Structural Health-Monitoring of GFRP Structures using Embedded Fibre Bragg Gratings

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KEYWORDS: Structural health-monitoring, vehicles.

INTRODUCTION

Structural health-monitoring (SHM) and temperature mapping are increasingly used in composite material applications since they make it possible to monitor the structure virtually during its entire life, from resin injection in the mould until the moment it is removed from service or it suffers an accident. SMH is even more important in high performance structures where the weight reduction places design in the limits of the material being used. In fact, the reduction in structural weight must balance with the increased demands on performance, damage tolerance, and lifetime durability. In many applications SHM and temperature monitoring is thus a crucial function.

Current monitoring systems are typically based on conventional electric sensing technology, which is characterized by a low degree of multiplexing. This feature compels major constrains in system design, ranging from short, noisy and heavy cable leads to cumbersome signal conditioning equipment.

In this scenario, fibre optic sensor technology exhibits long recognized advantages over conventional electric sensors. Among the most important advantages of this technology are: very high multiplexing capability, immunity to electromagnetic/radio frequency interference (EMI/RFI), remote monitoring, small size and weight, electrical insulation, intrinsically safe operation, high sensitivity and long-term reliability. These characteristics enable fibre optic sensors to mitigate well-known deficient performance of conventional technology in hazard-environments. Fibre Bragg grating (FBG) optical sensors add to these features multiplexing and self-referencing intrinsic capabilities that make Bragg grating technology particularly competitive for medium and large scale (+20 sensors) SHM and temperature mapping applications.

Structural components of a composite bus body were produced with embedded optical fibres and tested. The compatibility of the optical fiber sensors with the envisaged production processes and materials, and the behavior under impact loading are the main concerns in this work.

The paper now being proposed will present the manufacturing processes used to produce the sample components, the encountered difficulties and the adopted solutions, the tests carried and the results. The described work allowed the consolidation of the previous experience on structural health-monitoring in the specific field of transport structural applications. The work was done within the project LiteBus – Modular Lightweight Sandwich Bus Concept [1]. These tests are exploratory and preparatory for the testing programme to be undertaken with real scale bus pillars that are being constructed.

1 - OVERVIEW

The structural design and the production process are affected by the embedment of optical fibers (OF). On the other hand, optical fibers also impose requirements and restrictions to constructive and productive solutions. Their diameter (250µm) is one order of magnitude larger than single glass reinforcement fibers. In a unidirectional environment, where both optical and reinforcement fibers are perfectly aligned, problems arise in the resin rich zones surrounding the optical fiber. These zones are prone to entrapping air and voids, and the resin is a brittle material, promoting the initiation and propagation of cracks. Problems are not significant in tension loading in the fibers direction. Things change dramatically when loading imposes transverse effects (buckling, bending, shear), and under impact. Unfortunately, these are the most important ones.

Furthermore, the theoretical scenario seldom happens. Considering fiber section dimension, misalignment is the rule, even in a careful automated fiber placement.

Another important aspect is the fact that unidirectional fabrics are made of yarns – groups of large number of fibers -, with a total diameter several orders of magnitude larger than the optical fiber diameter. Yarn fibers tend to remain together, and to make it very difficult to align the optical fibers. The first plates produced proved that the UD fabric stitching also makes optical fibers unusable. Woven fabrics and NCF, with no interface with the optical fiber, are totally out of question.

Filament winding was used to obtain a reasonable UD environment without stitching. Results were poor but better than in the case of fabrics. Nevertheless, in an industrial process, the optical fiber introduction in the component is not safe.

