(FIRST PAGE OF ARTICLE)

## ABSTRACT

This work highlights some of the achievements obtained within the EU FP7 SmartFiber project, aiming to develop a fully embeddable optical fiber sensor system including the interrogator chip. The focus is on resolving issues holding back the industrial uptake of optical sensing technology. In a first section, the development of a placement head for automated lay-down of an optical sensor line (including the SmartFiber interrogator system) during composite manufacturing is discussed. In a second section, the attention is shifted to the occurrence of resin pockets surrounding inclusions such as the SmartFiber interrogator. A computationally efficient F.E. approach is presented capable of accurately predicting resin pocket geometries. Both small (i.e. optical fiber sensors) and large (i.e. the SmartFiber interrogator) inclusions are considered, and the F.E. predictions are validated with experimental observations.

## INTRODUCTION

During the last decades, composite structures have received a large amount of interest from both the research community as well as industry. Their high strength-to-weight ratio make them ideal candidates for high-performance, cutting-edge applications such as (aero)space, wind energy and sporting applications. However, while the benefits of composite materials are easily understood, their fibrous and layered nature leads to a strong orthotropic material response and advanced failure mechanisms such as delaminations, fiber breakage, matrix cracks… These failure modes raise the difficulties in safe design and exploitation of composite structures. Consequently, the concept of non-destructive testing/evaluation and structural health monitoring has become an important area of research within the composites field.

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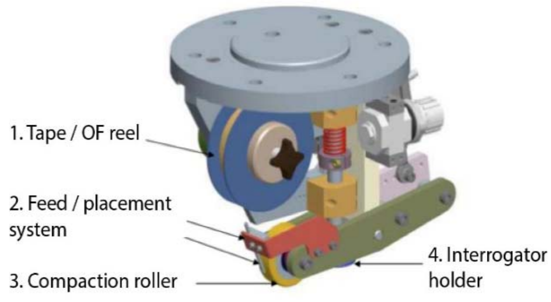
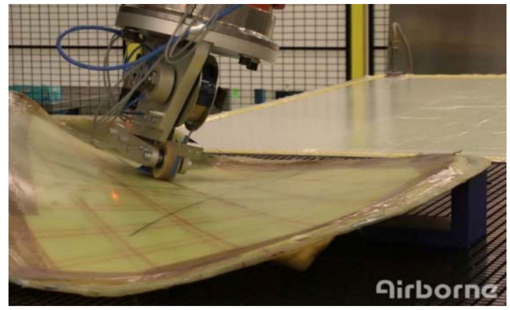


(a)



(b)

Figure 1. (a) Schematic of placement head, (b) placement head laying down an optical fiber sensor along a curved path

A common technology used in the field of structural health monitoring, is optical fiber based sensors. It has been demonstrated extensively, that – depending on the precise sensor design – a plethora of physical quantities can be measured accurately using optical fiber sensors. More specific, optical fiber Bragg gratings have been demonstrated as very accurate sensors for multi-axial strain measurements. In addition, the fibrous nature of the optical fiber makes them ideal candidates for embedding inside the composite host during manufacturing. This way, embedded optical fiber sensors are (i) protected from the elements and (ii) capable of providing multi-axial strain readings within the composite host during its entire lifespan, including manufacturing (during which significant residual strains may be produced).

A well-acknowledged issue however, is related to the fragility of the optical fiber sensor itself. This makes handling of the sensor during placement a very delicate matter requiring specialized, expertized workmanship to ensure proper placement of the fibers. Additionally, in order to extract the data encoded in the optical fiber sensors, they need to be connected to a read-out device (known as 'interrogator'). This results in a fragile egress point where the (brittle) optical sensor line exits the (stiff) composite host. As a result, even after embedding, handling the smart structure remains a delicate matter and does not represent an industrially robust solution. These limitations of the sensor technique are holding back the general industrial uptake of the sensing solution.

Within the European Union FP7 framework program, the 'SmartFiber' project set out to resolve these (and other) issues holding back the industrial uptake. A state-of-the-art, miniaturized interrogator was built, suitable for embedding inside the composite host in unison with the optical fiber sensor network. In order to avoid fragile egress points, all data and power transmission was designed to be wireless. In addition, the issue of repeatability and controllability of fiber placement during installation was tackled by designing an automated fiber placement robot capable of laying down the combined interrogator-sensor network system during manufacturing.

