

novel technique of embedding fibre optic sensors for curved composites for structural health monitoring

Structural health monitoring (SHM) of Aircraft composites is gaining prominence in the aero industry. Among the available SHM systems for Composites, usage of embedded fibre optic sensors for temperature, strain, pressure, acoustic emission, etc.



contents

1.0	Abstract	03
2.0	Introduction	03
3.0	Literature Review	04-05
4.0	Fabrication of Fibre Bragg Grating (FBG) sensor	05-07
5.0	Layup and Embedding of Optical Fibres for Curved Composites	07-11
6.0	FBG Survival after Specimen Manufacture	11
7.0	Conclusions	12
8.0	Acknowledgements	12
9.0	References	12
10	Appendix –VARTM Manufacturing Process	13
11	Author Profile	14
12	About QuEST Global	14



Abstract

Structural health monitoring (SHM) of Aircraft composites is gaining prominence in the aero industry. Among the available SHM systems for Composites, usage of embedded fibre optic sensors for temperature, strain, pressure, acoustic emission, etc. is increasing due to their smaller size (~125 microns). This requires an understanding on the complex sensor architecture, type of sensing required, location of the sensor and

ingress & egress of the optical fibre. In comparison with the flat panel, embedding and obtaining an egress of the optical fibre is a challenge for curved composites. The current paper describes a validated technique of optical fibre egress along with associated challenges for VARTM composite manufacturing technique. This technique could as well be applied for RTM and Prepreg manufacturing methodologies.

Introduction

The primary aim of SHM systems is to register the parameters required for proper functioning of structure and in-situ condition. The primary application of optical-fibre sensors (OFS) has been for data transmission in the telecommunications industry. Optical fibres can transmit light over a long distance with minimal loss and the properties of light inside the fibre are not affected by physical parameters outside the fibre. This implies that the fibre can be used as both the sensing element and the communication path for the signal between the sensor and the optical interrogator. These sensors are lightweight and deliver superior speed, sensitivity and bandwidth. The key attributes of OFS [Lee and Jeong, 2002] are: immunity to electro-magnetic interference (EMI), intrinsic or extrinsic placement, water and corrosion resistance, low maintenance, ruggedness, smaller size, low cost and they can be multiplexed in parallel or in series. Modern OFS are suitable for the measurement of temperature, pressure, strain, angular rotation speed, acceleration, curvature, flow, refractive index, and many other parameters [Staszweski et al., 2004]. The combination of high precision, high measurement speed and a broad wavelength measurement range is still quite expensive; however, in large measuring systems with many sensors per interrogator, the cost per channel can drop to a low level. Optical fibres are steadily becoming more cost effective due to recent advances in telecommunications, optoelectronic, and micro and nano industries.

Optical-fibre sensors (OFS) offer new capabilities, provide an alternative to electronic sensors and have a good record in terms of performance, reliability and cost. Development of OFS focuses on niche areas; the sensors are made to match the performance of electronic sensors while retaining their inherent advantages. With a variety of multiplexing schemes available, the number of sensors per optical fibre can be multiplied to reduce the cost per sensor. Some drawbacks also need to be addressed such as optical fibres (glass) have very poor elastic properties. They are very brittle and can easily break. Risk mitigation procedures are required during sensor fabrication, measurement and installation to avoid sensor failure. Also, In-situ measurement is cumbersome and time consuming since measurement setup of optical-fibre sensor systems involves several different modules, including the light source, coupler and receiver. In contrast, the well-established electronic sensor has all its system components on a single board, which is very convenient for on-site measurement. However, due to their low weight and compatibility with glass fibres, SHM with embedded optical fibre sensors is gaining prominence.

For effective embedding of optical fibre sensors, practical systems will require robust methods for sensor connection to instrumentation, both in production and service. The embedded sensors should have a minimal impact on the overall mechanical performance of a part [Green et al. 2000].

Literature Review

Basic Principle of Optical fibre sensors

Optical fibres consist of a high refractive index core, where broadband light travels. A low refractive index cladding surrounds the core (mostly glass) to reflect light back into the core, as shown in Figure 1. The total internal reflection guides the light is guided inside the

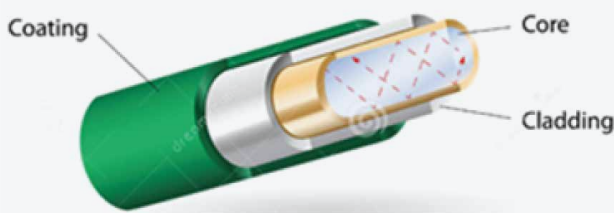


Figure 1: Schematic of the basic structure of an optical fibre [Schwartz, 2009]

Polymer optical fibre (POF) is gaining importance due to its increased strain limit of 10% (the strain limit of glass fibre is 1%, which makes it very brittle). The application of POF to advanced composite structures is limited, as the minimum diameter of POF is 1 mm, which is too thick for composites and may cause stress concentrations. Fundamental optical-fibre sensors used with composite structures are fibre Bragg gratings (FBG), intensity-based optical fibres, polarimetric sensors and a range of optical fibre interferometric sensors based on the Fabry-Perot, Mach-Zehnder and Michelson configurations [Kuang and Cantwell, 2003].

core. A coating (typically acrylate or polyimide) is applied to fibres to protect against environmental damage. Single-mode fibre (for distances >550 m) has a small core of 9 μm and can transmit broadband light from 1300–1550 nm. Multimode fibres (for shorter distances) have larger cores of 62.5 μm , capable of transmitting broadband light from 850–1300 nm.