Priority was given to infusion processes and the production of a pillar corner by RTM was envisaged. The corner must undergo corner opening/closing test. The main conclusions of the previous trials are:

1. The measurement signal quality is significantly improved when the optical fibers, and principally Bragg grating sensors, are enclosed between two layers of surface veil. The consequences of the veil on the measurement results (local mechanical properties) and the need to anchor the fiber to prevent it from slipping must be assed;
2. Whatever the chosen process, fiber introduction in the component is critical. Specific components must be developed to protect these critical zones. Those components must allow free fiber settle down during mould closing, be fully integrated in the final pillar and allow access for connecting purposes;
3. Reinforcement fiber placement proved to disturb optical fiber placement. This is expected to be more serious in the RTM process. The envisaged solution is the production of strip of veil reinforced resin containing correctly positioned optical fibers;
4. Embedded OF in the test samples will provide insight into material mechanical behaviour during material testing, thus providing valuable inputs and feedback for the model designers;
5. Both deep embedding and superficial mounting of the sensors are possible;
6. Employment of multiplexed FBG sensors during final vehicle testing (i.e. rollover test) will provide a higher number of measurement points during the test, providing a better understanding of material failure modes and collapse behaviour of the overall structure;
7. Integration of an embedded FBG based nervous system into the final vehicle structure would provide means for SHM during its whole lifetime.

Sensor system architecture should provide redundancy for fibre cuts of fibre interface failure. A preliminary study on the nervous system architecture as well as the corresponding interrogation unit has been performed. The following figure presents such an architecture including 80 strain sensors embedded on eight fibres.

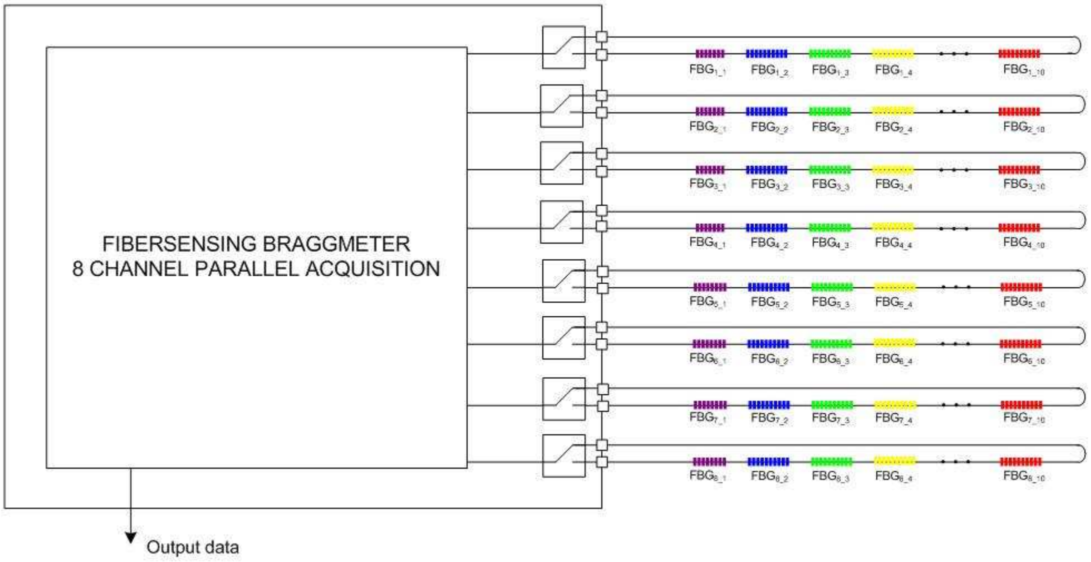

Figure 1 - Nervous system architecture providing 10 sensors on each fibre and fibre failure redundancy.

In this architecture each single fibre would be embedded either in a profile, panel, and pillar, on the floor or roof and can multiplex up-to 10 strain sensors. Each of these embedded fibres would be routed trough the part having both ends ending into the interrogation unit. The interrogation unit has two optical connectors for each optical fibre, and thus allows the fibre arrays to be interrogated from both sides. This architecture provides redundancy to fibre cuts and connector/splice failure, thus enhancing system reliability.

Strain sensor embedment can be performed by directly embedding the FBG sensors on the material, as performed in the preliminary validation tests. Sensors will be embedded on the sandwich material skin. Also evaluation is being performed on the possibility of embedding FBG sensors on the skin to core interface.

Embedding temperature sensors on materials involves additional issues, specially related to the fact that FBG sensors present high sensitivity to both temperature and strain, and therefore strain sensitivity must be removed in order to measure temperature. Work has also been done in the design of a temperature sensor for material embedment. These sensors must be carefully designed in order to remove strain induced effects on the sensor response. The following figure presents an initial temperature sensor for material embedment. By inserting the FBG sensor into a stainless steel capillary tube, strain effects can be effectively removed.

