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Fibre Bragg grating sensors for in-situ measurement of resin pressure in curing composites

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ABSTRACT

A fibre optic sensor was developed for in-situ pressure measurement based on the principle of differential pressure in liquids. This sensor system is very simple and consists of fibre Bragg grating (FBG) done on a fibre with core diameter of 9 μm . A calibration study was carried out with a water column and the pressure sensitivity was found to be $1.636 \times 10^{-2} \text{MPa}^{-1}$. The results show that response of FBG to the rise of water level is linear and agrees well with the theoretical results. The reliability of the sensors is confirmed by repeating the measurements for three times. The sensor is useful in applications that involve in-situ resin pressure measurement in manufacturing of laminated composite materials.

1. INTRODUCTION

The response of optical fibres to the thermal and mechanical fluctuations allows them to use in diverse applications. Electrical, mechanical and chemical durability is the prominent advantage of inert fibre optic sensors. Among them, FBG sensors hold more attention in recent years. FBG sensors are fabricated by grating the fibre core to produce a permanent periodic index modulation [1]. The wavelength of the grating is highly sensitive to the temperature and axial strain fluctuations [2].

FBG sensors are widely used in structural health monitoring of various civil and mechanical structures to monitor static and dynamic strains [3, 4]. Xu et al. [5] proposed a dual purpose FBG sensor to measure hydrodynamic pressure and temperature with a pressure sensitivity of $2.02 \times 10^{-6} \text{MPa}^{-1}$. The sensitivity of a bare FBG under direct pressure load is unremarkable and should be amplified by converting the pressure into axial strain. Sheng et al. [6] proposed a new mechanism of FBG to measure liquid pressure with an improved sensitivity of $2.2 \times 10^{-2} \text{MPa}^{-1}$. In this method, the liquid pressure is transformed into an axial strain in the fibre grating with the help of elastic polymers. The mechanism is such that a lateral pressure applied to the polymer extends the optical fibre encapsulated by it.

Bremer et al. [7] developed an FBG sensor with a fused-silica head to measure the pressure and temperature of geothermal wells. Sengupta et al. [8, 9] designed a hydrostatic pressure sensor with a hollow cylinder partially filled with silicone rubber to measure liquid level in storage tanks. Further, these sensors should be immersed in the tanks to measure the liquid pressure and are affected by dynamics of liquid. Therefore, the polymer encapsulated FBG pressure sensors are not preferred for regions with poor accessibility and dynamic high pressure applications.

In this work, a FBG sensor has been designed and fabricated to measure liquid pressure in such a way that it need not be immersed in the liquid under pressure. These sensors can be used in applications where the sensor head dimensions are of the main concern to the performance of a set up or process.

2. FBG SENSOR DEVELOPEMENT

In a single-mode optical fibre the refractive index of the fibre core is modulated periodically. This periodic modulation is written on the core of a photosensitive fibre using Excimer laser (248 nm). This allows the optical fibre to reflect some of the transmitted optical radiation from the grating region. The remaining radiation transmitted through the fibres without any loss. When light passes through a grating, a particular wavelength of light is reflected back by it. This

wavelength depends on the distance between the consecutive grooves of the grating (grating period) and is called Bragg wavelength (λ_B) which is described as

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

where, n_{eff} is effective refractive index and Λ is the grating period. The Bragg wavelength changes as the distance between two consecutive grooves changes. FBGs are considerably suitable for static and dynamic measurement of quantities such as temperature and axial strain or pressure. The relationship between the axial strain and the shift in Bragg wavelength of an FBG is given by

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon_z \quad (2)$$

where, $p_e = 0.22$ is the photo elastic coefficient of the fibre core [1, 9]. The schematic diagram of the newly proposed sensor is shown in Figure 1.

