Embedding Technologies of FBG Sensors in Composites: Technologies, Applications and Practical Use

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ABSTRACT

Surface mounted optical fibre sensors, like Fibre Bragg Grating (FBG) sensors, are gaining increasing attention in the field of experimental stress analysis and health monitoring of structures and gas turbines. Optical fibres lend themselves to integration within composite structures due to their small size and fibrous nature. But optical fibres are vulnerable at the ingress and egress regions of the composite structure. This makes the manufacturing process difficult and expensive. NLR has developed two embedding techniques to avoid the problem with emerged fibres from the laminates during manufacturing by hand lay-up as by fibre placement robot technology. These embedding techniques will be explained in this paper.

INTRODUCTION

Fibre optic sensors, like Fibre Bragg Grating (FBG) sensors, are increasingly being applied and become increasingly interesting for mechanical testing, conditioning monitoring of gas turbines and structural health monitoring (SHM) purposes. This is especially because of advantages like small diameter, light weight, flexibility, high strength, high sensitivity, heat and corrosive resistance, non-electrical and the immunity to EMI. The multiplexing capability of numerous sensors along a single optical fibre, with low signal loss over long cable lengths and the ability to measure different parameters such as strain, temperature, pressure, moisture and chemical compounds makes it very attractive sensors.

Perhaps one of the most significant attributes of fibre optics is that the small size and mass also allows these sensors to be embedded into structural composites (polymer, CFRP and fibre-metal laminates like Glare) enabling 'smart structures'. With this capability, the sensors cease to be an add-on feature and become part of the structure itself. As an integral element of the structure (embedded and/or surface

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bonded) the sensors are able to play a key role in validating the design and for other functions such as damage detection. The use of in-situ sensors for real-time (health) monitoring of (aircraft) structures can be a viable option to overcome inspection impediments stemming from accessibility limitations, complex geometries, and the location and depth of hidden damage.

The embedded optical fibres are vulnerable at the ingress and egress regions. This makes the manufacturing process difficult and expensive. NLR has developed two embedding techniques to avoid these problems during manufacturing by hand lay-up and by fibre placement robot technology. The work has been performed within the framework of the EU project CESAR "Cost Effective Small AiRcraft", WP2.4 "Smart Structural Health Monitoring" and NIVR-SRP 59705N: Development of a preliminary Structural Health Monitoring (SHM) system for composites [1].

This paper will concentrate, after an introduction to optical fibre sensors and its applications, on the development of different techniques for embedding FBG sensors in composites, focused on high survivability of the fibres and "easy to manufacture" techniques and supported by embedding experiments and mechanical tests.

EMBEDDED OPTICAL FIBRE SENSORS IN COMPOSITE MATERIALS

The most versatile method for installing sensing fibres on a structure is to surface mount them directly to it. Proven materials and methods are available and reliable for surface-bonding optical fibres onto structures of almost any material. But optical fibres also lend themselves to integration within composite structures with interesting advantages and possibilities creating new applications.

Applications of (embedded) optical fibre sensors

FBG sensors have the advantage that they can be used to form the basis of more complex transducers, which provide measurement of other environmental, physical, chemical and electrical variables. Examples [1,2] of applications with such sensors includes the detection of gases and liquids, the measurement of strain, temperature, humidity, salinity and corrosion and the analysis of pressure, vibration, inclination and fluid flow. Some others will be explained in more detail in the next paragraphs.

Impact detection/monitoring

Characterization of the response of composite structures to dynamic and impact loads is at the forefront of experimental mechanics. This is due to an ever increasing interest for long-term monitoring and control of (aerospace) structures. A first step towards addressing the pertinent problems is the real time strain response of the structure due to the external loads and the associated damage, in particular due to impact. The response of a structure to dynamic excitation is traditionally carried out using either local sensors like accelerometers, laser vibrometers for velocity measurements, piezoelectric sensors or strain gauges. FBG sensors can be used for detecting the impact event, for strain measurements after the impact event and to determine the impact location and impact energy for damage detection, possibly as alternative to acoustic emission (AE) inspection. Recent advances in high rate interrogation systems permit the use of FBG sensors in structural health monitoring.