Sensor Parameter	Single mode fibre (μm)	Multimode fibre (μm)	Material
Core	2-10	50-150	Silica-based
Cladding	80-120	100-250	Doped Silica
Coating	250	250	Polymer
Buffer	900	900	Plastic

Fibre Bragg Grating (FBG) sensors in optical fibres

Among the various types of sensors, FBG sensors are widely used in the strain monitoring of advanced composites. The basic principle of FBG technique is shown in Figure 2. A periodic variation etched directly into the core of an optical fibre creates a partially reflective mirror that returns selective wavelengths in the form of a narrow spectral peak determined by the grating's period. The gratings may be written using the following techniques: Split-beam interferometer, Diffractive optical element phase mask technique and Point-by-point method.

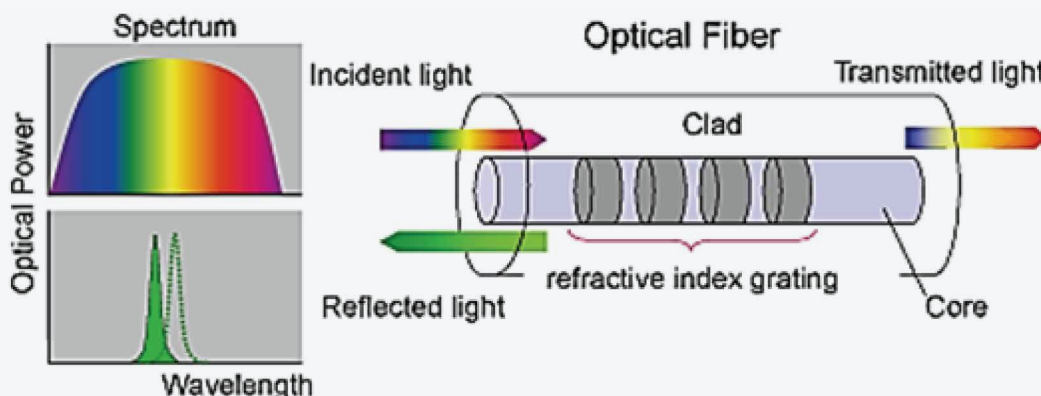


Figure 2: Schematic diagram of a FBG

To achieve a high Bragg reflectivity, the photosensitivity of the pristine fibre is enhanced, either by doping the core with elements such as Ge or Sn, or by hydrogen loading the optical fibre via immersion in high-pressure hydrogen. It was observed [Wei et al., 2002] that FBGs

written in hydrogen loaded fibres have less than 50 per cent of the mechanical strength of FBGs that have not been hydrogen loaded. To achieve high reflectivity, this loading is unavoidable and the strength issue must be addressed.

FBG Interrogation

A typical FBG sensing system, shown in Figure 3, consists of a broadband light source, coupler (to guide the emissive light to the specimen and the reflected light back to the optical spectrum analyser), an array of FBG sensors and an optical spectrum analyser (OSA). The sensor consists of two optical fibers called the measurement fiber and the reference fiber, both

contained in the same protection tube. The measurement fiber is coupled with the host structure and follows the deformations of the structure. In order to measure shortening as well as elongation, the measurement fiber is pre-strained to 0.5%. The reference fiber is loose and therefore independent of the structure's deformations; its purpose is to compensate thermal influences to the sensor.

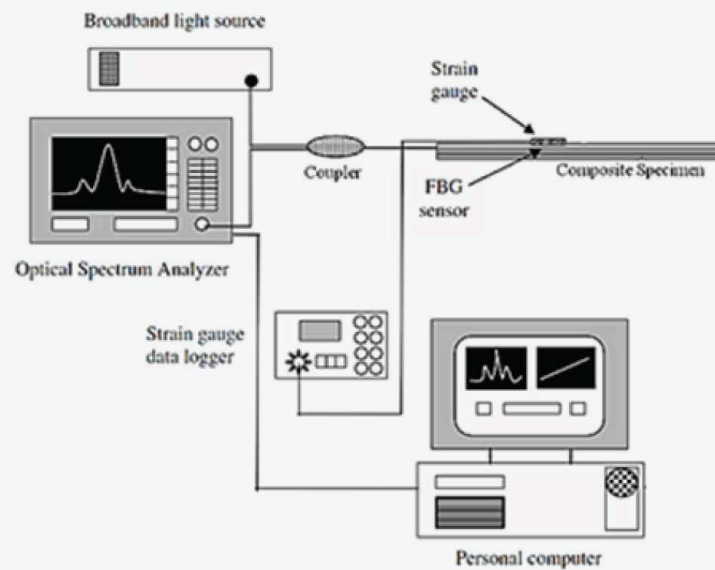


Figure 3: Data acquisition system for FBG interrogation [Ling et al., 2005]

The reflected signals from the specimen (sensor) are then recorded by the OSA, in which the reflection spectrum is observed with a sharp single peak. Both the

grating period and refractive index are dependent on the temperature and mechanical strain that the FBGs experienced [Erdogan, 1997].

