Development of Matrix Cracks in Cross-Ply Laminates under Bending and their Detection using FBG Sensors

by

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Submitted for the degree of Master of Philosophy

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April 2004

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To all my family,
who have been dealing with my requirements beyond the call of duty.
Unless I could unfailingly enjoy the support from each one of them,
I wouldn't have found the courage to undertake this project.

A tutta la mia famiglia,
che si è dedicata alle mie esigenze al di là di ogni misura.
Senza le certezze assolute, che ognuno di loro mi regala immancabilmente,
non avrei trovato il coraggio che ha fruttato questo.
THE DEVELOPMENT of matrix cracking damage in a double cross-ply laminate under four-point bending has been investigated for both quasi-static and fatigue loading. Under quasi-static loading, crack onset was found to develop at the interface between the outer 0° ply and the adjacent 90° ply on the tension side of the laminate. The cracks initiated at coupon edges and then extended across both the thickness and width of the 90° ply, crack growth occurring in a "stick-slip" manner. Under fatigue loading, additional damage in the form of delaminations developed, especially under "high" fatigue loads and splits developed in the outer 0° ply. The delaminations initiated at the point where the matrix cracks met the outer 0/90 interface. For both quasi-static and fatigue loading, the modulus reduction due to matrix cracking damage was in good agreement with the predictions of a model based on a one-dimensional shear-lag analysis.

A system for monitoring the output from a fibre Bragg grating sensor located within a 0° ply and near a 0/90 interface was developed, using a broad-band laser source and an optical spectrum analyser. The strain output from the sensors was correlated with measurements of strain in both tension and bending tests, and there was found to be good agreement between the measurements employing the sensor and those using the extensometer. The change in the spectrum recorded using the sensor when matrix cracks developed has been investigated for both tensile tests and bending tests. The reflected signal showed additional peaks on the long wavelength side when a matrix crack developed. These changes have been interpreted qualitatively in terms of the strain magnification experienced locally in the 0° ply due to the presence of the matrix crack. It has thus been shown that fibre Bragg grating sensors can both monitor strain and detect matrix crack development when the matrix cracks develop in the ply adjacent to the position of the sensor.
I MUST express my sincere gratitude to my three supervisors at the University of Surrey, Dr. Steve Ogin, Mr. Tony Thorne and Prof. Graham Reed for giving me the opportunity to take part in this project. To my colleague and friend Hongrui Wang, who helped me in overcoming a critical experimental problem. Also, the time spent sharing office room and laboratory facilities with him allowed me feeling the truly international atmosphere I was determined to experience by living this period of study. I learned a lot.

I am very grateful to Mr. Nigel Hooker for his expertise and outstanding patience in dealing with my requests for the manufacture of essential experimental equipment. I acknowledge the assistance of Mr. Reg Whattingham, in the initial period of my laboratory work, and of Dr. Brian Le Page, subsequently.

Many thanks to my tutor at the University of Naples, Prof. I. Crivelli Visconti, who agreed to the undertaking of this project.


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Chapter 1

INTRODUCTION

LAMINATED COMPOSITES build up a large class of structural materials, whose importance for advanced applications has largely increased over the past decades. The main characteristic of such materials is heterogeneity: they consist of the assemblage of two – or more – components, generally at the microscale level, with the aim of achieving superior properties than those of the single components. One of the components of laminated composites is made up of discrete fibres, which are used to reinforce the other component, a distributed phase, the matrix. This aspect brings another important characteristic: anisotropy. The presence of reinforcing fibres has the effect of establishing preferential directions inside the material, in which the properties (in particular, mechanical characteristics) are different from the properties measured in other directions. This is the principal difference between composites and traditional isotropic structural materials, such as metals, and this property allows the designer to specifically tailor the material to the intended purpose.

After the introduction of glass fibres in the 1940’s, the importance of composites in the field of structural materials has been growing rapidly. Traditionally the leading sectors for applications have been the aerospace and marine industries. However, in other engineering fields (e.g. civil engineering) a growing number possible applications have been demonstrated over the years. Nowadays, the employment of composites appears to be vital to both the feasibility and the development of the most demanding advanced applications, such as modern fuel-saving aircraft and coming single-stage-to-orbit spaceships.
Current demanding applications more often require materials functionalities ranging beyond the traditional thermo-mechanical resistance characteristics well known to designers and manufacturers. Among the opportunities offered by composites materials, particularly laminated fibre reinforced polymers, there is the possibility to build so called *smart* structures. In these structures the constituent material possesses, or is provided with, the capability to sense the presence and intensity of a physical field surrounding the structure and signal such presence to controllers; the sensing may eventually also return an actual measurement of the same field. Alternatively, a smart structure is able to respond to the action of a certain external field by modifying a set of its properties, e.g. the mechanical properties, so making it possible to build actuators.

An optical fibre is a cylindrical structure consisting of a micrometer-dimension core surrounded by a cladding, each consisting of a glass (or polymer) material, through which the guiding of light waves is possible. Generally used for communication purposes, optical fibres also form now the basic component of Fibre Optic Sensors (FOS’s). The modulation of one or more parameters of a light beam enables information to be carried by the light that is transmitted through the waveguide from a sending to a receiving point. A FOS is made when a light modulation is caused by a mechanism in which a measurable physical field surrounding the optical wave path comes to interact with the guided light. A guided light can be allowed, at discrete locations of its propagation path, to travel outside the optical fibre. If the modulation takes place outside of the optical fibre, the FOS is called extrinsic. On the other hand, if the light parameters are modulated by physical fields acting onto the beam through the waveguide structure, the information is imprinted to the beam when it is guided within the optical fibre and the sensor is called intrinsic.

One of the principal advantages of FOS’s is that they minimise intrusivity due to their very limited dimensions and weight when compared to a host. They are used both embedded in a host material and attached to a surface, which make them very suitable for use in the monitoring of composite material elements and structures. They are non-metallic, which makes them immune to the disturbance of external electromagnetic fields and cancels the need for
electrical insulation. Moreover, the typical optical fibre material is chemically inert, which makes
the sensors compatible with a wide variety of environments. Finally, FOS’s offer the possibility
to be interfaced with a large number of measurands: this makes the sensors remarkably
versatile. As a result of these properties, FOS’s appear as a very suitable means of obtaining
localised measurements of fields such as strain and temperature at particular locations inside
composite materials, as demonstrated by the current literature in the field.

The work presented in this thesis encompasses the use of optical fibre Bragg grating
sensors embedded within composite materials, and an analysis of the results using both closed-
form solutions and finite element modelling. In the next Chapter, a brief review of the literature
relevant to these areas is presented.
Chapter 2

LITERATURE REVIEW

2.1. INTRODUCTION

In the present Chapter a review of the relevant existing literature concerning studies on matrix damage in composite materials is given. This is preceded by a schematic description of the most common features characterising the damage of polymer composites. Moreover, some techniques experimented for implementing and operating an optical fibre sensor-based detection system to be utilised in the monitoring of strain and damage in polymer composites are also reviewed. Particular attention has been focused on FOS’s studies involving the use of a Bragg grating: this type of FOS has been chosen to carry out the strain and damage detection experiments for the present project. This Chapter is concluded with a brief account on some FEM analyses of composite laminates containing localised areas of damage.

2.2. TYPES OF DAMAGE IN COMPOSITE MATERIALS

The internal architecture of laminates is characterised by a layered structure (Figure 2.1), in which different layers include parallel fibres oriented in different directions (Agarwal and Broutman, 1990). The fibres are dispersed in the matrix, which provides the bonding between
the layers. The microstructural integrity of each layer is based on the adhesion between the fibres and the matrix, an essential element building the composite material concept. The fibre/matrix bonding takes place at the interface between the two components. The interfacial properties of a composite dictate the macroscopic properties of the material as much as the separate individual components do. In a composite laminate the fibre properties are exploited by a load transfer mechanism from the matrix, to which any external load is applied, to the fibres, which typically possess the properties to withstand the applied loads. In polymer matrix composites, a strong interfacial bonding is generally desired for structural purposes. However, in ceramic matrix composites a weaker interface is often desired to enhance the toughness properties.

Figure 2.1. Geometry and reference system of a laminated composite beam. 
\( x = \) direction of 0° fibres; \( y = \) width of the laminate; \( z = \) thickness direction

Anisotropy of the material properties includes anisotropy of failure characteristics. A number of failure modes can possibly occur in composites, due to their complex microstructure. The intralaminar and interlaminar stress state, established by the matrix curing process and by the application of applied loads, determines the onset of damage mechanisms which eventually lead to overall failure of the laminate. Since the fibres play a dominant role in carrying the external applied loads, the load configurations which most effectively exploit the properties of laminates have load components lying in the lamina planes. An overall classification of damage
in composites is obtained by distinguishing the in-plane failure modes from the out-of-plane failure modes (Masters, 1987). Intralaminar cracks in different separate laminae may then be led to join together by interlaminar cracks to form translaminar damage, which is most likely the final stage of the complete failure of composite element.

Figure 2.2. Schematic showing the evolution of intralaminar damage in a unidirectional lamina under a simple unidirectional tensile load.

The simplest load configuration to be considered in a laminate is a tensile load parallel to fibres. In this case, the strain-to-rupture values of the fibre and the matrix determine which of the two components fails first. The sequence of events is schematically depicted in Figure 2.2. A low toughness matrix, such as a ceramic, fails before the reinforcing fibres, giving birth to a brittle fracture surface approximately orthogonal to the fibre (and applied load) directions. In an initial stage, the fracture surface extends within the matrix material until encountering the fibre/matrix interface locations. If adhesion with fibres is limited, the growth of the fracture surface generally continues along the fibre/matrix interface with the micro-debonding of the two components. Subsequently, the crack propagation within the matrix is carried on beyond the fibre location and fracture of the debonded fibres occurs with extensive fibre pull-out after the breakage of fibres. This mechanism enhances the overall material toughness (especially in terms of impact resistance), since a considerable amount of energy is absorbed in the frictional
sliding of the pulled-out fibres onto the matrix. In the case where the fibre/matrix adhesion is strong, fibre fracture occurs in the proximity of the matrix fracture surface and the pull-out mechanism is very much reduced. In this way the material exhibits little toughness, as the frictional sliding between the fibres and the matrix is completely absent.

If the matrix is tougher than the reinforcing fibres, which is often the case in polymer matrix composites, fibre breakage occurs when the matrix stress is still below the strength value (Masters, 1987). This is due to lower matrix stiffness and higher strain-to-rupture with respect to fibres. In these materials, the dominance of fibres in bearing the external load is very large with respect to the matrix material; this dominance increases further when a high fibre volume fraction characterises the composite. As fibre breakage advances, the external load is redistributed over the intact fibres, whose stress is therefore increased. Matrix cracking orthogonal to the load direction starts when the amount of remaining undamaged fibres is lower than would be required to bear the applied load. At this point the load-carrying role is transferred to the matrix, which fails rapidly, due to lower mechanical properties with respect to reinforcing fibres. In this situation, fibre pull-out occurs when a weak fibre/matrix bond is present. More often, in these systems, the bonding between the two components is strong, and the matrix fracture is preceded by shear yield. As a consequence, the resulting fracture surface tends to be less smooth than in the case of a brittle failure, with the possibility to extend over different cross-sectional planes of the composite element.

When the applied load action takes place at non-zero angles to the reinforcing fibres, a major failure mechanism includes extensive matrix shear, particularly if the fibre/matrix bonding is strong (Masters, 1987); this particularly applies to matrices with a lower Young's modulus and shear modulus with respect to fibres. When the angle of applied load to the fibre direction increases, the damage in the composite material generally starts with microdebonding (e.g. Ogin et al., 1984). In fact, the fibre/matrix interface is highly stressed in this case, and the stress concentration around individual fibres increases the possibility for it to fail at early stages. Once debonding has occurred, the rupture spreads into the matrix material and the crack surfaces are opened in planes parallel to fibres. This type of damage mechanism, where
damage is characterised by failure initiation in the transverse plies, is particularly associated with cross-ply laminates. The load increase causes the density of transverse matrix cracks to increase along the longitudinal direction, which results in a lowering of the Young's modulus of the material. An image of a glass fibre/epoxy matrix cross-ply tensile specimen is shown in Figure 2.3, where the transparency of the material allows an array of transverse matrix cracks to be easily recognisable. In Figure 2.4 a schematic edge view of a cross-ply laminate is presented, showing transverse matrix cracks.

Figure 2.3. A GFRP cross-ply composite laminate with cracks in the transverse ply matrix. Transparency of the material allows this damage to be clearly visible.

Figure 2.4. Schematic of a cross-ply laminate edge view, showing an array of cracks in the transverse ply matrix.

There exists a limit to the maximum crack density which may develop in an off-axis ply under an in-plane tensile applied load. In order for a new matrix crack to initiate and
develop in the region between two existing cracks in a transverse ply of cross-ply laminates, a load transfer from the load-carrying longitudinal ply into the transverse ply has to take place in the same region. By increasing the crack density, the distance between two consecutive cracks is reduced. This has the effect to hinder the load transfer mechanism to the extent that it is impossible to have a sufficiently high stress in the transverse ply to start new cracks.

Once this saturation value has been reached, a further load increase results in the initiation of delaminations between the longitudinal and the transverse plies, starting from crack tips. A delamination is a matrix crack which develops at the interface between two plies of a laminate. This type of damage is very frequent in laminates, due to their characteristic layered structure. The onset of delaminations is often caused by the presence of out-of-plane stresses (mode I fracture), as a result of particular applied load configurations or because of the presence of other types of damage in the composite. However, the establishment of mode II and mode III loading dominating the interfaces between plies is not rare. Examples include matrix cracking present in the transverse plies of a cross-ply laminate. In this situation, under a longitudinal tensile loading, out-of-plane stresses develop at the crack tips and inevitably lead to delamination initiation at the same locations. For this reason, these stresses are often called "peeling" stresses.

As said, multidirectional laminates are very often characterised by an intralaminar damage initiation mechanism consisting of matrix cracking running parallel to reinforcing fibres in plies oriented at an angle to the direction of the external applied load. These plies are very frequently internal to the laminate, thus making the cracking invisible in most composite materials, e.g. carbon fibre reinforced polymers. Even though the structural integrity of the composite element is not totally destroyed, matrix cracking is often unacceptable as the design criteria are often such that any cracking is structurally unacceptable. Typical examples are:
(i) a fluid and/or pressure vessel; should damage occur, inner material cracks are viable pathways for fluid flows and invariably cause the stiffness of the structural element to decrease;
(ii) an aerospace structure, where any damage could result in mechanical property losses.

With regard to the latter, there exists interest in knowing the residual property values as a
function of the damage evolution.

The investigation of failure mechanisms associated with the matrix cracking is of further interest to aerospace industries as crack tips are often the initiation point for the onset of delaminations. There is a need for a deeper understanding of composite materials properties, in order to achieve a damage-tolerant structural element, since the applications for composites are being extended into safety critical areas such as the primary structures for aerospace vehicles. Composite materials provide the possibility to be exploited after the first material failure (internal delaminations or matrix microcracks) has occurred, as they still retain the greatest part of their mechanical properties once the initial damage has occurred.

Studies concerning the matrix damage in off-axis laminae have mostly concentrated on tensile loading conditions. This is largely as a result of the need of aerospace applications. Laminated composite material structural elements in aircraft and spacecraft are largely designed to carry in-plane loads. The requirements for the use of composites for the manufacture of structures subjected to bending is increasing; however, there is little in the literature to find research works dealing with analyses involving out-of-plane loading. From the general point of view of research activity in a laboratory environment, bending tests are very common. Specimen preparation and test equipment set-ups are simple, and test results enable direct assessment of important mechanical properties of materials.

Failure criteria have often been used to attempt predictions for the onset of damage and final material fracture. Typically there is poor agreement between the failure criteria and the experimental results, as explained in the following. The difficulty encountered by engineering failure criteria is mainly due to the fact that they typically do not keep the initial failure modes into consideration. The numerical failure criteria are currently unable to take this into account and there is a lack of experimental data for the failure modes in different laminates on which to base these criteria.

Other methods, based on general elasticity, fracture mechanics or damage mechanics, have been used in the past, to provide descriptions for different types of failures in composite laminates. The results have often been proposed as design tools to be used to support basic
linear elasticity design procedures founded on the laminated plate theory.

2.3. MODELLING MATRIX CRACKING DAMAGE IN COMPOSITE MATERIALS

2.3.1. GENERAL

The modelling of matrix cracking in composite materials has received considerable attention. First studies by Aveston and Kelly date back to the early 1970’s, when they considered the cracking in a brittle (low strain-to-rupture) cement matrix reinforced with glass fibres. They examined both unidirectional and randomly oriented reinforcement, in an attempt to predict the material stress-strain curve and the crack spacing. In polymer matrix composites failure in the matrix of a transverse ply can occur at a lower overall strain than the strain-to-failure of the polymer, due to strain magnification caused by the presence of the stiffer fibres, especially when closely spaced from each other. Garret and Bailey (1977) were among the first to investigate the cracking behaviour in the inner transverse ply of a glass/polyester three-layer cross-ply laminate. Quasi-static tensile tests demonstrated that increasing the tensile load increases the number of cracks parallel to 90°-ply fibres. The authors observed a very uniform spacing of cracks for all ply thicknesses examined and found a linear increase of the minimum crack spacing as a function of the increasing transverse ply thickness. Delaminations were totally absent, no debonding between the plies were observed as a result of the damage propagation. In a continuation of the study (Parvizi et al., 1978) showed the possibility to constrain the cracking development by reducing the thickness of the inner transverse ply; cracking did not occur in transverse plies with a lower thickness than 0.1mm.

Modelling to predict the first failure or the mechanical properties decay in angled and cross-ply polymer composites as a consequence of the damage progression has been attempted by a number of investigators. These studies provide considerable information on the material’s behaviour under uniaxial tensile load. Less attention has been devoted to the bending of laminates. More recently it has become apparent that phenomenological engineering
approaches are inadequate to predict intra-lamina failures, because they do not account for failure phenomena occurring at the micro-scale (e.g. McCartney, 1998 and Smith and Ogin, 1999). As a result, to date, failure criteria have failed to yield results in agreement with experimental findings. Other methodologies, based on fracture mechanics approaches, have demonstrated a more adequate approach when used to describe first ply failures: this is due to the microscopic insight on which they are based.

Boniface et al. (1989) demonstrated that stress intensity and strain energy release rate approaches provide consistent results with regard to the compliance change of a cross-ply laminate as a function of a single crack growth between two pre-existing cracks. The compliance is dependent on the cracks relative spacing and not on the crack length. Dependence of both the stress intensity factor $K$ and the strain energy release rate $G$ is proven to exist upon the crack spacing along the tensile specimen length. However, the quantities $K$ and $G$ are constant for any crack length: agreement with this is proven by the constant growth rate of cracks, found experimentally. The authors' proposed expression for the strain energy release rate was based on an earlier work by Ogin et al. (1985) in which the authors also demonstrated the possibility, with limited experimental data, to predict the curve of tensile modulus reduction due to matrix cracking in the transverse ply as a result of fatigue loading. Subsequent work (Boniface et al., 1997) investigated the onset and growth of transverse intra-lamina matrix cracks for differing $90^\circ$-ply thicknesses. The quasi-static tests carried out showed that in thick ply laminates (transverse ply thickness larger than 0.25mm) the cracking phenomenon was controlled by the initiation of the cracks, while for thin ply laminates (transverse ply thickness smaller than 0.25mm) the transverse ply cracking was propagation-controlled.

The relationships for stiffness reduction and strain energy release rate obtained in the studies mentioned earlier in this section were the basis for experimental observations on a $(0/90)_s$ and a quasi-isotropic $(\pm 45/0/90)_s$ glass/epoxy laminate to be used in aerospace constructions (Casini et al., 1987). The application of the Young's modulus reduction due to an increasing crack density in the transverse ply of a simple cross-ply laminate (Ogin et al., 1985)
was extended to a quasi-isotropic laminate: such an extension was acceptable, since the quasi-isotropic lay-up incorporated the same configuration of the 90° ply constrained between the two longitudinal plies. It was intended that the simple design-ready expressions could deal with the property loss of the laminates examined under initial failures. Delaminations starting at the edges of coupons were also considered. Expressions for the strain energy release rate and the fracture toughness were also derived, but the approach still did not provide reliable values for the predicted delamination toughness.

To this point, all of the solutions described above for the development of matrix microcracking in the transverse ply are based on the shear-lag theory. However, others (e.g. Nairn, 1989, and McCartney, 1998) have demonstrated that approximations in the shear-lag theory lead to some inaccuracy in the results.

In an attempt to overcome these limitations more complicated approaches have been undertaken. Nairn (1989) carried out a variational analysis to achieve a prediction of the intra-lamina stress state leading to the matrix crack onset in symmetric cross-ply laminates with two configurations: middle ply with parallel orientation to the load, and middle ply transversely oriented. The intra-lamina fracture toughness, which is defined as the critical energy release rate leading to matrix cracking opening in transverse plies, is distinguished from the delamination fracture toughness, and is suggested to be an important material property to be considered in design. This work accounts for the residual thermal stress in the laminate and its influence in the longitudinal extension of tensile specimens after cracking development. However, it contains a major approximation, assuming a non-uniform tensile stress distribution over the laminate length, while the tensile stress is considered as uniform over the laminate thickness. The author concedes that this approach does not support the possibility that delaminations will be started at the crack tips, which is a very likely occurrence when subjecting laminates to high tensile load or to fatigue cycles.

More recently McCartney (1998) proposed a method to describe the cracking of a multiple cross-ply laminate based on the linear elasticity theory, taking into account energy balance principles. The micromechanics model that was developed is expressed in terms of
macroscopic properties of the laminates. As these properties can be measured experimentally, the model has the potential to be a useful design tool. In fact, it is rigorous from a micromechanical standpoint as it requires input data retrievable at a macroscopic level. This study considers the fracture energy as a single ply’s resistance parameter, equivalent to energy release rate, as a means of predicting the stress level at which first cracking occurs. It is stated that the results proposed are not of use for predicting total material failure, i.e. laminate splitting into at least two separate pieces, since any micromechanics approach inherently contains too many unknowns to achieve such a prediction.

2.3.2. LAMINATES UNDER A BENDING LOAD

As already stated in the previous section, there are far fewer studies on damage as a result of bending loads. In the available literature, it is demonstrated that macroscopic failure criteria to predict first failures remain invalid. However, as a fracture mechanics approach in simple tension situations is more successful, there is interest in applying the same approaches to problems involving the flexural behaviour of off-axis plies that experience matrix damage.

Work undertaken by Lopez-Anido et al., 1995, investigated the modelling of bending stiffness in a series of $(\pm 45)$s CFRP laminates under three-point bending load. Three different theoretical methods were compared to experimental test results. Load-deflection curves were recorded for both major and minor axis loading. Experiments with several length-to-span ratios were carried out and the three theoretical methods were in agreement with the experimental results. The study was limited to the elastic region of the material behaviour.

Turvey (1980) proposed a theoretical analysis for the first failure in GFRP and CFRP cross-ply rectangular plates under different bending load configurations. The procedure involved the use of the Tsai-Hill criterion to model the individual lamina first failure, and resulted in a set of design-oriented charts plotting the first failure load level as a function of various geometrical parameters (i.e. plate aspect ratio, applied load surfaces). Additionally, one of the findings was a simple criterion to choose the laminate lay-up as a function of the plate aspect ratio. No experiments were reported in the paper.
Khdeir and Reddy (1997) proposed a comparison between different beam theories to predict the bending deflection of cross-ply laminates. First, second and third order theories, taking into account the shear stresses due to the bending deformation, were compared to the classical Euler-Bernoulli theory, whose applicability is limited to long thin beams. The results were calculated for several boundary configurations (e.g. clamped, hinged or free ends) and the results showed a close agreement of the corrected theories, whereas agreement between either of the above mentioned theories and classical theory was always poorer. Calculations considered both symmetrical, (0/90/0) type, and non-symmetrical, (0/90)n type, laminates: the deflection values calculated for symmetrical laminates were the lowest, which indicates that these laminates have a higher bending stiffness than the non-symmetrical laminates.

Experimental evidence for the inaccuracy of failure criteria to predict first ply failure is given in the work by Echaabi et al. (1996). Quasi-isotropic specimens of a (±45/90/0)_{3S} graphite/epoxy laminate were tested in three-point bending. Results were compared to predictions for three failure criteria, maximum stress, Tsai-Hill and Tsai-Wu, with regard to first ply failure and subsequent failures. Load-displacement diagrams were drawn for different span-to-thickness ratios and the types of damage developed during loading were visualised by C-scan techniques and microscopy of the longitudinal sections. A well-defined failure sequence was described: first failures were 90° ply matrix cracks, followed by matrix cracks in the 45° plies and subsequent longitudinal fibres breakage. It was shown that agreement was generally poor between the experimental data and the predictions from failure criteria.

The flexure of laminates containing off-axis plies, even if symmetrically laid up and balanced, resulted in the coupling of bending moments in the two in-plane directions. As a result, the bent specimens exhibit a composite flexure-torsion deformation that, in three or four point bending tests on off-axis specimens, leads to lifting of one specimen edge from the test supports. Additionally, the study includes quasi-isotropic laminates. These behave like isotropic materials tested under uniaxial in-plane tension, but not when they are tested under bending. One major drawback of this flexure/torsion coupling consists in the misleading results provided by the tests with regard to material parameters such as flexural compliance, which turns out to
be higher in reality than the measured value. For this reason, in one work the lower supports of a four-point bending rig was modified in such a manner that allowed the supports to rotate about an axis parallel to the beam specimen's longitudinal axis (Grédiac, 1993). This adjustment to the test equipment accommodated the out-of-plane deformation of a (0/±45/90)$_s$ specimen and yielded accurate measured values more consistent to the material's longitudinal flexural compliance and shear modulus.

The observation that 45° oriented unidirectional laminate specimens lift from the test supports led Mujika et al., 2002, to determine the in-plane shear modulus of the laminate by three-point bending tests. A theoretical model was proposed to derive the in-plane shear modulus value from the measurement of other elastic parameters in bending tests. Testing was carried out on a graphite/epoxy composite where several different span-to-width ratios were investigated. For values of span-to-width ratio lower than 2, the specimens behaved like plates with a very marked lift-off effect, while for increasing span-to-width ratio the lift-off effect was reduced: this effect was in agreement with previous work. This approach has the advantage of taking into account the deformation of the whole specimen, while other more traditional methods to determine the shear modulus rely on the output of localised strain gauges mounted in areas over which uniform strain configuration is established during the tests. Other advantages reported for the three-point bending test were that it was of low cost, relatively quick to preform and moreover it was simple.

The behaviour of composite panels under a transverse load is a very important engineering problem related to many different applications. Chen and Matthews (1994) examined the biaxial bending of a rectangular laminated composite plate by testing simply supported specimens under a central pin load. Various aspect ratio values for the plate (from 1 to 3) were considered under quasi-static and fatigue loading. The load-displacement curve in quasi-static loading exhibited marked changes in the gradients of differing linear portions. The differing linear portions of the curve were representative of the material response to the growing load, with an apparent reduction in stiffness at specific load levels. These distinctive changes in the material's behaviour were due to the onset and spreading of internal micro-
damage as revealed by X-radiography and C-scans. Two types of damage were identified: (i) matrix cracks originating at the load application point and spreading over circular paths in the laminate plane, and (ii) delaminations starting at crack tips. In fatigue bending both the stiffness reduction and the type of damage developed during the load cycles were described. The plates with the highest aspect ratios exhibited the best fatigue performance. However, tests suggested that, increasing values of the aspect ratio influenced the mechanical performance of plates less significantly. The reduction of flexural modulus, with respect to the initial value of the undamaged material, was plotted against the number of cycles. Three regions were identified in these results; within the first 10% of the fatigue life a 10 to 20% modulus reduction occurred; very little stiffness reduction was apparent in the next 70% of the total cycle count; finally, in the remaining 20% of the cycles run, the stiffness decrease was nearly apparent as for the first 10 to 20%. Damage due to fatigue was of the same type as that for quasi-static loading, where matrix cracks and delaminations were observed spreading, both in-plane and through-the-thickness, from the loading location at the top surface of the plates.

The occurrence of delamination in laminates under flexural loading is also reported. Yeh et al. (1997) carried out a finite element analysis and experimental investigations to determine the effect of the delamination on the response of the laminate to four-point-bending. The lay-up considered was made of 16 plies where the delamination was introduced artificially at different locations throughout the thickness. The analysis showed that, in the specimen region experiencing compressive stress whilst under a bending load, buckling occurs when the delamination is placed at a distance of less than 3/8 of the total thickness from the laminate surface on the compressive face. Where buckling does not occur, no change in the bending stiffness of the material is observed as the length of delamination increases. Analytical and experimental results were in reasonable agreement.

More recently, two studies have attempted the modelling of mechanical property decrease in a cross-ply laminate due to the onset and development of matrix cracks in a transverse ply due to the application of increasing external bending loads. In the first study, McCartney (1997) developed a very accurate model for the degradation of the flexural modulus
as a function of the increasing crack density in one transverse ply of a cross-ply laminate. The flexural modulus values were normalised by the initial value of the modulus for the undamaged material. The laminate under consideration for the analysis was a double cross-ply, which underwent matrix cracking in the transverse ply located in the tensile region of a four-point loading test. This model was based on a general elasticity analysis.

A similar problem was considered by Smith and Ogin (1999) but using a different approach. Based on a shear-lag analysis, the predictions of this model differ by less than 1% from those of the McCartney model. Moreover, the authors showed that a simplified linear version of the same model yielded predictions that were in good agreement when limited to low values of the crack density. In further work (Smith and Ogin, 2000) the model was extended to predict residual curvatures and was in reasonable agreement with experimental measurements. However, no observations of crack initiation and propagation were made.

The model by Smith and Ogin (1999) has been taken as a reference for the analysis of the results of an experimental investigation to describe the behaviour of a \((0/90_\circ, 0)\) glass/epoxy laminate under a quasi-static or cyclic four-point bending load. In particular, in the present work, observations on damage initiation and growth have been made.