The Technobis Deminsys interrogator, currently used at NLR, is capable to scan with 19 kHz a total of 32 FBG sensors. Recent developments promise scan rates even up to 200 kHz [3]. Recently FBG sensors were used to detect impacts to helicopter rotor blades, and to measure other features of the performance of the blade and for monitoring loads in the rotor head structure [4,5]. The advantage of in the blade integrated fibre optics is the undisturbed aerodynamic performance.

Residual strains measurements during composite manufacturing

With embedded FBG sensors the residual strains acting on the FBGs can be measured during composite manufacturing. After embedding, the wavelengths can be shifted, equating to residual strains of 0.05% [6].

Internal crack detection

A single-mode (small diameter of 52 µm) fibre with FBGs, positioned in a composite between 0° and 90° plies, is able to detect transverse cracking and delamination growth, see Figure 1. Results arising from the in-plane tensile load to the fibre have shown that the profile of the Bragg grating spectrum widens or splits as transverse cracking occurs [6,7]. Research in this area highlights the dual potential of (small diameter) optical fibres with FBGs to measure cracks, as well as strain.

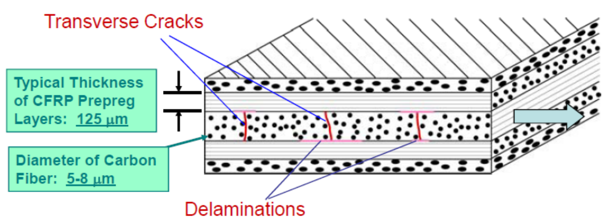

Figure 1. Transverse cracking in CFRP [7].

Effect of embedding on mechanical properties

Embedding optical fibre sensors into composite can have a detrimental effect on the mechanical performance of the composite. There is often concern with resin pockets that may occur as a result of embedded optical fibres. Finite element modelling was used to determine the effect of embedding optical fibre between plies ad different orientations. Static strength test showed no detrimental effect with the inclusion of optical fibres. Resin rich regions occur around optical fibres embedded into woven fabric; however woven fabric inherently has lots of resin rich regions due to the tows overlapping. Results of optical fibre embedded between 0/90° plies showed that the tensile properties were not affected significantly [6, 8, 9].

Fatigue durability of embedded optical fibre sensors

Tests with carbon fibre coupons have shown that embedded FBG sensors show no signs of fatigue or disbonding after one million cycles [10]. Similar tests with glass fibre materials have demonstrated that embedded sensors within wind turbine blades for instance will survive the 25-year service life of the blades themselves [11]. For surface mounted applications, optical fibre sensors are less prone to disbonding and are far more resistant to moisture and chemicals than most electrical gauge technologies.

Optical fibre specification

The optical fibre is an integral part of the sensor. For optimal performance, it is important to use the same fibre, which is used in the interrogator. For embedding purposes, where a typical prepreg ply thickness is 125μm, fibres with smaller diameters have a significant advantage. The current development of small diameter fibres has resulted in fibres with a total diameter of 52 μm, which are not commercial available yet [12]. A polyimide coating is preferred to use because polyimide is able to withstand (composite cure) temperatures up to 200°C. It also has the advantage of suppressing slippage at the coating / glass interface when high strains are applied.

EMBEDDING TECHNIQUES

Optical fibres are most vulnerable at the ingress and egress regions, whether the fibre is protruding through the surface or emerging from the edge of composite. Reinforcement of the optical fibre has to made at the ingress/egress regions, and typically PTFE (Polytetrafluoroethylene) or heat shrink tubing, or silicone impregnated thermoplastic braids are used. It is essential that the end of the (embedded) tube is sealed, so that the resin does not bleed down the tube. Any excess resin that coats the fibre makes it exceptionally vulnerable to damage.

Fibres emerging from the edge of a laminate are easier to embed, as the fibre can just be inserted between plies. The laminate edge, however, cannot be trimmed after manufacturing, which is often unrealistic and unacceptable for composite structures. Emergence of the fibre through the surface (away from edges) is much more difficult to achieve as the fibre has to be pulled through several plies. Several plies usually have to be cut with this method, and precautions need to be taken to ensure that the optical fibre does not bend excessively. The fibre needs to emerge at a shallow angle through the material and then be supported by wedges on the surface.

