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European Workshop on the use of Optical Fibres for monitoring Composites manufacturing process

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This workshop is organized in memoriam of Professor Alain Vautrin who passed away suddenly on 12th June, 2011.

The project of this Workshop was initiated during a meeting in his office in the *Ecole des Mines de Saint-Etienne*, in March 2011. It is noteworthy that this Workshop was originally his idea.

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PROGRAMME

Wednesday 28 November

13h45 Registration

14h15 Welcome address

14h30 Exploiting the temperature insensitivity of the modal birefringence of micro-structured fibre Bragg gratings for cure cycle monitoring
Francis COLLOMBET (ICA, Toulouse, France)

15h00 Distributed and quasi-distributed Optical Fiber Sensor technologies: Applications to Structure Health Monitoring
Pierre FERDINAND (CEA-LIST, Saclay, France)

15h30 Coffee Break

16h00 Development of Optical Fiber Sensor to monitor Liquid Composite Molding Process (LCM)
Emmanuel MARIN (Laboratoire Hubert Curien, Univ. St. Etienne, France)

16h30 Optical sensors: a opportunity for faster aircraft development?
Stéphane VACHER (AIRBUS Nantes, France)

17h00 Isothermal and non-isothermal thermoset cure and induced-strains monitored by optical fibre sensors
Laurent ROBERT and Gilles DUSSERRE (ICA, Mines Albi, France)

17h30 Free evening for delegates

Thursday 29 November

8h30 Registration - Welcome address

9h00 Process monitoring of fibre reinforced composites: a tribute
Gerard FERNANDO (University of Birmingham, UK)

9h30 Residual strain monitoring during composite manufacturing using the polarization dependent loss property of FBGs
Geert LUYCKX and Joris DEGRIECK (Univ. Ghent, Belgium)

10h00 Coffee Break

10h30 Monitoring of composite material processing and commissioning using a suite of optical fibre sensors
Edmon CHEHURA (Cranfield University, UK)

11h00 Semi-experimental methods for stress analysis in polymeric materials with embedded optical fibers
John BOTSIS (EPFL, Switzerland)

11h30 Monitoring the internal temperature and degradation by fire of composite laminates by embedded fibre optic sensors
Alfredo GÜEMES (Univ. Politecnica Madrid, Spain)

12h00 Closing address

12h15 Lunch

EXPLOITING THE TEMPERATURE INSENSITIVITY OF THE MODAL BIREFRINGENCE OF MICRO-STRUCTURED FIBRE BRAGG GRATINGS FOR CURE CYCLE MONITORING.

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The project called "Instrumentation with Multi-sensor for Composite Materials and structures (I2MC)" supported by RTRA STAE foundation puts together the expertise of research and industrial teams with the goal to study the in-core instrumentation of composites structures by applying the Multi-Instrumented Technological Evaluator toolbox (MITE toolbox) [1]. In this collaboration, we proposed a multi-instrumentation set up for monitoring a composite structure during its curing phase. The main goal is to show the complementarity of different embedded devices such as flexible ultrasonic transducers (FUT) [2] and micro-structured optical fibres (MOF) [3], in order to infer the initial state of the composite structure by means of its residual strains. The composite structure studied here is a M10 HS300 carbon-epoxy plate of 230 x 640 mm with two drop-off zones as shown in Figure 1. The composite plate has three zones with different thickness. In first place, the "current zone" has 20 plies with a quasi-isotropic lay-up: [0/45/0/-45/0/45/0/-45/0/90]s. Then, the "thick zones" have 36 plies with the following lay-up: [0/45/0/-45/0/45/0/-45/0/90/0/45/0/-45/0/45/0/-45]s. Finally the "over-thick zone" has 50 plies with the next lay-up: [(90/0/0/90/0/45/0/-45/0/45/0/-45/0/90/0/45/0/-45/0/45/0/-45/0/90/90/0]s. The drop-off zones are built with a 2.5 mm single latter step from the 11th ply to the 26th ply. This type of structure is representative of the design singularities currently found in aeronautics.