Fabrication of Fibre Bragg Grating (FBG) sensor

The grating for the sensor was written using the phase-mask technique writing facilities. As shown in Figure 4a, the writing system consists of three main components: an ion laser, grating fabrication enclosure and control system. The ion laser produces output power at 488 nm, which is then frequency doubled at 244 nm by a beta-barium borate (BBO) crystal. The standard operating power for the laser is between 200 and 300 mW at a tube current of 50 A. UV radiation exposure was minimised even when working with low power levels. The UV beam is aligned from the laser front towards the phase mask through multiple optics components, as

shown in Figure 4a. At the turning mirror, a small portion of the beam (~1 per cent) is passed through to a photodetector to observe beam vibration and provide feedback to the second tip/tilt mirror to compensate for the vibration. The UV beam was highly focused by a cylindrical lens so that the maximum UV power enters the fibre core. When the UV beam incident is on the phase mask, the diffracted plus and minus one orders are maximized (each contains approximately 35 per cent of the total incident power), while the zero order is suppressed. This scenario is shown in Figure 4b.

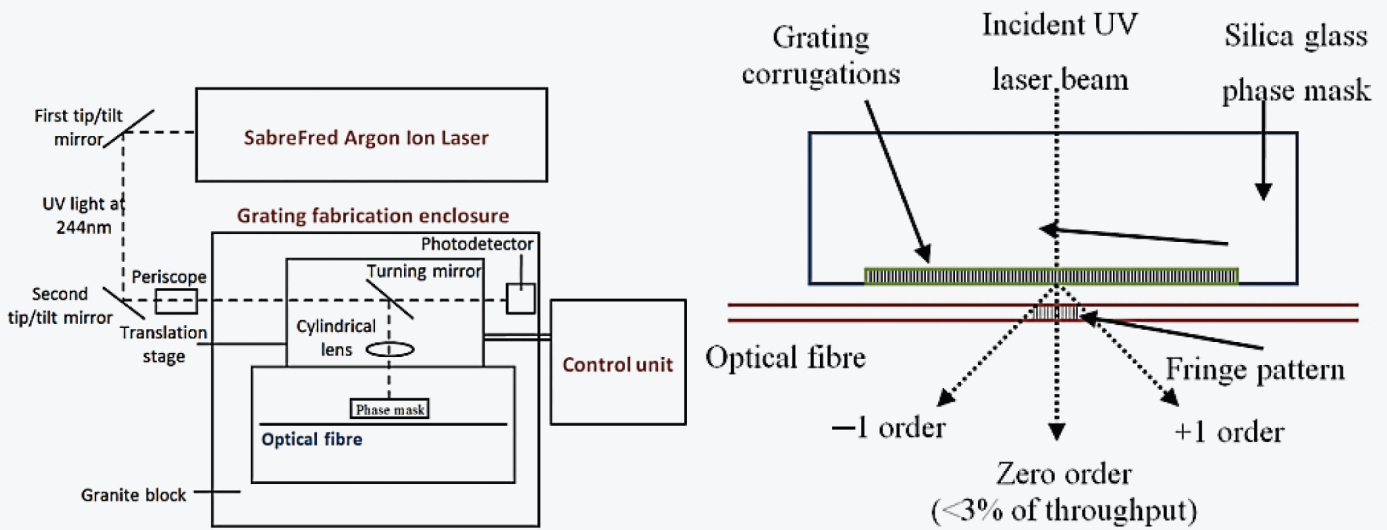


Figure 4: (a) Setup of FBG writing system; (b) Phase-mask technique for writing FBG

For writing a grating, a section of stripped optical fibre is placed close to the phase mask and clamped to secure its position. The UV beam is scanned along the intended FBG length by moving the translation stage at a controlled speed. A near field fringe pattern (grating) is formed on the fibre by the plus and minus first-order diffracted beam. The period of the fringe pattern is half of the phase mask period ($\Lambda B = \Lambda p m / 2$). The strength of the fringe pattern is controlled by the speed of the translation stage and the laser output power. For fabrication, several phase mask periods were used (1056.5, 1064.7, 1076.2 and 1081.9 nm) to obtain Bragg wavelengths of 1529, 1540, 1555 and 1565 nm, respectively. Different Bragg wavelengths were attained by applying different tensions during writing. A tension of approximately 100 g produces about one-nm wavelength spacing. The control unit handles all process of writing, gives

feedback to system and monitors the equipment status.

Once the writing process is completed, the grating position is labelled and annealed at 300°C for five minutes. Annealing is required to age the grating and to stabilise the wavelength and spectral drifts. If the grating needs to exhibit stable long-term behaviour, either a hydrogenated or non-hydrogenated fibre is required. The final process is to bake the entire fibre in oven at 80 °C for twenty-four hours to remove remaining hydrogen from other parts of the fibre. Then the FBG samples are ready for experimental testing. The writing facilities and fabrication procedures yield highly reliable and repeatable processes while producing excellent quality of FBG. Figure 5a shows the in-process FBG manufacturing control unit while Figure 5b shows a close-up view of the FBG writing equipment