## AUTOMATED SENSOR PLACEMENT

Current practice in embedding optical fiber sensors relies on experienced, skilled technicians to gently place the fiber at the approximate location in the mold. As a result, embedding optical fiber sensors is a time-consuming and costly process with a high risk

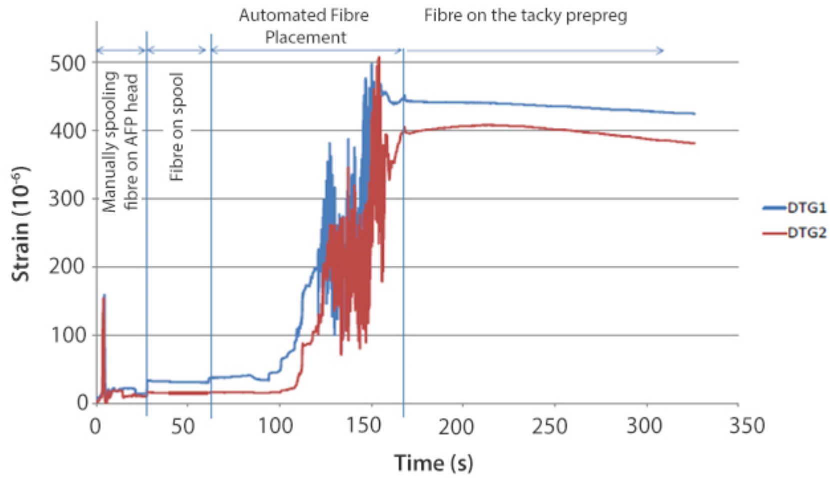



Figure 2. Pre-straining optical fiber sensor during lay-down showing the ability to controllably pre-strain the sensor

of damaging the optical fiber line. In addition, this manual process achieves a very low rate of repeatability and accuracy.

In order to overcome this issue, a fully automated robotic placement system was developed within SmartFiber. The robotic placement system shown in Figure 1, is mounted to a commercial robotic arm. The novelty of this system then, is not in the use of a robotic manipulation arm, but rather in the design of a placement head capable of laying down the interrogator system with connected optical fiber lines (using a suction cup approach), and subsequently being able to lay down the optical fiber sensor in a controllable fashion, without breaking the sensor system.

A compaction roller can be used to tune the amount of pressure applied to the optical fiber during lay-down, in order to hold a certain desired level of pre-strain on the optical fiber. In addition, heaters can be added to the placement system in order to increase the tackiness of the prepreg layers onto which the optical fiber is deposited.

Figure 2 shows the result of two independent pre-straining tests using this compaction roller to hold the pre-strain. It can be seen that a good repeatability is achieved. This allows the user to pre-strain the optical fibers, in order to allow measurement of compressive strains during curing without risk of buckling of the optical fiber sensor.

## EMBEDDED INTERROGATOR MODELING

In order to overcome issues related to the fragile egress point where the optical fiber leaves the composite host, SmartFiber envisaged to develop a fully embeddable interrogator system using wireless power and data transmission. While this in effect resolves the issues with egress points, it does mean that an additional system (the interrogator) needs to be embedded within the composite host.

Due to the fibrous nature of the composite reinforcements, a composite ply cannot mold perfectly around any arbitrary inclusion. As a result, resin rich zones (known as 'resin pockets') are created surrounding the inclusion (as shown in Figure 3). These

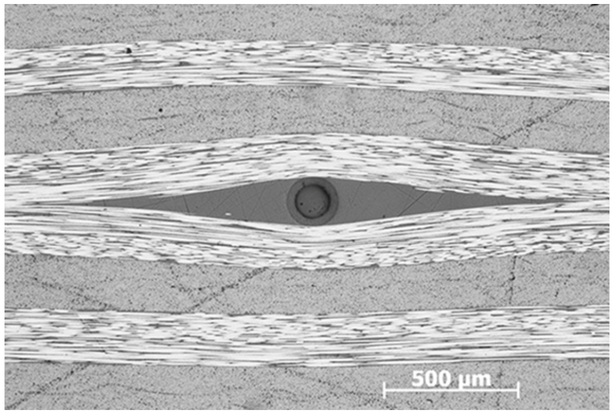



Figure 3. Resin pocket created around an embedded optical fiber in a cross-ply composite

resin rich zones represent weak spots in the composite host, which can lead to early failure of the host with embedded sensor.