An additional issue on FBG embedment is evaluating mechanical impact of fibre embedment on the material properties.

2 - STUDY OF THE EFFECT OF REINFORCEMENT FIBER TYPE

The configurations to consider in the monitoring of the LiteBus are:

- Optical fibre embedded between two layers of random mat
- Optical fibre embedded in unidirectional reinforcement environment:

    - With stitching (non-crimp-fabrics)
    - Without stitching
- All previous cases are possible in two variants:
    - FBG enclosed between two layers of veil (very light random mat)
    - FBG in direct contact with the reinforcement fibres

The main issues are the effect of the local fibre environment on the FBG and the effect of the fibre environment along the path on the optical fibre. Simultaneously, attention was paid to the process being used.

The first experiments were done using non-crimp fabrics and wound rovings.

Figure 2 – OF placed over the first ply of UD wound glass fibers.

The OF were aligned with the neighbour fibres. The plates were produced by hand lay-up and vacuum infusion. The results shown that the stitching interferes significantly with the fibre and the sensor spectral response is totally modified. The wound roving reinforced plates shown that it is very difficult to keep the OF in position during the process and that a slight deviation in the alignment also makes the reading meaningless. The main conclusion is that the OF should be embedded between two layers of random mat.

To produce a prototype of the pillar corner a RTM mould is needed. The geometry was received from ITALDESIGN and was used in the construction of a model. Before the final geometry was achieved, a rough approximation was used as a mould to obtain an RTM´d curved plate where the optical fibres would be embedded using the envisaged technique. The main objective is to study the effect of random fibre mat and veil on the performance of the optical fibres. The geometry of the pillar to be produced by RTM is shown in figure 3.

Figure 3 – pillar corner geometry

A model was built to allow the construction of a RTM mould of the corner of the pillar. A sample curve plate produced using RTM with embedded optical fibres was made.

Figure 4 shows the optical fibres (OF) in place. As can be seen, one layer of veil was placed on each side of the OF in one half of the corner (the lay-up sequence is symmetrical) and two layers of veil in the neighbourhood of the FBG. The path of the OF towards the left side of corner curve is made between random mat of fibres. Signals are read in both ends to evaluate the effects of OF enclosing.

Figure 4 – OF placement

The sample was then produced by RTM using a pressurised pot and let to cure. Measurements were made during injection only. The component was let to cure and measurements were made again before demolding.

Figure 5 shows the demoulded component, kept in counter-mould to protect the fibres until measurements are completed.

Figure 5 – sample curve plate

The Measurements performed on the embedded FBGs confirm that there is no relevant effect of the random mat in the performance of the optical fibres. Figures 6 and 7 show the comparison of the readings at both ends of the same optical fibre (right correspond to the end arriving from veil encapsulated paths and left to the ends arriving from a path in direct contact with random mat).