2.4. OPTICAL FIBRE SENSORS

2.4.1. GENERAL

The practice of inducing and interpreting a light modulation carried by an optical fibre medium to gain information about a particular physical field surrounding the fibre itself dates back a few decades and are summarised by Measures (1998). A considerable proportion of these works has focused upon the strain measurement of structural elements. The main advantage is that such sensors are based upon optical fibres made from glass, a dielectric material, making them electromagnetically inert (Dakin and Culshaw, 1988).

The sensing and measurement of a number of different physical fields has been
demonstrated by the use of different types of FOS's. The measurement of electrical and magnetic fields, as well as strain and temperature measurements are typical examples. Strain and temperature sensing are typically achieved by the dimensional change in the light wave optical path or by the optical waveguide structure. The principal types of FOS developed and used in the measurement of strain and temperature are: (i) intensity-based sensors, (ii) interferometric sensors, (iii) polarimetric sensor and (iv) fibre Bragg grating sensors.

2.3.2. INTENSITY-BASED SENSORS

The working principle of intensity-based sensors consists in a modulation of the intensity of the light travelling down the optical fibre, resulting from a change in the measurand acting on the optical fibre. This type of sensor formed the basis for early FOS development. The major drawback when incorporating an intensity-based FOS is the difficulty to discern the extent of intensity change caused by the change in the measurand. Typically the response is a drop in the intensity of the signal and this can be caused by a number of factors other than the measurement of a physical field change.

2.3.3. INTERFEROMETRIC SENSORS

Interferometric-based systems are inherently more reliable. The principle is based upon monitoring the interference fringes when combining light from two differing light paths. Only one of the two paths is exposed to the action of a strain or temperature field. In steady state conditions, there is no change of the interference fringes. When a change in the physical field value occurs, the length of the sensing path changes, and the state of the interference fringes change. Examples of the most common interferometric FOS schemes are described by Dakin and Culshaw (1988).

Mach-Zehnder: This sensor consists of two separate optical fibre arms, the reference arm and the sensing arm. Figure 2.5 schematically illustrates the principle behind the sensor. Two optical fibre couplers are used to join the respective ends of the two fibre arms. At the one end light is launched into the waveguide and, when reaching the first fibre coupler, is split into two parts,
each guided into one of the two fibre arms. Upon reaching the opposite ends of the two arms, the two light beams are allowed to interfere in the second fibre coupler. The interference pattern is detected by a receiver placed at the same end of the system (Figure 2.5). The sensing arm length can be mechanically loaded or thermally expanded, resulting in a change of length of the optical path travelled by the sensing beam. This occurrence has the effect of modifying the interference fringes detected by the light receiver.

Figure 2.5. Schematic illustrating the principle of a Mach-Zehnder interferometric sensor.

Michelson. A potential drawback of the Mach-Zehnder setup is the need to transmit and detect at opposite ends of the fibres. This is overcome by the Michelson sensor, where the ends of both the reference and the sensing arms are mirrored. Figure 2.6 schematically illustrates the principle where the splitting of the light source and the interference of the light travelling in the reference and sensing arms take place in the same fibre coupler. Both beams initially travel down the respective arms as in the Mach-Zehnder system. When reaching the mirrored ends of their respective arms, they are totally reflected back upon themselves. Interference of the two light paths takes place in the fibre coupler, where a fibre carries the resulting output to a light receiver. Again a change in the length of the sensing arm, as a result of a change in strain or temperature, will result in a change in the interference state detected by the receiver.
**Fabry-Perot.** Both the Mach-Zehnder and the Michelson rely on the use of a sensing arm and a reference arm. In order to reduce the intrusivity of the FOS, a Fabry-Perot can be adopted. Figure 2.7 schematically demonstrates the principle of the Fabry-Perot sensor. Again the light source and receiver are at the same end of the optical fibre. A light beam is coupled into the optical fibre and guided through the coupler to a fibre containing the sensor. A semi-reflective splice in this length of the fibre determines the onset of the sensing length. At this point a portion of the light is back-reflected to the coupler to form the reference light arm. The remainder of the light propagates through the sensing length where it is totally reflected by a mirrored end. Interference of the two reflections takes place at the coupler and this interference is monitored at the light receiver. A change in the length of the fibre between the semi-reflective splice and the mirrored end will result in a change of the interference state detected at the light receiver. The Mach-Zehnder, Michelson and the above version of the Fabry-Perot sensor are intrinsic. An extrinsic version of the Fabry-Perot sensor is also feasible. A cavity is formed by matching the ends of two separate fibre segments by means of a glass tube. The back-propagated sensing and reference beams are generated by light reflections at the two interfaces of the fibre ends and the cavity. The sensing length is now the length of the cavity. This provides a point value of strain or temperature change as opposed to a value integrated along a proportionally much longer length of fibre in the intrinsic version.
2.3.4. POLARIMETRIC SENSORS

The polarimetric sensor is a particular type of single arm interferometric sensor, based on the use of highly-birefringent (Hi-Bi) optical fibres. When linearly polarised light is launched into this type of optical fibre, the beam propagates down the waveguide maintaining its initial polarisation state (e.g. Barton et al., 2001). A basic property of this type of fibre is that there are two separate orthogonal propagation modes down which polarised light can travel. A detailed explanation of the underlying principles relevant to the operation of a FOS based on the use of such optical fibres is beyond the scope of the present report. A typical schematic illustration of a polarimetric sensor is shown in Figure 2.8.

Linearly polarised light is coupled into the fibre parallel to one of the polarisation axes. This will excite that polarisation axis and minimal light will travel down the other orthogonal axis. The light travels along this axis until it comes across a 45° splice in the fibre, at which
point approximately 50% of the light propagates down each axis. Due to the nature of the Hi-Bi fibre, the light now travels at two differing velocities down the two axes. At the end of the sensing section of the Hi-Bi fibre, the light comes upon a second 45° splice. As the light has travelled at different speeds to this second splice, it will now interfere in both orthogonal axes as it re-combines. If the power meter only monitors one of the orthogonal propagation modes, then any change in length of the sensing section will be evident as a change in the interference state.

2.3.5. FIBRE BRAGG GRATING SENSORS

Optical fibre sensors based on the use of Fibre Bragg Gratings (FBG) are single-arm sensors whose technology has more recently been developed in the past few years. This type of sensor is now one of the most widely used, particularly as an embedded sensor for point strain detection. The Bragg grating is an in-fibre structure consisting of a periodic variation of refractive index of the optical fibre core over a length of typically a few millimetres (Othonos and Kalli, 1999). The basic property of this structure is to impede the propagation of light beams in correspondence of a narrowband wavelength range. This range of operation is centred on a particular wavelength value, which is proportional to the length of the refractive index modulation period (or pitch length) of the fibre core in the grating region. Wavelength components of a guided broadband light beam, falling within the particular wavelength range, are back-reflected down the optical fibre. The operating principle of this type of sensor is schematically depicted in Figure 2.9. The composition of a broadband light signal is described by a diagram of the light intensity $\lambda$: the spectrum. When a broadband light beam is launched into an optical fibre containing a Bragg grating, part of this light is reflected back; the spectrum of this light is characterised by a narrowband single-peak shape, $\Delta \lambda$. The position of the peak is found for a value of wavelength proportional to the grating period. The remaining components are allowed through the grating and are transmitted to the opposite end of the fibre. If the transmitted light is monitored, the spectrum is characterised by the missing portion of light $\Delta \lambda$ that was reflected by the Bragg grating.
By varying the grating pitch length, the wavelength of the reflected spectrum peak varies proportionally. An axial strain (or thermal expansion) of the optical fibre in the grating causes the grating pitch length to vary, and this results in a wavelength shift of the reflected spectrum peak. A FBG sensor can be operated either by monitoring the reflected or the transmitted spectrum. The wavelength-encoded type of information provided by a FBG sensor is the most advantageous aspect of this class of sensors. It is very difficult to make it corrupted by any external source of disturbance.

2.5. USE OF OPTICAL FIBRE SENSORS TO MONITOR STRAIN AND DAMAGE

2.5.1. GENERAL

The most commonly used optical sensor scheme used to provide information about the measurand is the Fabry-Pérot interferometer. Both extrinsic and intrinsic versions of the
sensor have been widely utilised. The system has shown a linear response to both longitudinal strain and thermal stimuli (Zhang et al., 2001), for temperatures up to 70°C: Investigations have taken place for both laboratory uses and for monitoring a concrete/CFRP bridge in the field. The response of the sensor to temperature has been shown to be particularly sensitive, where readings to a fraction of 1°C (Lee et al., 1992) have been demonstrated when the sensor has been embedded in both composites and Aluminium. In the extrinsic configuration, which involves the examination of interference fringes resulting from in-fibre light ray and a ray whose light has been modulated by the measurand in an off-fibre path, the response shows some non-linearity (Bhatia et al., 1995). A method has been proposed to overcome this and other drawbacks, involving the launching of white light into two input fibres simultaneously; this method has allowed the measurement of a bi-component strain field and temperature up to 250°C. Additionally, the use has also been demonstrated for the extrinsic sensor in a multimode fibre to measure both tensile and compressive strain (Liu et al., 1997). The sensor was embedded in a composite laminate and showed excellent correlation with a conventional surface mounted extensometer in the strain range ±1% with a sensitivity of 30με, where it additionally proved insensitive to thermal disturbance between 38°C to 180°C. In the same study, a method was proposed to minimise temperature sensitivity. The principle was to minimise the length of the cavity in which the off-fibre ray is modulated. The required cavity length was determined by optimising the requirement for strain sensitivity, which requires a short length, with the strain range, which requires an increase of the cavity length.

The extrinsic Fabry-Pérot optical fibre sensor has been used in a partially multiplexing mode to detect the residual strain due to impact damage in a CFRP cross-ply composite (Liu et al., 1998). Two single mode fibres were embedded in two different layer interfaces to yield two point-measurements of strain. Tensile tests were used to calibrate the sensor. Excellent agreement with electrical resistance strain gauges (ERSG’s) was achieved, and it was claimed that a measurement of the residual strain state was achievable. Six individual sensors have been multiplexed in the same fibre using the same extrinsic Fabry-Pérot method (Singh et al., 1999). Strain was measured up to 4000με with a sensitivity of better than 10με. The system is
based on a unique length of the sensing cavity for each individual sensor. The residual internal stresses developed in a composite laminate as a result of the resin curing process have been successfully measured with this kind of sensor (Lawrence et al., 1998). The sensing ends of extrinsic optical fibre Fabry-Pérot interferometers were embedded within individual plies of a cross-ply laminate as well as thermocouples. Strain measurement took place throughout the cure cycle, yielding temporal diagrams of the plies' stress evolution, especially in the cooling stage of the cure. The results were in good agreement with those previously obtained from experimental data taken from other tests, as well as with theoretical calculations. More recently, a transmission, instead of reflection-based extrinsic Fabry-Pérot interferometer has been reported (Kim et al., 2001).

A system incorporating an extrinsic Fabry-Pérot sensor has also been utilised in the extremely severe conditions of a coal-fired combustor (Claus et al., 1992). The high sensitivity of the sensor, ±0.5με, has been exploited to monitor the in-operation performance of a ceramic filter over a temperature range of -200°C to +900°C. In addition, it was possible to measure the width of crack openings in the filter of the coal-fired combustor using a 10mm gauge length sensor (where the gauge length is the length of the Fabry-Perot cavity).

The Fabry-Pérot interferometer determines a point measurement of the strain or temperature field. A different optical interferometer has been exploited to build up long gauge length sensors, the Michelson interferometer. Individual sections of bridges and complete spans (Inaudi et al., 1998) and large composite and concrete cylinders (Fan et al., 1998) have been monitored for structural deformation, both in the laboratory and in the field.

The Mach-Zender interferometer scheme has been adopted to build an optical fibre sensor able to monitor ultrasonic waves in a CFRP composite undergoing non destructive testing to point out holes and impact-born delaminations (Pierce et al., 1996). The optical fibre sensor was attached at the surface of the plate specimens and showed a good resolution, while not affected the ultrasonic wave propagation.

As an alternative to the Mach-Zender interferometer, the Sagnac scheme has been proposed as a sensing system for acoustic waves in a marine environment (Vakoc et al., 1999).
The main advantage of the latter system is that it avoids source noise being converted into detected signal intensity noise. The system has been implemented into an array of sensors, and the work additionally deals with the signal treatment procedures carried out, such as time- and frequency-division multiplexing.

Raman spectroscopy is a technique also investigated in order to provide strain measurements in laminated composites. Optical fibres have been used not as the sensing element itself, but simply as the light carrier to the inspection point within the laminate (Arjyal et al., 1999). The inelastic radiation spread is recorded and related to the composite strain. The optical fibre was placed in both parallel and a perpendicular configuration to the composite reinforcing fibres, and the strain measurements carried out proved very accurate when compared to those obtained from surface mounted ERSG's. In another work a single aramid fibre had been used as a Raman microprobe, minimising the intrusion of the sensor in the host laminate (Arjyal et al., 1998).

One further optical technique has also proved useful for strain monitoring by optical fibre sensors. The Brillouin scattering method has been implemented to monitor the tensile and compressive strain of a steel beam (Bao et al., 2001). In the laboratory environment, the measurement accuracy was ±5με, while in the field the system was able to detect both thermal and elongation strains, as the signals for strain and temperature are distinguishable from one another. Diagrams of calculated and experimental values showed fairly good agreement throughout the beam span length. However, it has also been shown by a separate group that the Brillouin scattering measurements contain some intrinsic error due to the characteristics of the optical technique (Kim et al., 2002). The extremes of the measurement range require a compensation procedure to correct the measurement errors.

2.5.2. DAMAGE DETECTION

Characterisation of the optical fibre sensor’s output has been carried out when investigating crack growth detection following the buckling failure of delaminated composite beams (Park et al., 2000). While showing the success of the extrinsic Fabry-Pérot sensor when
detecting both the buckling occurrence and delamination growth, the study also investigated the actual position of the sensor in the laminate by measuring the movement of the optical fibre during the resin curing process. They also demonstrated the effectiveness of the sensor when detecting the onset of damage in a composite laminate tensile coupon. During the tensile test, they attempted real time monitoring of the tensile strain by a wavelength division multiplexing technique (Hong et al., 2001). Previously, they reported the use of a Michelson-type fibre optic sensor to monitor both strain and damage in a cross-ply composite specimen loaded in four point bending (Kwon et al., 1998). The strain to failure of the composite was determined by low-pass filtering of the optical signal. Failure was determined by a high-pass filter; no mention was made of detecting the location of the damage.

The use of extrinsic Fabry-Pérot optical fibre sensors to detect delamination in composites has also been implemented in conjunction with ultrasonic waves, as mentioned previously. The capability of the sensor to respond to ultrasonic wave stimulation when embedded in a laminate or even when attached to its surface has been demonstrated by Bhatia et al., 1995. The possibility to simultaneously deal with signals returned by several sensors resulted in embedding several Fabry-Pérot fibres at several interfaces. The results gave a more precise location of the delamination in the specimen.

An optical fibre sensor based on the Optical Time Domain Reflectometer Scheme has been embedded in a concrete beam to monitor the onset of cracking both in quasi static loading and in fatigue (Gu et al., 1999). This is a multiplexed sensor which is a quasi-distributed sensing system, where several portions of optical fibre were joined together in order to create an equal number of signal reflecting surfaces, each of which is actually a sensing point. The visual inspection of cracking occurring under test provided a basis to compare and evaluate the sensor output response. The sensor was shown to be able to measure various crack widths with respect to each sensing point. It was proposed that this system could be employed in fatigue measurement, due to its immunity to hysteresis. To detect fatigue crack growth, a commercial multimode optical fibre intensity-based sensor was employed to monitor the health of Aluminium alloy elements up to crack widths of 30µm. The sensor had a wide temperature
range (-196°C to +120°C) and functioned in wet conditions, including marine environments. The maximum amplitude of the cyclic loading strain was 100μe.

2.5.3. **VIBRATION MONITORING**

The capability of optical fibre sensors to detect vibration states of the structural element they are embedded in has been demonstrated in several environments. A multimode optical fibre sensor was used to detect the propagation of acoustic waves in a metal bar (Fuhr et al., 1992). The sensor was attached to the bar and was used to determine the resonant frequencies. At the same time, the fibre was used as a communication medium, where a television signal was multiplexed through the fibre and transmitted by realising a complete decoupling of the vibration from the video signal.

Chien et al. (1996) used a combination of a fibre optical sensor and a piezoelectric actuator to control the vibration of a cantilever beam. The optical sensor was a Michelson interferometer, where the advantages of a long gauge length were exploited, although it was stated that such a gauge length is not suitable for a non-cantilever beam systems, where the features of a point sensor are more appropriate. A similar structural control system has been reported elsewhere (Juang and Wu, 1995). Additionally, active control of a smart structure's vibrations has been achieved with a combination of an intensity-based fibre optic sensor and an electrorheological (ER) fluid actuator (Leng and Asundi, 1999). Thus it is now possible to design a smart structure system incorporating fibre optical sensors and piezoelectric or ER actuators. A cantilever beam, containing the ER fluid, was monitored whilst put into bending vibration by tuning the electric field applied to the ER. The sensor proved able to detect vibration of the beam even at low frequencies and with low amplitudes of vibration. Although this sensor was based on the detection of signal intensity, its construction is similar to an extrinsic Fabry-Pérot sensor. It worked on the principle of reducing the amount of light transmitted by the Fabry-Pérot cavity while the bending increased in amplitude. As a result an intensity loss was recorded at the fibre end opposite to the light source.

Yang and Chen (1996) reported another example of a smart structure involving the
use of an optical fibre sensor, a piezoelectric actuator and a control system. The Michelson sensor was able to detect the vibration state of the beam, additionally providing the input for the control section of the system. It was emphasised that a critical issue was the choice of the position of the sensor on the structure such that the sensor’s range was in its linear region. A computer FEM simulation has shown the advantages of a Mach-Zehnder optical fibre sensor when compared to conventional ERSG’s in the monitoring of a composite frame for aeronautical applications (Mrad et al., 1997). The better dynamic response of the former was revealed by the analysis, particularly for higher order vibration modes where the first to the fifth vibration modes were taken into consideration.

2.5.4. POLARIMETRIC SENSORS

Sensors based on the use of polarisation maintaining optical fibres (also called highly birefringent fibres) have been extensively exploited in scientific investigations and technical practice. Various types fibres are available, to enable the birefringence. Elliptical core fibres, panda fibres and bow-tie fibres have formed the basis for investigations.

A major driving force for the investigations of polarimetric sensors has been the need for only one fibre, since a second reference arm is not required (Murphy et al., 1991). Although these sensors have a sensitivity two orders of magnitude lower, they are useful in detecting both the static strain and the modal components of an element’s vibration state and can be embedded in composite laminates or attached to an element’s surface. The usual measurand is the phase shift between the two modes propagating in the fibre, while the common operating practice involves a mode-stripping technique consisting of several small radius (a few millimetres) loop to remove the light from one mode. This enables the monitoring of the interference fringes coming from the light of the only propagating mode left in the light path before the light detector end (Lisbôa et al., 1994). Using optical components such as frequency shifters, it has been possible to create several sensing regions along the same fibre, thus approaching quasi-distributed sensing. The problem of the optimal placement of the sensor exists for a polarimetric sensor as well. In vibration monitoring, it has been suggested that a
better comprehension for the right location of the sensor on a vibrating beam is achieved when the shapes of the vibration modes are already known (Han et al., 1995) where the study was conducted on an electrorheological fluid actuated smart beam.

An elliptical core fibre was the basis for two slightly differing sensors for strain and temperature measurement (Wang et al., 1995). In both cases the light coming out from the fibre is coupled into a multimode fibre, which is connected to the detector. The connection between the two fibres is realised in two different ways, making up the two sensors. In the first case a cavity is created between the two fibre ends connecting them by a hollow larger diameter fibre (similar to an extrinsic Fabry-Pérot sensor), with the elliptical core fibre end being cut at a non-90° angle. In the second, the two fibre ends are adhesively bonded to a metal strip. The temperature measurement is achieved in both cases by analysing one half of the two-lobe pattern characterising the light transmitted by the interference of the two modes in the elliptical core fibre. The pattern changes as a result of the thermal distortion either of the metal plate or of the hollow fibre connecting the two main fibres of the sensor. The strain measurement is realised by simply reading the interference fringes of the two modes, which change their own relative phase while the fibre is stretched. A strain sensitivity of 17μm-m⁻¹ was obtained, while a temperature reading to ±1°C was possible over a range of 0°C to 75°C.

The polarimetric sensor has more recently proved its effectiveness in damage detection. Cross-ply GFRP laminates loaded in tension have been monitored by embedding polarimetric sensors made of a segment of Hi-Bi commercial communication-oriented panda fibres spliced at a 45° orientation with respect to the input and output sections of the same fibre (Barton et al., 2001). The progressive cracking of the 90°-ply in the laminate could be detected by the sensor both in static loading and in fatigue tests until breakage of the sensor itself occurred. A progression of this work is still in progress, and new specimen and load configurations are under development (Wang et al., 2002).

2.5.5. INTENSITY-BASED SENSORS

Strain measurements by means of optical fibres can also be achieved without
interferometric techniques. Intensity-based sensors, that exploit the attenuation in the fibre, the intensity of any signal that progressively drops as a result of the distance travelled along the optical path. The evolution of the optical fibre technology could increase the attenuation characteristics of commercially available communications fibres, although any values different from zero are usually considered as a drawback in communication fibres (Mahlke and Gössing, 1987). The change in the attenuation of a transmitted signal, as a result of an external field applied to the optical fibre, is detectable and this is the principle of the intensity based sensors.

Different ways of inducing an attenuation change in optical fibres are effective. The microbending technique consists of loading the fibre in flexure in such a way as to induce a very small radius bend, when compared to the fibre diameter, at a point in the fibre. As a result, light radiates out of the core into the fibre cladding, due to the coupling of guided modes to leaky (radiating or cladding) modes. However, there are still considerable difficulties in achieving reliable strain measurements or even achieving damage detection with this kind of optical fibre sensor (Rippert et al., 2002). Another technique is based on the longitudinal strain-induced separation of the butted ends of two cleaved fibres embedded in a composite cross-ply laminate (Badcock and Fernando, 1995). The fibres were initially kept in place by a capillary tube joining them. The system proved successful for strain measurement both in static tests and in fatigue tensile-compressive cycles, since the sensor's experimental output was in very good agreement with the theoretically calculated predictions. The same technique was used by Lee et al. (2000) to manufacture a strain and damage sensor used to monitor a steel bridge truss structure. The sensor was first tested in laboratory dog bone cracked specimens, where the stiffness change of the material as a result of the crack growth was monitored. In the field operation, an interesting phenomenon was detected. Inadequate curing of the adhesive used to attach the sensor to the structure caused an hysteresis-like profile for the resulting stress-strain curves derived from the optical signal. However, the experiments showed the effectiveness of the sensor in determining field strain measurements. The sensor has also been embedded into a composite laminate, where satisfactory results were obtained in static and fatigue tests (Lee et al., 2001).

2.5.6. OPTICAL FIBRE STRAIN ROSETTES

The simultaneous measurement of strain in more than one direction is conventionally achieved by means of electrical resistive strain gauge rosettes. By recording the output derived from the strain gauges oriented in different directions to the applied load it is possible to work out the components of strain in the direction of the gauges as well as the values and directions of the principal strains. In the late eighties the technology achieving a strain rosette by means of optical fibre sensors was demonstrated (Valis et al., 1992). Some years later, the Canadian group of Valis and Measures presented a way to improve the existing polarimetric- and Michelson-based optical fibre strain rosettes by fabricating a Fabry-Pérot strain rosette. Like the previous methods, the new rosette was composed of three optical fibre sensors attached to the surface of a specimen and oriented in three directions. The advantages of this development was the ease of manufacture with respect to the Michelson rosette and a higher sensitivity. The sensitivity of the new Fabry-Pérot rosette is now comparable to the traditional ERSG's and is greater than that for the polarimetric sensors. The sensing portion of the three fibres was limited by a partially reflective splice and the totally reflective fibre end. In addition, the authors provided a mathematical model to link the optical output to the actual measured strain field. Case et al. (1994) have since demonstrated an ability for the same system to measure the strain within a composite laminate in the 0° and 90° direction when it is embedded in the laminate itself. However, a poor agreement with the surface mounted ERSG's was found. Moreover, it was demonstrated that a dramatic reduction of the composite compressive strength resulted, due to the presence of the embedded optical fibre rosette.

A novel strain rosette was fabricated by embedding an in-plane configuration of two extrinsic Fabry-Pérot sensors and a polarimetric sensor in a resin specimen (Grossmann and Huang, 1998). The aim of the study was to achieve a three-dimensional characterisation of the strain field through the bi-dimensional geometry of the rosette. The differing properties of the two types of sensors used with regard to sensitivity in the transverse direction were exploited. The Fabry-Pérot sensor is insensitive to the transverse strain, while the polarimetric sensor has a moderate orthogonal sensitivity. The phase-strain equation ruling the behaviour of the latter
contains the three principal strain components. Therefore, by independently measuring the strain in two of them, by the use of the two Fabry-Pérot sensors in mutually orthogonal directions, it was possible to derive the strain component in the third axis. This was achieved by placing the polarimetric sensor parallel to one of the two Fabry-Pérot fibres.

2.6. RESEARCH ON FIBRE BRAGG GRATING SENSORS

The main thrust to this research programme is to determine the damage sensing capabilities of a fibre Bragg grating (FBG) sensor. In the present section, attention is devoted to the existing literature concerning the technology of this type of optical fibre sensors.

2.6.1. PRINCIPAL FEATURES

Fibre Bragg Gratings have the distinct feature that they are independent of the signal intensity. The FBG technology takes advantage of the back-reflection of a very narrow band signal from the gratings, while all the other component wavelengths in the launched signal are transmitted through the grating region (Othonos and Kalli, 1999). Each grating is characterised by the pitch length (period), Λ, which unambiguously defines the reflected wavelength, the Bragg wavelength λ_B or even the resonance wavelength λ_res, of the grating. When an external physical field (predominantly strain and/or temperature) interacts with and induces a longitudinal deformation of the fibre, the pitch length of the sensor itself changes. As a result, the reflected wavelength is shifted. By determining the magnitude of the shift, it is possible to determine the change in the physical field (Kersey et al., 1997). The individual character of the Bragg wavelength in its response to the applied field results from the intrinsic characteristics of the FBG and is one of the most effective sensing tools available to date.

The typical grating length is of the order of a few millimetres, confining the sensor to point measurements of the field surrounding the fibre. A 1000με is detected by a 1nm shift in the reflected wavelength (at a wavelength of 1.3μm). For temperature, a wavelength resolution
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of 0.001nm is needed to detect a change of 0.1°C. However, the limitations of a point-sensing can be easily overcome with FBG’s if more gratings are written at different locations along the axis of the same fibre. Multiplexing is achieved by writing gratings having different values of the Bragg wavelength which makes it possible to sense both the field change and its location. The gratings are normally written in single mode fibres. However, the use of multimode fibres has been demonstrated (Mizunami et al., 2000, and Zhao and Claus, 2000).

The manufacture of the in-fibre gratings consists of illuminating a few millimetres section of a fibre with a coherent ultraviolet light beam propagating at an angle θ to the fibre longitudinal axis. By varying the value of θ, it is possible to determine the value of the reflected wavelength. It is possible to write a number of sensors in the same fibre, locating them at different points along the fibre axis. Optical multiplexing and de-multiplexing techniques allow for the analysis of the signals simultaneously coming from the different sensors. The ability to determine the vibration strain modes of a cantilevered Aluminium plate carrying two optical fibres attached to its surface, each containing 16 different gratings used for strain measurement at different locations on the plate has been demonstrated (Todd et al., 2001). It was possible to detect the frequencies and shapes of the initial 2D vibration modes of the plate, with acceptable agreement to analytical predictions. A damaged condition was also simulated by forcing the vibration after loosening the cantilever fixity. The Bragg gratings detected the modal differences between the undamaged and damaged vibration, showing, in particular, the modes that were not present in the damaged plate vibration with respect to those for the damaged condition.

The high sensitivity of FBG’s to both strain and temperature is often a problem when operating these sensors. One solution is to place two separate sensors in the configurations and to isolate one signal form the other, by locating the thermal sensor in a part of the structure that does not undergo any deformation. This dual sensitivity also applies to chirped gratings. Chirping refers to gratings whose period or average refractive index is made variable; sometimes both can be variable along the same grating. When the chirp is obtained by writing the grating on a tapered cladding optical fibre kept under tension, the resulting structure behaves in a unique manner. The strain causes the reflected signal to change both the band
width and the centre wavelength, while the temperature change only induces a shift of the centre wavelength. An experimental implementation of the principle was provided when tests were made to simultaneously measure the curvature and the temperature of a beam loaded in bending (Dong et al., 2001). The optical fibre sensor was attached to the lateral surface of the beam at an angled orientation to the neutral plane. The bending of the beam induced an actual chirp of the grating because of the strain difference occurring between the tensile and compressive side of the beam itself. It turns out that the reflected spectral width of the signal is proportional to the beam curvature, while the thermal information is always retrieved by the central wavelength shift.

The alternative to broad-band light sources, is a tuneable laser light source (Arie et al., 1999 and Ryu and Hong, 2002). The operation consists of a sweep over a wavelength range operated by the light source, while scanning of the reflected signal detects any shifts in the reflected wavelengths or, alternatively, scanning the transmitted signal detects any shifts in the missing wavelengths from the transmitted signal.