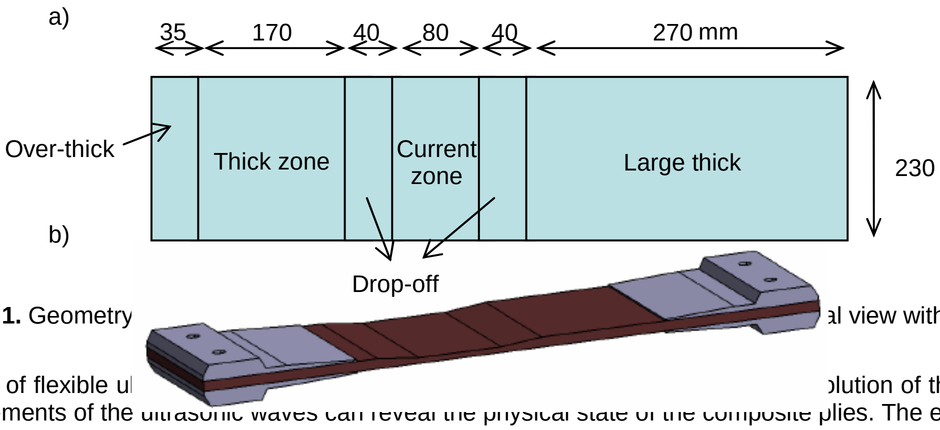

Figure 1. Geometry … al view with the jaws (b).

An assembly of flexible ul … ɔlution of the composite plate. The measurements of the ultrasonic waves can reveal the physical state of the composite plies. The evolution of the time delay during the curing cycle is analyzed which can be a measure for the different phases of the cure cycle. The curing phases are identified with a unique signature beginning with the mould-composite coupling, passing through resin reticulation and finishing with composite consolidation. With these recognizable signatures, the viability of FUT to estimate the composite polymerization evolution is proven. In addition MOF fibre Bragg gratings are used to monitor strain evolutions during curing. MOF FBGs are written in a fibre with a specialized design for purpose. In this case, the MOF is designed to be more sensitive in the transverse direction of the fibre which allows us to measure very small strain differences during curing in the transverse directions and in the longitudinal direction. The fibre shape is not completely round which forces the fibre to maintain its correct orientation in the structure, however orienting the is still necessary. Nevertheless, with this new technology of micro-structured optical fibres (MOF), the evolution of peak separation for the embedded FBG is shown and it allows qualitative indications of the appearance of transverse strains from the beginning of the cooling stage until composite consolidation. These transverse strains are directly linked with the appearance of residual stresses within and between the composite plies. The calculation of the magnitude of residual stresses (quantitative analysis) will be treated in upcoming studies.

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[2] M. Kobayashi, C-K. Jen. **Piezoelectric thick bismuth titanate/PZT composite film transducers for smart NDE of metals**. Smart Materials Structures 2004; 13: 951–956.
[3] C. Sonnenfeld, S. Sulejmani, T. Geernaert, S. Eve, N. Lammens, G. Luyckx, E. Voet, J. Degrieck, W. Urbanczyk, P. Mergo, M. Becker, H. Bartelt, F. Berghmans, H. Thienpont. **Microstructured Optical Fiber Sensors Embedded in a Laminate Composite for Smart Material Applications**. Sensors 2011, 11, 2566-2579; doi: 10.3390/s110302566.

DISTRIBUTED AND QUASI-DISTRIBUTED OPTICAL FIBER SENSOR TECHNOLOGIES: APPLICATIONS TO STRUCTURE HEALTH MONITORING.

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After three decades of R&D, Optical Fiber Sensors (OFS) now offer the same functionalities as conventional technologies: sensing, monitoring, alarm... Moreover, they provide additional benefits such as those provided by the fibers (small size and mass, wide bandwidth, low attenuation, immunity to electromagnetic perturbations, good resistance to ionizing radiation...), and those coming from the measurement systems (metrological performances, multi-sensing parameter …)

In addition, everybody knows that 'optics' if often considered as relatively expensive, but multiplexing of many (tens, hundreds, up to tens of thousands) sensors on a unique remote system, drastically reduces the cost of the measurement point, the optoelectronic system being the main cost of the instrumentation.

Nowadays, two complementary OFS families are available: the first one called "quasi-distributed" *i.e.* locally sensitive (the most well-known technology, due to their unequalled performances, being the "Bragg gratings"), and second the "distributed sensors", *i.e.* continuously sensitive along the fiber, providing a profile of the wanted parameters (temperature, strain, curvature ...) along a single optical fiber or cable. Optoelectronic systems belonging to this former category are based on scattering phenomena in silica fibers: Raman, Brillouin and now Rayleigh. These effects, combined with, time or frequency-based reflectometry (respectively OTDR and OFDR) provide the user with the desired sensing profile all along fiber(s) under test.