A more robust approach of accessing embedded optical fibre is to utilise a connector housing which is embedded into the surface of the composite and is used as the connection point after the curing process is complete. NLR has developed two manufacturing and embedding techniques with the emphasis on the survivability of the optical fibres during and after the embedding process in monolithic composite components/structures.

Embedding-during-manufacturing

Embedding optical fibres during manufacturing involves the technique of directly integrate the optical fibre with sensors into the composite laminate during manufacturing. The vulnerability and the difficult handling of the optical fibres during manufacturing make this method not very realistic for (automated) manufacturing processes.

Embedding-during-manufacturing of a spar by fibre placement

NLR has been participating in EU project CESAR WP2.2 with study, (tool) design and manufacturing of composite wing structure by fibre placement (material: thermosetting plastic and carbon fibres). This gave the opportunity to perform experiments with embedding an FBG sensor in the flange of the middle spar during the manufacturing by fibre placement robot technology, see Figure 2.

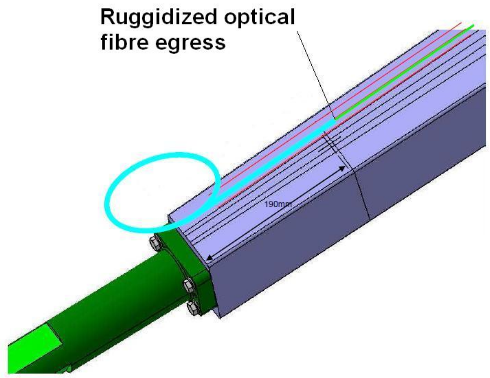

Figure 2. Embedding FBG sensor during manufacturing by fibre placement.

Embedding-during-manufacturing by hand lay-up

Embedding-during-manufacturing by hand lay-up is the traditional technique from the proposed embedding techniques. The optical fibre with FBG sensor is directly positioned between the plies during the manufacturing process. To protect the optical fibre ingress/egress points a PTFE tube is used at these points. Care was taken to protect the optical fibres outside the laminate during and after manufacturing. A cross-sectional schematic view of the specimen is presented in Figure 3.

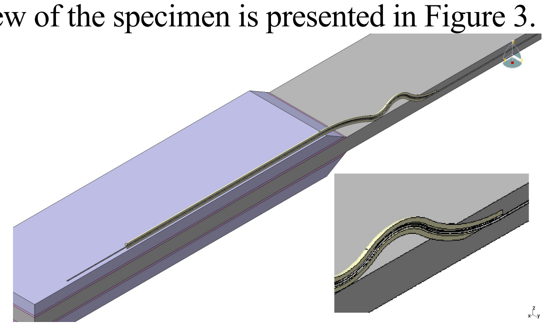

Figure 3. Cross-sectional view of specimen (embedded-during-manufacturing method).

Embedding-after-manufacturing

From the surface emerging fibres are very vulnerable to break during and after manufacturing of the laminates, due to the harsh manufacturing conditions and vacuum bag curing arrangements. To avoid fibre breaking NLR has developed a technique to embed the optical fibres after manufacturing of the composite laminate, by creating hollow tubes during the curing process of the laminate. After the curing process the optical fibre sensor is feed through the resulting hollow tube, positioned on the determined location and fixated by injection of epoxy resin, resulting in an embedded optical fibre sensor. One disadvantage of this technique is the relative big disturbance of the structure of the laminate due to the bigger diameter of the hollow tube compared to the diameter of the optical fibre sensor. The position of the optical fibre sensor was defined at the centre of the mid plane of the specimen. A schematic overview of the specimen with different hand lay-up embedding techniques and fibre egress points is given in Figure 4.

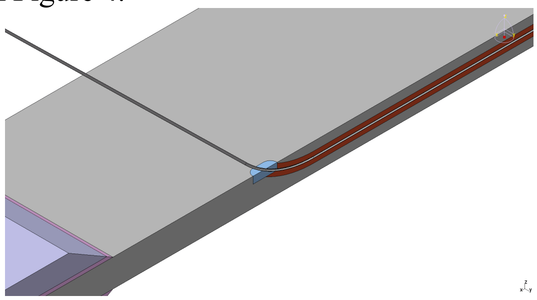

Figure 4. Cross-sectional view of specimen (embedded-after-manufacturing.

