Health monitoring of steel and concrete structures using fibre Bragg grating sensors


A fibre Bragg grating (FBG) sensor was developed and investigated for health monitoring of civil structures. Strain produced through applying tensile load has been measured using indigenously developed FBG sensors bonded to mild steel and concrete cylinder specimen. A temperature compensation scheme was introduced and tested. The article describes experimental details of grating fabrication and their implementation as sensing element for structures.

Civil structures such as buildings, bridges, dams, tunnels, ports, etc. are the most expensive assets of modern society that need to be functional for a very long time under complex conditions, thus their constant monitoring is pivotal to preventing catastrophe and ensuring safety. Health monitoring of civil structures used to involve strict periodic maintenance procedures, regular visual inspections and use of conventional sensors, i.e. electric strain gauge (ESG). Maintenance is expensive (especially when not required) while visual inspections mostly miss critical problems. As far as ESGs are concerned, they have a number of limitations: (i) they are prone to get detached from the surface, (ii) they have difficulties with embedding into composites and metallic materials, (iii) there are many input and output wires required for quasi-distributed sensing which may compromise the strength of the structure, (iv) are susceptible to electromagnetic interference (EMI) and corrosion, (v) are not suitable for multiplexing and long distance applications and (vi) they have limited life span. Development of fibre optics has revolutionized the field of sensors as they offer various advantages. Their small size, light weight, immunity to EMI, ability to work in harsh environments, suitability for embedding, multiplexing and remote sensing make them perfect alternatives for ESGs. If protected from breakage, they can operate without degradation for decades. The technology, though comparatively new, constitutes 75% of the fibre optical sensors used in structural health monitoring1-3. They offer all the advantages of optical fibres with some added advantages as well, such as, they offer self-referencing as the information is wavelength encoded, ease of multiplexing facilitating distributed sensing and they can be produced in cost-effective way. As the information is wavelength encoded, there is ease of multiplexing facilitating distributed sensing. Multiple FBGs can be surface mounted and/or embedded in structures to measure strain, temperature4, cracks and vibrations. Other parameters can also be measured by designing appropriate coatings or transducers. This technique can specify when and what corrective action is needed to repair the structure and thus large expenditure on unnecessary repair is saved and timely warning can prevent damage. Use of FBG sensors for real time health monitoring of various civil structures is well established in western world since the last decade5-8, whereas in the Indian context this technology is still in a nascent stage. Practical implementation of these sensors requires their indigenous development, as importing the FBGs from foreign manufacturers is an expensive and time consuming process. In this investigation, the FBGs have been developed indigenously and tested successfully in prototype of real structures.

FBGs are intrinsic fibre elements in photosensitive fibres where index of refraction in the fibre core is periodically modulated by illuminating with UV light. When a light wave enters a medium with varying refractive indices, it undergoes reflections from every interface. If all the individual reflections are in phase, they add constructively and the medium will strongly reflect the incident wave. Since the phase difference between adjacent reflections is dependent on the wavelength, this implies that the overall reflection from such a medium would be strongly wavelength dependent, given by Bragg condition:

\[ \lambda_b = 2n_{eff}\Lambda, \]

where \( \Lambda \) is the pitch of the grating, \( n_{eff} \) is the effective refractive index of the core and \( \lambda_b \) is the Bragg wavelength. When light from a broadband source is launched in an FBG, the Bragg wavelength defined by the above equation is missing from the transmitted spectrum. As evident from eq. (1), \( \lambda_b \) is shifted if \( n_{eff} \) or \( \Lambda \) or both are changed due to some perturbation9,10, in fact both these parameters are directly influenced by strain and ambient temperature with the associated wavelength shift is given as:

\[ \Delta\lambda_b = 2\left[ \lambda \frac{\partial n}{\partial l} + n\frac{\partial \lambda}{\partial l} \right] \Delta l \\
+ 2\left[ \lambda \frac{\partial n}{\partial T} + n\frac{\partial \lambda}{\partial T} \right] \Delta T. \]

Strain measurement alone can detect various parameters of structural health monitoring such as crack, damage, fatigue and vibrations. FBGs make high quality reliable strain sensor with major limitation of temperature cross-sensitivity. In this investigation, this problem has been addressed by using dual FBGs, one bonded to the structure for strain measurement and the other was kept free for temperature sensing without strain effect11.

Figure 1. FBG and LPG writing system.
FBGs were produced by exposing core of a photosensitive fibre (Stoecker-Yale Inc.) to intense UV light from a KrF excimer laser at 248 nm. The primary acrylate coating is first removed from the fibre section that is to be exposed to UV light, using a thermomechanical stripper to avoid mechanical degradation. This uncoated fibre is further loaded onto the fibre mounting stage and an appropriate tension is applied to keep it straight, using load cell. After that the fibre is first made to approach close proximity of the phase mask within 0.5 mm and vertical and horizontal alignments of 5 mm are performed with the visual techniques. Subsequently, light from the KrF laser is made incident on the fibre through a phase mask of period 1060 nm and scanned on the required length of the fibre to get the FBG inscription of the designed parameters, e.g. 1550 nm peak wavelength. To achieve FBG with more than 90% reflectivity 7–8 scans were applied. To monitor FBG parameter within the appropriate design, optical spectrum analyser with broadband ASE source is used. Figure 1 shows the experimental set-up for grating fabrication. To protect the FBG from external environment and to provide strength, the stripped fibre section was re-coated with acrylate. Finally, for stabilization of FBGs over long periods of time, thermal annealing at high temperature (~150°C) was carried out.