2.3.1.1. Long-Period Fibre Gratings

In order to further increase the sensitivity, another type of grating has been reported in the literature, the long-period fibre grating (LPG), whose pitch length approaches hundreds of micrometers. The principle underlying the behaviour of this structure is slightly different from the conventional Bragg grating and consists of the coupling of core propagation modes into the cladding modes at certain wavelengths, called resonance wavelengths and indicated as $\lambda_{LP}$. In such a way, some wavelengths are missing in the transmitted spectrum. The dependence of the transmitted spectrum on the cladding refractive index indicates that a strain or temperature-induced change in the cladding refractive index can yield a sensible modification of the spectrum itself. Temperature sensitivities of 0.015nm/°C and strain sensitivities of 0.0015nm/με have been reported. The properties of LPG's in sensing different physical fields can be summarised as follows: (i) as tensile strain sensors, the resonance loss varies but the resonance wavelength is the same; (ii) under a torsion load, the wavelength varies as a result of the applied torsion rate; (iii) as a bending sensor, the resonance wavelength increases until a
sensitivity limit is reached, beyond which, the resonance is completely cancelled (Lin et al., 2001).

The manufacture of LPG’s can be achieved by different techniques other than conventional UV exposure by utilising optical fibres with such a chemical composition that makes them have insufficient photosensitivity to successfully complete the UV treatment (Rego et al., 2001). One technique consists of exposing the uncoated fibre to an electric arc while keeping the fibre itself under a tensile load. The local increase in temperature induces the refractive index shift which is evident even when the stress in the fibre is released. The grating formation process is completed by repeating this operation at regular steps along the fibre axis. The authors demonstrated the stability of such gratings at high temperatures of up to 1200° demonstrating the evolution of the $\lambda_{1, p}$ value over the temperature range examined. There is a linear growth in $\lambda_{1, p}$ up to 800°C, while the increase is a reverse decay above that temperature. The sensitivity of the gratings to temperature also changes in the same way, with a minimum and maximum value of 0.06nm/°C to 0.55nm/°C as a function of both the thermal level and the particular chemical formulation of the fibre used.

The sensitivity of LPG’s is the subject of an extensive study (Shu et al., 2002). A general expression is provided for the grating sensitivity, depending on the first order derivative of the resonance wavelength with respect to the grating period and on the core and cladding effective refractive indices. It is shown in the theoretical analysis that the derivative has an infinite maximum for certain period length values for higher order cladding propagation modes. This indicates the possibility to construct very high-sensitivity sensors by suitably matching the grating pitch length and the relevant wavelength to the cladding mode. The infinite maximum in the derivative also implies the existence of two resonance wavelengths for each single period length. When the point where the derivative reaches its asymptotic maximum these two wavelengths coalesce, resulting in the condition for the very high sensitivity. The experimental results gave good agreement with theoretical predictions, particularly verifying the existence of the dual resonance and its coalescence at the specified conditions of cladding mode and grating pitch.
2.6.2. STRAIN AND TEMPERATURE SENSING

Like most of the optical fibre sensors, the FBG sensors are now widely used as strain and temperature sensors. Tang et al. (1999) carried out a numerical analysis to investigate the effectiveness of the strain measurement by the embedded optical FBG sensor while keeping the coating intact. The issues taken into consideration were: (i) the obtrusivity of the optical fibre sensor inside the host (isotropic) material, (ii) the difference, if any, between the optical fibre axial strain and the host material strain in the same direction and (iii) the change of the transverse stress, and hence strain, of the optical fibre throughout the host material load history. The study yielded the main conclusion that, the larger the host material, when compared to the optical fibre coating transverse dimension, and the longer the embedded fibre itself, the more effective the resulting measurements. The optical fibre strain measurement is not indicative of the host strain field in the vicinity of the fibre, but only of regions sufficiently far away from the fibre itself. Moreover, a sufficient length of the fibre must be utilised in the sensing system, since only the central section of the fibre is useful to the measurement. An experimental study has been carried out, addressing this problem. An uncoated optical FBG fibre was embedded in an epoxy resin block as well as the same fibre coated with three different coating materials, an epoxy, a silane agent and polypropylene (Wei et al., 2001). The block was loaded in tension and both the short term and long term optical responses were recorded. Then, they were compared to the output of a surface mounted ERSG by calculating a strain transfer coefficient, which evaluated the degree of agreement of the optical signal to the resistance signal. The gave the best comparison for the strain transfer followed by the epoxy, then the polypropylene. When looking at the long term response, a shear-lag effect was indicated for the three coating grating conditions, as the strain measurement converged on the value determined by the strain gauge. However, they reported that, under the constant load condition, the polypropylene coated fibre debonded from the host epoxy after a few hours.

Monitoring of vibrating beams with Bragg gratings is achieved by writing different Bragg wavelength gratings at several locations along one fibre axis and attaching the sensor to the beam. By determining the strain from each of the gratings, a reconstruction of the vibration
state of the beam is possible (Davis et al., 1996). The signals of all the gratings are multiplexed in the same fibre and analysed separately. Real time monitoring is almost effective in this case. By adequately choosing the locations of each point-sensor, the detection of individual vibration modes is possible. Additionally, the measurement of strain in several different locations is achieved by utilising an array of gratings in the same optical fibre, a method has been proposed to obtain a distributed strain measurement over short lengths (Huang et al., 1998). The method is based on a Bragg intra-grating sensing technique, where the short lengths are limited by the grating lengths themselves, typically up to a few centimetres. By a suitable analysis of the reflected light intensity spectra or phase diagrams, it is possible to determine the shape of very simple (monotonic) strain fields over the grating lengths. Moreover, a more complicated treatment of the optical output, involving Fourier Transforms, makes it possible to determine the strain field distributions.

As the FBG's are sensitive to strain and temperature, they are often used in conjunction with other optical fibre sensors to uncouple the thermal strain information from the strain due to mechanical load. An example is where a sensor head based on the Fabry-Pérot extrinsic sensor has been used together with a strain-free FBG as a simultaneous displacement and temperature sensor, where good agreement has been achieved with an analytical model set up for the particular system (L.A. Ferreira et al., 1998). A corrosion-temperature sensor has been demonstrated using two sections of the same FBG, after carrying out two separate treatments on the surface of the fibre where the grating was present (Lo and Xiao, 1998). The first half of the grating was pre-strained and covered with a known thickness of a copper coating, whose corrosion behaviour was under investigation. The second half was left unstressed. The copper corrosion consisted of a reduction in the coating thickness, which progressively caused the strain release of the pre-strained section. This section, the corrosion sensor, showed a shift in the Bragg wavelength, according to the strain-release process. The second section acted as a temperature sensor where only a wavelength shift determined from this section could result from a change in the temperature the optical fibre was experiencing. The two signals could be easily multiplexed into the same fibre, due to the difference between
the two reflected wavelengths. Experimental results were in good agreement with the theoretical analysis.

As purely temperature sensors, FBG's have been successfully embedded in metals. A technique based on a sputter coating process made it possible to cover the optical fibre with a double thin layer of Nickel and Titanium. A further Nickel layer was added to the fibre by electrolysis (Li et al., 2001). This treatment sequence made the optical fibre sensor suitable to undergo high temperature processes, allowing the fibre to be embedded into steel with minimal residual stresses. In such a system, the FBG was used as a temperature sensor and showed a measurement accuracy of ±2°C. The main errors in the measurement were due to the stresses in the host metal as a result of an inhomogeneous distribution of the current thermal level. Despite this, the reliability of the sensor was demonstrated experimentally, showing a good agreement with the temperature of the metal determined by thermocouple techniques.

2.6.3. FBG SENSORS IN COMPOSITES

When embedding FBG's in composite laminates, the most important aspect to be considered is the particular stress field which occurs around the optical fibre, particularly if the fibre is placed at an interface between two differently orientated plies. Such a stress configuration is totally different from the field created inside an isotropic material under an external load (Guemes and Menéndez, 2002). Experiments clearly show that, when the FBG sensor is subject to a transverse load together with a longitudinal stress, the original single-maximum reflection spectrum now returns two clear peaks, both obviously shifted with respect to the unloaded condition. It is suggested that this can be used to indicate residual thermal processing stresses in the laminate or to investigate stress relaxation in the material due to machining. The same phenomenon was experienced in the manufacturing of fibre-metal laminates, although a distinction should be made between laminates with different constituent materials (Kuang et al., 2001). When glass fibre pre-pregs are used to make up angle plies within a laminate, the wavelength-split reflected signal is clearly evident. The effect is much reduced when isotropic laminates are made with the same materials. Moreover, by using
Carbon fibre pre-pregs even in a unidirectional configuration, any change in the reflected spectrum shape is difficult to detect, if not completely absent. When loading a specimen in uniaxial tension, the whole spectrum is usually shifted on the wavelength axis, the usual in FBG behaviour, both in the case of single-peak spectrum and when the spectrum appears to split into two peaks. However, care should be taken when monitoring uniaxial strain from the shift of the maximum intensity wavelength. As the load increases it is evident that there is an exchange between the two peaks throughout the diagram shift resulting from the applied load growth. Potentially this could yield serious errors in the evaluation of the strain state if the phenomenon is ignored.

In spite of the complexity indicated above, the use of FBG sensors in composites for strain measurement is now widespread. The great sensitivity of the sensor and its linear behaviour have encouraged the use of FBG's in real applications, such as the monitoring of full wing bending tests (Kehlenbach and Betz, 2002). The sensitivity of the sensor was recorded for both the longitudinal and the transverse strain. The former was in fair agreement with the as mentioned above in a previous section, while the transverse strain sensitivity proved slightly inferior. In a cantilever beam configuration, the FBG sensor has also been used in series with a Fabry-Pérot sensor to multiplex strain and temperature measurement in the unidirectional graphite/epoxy host laminate (Jin et al., 1998). The system, as already mentioned above, showed excellent agreement with traditional strain and temperature gauges, where differences in the two separate measurement techniques were less than 5με and 0.5°C respectively.

A case study has been reported for FBG sensors embedded in a 0°/90° woven glass fibre reinforced polypropylene laminated plate. The optical fibre sensors were located in a central position with regard to the laminate width and at several different locations throughout the thickness (Bosia et al., 2002). The plate was loaded in three-point bending and a comparison was made between the optical output of sensors placed in the compression side to those in the tensile side. The reflected spectrum of those in tension was simply characterised by a very sharp Bragg wavelength shift. On the other hand, the spectrum output from the compression sensors, while undergoing an equivalent shift in the peak wavelength, showed a
severe shape deformation. This has been attributed to the occurrence of an inhomogeneous local strain distribution, very likely to be due to reinforcing glass fibre microbuckling. Nonetheless, all the sensors provided a linear output and demonstrated the non-destructive mechanical characterisation of the host material under study. Other examples exist of the internal strain monitoring in textile composites (Tao et al., 2000).

2.6.4. DAMAGE DETECTION

The use of the optical FBG sensors in detecting damage of a host material/structure has been demonstrated. A system for the detection of transverse cracks in the central 90° ply of CFRP cross-ply laminates under quasi-static tensile load has been investigated by placing the uncoated optical FBG sensor at the interface between two plies (Okabe et al., 2000). The shift in the Bragg wavelength and the shape of the reflected signal were recorded at several levels of the applied load and monitored to determine the crack onset and growth. In particular, the width of the spectrum at half maximum intensity could be related to the crack density, resulting in an indication of the damage evolution. It was noticed that the signal width increases with the first cracks, but reduces to a narrow signal close to crack saturation. Analytical predictions for the spectrum modification with the crack growth were in good agreement with that found experimentally. The main limitation in the study was the inability to point out the exact location of the cracks. The same study was repeated by utilising a polyimide coated small diameter (52µm) fibre, obtaining essentially the same results (Okabe et al., 2002). Recent work by Okabe et al. (2004) has shown that the use of a chirped FBG can locate the position of a matrix crack for low crack densities under tensile loading. The effect of a single matrix crack on the FBG spectrum has yet to be determined in either tension or flexure.

In addition to static tests, impact experiments have been carried out in order to determine if the FBG sensors could monitor the onset of damage. Low velocity impact tests were carried out on cross-ply laminates with a FBG sensing system embedded in one of the 0° plies (Dokos et al., 2001). The capability of the sensor was determined for monitoring both the impact occurrence as well as the resulting damage. The real time shift in the wavelength was
recorded by a grating interrogation rate of 1kHz, while the residual strain indicated by the final wavelength shift was taken as an indicator of the impact-induced damage. Not all specimens showed failure of the sensor under the same impact load. A different study provided information on FBG as impact damage sensors when embedded in fibre-metal laminates such as Glare® (Kuang et al., 2001). A polyimide coated optical FBG was embedded in one of the GFRP layers of the laminate, both in the unidirectional and in the cross-ply configurations. The wavelength change was first recorded after the material manufacturing process to determine the residual thermal strain. A clear shift was measured in both the 0° and the 90° directions. Additionally, the modified shape of the reflected spectrum in the cross-ply configuration revealed a process-induced chirping of the grating. The specimens were then tested in simple quasi-static cantilever bending to determine the linearity of the response to the applied load. Successively, impact tests were performed and the optical output at the end of each test was compared to the initial intact condition. These tests demonstrated a modification of the reflected spectrum with regard to both the wavelength peak and the shape of the diagram. Considerable deformation of the laminate in the sensor's surrounding area was discovered by observing the very large modifications undergone by the reflected spectrum. The modifications were more marked as the number of impacts increased. The sensor itself survived all the tests made, despite a large optical power loss that suggested its unsuitability for use in real field applications at the present stage of development of this technology. Finally, the linearity of the response in static bending was again checked after the impact damage had occurred and it was found to still exist.

2.6.5. APPLICATIONS

FBG's are the most recent development in optical fibre sensing technology. Despite this, the FBG sensors have already entered virtually all applications that have been demonstrated by alternative fibre optic sensing technologies. Health monitoring sensors for materials and structures, strain and temperature measurements and damage detections have all been reported. The most significant instances are reported in the following text.
Civil engineering. There is particular interest in bridges compliance and damage monitoring (Idriss et al., 1998 and Measures et al., 1995). The optical fibre sensors have been attached to the existing concrete structure or have been embedded in the FRP composite load-carrying elements of the structure or even embedded in the FRP plates used to strengthen beams (Lau et al., 1999). Work has been reported for the utilisation of FBG’s for health monitoring of new composite waterwork locks (Bugaud et al., 322).

Aerospace engineering. The major interest is in the real-time monitoring of aircraft and spacecraft structures for both strain and damage initiation. In-flight trials of the sensing systems have been carried out by attaching the sensor head to aerodynamic surfaces and monitoring the loading on the aircraft with the optical analysis instrumentation (Read and Foote, 2001). Impact damage monitoring has also been carried out on ground systems, such as radomes (Bocherens et al., 2000).

Process engineering. In addition to those previously reported above, the FBG’s have found an application in the resin cure process monitoring, where they are incorporated in hybrid sensing systems with other optical fibre sensors (Dewynter-Marty et al., 1998 and Leng and Asundi, 2002).

Naval engineering. Critical structural elements incorporated into a competition sailing craft have been manufactured with FBG sensing systems to enable the craft to be monitored during competition (Read and Foote, 2001).

The applications mentioned above are not the complete range of use for the FBG sensors. Other specific applications have been reported, for example, in the medical environment, where their use as alternative thermometers is most prevalent (Rao et al., 1997).

To overcome vast amount of sensor data related to systems consisting of large numbers of FBG’s distributed in a system, complex dedicated signal processing apparatus are required to deal with the simultaneous output from all the sensors (Jensen et al., 2000 and McGarrity and Jackson, 1998).
Chapter 2

LITERATURE REVIEW

2.7. FEM ANALYSES OF DAMAGED COMPOSITE LAMINATES

One of the earliest FEM analyses of the crack tip area in a composite laminate was reported by Caslini et al. (1987). The mesh was finer in the region of the interface between plies of different orientations. The model deals with a cross-ply lay-up and the results they obtained allowed a useful comparison between theory and experimental data in the modelling of the laminate longitudinal Young's modulus for increasing transverse crack density under increasing tensile load. Good agreement was found.

Guild et al. (1993) carried out a 3D FEM analysis on a simple cross-ply GFRP laminate in order to calculate the value of the fracture mechanics parameters (stress intensity factor and strain energy release rate) associated with the growth of a single transverse matrix crack across the width of a laminate. Due to the symmetry of the laminate lay-up, one half only of the lay-up thickness was modelled. The model extended longitudinally from the plane of a pre-existing crack fully grown across the laminate width to the plane of the partially grown crack. The modelled change in material compliance with the crack growth and the strain energy release rate were in good agreement with experimental results. A model with a more refined mesh in the proximity of the growing crack tip was also analysed and provided identical values for the crack growth parameters. In addition, this analysis demonstrated that 3D effects have little influence and hence can be ignored in the modelling of transverse cracking. This provided validation for an assumption frequently made while approaching the theoretical description of this phenomenon.

A similar study was undertaken by Venu Kumar et al. (1999), who extended the analysis to hybrid laminates. They considered different cross-ply laminates containing carbon fibre and glass fibre reinforced epoxy, with different longitudinal and transverse plies. Results were compared with the predictions of a shear-lag analysis. They found a negligible change of strain energy release rate as a function of a transverse matrix crack growth, whereas a monotonical increase corresponded to an increase in crack density. Stiffness reduction predictions of the model, as a function of the crack density, fell between the predictions of
shear-lag analysis and those obtained from a variational model.

In the detailed work by Tong et al. (1997) a more complex quasi-isotropic (0/90/-45/+45)s lay-up was considered in a 2D analysis. One half thickness of the symmetric laminate was modelled. Three models were analysed, for locations of a matrix damage parallel to fibres: (i) in only the 90° plies, (ii) in the 90° plies and in the middle double-thickness +45° ply and (iii) in all the off-axis plies. Predictions for the longitudinal stiffness reduction of the material due to cracking agreed with experimental results for low values of the 90° ply crack density. For increasing values of the crack density, the predictions of the model including damage in the 90° and +45° plies proved the closest to the experimental data. In particular, the modulus reduction was underestimated, due to neglecting the effect of matrix cracking in the -45° plies. However, the cracks developed in the -45° plies never extend over the whole laminate width, although they are large in number, and as a result they contribute little to the modulus reduction. In this study, longitudinal and transverse profiles of the longitudinal stress were provided by the FEM analysis. Moreover, the computation of shear stresses allowed the length of the stress-transfer area for cracks in the 90° ply to be calculated in the longitudinal direction. This length was found to be approximately equal to three times the 90° ply thickness.

A detailed finite element analysis of the stress field established at delamination tips in a cross-ply laminate under three-point bending load is reported by Zhao et al. (1999). A comparison was made between two meshing criteria, and a global/local approach utilising displacement elements provided reliable stress analysis results while saving considerable computer system resources when compared to analysis incorporating conventional meshing.

2.8. SUMMARY

In this Chapter a review has been reported of previous work in the fields of (i) modelling matrix damage in polymer composites, (ii) development of optical fibre sensors for strain and temperature measurement in composite materials and other systems and (iii) FEM analysis applied to the study of damaged areas inside composite laminates. The literature
review has shown that theoretical predictions of the development of matrix cracking in bending have been derived. However, there is little experimental data available at present, and the initiation and propagation of damage in bending has not been studied extensively for either quasi-static or cyclic flexural loading. With regard to the use of FBG sensors for detecting matrix cracking damage, there is a need to determine the effect on the reflected spectrum due to crack development for both tensile and flexural loading. These two areas, matrix crack development in bending and its detection using FBG sensors, are the areas to be investigated in this work.

In the next Chapter, relevant theories connected with the effect of matrix cracks on flexural stiffness and the operation of FBG sensors are presented.
The present Chapter is aimed at giving an introduction to the theoretical principles relevant to the work described in this report. The analysis for the prediction of mechanical properties of a cross-ply composite laminate containing transverse ply matrix crack damage is based on shear-lag theory. A brief description is given of photosensitivity, the property of some glass materials which enables the fabrication of Bragg gratings in optical fibres. Last, the equations are discussed for the theoretical calculation of a Fibre Bragg Grating reflected spectrum: these expressions are the results given by the application of a coupled-mode theory to the problem of FBG's.

3.1. SHEAR-LAG THEORY

3.1.1. SIMPLE CROSS-PLY LAMINATE UNDER A TENSILE LOAD

Among the methods existing to describe the effect of matrix cracking damage on the properties of simple cross-ply composites, there is the approach based on shear-lag theory. Described in the following is a discussion of this approach based on the work by Steif (in appendix to Ogin et al., 1984) and Smith and Ogin (1999, 2000).

The material taken as a reference for the study is a simple polymer matrix cross-ply laminate, whose ply thickness is identified with \( b \) for the longitudinal plies and \( 2d \) for the
transverse ply. A schematic diagram is shown in Figure 3.1.

Figure 3.1. Geometry and reference system of a simple cross-ply composite laminate.

- $X = \text{direction of longitudinal fibres}$,
- $Y = \text{direction of transverse fibres (width direction)}$,
- $Z = \text{laminate thickness direction}$.

The starting point of the discussion is the expression for the longitudinal modulus of the laminate. By the rule of mixtures, it is given by equation 3.1:

$$
E_0 = \frac{bE_1 + dE_2}{b + d}
$$

where:

- $E_0 = \text{laminate Young's modulus in the x direction}$,
- $E_1 = \text{Young's modulus of a longitudinal ply in the x direction}$,
- $E_2 = \text{Young's modulus of the transverse ply in the x direction}$.

Of course, an applied load in the direction of the longitudinal fibres is carried by all the plies of the laminate in proportion to the respective stiffness values.

When the transverse ply undergoes matrix cracking parallel to the fibres in this ply and perpendicular to the longitudinal direction, in the vicinity of the crack the whole of the longitudinal applied load is taken by the adjacent longitudinal plies. As a result, the displacement of the transverse ply in the crack region assumes a profile which is schematically depicted in Figure 3.2.
Figure 3.2. Schematic edge view of part of a simple cross ply laminate with a matrix crack in the middle transverse ply. Under an applied tensile load, the displacement of the points on the crack surface is described by a parabolic profile in the shear-lag theory presented here.

In the shear-lag analysis, the profile can be taken to be linear or parabolic (as shown in Figure 3.2). A parabolic variation of the longitudinal displacements across the transverse ply, $u$, can be described by the following expression:

$$ u = u_2 + \frac{z^2}{d^2} (u_1 - u_2) $$  \hspace{1cm} (3.2)

where (see Figure 3.2):

$u_1$ = displacement in the $x$ direction of the longitudinal plies,

$u_2$ = displacement in the $x$ direction of midpoint of the transverse ply.

Solution of the problem for the stresses in the $0^\circ$ and $90^\circ$ gives the expression for the longitudinal stresses in the longitudinal ($\sigma_{\chi,0}$) and transverse ($\sigma_{\chi,90}$) plies to be:
\[ \sigma_{x,0} = \sigma_A \left( \frac{b + d}{b} - \frac{E_1}{E_0} \right) \frac{\cosh \lambda x}{\cosh \lambda s} + \frac{E_1}{E_0} \sigma_A \] (3.3)

\[ \sigma_{x,90} = \sigma_A \frac{E_2}{E_0} \left( 1 - \frac{\cosh \lambda x}{\cosh \lambda s} \right) \] (3.4)

where:

\[ \lambda^2 = \frac{3}{b} \frac{G_{23}}{d^2} \frac{(b + d)}{E_1 E_2} \] (3.5)

For the expressions (3.3) and (3.4), 2s is the crack spacing. The location of x=0 is at the midpoint between two consecutive cracks, as shown in Figure 3.3. The stress \( \sigma_A \) is the applied load divided by the cross section. \( G_{23} \) is the shear modulus in the plane YZ.

**Figure 3.3.** Schematic edge view of part of a simple cross ply laminate with two consecutive matrix cracks in the transverse ply.

An expression for the reduction of laminate Young's modulus in the longitudinal direction can also be obtained. This is written in terms of normalised modulus, i.e. the fraction of the initial modulus of the undamaged material retained by the laminate after crack development:
\[
\frac{E}{E_0} = \frac{1}{1 + \frac{E_0}{E_1} \left( \frac{b+d}{b} - \frac{E_1}{E_0} \right) \tanh(\lambda s)}
\]  
(3.7)

where \( E \) is the residual longitudinal Young's modulus of the laminate after cracking.

The mean value of the strain of the laminate is, of course:

\[
\bar{E} = \frac{1}{2s} \int_{-s}^{s} \frac{\sigma_0}{E_1} \, dx = \frac{\sigma_A}{E}
\]
(3.8)

When the transverse ply matrix is cracked, the Young's modulus \( E_2 \) of the transverse ply degrades and assumes an actual value \( E_2^* < E_2 \). In this case, equation (3.1) could be rewritten as:

\[
E = \frac{bE_1 + dE_2^*}{b+d}
\]
(3.9)

By inserting the (3.9) into (3.7), an expression for the reduced modulus \( E_2^* \) of the transverse ply is obtained:

\[
E_2^* = \frac{\left(1 - \frac{\tanh\lambda s}{\lambda s}\right) E_2}{\left(1 + \frac{dE_2^*}{bE_1} \tanh(\lambda s)\right)}
\]
(3.10)
3.1.2. DOUBLE CROSS-PLY LAMINATE UNDER BENDING

The shear-lag theory enables cross-ply laminate behaviour to be analysed in different circumstances. For example, a study has been carried out on the characteristics of multiple cross-ply laminates undergoing matrix damage under a bending load (Smith and Ogin, 1999). In this case, a \((0/90/0)\), lay-up was analysed and the geometry of the laminate is shown schematically in Figure 3.4.

Figure 3.4. Schematic edge view of a double cross-ply laminate with a matrix cracks in the tensile transverse ply under an applied four-point bending load. The central region of the laminate, between the two inner rollers, is subjected to a uniform bending moment.

The change in the flexural modulus of such a laminate due to matrix cracking has been analysed by Smith and Ogin (1999). In Figure, 3.4 the coupon is shown in a damaged condition, with matrix cracks present in one of the two double-thickness transverse plies. This ply experiences tensile stresses when the laminate is loaded and between the two inner rollers the material is subjected to a uniform bending moment. When the material is undamaged, the
longitudinal stress distribution through the laminate thickness in this uniform bending moment region is represented by the following expression:

\[ \sigma_x = \frac{E(z) z}{R} \]  

(3.11)

in which:

- \( R \) = radius of curvature of the laminate under the bending moment in the uniform bending moment region,
- \( E(z) \) = longitudinal Young's modulus of the plies of the laminate.

The moment/curvature relationship for this laminate is given by the following relation:

\[ \frac{M}{\kappa} = M \cdot R = E(z) \cdot I = E(z) \int_{-t/2}^{t/2} w z^2 \, dz \]  

(3.12)

in which:

- \( M \) = applied bending moment,
- \( \kappa \) = curvature of the material,
- \( I \) = moment of inertia of laminate cross section with respect to the neutral axis,
- \( t \) = total thickness of the laminate,
- \( w \) = width of the beam specimen considered.

Integrating and rearranging equation (3.12) gives:

\[ \frac{M}{\kappa} = \left( \frac{w t^3}{12} \right) E_{flex}^0 \]  

(3.13)
in which the flexural modulus for the undamaged material $E_{\text{flex}}^0$ assumes the following form:

$$E_{\text{flex}}^0 = \left( \frac{219 E_1 + 124 E_2}{343} \right)$$  \hspace{1cm} (3.14)

When the tensile transverse ply of this laminate undergoes matrix cracking, the Young's modulus $E_2$ of this ply degrades to a smaller value $E_2^*$, similar to that already discussed in section 3.1.1 (equation 3.10). By using the same equation for the definition of $E_2^*$, an expression can be derived for the reduced flexural modulus of the $(0/90_2/0)_s$ laminate in the damaged state (Smith and Ogin, 1999):

$$\frac{E_{\text{flex}}}{E_{\text{flex}}^0} = \frac{((219 E_1 + 62 E_2 + 62 E_2^*)/343) - (108/343) \cdot ((E_2-E_2^*)/(3 E_1 + 2 E_2^* + 2 E_2))}{((219 E_1 + 124 E_2)/343)}$$  \hspace{1cm} (3.15)

Equation (3.15) predicts the decay of the flexural modulus value for the laminate as a function of crack density developing in the tensile transverse ply under four-point bending. The predictions of this equation have been verified to fall within 1% of a more accurate general elasticity analysis due to McCartney (1997). Equation (3.15) only takes into account the type of damage consisting of matrix cracking in the tensile transverse ply. If other damage occurs in the material, e.g. delaminations at 0/90 interfaces, the degraded stiffness predictions are likely to underestimate the reduction undergone by the flexural modulus of the material as a result of the damage. Agreement between equation (3.15) and experimental data will be investigated in this work.
3.2. PHOTOSENSITIVITY AND BRAGG GRATINGS

3.2.1. PHOTOSENSITIVITY

Silicon is the principal chemical constituent of any commercial optical fibres. In the late 1970's, a fundamental property was discovered of silicon-based optical fibres whose core contained sufficient amounts of doping elements (mainly germanium, boron or erbium): photosensitivity. When UV light irradiate the core, it is possible to locally induce a change in the index of refraction of the material. This refractive index change is permanent, although the long term stability of this change is still an issue. In the following, an account is given of photosensitivity in optical fibres, based on the work of Othonos and Kalli (1999).

Photosensitivity is the property by which some types of silicon-based glass reacts to UV illumination by affecting the chemical bonds at a molecular level. In this regard, the most suitably reactive sites in the glassy structure are the bonds involving atoms of the doping elements. In the case of germanium-doped cores, GeO molecules create microstructural defects in the glass called germanium oxygen-deficient centres (GODC's). Such defects are the most common sources of glass photosensitivity in optical fibres.

The understanding of all the physical and chemical mechanisms involved – at atomic, molecular and microstructural levels – in a change of refractive index in photosensitive glasses and glass fibre cores is still an issue. Many research programs are being undertaken to seek confirmation of various hypotheses; however, the majority of the results to date still provide contradictory information about the phenomena. Several qualitative descriptions of the influence, which individual parameters or sets of factors may have on photosensitivity properties shown by optical fibres, are reported in the form of models, each accounting for some aspects of the phenomena (Othonos and Kalli, 1999). The most important models available are (i) the Colour-Center Model, concerned with explaining connections between atomic level transformations and photosensitivity, and (ii) the Compaction/Densification Model, providing photosensitivity understanding at a meso- and a macro-scale level.