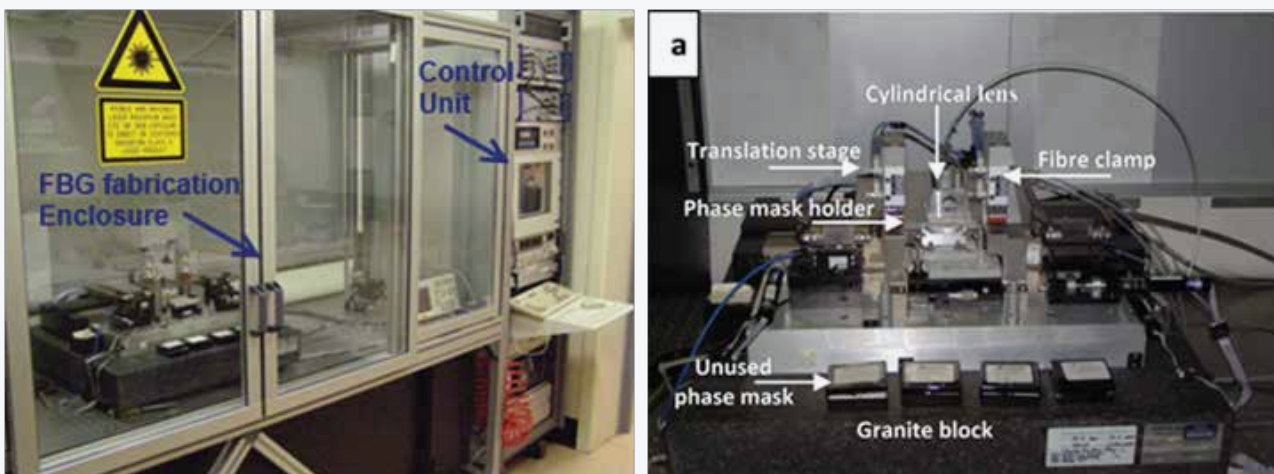


Figure 5(a): The grating fabrication enclosure & control unit; (b) Inside view of the grating writing enclosure

The optical fibre is hydrogen loaded to increase reflectivity of the sensor. As hydrogen loading increases the photosensitivity of the boron and germanium co-doped silica fibre [Lemaire et al., 1993], hydrogen loading into single mode fibre was performed prior to grating writing. This process is a relatively simple, cost effective and highly effective method of achieving high UV photosensitivity. In this process, the required length

of optical fibre was mixed with hydrogen in a hydrogen cell using the standard recipe—a duration of twenty-four hours, pressure of 200 atm and temperature at -100°C . The unused hydrogen loaded fibre is kept in refrigerator at low temperature (-20°C) to slow diffusion of hydrogen from the fibre core. This retains the fibre photosensitivity for up to three days without the need of re-hydrogenation.

Layup and Embedding of Optical Fibres for Curved Composites

The interlaminar stresses (tensile, compressive or shear) are maximum around the mid-thickness of the laminate (depending on the loading mechanism) and have a near zero value at the outer surface during structural loading. Cracks initiate between the plies, where strain anomalies within the thickness of the laminate are much greater than at the surface. Hence, embedding an optical-fibre sensor in the composite laminate is preferable in comparison to surface bonding for capturing strain variations due to interlaminar cracks. The FBG is well protected inside the laminate rather being exposed on the outer surface, and embedding

procedure achieves good bonding between the host material and the sensor. An optical fibre must be properly protected and reinforced since the optical cable at the ingress/egress point is structurally very weak during both curing process and in-service. Each optical fibre consists of one FBG strain sensor. Two optical fibres were embedded at each of the two crown bends, with sensor location as shown in Figure 6a. Figures 6a, 6b and 6c show the location of the FBG sensor at the crown bend of the Top-hat-stiffener curved bends in the laminate for three different layups.