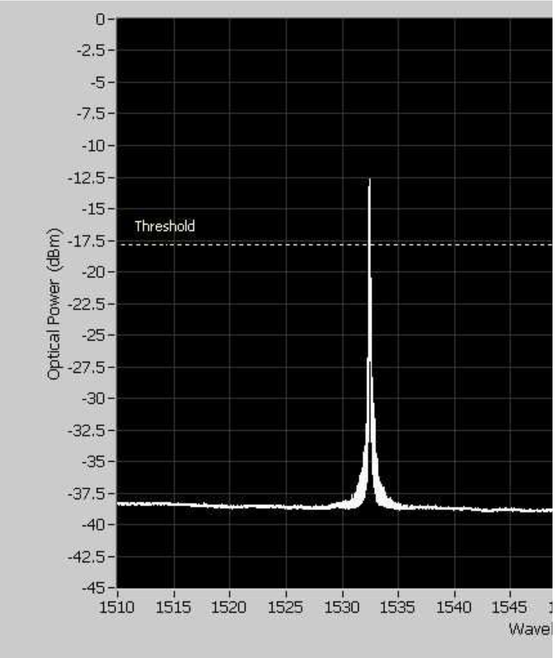

Figure 6 – FBG1 left-side

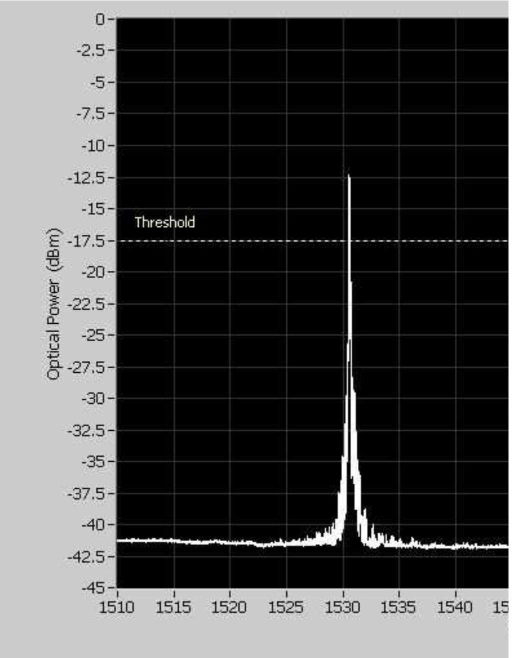

Figure 7 – FBG1 right-side

The main conclusion are:

- veil is considered mandatory in the neighbourhood of the FBG;
- veil is beneficial in the remaining path, although not mandatory.

3 - STUDY OF THE EFFECT OF FIBER ANCHORAGE

A sample sandwich plate was produced. Six optical fibres were embedded, three were anchored. The other three were not. The sandwich is 150x200mm in area and 43mm thick. The OF were embedded underneath the skin, enclosed by two layers of veil on each side. The first reinforcement ply is COREMAT, so to have a random reinforcement close to the OF. The upper 7 plies are unidirectional fabric (5% at 90º).

Figure 8 – Sample sandwich and testing machine

The plate was then tested to compression. The upper face was covered with a stiff plate to ensure a uniform distribution of load. The results are shown in Figure 11.The nominal compressive load steps were 100N (point 1), 200 N (point 2) and 300 N (point 3). As the degrees were kept, some relaxation was verified on the foam. The maximum displacement at 300N was 0.6mm. Some relaxation is visible immediately after the indicated points: 1-1', 2-

2’, and 3-3’. From 3’ to 4 the sample was unloaded. After point 4 unloaded relaxation is visible. Relaxations occur both at the foam and at the sample fixations.

The objective of the test was to investigate any possible behaviour difference between anchored and non-anchored OF. The load level was kept low so to allow the use of the sandwich in the impact test.