The Colour-Center Model deals largely with the glass microstructural defects which have been said above to be the most reactive sites to UV illumination during the manufacture of
FBGs. This model concentrates on transformations of the atomic structure occurring at an atomic level when electron band transitions are stimulated by a laser UV light irradiation of the glass. To date, experimental results seem to show that the most part of the fibre core refractive index change after UV illumination is accounted for by such transformations (Othonos and Kalli, 1999). On the other hand, the Compaction/Densification Model describes the change in refractive index from the point of view of the mechanics of materials. UV illumination, which an optical fibre core is subjected to during the FBG-writing process, typically induces a densification of the material via a re-structuring of the chemical bonds: the core density is increased and the material tends to contract. This produces an increase in refractive index. At the same time, core material compaction gives birth to tensile stresses in the optical fibre core itself, which tend to decrease the refractive index. Therefore, the overall index change induced results from the balance between these two effects (Othonos and Kalli, 1999).

Finally, there exists a set of chemical elements (e.g. nitrogen) whose presence inside the glass of an optical fibre provides the fibre with remarkable photosensitivity properties. Such elements can either be used as co-dopants of germanosilicate glasses or as main doping components in germanium-free fibres (Othonos and Kalli, 1999).

3.2.2. BRAGG GRATING DEFINITION

When producing a Bragg grating sensor, it is necessary to control the UV-induced refractive index change in the core of the optical fibre since a fibre Bragg grating is a length of an optical fibre core within which a periodic variation of the index of refraction exists. For a typical Bragg grating, this variation is represented by a cosine function and the period of the function constitutes the pitch length of the grating. Both the amplitude of the induced index change and the pitch length are the principal parameters which characterise any Bragg grating. Together with the total grating length, these parameters determine the properties of the grating and the way in which light waves interact with it.

There are several processes used to manufacture a Bragg grating (Othonos and Kalli, 1999). In the most common method, UV light is launched at right angles to the optical fibre
through a diffraction mask, so creating an interference pattern with a regular spacing. Exposure of an optical fibre to such an interference pattern formed from the UV light is one of the most common transverse writing techniques used for inscribing a Bragg grating in the core of the fibre.

The basic property of a Bragg grating is the capability to act as a wavelength filter of broadband light propagating along its length. Light of wavelength $\lambda_b$, called the Bragg wavelength, is reflected by the grating back down the optical fibre and the spectrum of the reflected light presents a single peak corresponding to the Bragg wavelength, as shown schematically in Figure 3.5. The pitch length, or period ($\Lambda$), of the Bragg grating and the Bragg wavelength are related by the following equation:

$$\lambda_b = 2 n_{\text{eff}} \Lambda$$

where $n_{\text{eff}}$ is the effective index of refraction of the optical fibre core. Further theoretical aspects relating to this equation are discussed in section 3.3.

![Figure 3.5. Schematic representation of the working principle of a Bragg grating (after Othonos and Kalli, 1999).](image)

The basic mechanism by which a FBG is capable of yielding information on the fibre
core strain state consists of the shift undergone by the Bragg wavelength, $\lambda_B$, as a result of the variation of the grating pitch $\Lambda$. The latter may typically occur as a consequence of the strain change of the optical fibre due to an externally applied mechanical load or a change in temperature. A positive strain gives rise to an enlargement of the pitch length and the Bragg wavelength is shifted towards longer wavelengths. On the other hand, a compressive strain reduces the grating pitch and causes the Bragg wavelength to be shifted towards shorter values (Othonos and Kalli, 1999).

### 3.3. BRAGG GRATING THEORY

The theoretical description of the light-reflecting behaviour of Fibre Bragg Gratings (FBG) is achieved by the use of a general theory known as the Coupled-Mode Theory. Extensive description of the general theory can be found in the literature (e.g. Kogelnik, 1972). When the theory is applied to the Bragg grating problem, it is possible to obtain the calculated shape of the reflected and transmitted light spectra from a grating with particular characteristics. The discussion that follows in the present section deals with uniform gratings. A brief description is also included of grating chirping, i.e. the variation of the grating periodicity over the grating length.

The grating characteristics of interest to this discussion are the principal physical parameters defining the grating structure. As indicated in section 3.2.2, the periodicity – or pitch length, $\Lambda$ – is related to the Bragg wavelength $\lambda_B$ by:

$$\Lambda = \frac{\lambda_B}{2 \cdot n_{\text{eff}}} \quad (3.16)$$

where $n_{\text{eff}}$ is the refractive index of the fibre core, as seen by a light wave propagating down the cylindrical waveguide through one of the guided modes.

The refractive index distribution along the Bragg grating in the optical fibre core is
described by the following expression:

\[ n(x) = n_{\text{eff}} + \Delta n \cdot \cos\left(\frac{2\pi}{\Lambda} x + \varphi(x)\right) \]  

(3.17)

in which:

- \( x \) = direction of the optical fibre axis,
- \( \Delta n \) = the maximum refractive index change induced by the grating writing process,
- \( \varphi(x) \) = chirping function (it is identically zero for uniform gratings).

A plot of the \( n(x) \) function is shown in Figure 3.6 for \( \Delta n = 0.0001 \), \( \lambda_0 = 2n_{\text{eff}} \Lambda = 1550\text{nm} \) and \( n_{\text{eff}} = 1.4 \).

**Figure 3.6.** Diagram of the refractive index variation along the optical fibre axis core within the length of a Bragg grating (\( \lambda_0 = 1550\text{nm} \)).

A generic light wave travelling in a propagation medium is characterised by a propagation constant \( \beta \), defined as follows:

\[ \beta = \frac{2\pi \cdot n_{\text{eff}}}{\lambda} \]  

(3.18)

In the case of \( \lambda = \lambda_0 \), the propagation constant is written in the form:
A measure of the index of refraction change, \( \delta \bar{n}_{\text{eff}} \), obtained in the core material by the grating writing process is given by the variable \( \sigma \):

\[
\sigma = \frac{2\pi}{\lambda} \cdot \delta \bar{n}_{\text{eff}}
\]  

(3.20)

Defining the following:

\[
\delta = \beta - \beta_B
\]

(3.21)

\[
\hat{\delta} = \delta + \sigma - \frac{1}{2} \frac{d \phi}{dx}
\]

(3.22)

then an expression for predicting the shape of a FBG reflected spectrum from a FBG of length \( L \) is obtained with the Coupled-Mode Theory (Erdogan, 1993) and is given by:

\[
R = \frac{\sinh^2 \left( \sqrt{\kappa^2 - \hat{\delta}^2} \cdot L \right)}{\cosh^2 \left( \sqrt{\kappa^2 - \hat{\delta}^2} \cdot L \right) - \frac{\hat{\delta}^2}{\kappa^2}}
\]

(3.23)

where \( R \) describes the relative amount of the power of the incident light which is reflected by the grating for each wavelength.

In the case when there is no chirping, \( \phi(x) = 0 \) and \( \frac{d \phi(x)}{dx} = 0 \), then, in equation (3.23), the variable \( \kappa \) assumes a constant value \( \kappa^* \) given by:
\[ \kappa = \kappa^* = \frac{\pi}{\lambda} \delta n_{\text{eff}} \]  

(3.24)

Figure 3.7 shows a plot of \( R \) (i.e. equation 3.23) for a FBG with a nominal Bragg wavelength \( \lambda_B = 1550\text{nm} \) and a length \( L \) of 7mm. Such a calculated spectrum is in excellent agreement with experiment, as shown by the experimental data points shown in Figure 3.7.

Any uniform Bragg grating reflected spectrum is characterised by the presence of a main peak and a number of secondary peaks, symmetrically located with respect to the main peak, whose intensity is much weaker. By varying the length \( L \) of the grating, a variation of the reflected power results. Such behaviour is predicted by the theory, as shown in Figures 3.8 and 3.9, where a predicted reflected spectrum is plotted for gratings of the same type, but having
different lengths. It can also be noticed, by comparison of Figures 3.8 and 3.9, that the number and width of secondary side-peaks presented by each spectrum also vary in proportion to the grating length.

![Calculated reflected spectrum by a Bragg grating](image.png)

**Figure 3.8.** Calculated reflected spectrum by a Bragg grating (nominal $\lambda_B = 1550\text{nm}$, length $L = 5\text{mm}$).

Obviously, the maximum value of the reflected spectrum cannot exceed the value of 1 since a peak height equal to this value indicates that the grating is reflecting the whole power of the incident beam at the corresponding wavelength. The predictions show that any further increase of the grating length results in a flattening of the grating peak, meaning that the whole incident power is reflected for more wavelengths.
3.4. SUMMARY

In this Chapter essential elements have been given of the theoretical principles underlying the execution of the work reported in this thesis. The main results of shear-lag analysis concerning the predictions for elastic modulus decrease, as a function of an increasing crack density, have been described for cross-ply laminate subjected to tensile and bending loads. The main characteristics of the behaviour of Bragg gratings have been described, forming the basis for explaining the response of FBG sensors to strain.

In the following Chapter details are reported of the experimental work carried out for the investigation of the behaviour of a GFRP double cross-ply laminate under both quasi-static and fatigue bending loading. Moreover, the methods used to study and develop the embedded
FBG sensors are described. The overall aims of the study were to investigate matrix crack development in bending under quasi-static and fatigue loading, and to investigate the use of FBG sensors as matrix crack detection devices in composite materials.
Chapter 4

EXPERIMENTAL METHODS

The present Section describes the methods adopted to carry out the experimental investigations included in the present work. The manufacturing process of glass fibre/epoxy matrix cross-ply laminates is described. The procedures for obtaining the data regarding the crack density development and the flexural modulus reduction in one transverse ply of a cross-ply laminate in four-point bending tests are outlined in the first part of the Chapter. The second part is devoted to a description of the instruments used to build and operate the FBG sensor system. In the second part, the process of sensor embedment into glass/epoxy cross-ply laminates is first described. Subsequently, details are given of the system operation carried out to characterise the sensor response in various conditions. These include longitudinal quasi-static loading of a free sensor and the tensile and four-point bending loading of GFRP cross-ply composite specimens with embedded FBG sensors.

4.1. EXPERIMENTAL METHODS ASSOCIATED WITH THE FOUR-POINT BENDING TESTS ON A GFRP CROSS-PLY LAMINATE

4.1.1. MATERIALS

The laminate manufactured for the investigation was made of a tri-component epoxy
resin reinforced with E-glass fibres. The resin composition by weight was: 100 parts of Bisphenol A Epichlorohydrin resin 300; 60 part of MNA hardener; 4 parts of Ancamine K61B catalyser. The lay-up of the laminate was \((0/90_2/0)_s\), as shown in Figure 4.1.

![Figure 4.1. Geometry of the glass-epoxy double cross-ply laminate under investigation.](image)

The reason for the choice of this configuration is as follows. Under a four-point bending load the neutral axis of the beam specimens falls within the thickness of the middle 0°-ply. As a result, the bottom transverse ply is completely under a tensile stress in four-point bending, while the top transverse ply is under compression. This stress system causes the development of matrix cracks only in the bottom transverse ply, as also schematically depicted in Figure 4.1.

The production of specimens included several steps. A dry preform was first manufactured by winding a 600 TEX glass roving onto a square steel frame with dimensions 450mmx450mm. The fibres of different plies could be placed in subsequent steps of the winding procedure. The middle 0° ply fibres were wound first, then the frame was rotated through 90° and the fibres of both double-thickness transverse plies were wound. The process was completed by again rotating the frame by 90° and the winding the fibres of the two outer longitudinal plies. A liquid impregnation process was used to introduce the resin to the dry glass reinforcement. The impregnation process consisted of two stages: liquid resin was first
manually spread over the reinforcement stack, and then a vacuum stage followed, aimed at removing any air bubble content in the matrix. An air-circulating oven cure of the polymer took place at a maximum temperature of 100°C. During the curing cycle, a pressure of 100kPa was applied for consolidation, which yielded a final thickness of the laminate of about 3.5mm, with an individual ply thickness of approximately 0.5mm. The volume fraction of reinforcement in the final composite material, was measured using burn-off tests and found to be 55.2%±0.2%. The laminate was then post-cured at a temperature of 150°C for 3 hours.

From the laminated plate so obtained, specimens were cut for the four-point bending tests using a diamond disc saw. The specimen dimensions were typically 20mm×200mm. No preparation of the specimen edges was carried out before subjecting the coupons to mechanical tests.

4.1.2. QUASI-STATIC TESTS

The quasi-static four-point bending tests have been carried out with the aid of a computer controlled Instron 8000 servo-hydraulic testing machine. The machine was equipped with a four-point-bending test rig specifically designed and built for the purpose. Design drawings of the rig are given in Appendix A. The machine load cell provided measurements of the applied force needed to bend the specimens, while the strain was measured by a surface mounted extensometer. A sketch of the experimental arrangement is shown in Figure 4.2. The extensometer measurement data were suitably transformed in the data processing in order to determine the longitudinal strain in the specimen (see section 4.3.1).

In quasi-static tests, the specimens were subjected to incremental loading. In each test, the cross-head displacement was advanced 2mm further than the previous one, although the cross-head displacement rate was kept constant at 20mm/min. The initial flexural modulus of the undamaged material was measured by running a test with a very low maximum load level, so as to prevent the specimen from undergoing any damage. Subsequently, the bending load was applied incrementally (as explained above).
Figure 4.2. Schematic view of the experimental set-up for the quasi-static four-point bending tests.

The result of the increasing load on the specimens was the initiation of damage in the material, which appeared in the form of transverse matrix cracks in the 90°-ply subjected to tensile stresses. By progressively imposing a higher load to the specimens, the number of cracks grew in the matrix of the transverse ply. This increase of the crack density was monitored and recorded by taking digital photographs of the specimens at the end of each load increment using a camera, which was positioned on a tripod in front of the test machine. In order to take the pictures of the specimen top side, the coupons were removed from the bending rig and rotated to place the top surface in front of the camera. The photographs were used to measure the crack density. From each picture, the individual crack lengths, enabling the current crack density, $1/2s$, to be determined with the aid of the following expression:

$$ D = \frac{1}{2s} = \frac{\sum_{i=1}^{n} l_i}{wL_g} $$

(4.1)

In Equation (4.1), the terms have the following meaning:
\[ D = \text{crack density}, \]
\[ 2s = \text{average crack spacing in the gauge length}, \]
\[ i = \text{number of cracks in the gauge length}, \]
\[ l_i = \text{length of a particular crack across the specimen width}, \]
\[ w = \text{specimen width}, \]
\[ L_g = \text{gauge length (equal to the extensometer gauge length)}. \]

All the values \( D \) of the crack density were obtained by measuring the lengths \( l_i \) and the specimen width \( w \) on the picture taken and then applying the formula (4.1) for each picture.

Immediately after taking each photograph, a separate quasi-static four-point bending test was carried out to measure the value of the residual flexural modulus of the material corresponding to the current crack density.

4.1.3. **FATIGUE TESTS**

4.1.3.1. **Modifications to experimental arrangement**

The experimental arrangement used for these experiments was similar to the arrangement for the quasi-static tests. However, when running fatigue cycles under a four-point bending load, a problem was encountered with setting up the specimen fixture system.

In quasi-static loading, the beam specimens have to be placed on the bottom supports of the bending rig (see Fig. 2.3), as it needs to be simply supported. The load is then applied quasi-statically by raising the bottom supports at a rate of 20mm/min. When the four-point bending load is applied dynamically, during fatigue cycling, the support of the specimen allows a few cycles to be run without any difficulty. However, it was not sufficient to keep the coupons in the correct position for the whole duration of the cycle count, typically to a minimum of many thousands. This was due to a number of factors. Firstly, the specimens may contain some non-uniformity within its volume and even minimal asymmetry in the experimental arrangement was enough to produce small movements of the specimen from its original position. These movements were cumulative after each fatigue bending cycle until the specimen
had moved well away from its original position.

In order to cope with this problem, a modification to the bending rig supports was manufactured. This involved a suitable specimen fixture which kept the specimens in the correct position throughout the fatigue cycles, without introducing unwanted loading. With reference to Figure 4.3, the requirement was to prevent the specimen from moving in the xy-plane and allowing it to rotate freely in the yz-plane.

The design involves a simple modification to the bottom supports of the bending rig. These modifications are schematically shown in Fig. 4.4. The rollers on the bottom supports of the test rig were modified to include a smaller diameter in the middle third of their axial length. The length of these thinner regions was 22mm in an overall length of 60mm. These portions of reduced diameter made up a seat for the 20mm-wide specimens to be placed, with the thicker segments of the rollers acting as shoulders. The reduced section had a diameter of 8mm, compared to 13mm for the shoulders. Movement along the x-axis of the specimens was prevented by these shoulders, although the specimens could still move parallel to the y-direction. This movement was prevented by attaching a vertical pin of 5mm diameter and a length of 12mm to one of the rollers. The test arrangement was completed by drilling a hole, 5.1mm in diameter, in each specimen manufactured for a fatigue bending test. The pin was then inserted through the machined hole in the specimen when the specimen was positioned on the lower rollers.

Figure 4.3. Reference system of the four-point bending test arrangement.
It should be noted that the required rotation of the specimen in the yz-plane during bending was not hindered by the presence of the pin, since the free rotation of the rollers around their principal axis on the V-edge of the supports was not impeded in any way. Details of the supporting rolls geometry can be found in the design drawings provided in Appendix A.

4.1.3.2. Test Procedure

Two different series of fatigue cycles have been run for this study, characterised by two different load levels. The determination of the crack density versus bending moment plot which was developed in the quasi-static tests, was used as a reference to set the load level for the fatigue cycles. The first series of cycles has been carried out with a peak bending moment of 26.5Nm, which is the threshold value above which cracking started in quasi-static loading. This series of cycles was identified by the name "LOW LOAD" cycles. The second series of cycles had a peak bending moment of 34Nm, capable of producing a crack density, in quasi-static loading, very close to saturation. Cycles of this second series were called the "HIGH LOAD" cycles. A frequency of 3Hz was adopted for all the cycles.

All fatigue cycles had an R-ratio of 0.1. All the specimens tested in fatigue were subjected to 10,000 cycles. At regular intervals, the fatigue loading was stopped and a single
quasi-static test was run. This was aimed at recording the current value of the residual flexural modulus of the specimens. At the same time, digital photographs of the specimens were taken so that the measurements of the current crack density could be made.

### 4.2. OPERATION OF THE FBG SENSORS

In this section experimental details are given with regard to the manufacture and operation of the FBG strain sensors, whose response has been studied both as a free sensor and as an embedded sensor within glass-epoxy cross-ply laminates.

#### 4.2.1. OPTOELECTRONIC ARRANGEMENT

A schematic picture of the experimental FBG arrangement is shown in Fig. 4.5. All the connections in the system were made using lengths of single mode optical fibre. The starting point of the system is the broadband light source. This was an Amplified Spontaneous Emission (ASE) source made by Thorlabs. It was connected to one of the four arms of a 3dB coupler. The second arm, at the same end of the coupler, was connected to an Optical Spectrum Analyser (OSA) type AQ-1425 manufactured by Ando Electric. The light passed through the coupler and was split evenly into two parts. The FBG sensor was connected to one of the two arms of the other end of the coupler. The FBG sensors for this work were supplied by the optoelectronic laboratory of the Nanyang University of Singapore. The other arm is terminated into a container of refractive index matching liquid. This liquid (paraffin was used in this work) possessed the same refractive index as the optical fibre material. This enabled any reflections at the interface between the optical fibre and the liquid to be absorbed so that the light travelling down this arm was dispersed into the liquid and absorbed by the black walls of the container. The light that reached the FBG sensor in the other arm is partly back-reflected and partly allowed to go through the grating. The latter portion of the light is dispersed into a second container of refractive index matching liquid and absorbed by the black walls of the container.
Reflected light passed back through the coupler to be analysed and recorded by the OSA.

In Figure 4.5 the FBG sensor is shown schematically as embedded in a composite specimen. However, experiments on free sensors have also been carried out.

Two different types of light source were used in these experiments, initially a tuneable laser and subsequently a broadband source.

4.2.1.1. Tuneable Laser Source

For the first experiments, a Tuneable Laser Hewlett-Packard 8168E was used as the light source. This instrument is capable of generating narrowband light with a spectrum peak within the interval 1360nm to 1600nm. The output wavelength value can be set with a 0.005nm accuracy together with the output power (which was normally set to 1mW). The nominal Bragg wavelength of the FBG sensors used in the present study was about 1550nm, a value within the operating range of the Tuneable Laser. Examples of five different spectra in the range 1546nm
to 1554nm are shown in Figure 4.6.

A series of parameters can be set-up by the operator, depending on the operation mode chosen for the experiments. In these experiments, the sweep mode was used. During the sweep, a series of light beams are launched, whose peak wavelengths differ by an interval which is defined by the operator. In this mode, the operator sets the values for the upper and lower bounds of the sweep interval, the amplitude of the sweep steps (i.e. the separation between peak wavelength values of the spectra output in two consecutive steps of the sweep) and the dwell time (the length of the time interval during which the instrument outputs a light spectrum centred on a particular wavelength).

Figure 4.6 shows a series of spectra recorded by the spectrum analyser with tuneable laser operating with a sweep interval of 1545nm to 1555nm, sweep steps of 2nm and a dwell time of 7.5 seconds.

4.2.1.2. ASE broadband source

The tuneable laser source was replaced subsequently with an Amplified Spontaneous Emission (ASE) broadband source. The instrument used was a ThorLabs ASE-FL7002. This type
of sources generate light composed of a range of wavelengths: the wavelength output range of the instrument used in this work was approximately 1520nm to 1610nm. The spectrum of the source is shown in Figure 4.7.

The output power was about 30mW distributed over the whole range of wavelengths so that the light intensity at each wavelength is lower than the intensity of the tuneable laser at the same wavelength. With the ASE source, no parameter adjustments were possible, but the use of this source led to a dramatic reduction in the time required to interrogate the FBG sensors.

![Figure 4.7. Spectrum of the light output by the ASE source.](image)

### 4.2.1.3. Optical Spectrum Analyser (OSA)

The OSA used in the arrangement shown in Figure 4.5 was a Type AQ-1425 manufactured by Ando Electric Co., Ltd., Japan. This instrument detects the intensity of each wavelength component of a light beam and the shape of the intensity vs. wavelength diagram (i.e. the light spectrum) is displayed on a monitor. The way this analysis is carried out by the device is by sweeping over a preset wavelength range defined by the operator. The control
panel of the OSA enables the setting of a series of parameters whose values need to be adjusted to run the analysis of a specific light source in the most efficient way. The principal parameters to be set are:

- **the centre wavelength**: *i.e.* the central value of the wavelength interval to be swept;
- **the sweep width**: *i.e.* the amplitude of the wavelengths to be swept;
- **the resolution**: *i.e.* the size of wavelength interval to which a single intensity data point is assigned;
- **the reference level**: it is the intensity of the noise level for the current analysis,
- **single or repeated sweep**: this command asks the instrument whether to run a single sweep over a predefined wavelength range or to sweep that range repeatedly until a new command is given;
- **the peak search**: the instrument displays the wavelength with the maximum intensity within the range analysed.

Once the sweep width and the centre wavelength have been given a value, the sweep interval is completely defined. The instrument is capable of analysing wavelengths in the range 400nm to 1600nm with a resolution achievable of 0.1nm. All the above listed commands can be sent to the machine locally, *i.e.* by operating on the instrument's built-in control panel. This method of operating the OSA was adopted in all the experiments involving the use of the tuneable laser light source. However, when the broadband light source was used, the OSA was controlled remotely by a PC.

### 4.2.1.4. Spectrum acquisition procedure with the tuneable laser

The recording of the reflected spectrum was the key operation in the experiments with the FBG sensor. This operation was carried out by two different procedures, depending on whether the tuneable laser source or the ASE broadband source was used.

In the procedure involving the use of the tuneable laser, the spectrum shape was recorded by constructing two columns of data, the first representing the wavelength values and the second listing the intensity values at each wavelength. The spectra shown in Figure 4.6 are typical light spectra emitted by the tuneable laser; it can be noticed that they are narrowband
spectra (they extend over a wavelength range about 1nm wide). A typical spectrum back-reflected by a FBG extends over a wider range of wavelengths. Hence, when launching the tuneable laser light into the optical fibre containing the FBG, the spectrum reflected by the grating was narrower than the reflected spectrum characteristic of the Bragg grating. Consequently, the description of the whole FBG spectrum shape was achieved by analysing several spectra reflected by the grating, each centred on closely spaced wavelengths. In this way, it was possible to describe the shape of the whole reflected spectrum with a linear interpolation between consecutive points. This rather time-consuming allowed a preliminary understanding of the sensor's sensitivity and strain detection capabilities.

Figure 4.8. Example of a FBG reflected spectrum (bold line) described by interpolation of data points (■) representing the maxima of reflected spectra of tuneable laser light sweep steps.
reflected spectra of a sweep series using the tuneable laser have been plotted, together with
the FBG spectrum given by the set of maxima readings of each spectrum of the sweep series. A
single sweep was set to 10 nm and the sweep steps were 0.1 nm. The wavelengths indicated in
Figure 4.8 indicate the individual steps of the laser sweep.

4.2.1.5. Spectrum acquisition procedure with the ASE broadband source
Replacing the tuneable laser by the ASE broadband source removed the requirement
for multiple sweeps. With the ASE source, an entire spectrum reflected by an FBG sensor was
analysed and recorded using a single OSA sweep over the required wavelength range. The
spectrum of the ASE source itself is shown in Figure 4.7. The output, which extends over a
100 nm wavelength range, is much larger than the wavelength range covered by a single FBG
reflected spectrum. As a consequence, by launching broadband light into the single mode fibre
containing a FBG, the reflected signal contains all the wavelengths which can be reflected by
the FBG. An example is shown in Figure 4.9.

![Figure 4.9. Example of a FBG reflected spectrum recorded by the procedure using the ASE broadband source.](image-url)
It has been already mentioned that no parameters need to be adjusted for the ASE source. Therefore, during the FBG experiments, the only optical instrument to be controlled was the OSA and for each experiment, it was necessary (a) to run a single sweep of the OSA over the wavelength range required and (b) to store the data for further processing.

The procedures could only be carried out with the aid of a PC, used to control the OSA operation and to store the reflected spectrum data in an MS-Excel readable file. The readable file was made of 560 data points, representing the results of the spectrum analysis carried out by the OSA. A specific computer program was written to carry out the spectrum acquisition procedure. Details of the program are given in Appendix B. The MS-Excel data file was then used to plot a diagram of the recorded spectra. Use of the broadband source in this way enabled a more detailed description of the reflected spectra to be achieved than with the tuneable laser, due to the higher number of data points recorded. In addition, the rate of data acquisition was increased by about a factor of 20.

4.2.2. LOADING THE FREE SENSOR

The first experiments involved investigating the behaviour of FBG sensors in strain with a free FBG sensor subjected to a longitudinal tensile strain. The device used to carry out these experiments was the mechanical rig shown in Figure 4.10. The optical fibre is clamped at two points, indicated by A and B in Figure 4.10, and the fibre strain is applied quasi-statically by manually turning the knob C, which either loads the fibre in tension or unloads the fibre when the direction of turn is reversed. It was possible to read the displacement of the moving clamp B using the scale present on knob C.

The free sensor experiments allowed the shift of the peak wavelength of the reflected spectrum as a function of the longitudinal strain imposed on the optical fibre containing the FBG to be recorded. In this case the tuneable laser source was used, but the full spectrum acquisition procedure described in the above was not carried out. The tuneable laser was set to run a sweep over a 10nm wavelength range comprising the value of the nominal Bragg wavelength of the gratings under study and the peak of the recorded spectrum was assumed to
represent a point of the spectrum characteristic of the FBG being studied and related to the corresponding wavelength.

Figure 4.10. The mechanical rig used in preliminary studies on free FBG sensors.

The strain applied to the optical fibre was increased by discrete steps of 0.016%. After each step, the strain was kept constant while the interrogation procedure of the FBG was carried out. After each step in strain, the fibre was unloaded completely before being loaded to a higher strain. Optical fibre fracture of these free sensors occurred at a strain level of about 0.35%.

4.2.3. SENSOR EMBEDMENT IN A CROSS-PLY LAMINATE

Optical fibres incorporating FBG’s were embedded in glass/epoxy cross-ply laminates, in order to carry out experiments aimed at describing the sensor’s optical output when the host material was subjected to either an external tensile or bending load. The manufacturing process for embedding the optical fibre into a cross-ply laminate required a small alteration to the
process already described in section 4.1.1 for fabricating glass-epoxy composite specimens.

Individual segments of single mode (SM) optical fibre, each 200mm long and containing a single Bragg grating, were supplied by the optoelectronic manufacturing laboratory of the School of Electrical and Electronic Engineering at Nanyang Technological University of Singapore. The Bragg gratings themselves were 10mm long and the nominal Bragg wavelength was 1550nm. The whole length of the segment was coated with an acrylate resin, except a short length of 45mm, located in the middle of the optical fibre segment, in which the Bragg grating was inscribed. In order to embed the FBG sensor into the composite specimens, additional sections of SM optical fibre – approximately 500mm long – were spliced to both ends of the segment containing the Bragg grating, so that sufficient lengths of non-embedded optical fibre emerged from both ends of each specimen. This enabled the embedded sensors to be connected to the instruments of the optoelectronic arrangement shown schematically in Figure 4.5.

Before embedding a sensor, the reflected spectrum of the free sensor was recorded when the sensor was simply resting unloaded on a flat surface. This was done by running one of the two spectrum acquisition procedures, using either the broadband source or the tuneable laser, as outlined above. This spectrum served as a reference for comparison with the spectra of the same sensor when embedded in the composite and under load.