The precise influence of resin pockets surrounding optical fiber sensors, has been the subject of several publications [1-3]. Lee et al. [1] found that fatigue behavior was affected by the presence of an optical fiber sensor. Shivakumar et al. [2] found that these resin pockets can induce strength reductions of up to -40% in static compression tests. Surgeon et al. [3] found that a strong influence could be observed in bending experiments. The common observation in all these publications, is that the resin pockets tend to have a significant effect on the structural performance of a composite host structure.

It stands to reason that the precise geometry of the inclusion will have a distinct effect on the resulting resin pocket geometry, and consequently on the structural behavior of the final part. Herranen [4] performed an extensive experimental study on different inclusion geometries manufactured through laser sintering of PA12, and found that indeed an optimal geometry could be found optimizing the structural performance of the smart composite.

In order to maximize the structural performance of the composite, an optimal interrogator geometry for the SmartFiber interrogator had to be determined. In this work, the finite element approach used within the SmartFiber project is presented. The novelty of the presented method is that it relies solely on standard material models and element formulations readily available within commercial F.E. packages (ABAQUS is used in this work), instead of relying on custom-coded user elements [5-7] which require an extensive amount of coding efforts and advanced understanding of computational mechanics. In addition, it only requires a limited amount of experimental material characterization, and relies mostly on manufacturer datasheets. The applicability of the methodology is validated by comparison to microscope images of different experimental samples with embedded optical fiber sensors, and on larger samples with interrogator dummies.

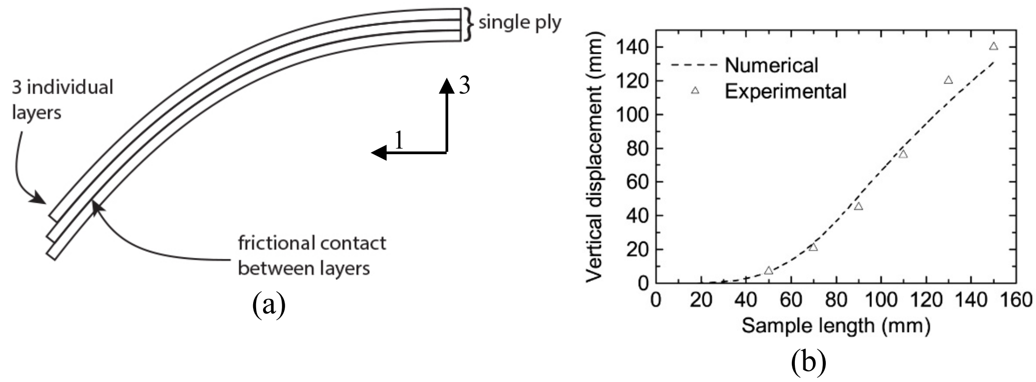



Figure 4. (a) Finite element modelling approach of bending response of an uncured prepreg, (b) Numerical and experimental comparison of bending response of uncured cantilever sample

## Finite element simulations

Modelling the resin pocket geometry surrounding the SmartFiber interrogator (or any other inclusion, such as optical fiber sensors) requires the simulation of the forming process during curing of the composite.

Standard element formulations within ABAQUS all assume that bending stiffness is related to in-plane properties of the element. During curing of a composite however, the individual reinforcements making up a single ply are free to slide over each other while the matrix material is in a low-viscosity state. During this stage, assuming bending stiffness to be related to in-plane stiffness properties (i.e. the high-stiffness reinforcement fibers) would severely over-estimate the true bending stiffness of the ply, and therefore lead to significant mismatches between experiment and simulation. In order to overcome this issue without needing to resort to purpose-written user elements, within this work a single ply is modelled in ABAQUS as a series of sub-plies which are free to slide over each other with a given friction coefficient (Figure 4(a)). As a result, the individual sub-plies can have in-plane properties corresponding to the (uncured) material properties, while the bending stiffness of the entire ply can be tuned by changing the number of sub-plies contained within one ply.