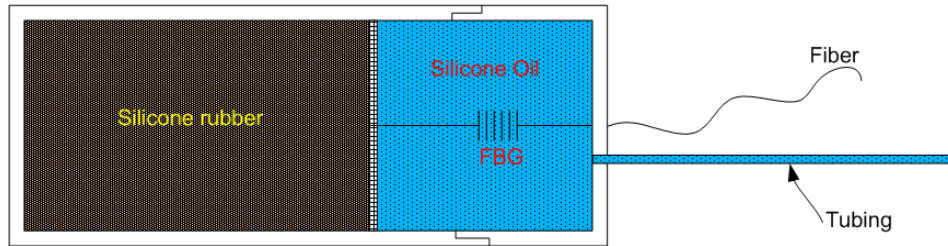


Figure 1. Schematic diagram of FBG pressure sensor

It is a stainless steel hollow cylinder with one end open and a cap to shut this open end. A hole of diameter 1mm was drilled at the centre of the cap to facilitate the FBG fibre along the axis of the cylinder. Another hole of diameter 1.5 mm with an offset of 2.5 mm from the axis centre is drilled to accommodate a needle tube of 1.4 mm diameter. The cylinder is partially filled with a stable and nonreactive silicone rubber (SR). An FBG with a core cross sectional area of ' A_f ' is glued firmly to a round plate, which is further glued to one of the ends of a silicone rubber block. The other end of the FBG is fixed onto a cap with the fibre parallel to the cylinder axis. The empty portion of the cylinder and the needle tubing is filled with inert silicone oil. This avoids the direct contact of the fibre core to the chemically reactive liquids such as an epoxy resin in curing composites. The fabricated sensor is shown in Figure 2.



Figure 2. Fabricated FBG Sensor

When the needle tubing is inserted into the bottom of a liquid column or a tank, the liquid pressurizes the silicone oil and compresses the silicone rubber. Unlike the earlier sensors [8, 9], silicone rubber is axially compressed due to liquid pressure. This creates an axial stain in the FBG which is proportional to the liquid pressure. The strain experienced by the FBG fibre and silicone rubber due to liquid pressure (P_l) is derived as

$$\varepsilon_z = \varepsilon_f = \varepsilon_R = \frac{P_l}{E_f \left(\frac{A_f}{A_R} \right) + E_R \left(\frac{L_f}{L_R} \right)} \quad (3)$$

where, A_R is the cross sectional area of the silicone rubber, E_f is the elastic coefficient of fibre (70 GPa) and E_R is the elastic coefficient of silicone rubber (127.55 MPa). For a water column of height H , the liquid pressure could be defined as

$$P_l = \rho_l g H \quad (4)$$

where, ρ_l is density of liquid and g is the gravity constant. Therefore, equation (3) becomes

$$\frac{\Delta \lambda_B}{\lambda_B} = (1 - p_e) \frac{\rho_l g H}{E_f \left(\frac{A_f}{A_R} \right) + E_R \left(\frac{L_f}{L_R} \right)} \quad (5)$$

3. EXPERIMENTS AND RESULTS

To calculate the sensitivity of fabricated sensor head, an experimental set up was arranged as shown in Figure 3. The needle tube was inserted at the bottom of a water column of height 100 cm. The FBG sensor was connected to an Optical Spectrum Analyser (OSA) through a 1x2 fibre coupler to read Bragg Wavelength λ_B .