After recording the reflected spectrum by the free sensors, the sensors were positioned in the desired locations inside the preform of dry fibres produced by the frame winding process. This was achieved by gluing the optical fibres onto two 5mm wide flexible strips. The strips were then bolted to the winding frame. Two small lengths – about 50mm long – of the optical fibre sections spliced to the segment containing the FBG were covered with silicone glue. These lengths were the positions where the embedded section of the fibre joins the non-embedded segments, and were therefore the weakest point of the optical fibre from a mechanical point of view. The covering with silicone rubber successfully provided additional protection to the normal acrylate coating and prevented handling fracture at these points. The portion of the silicone coating embedded within the composite did not affect the experimental
results, as these sections were located far from the gauge length in each specimen. The specimens to be subjected to tensile tests were end-tabbed with 1mm thick aluminium plates.

The desired location of the optical fibre in the lay-up of laminates was always to be within a 0° ply and at the interface between the 0° ply and an adjacent 90° ply. Since the reinforcing fibres of the longitudinal and the transverse plies were wound onto the frame in separate winding steps, the plastic strips carrying the optical fibres were mounted onto the frame after the winding of the two 90° plies had been carried out and before the winding of the adjacent 0° ply was started. In all cases, the optical fibres were put in place in parallel directions to the longitudinal reinforcing fibres. Cross-ply laminates with three different lay-ups were manufactured for the present study, as listed in Table 4.1. lay-up A is a simple cross-ply laminate, whereas lay-ups B1 and B2 are double cross-ply laminates, but with the FBG in different locations.

Table 4.1. Lay-ups of the laminates manufactured for this study.

<table>
<thead>
<tr>
<th>LAY-UP ID.</th>
<th>LAY-UP configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(0 / 90 / {FBG} 0 )</td>
</tr>
<tr>
<td>B1</td>
<td>(0 / 90 / 0 {FBG} / 90 / 0 )</td>
</tr>
<tr>
<td>B2</td>
<td>(0 / 90 / 0 / 90 / {FBG} 0 )</td>
</tr>
</tbody>
</table>

Figure 4.11. Schematic view of a type-A laminate with an optical fibre embedded in one of the longitudinal plies, at the interface with the transverse ply.
In Figures 4.11, 4.12 and 4.13 schematic pictures are shown of the structure of each laminate type. In particular, the location of optical FBG sensors is pointed out in each of the three different lay-ups.

**Figure 4.12.** Schematic view of a type-B1 laminate with an optical fibre embedded in the middle longitudinal ply, at the interface with one transverse ply.

**Figure 4.13.** Schematic view of a type-B2 laminate with an optical fibre embedded in one of the outer longitudinal plies, at the interface with the transverse ply adjacent to it.
Figure 4.14 shows a micrograph of a portion of cross-section of a specimen showing the optical fibre location in a type-B2 laminate at the interface between one longitudinal and one transverse ply.

Figure 4.14. Optical micrograph (100×) of a type-B2 specimen cross-section showing the optical fibre location at the interface between two adjacent plies.

4.2.4. TENSILE TESTS

Tensile tests were carried out on all the specimens manufactured, in order to (i) study the sensor response of the FBG sensors to simple unidirectional loading of the host material, and (ii) analyse the optical output of the sensors when a crack developed in the adjacent transverse ply at a location included within the length of the FBG.
One of the two sections of optical fibre protruding from the specimen was spliced to one arm of the 3dB coupler, while the second one was sunk into an index-matching liquid container, as shown in Figure 4.5. The spectrum acquisition was carried out with one of the two procedures outlined in the previous sections (i.e., either using the tuneable laser or the broadband source). The FBG reflected spectrum was first recorded when no load was applied to the composite specimen. Subsequently, a unidirectional tensile load was applied quasi-statically to the specimens using a computer controlled Instron 8000 servo-hydraulic test machine and increased in discrete steps. The parameter controlled in the loading process was the longitudinal strain of the specimens, measured by a surface-mounted extensometer with a gauge length of 50mm. Each discrete loading step produced a coupon longitudinal strain which was 0.05% higher than the previous step. After each loading step, the strain was held constant for as long a time period as necessary to record the spectrum reflected by the FBG under each strain level of the host material. In the first phase, the specimens were strained up to a maximum of 0.35%. Up to such a strain value, both the optical fibres and the cross-ply specimens behave elastically: upon unloading, no damage is found. This operation allowed the study of the FBG sensors for strain measurement.

**Figure 4.15.** Schematic of crack initiation at the edge of the transverse ply in a cross-ply specimen; under a cyclic tensile load, the crack grows past the FBG location.

The next action was to manually initiate and grow a matrix crack in a specimen's transverse ply within the length of the FBG sensor (the location of the Bragg grating along the length of the embedded optical fibre was known beforehand, being in the middle of the 45mm
length of optical fibre over which the acrylate coating was absent). Crack initiation was obtained by introducing a notch in the transverse ply edge with the use of a scalpel blade. By running a few tensile fatigue cycles at a low maximum load level (equivalent to a strain of 0.2%), the crack initiated from the notch was grown across the full width of the specimen (see Figure 4.15).

After producing a crack in this way, the cracked specimen was again subjected to quasi-static tensile load applied in increasing discrete steps of 0.05%. FBG reflected spectra were recorded after each step, while holding the specimen at a constant. The results obtained for the cracked specimens could then be compared with the spectra obtained from the undamaged material.

4.2.5. **FOUR-PONT BENDING TESTS**

4.2.5.1. **Overview**

In order to investigate the optical output of the optical FBG sensors under different load conditions, four-point bending tests were carried out on specimens for each of the three types of lay-ups listed above.

The bending load was applied under quasi-static conditions similar to the tensile tests, and, again, load increments were applied in discrete steps due to the need to record the FBG reflected spectra for increasing bending loads. Strain measurements were obtained using a surface mounted extensometer. The four-point bending test configuration is shown in Figure 4.16.

4.2.5.2. **Tests on type A specimens**

The bending of type A specimens (having a simple cross-ply lay-up) induced either a compressive or a tensile strain in the FBG sensor, depending on the sensor position, *i.e.* either on the compressive side of the neutral axis of the coupon. Figure 4.17 shows schematically the position of the sensor when under compression or tension.
Figure 4.16. Four-point bending arrangement with a double-cross-ply specimens embedding a FBG sensor.

Figure 4.17. Schematic of the stress configuration induced by a four-point bending load on type A specimens.
In all bending experiments, the FBG sensor was always lying in the region of constant bending moment, which produced a uniform longitudinal strain along the whole length of the Bragg grating for an undamaged specimen. Only one sensor was put in each coupon, and it was placed in either of the two positions shown in Figure 4.17. After testing the coupon in one orientation (for example with the sensor in compression), the specimen was inverted and the same procedure was repeated with the sensor loaded in tension.

![Figure 4.17. Schematic of the stress configuration induced by a four-point bending load on type B1 and type B2 specimens.](image)

Undamaged specimens were tested first and then a notch was initiated at the edge of the transverse ply of a coupon at the location of the FBG using a scalpel. The crack was then grown in fatigue, as described above. After developing a crack, the coupons were then subjected to the same loading sequence and spectrum acquisition as the uncracked coupons. The results allowed a comparison between the optical outputs of the sensor for undamaged and damaged laminates under four-point bending conditions.

**4.2.5.3. Tests on type B1 and B2 specimens**

Four-point bending tests were also carried out on type B1 and type B2 specimens, which incorporated a FBG sensor in a double-cross-ply lay-up. Sensor location in the specimens
of the two types was at the interface between one of the transverse plies of the double-cross-ply laminate and one of the two longitudinal plies adjacent to it (this has been shown in Figures 4.12 and 4.13). In these tests on coupons B1 and B2, the only FBG configuration was with the sensor below the neutral axis, thus putting the sensors into tension. The two locations of the FBG sensors in the experiments carried out are depicted in Figure 4.18. Of course, in any one coupon, there was only one sensor.

The distance of the sensors from the neutral axis affects the strain experienced by the sensor for the same bending of the coupon. The neutral axis of these laminates, when loaded in bending, is always within the boundaries of the middle longitudinal ply (Smith and Ogin, 1999). When the sensor was placed at the interface between the tensile transverse ply and the middle longitudinal ply (type B1 specimens), the sensor undergoes a small tensile strain under a bending load (due to its vicinity to the neutral axis) compared to sensors positioned at the interface between the tensile transverse ply and the outer tensile 0° ply (type B2 specimens), which experience a larger strain.

In these tests, particular attention was devoted to the crack detection behaviour of the sensors. Under an increasing bending load, the tensile transverse ply, located below the neutral axis in the experimental arrangement, undergoes matrix cracking due to the tensile stress which develops. In this case, no notches were carved in the edge of the tensile transverse ply in order to initiate a crack in the desired location (i.e. within the Bragg grating length). In fact, preliminary tests proved that transverse cracks developed in bending were notch-insensitive, i.e. cracks developed at locations not influenced by the presence of notches. Therefore, a few matrix cracks were simply allowed to develop in the tensile transverse ply by quasi-statically increasing the bending load. The load was increased until reaching a crack density value between 0.10 and 0.18 mm⁻¹, which corresponds to an average number of 1 to 2 cracks grown past the Bragg grating location within the grating length.

The four-point bending load configuration yields a crack geometry expected to be similar to the schematic picture shown in Figure 4.18. At the interface between the 90° ply and the outer 0° ply, the crack opening displacement of the matrix crack is expected to be larger
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than at the other interface. Hence, it was of interest to investigate the FBG sensor response to crack detection for these two situations.

Figure 4.18. Schematic picture of crack opening geometry in the tensile transverse ply of double cross-ply laminates under four-point bending load.

4.3. ANALYSIS OF THE USE OF AN EXTENSOMETER IN FOUR-POINT BENDING TESTS

4.3.1 CONVERSION OF EXTENSOMETER STRAINS TO LONGITUDINAL STRAINS IN THE COUPON

The experimental set-up of the four-point bending tests has been shown in Figure 4.2. The question addressed here is how the readings from the extensometer can be connected to longitudinal strains experienced by the FBG sensor. The analysis follows the treatment by Wang (2003).

Figure 4.19(a) reproduces schematically a portion of a specimen, $AA'CC'$, within the middle region, where the bending moment is uniform. The line BB' represents the neutral axis when the specimen is bent. In the present work, the extensometer was mounted in such a way that the two knives were in contact to the upper coupon surface at points $C$ and $C'$.
Before applying the bending moment, the lines \( BB' \) and \( CC' \) are straight and have a length of 50mm, which is also the gauge length of the extensometer. Under bending, the straight lines \( BB' \) and \( CC' \) in Figure 4.19(a) become curved lines \( BPB' \) and \( CQC' \) in Figure 4.19(b) respectively. The length of line \( CC' \) is reduced and the length of line \( BB' \) remains unchanged.

The extensometer measurement is the variation (reduction) of length of the straight line connecting points \( C \) and \( C' \) in Figure 4.19(b). The following equations describe the system geometry under bending, which is schematically depicted in Figure 4.19(b):

\[
\text{Figure 4.19. The geometry model of the extensometer and the coupon.}
\]

- (a) 50mm-long portion of an unbent specimen.
- (b) 50mm-long portion of a specimen under bending.
\[ \frac{BP}{OB} \frac{L/2}{R} = (OB - BC) \sin \theta = (R - d) \sin \theta = L'/2 \quad (4.2) \]

and

\[ CS = OC \sin \theta = (OB - BC) \sin \theta = (R - d) \sin \theta = L'/2 \quad (4.3) \]

where:

\( L \) = extensometer gauge length,

\( L' \) = extensometer length under the action of the bending moment,

\( R \) = radius of curvature of the specimen under bending \((R = OB)\)

\( d = AB = BC \) = half of the thickness of the specimen.

Combining equation (4.2) and (4.3), the following equation results:

\[ \sin \left( \frac{L/2}{R} \right) = \frac{L'/2}{R - d} \quad (4.4) \]

with identical meaning of the terms. Equation (4.4) allows to calculate the radius of curvature of the specimen \( R \). In fact, the term \( d \) is measured and \( L' \) can be obtained from the strain signal provided by the extensometer. The longitudinal strain \( \varepsilon_x \) at any location along the \( z \) axis inside the coupon is given by:

\[ \varepsilon_x = \frac{z}{R} \quad (4.5) \]

where:

\( z \) = is the distance to the neutral axis (thickness direction of the coupon), positive in the direction of line \( PO \) in Figure 4.19(b).

An accurate value for \( R \) in Equation (4.3) can be calculated using Maple® software.
(Wang, 2003). However, due to the large amount of strain data recorded by the computer controlling the test machine, thousands of \( R \) values should be calculated; therefore a combination of Maple and MS-Excel needs to be used. The Maple calculations are carried out via an expansion of the left term of equation (4.4), as follows:

\[
\sin\left(\frac{L/2}{R}\right) = \frac{L/2}{R} - \frac{(L/2)^3}{6R^3} \approx \frac{L/2}{R - d} \tag{4.6}
\]

In this expansion, the powers higher than 3 are ignored, so the calculation is always affected by some approximation. The roots of equation (4.6) are calculated by the Maple software (see Wang, 2003). Three roots are found, of which only one is reasonable. In the bending experiments carried out in the present work, the extensometer was attached to the upper face of the coupon, which becomes concave under the action of the applied bending moment. Figure 4.20 shows the profile of the strain recorded by the extensometer as the radius of curvature of the specimen increases in this condition.

![Figure 4.20](image.png)

**Figure 4.20.** Change of strain with \( R \) for the extensometer attached to the upper (concave) surface of the specimen.
In Figure 4.20 it can be seen that for an extensometer attached to the upper surface of the coupon, the relationship between the extensometer measurements and the radius of curvature is one-to-one. For a value of -0.4% of the extensometer-recorded strain, Maple software calculations return two positive roots for the radius of curvature (Wang, 2003):

\[ R_1 = -61.16948 \text{mm} \]
\[ R_2 = 1.46905 \text{mm} \]
\[ R_3 = 434.70044 \text{mm} \]  
(4.7)

However one of the two positive roots \((R=1.469 \text{ mm})\) is obviously unreasonable, so only the largest figure of the three results is considered in every calculation.

The conversion of the extensometer readings of strains to the strains at the position of the sensor in the laminate is carried out using MS-Excel. An example of the results is shown in Table 4.II for a sensor embedded at the interface between a transverse ply and an outer 0° ply (Wang, 2003).

**Table 4.II.** Example of the conversion of extensometer measurements to sensor strains (MS-Excel calculations).

<table>
<thead>
<tr>
<th>Time (sec's)</th>
<th>Load (kN)</th>
<th>Extensometer strain (%)</th>
<th>Radius of curvature, R (mm)</th>
<th>Curvature, 1/R (mm⁻¹)</th>
<th>Longitudinal strain at position of embedded sensor, (\varepsilon_x) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>-4.71E-03</td>
<td>-4.62E-02</td>
<td>3.98E+03</td>
<td>2.51E-04</td>
<td>3.14E-02</td>
</tr>
<tr>
<td>0.5</td>
<td>-1.46E-03</td>
<td>-5.11E-02</td>
<td>3.95E+03</td>
<td>2.53E-04</td>
<td>3.16E-02</td>
</tr>
<tr>
<td>1.0</td>
<td>-2.87E-03</td>
<td>-5.58E-02</td>
<td>3.30E+03</td>
<td>3.03E-04</td>
<td>3.47E-02</td>
</tr>
<tr>
<td>1.5</td>
<td>-9.36E-03</td>
<td>-6.08E-02</td>
<td>3.04E+03</td>
<td>3.29E-04</td>
<td>3.78E-02</td>
</tr>
<tr>
<td>2.0</td>
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<td>-7.92E-02</td>
<td>2.36E+03</td>
<td>4.26E-04</td>
<td>4.91E-02</td>
</tr>
<tr>
<td>3.5</td>
<td>-2.25E-02</td>
<td>-8.55E-02</td>
<td>2.18E+03</td>
<td>4.59E-04</td>
<td>5.33E-02</td>
</tr>
<tr>
<td>4.0</td>
<td>-3.20E-02</td>
<td>-9.17E-02</td>
<td>2.03E+03</td>
<td>4.92E-04</td>
<td>5.74E-02</td>
</tr>
<tr>
<td>4.5</td>
<td>-4.07E-02</td>
<td>-9.81E-02</td>
<td>1.90E+03</td>
<td>5.25E-04</td>
<td>6.15E-02</td>
</tr>
<tr>
<td>5.0</td>
<td>-4.71E-02</td>
<td>-1.03E+00</td>
<td>1.52E+03</td>
<td>5.66E-04</td>
<td>6.56E-02</td>
</tr>
</tbody>
</table>

The first three columns in Table 4.II, list the real experimental data recorded by the computer controlling the test machine. The values of \(\varepsilon_x\) listed in the last column, represent the longitudinal strain in the specimen at the interface between one outer 0° ply and the adjacent...
90° ply. This is one typical location of optical fibre sensors in the laminates manufactured for the present work. Only input data and final results of the calculations are shown in Table 4.1.

It is important to check the errors introduced using the approximate solution provided by the Maple software. The comparisons for three strain readings from the extensometer are given in Wang, 2003. The error introduced by the approximation used in equation (4.7) is not larger than 0.56%, even for the largest bending deformations in this work.

### 4.3.2 MEASUREMENTS OF FLEXURAL MODULUS

The analysis reported above was used to obtain values of the longitudinal strain experienced by the sensors during the four-point bending tests. By using equation (4.4) the flexural modulus of the coupon can also be obtained. In four-point bending, the flexural modulus of the specimen $E_{\text{flex}}$ is linked to the radius of curvature of the specimen and the and the applied bending moment by the following relationship:

$$M_B \cdot R = E_{\text{flex}} \cdot I_y$$  \hspace{1cm} (4.8)

where:

- $M_B$ = the applied bending moment (which can be calculated from the applied load and dimensions of the coupon),
- $I_y$ = the 2nd moment of area of the specimen cross-section (which can be calculated).

Hence $R$ can be calculated solving Equation (4.4) and $E_{\text{flex}}$ can be obtained from Equation (4.8). In particular, equation (4.8) can be written in the following form:

$$E_{\text{flex}} \cdot \frac{1}{R} = M_B \cdot \frac{1}{I_y}$$  \hspace{1cm} (4.9)

During the four-point bending tests, the test machine was operated in position control mode. The computer controlling the machine recorded, in each test, the vertical load, $F$, and the
externsometer strain signals as a function of time. Both sides of the (4.9) can be differentiated against time, t. This operation gives:

\[
\frac{d}{dt} \left( \frac{1}{R} \right) = \frac{1}{l_x} \frac{dM}{dt}
\]

Equation (4.10) has been used to derive values of the flexural modulus of the specimens tested with the aid of MS-Excel calculations. A plot of 1/R versus time, t, is a straight line, with gradient expressed by d(1/R)/dt. The ratio dM/dt can be calculated as the gradient of a load-time plot. These plots can be easily drawn by again using the MS-Excel software. The flexural modulus of the coupon can now be determined from equation (4.10); in fact:

\[
M_{\text{flex}} = \frac{F}{2} \cdot S
\]

where \( F \) is the load signal and \( S \) is the distance between the outer roller and inner roller.

The measured flexural modulus in bending of the coupons with a lay-up of (0/90/0/90/0) was found to be 32.5±1.0 GPa. This can be compared with the theoretical prediction of the flexural modulus of the laminate calculated using the theory by Smith and Ogin (1999). When \( E_1 = 39 \) GPa and \( E_2 = 11 \) GPa, then the predicted value is 28.9 GPa. The difference between the theoretical value and the experimental value is likely due to the fact that the 0° plies and 90° plies do not have the same thickness as assumed in the prediction (the 0° plies are slightly thicker than the 90° plies).

### 4.4. SUMMARY

In this Chapter, a description has been reported of the principal experimental methods used in the experiments for this work. The procedures used to investigate the behaviour of a double cross-ply composite laminate in quasi-static and fatigue tensile four-point bending tests
have been outlined. The experimental arrangement used to operate optical FBG sensors has
been described, as well as the methods to examine the behaviour of the FBG sensors when
embedded in composite laminates subjected to tensile and four-point bending tests.

A description of the results of the experiments is reported in Chapters 6 to 9.
5.1. INTRODUCTION

MODELING OF the off-axis ply matrix cracking in multidirectional composite laminates has been attempted in a number of different theoretical approaches. Besides closed-form descriptions of various aspects, such as stiffness reduction or stress distributions, numerical solutions of the problems involved have been proposed. Among the latter class of studies, Finite Element Method (FEM) analyses have been carried out, showing applicability of the method to the computation of fracture mechanics parameters and to the description of stress fields.

Relevant to the present work is a description of the longitudinal strain field established in a 0° ply of a cross-ply laminate as a result of the development of a crack in the adjacent transverse ply. The shear-lag theory presented in Chapter 3 is based on a one-dimensional analysis, and hence it assumes a uniform strain in all points across the thickness of the longitudinal ply. In this Chapter the results are reported of a FEM analysis carried out to achieve
a description of the longitudinal strain distribution established in the outer longitudinal plies of a GFRP cross-ply laminate due to the presence of a single matrix crack in the adjacent transverse ply. In particular, attention was focused on 0°-ply points close to the interface with the damaged transverse ply since the FBG sensors are loaded at these positions.

### 5.2. MODEL DESCRIPTION

The FEM analysis described in the following is based on a 2D model of a (0/90₂/0) cross-ply laminate made of continuous glass fibre-reinforced epoxy resin. The model, a tensile dimensions are shown schematically in Figure 5.1.

![Figure 5.1](image_url)

Figure 5.1. Schematic (not to scale) diagram of the middle longitudinal section of a tensile specimen of (0/90₂/0) glass-epoxy laminate modelled in the present analysis. Dimensions and reference system of the specimen are indicated. The FE model is of the shaded area.

The section modelled in the FEM analysis is also shown in Figure 5.1. The shaded area ABCD is the region included in the FE model. Due to the symmetry of the lay-up, the model
extends over one half of the laminate thickness. The longitudinal dimension of the model was limited by the transverse crack plane, at the one end, and by the position of end-tabs at the other end. The transverse matrix crack was located in the middle of the specimen length. The values of dimensions b and d were: b = 0.5mm and d = 1.25mm. Constraints were applied to all model edges to comply with the symmetry with respect to both the laminate mid-plane and the specimen middle cross-section, in which the transverse crack plane was contained. The latter coincided with the matrix crack surface. In order to simulate a longitudinal applied tensile load, a finite displacement in the x direction was imposed to points of the BG edge. The points of edge CG were kept fully constraint-free to simulate the presence of a matrix crack. All degrees of freedom of points of edge AD were constrained.

The mechanical properties of the lamina material adopted for the model were as listed in Table 5.I.

**Table 5.I.** Elastic properties of a lamina of the GFRP material considered for this analysis. The values are taken from Tong et al., 1997.

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>SYMBOL</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Young's modulus</td>
<td>$E_1$</td>
<td>40.0 GPa</td>
</tr>
<tr>
<td>Transverse Young's moduli</td>
<td>$E_2$, $E_3$</td>
<td>11.6 GPa</td>
</tr>
<tr>
<td>Longitudinal shear moduli</td>
<td>$G_{12}$, $G_{13}$</td>
<td>5.0 GPa</td>
</tr>
<tr>
<td>Transverse shear modulus</td>
<td>$G_{23}$</td>
<td>4.6 GPa</td>
</tr>
<tr>
<td>Poisson's ratios</td>
<td>$v_{12}$, $v_{13}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>$v_{23}$</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The model meshing was obtained by assigning different geometry of elements to regions corresponding to the longitudinal ply and to the transverse ply respectively. Four-node quadrilateral elements were assigned to the longitudinal ply and triangular elements were adopted for the transverse ply. Quadrangular elements were square-shaped in the undeformed model; five elements filled the thickness of the longitudinal ply. Dimensions of the transverse ply triangular elements were varied across the ply thickness. In particular the mesh was finer at
the interface between the two plies, to match the longitudinal ply mesh dimensions, and was gradually coarser towards the transverse ply edge corresponding to the laminate mid-plane. This was done to save computational resources. Figure 5.2 shows a detail of the model mesh.

Figure 5.2. Detail of the FE model mesh. Generalised plane strain elements were used. Four-node quadrangular elements and three-node triangular elements were respectively used for the longitudinal and transverse ply.

The whole model was assigned generalised plane strain elements, allowing for out-of-plane deformation and stress computations. The model described was built with ABAQUS-CAE 6.3.1 pre-processor, which was also used for the graphical treatment of results. Analysis was run using ABAQUS-Standard 6.3.1 solver.

5.3. RESULTS AND DISCUSSION

The model was first analysed as an undamaged material. The results obtained for stress and strain values in the individual plies agreed with laminated plate theory calculations. In particular, for a 0.1% applied longitudinal strain, the longitudinal stress in the 0° ply was found to be 40.03MPa, while the longitudinal stress in the 90° ply was 11.62MPa. These results
agree with the laminated plate theory calculations within 0.1%.

Subsequently, the model was analysed when a strain of 0.1% was applied to the material containing a single matrix crack in the transverse ply. A deformed shape plot of the model containing the single crack is shown in Figure 5.3.

Figure 5.3. Image showing a detail of the deformed shape of the model analysed. Visible on the left side is a detail of the undeformed shape superimposed to the deformed plot to allow for a comparison.

The most relevant results of this analysis concern the longitudinal strain distribution in the 0° ply at points near the interface with the adjacent 90° ply. In Figure 5.4, a diagram is shown of the longitudinal strain distribution calculated by the FEM analysis at the interface between the transverse ply and the adjacent longitudinal ply. The diagram relates to an applied strain of 0.1%.

The x axis scale, which reports the longitudinal distance from the crack plane, has been normalised with respect to the whole length of the model, that was 100mm, extending from the crack plane to the end tab limit. It can be noticed that the strain magnification in the 0° ply, due to the presence of the single transverse crack, extends to a normalised distance of approximately 0.03, corresponding to a real length of about 3mm. This length is similar to the thickness of the transverse ply 2.5mm). The maximum of the plot has a value of 0.224% at a normalised length of zero, which means that, the strain magnification at the interface is just over 2 for the mesh size used in this analysis.
Figure 5.4. Distribution of longitudinal strain along the length of the $0^\circ$ ply of the cross-ply laminate at the interface with the cracked transverse ply. Normalised length scale: $1 = 10\text{mm}$.

Figure 5.5. Distribution of longitudinal strain along the thickness of the $0^\circ$ ply of the cross-ply laminate in correspondence of the transverse crack plane.
With regard to strains across the 0° ply in the crack plane, the variation in strain across the longitudinal ply thickness, is shown in Figure 5.5. The longitudinal strain decreases from a maximum of 0.224 at the interface to a value of 0.125 at the surface of the 0° ply. This reduction is relevant to the experimental investigations of composite specimens with an embedded FOS, because the response of sensors to an applied strain is expected to be influenced by the particular location of the optical fibre across the longitudinal ply thickness. This position varies slightly due to the manufacturing process.

![Crack surface longitudinal displacements (0.1% applied strain)](image)

**Figure 5.6.** FEM calculations and shear-lag theory predictions of longitudinal displacements undergone by points belonging to the transverse crack surface under the action of an external 0.1% applied strain.

The FEM analysis carried out allowed an assumption made in the shear-lag theory presented in Chapter 3 to be investigated. In this analysis, a parabolic profile for the longitudinal displacement distribution, across the transverse ply is assumed. The shear-lag
assumption (equation 3.2) is shown in Figure 5.6 and the results of the FEM analysis are plotted in the same Figure. In Figure 5.7, the x axis represents the distance from the laminate mid-plane across the thickness direction of the laminate normalised by the thickness of the cracked transverse ply. It should be noted that the thickness used for the shear-lag expression is the nominal thickness of the transverse ply, i.e. 1.25mm, while the thickness considered in the FEM numerical calculations is the thickness of the transverse ply in the deformed model (in the FEM analysis the Poisson's contraction in the thickness direction gives rise to a lower thickness of the transverse ply in the deformed model with respect to the undeformed model). Reasonable agreement can be seen between the shear-lag and FEM plots in Figure 5.6, which supports the use of the shear-lag assumption for the displacement profile of the transverse ply at points in the crack plane.

5.4. SUMMARY

A 2D FEM analysis of a cracked cross-ply laminate with a 0° ply thickness of 0.5mm and 90° ply thickness of 2.5mm has been carried out. Results of the analysis showed that the presence of a transverse matrix crack alters the longitudinal strain in the 0° ply adjacent to the damaged 90° ply over a distance equal to about one transverse ply thickness on both sides of the crack plane. Moreover, the analysis showed that the strain magnification due to the crack decreases by about a factor of 2 with the distance from the interface to the surface of the longitudinal ply in the crack plane.
Chapter 6

BEHAVIOUR OF A GFRP CROSS-PLY LAMINATE UNDER BENDING — RESULTS AND DISCUSSION I. QUASI-STATIC TESTS

The results of the quasi-static tests carried out to investigate the behaviour of a double cross-ply laminate (having a $(0/90_2/0)$ lay-up) are presented. Particular attention has been paid to the onset and development of matrix cracking in one of the transverse plies under quasi-static loading.

6.1. DAMAGE IN ONE TRANSVERSE PLY

6.1.1. CRACK DENSITY AND CRACK INTERACTION

As described in Chapter 4, quasi-static bending tests were carried out by applying an increasing load in discrete steps. As a result of the load increase, the damage induced was in the form of matrix cracks growing parallel to the reinforcing fibre direction in the transverse ply which was under tensile stress. In Figure 6.1, the sequence of pictures shows an example of
the increase in crack density due to an increase in the applied bending moment. The specimen is shown together with the surface-mounted extensometer used for strain measurements.

Figure 6.1. Sequence of pictures relating to four stages of the crack density growth due to the application of increasing values of the external bending moment (specimen width: 20mm). The bending moment value which produced the damage in each picture is indicated next to each picture. The values were: (a) 27.3Nm, (b) 29.8Nm, (c) 32.1Nm and (d) 38.6Nm.
The transparency of the glass/epoxy composites enables a direct observation of the damage occurring in the tensile transverse ply to be made.