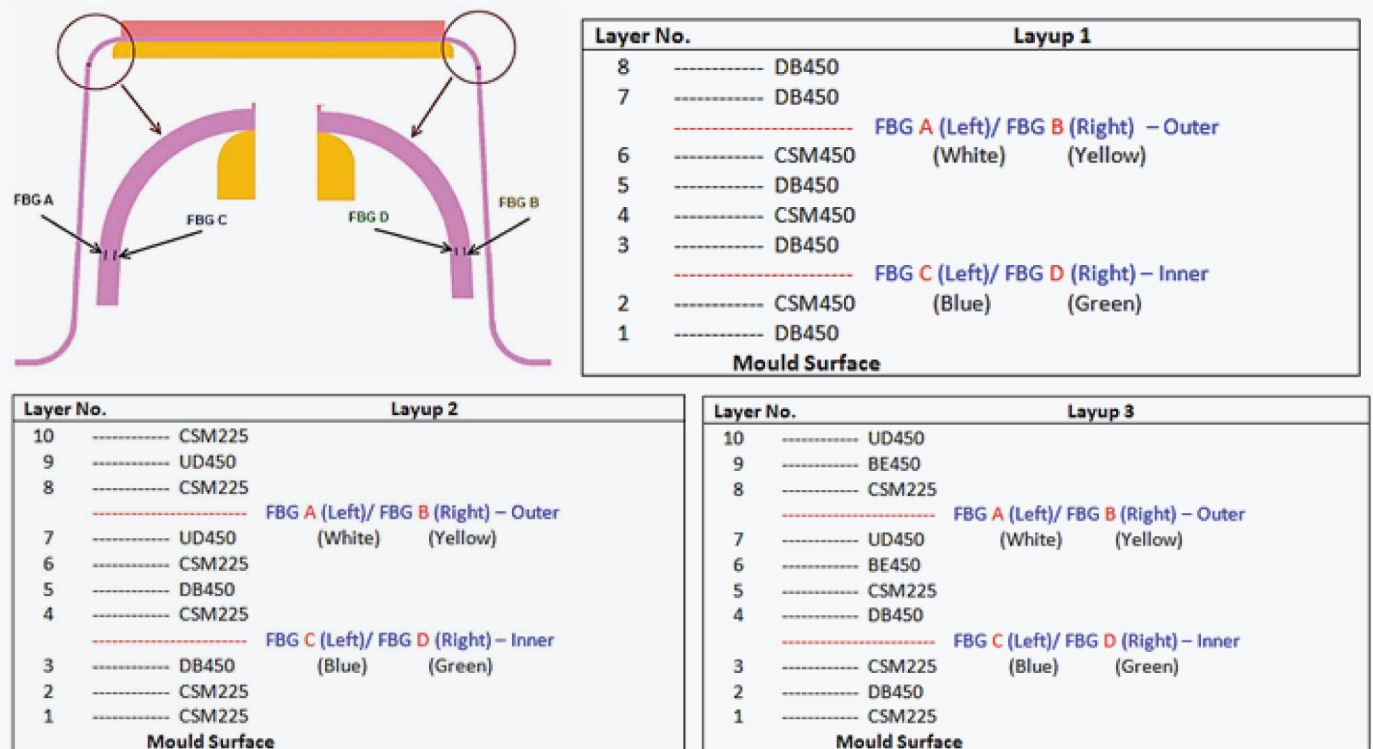


Figure 6: Location of four FBGs on a Top-hat-stiffener specimen; FBG location in Layups 1, 2, 3

The four different wavelengths of FBGs for the four different locations are 1529, 1540, 1555 and 1565 nm. The optical fibres were colour coded, as shown in Figure 7a.

Prior to embedding, all fibres were wiped with acetone to ensure a clean surface, promoting matrix wetting and adhesion. Polyolefin heat-shrink tubes were found to be able to provide sufficient protection and flexibility to optical fibre during VIP. When bent, this tube produces rounded bending rather than V-shape bending, which ensures survival of optical fibre when small radius bending is required. Each wavelength was designated with distinguished tube colours for easy tracking of sensor location. The sensor head was left exposed, as this gives direct strain measurement, while other section was protected by the tube. The diameter of primary tubing used was 3 mm, which further shrunk when blown with industrial heat gun. All tubes were applied to optical

fibres prior to embedding as this saves time compared to its application during embedding process. The applied tubes were colour-coded for easy tracking of the FBGs. A small amount of super glue was then applied at the tube edge to fix the optical fibre position, and also to seal the tube against the entry of resin during vacuum infusion. A secondary coating was applied at the ingress/egress points using heat shrink tubes with 3 mm diameter. This would provide additional protection to optical fibre against sharp resin points during residual removing.

The heat shrink tubes containing the optical fibre were penetrated into the fibre mat (in the web section of the Top-hat-stiffener). An FEA analysis showed no reduction in strength of the structure due to this penetration as the bends fail prior to the web during actual loading. Figure 7b shows the optical fibres on the mould prior to resin infusion.

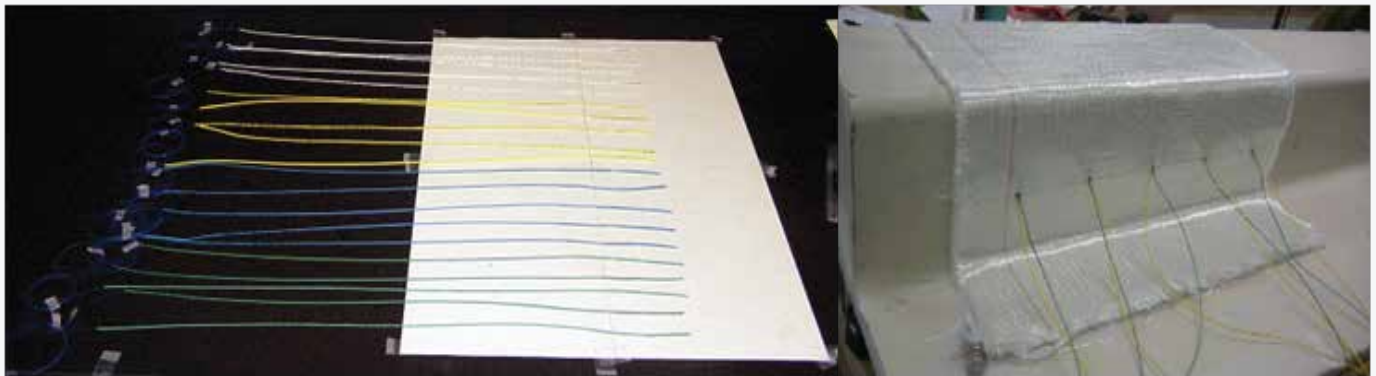


Figure 7: (a) Optical-fibre preparation and (b) Positioning of optical fibres on the THS mould prior to VARTM

All specimens were manufactured at EMP Composites fabrication facilities (EMP Composites, Boat builders, Sydney). Different E-glass reinforcement fabrics were measured to the required size of manufacturing 5 specimens at a time. The first fabric layer was laid onto the mould surface and fixed with a small quantity of 3M spray adhesive. The fabric layer was gently rubbed in from top surface towards bottom flange-web bend to smoothen the fabric layer at the bends. This procedure was applied to ensure that the produced shape and thickness will be uniform. Unused space at all sides of the mould was created to make room for resin infusion

process. Figure 8 (a) shows the process of positioning of FBG sensors on the desired composite layers. The two lines designate horizontal axis for sensors and fibre ingress/egress point. For each side, a common ingress/egress point was used to retrieve inner and outer layer FBGs. Figure 8 (b) shows that sensors with white and blue coatings (FBGs A and C) shared a similar ingress/egress point. Optical fibres were temporarily held up vertically by applying adhesive tape to the fibre. Top and bottom ends of in-positioned FBG sensors were applied with a small amount of super glue to ensure a constant position of FBG sensors during resin infusion.