The bending behavior is extracted from a series of cantilever beam tests: an uncured material sample is fixed at one end and allowed to bend under gravity load while it is curing. The vertical displacement of the sample after curing is recorded in order to extract the bending response of the ply. Note that as large deformations are involved, beam theory can no longer be used and a more advanced formulation as presented in [8] should be used.

The F.E. simulation is built up of flat, rectangular sub-plies with an inclusion in between the plies. Symmetry conditions are exploited to reduce the number of finite elements, and a generalized plane strain approach is used to further increase the efficiency of the F.E. algorithm. External loads representative for the applied pressure and gravity are added. Due to the large deformations, non-linear geometric effects are accounted for by the algorithm. In addition, a mesh convergence study was performed to ensure proper deformations were obtained from the algorithm.

## Material properties

The material used in this work is a unidirectional M55J/M18 carbon fiber prepreg manufactured by Hexcel. Corresponding to this unidirectional material, the material model in ABAQUS is chosen as a transversely isotropic material. The relevant material properties are derived from straight-forward measurements of cured-ply-thickness (CPT) and manufacturer datasheets.

The M55J/M18 prepreg was used to study resin pockets surrounding optical fiber sensors. An identical technique was used to study the resin pockets surrounding larger inclusions with arbitrary shapes, representing the SmartFiber interrogator system. For this study, an M34N/G-136x5 glass fiber reinforced prepreg was employed. The relevant material properties for both (uncured) prepregs are given in Table I.

Table I. Uncured material properties for used prepreg materials

| | M55J/M18 | M34N/G-136x5 |
|---|---|---|
| Number of sub-plies | 12 | 11 |
| E11 | 298 GPa | 34 GPa |
| E22 | 13.5 MPa | 4 GPa |
| E33 | 13.5 MPa | 50 MPa |
| $\nu_{12} = \nu_{13} = \nu_{23}$ | 0.5 | 0.5 |
| G12 | 300 MPa | 2 GPa |
| G13 | 300 MPa | 30 MPa |
| G23 | 4.5 MPa | 30 MPa |

## Results

### OPTICAL FIBER RESIN POCKETS

Several different composite lay-ups, thicknesses and optical fiber orientations were considered in order to prove the general validity of the algorithm. The F.E. predictions are compared against microscopic images of actual samples. The results of this study are shown in Figure 6.

Figure 6(a) – 6(c) show the resin pockets in increasingly thick laminates with the reinforcements oriented perpendicular to the optical fiber sensor. In contrast, in Figure 6(d) – 6(f) the reinforcements are aligned at an angle of 45° relative to the axis of the optical fiber sensor. In addition, the optical fiber diameter is varied between Figure 6(d) – 6(f) from a 60µm optical fiber diameter (developed within SmartFiber), to a commercial 125µm diameter optical fiber.