In quasi-static loading, the matrix cracks which developed in the tensile 90° ply initiated from the coupon edges and an example is shown by crack x in Figure 6.1(a). The cracks grew parallel to reinforcing fibres of the same ply across the specimen width. The growth across the width did not take place in one step. “Stick-slip” behaviour was observed, meaning that each crack extended by a discrete distance during each load increment. In Figures 6.2(a) to 6.2(d) a sequence of pictures is shown, in which it is possible to follow the growth of individual cracks. In Figure 6.2(a), a crack initiates from the edge, as indicated by the arrow. In Figure 6.2(b) the same crack is shown after an increase in length due to the application of a higher bending moment.

The initiation of cracks occurred from both edges of coupons and frequently, the two cracks, which had started from opposite edges of a coupon, passed close to each other at the middle of the coupon. When the cracks were very close, the effect of the interaction between the cracks was to stop the growth of both cracks at the point where the interaction took place. This crack growth arrest of two cracks growing from opposite sides occurred every time the crack spacing was lower than about 1mm, which corresponds to the ply thickness of the 90° plies in this laminate. An example of such a crack interaction is shown in the sequence in Figures 6.2(c) and 6.2(d). In Figure 6.2(c), the same crack highlighted in Figures 6.2(a) and 6.2(b) interacts with a crack growing from the opposite edge of the coupon and the growth of both cracks is arrested. The proof of the strength of the interaction is given in Figure 6.2(d), where it is seen that even after an increased applied bending moment, the cracks are unable to grow passed each other.
Figure 6.2. Crack growth due to the application of an increasing bending moment. Individual cracks initiated at the coupon edges and grew in discrete steps. Cracks spaced less than 1mm apart interacted, stopping each other's growth.
The interaction between two cracks growing from opposite edges may be given a simple phenomenological explanation with the aid of schematic diagrams, as shown in Figure 6.3. When a composite laminate is undamaged, the applied external load is carried by each of the plies, in proportion to the ply stiffness values. And its distance from the neutral axis. When a transverse ply undergoes matrix cracking, the load previously carried by the cracked ply is completely transferred to the adjacent longitudinal plies in the plane of a crack. Away from the cracks, the stress is transferred from the longitudinal ply back into the damaged transverse ply in the same proportion as in the undamaged situation. This distance is approximately equal to one transverse ply thickness on both sides of a crack, as confirmed by the FEM analysis in Chapter 5.

Figure 6.3. Schematic diagrams showing the different stress configurations established in adjacent plies of a cross-ply laminate on the tensile side of a specimen under bending load. (a) – When two matrix cracks are spaced more than about 1 mm apart, the cracks are not shielded.

(b) – When the crack spacing is less than 1 mm, the stress is not transferred to the cracked ply between the closely-spaced cracks, the cracks are shielded and hence crack arrest occurs.
Hence cracks closer than about one transverse ply thickness are shielded from the stress during crack growth at the crack tip, and cracks are arrested. The diagrams in Figure 6.3 show this schematically.

6.1.2. **INDIVIDUAL CRACK GROWTH**

It was possible to determine the profile of the cracks and the crack development.

![Diagram](image)

Figure 6.4. Schematic representation of a specimen's cross section, showing the development of a single matrix crack.

(a) – the crack initiation is at the interface between the tensile $90^0$-ply and the outer $0^0$-ply.
(b) – the crack grows across the thickness of the $90^0$-ply and across the width of the coupon.
(c) – when the crack is 1mm long across the width, it also fills the thickness of the $90^0$-ply.
(d) – the crack grows in length across the width of the coupon.

Figure 6.4 is a schematic showing the overall crack development. Cracks developed from the edge at the $0/90$ interface at which the maximum tensile stress in bending was produced.
Cracks grew as thumb-nail cracks from this position (Figure 6.4(b)) and the crack front had a pronounced curvature. When the cracks were approximately 1mm long (as measured at the same 0/90 interface), the cracks now extended fully across the 90° ply thickness, as shown in Figure 6.4(c). Cracks longer than 1mm grew with a curved crack front across the width of the coupon.

Figure 6.5 shows the edge of a specimen which has been ground down and polished so that 1mm of the width of the coupon has been removed. Differential Interference Contrast microscopy has been used to obtain this image which shows two cracks. The crack labelled A in this Figure does not extend across the full thickness of the transverse ply. On the other hand, cracks which extend across the full width of the coupon, such as crack B in Figure 6.5, also extend across the full thickness of the transverse ply.

Figure 6.5. Optical microscopy image of a polished edge of the cracked tensile transverse ply of a bending specimen. Crack A, shown on the right, extends across the specimen width (direction orthogonal to the picture plane) by less than 1mm.
Crack B is fully developed across the width.
Images such as Figure 6.5 were obtained after a careful polishing process of the specimen edge. In particular, the initial material grinding had to be accurately controlled, since the surface to be uncovered was comprised in a very thin layer (about 1mm thick across the specimen width), within which the crack tip was confined. This was achieved by carrying out the grinding in steps. Between each step, the surface was checked by microscopy, in order to verify visually the amount of material removed.

Figure 6.6 shows two overlapping cracks. Here a specimen has been sectioned along its length, so creating two new edges. One edge has then been polished. The focus is on the region where two cracks, growing from opposite sides, come together in the middle of the coupon. The cracks have overlapped and there is a distance of less than 1mm between them. The plane of the picture is just at the tip of crack B.

Figure 6.6. Optical microscopy image. Longitudinal section of a cracked tensile transverse ply of a bending specimen. The two cracks shown are spaced less than 1mm apart. Crack A, on the right, initiated from one edge, while crack B initiated from the opposite edge of the coupon. The plane of the picture is closer to the tip of crack B.
6.2. MECHANICAL BEHAVIOUR

6.2.1. CRACK DENSITY

The four-point bending tests carried out under quasi-static conditions were also aimed at studying the change in flexural modulus as a result of progressive cracking.

Measurements of the damage sustained by the coupons was achieved by examining the digital pictures taken at increasing load (details were given in Chapter 4). Damage accumulation has been plotted as crack density against bending moment and examples of these plots is shown in Figure 6.7 for four coupons loaded in four-point bending.

![Figure 6.7](image)

Figure 6.7. Increasing crack density values as a function of increasing applied bending moment in quasi-static tests.

Figure 6.7 shows that there is a threshold value of the applied bending moment, below which no damage is introduced into the material by application of the external load. The threshold bending moment for this material was about 25Nm. Above this value, matrix cracks in the tensile transverse ply started to appear, and their density increased with increasing values of the external load. At high values of the applied bending moment, the crack density saturated.
at about 0.4 cracks per millimetre. This corresponds to an average crack spacing of approximately 2.5mm, i.e. just over twice the thickness of each transverse ply. It can be noticed from Figure 6.7 that when the crack density approaches these high values, the experimental points do not follow the previous regular trend of the relationship between crack density and bending moment. In particular, after the crack density reached a value of about $0.35\text{mm}^{-1}$, a much higher bending moment was required to produce a noticeable increase in crack density. The plot in Figure 6.7 served as a guide to set the value of the maximum bending moment applied during the fatigue cycles (the results of the fatigue tests are shown in the next Chapter).

The existence of a saturation limit for the crack density may be explained in a similar manner to that described for the interaction of two closely spaced cracks. Once the crack spacing becomes small (about 3mm), it becomes more difficult to initiate new cracks since flaws are shielded by cracks adjacent to them. Hence a high increase in the applied bending moment is required to initiate a new crack.

### 6.2.2. FLEXURAL MODULUS REDUCTION

As a result of the progressive transverse ply cracking, the flexural modulus reduced. In Chapter 2, theoretical models to describe the decrease in the flexural modulus as a function of the crack density were mentioned. The model by Smith and Ogin (1999) has been used here to compare theory with experiment. The model is based on a one-dimensional shear-lag analysis, and predictions are made for the flexural modulus reduction as a function of crack density for a laminate with a $(0/90_{2}/0)$ lay-up. This lay-up is identical to the lay-up of the specimens used in the present work.

In order to use the model here, it was necessary to use the individual ply thicknesses measured in these experiments. The model assumes a thickness of individual plies to be 0.125mm, while for the laminates used in the present work, the ply thickness was 0.5mm. The predictions of the model for a laminate with ply thicknesses of 0.5mm are shown in Figure 6.8 together with the predictions provided by a simplified (linearised) version of the same model.
Figure 6.8. Predictions of the shear-lag model (Smith and Ogin, 1999) for a $(0/90_2/0)_s$ laminate with individual ply thicknesses of 0.5mm.

Figure 6.9. Comparison between the experimental data ($\uparrow$) from the present work and the predictions of the shear-lag model by Smith and Ogin (1999).
A comparison between the model predictions of Figure 6.8 and the experimental data produced in the present study is shown in Figure 6.9 for the full, non-linearised model. Good agreement between the experimental data for the reduction in normalised flexural modulus versus crack density and the theoretical model can be seen. Similar good agreement was found by Smith and Ogin (2000) when they compared the model predictions to results for a $(0/90)_{2s}$ laminate.

**5.3. SUMMARY**

The decrease in mechanical properties and the features of matrix cracking damage has been discussed for a $(0/90_2/0)_s$ glass/epoxy laminate subjected to quasi-static four-point bending tests.

The development of matrix cracking damage in a $(0/90_2/0)_s$ laminate in four-point bending has been described. The crack onset has been shown to be located at the interface between the tensile transverse ply loaded in tension and the adjacent outer longitudinal ply. Cracks initiate at the coupon edge and a crack extends across both the ply thickness and width when its length is approximately 1mm. Cracks less than 1mm in length have been shown to be grown only part-way across the cracked ply thickness.

The growth of the matrix occurred in a "stick-slip" manner for increasing applied bending moment. Cracks started at opposite edges of a coupon were able to "shield" each other when they were spaced apart by less than 1mm along the coupon length.

The degradation in flexural modulus due to an increasing bending moment has been measured in terms of flexural modulus decrease as a function of the matrix crack density. It has been shown that the experimental data are found in good agreement with the predictions of a theoretical model based on a shear-lag analysis.
Chapter 7

BEHAVIOUR OF A GFRP CROSS-PLY LAMINATE UNDER BENDING – RESULTS AND DISCUSSION II.
FATIGUE TESTS

DOUBLE CROSS-PLY coupons were subjected to fatigue cycles under four-point bending load. Damage development under cyclic bending has been investigated in these tests and is reported in the following. The experimental data in fatigue allowed a comparison with the quasi-static test data described in the preceding Chapter.

7.1. DAMAGE DEVELOPMENT

Two series of fatigue tests were carried out on separate specimens; the two series differed in terms of the maximum applied load of the bending cycles. The first series cycles had a maximum bending moment of 26.5Nm (called "low load" cycles), while the maximum bending moment applied in the cycles of the second series was of 34Nm (called "high load" cycles). In both series, an R-value of 0.1 was adopted. The value for the maximum bending moment to be
applied was chosen with the aid of the crack density development results from the quasi-static tests (see Chapter 6). The plot in Figure 6.7 shows examples of the crack density evolution as a function of the applied load. Based on the data points of the plot, the "low load" fatigue cycles were chosen since there was a threshold load value, below which no matrix cracks had appeared in the tensile transverse ply of the specimens under quasi-static loading conditions. The "high load" value was in the region where the crack density approached saturation in quasi-static conditions.

Before outlining the results, it is useful to note a well-known aspect of the four-point bending load configuration. The beam under four-point bending can be divided into three distinct regions (see Figure 7.1). In the middle of the test specimen, between points A and A' in Figure 7.1, the bending moment has a uniform value. Included in this region is the gauge length of the extensometer, which was mounted on the top surface of coupons between the points A and A' (i.e. the surface which becomes concave under load).

![Figure 7.1. Schematic diagram of the load configuration established in four-point bending.](image)

Between the load application points A, A' and points B, B', the specimen undergoes two kinds of load at the same time:

- a bending moment, linearly decreasing from the maximum value at A (or A') to a null value in B (or B'),
- a shear load, uniform over the length of the two regions B-A and A'-B' and
symmetrically configured with respect to the centre of the beam.

The effects of this load configuration are clearly found in the damage produced in the specimens tested. The characteristics of the damage induced by the four-point bending fatigue cycles are different between the regions A and A' and the other regions (B to A and A' to B'). In the following section a description is given of these characteristic differences after the coupon was subjected to "high-load" and "low-load" cycles.

7.1.1. MATRIX CRACKING

As in the quasi-static loading results, also in fatigue cycling the main type of damage induced in the bending specimens was an increasing crack density in the matrix of the 90° ply which experienced tensile stresses in the longitudinal direction. A plot of experimental data relating the crack density development to the number of cycles is provided in Figure 7.2 for the "low load" and "high load" cases. To be noticed in the plot is that the maximum value of crack density reached after 10,000 fatigue cycles was higher than the value reached under quasi-static loading. In particular, with the "high load" cycles, the crack density frequently reached values above 0.5mm⁻¹, meaning more than one crack every two millimetres of length of the specimen.

![Figure 7.2: Increasing crack density for increasing number of fatigue bending cycles.](image_url)
7.1.1.1. Matrix Cracking in the Constant Bending Moment Region

Crack initiation generally started at coupon edges. However, one distinctive feature of matrix cracking in fatigue proved to be the possibility of the occurrence of crack initiation away from coupon edges. In fact, in some cases the initiation has been noticed of a matrix crack in a location towards the middle of the specimen. Examples of such an occurrence are shown in Figure 7.3. An example of the increase in crack density produced by running "low load" bending fatigue cycles is shown in Figure 7.4 for the gauge length region.

Figure 7.3. Sequence showing the initiation of cracks away from coupon edges and crack interaction ("low load" cycles). Specimen width 20mm.

From the sequence shown in Figure 7.4 it is possible to notice that even under fatigue load conditions the crack shielding phenomenon, already observed in quasi-static tests, is present. Cracks starting at opposite edges of a coupon can interact and stop each other's growth when their relative spacing does not exceed 1mm. An example of this is shown by the cracks indicated by arrows in Figure 7.4(c). This is also observable, not surprisingly, in Figure 7.3 for cracks that started away from coupon edges.
Figure 7.3. Sequence showing the matrix crack density development in one transverse ply after "low load" (26.5Nm) fatigue cycles under a four-point bending load. Specimen width 20mm.
As in the case of quasi-static loading, it is possible to qualitatively describe the development of the cracks. For cracks initiating at the edge, the crack growth has been already described in Chapter 6 for quasi-static loading. The same applies to the fatigue case. For cracks initiating away from the edge, a schematic sequence of the initiation and growth process is shown in Figure 7.6.

Figure 7.6. Schematic sequence showing, in a cross-sectional plane of a bending coupon, the development of a crack initiating away from the coupon edges.

The crack initiates at the 0/90 interface at an internal point along the width of the specimen and only fills the whole transverse ply thickness when its length across the width of the coupon exceeds 2mm. This length is twice the length indicated in Chapter 6 for cracks initiated from coupon edges. This is consistent with the fact that cracks initiated away from the edges have two tips and hence two growth fronts.
a longitudinal surface which was contained within that length at one end of a crack.

A microscopy examination confirmed this statement and showed that, as in the case of cracks initiated from coupon edges, cracks initiated away from the coupon edges at points where the stress due to the bending load is the highest over the thickness of the tensile transverse ply, i.e. at the interface between the 90° ply and the outer longitudinal ply.

Figure 7.5. Optical microscopy image showing a crack spanning over the whole specimen width (crack w) and the tip of a crack initiated away from the coupon edge (crack x).

By cutting a specimen parallel to the longitudinal axis, it was possible to create a new edge located at one tip of a crack initiated away from the specimen edges. Such an internal surface of a specimen is shown in Figure 7.5. The picture shows the lower transverse ply of the specimen, which undergoes matrix cracking, and part of the adjacent longitudinal ply. Two
cracks are shown, spanned both the ply thickness and the coupon width. Crack w, appearing on the left, had already fully grown across the specimen width and it also had grown across the whole thickness of the transverse ply. Crack x is the tip of a crack initiated away from the edge of the specimen, which has not yet grown across the width of the full width of the coupon.

**7.1.1.2. Matrix Cracking in the Shear Regions**

Due to the presence of shear in addition to a bending moment in the coupon regions located on either side of the central uniform bending moment region the cracking of the matrix showed particular characteristics. For example, the cracks which occurred in these regions did not grow at 90° to the 0° ply direction. In Figures 7.7 and 7.8 two micrographs are shown of a polished edge of a cracked tensile transverse ply of a coupon.

**Figure 7.7.** Optical microscopy image showing the polished edge of a cracked tensile transverse ply in the negative shear region of a specimen.
The pictures were taken in a left side region and in a right side region, respectively, where the sign of the shear was respectively negative and positive (see also Figure 7.1). It can be noticed that the cracks tend to grow on a plane inclined towards the middle of the coupon. The cracks again initiated at the interface between the transverse ply and the outer longitudinal ply. This is shown in the micrograph of Figure 7.9, where two cracks are depicted. Crack z on the right of the picture is the tip of a crack which spans over the width of the specimen by less than 1mm. The delaminations which can be seen in Figures 7.8 and 7.9 are discussed in the next section.

Figure 7.8. Optical microscopy image showing the polished edge of a cracked tensile transverse ply in the positive shear region of a specimen.
7.1.2. OTHER DAMAGE

In addition to matrix cracks running parallel to reinforcing fibres in the transverse ply put into tension, other different types of damage developed during "High load" bending fatigue cycles. They can be grouped into the categories of the following list:

- longitudinal matrix cracks (splits) in the outer 0° ply under tension
- fibre bundle fracture in the outer 0° ply under tension
- delaminations at interfaces between the damaged transverse ply and the two adjacent 0° plies.

7.1.2.1. Splits in the 0° plies and fibre bundle fractures

Matrix cracks parallel to fibres and fibre bundle fractures appeared in the lower
longitudinal ply, where the highest tensile stresses are established by the four-point bending load. An example of splitting occurred in the specimen parallel to longitudinal fibres in the outer tensile $0^\circ$ ply is shown in Figure 7.10.

![Splits in the outer 0° ply after loading in "high load" fatigue bending.](image)

**Figure 7.10.** Splits in the outer 0° ply after loading in "high load" fatigue bending.
The specimen is 20mm wide.

Splits such as the one shown in Figure 7.10 developed during "high load" bending cycles, initiating away from coupon edges and between points B and B'. Once initiated, the splits grew parallel to 0° reinforcing fibres extending from the initiation point towards both ends of the specimen.

Examples of fibre bundle failure are shown in Figures 7.11 and 7.12. The sequence in Figure 7.11 shows that particularly severe damage due to bundle fracture in the tensile longitudinal ply has already occurred after a few thousands cycles at "high load". The fracture of longitudinal fibre bundles took place in the outer 0° ply of coupons at locations between points B and B'. Fracture initiation was always located at the edges of coupons, suggesting that this phenomenon be caused by edge effects. A bundle fracture initiated a separation of the bundle from the outer longitudinal ply; such a separation extended parallel to 0° ply fibres.
Figure 7.11. Bundle fracture development during "High load" fatigue bending (the bundle fracture is indicated by the arrow). Specimen width 20mm.

Figure 7.12. Fibre bundle fracture in the outer 0° ply after "High load" bending fatigue cycles (arrow). Delaminated areas occurred within the region highlighted by the ellipse.
7.1.2.2. Delamination development

In Figures 7.13 and 7.14 examples of delaminated areas are shown at the edges of coupons. Figure 7.13 shows the middle region of a specimen, where the bending moment was uniform. In this region all delaminations started, during “high load” cycles, from cracks which had fully grown across the specimen width and after the material reached the saturation value for the crack density before the cycle count reached 10,000 cycles. When this damage occurred within the constant bending moment region, it mainly took place at the edges of coupons. Therefore, in this case, it has to be considered as an edge effect.

![Figure 7.13. Delaminations after “high load” bending cycles. Specimen width 20mm.](image)

However, the most extensive delaminated areas were present in the side regions of coupons, i.e. the regions where the bending moment is present together with the shear load. In Figure 7.14 one such area is shown, where delaminations are visible together with a split in the outer longitudinal ply. The picture shows one shear region of a specimen. In this region, similarly to the middle region, the first damage to appear consisted of matrix cracks in the transverse ply put into tension. It is shown in Figure 7.14 that the crack density reduces towards the outer roller (on the left): at this point the applied load assumes a zero value and no damage is found in the material. In the shear regions, delaminations started from cracks located in zones where the crack density was higher, i.e. towards the boundary with the
constant bending moment region (towards the right side in Figure 7.14). Moreover, the delaminations generally developed from transverse matrix cracks which already filled the whole specimen width. Figure 7.14 also shows that delaminations grew more quickly when a split in the 0° ply had occurred.

![Figure 7.14. Delaminations (shaded areas) in the shear region of a “high load” coupon. Specimen width 20mm.](image)

The edge-effect delaminations found in the constant bending moment region of a coupon (e.g. as shown in Figure 7.13) initiated from transverse matrix cracks at the interface between the cracked transverse ply and the outer longitudinal ply. These delaminations always extended from the matrix crack toward the region of lower bending moment rather than toward the middle of the specimen.

The ply interfaces at which delamination developed in the shear regions were both interfaces between the tensile transverse ply and the adjacent longitudinal plies. Delaminations initiated at all positions along the matrix cracks and grew towards opposite directions depending on which interface was delaminated. In particular, delaminations of the interface between the 90° ply and the outer 0° ply grew towards the region of lower bending moment, while the delaminations of the opposite interface grew in the opposite directions, i.e. towards the constant bending moment region (middle of the specimen).
Figure 7.15. Optical micrograph of the edge of a "high load" coupon in the negative shear region. Delaminations (indicated with arrows) are at the interfaces of the 90° ply with the outer 0° ply (extensive) and with the middle 0° ply. The delaminations initiated from a matrix crack.

Figure 7.16. Optical microscopy image of the edge of a "high load" coupon in the positive shear region. The delamination is indicated by the arrow.
Evidence of this damage is provided very clearly by microscopy images taken at the edges of the coupons where the delaminations occurred. In Figure 7.15 the delaminated edge of a coupon is shown at a location in the negative shear region. A similar situation is found, of course, on the right (positive shear) side of coupons, where delaminations always initiated at matrix cracks and propagated in the opposite direction. This is shown in Figure 7.16.

The development of delaminations in these laminates is presumably due to the out-of-plane ("peeling") stresses caused by the transverse matrix cracks (mode I fracture). Since the largest amount of delaminations appeared in the shear regions, the occurrence of delaminations must also be driven by shear stresses, which lead to mode II fracture. However, the assessment of which of the two effects is prevalent needs further investigation. The tensile stress in the 90 ply is a maximum at the outer 0/90 interface and reduces as we move into the laminate towards the mid-plane. The shear stresses have the signs indicated in Figure 7.17. The combination of shear stresses and tensile stresses cause the crack to grow at an angle. When the crack meets the interface, the combined stresses (still acting at an angle) will tend to open up the delaminations.

**Figure 7.17.** Diagram showing the shear and tensile stresses established by a four-point bending load in the negative shear region of the 90° ply under tension of a double cross-ply laminate.
Figure 7.18. Optical microscopy image of the edge of a “high load” coupon in the negative shear region. The delaminations shown initiated at the tips of a transverse ply matrix crack and propagated in opposite directions.

The interface between the cracked transverse ply and the outer longitudinal ply was the surface where delaminations developed first and grew fastest. The interface between the cracked transverse ply and the middle longitudinal ply was also a delamination location. The delaminations here always occurred after the growth of delaminations at the formerly mentioned surface presumably because the out-of-plane stresses are lower here. In addition, these delaminations propagated in the opposite direction to the previous ones, i.e. toward the higher bending moment region. A further example of such delaminations is shown in Figure 7.18, where a delaminated area on the negative shear region (see Figure 7.1) of a coupon is shown.
Figure 7.19. Optical microscopy image of an internal longitudinal surface of a "high load" coupon in the negative shear region. Also in this case, delaminated areas (indicated by arrows) started at the tip of a matrix crack occurred in the adjacent transverse ply.

An optical micrograph showing a delaminated area inside a coupon, about 10mm from the coupon edge, is shown in Figure 7.19. Delaminations of both interfaces can be seen.

7.2. FLEXURAL MODULUS REDUCTION

The effect of bending fatigue cycles on the flexural modulus of the (0/90,-θ), cross-ply laminate has been monitored by measuring the decrease in the value of the residual flexural modulus as a function of the increasing crack density. The cycling was interrupted in order for the quasi-static measurement of the flexural modulus to be made. In order to compare the
results of the fatigue tests to the results given by quasi-static tests, the values of residual flexural modulus versus crack density have been plotted on the graph already shown in Figure 6.4. The comparison is shown in Figure 7.20.

The agreement between the theoretical model of Smith-Ogin (1999) and experimental results of quasi-static tests had already been shown in the previous Chapter. In Figure 7.19, it can be seen that reasonable agreement exists between the same model and the fatigue experiments results. The agreement is better for the "Low load" cycles data points and most of the points relating to "High load" cycles fall below the predictions of the model. The reason for this is that only the matrix cracking damage in the tensile transverse ply is considered in the predictions, as explained in detail in the preceding section, bending fatigue cycles produced delaminations and fibre bundle fractures in addition, especially for the "high load" case. This additional damage produces a lower residual flexural modulus predicted by the shear-lag
A further source of flexural modulus reduction is known to be present in the fatigued coupons, although no evidence has been produced in this work. It is expected that there will be breakage of individual fibres within the longitudinal plies adjacent to the cracked transverse ply. This damage typically occurs adjacent to transverse ply cracks and has been found in the work of other researchers for tensile loading (Jameson).

### 7.3. SUMMARY

The development of damage in a glass/epoxy double cross-ply laminate under bending fatigue loading has been described. The prime damage occurring during bending fatigue was the development of matrix cracks in the tensile transverse ply, as happened in the quasi-static tests. The cracks grew in planes positioned at angles other that at 90° to the 0° ply when occurring in the regions of the specimens where shear load existed.

Other types of damage were seen in the fatigued specimens, which did not appear in the quasi-static tests. Splits were found to develop in the outer tensile longitudinal ply, and bundles of reinforcing fibres failed in the same ply at the surface of the specimens. In addition, delaminations at the interfaces between the transverse ply put into tension and the adjacent longitudinal plies occurred, especially after "high load" fatigue cycles. Delaminations started at the points where these cracks met the 0/90 interface at the coupon edge. The most extensive delaminations were found in the shear regions of coupons. These delaminations grew at the interface and along the full width of the specimen. The delaminations initiated from the points where the 90° ply cracks met the 0/90 interfaces. Delaminations grew more quickly at the outer 0/90 interface and in the direction of decreasing bending moment. At the other 0/90 interface, the delaminations grew in the direction of increasing bending moment. The latter delaminations initiated later than the former delaminations.

Once investigated the behaviour of matrix cracks in flexural loading, the following chapters address the issue of crack detection using a fibre Bragg grating sensor.
Chapter 8

RESPONSE OF A FBG SENSOR TO MATRIX CRACK DEVELOPMENT – RESULTS AND DISCUSSION I. TENSILE TESTS

8.1. INTRODUCTION

THE PRESENT and the next Chapter deal with the results obtained in the use of an optical fibre sensor, based on fibre Bragg gratings, as an embedded sensor to detect matrix cracking damage. The sensor has been used as a strain sensor and its capabilities in damage detection have also been experimentally investigated.

In this Chapter the results of preliminary tests are shown to gain information firstly about the behaviour of the free (non-embedded) sensor under a tensile load. Then, results of tests on GFRP composite cross-ply specimens containing a single embedded sensor are reported. These tests have been run under a tensile applied load. The optical output of the sensor has been investigated with regard to the response of the undamaged host material and to the development of a single matrix crack in single and double cross-ply laminates.
8.2. RESULTS OF PRELIMINARY TESTS

8.2.1. FREE SENSOR TESTS

In order to produce initial data on the optical output of a fibre Bragg grating, the first tests were carried out on free sensors. As described in Chapter 4, after splicing the optical fibre containing the FBG to the optoelectronic arrangement, a mechanical rig was used to hold the fibre. The sensor was operated by launching light from a tuneable laser. The spectrum of the reflected light for the free sensor is shown in Figure 8.1.

![Figure 8.1](image-url)  
*Figure 8.1. Plot of the light spectrum reflected by the free FBG sensor when unloaded. The (♦) signs denote experimental data points.*

The nominal Bragg wavelength of all the sensors used in this study was 1550nm. However, as shown in Figure 8.1, the experimental peak wavelength of the reflected spectrum was generally different from the nominal value. This is thought to be due to some uncertainty in the production process of the gratings.
The use of the mechanical rig allowed an axial tensile loading to be applied to the optical FBG sensor. The load was manually applied to the sensor and increased in discrete steps and the applied strain could be calculated from the measured of the optical fibre. By recording the reflected spectra at each step of the load increase, it was possible to observe the shift undergone by the peak wavelength of the spectra as a result of the longitudinal strain of the optical fibre under the applied load. The results of this experiment are plotted in Figure 8.2.

![Figure 8.2. Strain-optic response of an FBG free sensor: shift in the Bragg wavelength, as a result of strain.](image)

It can be observed that the trend shown by the plot is reasonably linear. The uncertainty in each strain measurement was about 0.1%. After the last data point of the series shown in the plot was taken, fracture of the optical fibre occurred. The strain to failure was 0.35%. The shift in the Bragg wavelength as a result of an increase in longitudinal strain enables a sensitivity value for the FBG sensor to be calculated. Since the response of the free sensor to strain was not perfectly linear, a mean sensitivity value was calculated, by fitting the experimental points over the whole experimented strain range with a straight line. The slope of the line was the sensitivity, which was found to be $1.11 \times 10^{-3}$ nm/με. This can be compared to a typical value of $1.25 \times 10^{-3}$ nm/με (Okabe et al., 2000).
8.2.2. SENSOR EMBEDDED IN UNDAMAGED LAMINATES

8.2.2.1. FBG sensors embedded in simple cross-ply laminates

After examining the response of the free sensor to unidirectional tensile strain, experiments on the embedded sensor were carried out. Individual FBG sensors were embedded both into simple (0/90/0) cross-ply laminates and into double (0/90/0), cross-ply laminates. These tests were aimed at investigating the response of the FBG sensor to strain induced in the host material under unidirectional tensile load. The tests on simple cross-ply specimens were carried out with the use of both the tuneable laser and the broadband source. The broadband source only was used in the tests on double cross-ply specimens.

