1. Abstract

A multi-disciplinary study is described, aimed at the development of health and condition monitoring systems for advanced composite aerospace structures, using an embedded optical sensor technology. The study encompasses various aspects of the subject, including the embedding of optical fibers in composite structures, analysis of the effects of the embedded fibers on the mechanical performance of the composite, designing the sensors and the measurement techniques, and developing methods of ingress and outgress of the fibers to and from the structures.

The addition of self-monitoring capabilities to advanced structures, mainly in the aerospace industry, may significantly boost their performance by supplementing extra value in terms of implementation, real-time health monitoring, maintenance programs, etc. The maturing technology of optical fiber sensors seems to be a natural candidate for this application, whereas structures made of composite materials are the perfect "hosts". Potentially miniature fiber sensors, which are immune to electromagnetic interference, may be embedded in a structure during its manufacture and be concatenated (multiplexed) so that several or often even dozens of them may be built into a single hair-like optical fiber, whose interference with the host structure is usually minor. Important parameters concerning the host structure, like temperatures, strains, vibrations, etc., may be monitored by these sensors, serving both real-time and post-flight decision-making processes. However, embedding these sensor systems in composite materials with the aim of producing such "Smart" components for future aerospace

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applications, requires research and development in various fields before it can be realized. In the study reported here the following issues were addressed:

- Developing fiber-optic sensors for strain measurement;

- Embedding the fibers and sensors so that they will have a minimal impact on the overall mechanical performance of the host material;

- Multiplexing several sensors on a single optical fiber;

- Studying the effects of the embedded sensors on strain distribution in the host material; and,

- Developing robust termination methods, i.e., methods to optically connect the sensors between different host components and external instrumentation.

The multi-disciplinary team studied these aspects of embedded fiber-optic sensor technology in order to establish the necessary infrastructure for a practical system.

Optical fiber embedding was studied using mostly autoclave cured prepreg lay-up composite materials. At processing conditions of up to 185°C and 7 bar pressure, acrylic jacketed fibers were unstable. Accordingly, all development work reported here has been based on commercial polyimide jacketed fibers. Embedding these fibers was straightforward, except for the problem at the laminate edge, described in more detail in the next
section. Since the individual thickness of the plies was of the same order as the fiber diameter, i.e., approximately 145 μm, substantial disturbance was caused to the local arrangement of laminate plies, producing resin-rich areas adjacent to the fiber. It was found possible to embed crossed fibers into a laminate without mechanical failure of the fibers. However, it was decided not to use fiber crossovers between the same two plies due to the gross disturbance that the crossover produced in the local laminate structure. It was found that fiber crossovers, where fibers were situated between different laminate plies, produced a smaller disturbance, as shown in Figure 1. Should an optical fiber arrangement of this type be required, e.g., for a strain sensing array, it is recommended that the individual fiber segments in the crossover be separated between laminate plies.

Fig. 1: Crossover of three optical fibers in different planes within a laminate.
When embedding optical fibers into laminates in order to provide a strain sensing capability, the strain in the optical fiber should reflect the strain in the laminate. Good adhesion between the optical fiber and the laminate matrix is required in order to achieve this aim. Prior to embedding, all fibers were wiped with acetone or MEK to ensure a clean surface, and to promote matrix wetting and adhesion. In addition, the level of adhesion of the optical fibers to the epoxy resins was checked, using a variant of the well-known tensile fiber microfragmentation test. This test revealed that with a properly cleaned fiber, the adhesion of the matrix resin to the polyimide jacket was better than the excellent adhesion of the jacket to the fiber. Thus, the cleaning methods used were assumed to be adequate for ensuring proper adhesion between optical fibers and the laminate matrix.

The development of self-monitoring ("Smart") composites for future aerospace applications requires an infrastructure for the optical connection of the various structural parts, as well as the connection to electro-optical equipment. Interrogation of optical fiber sensor systems requires precision contact with the circuitry of the monitoring instrumentation in order to enable meaningful measurements. The development of practical connection methods was divided into three stages: studies on bare fibers, use of edge connectors, and use of surface mounted connectors.