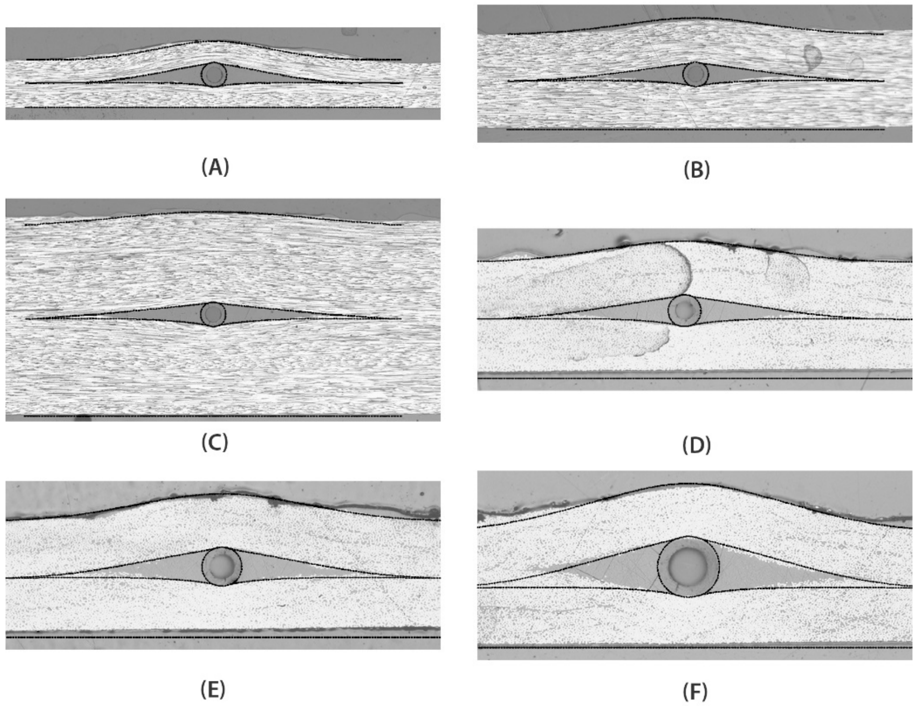



Figure 6. Resin pocket geometries as predicted by finite element analysis (black lines) overlaid on top of microscopic images of different composite lay-ups

## EMBEDDED INTERROGATOR RESIN POCKETS

Larger inclusions (7mm thickness with square and curved geometries) were embedded in a glass fiber prepreg (M34N/G-136x5). Using an identical technique as the one used for the optical fiber analysis, resin pocket surrounding these inclusions were simulated. The results are shown in Figure 7.

Figure 7(a) – 7(b) show the results for a square and curved inclusion made out of a (relatively) stiff epoxy. Figure 7(c) – 7(d) on the other hand show resin pockets surrounding geometrically identical inclusions as in Figure 7(a) – 7(b). However, in Figure 7(c) – 7(d), the inclusion is made out of a very flexible (4 MPa) silicone rubber. The resulting resin pocket geometry is found to be only minimally affected by the choice of inclusion material. However it was observed that differences in inclusion material properties affect the bonding properties between host and inclusions and as a result, affect the structural performance and stress distribution within the part.

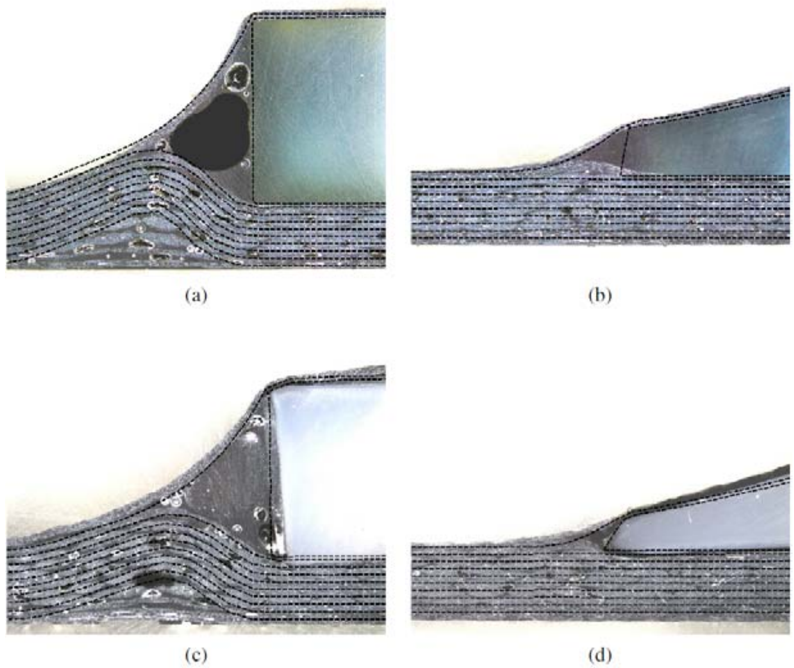


Figure 7. Resin pockets surrounding the SmartFiber interrogator dummies

## CONCLUSIONS

This work has presented achievements obtained within the SmartFiber project. A robotic placement system developed within the project was discussed, showing the ability to lay-down an optical fiber along a predetermined path, with a desired amount of pre-strain in an automated fashion. In a second section, a finite element method was described capable of predicting resin pocket geometries surrounding arbitrary inclusions. The method showed a good correspondence between F.E. prediction and microscopic cross-section.

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