Figure 8: (a & b) Positioning of bare FBG sensors on the marked area; (c) specimen ready for infusion

The next fabric layer was placed on top of the fabric layer that was attached with the FBG sensors. Initially only the flat top part was fixed with spray adhesive, while the left and right fabrics at flange were folded upward as shown in Figure 8 (b). The fibre ends were stitched through instantly made small holes in the top fabric layer. These holes would have quickly shrunk as the tension of the weave brought the reinforcement fabric threads to its original position. Experiment has shown that the structural strength will be not affected by this penetration, as the web did not fail during the experiment. A small amount of spray adhesive was then applied on other parts of the fabric. As all optical fibres were completely stitched through, the upper fabric layer was then gradually unfolded. At the same time the optical fibres were pulled to straighten the underneath alignment. The FBG sensors located at the crown bend gradually obtained firmer hold from the fabric adhesion. At this time, the 3M adhesive tapes used previously were removed. The alignment of underneath optical fibres was checked to ensure no optical fibres were bent.

The following steps were related to standard VIP. Figure 9 (a) shows the arrangement of the materials used for VIP. Peel ply, perforated film, and flow mesh were aligned and secured around the mould perimeter. Additional polyolefin heat-shrunk tubes (black colour) with 5 mm diameter were inserted for additional protection to the first coating. The cured resin may cause optical fibre to become inflexible and fragile; therefore both ends of the black tube were sealed using industrial wax. The ingress/egress pipes on LHS and RHS of the specimen suggest the resin was infused from left to right, due to superiority of this procedure over top-to-bottom infusion. The specimen was cured under a

vacuum bag for 24 hours at 20°C temperature. Figure 9 (b) shows a fully cured specimen. The process of residual removal which included scissoring, cutting, and tearing, became complicated as the cured resin was very stiff and strongly bonded to the structure. The weakest point of ingress/egress optical fibre was at high risk of being cut by the sharp end of broken resin. At this stage, it was found that stronger material for secondary reinforcement, e.g., Teflon or steel tubes, at the ingress/egress point would be more advantageous in terms of protection. However, the usage of these tubes was not preferred due to their inflexibility that could raise handling intricacy. Precautions to be taken were:

- i) The optical fibre (cable) near the ingress/egress point is structurally so weak that the optical fibre was often broken at this point, hence, this point was reinforced using heat shrink tubes.
- ii) The exposed optical fibre to the outside of a composite laminate must be safely preserved in the curing environment of high temperature and high pressure. This was taken care by enclosing the optical fibre into a closed sealed bag made of VARTM plastic bag.

Coloured, protected optical fibres were again inserted into a 5 mm heat shrink tube and the edges sealed to protect the optical fibre from resin during infusion. After curing, the Top-hat-stiffener was sliced to the required dimensions using a band-saw and the edges were sanded and cleaned with acetone, as shown in Figure 9c.



Figure 9: (a) Preparation for VIP; (b) Infusion process; (c) Specimen with embedded FBGs, bag removal process

During the curing process, the optical-fibre FBG sensor may be subjected to high temperature variations and residual stresses may be induced in the laminate. This can vary the wavelength of the fibre Bragg grating significantly. Some optical fibres may be misaligned or broken during the installation, resin infusion process and specimen trimming process. Post-cure wavelength measurement was taken to examine survival of the embedded FBGs and also to record the final Bragg

wavelength which was required for the actual failure monitoring process. Tables 1 to 3 show the magnitude of the signal before and after embedding. FBGs marked 'w' had a weak signal, which were unable to provide adequate results. Those marked 'X' were either broken or misplaced from the original location, and were not tested during the experimental study. The detailed procedure of Vacuum Assisted Resin Transfer Moulding (VARTM) is discussed in Appendix 1.

		Left Outer		Left Inner		Right Outer		Right Inner
FBG λ Before	A1	1528.8510	C1	1556.6862	B1	1540.5393	D1	1565.1653
FBG λ After		1529.46 (w)		1557.2025		1541.1825		1565.4175 (w)
FBG λ Before	A2	1528.7612	C2	1556.5934	B2	1540.4914	D2	1565.2115
FBG λ After		1529.0800		1556.7538		1541.0400		1565.4900
FBG λ Before	A3	1528.8580	C3	1556.6044	B3	1540.5408	D3	1565.0314
FBG λ After		1529.6500		1557.48 (w)		1540.8800		X
FBG λ Before	A4	1528.8746	C4	1556.7714	B4	1540.5485	D4	1565.1033
FBG λ After		1529.0400		1556.9970		1540.724 (w)		1565.5800
FBG λ Before	A5	1528.8553	C5	1556.4556	B5	1540.5310	D5	1565.2342
FBG λ After		1529.5375		1556.8975		1541.1625		1566.2346

Table 1: FBG wavelength survival details for VIP THS Layup 1 specimens

		Left Outer		Left Inner		Right Outer		Right Inner
FBG λ Before	A1	1528.7818	C1	1556.8218	B1	1540.2971	D1	1564.9772
FBG λ After		X		X		1540.9800		X
FBG λ Before	A2	1528.8474	C2	1556.7265	B2	1540.3359	D2	1564.6499
FBG λ After		1529.5672		X		X		X
FBG λ Before	A3	1528.8322	C3	1556.8223	B3	1540.3054	D3	1565.1606
FBG λ After		X		X		X		X
FBG λ Before	A4	1528.8223	C4	1556.6548	B4	1540.2222	D4	1565.1221
FBG λ After		X		X		X		X
FBG λ Before	A5	1528.7583	C5	1556.5211	B5	1540.2006	D5	1565.1452
FBG λ After		X		1557.3453		1540.6996		X