Initial studies concentrated on embedding unprotected optical fibers into simple laminated plates for laboratory assessment purposes. It became immediately obvious that the entry and exit points of the fibers at the

3.2 Terminations and Connections

3.2.1. Bare Fibers
laminate edges were problematic. The laminates were manufactured using conventional aircraft industry prepreg lay-up, vacuum bag and autoclave cure techniques incorporating cure and post-cure temperatures up to 185°C and pressures up to 7 bar. During the heating phase of the curing process, the resin viscosity dropped to a very low level prior to the start of gelation. Consequently, substantial resin flow occurred, usually into areas of the vacuum bag and auxiliary materials within the bag outside the area of the laminate itself. This resin flow onto optical fibers extending from the area of the laminate (see Figure 2) caused embrittlement of the optical fibers to such an extent that demoulding and handling of the laminate without breaking the optical fibers was very difficult.

Fig. 2: Resin flow onto exposed ends of embedded optical fibers.

Methods similar to those described by Spillman and Lord were developed, using embedded thermoplastic sleeves and locally laminated restricted flow film adhesives for resin flow control at the laminate edges. This study was reported by us elsewhere. The sleeves
thus made were used to produce a variety of test coupons, in which long lengths of bare fiber protruded from the edges for interfacing with the optical instrumentation. The sleeve/adhesive combination provided both fiber protection from resin flow and local stress concentrations during the cure process, as well as a strain relief interface at the entry and exit points in order to reduce fragility during handling in subsequent laboratory testing. The method described enabled the making of laboratory test articles, but would be impractical for any realistic in-service application. A similar approach was used in experimental studies, in which silicone rubber impregnated thermoplastic braids were used for edge protection. Here again, while providing solutions for laboratory studies, the developed solutions were impractical for routine service. A somewhat different method for fiber entry and exit point protection, using locally procured synthetic rubber implants, was also reported. There, the stated aim was to provide protection for an optical fiber during the composite manufacturing stage as well as a strain relief interface, enabling subsequent attachment to a connector. While this may be practical for the press-molding process, it is difficult to envisage how the autoclave process, which requires a long unprotected length of fiber for the optical connection, could ever be robust enough for any practical application.

The next phase of our development program concentrated on using components of standard optical fiber connectors embedded into the laminate. The

3.2.2 Edge Connectors
concept was to produce a part in which all the required connection hardware was effectively molded in. Conventional single mode optical fiber plugs and connectors, which have a diameter of approximately 8 mm, are clearly unsuitable for embedding into a composite part. The critical component of these connectors is a precision 2.5 mm diameter ferrule, usually ceramic, into which the fiber is bonded. Following bonding, the ferrule end is polished together with the fiber to provide the required smooth contact surface for low-loss optical signal transmission.

Our concept was to embed just the ferrule into the edge of a laminate, subsequent to bonding the fiber and polishing the ferrule end. Hardware was also embedded next to the ferrule in order to enable mechanical attachment to a standard straight-through optical plug adapter. This enabled direct attachment of a standard optical fiber cable with a FC-PC type connector, as shown in Figure 3. The measured losses of two sequential embedded connectors were in the range of 3-4

Fig. 3: FC-PC connector installation at laminate edge.
dB, about 2 dB above the typical level of two such sequential, free, i.e., non-embedded, connectors. These relatively small signal losses demonstrate that protection of the polished fiber end from resin flow, and mechanical protection of the fiber/ferrule assembly during the aggressive processing conditions typical of composite manufacture, were achieved. This connection was reasonably robust, but required a purpose designed local laminate build-up to accommodate the embedded ferrule and attachment hardware. Obviously, laminate trim in these areas was impossible.

A modified ceramic ferrule, disassembled from a commercial FC connector, was also utilized for the edge connector development reported by Spillman and Lord. In this case, the ferrule was embedded with the fiber during the laminate manufacturing process, and subsequently assembled by bonding to a purpose designed housing and alignment sleeve. The mating connector was also redesigned, incorporating a captive compliant bushing as the strain relief mechanism, minimizing the connector length. Unlike this approach, in the present work we used only standard commercial components (except for a simple modification of the ferrule to enable embedding), and light input and output was achieved via standard FC-PC terminated fiber cables. Optical testing of the connectors, showed low coupling losses of about 0.5dB, comparable to manufacturers' data for FC type connectors, after 25 disconnections and matings. As with the development reported here, laminate trim in the connector area was impossible, and connector mounting required a certain minimum laminate thickness.
A similar approach was used by Claus et al.\textsuperscript{7} In this case, a specially purpose designed embeddable miniaturized connectors were used as component-to-component edge connectors. The use of edge-embedded optical fiber connectors for the monitoring of optical fibers used as Lamb wave detectors as an in-situ composite NDT technique, has been also reported.\textsuperscript{8} In this case, it is not clear which components of the connector were incorporated during the manufacturing process of this laboratory demonstration item, and how positive an attachment to the monitoring instrumentation was achieved.