Embedding with integrated miniature connector

A robust approach of accessing embedded optical fibre is to utilise a miniature connector housing which is embedded into the surface of the composite and is used as the connection point after the curing process is complete. NLR and Diamond Kimberlit BV evolved an entirely new connector concept by adapting connector design to the composite lay-up and manufacturing process. This was achieved by redesigning a standard Diamond Micro Interface (DMI) connector (Figure 5) for embedding, comprising a partially embedded portion with a fully terminated length of optical fibre containing sensors. The fibre and the connector base are incorporated into the surface plies of a carbon fibre structure as the laminates are being laid. The connector can be placed anywhere on the composite surface. Once embedded, the connector base is encased in customized tooling designed to seal inside the vacuum bag assembly while curing takes place in the autoclave. When the manufacturing cycle is complete, the connector tooling is removed along with the bagging material. The composite components can then be machined and trimmed in the normal way while the connector base is still protected with a protective cap. Once the machining of the structural item is complete, the protective cap is removed. The Diamond DMI connector incorporates components and processes that have already been qualified to aerospace standards and used by NASA in Mars explorer vehicles. The connectors are easily mated and de-mated using standard tooling.

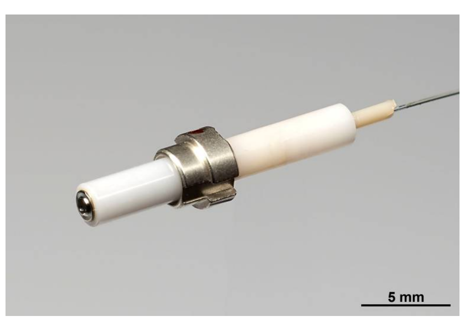

Figure 5. Modified DMI connector for embedding purposes.

To demonstrate the principle a relative simple connector housing (block of aluminium) was designed and used to support the DMI connector during and after manufacturing, see Figure 6 and Figure 7 for the design of the specimens.

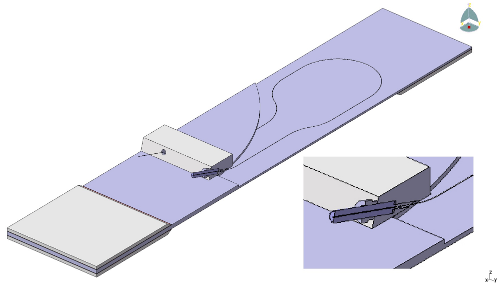

Figure 6. Internal lay-out of embedded optical fibre with integrated connector.

The position of the FBG sensor was defined out of the centre of the mid plane of the specimen. By taking out both fibre ends gives not only the possibility to check the FBG sensor, but also gives the possibility to use the opposite fibre path to the FBG sensor when the other fibre path fails.

Figure 7. Specimen with prototype design embedded optical fibre connector assembly.

MECHANICAL TESTING

The preliminary mechanical testing program demonstrated the feasibility of the embedded sensors and the embedding techniques during static loading (Figure 8). The results from the FBG sensors were compared to strain gauges, extensometer and ARAMIS (optical deformation system) results. Future extensive testing is needed to prove further feasibility like sensor/host and connector/host interaction and influence on the structural integrity.

Figure 8. Test set-up with specimen in Instron 5882 static testing machine.

CONCLUSION

NLR has developed two embedding techniques with the emphasis on the survivability of the optical fibres during and after the embedding process in monolithic composite components/structures. The developed "easy to manufacture" techniques were supported by embedding experiments and successful preliminary mechanical tests. Optimisation and miniaturisation of surface emerging connector assembly/housing for DMI connector followed by extensive (mechanical) testing is needed to prove further feasibility like:

- sensor/host and connector/host interaction and influence on the structural integrity
- Durability tests for life expectancy determination of embedded optical fibre sensors
- Development of repair techniques for broken/not functioning fibres.

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