Nowadays, they are many market sectors for these techniques, and there is no industry which may not be concerned by an application or another. Many applications are often defined as "Structural Health Monitoring" of materiel and structures. Today, "distributed" and "quasi-distributed" sensors have already begun to penetrate several industrial sectors: civil engineering, oil & gas, energy, security... as well as those involved in composite materials (marine, aeronautics, railway,... industries).

It is now obvious that, risk reduction, security, and lower costs, are main motivations for end users who, more and more, consider as a matter of concern both quality and health of the structures they manufacture, use or manage (buildings, bridges, tunnels, dams, pipelines, transportation means ...) . As a conclusion, the economy is now the main driver for OFS, and underlies many of their achievements.

DEVELOPMENT OF OPTICAL FIBER SENSOR TO MONITOR LIQUID COMPOSITE MOLDING PROCESS (LCM)

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An instrumentation system based on specific optical fiber sensor (OFS) was developed during the LCM Smart project in order to improve the reliability of LCM processes. First applications of this instrumentation were developed and adapted to a semi-industrial LCM system for the monitoring of the resin transfer molding process (RTM). The main challenges were the integration of the sensors to the process and the analysis of the OFS's responses. Specifically, these sensors require a special caution to be embedded into the materials, to ensure reliable information about the process.

In this project the instrumentation was applied to the case of the manufacturing of flat part. We have demonstrated the capacity of OFS to monitor temperature, flow front, degree of cure and internal strain in various geometries including thickness variations and ply-drops. A first comparison was carried out with some results from manufacturing simulations, in order to evaluate the reliability of both measurements methodology and numerical models. The instrumentation has highlighted the limits of the modeling, particularly for the prediction of the residual stresses. We have noticed an additional major source of residual stress coming from the Part/Tool interaction during the cooling stage. A first prototype of RTM composite Tool made up with HexTool material has been developed and proved to reduce this interaction. Finally this instrumentation was extended to the development of two industrial parts processing made by Issoire Aviation and SKF Aerospace.

OPTICAL SENSORS: AN OPPORTUNITY FOR FASTER AIRCRAFT DEVELOPMENT?

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At the beginning of 2007, Airbus launched a four-year restructuring programme referred to as 'Power8'. Power8 aimed to build a fully integrated company that would be leaner, more efficient and more productive in order to improve the Airbus' competitiveness. One the eight levers was to develop faster new aircrafts. This new way of working has been applied for the A350 XWB reducing by 2.5 years the development cycle. It has reduced by about one year the industrialization cycle of a completely new aircraft although this one is more than 50% in weight manufactured with composite materials.

This article deals about the challenges faced on the development of the A350 components specially composite parts, in a difficult environment constrained by tight development schedule, productivity goals, weight targets, new high performance materials, new stronger lighting strike protection requirements, harmonization inside airbus, high level of quality required for allowable never used before, and constraints linked to the assembly of composite parts. In particular it was the first time that a long range aircraft was designed with carbon fuselage panels. The A350 fuselage's structural design comprises carbon fibre panels and frames, together with metallic cross-beams - a departure for Airbus which has traditionally used aluminium for the bulk of the fuselage structure. The goal was to achieve a very mature technology both from the technical and the manufacturing point of view. For this, an ambitious demonstrator programme has been launched to ensure both "maturity and certification" compliance of the design.

Figure 1- 16 m-long shell demonstrator.

Embedment of very low intrusive sensors like optical fibre sensors represents a real importunity to monitor lot of process parameters during the manufacturing of these demonstrators. One goal can be to detect possible indications during the manufacturing process anticipating the presence of defects and therefore enabling a sooner actuation to mitigate problems and avoiding systematic repetitions. Then these sensors can be used during test campaigns completing data habitually obtained by electric gauges. Finally it can also reduce or even eliminate partially the number of Non Destructive Inspections that today are mandatory performed during the production of composite parts.

ISOTHERMAL AND NON-ISOTHERMAL THERMOSET CURE AND INDUCED-STRAINS MONITORED BY OPTICAL FIBRE SENSORS

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Introduction

Thermosetting-based composites are generally used as structural materials because of their excellent specific strength. However, they can suffer for sensitivity to damage and impact, and their properties are not always well predicted. This is caused partially by residual internal stresses and flaws, originating from the elaboration process. This latter can be monitored by including adequate high performance in-situ sensing systems, allowing a better knowledge of the process cycle and its related parameters.