Table 2: FBG wavelength survival details for VIP THS Layup 2 specimens

		Left Outer		Left Inner		Right Outer		Right Inner
FBG λ Before	A1	1528.8394	C1	1556.7849	B1	1540.2433	D1	1565.1597
FBG λ After		X		X		X		X
FBG λ Before	A2	1528.8473	C2	1556.8592	B2	1540.5884	D2	1565.1291
FBG λ After		1529.6375		X		1541.0650		1565.3984
FBG λ Before	A3	1528.7745	C3	1556.6637	B3	1540.1857	D3	1565.2083
FBG λ After		1529.6217		1557.8308		X		X
FBG λ Before	A4	1528.8197	C4	1556.5003	B4	1540.5235	D4	1565.1896
FBG λ After		1529.6000		1557.6800		X		X
FBG λ Before	A5	1528.8385	C5	1556.6013	B5	1540.5528	D5	1565.0603
FBG λ After		1529.4375		X		1540.9325		X

w – FBG with weak reflection which can be measured using tunable laser system
 X – FBG either broken or drifted away from the original location

Table 3: FBG wavelength survival details for VIP THS Layup 3 specimens

FBG Survival after Specimen Manufacture

After specimen manufacturing, some FBGs were lost due to weak reflection, optical fibre breakage or

misalignment. Summaries of the test specimens are presented in Tables 7.7, 7.8 and 7.9.

Specimen	Strain-FBG
A1	3 FBG Tested – Good
A2	3 FBG Tested – Not OK
A3	2 FBG Tested – OK / Spectral split
A4	2 FBG Tested – Not Good /
A5	4 FBG Tested – Good

Table 4: VIP THS Layup 1 FBG survival summary

Specimen	Strain-FBG
B1	1 FBG Tested – Good
B2	1 FBG Tested – Good
B3	No FBG survival
B4	No FBG survival
B5	1 FBG Tested – Good

Table 5: VIP THS Layup 2 FBG survival summary

Specimen	Strain-FBG
C1	No FBG survival
C2	3 FBG Tested – Good
C3	No FBG survival
C4	2 FBG Tested – Partially Good
C5	Tested – Not OK / Lost spectral reference

Table 6: VIP THS Layup 3 FBG survival summary

The order of specimen manufacturing was Layup 2, 3 and then Layup 1. Most of the manufacturing and handling mishaps were minimised by the last layup. As a

result, as shown in the tables, FBG survival rate was higher for Layup 1 compared with the other two layups.



Conclusions

This study has effectively proposed an infrastructure for embedding optical fibre sensors into future Composite structural components, capable of extension to formalized procedures for design, structural analysis and manufacture. Practical methods have been developed for embedding and connecting to optical

fibres in composite materials, while maintaining adequate optical performance using heat-shrink-tubes. Further assessment is required of the long-term performance of the embedded sensors and connectors in typical operating environments.

Acknowledgements

The author would like to thank Prof. Ganga Prusty, Prof. Don Kelly from UNSW, Australia for their timely advice; Mr. David Lyons of EMP Composites, Sydney, Australia for the manufacturing of composite

specimens and Prof. Peng G.D. and their team from UNSW, Australia for the manufacture and testing of FBGs.

References

- 1) Erdogan T. (1997). Fiber grating spectra. *Journal of Lightwave Technology* 15: 1277–94.
- 2) Green AK, Zaidman M, Shafir E, Tur M and Gali S (2000). Infrastructure development for incorporating fibre-optic sensors in composite materials. *Smart Materials and Structures*, 9:316–321
- 3) Kuang K.S.C. Cantwell W.J. (2003). Use of conventional optical fibers and fiber Bragg gratings for damage detection in advanced composite structures: A review. *Applied Mechanical Review* 56(5): 493-513.
- 4) Lee J. R., Jeong H. M. (2010). Design of resonant acoustic sensors using fiber Bragg gratings. *Measurement Science and Technology* 21(5): 1–6.
- 5) Lemaire P.J., Atkins R.M., Mizrahi V., Reed W.A. (1993). High pressure HZ loading as a technique for achieving ultrahigh photosensitivity and thermal sensitivity in GeO₂ doped optical fibres. *Electronics Letters* 29:13 1191-1 193.
- 6) Ling H.Y., Lau K.T., Cheng L., Jin W. (2005). Utilization of embedded optical fibre sensors for delamination characterization in composite laminates using a static strain method. *Smart Materials and Structures* 14: 1377–1386.
- 7) Schwartz M. (2009). *Smart Materials*. CRC Press, ISBN: 13:978-1-4200-4372-3, Florida, USA.
- 8) Staszewski W., Boller C., Tomlinson G. (2004). *Health monitoring of aerospace structures: Smart sensor technologies and signal processing*. John Wiley & Sons, Ltd, England, 2004, ISBN 0-470-84340-3.
- 9) Wei C. Y., Ye C. C., James S. W., Tatam R. P., Irving P. E. (2002). The influence of hydrogen loading and the fabrication process on the mechanical strength of optical fibre Bragg gratings. *Optical Materials* 20(4): 241-251.