In all tensile tests, the full reflected spectra of each specimen were recorded for each value of the specimen longitudinal strain. This allowed two different sets of information to be retrieved from the test results: (i) the Bragg wavelength shift due to the host material strain, and (ii) any shape changes occurring among the spectra reflected by the FBG for different strains. In Figure 8.3(a) an example is reported of a FBG’s reflected spectra for different values of the host material strain.

![Figure 8.3.](a) Tuneable laser light spectra reflected by a FBG sensor for different values of the strain applied to the host material (simple cross-ply composite).
The plots in Figure 8.3(a) were obtained by using the procedure involving the use of a tuneable laser source. Therefore, each spectrum was described by providing the peak wavelength for a range of tuneable wavelengths. The reflected spectrum shift due to strain did not involve a shape change.

Further experimental investigation on other specimens, carried out by replacing the tuneable laser source with a broadband source, confirmed the above results.

Figure 8.4. (A) Broadband source light spectra reflected by a FBG sensor for different values of the strain applied to the host material (simple cross-ply composite).
In Figure 8.4 a series of reflected spectra are shown for single cross-ply specimens. The results were obtained with the aid of computer control of the optical spectrum analyser, as described in Chapter 4. Moreover, the time needed to achieve a single spectrum acquisition was dramatically reduced, when using the broadband source, from several minutes to a few seconds. Figure 8.4(a) shows the spectrum for values of applied strain (from no strain to 0.35%) and Figure 8.4(b) shows the peak wavelength of each spectrum plotted against applied strain.

Figures 8.3 and 8.4 also provide experimental data relating the Bragg wavelength shift to the strain of the composite material. In all the plots, the strain-optic response is remarkably close to linearity. All the sensors used in the present work showed sensitivity values between $1.18 \times 10^{-3}\text{nm/}\mu\text{e}$ and $1.28 \times 10^{-3}\text{nm/}\mu\text{e}$. These values of FBG sensor sensitivity to strain are close to the value of about $1.25 \times 10^{-3}\text{nm/}\mu\text{e}$ typically reported in the literature for the strain sensitivity of FBG sensors (e.g. Okabe et al., 2000).

### 8.2.2.2. FBG sensors embedded in double cross-ply laminates

Similar experiments were carried out on FBG specimens embedded in double cross-ply specimens. The sensors were placed in two different locations: (i) at the interface between one of the two transverse plies and the middle longitudinal ply, and (ii) at the interface between one transverse ply and the outer longitudinal ply adjacent to it. However, no appreciable difference was observed in the optical output characteristics between the two situations, when the strain-
optical response was examined. In Figures 8.5 and 8.6 two examples are shown of the FBG spectra reflected by sensors placed at each of the two interfaces. There is, as expected for tensile loading, no difference in the sensitivity recorded for either location (both approximately $1.27 \times 10^{-3} \text{nm/\mu e}$).

![Figure 8.5. (a) Broadband source light spectra reflected by a FBG sensor for different values of the strain applied to the host material (double cross-ply composite, sensor located at interface between one transverse ply and the middle longitudinal ply). (b) The Bragg wavelength shift shown as a function of the applied strain.](image-url)
Figure 8.6. (A) Broadband source light spectra reflected by a FBG sensor for different values of the strain applied to the host material (double cross-ply composite, sensor located at interface between one transverse ply and one outer longitudinal ply).

(B) The Bragg wavelength shift is shown as a function of the applied strain.
8.3. REFLECTED SPECTRUM CHANGE DUE TO CRACKING

8.3.1. FBG SENSORS IN SINGLE CROSS-PLY LAMINATES

The results reported in the previous section formed the basis for an understanding of the sensor behaviour in strain detection. However, it was also of interest to investigate the opportunities offered by an FBG sensor for detecting the onset of a first ply failure in a cross-ply composite laminate under a tensile load. To this aim, the tensile tests, whose results have been illustrated in the preceding section, have been repeated on the same specimens after a single matrix crack had been deliberately introduced in one transverse ply of the cross-ply laminate. As explained in Chapter 4, cracks were initiated by a scalpel blade and grown with a few tensile fatigue cycles. Since the location of the Bragg grating along the optical fibre was known \textit{a-priori} with a reasonable approximation, the crack could be initiated and grown in a position included in the length of the grating.

Analysis of experimental data for these experiments consists of a comparison between the light spectra reflected by a FBG sensor before and after cracking. In Figure 8.7 such a comparison is shown, for the tuneable laser, with regard to the specimen whose spectra have been shown in Figure 8.3 for the loading of the undamaged host material. Examination of the shape of the spectra reflected by the FBG sensor before and after the cracking of the cross-ply laminate shows clear differences. The comparison needs to be made between the spectra relating to the two situations under the same strain level. As Figure 8.7(a) shows, the spectra reflected by the sensor in the undamaged material presents a narrowband single-peak shape. On the other hand, the spectra relating to the cracked material (Figure 8.7(b)) still include the same main peak as the undamaged material spectra, but side-band peaks of lower intensity are developed in addition to the main peak at longer wavelengths. This contributed to broaden the spectrum reflected by the FBG sensor.

In Figure 8.8 the trends are shown of the spectrum's main peak shift due to longitudinal strain of the composite specimen for a range of applied strains for both the uncracked and cracked coupon. The data points in the two cases nearly overlap to each other, meaning that the crack development does not have effect on the principal spectrum peak on
loading the host material in the uncracked and cracked state.

Figure 8.7. Comparison between FBG sensor reflected spectra before and after cracking, (a) tuneable laser light spectra from sensor embedded in undamaged single cross-ply coupon; (b) tuneable laser light spectra from sensor embedded in cracked single cross-ply coupon.

Figure 8.8. Comparison between peak wavelength shift before and after cracking.
Qualitative understanding of this result may be achieved by consideration of the strain experienced locally by the fibre Bragg grating in the vicinity of the crack. In Figure 8.9, the situation is shown in which the FBG sensor is shown when the host material is undamaged.

![Diagram](image)

**Figure 8.9.** Schematic showing the uniform strain experienced by the FBG sensor in an undamaged cross-ply composite under tensile load. (a) unloaded; (b) loaded.

When the undamaged cross-ply composite (Figure 8.9(a)) is subjected to longitudinal load, the FBG sensor undergoes a uniform strain over whole length of the grating (Figure 8.9(b)). This is very similar to having a new grating, whose pitch length $\Lambda_2$ is longer than the original pitch length, $\Lambda_1$. The effect of the strain on the optical output is to shift the characteristic wavelength of the grating to a larger value than it is in the unloaded situation. Any further increase in the applied load produces an increase in the strain of the composite and of the optical fibre containing the grating. As a result, the pitch length is increased and the main peak wavelength of the reflected spectrum is further shifted along the wavelength axis towards longer wavelengths.

When the cross-ply composite with the embedded FBG sensor experiences the...
development of a single matrix crack in the transverse ply adjacent to the FBG sensor, a situation is established schematically depicted in Figure 8.10. When the material is unloaded (Figure 8.10(a)), the effect of the presence of a transverse matrix crack is to locally release the processing thermal stresses which are tensile in the transverse ply and compressive in the longitudinal ply, in the sensor direction.

![Figure 8.10. Schematic showing the uneven strain experienced under tensile load by the FBG sensor in a cross-ply composite in which a transverse matrix crack is present within the length of the Bragg grating. (a) unloaded; (b) loaded.](image)

The consequence is that the residual thermal compression stress in the 0° ply is released locally, and the specimen length increases locally the effect on an embedded Bragg grating in the 0° ply is show schematically in Figure 8.10(a). The light spectrum reflected by the grating in these conditions is composed of contributions coming from both the unchanged
segment away from the crack and the segment unevenly strained. The former contribution is seen in the main peak of the spectrum, which is at approximately the same wavelength as the peak for the undamaged laminate. Comparison of the undamaged and cracked spectra for increasing strain values shows that the position of the main peak remains nearly unchanged from the undamaged to the damaged situation as the strain increases from zero (see Figure 8.8). Of course, as the applied strain increases, the grating spacing away from the crack increases in the same way for both the undamaged and damaged coupon.

However, additional changes occur in the reflected spectra for the damaged coupons in the form of sideband peaks. These secondary peaks which appear in the reflected spectra after cracking are located on the longer wavelength side of the main peak. The reflections giving rise to these higher wavelengths are produced by portions of the grating with a larger periodicity caused by the enhanced longitudinal strain in the 0° ply due to the presence of the transverse ply crack.

To summarise, when the cracked material is loaded in unidirectional tension, the longitudinal strain is uniform across the whole specimen length, except in the immediate vicinity of the crack, where the FBG sensor is located. In the vicinity of the crack a strain magnification occurs in the 0° ply, which affects a length of approximately one transverse ply thickness on either side of the crack. As a result, the spectra reflected by the FBG sensor is composed of the contributions from the regions far from the crack and regions close to the crack. The region where the strain magnification occurs produces the secondary peaks in the spectra on the longer wavelength side.

The results discussed here and shown in Figures 8.7 and 8.8 relate to sensor in a simple cross-ply specimen illuminated with a tuneable laser source. However, these results were confirmed by experiments carried out on different simple cross-ply samples by using light from the broadband source described previously. For example, Figure 8.11 shows a comparison between the spectra before and after cracking for the growth of a single matrix crack. Figures 8.11(a) and 8.11(b) show the spectra reflected before the growth of the crack.
As before, the spectra are reasonably symmetric about the peak wavelength. Figures 8.11(c) and 8.11(d) show the spectra at the same strains after the growth of a crack. As before, secondary peaks can now be seen in the longer wavelength side of the main peak.
Figure 8.12 provides a comparison of the wavelength shift of the main peak for the uncracked and cracked material. Again, as seen with the tuneable laser source (e.g. Figure 8.8), the data points overlap for the shift of the main peak.

Figure 8.12. Comparison between peak wavelength shift before and after cracking in a simple cross-ply laminate.

An experiment was performed to show that the sensor optical output is only affected by the matrix cracking when the transverse matrix crack grows past the sensor location. The reflected spectra of FBG sensors embedded in simple cross-ply specimens were recorded when the coupon was undamaged. Subsequently, in the same specimens a crack was initiated by carving a scalpel blade notch in the edge of the transverse ply at a location within the length of the Bragg grating. The crack was gradually grown from this notch by running a few thousand tensile fatigue cycles at a maximum load level of 10Nm, which is well below the stress for the onset of cracking in the transverse ply under quasi-static loading.
Figure 8.13. A single transverse matrix crack which has grown partially across the transverse ply. The crack has grown to within 2mm of the sensor location. (Specimen width: 20mm)

Figure 8.14. Digital photograph showing a single transverse matrix crack at an intermediate stage of growth. The crack has reached the FBG sensor location. (Specimen width: 20mm)
Figure 8.13 shows the specimen at time when the crack growth was interrupted by stopping the fatigue cycles. At this stage, the growing crack was about 2mm away from the sensor location. Figure 8.14 shows the same crack after growing further a little distance across the specimen width. Now the crack had reached the sensor location.

Reflected spectra were recorded at various steps of this test. Figure 8.15 shows the spectra reflected by the FBG sensor embedded in the specimen before the initiation of the crack and Figure 8.16 shows the spectra reflected by the sensor when the crack had grown partially across the specimen without reaching the sensor location as shown in Figure 8.13.

A comparison of the spectra at 0.05% and 0.15% strain in Figure 8.14 and 8.15 shows that these spectra are unchanged. However, the spectrum for 0.25% is different and requires explanation. In order to record the reflected spectrum at each strain, a static tensile load had to be maintained on the specimen for a few seconds at each strain. Under the action of static load equivalent to the 0.25% strain, the partially grown crack grew a small distance and then stopped growing at the position shown in Figure 8.16. In this position, the crack had grown past the sensor and the spectrum shows a small but significant difference of shape with respect to the spectra recorded for lower values of the specimen strain. In particular, the spectrum broadened in the longer wavelength side and secondary peaks appeared in this side.

By further increasing the static applied tensile strain to 0.3%, the transverse matrix crack grew rapidly across the full specimen width. The light spectra reflected by the FBG sensor when the crack had grown across the full width are shown in Figure 8.17. The characteristics of the shape change with respect to the undamaged case can be noticed by comparing the spectra shown in Figure 8.17 with the spectra shown in Figures 8.15 and 8.16: the spectra are broadened on the right side of the main peak, where secondary peaks are present, yet visible with difficulty. The final crack is shown in Figure 8.18.
Chapter 8

RESPONSE OF A FBG SENSOR TO MATRIX CRACK DEVELOPMENT
RESULTS AND DISCUSSION I. TENSILE TESTS

Figure 8.15. Broadband light spectra reflected by a FBG sensor embedded at the interface between one outer 0° ply and the middle transverse ply of an undamaged simple cross-ply.
(a) spectra recorded at 0.05% and 0.15% applied strains;
(b) spectra recorded at 0.25% and 0.35% applied strains.

Figure 8.16. Broadband light spectra reflected by the FBG sensor embedded in the cross-ply specimen with a transverse crack partially grown across the specimen width.
(a) spectra recorded at 0.05% and 0.15% applied strains;
(b) spectra recorded at 0.25% applied strain. This spectrum was recorded when the crack reached the sensor location.

Figure 8.17. Broadband light spectra reflected by the FBG sensor embedded in the cross-ply specimen with a transverse crack grown across the full specimen width.
(a) spectra recorded at 0.05% and 0.15% applied strains;
(b) spectra recorded at 0.25% and 0.35% applied strains.
Figure 8.18. Digital photograph showing a single transverse matrix crack grown across the full width of a single cross-ply specimen embedding a FBG sensor.

(Specimen width: 20mm)

Figure 8.19. Shift of the highest peak of the reflected spectrum in the three damage conditions examined for the simple cross-ply specimen embedding a FBG sensor.
In Figure 8.19 the wavelength shift undergone by the highest spectrum peak is shown in the three situations described above. Even in this case the experimental data point overlapping of the series is clear, meaning that the reflection produced by the region of the grating unaffected by the strain magnification due to the crack development remains unchanged.

8.3.2. FBG SENSORS IN DOUBLE CROSS-PLY LAMINATES

Similar experiments were carried out on FBG sensors located in double cross-ply specimens at the interface between one transverse ply and the middle longitudinal ply. During tensile loading of a double cross-ply coupon, the cracks do not, of course, develop in only one transverse ply. In order to produce cracks in only one of the 90° plies the specimens were loaded by means of a quasi-static four-point bending load. It was not possible, in this way, to only introduce a single crack in the material in a pre-defined location, because crack development under four-point bending proved to be notch-insensitive. When increasing the quasi-static four-point bending load, more than one crack developed in the tensile 90° ply, even when the tensile 90° ply was notched with a scalpel blade. Indeed, the cracks did not form preferentially at such a notch. However, the crack density was kept to a very low value in the range between 0.10mm⁻¹ and 0.18mm⁻¹. This meant that there could be up to two cracks present within the 10mm length of the Bragg grating. After introducing the cracks in this way, tests were then carried out under unidirectional tensile loading as for the specimens considered in the previous section.

The results of these experiments are shown in Figure 8.20 for the sensor location at the interface between the middle 0° ply and one 90° ply. Figures 8.20(a) and 8.20(b) show the spectra reflected by an FBG sensor when embedded in an undamaged double cross-ply specimen. Figures 8.20(c) and 8.20(d) show the spectra reflected by the FBG sensor when the embedding specimen was damaged. From this plots, it is seen that when more than one crack is present in one transverse ply adjacent to the sensor location, the reflected spectra are modified with respect to the undamaged conditions. In particular, the spectra are broadened on
the longer wavelength side, where additional peaks are also present. This is an extension, for the double cross-ply case, to the observations already described for the FBG sensor behaviour when embedded in a single cross-ply composite.

Figure 8.20. Broadband source light spectra reflected by FBG sensor embedded in a double cross-ply specimen at the interface between the middle $0^\circ$ ply and one adjacent $90^\circ$ ply. Spectra reflected by the sensor in the undamaged specimen: (a) no applied strain and $0.1\%$ applied strain; (b) $0.2\%$ and $0.3\%$ applied strain. Spectra reflected by the sensor in the cracked specimen: (a) no applied strain and $0.1\%$ applied strain; (b) $0.2\%$ and $0.3\%$ applied strain.

Figure 8.21 shows the results related to a sensor position at the interface between one $90^\circ$ ply and the adjacent outer $0^\circ$ ply. Figures 8.21(a) and 8.21(b) show the FBG reflected spectra for the undamaged and unloaded case and for three values of the strain applied by tensile load to the coupon containing cracks in one $90^\circ$ ply. Figures 8.21(c) and 8.21(d) show
the spectra reflected by the sensor when the embedding composite coupon is cracked. As in the previous case, the FBG spectra reflected in the undamaged case appear to be single-peaked and symmetric around the peak. The spectra recorded for the same applied strains in the cracked case are characterised by a spectrum broadening on the longer wavelength side of the main peak with the rise of secondary lower peaks on this long wavelength side of the spectrum.

![Graph](image)

**Figure 8.21.** Broadband source light spectra reflected by FBG sensor embedded in a double cross-ply specimen at the interface between the one outer 0° ply and the adjacent 90° ply. Spectra reflected by the sensor in the undamaged specimen: (a) no applied strain and 0.1% applied strain; (b) 0.2% and 0.3% applied strain. Spectra reflected by the sensor in the cracked specimen: (c) no applied strain and 0.1% applied strain; (d) 0.2% and 0.3% applied strain.

These results also extend the previously described results to the case when more than one transverse matrix crack is present. In particular, both Figure 8.20 and Figure 8.21 show that modification of the FBG sensor reflected spectrum due to cracking of the embedding
material is characterised by side peaks and broadening (on the longer wavelength side of the spectrum) which are more pronounced than in the case when a single matrix crack was present in the transverse ply adjacent to the sensor location in a simple cross-ply coupon. When there are two cracks and hence two enhanced strain regions in the grating length, the reflection causing the spectrum broadening and side peaks would be expected to be stronger (i.e. gives a higher intensity signal and involves more energy) than in the case of a single crack. As a result, the longer wavelength side of the spectrum is modified by the rise of higher and broader secondary peaks.

![Graph showing wavelength shift against strain]

**Figure 8.22.** Comparison between peak wavelength shift before and after cracking for a FBG sensor embedded in a double cross-ply specimen at the interface between the middle 0° ply and one adjacent 90° ply.

There was an interesting difference in the experimental data showing the shift of the highest peak of the spectra due to the applied tensile strain when the undamaged and damaged conditions are compared. Figure 8.22 shows this comparison for the case of a sensor embedded at the interface between the middle 0° ply and the tensile 90° ply. The slope of the wavelength shift against strain is smaller for the damaged material than for the undamaged material. Figure 8.23, which shows similar results but with the sensor located at the interface...
between the 90° ply under tension and the outer 0° ply, the difference between the peak shift for the damaged and undamaged material is even larger.

Figure 8.23. Comparison between peak wavelength shift before and after cracking for an FBG sensor embedded in a double cross-ply specimen at the interface between the one outer 0° ply and the adjacent 90° ply.

These results are difficult to explain in a completely satisfactory manner. When the 90° ply cracks during the bending test, thermal strains are relaxed and when the laminate is unloaded, it is found to have a permanent curvature with the cracked 90 ply towards the convex surface (Smith and Ogin, 1999). In the current experiments, the laminate is then loaded in tension, and the strain recorded by an extensometer. The extensometer strain is shown on the x-axis and the peak wavelength shift, which is a measure of the strain experienced by the fibre Bragg grating, is shown on the y-axis. Figure 8.22 and 8.23 show that for a given applied mechanical strain, the strain experienced by the sensor is smaller for the laminate that has been damaged, and that this difference increases with the applied strain and with the distance from the laminate mid-plane. The cracked 90° ply is already slightly longer due to the release of the thermal strain and the applied mechanical strain reduces the curvature in the cracked coupons without subjecting the sensor to the same strain as it would experience
in an uncracked coupon. Additionally, in fact, the regions where the cracks are present are always more compliant than the undamaged regions of the coupons. The latter regions, unaffected by the strain magnification due to the presence of cracks, produce the reflections which give rise to the highest peak of the reflected spectrum. Under the same applied longitudinal strain, in the damaged specimens these unaffected regions are expected to be strained less than in the undamaged case. As a result, the shift of the highest peak of the reflected spectrum is smaller when the composite is damaged than in the case of undamaged material.

### 8.4. SUMMARY

Quasi-static tensile tests carried out on optical FBG sensors enabled a description of the characteristics of these sensors response to strain to be determined. The light spectra reflected by the FBG’s were characterised by a narrow single-peak symmetrical with respect to the centre wavelength. The longitudinal strain experienced by a free sensor shifted the reflected spectrum main peak along the wavelength axis. The sensitivity was found to be approximately $1.11 \times 10^{-3}$ nm/με. Sensors embedded into composite specimens showed a similar response with a slightly higher sensitivity of $1.23 \times 10^{-3} \pm 0.5 \times 10^{-3}$ nm/με.

Tensile tests were carried out on single cross-ply specimens in which a matrix crack had been introduced in the transverse ply of the laminates at a location within the Bragg grating length. Reflected spectra in these conditions showed different characteristics with respect to the reflected spectra for the undamaged material. In all cases the spectra relating to the cracked material were characterised by the presence of a main peak and additions at longer wavelengths. The main peak was shifted along the wavelength axis as a function of strain to the same extent as the main peak for undamaged material. The spectra relating to the cracked material showed a broadening on the right side of the spectrum’s main peak and the rise of secondary peaks. The presence of the side peaks has been has been explained by the existence of reflections taking place in the portion of the Bragg grating immediately adjacent to the crack
in the 90° ply; the grating was thus affected by locally enhanced strains next to the crack. The unchanging nature of the main peak in the reflected spectrum of cracked specimens was explained by reflections from portions of Bragg grating which are outside the zone of influence of the matrix crack.

Tensile tests were also carried out with FBG sensors embedded in double cross-ply specimens. The sensors were embedded at two different interfaces of the laminates, within the longitudinal plies adjacent to the 90° ply undergoing matrix cracking. Results of such tests showed an extension of the sensor response to the onset of more than one crack in one transverse ply matrix. The spectra reflected by the FBG sensors when the material was undamaged were single-peaked and symmetric. Spectra reflected by the FBG's after matrix cracking were broadened on the longer wavelength side of the highest peak with the rise of secondary lower peaks. Data points of the wavelength shift undergone by the spectrum highest peak as a function of the applied strain showed that a smaller shift occurs when the material is cracked than when the material is undamaged. The difference between the damaged and undamaged cases was more pronounced when the sensor was embedded at the outer interface of the cracked transverse ply.

In the following Chapter, the response of the FBG sensor to strain and matrix cracking under bending is presented.
EMBEDDING an optical FBG sensor in composite laminates provides the opportunity to achieve a measurement of local strain states in particular locations inside the material. When a plate is subjected to bending, a strain distribution is established throughout the plate's thickness, which includes locations where the local longitudinal strain is zero. Sensor placement in correspondence of different interfaces between adjacent plies of a composite laminate beam has enabled the measurement of strains across the thickness of the laminate.

In this Chapter a discussion is reported upon the results of tests carried out on FBG sensors embedded in glass-epoxy cross-ply laminates loaded in four-point bending. For the bending tests, two different locations of the FBG sensors within a double cross-ply laminate have been used. In addition, positioning the sensor on the compressive side of a bending
specimen made of a simple cross-ply laminate allowed an examination of the sensor response under axial compressive strain.

The sensor response to cracking of the laminate under bending has also been studied. Matrix cracks have been produced in the tensile transverse ply of double cross-ply specimens and the differences between the sensors' reflected spectra before and after cracking are described here. In the first section, the strain detection under bending for the FBG sensors embedded in double cross-ply coupons or simple cross-ply coupons is described.

9.2. STRAIN DETECTION UNDER BENDING

9.2.1. FBG SENSORS IN TWO LOCATIONS OF A DOUBLE CROSS-PLY LAMINATE

The \((0/90^\circ_2/0^\circ)\) lay-up characterising the double cross-ply GFRP laminates manufactured for this study allowed the FBG sensors to be located at the interface between two adjacent plies in two different positions: (i) between one outer \(0^\circ\) ply and the \(90^\circ\) ply adjacent to it, and (ii) between one \(90^\circ\) ply and the middle \(0^\circ\) ply.

![Figure 9.1. Schematic of the longitudinal strain state experienced by the double cross-ply specimens in four-point bending. On both sides of the neutral axis there exist two differently stressed interfaces.](image-url)
As shown in Figure 9.1, in the four-point bending configuration used in the present work the interfaces above the neutral axis were stressed in compression in the specimens’ longitudinal direction, while the interfaces below the neutral axis were under tension in the same direction. Of course, the two 0/90 interfaces which bound the middle longitudinal ply are closer to the neutral axis and experience a lower absolute value of the longitudinal strain than the two 0/90 interfaces joining the transverse plies and the outer longitudinal plies.

![Figure 9.2](image_url)

**Figure 9.2.** Optical micrograph of part of a cross section of a double cross-ply specimen with an FBG sensor embedded at the interface between the middle 0° ply and the adjacent 90° ply.

In each double cross-ply specimen used in this study, a single FBG sensor was located near one of the two 0/90 interfaces on the tensile side of the specimen under the action of the applied bending moment. In Figure 9.2 an optical micrograph is shown of part of the cross
section of a cross-ply specimen with a FBG sensor embedded in the middle longitudinal ply, at the interface with the tensile transverse ply. Figure 9.3 provides a similar image but this time for a sensor embedded in the outer tensile longitudinal ply, near the interface with the adjacent transverse ply.

Figure 9.3. Optical micrograph of part of a cross section of a double cross-ply specimen with an FBG sensor embedded at the interface between the outer 0° ply and the adjacent 90° ply.

The bending tests were carried out in quasi-static loading with a step increase of the applied load, as already explained in the previous Chapters. Experimental results for the Bragg wavelength shift experienced by two sensors placed at different tensile interfaces are shown in Figure 9.4. The wavelength shift is plotted as a function of curvature, which was determined as the inverse of the radius of curvature, whose value was provided by the calculations described in Chapter 4 for the use of an extensometer in four-point bending.
Figure 9.4. Plot of experimental data describing the Bragg wavelength shift undergone by two FBG sensors placed at two different tensile interfaces in a double cross-ply laminate subjected to four-point bending.

2B1-2: FBG sensor at interface between middle 0° and tensile 90° ply.
2B1-4: FBG sensor at interface between outer tensile 0° and adjacent 90° ply.

Each data point provides the position of the reflected spectrum peak on the wavelength axis as a function of the specimen curvature. Of course, for the same specimen curvature, the sensor near the interface between the outer 0° ply and the adjacent 90° ply is subjected to a higher strain than the sensor located at the interface between the middle 0° ply and the adjacent (tensile) 90° ply.

Reflected spectra for different curvatures are shown in Figures 9.5 and 9.6 for the undamaged material. In both pictures it is possible to notice that, similarly to what was described for the tensile experiment results, under a bending load the shape of the reflected spectra is unchanged for higher curvatures (higher longitudinal strains) while shifting along the wavelength axis as a consequence of the increasing strain.
Figure 9.5. Light spectra reflected by FBG sensor in undamaged double cross-ply laminate for various levels of applied load. Sensor at interface between middle 0° and tensile 90° ply.

(a) spectra reflected with no curvature and under an applied curvature of 0.003743/m.
(b) spectra reflected under applied curvatures of 0.001074/m and 0.004512/m.

Figure 9.6. Light spectra reflected by FBG sensor in undamaged double cross-ply laminate for various levels of applied load. Sensor at interface between outer 0° and tensile 90° ply.

(c) spectra reflected with no curvature and under an applied curvature of 0.001074/m.
(d) spectra reflected under applied curvatures of 0.002490/m and 0.003743/m.

9.2.2. COMPRRESSIVE STRAIN IN SIMPLE CROSS-PLY COUPONS

The experiments described in section 9.2.1 put the FBG sensors into tension. Four-point bending experiments were also carried out on (0/90/0) simple cross-ply laminates, which enabled an examination of the sensor behaviour when subjected to a compressive axial stress.
Full spectra were not recorded during these experiments, the main interest being focused on the Bragg wavelength shift behaviour. After recording the shift data with the sensor under a compressive stress (sensor placed below the neutral axis), the same specimens were inverted in the bending rig, which allowed the embedded sensor to experience a tensile strain under the bending moment applied to the host material. In Figure 9.7 a schematic drawing is reported depicting the experimental configuration for these tests.

![Diagram of longitudinal strain](image)

**Figure 9.7.** Schematic of the longitudinal strain experienced by simple cross-ply specimens in four-point bending. Sensor placement above the neutral axis leads it to be strained in compression.

The experimental results showing the Bragg wavelength shift as a result of the applied type of strain experienced by the sensor are reported in Figure 9.8. In these experiments, strain measurements were carried out with a surface mounted extensometer and these data were then transformed into the real strain experienced by the specimen. For this calculation the FBG position within the coupon was required to be measured. This was achieved by subsequent sectioning, polishing and microscopy of the cross-section of coupons. The strain values determined in this way were plotted on the x-axis values in the diagram of Figure 9.8.
The results show (i) linearity of the sensor response in tension and compression; (ii) reasonable agreement in the sensitivity of the sensors in tension and compression. The sensitivity of the FBG sensors determined from these bending results is $1.28 \times 10^{-3} \text{nm}/\mu\varepsilon$, which is close to the value found in the tensile tests ($1.23 \times 10^{-3} \text{nm}/\mu\varepsilon$).