One of the key parameter is the degree of conversion and the temperature history experienced by the matrix resin, that ensure partly the quality of the composite part. However, as thermosetting reactions are exothermic, purely isothermal curing is often not strictly reached and temperature should be measured and highly controlled. If this is not the case, this can result e.g. for thick parts, in matrix degradation or incomplete curing. Secondly, conceptually the process and the materials in presence induce inevitably the development of cure residual stresses (CRS) that can affect the final material properties. CRS have three main origins: chemical (cross-linking shrinkage), thermal (mismatch between the thermal expansion of all the components at different scales), and mould-laminate interaction origins. The knowledge of the development, characterisation and amplitude of these CRS is thus necessary to reduce their effects thanks to an optimisation of the cure cycle (by adjusting the process parameters) and materials.

Cure monitoring assessment

In this study, we first report on the cure monitoring of a thermosetting resin usually used in liquid composite moulding processes (RTM6), by using simultaneously a multiinstrumentation based on a Fresnel refractometer sensor together with a dielectric analyze (flexible PI interdigitated electrodes sensor). The measurements were compared and a high correlation between dielectric and optical signals was shown. It allowed to base our analyses of the curing only on the signal from the weak-intrusive optical sensor. In a second step, Fresnel signal was calibrated with the predictions of a classical thermo-kinetic model of the RTM6 resin cure, assuming parameters values from the literature, and temperature measurements for inverse identification of the heat exchange coefficient between the resin and its environment.

Two mould materials were used to enhance or reduce the exothermic phenomenon, leading to isothermal and non-isothermal cures. In both cases quantitative values of the degree of conversion were deduced from the experimental Fresnel signal together with the numerical model of the cure. Under isothermal conditions, results showed that the Fresnel signal can be directly exploited to obtain qualitatively the degree of conversion. This was also demonstrated in non-isothermal conditions by correcting the Fresnel signal from its temperature dependence. If the initial degree of conversion is known, its quantitative assessment can be achieved using the Fresnel and temperature measurements.

Cure-induced strains by fibre Bragg grating sensor

The different curing experiments were also monitored using fibre Bragg grating (FBG) sensors and thermocouples to assess the cure-induced strains, the evolution of the degree of conversion of the resin being known. For all experiments (isothermal or non-isothermal), at the onset of stress transfer to the optical fibre, the degree of conversion ranged between 0.63 and 0.68 (slightly higher than the degree of conversion at gel point). It was also reported that the FBG deformed under chemical shrinkage with an amplitude widely lower than the expected chemical strain, showing that the FBG signal was not directly related to the actual chemical shrinkage. However, once the resin was cured, the FBG provides directly the coefficient of thermal expansion of the resin, which was calculated for the different experiments as a function of both the temperature and degree of conversion. Finally, glass temperature transition and debonding from the mould were also clearly detected by the FBG sensor.

PROCESS MONITORING OF FIBRE REINFORCED COMPOSITES: A TRIBUTE

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1. Introduction

Advanced fibre reinforced composites (AFRCs) are used extensively in industrial sectors where weight is at a premium, for example, aerospace, automotive, marine and sport. AFRCs consist of three key components: (i) the reinforcement; (ii) the matrix; and (iii) the interface between the reinforcement and the matrix. The reinforcement can be in the form of continuous fibres or rovings, short-fibres, woven, knitted and stitched fabrics, braided preforms and prepregs. AFRCs can be manufactured using a number of techniques including the following: (i) filament winding; (ii) pultrusion; (iii) pull-winding, (iv) resin transfer moulding, (v) resin/film/vacuum infusion, (vi) autoclaving, (vii) out-of autoclave moulding, (viii) hand/spray layup, (ix) diaphragm forming, (x) reaction injection moulding and (xi) tape laying.

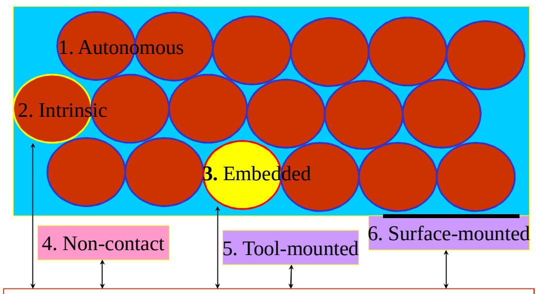
The manufacturing of AFRCs, using thermosetting matrices, starts with the impregnation of the reinforcement by the matrix; this is followed by consolidation (vacuum and external pressure) of the laminated preform, and cross-linking of the matrix, generally by the application of heat. The cross-linking reactions of certain classes of thermosetting resins can also be initiated by UV-visible light, electron-beam and microwaves.