Note, that edge embedded optical connection hardware could cause substantial limitations on its applications. Most aircraft composite components require either edge trimming or molding to final dimensions using net dimension tooling. Additionally, such components need to be mechanically attached to adjacent structures. Obviously, edge-embedded connectors do not satisfy these requirements and therefore their applicability is limited. Hence it was decided to concentrate our efforts on methods where the connection is remote from the component edges.

### 3.2.3 Surface Mounted Connectors

The objective of this phase of our work was to identify an industrial, standard optical fiber plug or socket (or parts thereof), that could be used as an embeddable detail within a composite part free surface, and enable subsequent assembly into a robust connector system. Following a survey of the available hardware, a commercial fiber-optic printed circuit connector was selected. This connector is designed to provide optical
interconnection of daughter cards to motherboards in electronic equipment containing optical components. Single mode and multi mode versions are available, with 2, 4 or 8 connection channels, with a claimed single mode typical insertion loss of 0.5 dB. The daughter card assembly provides a floating connection, and alignment pins on the motherboard component assure mating. The motherboard component incorporates an interface for standard SC terminated optical cable assemblies.

The daughter card assembly contains removable spring loaded ceramic ferrule termini that enable floating connection. These termini are rugged units that can be protected from the rigors of composites manufacturing processes, in a similar manner to the one previously described for edge mounted ferrules. Efforts were concentrated on the development of the daughter card assembly as a surface mounted connector. This was achieved by incorporating the termini during the composite curing process and a subsequent attachment of the assembly body to the composite part, and insertion of the termini after curing.

First, polyimide jacketed fibers were bound into the termini, and the exposed ferrule end containing the fiber was polished, using the same procedures developed for the edge-mounted ferrule, which essentially were modifications of standard procedures for fiber connector assembly. Various diameter polytetrafluoroethylene sleeves were slid over the fiber and seated onto the termini ends to provide fiber protection over a length of a few centimeters. Where
termini were mounted onto both fiber ends, the sleeves were slid into place prior to bonding the termini to the fiber. Sleeve ends were potted with RTV silicone rubber to provide local fiber strain relief protection, and prevent resin flow into the sleeves during the composite cure process. Terminated fibers were then incorporated into the prepreg composite lay-up, using small apertures cut into the surface plies of the laminate to enable passage of the termini. Where a fiber with a terminus on one end only was concerned, this was achieved by piercing the surface plies with a hypodermic needle, and using the needle as a guide for fiber insertion.

At this stage, the lay-up was ready for autoclave consolidation. However, additional mechanical protection was needed in order to prevent physical damage of and resin ingress into the terminations during the cure process, and to avoid the terminations from embedding themselves into the laminate surface. Combinations of rigid and flexible tooling blocks were tried as protection methods with varying degrees of success. Eventually, a solution evolved that employed a silicone rubber block, cast in conform to the profile of the termini and the PTFE sleeves. The area and shape of the block was designed to minimise the print produced on the laminate surface at the block edges. Figure 4 illustrates a panel with embedded fibers and termini inserted into the daughter card assembly. Figure 5 shows the daughter card assembly attachment to the panel, and the insertion of the mating motherboard component. In this case, only 2 pins of a 4-pin connector were utilized. During optical testing of this assembly, a total signal loss of 1.5dB was measured, reasonably consistent with the
plug manufacturers' claim of 0.5dB insertion loss per terminus. An additional panel is shown in Figure 6. Here, a connector with an added shield, intended to protect the exposed segment of the fiber/sleeve assembly, was employed. Based on its performance we conclude, that our design of the surface mounted connectors meets the requirements for a robust, optically efficient system that can be incorporated readily with minimal geometrical disturbance into structural parts, using commercially available hardware.

Fig. 4: Embedded optical fibers and a surface mounted daughter-card assembly.

Fig. 5: Surface mounted daughter-card assembly and the insertion of the mating motherboard component.
3.3 Strain Measurement

Many approaches have been described in the literature for fiber-optic strain sensing. Some of these methods are suitable for measuring strain in composites with embedded sensors. We studied the use of two of these methods, i.e., RF modulation and Bragg gratings.