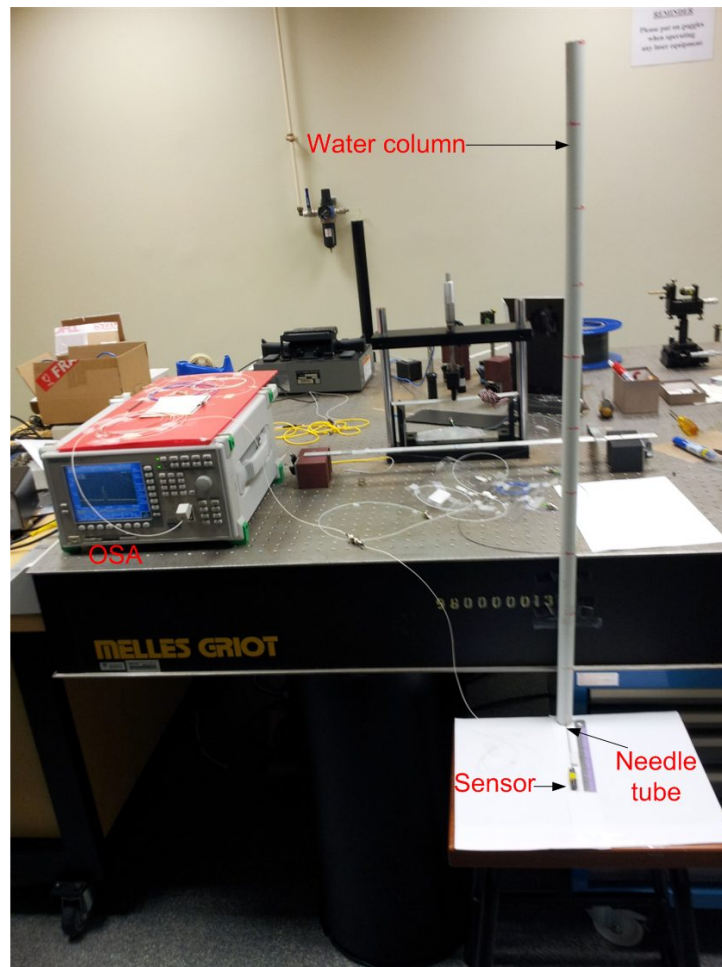


Figure 3. Experimental set up

As the liquid level rises, pressure at the bottom of water column increases. This pushes the silicone oil in the needle tubing due to the differential pressure and compresses the silicone rubber. As a result, the FBG experiences elongation along its axis due to which the Bragg wave length shifts. The liquid level was gradually increased at a step of 10 cm and the shift in wavelength was noted.

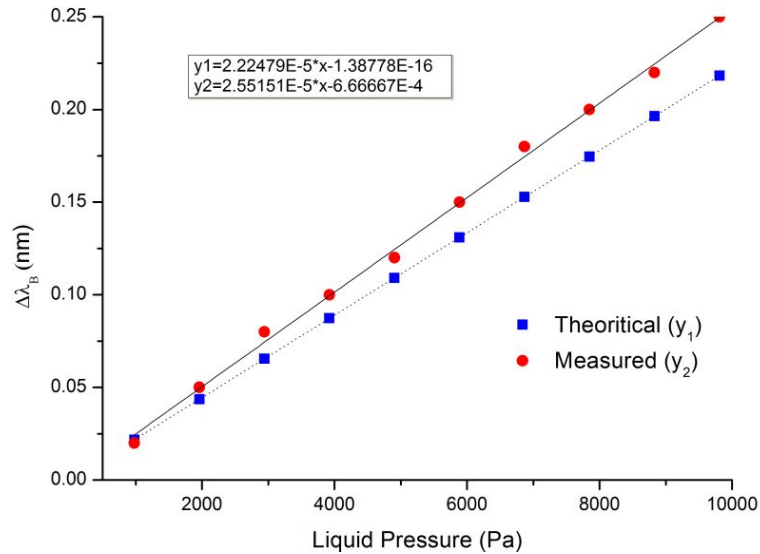


Figure 4. Response of the sensor

The theoretical shift in wave length was calculated by using equation (5). The theoretical and experimental response of FBG as the water level rises is compared in Figure 4. This results shows that the shift in Bragg wave length is linear with the water height with a pressure sensitivity of $1.636 \times 10^{-2} MPa^{-1}$. The theoretical pressure sensitivity was obtained as $1.4266 \times 10^{-2} MPa^{-1}$. The difference in pressure sensitivity of the theoretical and experimental values is $0.2094 \times 10^{-2} MPa^{-1}$. This deviation is due to the error involved in measuring the length ratio of fibre and silicone rubber.

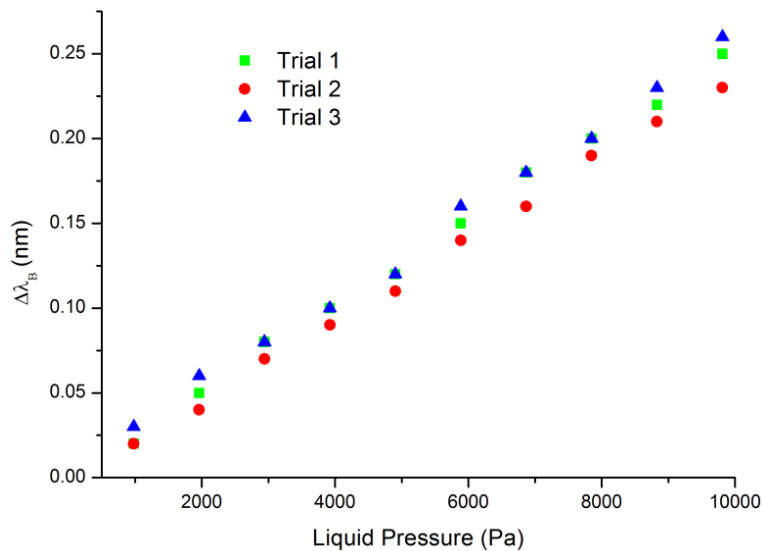


Figure 5. Repeatability of the sensor

The repeatability of the sensor was confirmed by repeating the experiments three times with their results as shown in Figure 5. A small deviation in the shift of wave length was found between each trial. This is due the sluggish movement of the silicone oil once it is disturbed from the rest. Therefore, a settling time for the silicone oil should be allowed before starting each experiment.

