# 1 BACKGROUND OF THE PROJECT

Fibre reinforced composite materials are widely used in aerospace and space applications as secondary but more and more also as primary (load-carrying) parts. Due to fatigue, repeated excitation, environmental conditions, and/or other loads these structures undergo a gradual degradation during their lifetime. For example, because of the anisotropic behaviour and composition of these structures a load applied along the fibre direction can lead to stresses perpendicular to the reinforcement fibres resulting in permanent damage (matrix cracks, delaminations) and as such in a decreasing stiffness.

Although this damage is not catastrophic in terms of the safety of the structure, regular inspection is needed. At present, the surveillance of composite structures under high load is mainly based on regular visual inspections, possibly supplemented with techniques such as ultrasonic inspection, acoustic emission or radiography which are labour intensive and during which strain mapping is impossible. A solution for this problem is the development of an online monitoring system that records the mechanical behaviour of composite structures. In addition, strain monitoring of an in-service structure should greatly enhance the insight and confidence in the (long-term) behaviour of high performance composite structures. The feedback from recorded loads, deformations and temperatures of (parts of) existing structures in real conditions, can lead to very valuable information for design conditions. Structural Health Monitoring can already start by mapping residual strains during the production process.

For these reasons, interest is increasing for techniques that can monitor permanently and continuously the structural integrity (sometimes referred to as condition or health monitoring) of mechanical and civil engineering structures during their fabrication, installation and lifetime.

This project focuses on the use of fibre optic sensors, since they have specific advantages (immunity against EM radiation, explosion safeness, multiplexing capability, small light weight) over classical strain sensors. These make them both operationally and mechanically compatible with the material and the functional specification of structures in general. More specific, fibre Bragg gratings inscribed in polarization maintaining optical fibres were used to compose a sensor able to map the total strain field of a structure. The Calibration-, the orientation- and the embedding procedure of these sensor was investigated on coupon level. In addition, a static as well as a dynamic test program was carried out on coupon level.

At the end of the project, two demonstrators (Mapping residual strains during production and a Tee joint) were being produced and tested. During the curing process residual stresses/strains are necessary for the stability and the mechanical performance of the structure. A sensor able to map the total strain field can play a great role in understanding and characterizing residual strains. Tee joints are merely used as stiffeners in constructions, loosening or premature failure of these joints can lead to a reducing load capacity of such a construction.

# 2 OBJECTIVES AND REALISATIONS

The objective of this project is to measure 3-dimensional strain components inside high performance thermo-set carbon fibre reinforced composites suitable for use in spacecrafts.

Within the MASSFOS project a fibre optical monitoring system based on Fibre Bragg Grating (FBG) sensors written in polarisation maintaining optical fibres to measure the multi-axial stress and strain in thermo-set composite elements has been developed for static as well as dynamic strain measurements. In order to achieve this, different developments have been undertaken:

## 2.1 Development of a new sensor design

In the MASSFOS project we have chosen to use an embedded multiplexed sensor configuration with two fibre Bragg gratings (FBG) put in series to measure multi axial stress and strain (MAxS-sensor). The two FBGs are written in an 80µm (cladding diameter) HiBi polarization maintaining Bow-Tie fibre and are embedded inside M18/M55J carbon/epoxy material. One FBG is surrounded by a capillary with small diameter (i.e. 340µm) in order to exclude transverse strain which is imposed upon the FBG whenever it is embedded and loaded.

The monitoring principle using single axial FBGs is relative simple and straight forward and has been extensively explained and shown in literature, however interpretation of measurements from embedded sensors needs extra attention as transverse strain components strongly influence the strain response of the FBG (deforming the back reflected spectrum, give rise to an extra peak shift…). Therefore, the multi-axial strain measurement principle is proposed and employed within this project. It is based on the fact that a FBG written inside a Hi-birefringent fibre has two Bragg peaks arising from the fact that there are two optical axis (i.e. slow –and fast axis) in such a fibre, and with each Bragg peak reacting differently to transverse strain but identical to longitudinal strain. Therefore, when employing an FBG-pair in series, with one FBG excluded from transverse influence, such a sensor configuration has the ability to distinguish 3-dimensional strain effects. However, this approach is quite complex and the overall accuracy of the MAxS-sensor relies strongly on the strain transfer from the “far field” strain in the host material to the core of the fibre optic sensor.