3.3.1 RF Modulation

In RF (Radio Frequency) measurements, the effect measured is the change of transit time of light along the embedded fiber as a function of axial strain. To measure this change efficiently, the embedded fiber forms part of an interferometer driven by a RF frequency modulated diode laser, as shown in Figure 7. Since the RF phase,
with which the light emerges from the embedded fiber, depends on transit time, measurement of this phase, enabled by the interferometric scheme, yields the desired strain value. The method was applied to various composite parts, equipped with conventional electrical resistance strain gauges for comparison purposes. A 2.5GHz RF source was used to amplitude modulate a 1.3μm optical carrier. The method was also used on a free fiber with direct micrometer measurement of strain, for reference and calibration purposes.

The method for deriving fiber strain from the measured phase shift has been described by Ben Artzi et al. The free fibers produced a linear strain indication as a function of the directly measured applied strain. However, deviations from linearity were observed in the case of embedded fibers; see Figure 8. The optically indicated strain fluctuated periodically around the strain value indicated by the electrical strain gauge, but the overall (smoothed) response of the two strain sensing systems was similar; a fact not observed in the figure, where the two response curves were separated for clarity.

![Fig. 8: Experimental results of RF interferometer strain measuring system and an externally adhered electrical strain gauge. The two curves are separated for clarity.](image)
The optical results for the embedded fiber were found to be highly sensitive to the polarization of the incident light. A polarization controller was installed just in front of the sample under test and, instead of increasing the applied load monotonically, the load was held at various fixed values. At these fixed points strain measurements were taken for different settings of the polarization controller, i.e., for different input polarization states. It was observed, that the variations in sensor output, caused by the changes in the input polarization state, were of the same magnitude as the fluctuations observed in the signal from the monotonically loaded embedded fibers, interrogated at a fixed input polarization state. Based on this as well as on other observations, it was concluded that the fluctuations had been the result of a collapse of the fiber axial symmetry during the high temperature/high pressure composite manufacturing process. This, in turn, produced a difference in the propagation constants of the two orthogonal polarization states, a fact known as polarization mode dispersion. Notwithstanding this effect, it was found possible to use the RF technique for measuring the integrated total strain along the embedded fiber length.

3.3.2 Bragg Gratings

Aerospace component structural monitoring usually requires localized strain measurements. The integrated strain sensing characteristic of the RF modulation technique described above makes it unsuitable for point measurement. Accordingly, the use of Bragg grating sensors, which provide a ~10mm measurement resolution capability, was studied as well. The Bragg grating⁹
consists of a permanent periodic optical structure, i.e., a permanent diffraction grating, written by UV light onto the fiber core. Out of a broad spectrum light, travelling down the fiber, a specific wavelength is back reflected by the grating with a high optical efficiency. This wavelength is a function of the grating period, and thus indicates the local strain at the grating location as a shift in the reflected wavelength. \(^9\) This approach is being actively studied worldwide, following the recent commercial availability of these gratings.

Initial trials, performed in this study with Bragg type sensors embedded into composite samples, indicated good linearity and repeatability of response, using electrical gauges as references. In one of the instances one optical fiber containing two Bragg gratings was embedded in the beam, while electrical strain gauges were externally adhered to it in order to supply reference strain readings. The orientations of the gratings were along the beam's two orthogonal axes. Figure 9 shows typical results obtained for the optical spectra of the light back-reflected from the fiber by the two gratings, with and without a 300\(\mu\)s tensile strain. The right-hand peak in that figure, originating from the grating along the rectangular length and along the carbon-fiber direction, shows the expected single peak form as in the case of an un-embedded fiber. However,

![Graph showing optical spectra](image-url)

**Fig. 9: Optical spectra of the back reflection of two perpendicular gratings in a single embedded fiber with (green) and without (red) a 300\(\mu\)s tensile strain.**
the left-hand one, originating from the orthogonal grating, is clearly split into two peaks. The origin of this new feature is currently being investigated. However, initial indications show that the observed behavior may be ascribed to the asymmetric stresses induced into the host fiber by the orthogonal carbon fibers during the manufacture process. As for the right-hand peak, its position changed linearly as tensile force was applied to the beam. This can be seen in Figure 10.