4. DISCUSSION

A curing composite behaves similar to a fully saturated porous media until the resin phase attains gelation. Resin movement through porous fibre beds is slow and considered as a laminar flow with low Reynolds number. External compaction pressure applied on such a resin saturated media is shared by both resin and fibres. The behaviour of curing composite before resin gelation could be described with the help of piston-spring analogy adopted in geo-mechanics as shown in Figure 6. Initially, any applied load (P_a) on the piston is completely transferred to the liquid as a hydrostatic pressure (P_r) (Figure 6(a)). Once the liquid is allowed to flow through an opening provided in the piston, spring compress to share the applied load corresponding to the amount of liquid loss (σ) (Figure 6(b)). After a significant loss of liquid, the applied load is entirely carried by the spring with a minimum amount of liquid left over (Figure 6(c)). In one dimensional consolidation of composites with escape of resin through boundaries, compression of resin in the pores and capillary movement are negligible. Thus, stress at any point in the laminate described as [10-13]

$$P_a = P_r + \sigma \quad (7)$$

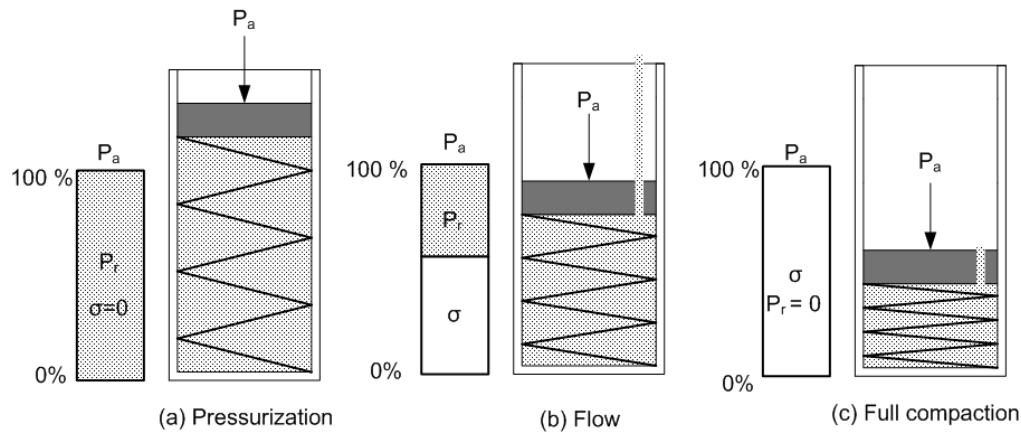


Figure 6. Piston-spring analogy for a resin saturated fibre beds

The sensor developed in the present work will be used to measure the resin hydrostatic pressure. For this purpose the needle tube of the sensor will be inserted in between the prepreg lay ups and cured in a convection oven as shown in Figure 7. As the temperature increases the prepreg resin becomes liquid and shares the applied load as hydrostatic pressure. This pressure will be sensed by the FBG and the corresponding resin volume fraction could be obtained at specific locations of composites. Since the FBG is sensitive to the temperature, it is possible to measure the resin pressure inside the laminate and temperature in the oven simultaneously.