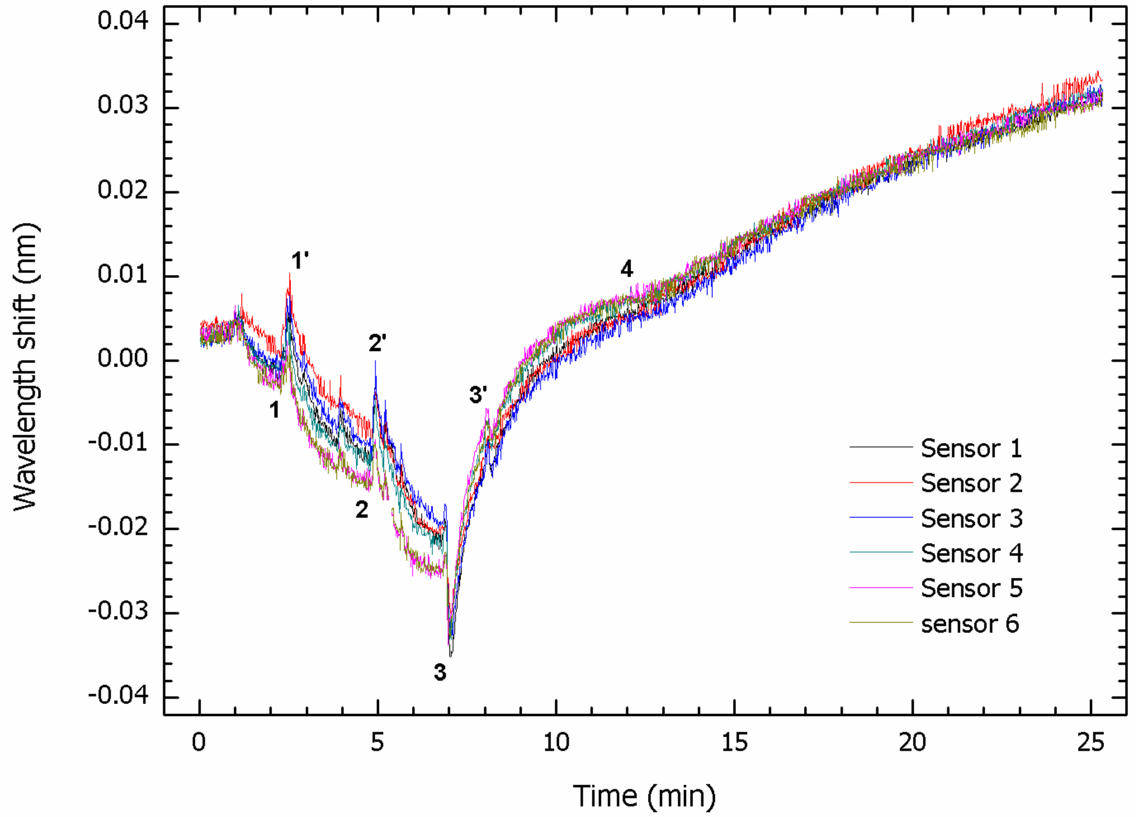

Figure 9 – Static results

No relevant difference is observed in the response of anchored and non-anchored FBG. Both types of sensors show good response to strain.

4 - STUDY OF THE EFFECT OF IMPACT LOADING

The sandwich sample was used to perform two impact tests. The plate was laid on hard flat ground and covered with a thick wood to avoid localised damage and to distribute the load. Two heavy objects, the first weighing 0.977Kg and the second weighing 2.875Kg were let to fall from 2.5m above the sandwich. The lighter object rebounded over the covered sandwich, so two events may be identified. The heavier rebounded and fell over the loose OF protection, which was not sufficient to avoid one of the serial connections to be broken. Anyway, the main event was fully monitored. The spectral response of each fibre was not changed in any of the events. The second test is the most significant. The results can be seen in Figure 10.

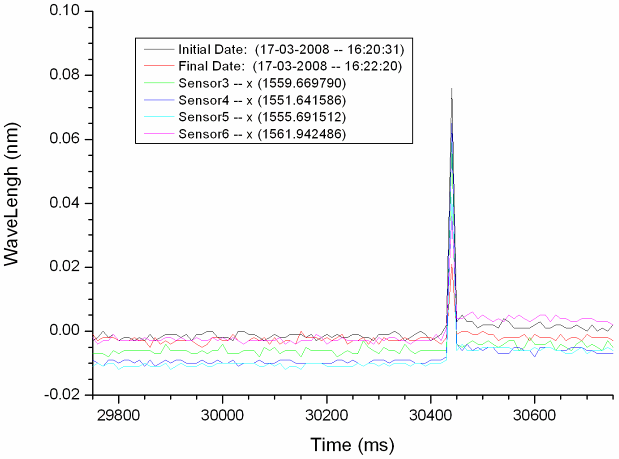

Figure 10 – Impact testing results

The wavelength variation ranges from 0.02 and 0.075nm. This is due load eccentricity, since no pattern was detected between anchored and non-anchored OF. The energy level is E=0.75Mh (M being the mass of the impactor and h the height). In the second test this value is E = 0.75 x 2.875 x 2.5 = 5.39Nm. The equivalent imposed energy is:

$$E_{eq} = E / A_{sandwich} = 5.39 / (0.2 \times 0.15) = 179.7 \text{ Nm/m}^2$$

The expected rollover energy is E_r = 125KNm. Considering this energy is distributed by 20 pillars, each having a free span of 1m and 0.15m in width, the expected energy density is

$$E^* = E_r / A = 125000 / (20 \times 1 \times 0.15) = 41667 \text{ Nm/m}^2$$

Finally, the equivalent imposed energy in the second impact represents 0.43%.