Appendix –VARTM Manufacturing Process

- 1) Apply Mould Release coat 1 on the mould surface.
- 2) Plan the Layup. On the mould, at least 100 mm should be left free on all sides.
- 3) Plan for the resin ingress and exit end space allowance, which requires at least 50 mm from the each end of the mould.
- 4) Calculate the length and width of specimen for cutting reinforcement fabric. Allow 25 mm on both ends and 2.5 mm per cut (including sanding/polishing).
- 5) Calculate the dimensions of the fabric for extra CSM layers at bottom bend - Ply drop.
- 6) Apply Mould Release coat 2 on the mould.
- 7) Cut Fabric to required size - for Laminate and for ply drop layers. Organise the fibre mats as per the layup including ply-drop layers (Do not use Tack Spray at this stage)
- 8) Once the layup is checked, lay the fibre mats on the mould and remember to use Ply-drop layers as well. Use light tack-spray between the layers to prevent fabric slippage.
- 9) If two layups are manufactured at a time, then add a bridging material between the layups over the mould surface to facilitate easy resin flow.
- 10) Cut Peel ply to size and lay it over the entire laminate, 10 mm extra on all sides - Use tack-spray. The resin ingress and egress ends should cover the resin inlet pipe.
- 11) Cut perforated film and place it on top of peel ply - use tack-spray.
- 12) Cut flow mesh and align over the perforated film. Fix it using adhesive tape. Cut and place flow medium (50 mm wide, white honey comb structure) at the ingress side. It should sit on top of peel ply and a bit on the laminate and flow mesh.
- 13) Fix tacky-tape all around the perimeter of the mould. Cut the resin inlet hose to size and fix it at the ingress end using tacky-tape pieces over the flow medium.
- 14) Take a T-joint; connect a hose to the central inlet and the sides to the resin inlet pipe.
- 15) Cut the resin inlet hose to size and fix it at the egress end using tacky-tape pieces.
- 16) The resin flow needs to be restricted at the egress end. Take 600 gsm CSM, cut into pieces, apply tack-spray and fix it over the resin outlet pipe. Connect the egress pipe to the outlet pipe using T-joint.
17. Connect the ingress and egress pipe to the mould using tacky-tape.
- 18) Cut the Nylon sheet (for vacuum bagging) to size; fix it on the mould with the glued tacky-tape slowly. Make pleats at corners for efficient circulation of resin.
- 19) Secure the nylon sheet applying thumb pressure all along the length of the tacky-tape.
- 20) Close the inlet pipe using a clamp. Egress pipe will be in catch pot.
- 21) Switch on the vacuum slowly and align the nylon cover, fibre mat, and everything in the nylon bag to be secured on the mould properly. Increase the suction up to 100 kPa.
- 22) Conduct drop test, check to see if the vacuum pressure drops from 100 kPa, which indicates an air leak. Use acoustic-emission headphones and fix all the leaks.
- 23) Estimate the amount of resin (Vinylester SPV 6036) and hardener (CHM 50/925H - 1.5% of resin).
- 24) Mix resin and hardener thoroughly in an appropriate container. The estimated gel time is around 30 min.
- 25) Place the container near the mould and immerse ingress pipe end in the container. Re-check the vacuum strength. Slowly release the clamp and allow resin to infuse into the laminate slowly.
- 26) Observe the generation of air bubbles in the ingress pipe as well as in the laminate (resin front).
- 27) Keep an eye on the resin container; the ingress pipe should always be immersed in the container. If there is a shortage of resin, stop the flow using the clamp, prepare new resin-hardener mix and place it carefully under the inlet pipe.
- 28) Allow the whole laminate to infuse, frequently checking for any leaks and fix the leaks by patching with tacky-tape. Disconnect the resin supply after successful infusion and seal the ingress and egress hose.
- 29) Keep the mould under vacuum overnight.
- 30) Disconnect all the pipes, remove nylon bag, flow medium, perforated film along with peel ply and slowly release the laminate from the mould.

Author Profile



Dr. Raju

MTech and PhD from UNSW, Australia. Over 14 years of experience in Structural analysis of metal and Composite Structures. Working in Airbus ODC and Professor at VTU, Bangalore. Active participation in NASSCOM and SAE initiatives for Industry-Academia interaction. Supporting Board of Studies for Aerospace Engineering, VTU, Karnataka. Has over 50 refereed publications in International Journals, Conferences and Book chapters. Areas of interests are:

Damage mechanics; Progressive failure analysis; Structural Health Monitoring; Fatigue and Damage tolerance; Damage prediction and analysis of Metallic and Composite structures. Certified Naturalist and Yoga Teacher.

About QuEST Global

QuEST Global is a focused global engineering solutions provider with a proven track record of over 17 years serving the product development & production engineering needs of high technology companies. A pioneer in global engineering services, QuEST is a trusted, strategic and long term partner for many Fortune 500 companies in the Aero Engines, Aerospace & Defence, Transportation, Oil & Gas, Power, Healthcare and other high tech industries. The company offers mechanical, electrical, electronics, embedded, engineering software, engineering analytics, manufacturing engineering and supply chain transformative solutions across the complete engineering lifecycle.

QuEST partners with customers to continuously create value through customer-centric culture, continuous improvement mind-set, as well as domain specific engineering capability. Through its local-global model, QuEST provides maximum value engineering interactions locally, along with high quality deliveries at optimal cost from global locations. The company comprises of more than 7,000 passionate engineers of nine different nationalities intent on making a positive impact to the business of world class customers, transforming the way they do engineering.



BORN TO ENGINEER

<http://quest-global.com>