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Integration and assessment of fibre Bragg grating sensors in an all-fibre reinforced polymer composite road bridge

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Abstract

This paper reports on the integration and assessment of 40 ruggedly protected fibre Bragg grating sensors (FBGs) in an all-glass fibre reinforced polymer composite road bridge. This bridge is reported to be Europe's first all-fibre reinforced composite bridge. A unique feature of this bridge was that it was constructed from pultruded glass fibre composite sections, which were bonded on site. The FBGs were integrated at specified sections during the assembly and bonding phase of the bridge. The primary functions of the fibre optic sensors were to provide: (i) real-time and in situ strain and temperature data from the bridge and (ii) strain data to enable the validation of design codes for the all-composite bridge. Results from laboratory tests and field trials during the proof testing of the bridge are presented. The latter included loading the bridge with a 30 tonne lorry.

Keywords: Bragg grating; Sensor multiplexing; Composite structure; Structural integrity

1. Introduction

As an enabling technology, fibre optic sensing schemes offer a number of advantages with regards to real-time structural health monitoring of engineering materials and smart structures [1–6]. For example, a large number of sensors can be multiplexed along a single length of optical fibre enabling single or multi-parameter measurements to be made. The measurands of general interest for civil structures include strain, temperature, vibration, corrosion and acoustic emission. The data are generally used to validate engineering designs, optimise manufacturing processes and/or to facilitate structural health monitoring. Optical fibres are intrinsically safe and hence they can be used in extremely harsh environments and also where conventional electrical-based sensor systems cannot be used. Significant advances have been made over recent years on the design and deployment of optical fibre-based sensor technologies which demonstrate fibre optic sensing as an ideal candidate for remote and online structural health monitoring of engineering structures. In particular fibre Bragg grating technology [7,8] has enabled the implementation of relatively simple and compact sensing approaches for strain or temperature metrology in which the FBG sensor elements have been integrated into existing structures [9] or embedded into new ones, as demonstrated in this work. Owing to their small size (250 μm) and the circular cross-section, these devices have been integrated and deployed extensively in concrete, carbon or glass fibre reinforced composite structures [10–22] with minimum intrusion

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and thus without degrading the mechanical performance of the structure. However, there is comparatively little information on the integration and use of optical fibre sensors in 'real world' civil structures during their construction and commissioning phases. In the context of the current study, which involved instrumentation of a new glass fibre reinforced composite (GFRP) bridge during its construction stage, the design of the bridge was unique and warrants further elaboration.

The West Mill Bridge (Oxfordshire, UK) uses GFRP profiles spanning transversely as the decking system supported on advanced composite – hybrid of glass and carbon fibre (GFRP/CFRP) longitudinal beams. These beams were comprised of four GFRP composite box sections bonded together with uni-directional (UD) CFRP composite on top and bottom flanges providing the majority of the required longitudinal stiffness. The UD-CFRP composite flanges were manufactured directly onto the bonded GFRP composite box beams using the resin infusion technique. The concrete edge parapet beams on the bridge deck used standard GFRP composite angle sections as permanent shuttering and provide a robust structural base for the parapet posts and crash barrier. A more detailed description of the design process is given in Canning et al. [23].

From an end-user perspective, the availability of an online and remote structural health monitoring capability for civil structures such as this bridge will accrue significant economic and safety benefits in which informed decisions can be made on maintenance and inspection. A resident sensing system integrated into the structure enables continuous monitoring of strain, temperature, deflection, degradation and damage of the structure throughout its service life. This information is invaluable in structural integrity monitoring procedures and in the maintenance scheduling of existing structures and in comparing actual loading to design limits. Furthermore, the information can be a useful input into future design specifications and developing appropriate maintenance guidelines.

2. Fibre Bragg gratings

The fibre Bragg grating sensing element is fabricated by inscribing a periodic perturbation of the refractive index of the core of the optical fibre, usually in a single mode fibre, with a UV light interference pattern [24]. The refractive index modulation over a few millimetres of the fibre makes the Bragg grating essentially a wavelength selective mirror, such that the grating reflects a narrow band of the incoming broadband radiation characterised by the Bragg equation, $\lambda_B = 2ne\Lambda$, where λ_B is the centre wavelength of the reflected spectrum, ne the effective core refractive index and Λ the pitch length. The sensor response arises from changes in both the grating pitch length and the perturbation of the effective core refractive index, which then translates into a wavelength shift. Such changes can be induced due to variations in strain, temperature, pressure etc. Strain and temperature measurements are of particular interest in Bragg grating sensor applications for long-term structural integrity and condition monitoring of civil or industrial structures. The combined strain and temperature sensor response (given by a single combined Bragg wavelength shift, $\Delta\lambda_B$) can be represented by the linear relationship:

$$\Delta\lambda_B = [\kappa_T \Delta T + \kappa_\varepsilon \Delta\varepsilon]\lambda_B \quad (1)$$

where $\Delta\varepsilon$ is the change in strain, ΔT the change in temperature, κ_T the combined effect of the thermal linear expansion and the thermo optic coefficient of the fibre and κ_ε its strain-optic coefficient. Once these coefficients are known for a specific type of fibre on which the FBG sensor is written, the changes of strain and temperature can be determined in the sensing method that is self-calibrating and it allows drift free long-term measurements. This arises due to the spectral nature of the signal from the Bragg grating sensor allowing absolute wavelength shift measurements, without the need for optical phase measurements. Furthermore, since these gratings can be written at different wavelengths, many individual sensors can be interrogated using the time domain multiplexing (TDM) or wavelength-division multiplexing (WDM) and integrated onto a single fibre optic strand [25–30].

In this work, the FBG sensor elements were written on intrinsically photosensitive single mode fibre, obtained from Fibercore around the familiar communications C-band range. Laboratory experiments conducted showed that this particular fibre responds to strain such that a 1.24 pm wavelength shift is equivalent to an applied strain of 1 $\mu\varepsilon$ and a 1 °C change translates to a 10 pm spectral shift.

The current work reports on the advances in implementing this technology for structural integrity monitoring applications and on the results obtained from the initial design verification tests of the newly constructed composite West Mill Bridge.

In addition to utilising established FBG sensing technology for this application, the major additional challenges of this particular programme include: (i) the design of the instrumentation system and the specific software requirements, (ii) sensor attachment and protection in a composite structure application and (iii) on-site sensor system installation and cabling.

3. Fibre Bragg grating sensing system

The authors have developed, tested and assembled a high-performance strain monitoring system based on the wavelength division multiplexing technique of interrogating fibre Bragg grating sensors, which meets the desired performance specifications. The system uses a tuneable Fabry-Perot filter, which scans across the 35 nm spectral width of a broadband Superluminescent diode source developed for and used in this application. The considerable spectral width of this source allows demultiplexing an array of eight Bragg grating sensors per each of the eight parallel channels and it is ide-