On the other hand, the maximum wavelength variation represents 0.48% of the expected value at OF tensile failure. Since this percentages are comparable and since damage and energy density is concentrated in the impact area, it was concluded that the structure can be monitored in areas sufficiently far from that area and no monitoring is possible there. In the impact area, damage by local buckling and delamination will occur well before the OF limits, but such damages make OF unusable. The maximum proximity will be investigated with the sample real scale pillars. Another aspect to consider in the next test programme is the fact that the main loading pattern is no longer compression, as expected in the impact area, but tension and compression instead. This means the energy will not be absorbed by the core in the same percentage and will be more efficiently transferred to the OF.

In case of necessity, the use of OF can still be made possible by reorienting them away from the 0º direction. The impulse was clearly followed by the monitoring system.

5 - STUDY OF THE EFFECT OF FIBER INTRODUCTION

OF introduction in the samples or in the components proved to be very important when using it in the envisaged production processes. The introduction strategy influences the OF positioning, integrity and connectivity. Considering the beneficial effect of veil, it was accepted to use pre-mould veil reinforced bands containing the OF in position and to place them in the mould. This band is terminated at both ends with an accessory designed to fit a gate in the pillar mould. The accessory, proposed by INEGI, is shown in figure 11.

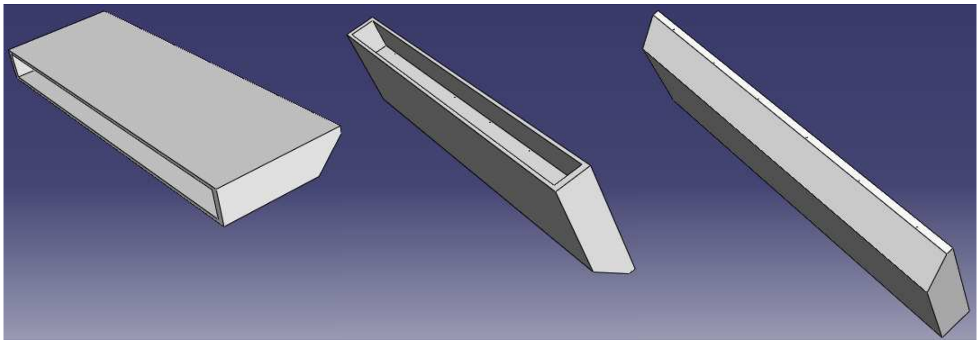

Figure 11 – OF Gate

The gate can fulfil the requirements previously explained and is going to be produced and used in the next trials. The gate is assembled in the mould prior to OF positioning. The assembly is shown in Figure 12.

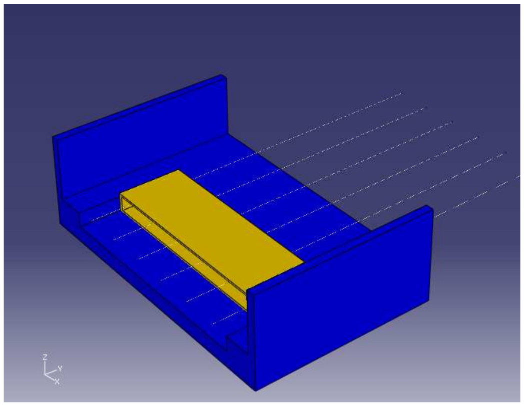

Figure 12 – OF positioned

5 - CONCLUSIONS

From the above experimental results, the main conclusions are:

- Stitching and crossed fibres are not admissible in the FBG neighbourhood.
- Pure unidirectional environment is admissible but positioning must be careful. Slight deviation invalidates the use of the OF.
- Veil enclosing the FBG is mandatory, even when using random mat.
- Veil is beneficial in the remaining path, although not mandatory.
- No fibre anchorage is required because FBG exhibit good sensibility to strain once the curing process is finished and no relevant difference was observed in the response of anchored and non-anchored sensors.
- The optical fibres can withstand most of the impact energy expected during the bus rollover and the impulse was clearly followed by the monitoring system.
- Gates are mandatory to position the OF, to ensure its integrity and to allow for connection to the reading system.

6 - REFERENCES

[1] www.litebus.com