The rate and extent of chemical conversion of the functional groups present in the matrix or resin system can be influenced by parameters such as: (i) the chemical integrity of the constituent components of the resin; (ii) the number of freeze/thaw cycles experienced (relevant to prepregs that are stored at sub-ambient temperatures; (iv) the moisture content on the surface or the fibres or binder; (v) the rate of heating and the heat-transfer efficiency in and out of the preform; and (vi) the surface chemistry of the reinforcing fibres (including the chemistry of the binder).

chemical reactions involving the monomers in thermosetting resins result in shrinkage during cross-linking as new covalent bonds are formed. Furthermore, thermosetting reactions are exothermic and therefore, efficient thermal management is important especially for large and thick laminated preforms. Failure to control the temperature within the laminate can lead to an "exotherm" where the temperature released during the cross-linking reactions exceeds the desired processing (isothermal) temperature; this can lead to the thermo-oxidative degradation of the matrix. Under normal processing conditions, when the composite is cooled down from its processing temperature, residual stresses can develop in the material due to the thermal expansion mismatch between the fibres and the matrix, and other factors such as tool/preform interactions. The magnitude of the residual fabrication stresses can be large enough to cause warping of the composite; these stresses can also be high enough to initiate cracking and delamination.

2. Criteria for selecting sensor for process monitoring

The selection of the most appropriate sensor system for process monitoring of AFRCs is not straight forward as due consideration has to be given to a multitude of factors. With reference to process monitoring of AFRCs, Figure 1 presents a schematic illustration of possible sensing strategies.



(i) Interface engineering, Sensor protection, Dimensions, Fibre route. (ii). Integration, Minimise perturbation, Inter-connection. (iii). Power, Data acquisition, Data Management, Interpretation. (iv). Response, Repair, Redundancy, Cost, Ease of use, Re-certification, Fit-for-purpose.

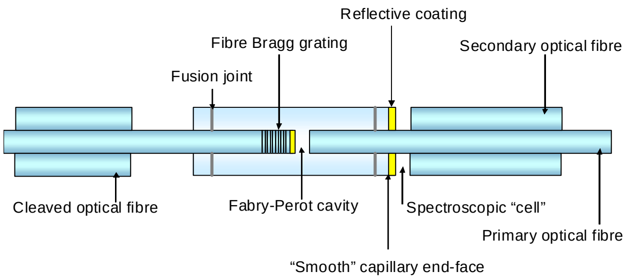
Figure 1 illustrates five sensing strategies for AFRCs. The first is referred to an autonomous composite which by definition is capable of sensing and responding to the stimuli/measurand without any human intervention. The second is the situation where the reinforcing fibres are used as the sensor (optical or electrical). In the optical case, the assumption is that the reinforcing fibre is capable of transmitting light; here the matrix acts as the cladding for the core of the "optical fibre". The third sensing strategy is where the sensor is embedded or integrated into the preform. The fourth approach is where the sensing system offers a non-contact route for process monitoring. Here the sensor system is position over the preform to facilitate process monitoring. The final sensing strategy considered here is surface-mounted sensor systems. The double-sided arrows indicate some of the key issues that need to be considered. A similar approach can be taken with regard to the integration of specified classes of sensor systems for specified classes of preforms, manufacturing process and end-use application.

In situations where quantitative information is required on the cross-linking kinetics of thermosetting resins, the only traceable option is to use spectral techniques where the depletion and formation of specified chemical functional groups in the resin system can be tracked in real-time. A primary perquisite for kinetic modelling is that information on the temperature of the resin system during cross-linking is also required. As indicated previously, it cannot be assumed that the set isothermal temperature is a true representation of the temperature within the resin system during cross-linking. The other complication is the spatial location of the sensor within the preform where the shrinkage of the resin can be influenced by the degree of "bonding" between the preform and the surface of the mould/substrate.

3. Overview of the Presentation

This talk will discuss briefly, the above-mentioned issues and proceed to give an overview of optical fibre-based sensor system that have been demonstrated in the Sensors and Composites Group including the following categories: (i) transmission; (ii) reflection; (iii) evanescent wave; (iv) Fresnel; (v) non-contact probes; (vi) self-sensing reinforcing fibre light guides; and (vii) multi-functional sensors.