![Graph](image)

**Fig. 10:** Response of a Bragg grating embedded along the carbon fibers to an increase of the external tensile force (green line) compared to the readings of an electrical strain gauge (red crosses).

### 3.4 Separation of strain and temperature effects

A significant advantage of the described sensors is that by suitable multiplexing arrangements it is possible to incorporate multiple sensors on a single fiber to provide a multi-point strain measuring capability. A system was developed for the multiplexing of ten sensors, via interrogation of individual sensors in appropriate time windows.

An inherent problem of the Bragg sensors is the superposition of the effects of temperature and strain.\textsuperscript{11} Strain applied to a Bragg sensor alters its reflected
wavelength, which unfortunately is affected also to approximately the same extent by temperature changes encountered during flight. Many solutions of this problem have been suggested, but very few appear to be applicable under practical conditions. In an interesting solution, which was also explored by us, the optical fiber was tapered over a length of a few millimeters and the grating then written in the tapered area while the fiber was under tension. For a sensor of this configuration, if the spectral width of the grating reflection (rather than the central peak wavelength) is monitored, a signal is obtained that depends only on strain and not on temperature.

Another approach that we are currently investigating is dedicating special Bragg grating sensors to temperature measurements. These gratings are ordinary, with a host fiber that is mechanically, but not thermally, isolated from its surrounding. This way, only temperature changes but not strain variations affect the sensors that report on the local temperature. This information then serves to cancel the temperature effect from nearby sensors' responses. We are currently investigating this approach.

An embedded optical fiber in a composite structure might affect the strength of the host composite material. We have tried to quantify this effect by computing the change in the stress field of the composite material, due to the presence of an embedded coated (jacketed) optical fiber. In fact, since the embedded optical fiber is meant to be used as a strain gauge, it is important to know how much does the strain "felt" by the fiber differ from the strain that would have been present in the composite, should the fiber not be there. To

3.5 Stress and strain changes due to the presence of an embedded optical fiber
this end, the strain field in a system consisting of an optical fiber, its coating, and a host material, was analytically computed as well as the change in strain reading due to the presence of the optical strain gauge.

A simplified model of the composite structure and the embedded optical fiber was used in order to compute the stress and strain fields. The fiber was assumed to be embedded in a transversely isotropic material along the symmetry axis. Both the fiber and the coating were assumed to have isotropic mechanical properties, and the bonding between the three materials was assumed to be perfect. Figure 11 describes a cross-section perpendicular to the fiber axis with a cylindrical coordinate system. The symmetry axis of the fiber is parallel to the Z axis, while rf and rj are the radii of the fiber and the jacket (coating), respectively.

Fig. 11: Model description.

The material properties and dimensions used for the solution process are:

\[ rf = 62.5 \mu m, \quad rj = 75 \mu m, \quad rc = 5 rf \]
\[ E' = 60 \times 10^9 \text{Pa}, \quad \nu' = 0.2 \quad E'' = 10^9 \text{Pa}, \quad \nu'' = 0.3 \]

\[ E_{11}'' = 180 \times 10^9 \text{Pa}, \quad E_{22}'' = 5 \times 10^9 \text{Pa}, \quad \nu_{12}'' = 0.25, \quad \nu_{23}'' = 0.35, \quad G_{12}'' = 4 \times 10^9 \text{Pa} \]

where \( E, \nu \) and \( G \) are the elastic moduli of the materials involved (\( f \)=fiber, \( j \)=coating and \( c \)=composite).

The composite material is subjected to uniaxial traction \( S \), which can be described in a cylindrical coordinate system, along the radius \( r_c \) and on the cross section at \( z=L \), in the form:

\[
\sigma_r(r_c) = \frac{1}{2} S [1 + \cos(2\theta)]
\]

(1)

\[
\sigma_\theta(r_c) = -\frac{1}{2} S \sin(2\theta)
\]

\[
\int_A \sigma_\alpha(z=L) dA = 0
\]

