the application of fiber-optic sensors in concrete structures started in the late 1980s, with several laboratory and field demonstrations of the use of these sensors for strain, vibration and temperature measurements. A detailed state-of-the-art review of work up to 1996 on the applications of fiber-optics sensors to cementitious materials was given by Ansari [3]. Some more recent studies on the strain monitoring of concrete with fiber-optic sensors are briefly listed as follows. Davis et al. [8] described the use of a prototype FBG instrumentation system for monitoring strains at several locations in RC beams and decks tested to failure. Lee et al. [22] illustrated the development of a fiber-optic sensor for embedment in cementitious composites and the measurement of displacements associated with the opening of micro-cracks. Yuan and Ansari [32] used white light interferometric fiber-optic strain sensors to monitor crack-tip opening in concrete beams. Gu et al. [14] developed a distributed fiber-optic sensor system for detecting cracks in structural concrete. Yuan et al. [33] developed a fiber-optic two-dimensional strain-sensing system for the measurement of strains in concrete. Li and Ansari [23] used fiber-optic sensors for the circumferential strain measurement of high strength concrete under triaxial compression. Zhang et al. [35] tested a one-way RC slab to demonstrate strain measurements using fiber-optic sensors under monotonic and fatigue loads. Bonfiglioli and Pascale [6] used Fabry–Pérot sensors for measurement of internal strains in concrete cylinders. Casas and Cruz [7] provided an overview of the physical fundamentals of intensity modulated and spectrometric fiber-optic sensors, and of a broad range of their possible applications for assessment of existing and new bridges. Li et al. [24] presented a theoretical model for calibration of embedded fiber-optic sensors used for strain measurements of concrete under biaxial compression. Li et al. [25] proposed a practical method for the measurement of the crack-tip opening displacement of a semi-elliptical surface crack in concrete by means of an embedded fiber-optic sensor. Yuan et al. [34] developed a fiber-optic ultrasonic sensor with a long gage length and demonstrated its use for crack monitoring of large-scale concrete structures. Zhang and Ansari [36,37] developed a fiber-optic laser speckle-intensity sensor and demonstrated its use as embedded sensors in concrete for the detection and measurement of crack-opening displacements.

In parallel with the growing worldwide interest in the use of FRP composites for reinforcing and strengthening concrete structures, an increasing number of studies have recently focused on the application of fiber-optic sensors for the strain monitoring of structures either with FRP bars as internal reinforcement, or with externally bonded FRP laminates as external strengthening systems. Maaskant et al. [26] reported on the installation of an FBG sensor array on the Beddington Trail Bridge in Calgary (Canada), for strain monitoring of steel and FRP prestressing tendons. Benmokrane et al. [5] described the use of integrated fiber-optic sensors in FRP bars used as reinforcement in the decks of the Joffre Bridge in Canada. Belarbi et al. [4] embedded fiber-optic sensors in a pultruded carbon fiber core. A layer of carbon fibers was then filament-wound around the core to form a shell to produce pseudo-ductile and smart hybrid FRP rods. Tests of FRP rebars and of FRP-reinforced concrete beams proved the capability of fiber-optic sensors to read internal strains. Lau et al. [19,20] conducted a series of tests on concrete cylinders and small-size beams strengthened with externally bonded FRP and equipped with fiber-optic sensors for strain measurements. Zhao and Ansari [38] used interferometric quasi-distributed optical fiber sensors to monitor interfacial strains in FRP-strengthened concrete elements and hence to investigate FRP debonding mechanisms. El-Salakawy et al. [12] reported the use of Fabry–Pérot sensors for short- and long-term measurements of strains and temperatures in the internal FRP reinforcement of Wotton Bridge, in Canada. Mufti [27] provided a comprehensive overview of recent ISIS Canada projects combining innovative construction technologies, focusing mainly on the use of FRP internal reinforcement for concrete bridges and the long-term health monitoring with fiber-optic sensors. Kalamkarov et al. [15–18] developed a modified pultrusion technique to embed Fabry–Pérot or FBG sensors in glass FRP (GFRP) pultruded bars to be used as reinforcement in concrete structures. Strain monitoring of the stand-alone bars was demonstrated under the thermal stresses induced by manufacturing, as well as under monotonic, cyclic, short-term creep and environmental loading. Kalamkarov et al. [18] used the GFRP pultruded bars with embedded sensors as internal reinforcement in two concrete beams subjected to static and repeated loading to failure.

All studies mentioned above documented a satisfactory performance of fiber-optic sensors. In particular, it was shown that these sensors can be embedded in an FRP bar giving long-term access to previously un-measurable internal strains. As embedded devices, they are not susceptible to debonding from the host material and are physically protected, which facilitates the long-term monitoring of structures. Fiber-optic sensors have the capability to measure not only strain variations but also absolute strains, thereby removing the need for continuous data acquisition. Their small-size does not significantly alter the behavior of an FRP bar. Furthermore, they are resistant to the high temperatures experienced during the manufacturing of an FRP bar.

2. Objectives

In the field of strengthening concrete structures with FRP composites, fiber-optic sensors have thus far been used for the measurement of strains in externally bonded FRP laminates and their interfaces with the concrete[19,20,38]. One of the practical advantages of fiber-optic sensors for this application is that they can be located at the laminate-concrete interface, unlike strain gages which are too large to be located at the interface without affecting interfacial properties and can thus only be attached to the external surface of the laminate.

Due to the novelty of the NSM method, no study appears to have yet been conducted on the strain monitoring of NSM FRP reinforcement with fiber-optic sensors. In the NSM method, the use of fiber-optic sensors is even more convenient and attractive than in the externally bonded FRP method. In laboratory research, the bond behavior of NSM reinforcement is a major focus, and studies on this topic rely heavily on the measurement of strains at a large number of locations along an NSM bar embedded in a concrete member. A number of problems exist if these strains are measured with electrical strain gages [10]. If the NSM reinforcement consists of round bars (typically with a 6–12 mm diameter), the strain gages must