To-date, majority of the fibre optic-based sensor systems have been single or at the most, dual-measurand systems. This paper presents an overview of the design and deployment of a multi-measurand optical fibre sensor (MMS). The MMS is capable of monitoring four independent measurands simultaneously: strain, temperature, relative concentration of specified functional groups in the resin system and refractive index. The sensor design is based on the extrinsic fibre Fabry-Perot interferometer. A unique feature of this design is that a conventional fibre-coupled near-infrared spectrometer is used to monitor the four independent parameters.



A schematic illustration of the multi-functional sensor is presented in Figure 2.

RESIDUAL STRAIN MONITORING DURING COMPOSITE MANUFACTURING USING THE POLARIZATION DEPENDENT LOSS PROPERTY OF FBGS

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Keywords: Fibre Bragg gratings, Optical fibres, Polarization dependent loss, cure cycle monitoring, residual strain monitoring

In general, structural health monitoring (SHM) of composite structures is considered very valuable certainly in terms of determining a correct maintenance or repair services. SHM, however, can already start at the beginning of the production process! A very important aspect of the composite manufacturing process is the appearance of residual strains and stresses during the curing cycle. Composites exhibit large residual strains after curing, which vary depending on the type of composite constituents, composite lay-up and manufacturing technology. The formation of thermal residual strains in unidirectional and cross-ply laminates arises mainly from the difference in thermal expansion between the reinforcement fibres (~ -0.55 x 10-6) and the matrix (or resin) material (~30 x 10-6) but the origin of strain development is completely different than mechanical induced strains.

Fibre Bragg gratings (FBG) are very well suited to serve as embedded strain sensor to monitor the internal strain state of composite structures. It is the reason why, when embedded into a composite laminate, their spectral response (wavelength shift) will depend on external perturbations (or deformations) of the structure. Next to deformations, temperature as well has a large influence on the spectral behaviour of the FBG. Therefore, during monitoring (in whatsoever application) temperature compensation is necessary. Temperature compensation methods are numerously discussed in literature however in most cases they are impractical for real life and certainly for embedded sensor applications. Therefore, we suggest to combine the wavelength shifts with an extra parameter which we can measure namely the polarization dependent loss (PDL). The PDL is defined as the maximum change in the transmitted power when the input state of polarization is varied over all polarization states. This parameter allows us to do temperature compensation at the exact position of the sensor using a standard single-mode optical fiber. This is particularly interesting in cure cycle monitoring, since because of exothermic reactions the temperature can vary in different locations of the laminate (making temperature compensation a hard job when considering conventional TC-methods).

In this presentation, the authors are investigating the possibility to estimate the magnitude of residual strains during the autoclave manufacturing process of carbon fibre reinforced cross-ply laminates (M18/M55J CFRP) by combining the wavelength shift of the grating, its amplitude spectrum and in addition using the temperature insensitive polarization dependent loss of the grating.

MONITORING OF COMPOSITE MATERIAL PROCESSING AND COMMISSIONING USING A SUITE OF OPTICAL FIBRE SENSORS

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A unique characteristic of optical fibre sensors is that they can be embedded within a composite part to monitor the entire manufacturing process because of their small diameter, typically 80-125 μm. They are suitable for embedding into carbon fibre reinforced composites as, unlike the dielectric sensors, they do not have electrical connections. This offers unrivalled capability to monitor composite material processing on-line and *in-situ*. It is important to monitor critical manufacturing stages, so as to guarantee consistent quality in the product. The progress of infusion, the degree of cure, temperature and strain development are important parameters to monitor.

A suite of optical fibre sensors were embedded in various composite parts, both simple and complex shaped. The composite parts included components manufactured from prepregs, hand-laid preforms, and preforms made by the automatic dry fibre placement (ADFP) process using an industrial robot system. The components included aerospace structures such as tail-cones and wings, and industrial superconducting magnets. Some of the preforms were reinforced by through-thickness tufting. Infusion and cure of the laid-up components was carried-out using various processes; resin transfer moulding (RTM), vacuum bagging in an oven, and autoclave systems in both laboratory and industrial environments.