### *2.1.1 Development of sensor embedding procedure in composites*

Embedding a polarization maintaining optical fibre sensor during lamination looks like a quite simple action, however, it is a quite time consuming occupation and there are a few critical points of attention which need special care to obtain a well and accurately functioning sensor solution:

- **First,** one has to define the proper sensor position (i.e. correct depth) and proper orientation (i.e. parallel to the reinforcement fibres).
- **Secondly,** the Bow-Tie orientation and fixation (i.e. polarization axis) of the PM fibre is of major importance to achieve the maximum (strain) sensitivity and accuracy.
- **Thirdly,** elimination of transverse influence for one FBG (i.e. capillary) without losing too much of the sensor accuracy. This isolation of transverse strains should be as small as possible.
- **Finally** in –and egress points (i.e. kapton foil/tape or PTFE buffer) and fibre connectorization need to be thought off to have a good handling of the composite structure afterwards without breaking one of the fibre outcomes.

One of the most important issues is the Bow-Tie orientation inside the composite structure and the capillary surrounding the second FBG. In order to well orient the sensor we have come to a satisfying solution by using a transverse calibration setup to find the maximum transverse strain sensitivity of the FBG. After recording the sensor is fixed using epoxy tabs (drops) or small pieces of prepreg tabs, as such rotation of the fibre during embedding is excluded. The best solution in excluding one sensor from transverse strains is the capillary design. However, there are still some issues concerning the outer diameter (i.e. distortion of host material and fibre concentricity, fibre position through the depth of the structure) and complete sealing of the capillary ends (i.e. flow of epoxy and thus disturbance of the sensor).

### 2.1.2 Characterization of embedded sensor response and algorithm development

The relationship between the strain in the host material and the fibre optic sensor is found by using a combined approach of extensive simulation of composite laminates under different loading conditions with a FEM software tooling and an extended mechanical test program using a series of different test-coupons. We used a refined calibration procedure to determine the strain-optic coefficients of the (core of the) optical fibre. To link the strains in the sensor with those of the structure, a combined approach of experiments and FEM with a closed loop configuration is used (i.e. output of the experiments used as input for the simulations and vice versa); an algorithm is being developed to directly convert the measurements of the MAxS-sensor into the strain (or condition) of the structure. This algorithm is named the strain transfer matrix.

Mostly static test-setups are used to define and fine-tune the strain transfer matrix. When all coefficients are determined even dynamic strain measurements are possible to measure with the same formalism.

## 2.2 Demonstration technology

*Curing monitoring during laminate fabrication*

Residual strains exist in a structure in the absence of any external load (mechanical, and thermal) and are purely related to the composite materials and of course the fabrication technology. On the microscopic level they in fact arise from the mismatch in material properties between the (stiff) reinforcement fibres and the (soft) resin; for instance the coefficient of thermal expansion, $-1.1*10^{-6}K^{-1}$ and $55*10^{-6}K^{-1}$, respectively. On the macroscopic level they can arise from ply anisotropy (e.g. non balanced, non symmetric lamina) which can lead to mechanical instability of the structure (e.g. deformed structures). On both levels, the MAxS-sensor can play an important role in mapping, understanding and characterizing this residual development. We have showed that using the MAxS-sensor we can distinguish transversal and longitudinal strains and thus it is possible to monitor in a very detailed manner the cure cycle of composites during the autoclave process. As we tend to have mostly symmetric and balanced composite laminates this demonstrator focuses mainly on the microscopic level of the residual strains.

*T-Joint demonstrator*

T-joints are merely used as blade stiffeners. The T-section hence mostly carried in-plane shear loads from the stiffener plane to the skin plane. Currently, T-joints are also finding increased application in 3-D structures to carry all kinds of loads from one plane (e.g. X, Y) to another plane (e.g. Y, Z). A specific weakness of T-joints is pull-off loads. According to an internal document of the Boeiing company, with respect to aircraft construction, pull-off refers to the tendency of joints between wing skins and spars to separate under aggressive loading conditions.

Detailed finite element analysis has been performed on a T-joint in order to find the optimal positions to place the FBGs. Therefore the complete full scale T-joint with lay-up $[\pm45_2,0_4,90_4]_s$ (see WP4000 test reports document) was modeled for two loading cases:

1) Four point bending and

2) Pull off.

With these two simulations we were able to determine the ideal locations for the sensors. According to the model there is quite a difference in strain rates/gradients between the two loading conditions. In order to collect as much interesting strain measurements we have chosen to put the sensors in the zones were large longitudinal and transverse strain arises.
The use of the MAxS-sensor during these two loading cases is giving us real-time intrinsic information of the microscopic strain developments in different areas of the T-joint. This is impossible to monitor with another technology in one time using the same technology; therefore this T-joint demonstrator is chosen.