The form of the boundary conditions suggests deflections of the form given by Pagano and Tandon\(^{14}\):

\[
u' = \left( A'_{11} r^3 + \frac{A'_{12}}{r^3} + A'_{13} r + \frac{A'_{14}}{r} \right) \cos(2\theta) + D'_{11} r - \frac{D'_{12}}{r^2}
\]

\[
u' = \left( B'_{11} A'_{11} r^3 + \frac{A'_{12}}{r^3} - A'_{13} r + B'_{14} \frac{A'_{14}}{r} \right) \sin(2\theta)
\]

\[
u' = D'_{13} z + \left( \frac{F'_{15}}{r} + F'_{16} r \right) \cos(\theta) + \left( \frac{H'_{15}}{r} + H'_{16} r \right) \sin(\theta)
\]

and

\[ B'_{11} = -\frac{3 C'_{12} + C'_{23}}{2 C'_{23}} \quad B'_{14} = \frac{C'_{23} - C'_{22}}{2 C'_{22}} \]

where \( C'_{kl} \) are the components of the stiffness of material \( i \).
In a similar manner to the treatment applied by Carman and Reifsnider, we use the strain deflection relations

\[
\varepsilon_\tau = \frac{\partial u_\tau}{\partial r}, \quad \varepsilon_\theta = -\frac{1}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{u_\tau}{r}, \quad \varepsilon_z = \frac{\partial u_z}{\partial z}
\]

\[
\varepsilon_\tau = \frac{1}{2} \left( \frac{1}{r} \frac{\partial u_\tau}{\partial \theta} + \frac{\partial u_\theta}{\partial r} + \frac{u_\tau}{r} \right), \quad \varepsilon_z = \frac{1}{2} \left( \frac{\partial u_z}{\partial r} + \frac{\partial u_\tau}{\partial z} \right)
\]

and Hooke's law for transversely isotropic materials, to write the continuity conditions for displacements and traction at the material interfaces, rf and rj, and the stress boundary conditions (1). Together with the fact that the displacements at r=0 are finite, this set of equations can be solved for the coefficients A, D, F, and H.

The first goal, i.e., of finding the effect of the presence of an optical fiber on the stress field, is obtained by solving the equations for the stress field in the composite material, and comparing this field to the field without presence of an optical fiber. In Figure 12 are plotted the stresses \( \sigma_\tau, \sigma_\theta \) and \( \sigma_z \) along the coating host interface in the composite host material. The stresses are normalized with respect to the maximum equivalent stress component for the same boundary conditions without the fiber and the coating. The stress decreases as the distance from the interface increases. From the plots it can be seen that the presence of the optical strain gage causes a "stress concentration" as high as 1.2. This effect should be considered in structural design, especially because the
optical strain gauges are intended to be used in critical load carrying regions of the structure.

![Graph showing stress components](image)

*Fig. 12: Stress components along the coating/composite interface (at r = rj).*

The longitudinal strain component, $\varepsilon_{xx}$, is a constant, and with the material properties we have used, its value is 1.1 times strain component as if the whole space was composed of the composite material. The presence of a relatively compliant fiber causes the strains in the fiber (the strain reading), under the prescribed boundary conditions, to be different from the "undisturbed strain". With the materials we currently use, this difference is about 10% and should therefore be considered when accurate measurements are required.

It has been suggested,\(^{15}\) that a possible way to overcome the problem of stress concentration is to choose a suitable coating material. The same solution may be used in order to decrease the strain reading inaccuracy. Nevertheless, the choice of coating material takes into account other considerations, such as process temperature, protective properties, etc. In addition, only a limited
number of coating materials are commercially available, and thus the pros and cons of commercial coatings must be thoroughly examined with relation to the mechanical properties of the system, and the parameters of the selected coating should be incorporated as design parameters.

4. Conclusions

The work described herein has established infrastructure for incorporating optical fiber sensors into future "smart" aerospace components, with a capability of extension to formalized procedures for design, structural analysis and manufacture. Practical methods have been developed for the embedding of and connecting to optical fibers in composite materials, while maintaining adequate optical performance with minimal interference with the host structure. Standard optical fiber communications hardware was exploited to assure connectivity with monitoring instrumentation. Further assessment is required of the long-term performance of the embedded sensors and connectors in typical operating environments.

Strain measurements have demonstrated good correlation between embedded optical sensors and conventional strain gauges. The potential of multiplexing in order to provide a multi-point sensing capability with a single fiber was verified. This capability is critical for providing multi-axial strain measurement at a specific location as required for analysis of structural performance. Analytical methods developed for assessing the effect of embedded fibers on composite properties, enabled prediction of local stress and strain distributions. These findings provide a
basis for further development of design and analysis methods for composite structures which will incorporate sensors in stress critical locations.
5. References