The tufting of the composite preform was monitored using multiplexed fibre Bragg grating (FBG) strain sensors which were affixed to the tufting needle. The infusion of resin through dry fibre composite preform was monitored by detecting the change in refractive index surrounding the optical fibre when the resin arrived at the sensors locations. Optical fibre Fresnel refractometers, tilted fibre Bragg grating (TFBG) sensors, tapered optical fibre sensors, and chirped long period grating (CLPG) sensors were used for infusion monitoring. The subsequent cure of the resin was monitored by measuring changes in the refractive index of the resin using Fresnel refractometers, TFBG sensors, long period grating (LPG) sensors, and also by monitoring the development of transverse strain as a measure of resin gelation using FBG sensors fabricated in highly linearly birefringent (HiBi) fibre. Such strain measurements are also necessary for determining the presence of residual strain, a property that also characterises the quality of the final composite part. A number of HiBi FBG sensor orientations within the preforms were investigated. The HiBi FBG sensors were also used to measure the longitudinal and transverse strain during the subsequent mechanical testing of the final composite part.

The monitoring of the load experienced by the needle during tufting could provide vital information on a number of important issues; wear of the needle, the mechanical configuration and alignment of the tufting head, detection of damage caused to the reinforcing fibres, resin build-up on the needle when tufting prepregs or binders, and the influence of the ADFP process on the composite quality. The experimental results showed that it is also possible to determine the number of layers locally within preform.

A multiple channel fibre optic Fresnel refractometer was developed exploiting electronic-board lock-in amplifiers, allowing measurements to be made at multiple locations within the component simultaneously. The refractometer relies on monitoring the amount of light reflected off a cleaved end of an optical fibre and was used to monitor resin infusion and cure. The arrival of resin at the location of the sensor is detected as a sudden attenuation in the reflected light signal. Infusion, both in-plane and through-thickness, was performed with aerospace resins such as RTM6 into carbon fibre preform laid up by various processes. The measurements demonstrated the capability of the sensors to map the presence of resin at specific locations within the preform and to map the flow of the resin during infusion.

Experimental characterisation of the resins in terms of the degree of cure and change in the refractive index during cure were performed. The degree of cure was determined from temperature-modulated differential scanning Calorimetry (DSC) measurements. The change in the refractive index of the resin was measured using the Fresnel refractometer. The refractive index was well correlated with the degree of cure, providing a correlation function for an isothermally cured resin. Good correlation between the refractive index change and degree of cure was also obtained when resin systems were modified by the addition of multi-walled carbon nanotubes (CNT).

The refractive index of a medium immediately surrounding an optical fibre can be measured using an optical fibre taper, because it facilitates strong interaction between the light propagating in the fibre and its surroundings. High spatial resolution optical frequency domain reflectometry was used to interrogate a serial array of multiplexed tapered optical fibre sensors (50 μm diameter) when monitoring resin infusion. The technique relies on monitoring the change in the attenuation of the Rayleigh backscattered signal from the tapered regions. The tapers were used to monitor resin infusion, both in-plane and through-thickness, in carbon fibre preforms.

The core–cladding mode coupling resonances of TFBG and of LPG sensors are sensitive to the refractive index of the surrounding medium. Multiplexed TFBG sensors of relatively large tilt angle have been used to monitor resin infusion at multiple locations within carbon fibre preform. The coupling to the cladding mode (on the blue side of the Bragg resonance) from a TFBG of relatively low tilt angle is insensitive to the surrounding refractive index and such TFBGs have been used to measure temperature during resin cure. The response of an LPG to the refractive index of the surrounding medium is manifested as a shift in the central wavelength of the attenuation bands. A CLPG was demonstrated for monitoring the direction of flow of resin during infusion. The asymmetry in the CLPG provides the ability to distinguish the direction in which the resin flows over it. Both uniform period LPG and CLPG sensors were used to monitor the cure process of a UV-cured resin and the results compared very well to results from a Fresnel refractometer.

HiBi FBG sensors were embedded in glass fibre/epoxy composites to monitor the effective transverse strain development during cure. The transverse strain demonstrated high sensitivity to the degree of cure and this sensitivity was shown to depend on the orientation of the HiBi FBG sensors to the reinforcement fibres. HiBi FBG sensors were also embedded within superconducting magnet structures. The superconducting magnets were infused with MY750 resin system and cured in an autoclave. The sensors were subsequently used to monitor orthogonal strain components during energisation and quench processes which are part of the commissioning process of the magnets.

In summary a range of optical fibre sensors have been used to measure refractive index and strain during the processing of carbon and glass fibre reinforced composites, from which information on the infusion and degree of cure of the resin, and the development of residual strain can be determined. FBG sensors were also used to monitor the strain on a tufting needle.