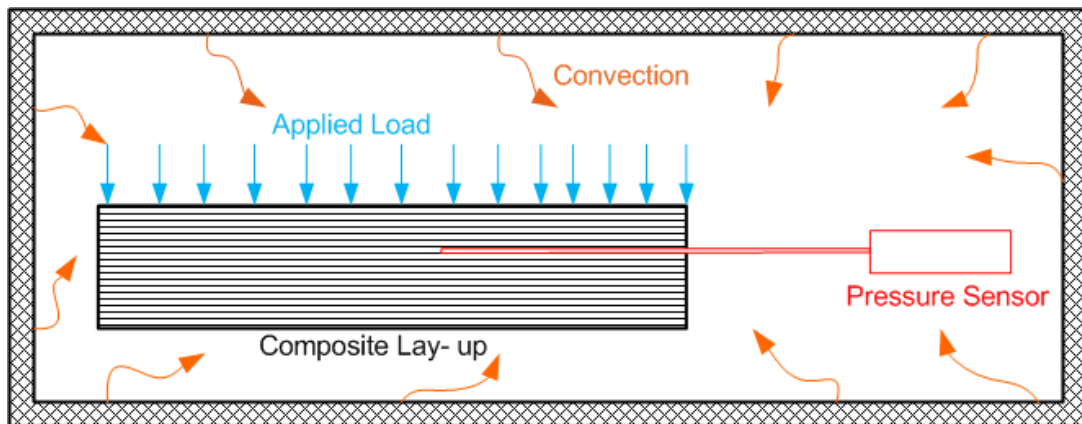


Figure 7. Schematic of in-situ resin pressure measurement

5. CONCLUSIONS

In this work, a low cost, special purpose fibre optic sensor with needle tubing is designed and fabricated to measure positive pressure in liquids. The response of the sensor is calibrated against the theoretical water pressure using a simple water column experiment. The sensitivity of the sensor is found to be $1.636 \times 10^{-2} \text{MPa}^{-1}$ which is higher than the lateral pressure sensors available elsewhere. The materials used and the needle tubing arrangements enables the sensor to be used in special application such as resin flow pressure measurement of composite processing. The reliability of the sensor is confirmed through repeated experiments. For an improved stability of the measured data, a time delay should be allowed before recording an each change in the Bragg wavelength. Finally, a potential application of this sensor is discussed to measure the hydrostatic resin pressure of oven cured composites.

REFERENCES

- [1] Morey W.W., Meltz G., and Glenn W.H., *Fiber optic Bragg grating sensors*, Proc. SPIE, **1169**, Fiber Optic and Laser Sensors VII (1989).
- [2] Udd E., *Review of multi-parameter fiber grating sensors*, Proc. SPIE, **6770**, Fiber Optic Sensors and Applications V (2007).
- [3] Chan T.H.T., Yu L., Tam H.Y., Ni Y.Q., Liu S.Y., Chung W.H., and Cheng L.K., *Fiber Bragg grating sensors for structural health monitoring of Tsing Ma bridge: Background and experimental observation*, **28**(5), Engineering Structures (2006).
- [4] Maheshwari M., Asundi A. K., and Tjin, S. C., *Effect of the location and size of a single crack on first fundamental frequency of a cantilever beam using fiber optic polarimetric sensors and characterisation of FBG sensors*, Proc. SPIE, **8793**, Fourth International Conference on Smart Materials and Nanotechnology (2013).
- [5] Xu M. G., Reekie L., Chow Y. T., and Dakin J. P., *Optical in-fiber grating high pressure sensor*, **29**(4), Electronics letters (1993).
- [6] Sheng H.J., Fu M.Y., Chen T.C., Liu W.F., and Bor S.S., *A Lateral pressure sensor using a fiber Bragg grating*, **16**(4), IEEE Photonics Technology Letters (2004).
- [7] Bremer K., Lewis E., Leen G., Moss B., Lochmann S., Mueller I., Reinsch T., and Schroetter J., *Fibre optic pressure and temperature sensor for geothermal wells*, IEEE Sensors Conference (2010).
- [8] Sengupta D., Sai Shankar M., Saidi Reddy P., Sai Prasad R.L.N., and Srimannarayana K., *An FBG based hydrostatic pressure sensor for liquid level measurements*, Proc. SPIE, **8426**, Microstructured and Speciality Optical Fibres (2012).
- [9] Sengupta D., and Kishore P., *Continuous liquid level monitoring sensor system using fiber Bragg grating*, **53**(1), Optical Engineering (2014).
- [10] Oh J.H., Lee D.G., *Cure cycle for thick Glass/Epoxy composite laminates*, **36**, Journal of Composite Materials (2002).
- [11] Yan X., *Consolidation and cure simulations for laminated composites*, **40**(20), Journal of Composite Materials (2006).
- [12] Young W.B., *Compacting pressure and cure cycle for processing of thick composite laminates*, **54**, Composite Science and Technology (1995).
- [13] Li Y., Li M., Gu Y., and Zhang Z., *Numerical and experimental study of the bleeder flow in autoclave process*, **18**(4), Applied Composite Materials (2010).