The surfaces of the two specimens – mild steel (length: 300 mm, neck width: 25 mm) and concrete cylinder (length: 300 mm and diameter 150 mm) – were first cleaned and prepared for bonding of the FBG sensor. The FBG sensor was surface mounted/bonded on these prototype specimens along with an ESG to compare the performance in each case. The Bragg wavelengths were measured using commercially available interrogator (Micron Optics). The specimens with bonded FBG sensors were mounted one after another on the Universal Testing Machine (UTM) and initial readings were recorded. The experimental data were recorded for different tensile load of the mild steel specimen and compressive load of concrete specimen.

First of all to validate the sensing properties of the indigenously fabricated FBGs, their strain response was compared with that of a commercially available FBG from Micron Optics, USA. For that a single FBG of 15 mm length at wavelength of 1545.618 nm with Δλ = 0.122 nm was surface mounted on the 1st mild steel specimen along with the commercial FBG (spot welded) on the other side of the specimen for measuring tensile strain and comparing their performance vis-a-vis ESG.

Two FBG sensors having 3 cm grating length each, Bragg wavelengths of 1550.343 and 1550.455 nm with Δλ = 0.100 and 0.102 nm were surface mounted on the mild steel specimen along with the ESGs as indicated in Figure 2a. On the lateral (longitudinal) surface of the concrete cylinder specimen, three points were located at an angle 120° each for bonding FBGs and strain gauges. Three FBGs each having length of 30 mm, wavelengths of 1545.49, 1550.410 and 1555.348 nm and Δλ of 0.083, 0.088 and 0.085 nm respectively were bonded on the indicated points. A cyanocrylate (CN) adhesive is used for bonding and the specimen was left for 24 h to gain full strength. The set-up along with schematic is shown in Figure 2b.

To perform the strain-temperature discrimination, a dual FBG sensor each with
Figure 3. Performance comparison between CS10 FBG and micron optics FBG with ESG for the tensile loading (MS specimen).

Figure 4. Performance comparison for the tensile strain between two FBGs and ESG.

Figure 5. Performance comparison among three FBG sensors with strain gauge sensor at three different locations in a concrete cylinder.

grating length of 15 mm at wavelengths 1551.495 and 1556.454 nm with $\Delta \lambda = 0.150$ and 0.153 nm were surface mounted on mild steel specimen along with the electrical temperature gauge. First FBG with central wavelength of 1551.495 nm was surface mounted on the specimen to measure the thermal strain whereas the second FBG with central wavelength of 1556.454 nm was kept free ended to measure the temperature in strain-insensitive mode. Specimens were placed inside the oven and temperature initialization was carried out at 26.4°C. Temperature was increased up to 65°C at 5°C interval. Wavelength shifts in both FBG sensors were recorded for thermal strain and temperature. Data was also recorded from the electrical temperature sensor for measuring actual temperature at the specimen. The Bragg wavelength shifts in both the FBGs are the same due to temperature, while additional effect of strain results in larger wavelength shifts for the FBG which is surface mounted. Wavelength shift due to temperature is subtracted from total shift of the first FBG and divided by 1.2 (standard calibration factor for bare silica gratings)\(^{11}\) to get the pure strain, which attributes the temperature compensation nature of the sensor. All the procedures were repeated a number of times in both the specimens to establish the reliability of the measurement.

The performance comparison for tensile strain between commercial as well as indigenous FBG sensors and electrical gauges is shown in Figure 3. The strain values were calculated from the wavelength shift recorded using standard calibration factor of 1.2 pm/µε. The strain sensitivity of commercially available FBG is slightly higher than that of fabricated FBGs as well as of ESG whereas the latter two match perfectly. This mismatch can be attributed to special packaging and spot welding of commercial FBG so that the calibration factor is different from that for bare FBG. This difference in the calibration factor was not taken into account in the calculation since it was not known. Apart from this, the response of fabricated FBG is as good as that of commercial FBG.

Results show that, for the mild steel specimen, strain measurement performed with FBGs and ESG is in a close agreement, as shown in Figure 4, both the gratings as well as ESG giving similar results as expected. In concrete cylinder
specimen, three FBGs exhibit different responses with respect to each other as shown in Figure 5. This deviation could be attributed to the inhomogeneous nature of the concrete material, e.g. imperfect surface finish, local defects/blow holes, varying aggregate size and placement of the sensors at different locations. Also, responses of two of the FBGs are slightly different from that of the ESG. This is because FBG and ESG are not perfectly collocated and as discussed earlier, in case of concrete specimen, the strain response at different locations is different for the same applied load. Figure 6 depicts the result of temperature compensation technique using dual FBG. The temperature values calculated from the wavelength shifts using standard calibration factor 11 pm/°C (ref. 11) are in conformity with the measured data.

In this study, a fibre Bragg grating sensor was developed and investigated for civil structure health monitoring. The article describes all the experimental details of grating fabrication and their implementation as sensing system for condition monitoring of prototype of real structures. Strain produced by tensile load was measured using indigenously developed FBG sensors bonded to mild steel and concrete cylinder specimen and the results obtained were compared with conventional electrical gauges and found to be in good agreement. A temperature compensation scheme was introduced and tested. These gratings give repeatable results and their performance is comparable with commercial FBGs.


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