SEMI-EXPERIMENTAL METHODS FOR STRESS ANALYSIS IN POLYMERIC MATERIALS WITH EMBEDDED OPTICAL FIBERS

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Characterization of internal strains in polymers and composite materials is at the forefront of experimental mechanics. Experiments and analysis have demonstrated that embedded optical fiber Bragg grating (FBG) sensors are well suited for single and multiplexed strain measurements in composite materials and structures. They show an intrinsic self-referencing capability, have excellent resistance to corrosion and high temperatures, are immune to electromagnetic interference and are not susceptible to power fluctuations. Thus such sensors have attracted particular attention over the past few decades in the aerospace and automotive industries, manufacturing process monitoring, structural health monitoring, etc. While the advantages of embedded FBG, over other techniques, are very clear, a number of problems exists that need to be properly addressed and resolved. These relate to the fact that (i) strain measurements are made on the fibre itself while the interest is on the strains in the host material and (ii) the non-homogeneous strain field along the fibre which is difficult to construct with sufficient resolution.

Mechanically, the FBG sensor acts as an elastic inclusion in the host material. To obtain the strain and stress fields in the surrounding material a realistic micro-mechanics, physically based, model is needed. Such a model is not easy to establish given the essentially 3D nature of the problem and the local material morphology, especially in composite materials. When the sensor is embedded in a non-homogeneous strain field the interpretation of the sensor response, along its length is complicated. Typically the reflection spectrum becomes broader and several peaks appear. Such spectra modifications may be due to polarisation induced lateral strains and/or non-homogeneous strains along the fibre axis. In addition a spectrum obtained by standard procedures is an integral form of response and details regarding the strain distribution are not apparent. This form of the signal complicates the identification of the actual distribution on the fibre, especially in cases of high strain gradients. Even if various techniques, like the T-matrix formalism, are available to predict spectra modifications, from a given strain distribution, the inverse problem, i.e. the determination of the applied strain from a measured spectral response, is a tedious task and require assumptions on the strain profile and several iterations. In cases where non-homogeneous strains prevail, technique based on FBG spectra synthesis should be used. Such methods can provide distributed strains over several millimeters thus, capturing the essential attributes of the actual strains due to damage, delamination, residual strains, etc. However they are not always suited for measurements under dynamic loads.

One of the major advantages of the FBG sensors is that they can be multiplexed. It means that several short FBGs, each one with slightly different Bragg wavelength, can be inscribed on the same fiber and be interrogated simultaneously. Thus, strain data can be obtained in several points of the structure by monitoring the wavelength changes of each FBG sensor. Such quasi-distributed strains can be very useful in damage characterization and structural monitoring. Progress in high rate interrogation systems for short Bragg gratings permits the use of FBG sensors in dynamics experiments. In this presentation, the merits and limitations of FBG sensors for internal strains are mentioned and experimental results are presented in various configurations. These include: (a) residual strains due to curing, (b) strains through the thickness of a composite, (c) strains due to delamination, (d) modal and damage analysis due to low energy impact, etc. Such strain data are confronted with analytical and numerical models. The present studies demonstrate that internal strain measurements using embedded FBG sensors, accompanied by appropriate modeling, can provide important data for the characterization of deformation and fracture of polymeric materials. Such results can also offer sound basis for the development of realistic structural health monitoring methods.

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MONITORING THE INTERNAL TEMPERATURE AND DEGRADATION BY FIRE OF COMPOSITE LAMINATES BY EMBEDDED FIBRE OPTIC SENSORS.

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Fire resistance is a critical requirement for some components of the aircraft structure, such as engine cowlings; the structural material must be able to contain an internal fire for at least 15 minutes, to allow the extinction system to extinguish the fire before it propagates to the structure. Composite materials degrade under fire, but the char layer is an effective low thermal conductivity protecting layer, insulating the material and delaying the degradation. Detailed mathematical models for the composite behavior are available, but to obtain accurate predictions, temperature dependent experimental parameters are requested. Only with knowledge of the internal temperature distribution a quantitative prediction can be done. Fiber optic sensors have a thickness similar to the lamina, and consequently can be embedded without disturbing the laminate. FBG sensors can withstand temperatures up to 900 Celsius for several minutes, so a detailed mapping of internal temperatures may be obtained. The paper describes the experimental setup and the obtained results on real aeronautic parts submitted to fire.