### 9.2.3. COMPARISON BETWEEN EXTENSOMETER AND FBG SENSOR MEASUREMENTS OF STRAIN

A small extension of the results in the previous section is to compare the strain measurements obtained by the extensometer and the embedded FBG sensors in the composite specimens under bending. The sensitivity of the embedded FBG sensors is known, so the Bragg wavelength shifts can be converted to strains directly. For example in Figure 9.9(a) the results shown in Figure 9.8 for Bragg wavelength have been converted strains. Similarly, some results for Bragg gratings at the two different locations of a double cross-ply laminate are shown in Figure 9.9(b) (the position of the optical fibres was determined by sectioning and polishing).
Figure 9.9. Comparison between strain measurements with extensometer and FBG sensors.
(a) FBG sensors embedded at the interface between the transverse ply and one outer longitudinal ply in simple cross-ply laminates.
(b) FBG sensors embedded at the two interfaces of the tensile transverse ply in double cross-ply laminates.

Figure 9.10. Comparison between strain measurements with extensometer and FBG sensors.
The trends show good agreement existing between the two measurements.
In Figure 9.10 all of the experimental data are plotted in one graph for better comparison. Agreement is good in all cases, and a slope of one is confirmation that (i) the conversion of the extensometer strains in bending has been satisfactorily achieved, and (ii) the FBG sensors perform as expected in bending, whether subjected to a tensile or compressive strain.

9.3. OPTICAL OUTPUT CHANGE DUE TO CRACKING

9.3.1. REFLECTED SPECTRUM CHANGE FOR SENSOR NEAR 0/90 INTERFACE CLOSE TO NEUTRAL AXIS

In this section, results will be presented on the detection of matrix cracking under bending using a FBG sensor. The use of a FBG sensor for detection of matrix cracks in a composite material under bending is a fully novel experimental contribution (to the author's knowledge). The method used is based on the comparison between the reflected light spectra when the host material was undamaged and when a crack was present. A comparison is also made between the behaviour of sensors embedded at different interfaces of double cross-ply specimens.

Figure 9.11 shows spectra reflected by a FBG embedded in a double cross-ply specimen at the interface between the middle 0° ply and the tensile 90° ply, both in undamaged and damaged conditions. The damage, in this case, consisted of matrix cracks in the 90° ply subjected to tensile stresses under bending. In particular, a crack density of approximately 0.2/mm was present in the specimen region which included the FBG sensor. Four conditions are shown for comparison: unloaded and curvatures of 0.001074/m, 0.003743/m and 0.004512/m. Based on previous results, these curvatures correspond to local FBG strains of approximately 0%, 0.027%, 0.094% and 0.113%. For each curvature, the spectra reflected in the undamaged and damaged conditions are shown for comparison.
Figure 9.11. Light spectra reflected by a FBG sensor embedded at the interface between the middle 0° ply and the tensile 90° ply of a double cross-ply specimen subjected to bending.

(a) Undamaged material unloaded; (b) material with cracked tensile 90° ply unloaded;
(c) undamaged material under a curvature of 0.001074/m; (d) material with cracked tensile 90° ply under a curvature of 0.001074/m; (e) undamaged material under a curvature of 0.003743/m;
(f) material with cracked tensile 90° ply under a curvature of 0.003743/m.
It can be noticed that the difference between spectra reflected in the undamaged and damaged material in all cases consists of a spectrum broadening. The spectra of the undamaged material possess a nearly symmetrical shape, while the spectra reflected when matrix cracks are present appear broader on the right hand side of the highest spectrum peak. The shape difference between the undamaged and the damaged cases is increasingly clear for increasing values of the curvature of the specimen. At higher curvatures, the FBG sensor output shows the onset of secondary peaks at longer wavelengths.

The broadening and the onset of secondary peaks on longer wavelength side of the reflected spectrum is similar to those described in Chapter 8 for tensile loading of double cross-ply specimens, and may be given an explanation similar to analogous phenomena already discussed for bending in Chapters 6 and 8. The presence of matrix cracking in the transverse ply adjacent to the sensor location modifies the strain distribution in the vicinity of the sensor because the onset of matrix cracks is always accompanied by a local release of residual thermal stresses. In the double cross-ply laminate with cracks in one 90° ply, the effect of the cracks is to produce a local curvature of the coupon which dictates the shape of the transverse matrix crack opening. This opening results in enhanced strains in both 0° plies, but a lower strain is expected at the interface with the middle longitudinal ply, the location where the FBG sensor
was placed in this case (see Figure 4.18 in Chapter 4). This explanation suggests that more pronounced side peaks and broadening should be seen for the same curvatures with the sensor at the interface between the cracked 90° ply and the outer 0° ply. This is investigated in the next section.

9.3.2. REFLECTED SPECTRUM CHANGE FOR SENSOR NEAR 0/90 INTERFACE BETWEEN CRACKED 90° PLY AND OUTER 0° PLY

Results for the optical output of FBG sensors placed at the interface between the outer longitudinal ply and the cracked transverse ply are shown in Figure 9.12. Again, comparisons between FBG reflected spectra before and after cracking are shown. Figure 9.12 shows spectra reflected by a FBG sensor embedded in a double cross-ply specimen at the interface between the outer 0° ply and the tensile 90° ply in undamaged and damaged conditions. When the laminate was in "damaged" conditions, a matrix crack density of 0.2/mm was present in the transverse ply subjected to tensile stresses under bending. Figures 9.12(a) 9.12(b) show the spectra recorded in the two conditions with no curvature of the specimen. Figures 9.12(c) and 9.12(d) were recorded under an applied curvature of 0.001074/m, Figures 9.12(e) and 9.12(f) are related to a curvature of 0.002490/m; figures 9.12(g) and 9.12(h) correspond to a curvature of 0.003743/m.

![Graphs showing reflected spectra](image)

**Figure 9.12.** Light spectra reflected by a FBG sensor embedded at the interface between the outer 0° ply and the tensile 90° ply of a double cross-ply specimen subjected to bending.

(a) Undamaged material unloaded; (b) material with cracked tensile 90° ply unloaded.
Figure 9.11. Continued.

(c) undamaged material under a curvature of 0.001074/m; (d) material with cracked tensile 90° ply under a curvature of 0.001074/m; (e) undamaged material under a curvature of 0.002490/m; (f) material with cracked tensile 90° ply under a curvature of 0.002490/m. (g) undamaged material under a curvature of 0.003743/m; (h) material with cracked tensile 90° ply under a curvature of 0.003743/m.
Based on previous results, these curvatures correspond to local FBG longitudinal strains of approximately 0%, 0.134%, 0.311% and 0.468%.

Comparing the results in Figure 9.11 and 9.12, it is possible to notice that the shape difference between the spectra related to the undamaged and damaged material is clear, in this case, even for lower values of the specimen curvature under the bending load. This can be explained, consistently with what explained in the above, with the fact that the strains near this interface are larger than at the interface previously examined. However, closer comparison of the two sets of results in Figures 9.11 and 9.12 shows some differences. Comparing the results for approximately the same curvature (i.e. Figure 9.11(f) and Figure 9.12(h)), it can be seen that the spectrum in Figure 9.12(h) appears broader. This is consistent with a larger crack opening displacement of the matrix cracks at the interface between the cracked 90° ply and the outer 0° ply.

9.3.3. BRAGG WAVELENGTH SHIFT

In Figures 9.13 and 9.14 the wavelength shift characterising the highest spectrum peak is shown for each of the two sensor locations in both the undamaged and damaged material. The highest spectrum peak is defined as the point with highest intensity in the spectrum. Figure 9.13 shows that there is very little difference between the points representing the shift of the peak in undamaged and damaged conditions for the sensor located at the inner interface of the tensile 90° ply. In fact, the sensor longitudinal strain in this case is very limited in both conditions. Figure 9.14 shows the peak shift when the sensor is embedded at the outer interface of the tensile 90° ply. It can be noticed that the slope of the shift is lower when the material is damaged. As in the results for tensile loading, this is a further confirmation of the fact that a region of the grating exists which is not under the influence of the strain magnification due to the presence of cracks. Under tensile load, this region is strained less when transverse matrix cracks are present than it is in the undamaged case.
Figure 9.13. Wavelength shift of the reflected spectrum main peak as a function of the specimen curvature. FBG sensor at interface between the middle longitudinal ply and the tensile transverse ply.

Figure 9.14. Wavelength shift of the reflected spectrum main peak as a function of the specimen curvature. FBG sensor at interface between the outer tensile longitudinal ply and the tensile transverse ply.
Chapter 9

RESPONSE OF A FBG SENSOR TO MATRIX CRACK DEVELOPMENT
- RESULTS AND DISCUSSION II. BENDING TESTS

9.4. SUMMARY

The behaviour of a FBG sensor embedded in GFRP cross-ply laminates subjected to bending has been described. The experiments were carried out under quasi-static four-point bending load with an incremental increase of applied bending moment.

Experiments on sensors embedded in single cross-ply specimens allowed an examination of the sensor response to both tensile and compressive axial strain. Comparison between the strains recorded by an extensometer and the strains recorded by FBG sensors showed linearity of the Bragg wavelength shift as a function of strain in both the tensile and compressive side of the wavelength-strain diagram. Similar experiments on double cross-ply laminates with the sensors tested in tensile strain conditions located at the interface between the middle 0° ply and the tensile 90° ply or at the interface between the tensile 90° ply and the outer 0° ply also produced good agreement.

In the case of sensors embedded in double cross-ply specimens, reflected spectra were recorded for the undamaged material and after matrix cracking had occurred in the 90° ply loaded in tension. All the spectra reflected by the sensors embedded in the damaged material showed a shape broadening at longer wavelengths with respect to the spectra related to the undamaged material as in the case of monitoring matrix cracking under tensile loading.
Chapter 10

CONCLUSION

10.1. MATRIX DAMAGE IN CROSS-PLY COMPOSITES

The behaviour of a GFRP double cross-ply laminate has been investigated under an applied four-point bending. Quasi-static and fatigue tests have been carried out to study the development of matrix cracks in the transverse ply subjected to longitudinal tensile stresses under the action of the bending load.

Transverse matrix cracks observed in quasi-static bending tests developed from coupon edges. The crack growth across the specimen width took place in discrete steps, following step increases of the applied quasi-static load. Cracks growing from opposite edges at a distance of less than one transverse ply thickness showed crack arrest due to stress shielding. This was observed by taking digital camera images of the transparent specimens during the increasing load application. Crack initiation occurred at the interface between the tensile transverse ply and the outer $0^\circ$ ply of the laminate. An individual crack extended across the full transverse ply thickness when it had a length of approximately one ply thickness across the coupon width. This was revealed by optical microscopy images taken during observations following the bending tests.

It was found that degradation of the flexural modulus of the material, as a function of increasing crack density, is well described by a theoretical model based on a one-dimensional shear-lag analysis. The experimental data were in reasonable agreement with the predictions of
the model.

During four-point bending fatigue tests at “low loads”, the damage behaviour was similar to the characteristics observed under quasi-static loading. However, there were some differences. Crack initiation at internal locations of the specimens, away from the coupon edges, was observed. In this case, the initiation point was again located at the interface between the tensile transverse ply and the outer longitudinal 0° ply. For the fatigue cracks which developed away from the coupon edges, cracks extended across the full transverse ply thickness when the crack length across the specimen width became greater than about two ply thicknesses. Crack interaction for cracks growing from opposite edges occurred as described, i.e. crack arrest occurred for cracks less than one transverse ply thickness apart. In the regions where a shear load was established in addition to the bending moment, matrix cracks in the tensile transverse ply developed at obtuse angles to the 0° ply directions.

Subjection of the double cross-ply material to “high-load” fatigue bending cycles caused the development of damage in addition to matrix cracking. Delaminations were initiated from crack tips at the interface between the tensile transverse and the outer longitudinal plies. In the constant bending moment region, delaminated areas developed at the coupon edges, due to edge effects. However, in the regions where the bending moment was present in addition to shear, delaminations also initiated away from coupon edges. Extensive outer tensile longitudinal ply fibre bundle failure was also observed in “high-load” fatigue cycles.

With regard to flexural stiffness reduction relating to tests carried out under cyclic bending load, it was found that the model predictions were in good agreement for “low-load” fatigue tests. However, the model tends to underestimate the flexural modulus decay due to damage development when the maximum load level of the fatigue cycles is close to a value that causes the crack density to approach the saturation value in quasi-static tests (i.e. “high-load” fatigue cycles). In these conditions, the additional types of damage developed in the laminate (delaminations and fibre bundle fracture), which are not accounted for in the theoretical model result in the predictions of stiffness reductions being slightly higher than the measured values.
10.1.1. F.E.M. ANALYSIS OF A CRACKED CROSS-PLY LAMINATE

Analysis of a simple cross-ply laminate by finite element method provided useful information about the strain field established in the middle longitudinal section of a typical tensile specimen used for mechanical testing. It was shown that the presence of a transverse matrix crack in the middle cross-section of the specimen produces a strain magnification in the adjacent longitudinal ply in the vicinity of the crack tip. The effects of such a magnification extend over a length approximately equal to one transverse ply thickness on both sides of the crack plane. Moreover, the strain magnification amplitude decreases rapidly with the distance from the crack tip, measured along the longitudinal ply thickness direction. The longitudinal displacements across the thickness of the transverse ply were in reasonable agreement with the assumptions of a simple shear-lag model.

10.2. FBG SENSORS FOR SMART COMPOSITE MATERIALS

Optical fibre Bragg sensors have been used to manufacture specimens of smart composite materials. Experiments carried out by manually applying an axial tensile load to the free sensor allowed preliminary investigation of the optical output of the sensors in terms of shift of the reflected spectrum peak as a result of tensile strain experienced by the optical fibre. The measured value of sensitivity of the free sensor was $1.11 \times 10^3 \text{nm/\mu e}$. Quasi-static tensile tests were carried out on single and double cross-ply laminates of a GFRP composite material containing FBG sensors within a longitudinal ply and close to a 0/90 interface. The reflected spectrum shape remained unchanged while undergoing a shift along the wavelength axis, due to the strain experienced by the undamaged host material under the applied load. A measure of this shift provided the sensitivity of the embedded sensor, which was found to be in the range of $1.23 \times 10^3 \text{nm/\mu e} \pm 0.5 \times 10^3 \text{nm/\mu e}$, which is in good agreement with previous work. The reflected spectrum typically presented a single peak and a symmetric shape with respect to the
main peak.

On the other hand, for sensors embedded in simple cross-ply coupons, the FBG response to the onset of a single matrix crack, developing within the Bragg grating length in the transverse ply adjacent to the sensor location, was characterised by a significant change in the reflected spectrum shape. This change consisted of a broadening on the longer wavelength side of the original spectrum, with secondary lower peaks also observed. These additional features can be understood qualitatively by consideration of the strain magnification produced local to matrix cracks in the transverse ply adjacent to the sensor. The highest intensity point of the reflected spectrum showed a similar shift both in the case of undamaged material and after cracking, suggesting that this peak was the result of reflections occurring in the regions of the Bragg grating located out of the region of strain magnification associated with the matrix crack.

Sensors embedded in double cross-ply laminates, in which the 90° ply adjacent to the sensor location was damaged, were also investigated. The damage consisted of a crack density of 0.10/mm to 0.18/mm and was caused in the tensile 90° ply of the double cross-ply laminates under a bending load. In these damage conditions, observation of shape change of the FBG sensor reflected spectrum could be extended to the case when the strain magnification effect of more than one crack influenced the longitudinal strain of the Bragg grating. Enhanced broadening and side peaks were found in the spectra reflected by sensors embedded in double cross-ply laminates in this case. Moreover, the shift of the highest intensity peak for the sensor embedded in the undamaged material was larger than in the case of cracked laminate. This is explained with the reduced strain experienced by the grating segments out of the strain magnification regions associated with the cracks.

Simple cross-ply laminates were also subjected to quasi-static four-point bending tests. Placement of FBG sensors on the compressive side of single cross-ply specimens enabled an examination of the sensor response to compressive strain. Linearity of the sensor response was verified in this case and good agreement was found with measurements made using an extensometer. Double cross-ply specimens with an embedded single FBG sensor were also examined. In these coupons, location of FBG sensors at two different interfaces was
investigated: (i) at the interface between the middle longitudinal ply and the tensile transverse ply and (ii) at the interface between the tensile transverse ply and the outer longitudinal ply. In both of these cases, experiments were carried out with the sensors placed in the tensile side of the beam specimens. As expected, the reflected spectrum of the FBG showed a smaller shift when the sensor was embedded at position (i) than when it was embedded at position (ii). Response of the FBG sensors to matrix cracking of the double cross-ply laminate was also examined in bending tests. Similar features to those described for the tensile tests were found in the change, occurred after cracking, in the shape of the spectrum reflected by the sensor under bending.

Operation of the FBG sensors with a broadband light source proved far more convenient than operation using a tuneable laser source, with dramatically reduced data collection time. Remotely controlling the optical spectrum analyser used to record the light spectra also produced an improvement in the collection of the results.

10.3. FURTHER WORK

In this work, the development of matrix cracking damage under quasi-static loading and fatigue loading under four-point bending was investigated. Double cross-ply GFRP laminates have been investigated with quite thick transverse plies. An obvious extension is to investigate whether the same crack development phenomena are seen in laminates with thinner plies, and in other materials (e.g. CFRP or aramid fibre reinforced polymers). Additionally, the development of matrix cracks in off-axis plies (e.g. 45°) would also be important to investigate.

The FBG sensors have been shown to be able to both detect matrix crack development under tensile and bending loading, as well as monitor strain. Again, it is important to show that this can be achieved in other laminate systems and to investigate whether cracks in off-axis plies (e.g. 45°) can be detected.

Finally, the development of side-bands in the reflected spectrum of the FBG sensors as a result of matrix crack formation has been explained qualitatively. The next stage of the
work would be to predict these side-bands theoretically. The solution of the equations
describing the reflection behaviour of the FBG sensor would provide predictions of the reflected
spectrum shapes in different non-uniform strain fields. This modelling is likely to also require a
3D finite element analysis.


References


References


Kehlenbach M., Betz D., "Fibre-optic Bragg grating sensors for strain measurement inside composite materials", in *Proceedings of ECCM-10*, Bruges – Belgium (June, 2002).


Wang H., Ogin S.L., Thorne A.M., Reed G.T., "Use of a polarimetric sensor for damage detection in a cross-ply composite laminate", in Proceedings of ECCM-10, Bruges – Belgium (June, 2002).


Appendix A

BENDING RIG DESIGN DRAWINGS

FOUR POINT BENDING TEST RIG

Table 1. UPPER BEAM

Table 2. LOWER BEAM

Table 3. SUPPORTS

Table 4. OTHER COMPONENTS

Table 5. ASSEMBLY
Appendix A

BENDING RIG DESIGN DRAWINGS

---

Table 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Q'ty</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom beam</td>
<td>1</td>
<td>Steel</td>
</tr>
</tbody>
</table>

FOUR-POINT BENDING TEST RIG

Scale 1:2 June 2002

UniS School of Engineering
B.1. THE PC-Osa COMMUNICATION SYSTEM

IN ORDER to examine the light spectra reflected by the FBG sensors for all the different external load conditions, the instrument used was an Optical Spectrum Analyser (OSA) ANDO - Type AQ 1425 produced by Ando Electric Co., Ltd. – Japan.

The instrument is usually operated locally, but it also offers the possibility to be controlled remotely via a PC interface. The OSA can be connected to a PC by its built-in GPIB (General Purpose Interface Bus) port. Formerly named HPIB (acronym for Hewlett-Packard Interface Bus, after the company name who first registered the technology), the GPIB is an hardware interface which has in recent years become a standard way for connecting measurement instruments and other laboratory devices to PC’s to allow them to be remotely controlled. The two-way communication between the PC and the OSA can only take place by providing the PC with a separate GPIB board. A GPIB cable connects the OSA’s GPIB port to the PC’s GPIB board: a schematic of the system is depicted in Fig. B.1.
The GPIB board used to build the PC-OSA interface was a PCI-GPIB-488.2 board carrying 1 MB memory; it was supplied by Amplicon, Brighton – U.K. The board is accompanied by a software package including programs needed to both set up and operate the board from the host PC. The software package is made up of three programs, all built up in the form of MS-DOS shells to be launched under a MS-Windows environment. They are called CBCONF, CBTEST and CBIC. A brief description of features of the three programs is reported in the following.

![GPIB board connection scheme](image)

**Figure B.1.** Representation of the GPIB connection scheme.

### B.1.1. CBCONF

The CBCONF shell is structured in the form of a list of parameters whose value has to be set up in order to complete the correct installation of the board. At the end of the installation process, the board is a peripheral of the PC system and the processor is able to exchange commands and data through it.

Set-up parameters which are assigned values with this program are listed in Table B.I.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board Name</td>
<td>GPIB0</td>
</tr>
<tr>
<td>Board Type</td>
<td>PCI-GPIB</td>
</tr>
<tr>
<td>Slot Number</td>
<td>3</td>
</tr>
<tr>
<td>Primary GPIB Address</td>
<td>1</td>
</tr>
</tbody>
</table>
The Slot Number is the location of the board onto the PC motherboard, where it is physically mounted. The Primary GPIB Address is an integer ranging between 0 and 31. It represents the address of each external GPIB device connected to the PC via the board: in this case the only device present is the OSA and it is assigned the address 1.

Other parameters are dealt with by this program, but none of them needs to be changed by the operator, since the default value is already operational.

**B.1.2. CBTEST**

The CBTEST routine is a single-task program carrying out the verification of correct installation of the board. When the program is launched, it runs a small set of tests to check whether the values of the parameters mentioned in the previous section match the actual characteristics of the GPIB board. The results of each test are displayed in the program’s MS-DOS shell by a series of “OK” or “NOT-OK” messages. Of course, the correct installation of the board returns an “OK” message for each of the tests executed.

**B.1.3. CBIC and the OSA commands**

The CBIC is the tool that allows the remote control of the GPIB devices to be operated.

When the program is launched, the MS_DOS shell which is opened prompts the operator to type commands used to lead the board to take actions over the GPIB line. There exist two libraries of commands which the board can execute: the 488.1-Library and the 488.2-Library. Both Libraries enable the board to run tasks by which the board carries out the management of the GPIB line. The two libraries are equivalent, as either contains commands having identical functions; the only difference between them consists in the syntax of each command. The GPIB board used in the present work is capable of interpreting both sets of commands, each typed with its own syntax.

The detailed explanation of individual command functions is not necessary here.
However, typical management operations completed by commands are: (i) polling (i.e. interrogation) of the GPIB line in search for operational devices (the OSA only, in the present study), (ii) polling of GPIB devices, (iii) triggering of single devices, (iv) input/output of data and commands to/from devices and so on. Each command is a subroutine which carries out one of the tasks just mentioned.

One of the commands requires a detailed mention and illustration, due to its importance with regard to the remote operation of the GPIB devices. The "send" command is the most frequently used for remotely controlling an instrument: it allows the operator to send the device instructions it can interpret and execute. The 488.2 syntax of the "send" command is as follows:

```
GPIBO: Send
    Enter address of device: 
    Enter string to be written: 
    Enter EOTMode: 
```

After typing the GPIB address of the device to be sent an instruction, the instruction itself is typed in the syntax comprehensible to the instrument which will then execute it. As an example, here follow the command lines for the OSA to run a single sweep of a previously defined wavelength interval:

```
GPIBO: Send
    Enter address of device: 1
    Enter string to be written: SINGLE
    Enter EOTMode: DABend
```

EOTMode is an alpha-numeric character informing the instrument of the end of the instruction sent. Instructions sent to the device remotely have the same effect as triggering switches and knobs on the front panel of the instrument when operated in local mode.

Each GPIB-controllable instrument has a set of commands it can interpret and execute. In order for them to be used to remotely control the GPIB instrument, they have to be individually typed in the "Enter string to be written:" line of a "send" command in CBIC. Each command has its own syntax which has to be followed strictly in order for the device to correctly interpret and execute it. In Table B.II a list is reported of the most
frequently used command to carry out the spectrum acquisition procedure by remotely controlling the OSA.

Each asterisk in the right column of Table B.II represents a single digit. All the alphabetic characters must be written in block capitals (the syntax is case sensitive). No spaces are allowed in the typing of a command. When any mistake is made in typing a command, it is ignored by the device.

**Table B.II.** The most frequently used commands to record a light spectrum with the OSA.

<table>
<thead>
<tr>
<th>COMMAND</th>
<th>SYNTAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre Wavelength</td>
<td>CWL****.*</td>
</tr>
<tr>
<td>Sweep Width</td>
<td>SW***.*</td>
</tr>
<tr>
<td>Single Sweep</td>
<td>SINGLE</td>
</tr>
<tr>
<td>Repeated Sweep</td>
<td>REPEAT</td>
</tr>
<tr>
<td>Resolution</td>
<td>RES**.*</td>
</tr>
<tr>
<td>Reference Level</td>
<td>REPLVL-**</td>
</tr>
</tbody>
</table>

A brief comment follows on each command listed in Table B.II.

**CWL****.***: To set up the centre wavelength (in nm) of the bandwidth to be swept by the OSA to acquire the shape of the light spectrum. In the present study the value was typically set to 1550.00nm.

**SW***.***: To set up the width of the wavelength range to be swept (in nm). The value used in this work was always fixed to 10.0nm.

**SINGLE**: This command instruct the OSA to carry out a single sweep over the specified wavelength range.

**REPEAT**: By sending the OSA this command, the instrument is instructed to sweep the specified wavelength range continuously. The command was used to carry out preliminary checks when starting up the whole system and immediately before
Appendix B

B.1. OPTICAL SPECTRUM ANALYSER REMOTE CONTROL SYSTEM

running the experiments which are relevant to the study.

RES**:*: To set up the resolution of the OSA (in nm). The resolution used for the present work was the finest the device offers: 0.1nm

REFLVL-**:*: This command tells the OSA the intensity level (in dB) to be taken as a reference while analysing a light spectrum. It basically defines the intensity level below which the signals read must be considered as noise. A typical value of the noise in this work was -55dB.

B.2. THE SPECTRUM ACQUISITION PROGRAM

The remote operation of a GPIB device is easily and immediately achieved by sending it individual commands one at a time through the CBIC shell. However, when a complex set of tasks need to be carried out by the instrument repeatedly, the use of CBIB may be time consuming. In order to overcome this, a convenient method has been adopted by building a user-friendly PC interface enabling a fast and easy operation of the OSA to analyse and record the light spectrum back-reflected from a FBG sensor. This is outlined in the following.

B.2.1. THE VEE-PRO 6.0 SOFTWARE

The VEE-Pro 6.0 software is a programming language specifically devoted to build PC user interfaces to remotely control laboratory instruments. The package used in the present study was purchased from Agilent Technologies Inc. – USA. It operates under the common MS-Windows environment. VEE has been used to build the routine procedure of acquiring a light spectrum data by the OSA and creating an MS-Excel readable file with the data.

Programming technique adopted with this software is by objects. A blank work area appears in the software window when the software is launched. The programs built by the user with this software consist of the procedures to control the instruments connected to the PC station and are stored in the form of files with “.vee” format. These programs are built by placing suitable objects onto the work area and by creating links between them, so as to define...
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OPTICAL SPECTRUM ANALYSER REMOTE CONTROL SYSTEM

an order among a series of actions to be taken to carry out the desired instrument's control. Objects by which it is possible to run different individual operations have to be chosen and organised in the work area. Each object is only devoted to a single operation of the whole control process.

Once the program has been completed, it can be saved and stored in a file for future usage. Upon opening the file, VEE-Pro provides the functionalities to RUN, PAUSE and STOP the program. An illustration of features of a few objects used to build up the spectrum acquisition process remote control is given in the following section.

B.2.2. THE SPECTRUM ACQUISITION

In order to realise the acquisition and storage of the data describing the shape of a light spectrum by remotely controlling the OSA, a series of elementary operations have to be carried out by the instrument:

- to sweep a pre-defined wavelength range,
- to record the set of data points coming from the sweeping operation, and
- to send the data to the PC unit for it to manage the storage of them into a file previously named by the operator.

A separate VEE object exists to fulfil each one of these functions. Once chosen and put into the work area, the objects have to be suitably linked together to build up the entire procedure.

The operations needed to configure some parameters of the OSA are executed by directly running the corresponding commands from within the previously described CBIC shell. In such a way, all the sweep parameters are set up before operating the VEE-borne interface. This preliminary set up includes the definition of: centre wavelength, sweep width, reference level and resolution.

The object by which the OSA can be instructed to run a single sweep of the pre-defined wavelength bandwidth is shown in Fig. B.2: it is named "DIRECT I/O" object.
This object incorporates one or more user-defined transactions to be executed between the controller PC and the controlled instrument (OSA). The transaction defined to allow the OSA carry out a single sweep consists of sending ("WRITE") the command ("TEXT") SINGLE to the OSA. The effect of the transaction is that the instrument runs a single sweep over the pre-defined wavelength sweep and stores the read data in its local memory area.

The following step is the transfer of data from the OSA to the PC. This is achieved by using another DIRECT I/O object containing the transaction by which the PC is ordered to read ("READ") the numerical data representing the measurement completed by the OSA in the last sweep: the format of the data is an array of 560 elements ("ARRAY:560") and the elements are real numbers ("TEXT x REAL64"). This information needs to be specified in the transaction in order to enable the PC give a correct interpretation of the bytes coming from the OSA.

The object just described is depicted in Fig. B.3.
After reading from the instrument, the PC is instructed to store the data into a file in the format of a column of 560 numbers. The operator defines the file name. These two actions are carried out by using a "TO FILE" object, shown in Fig. B.4.

Figure B.4. VEE-Pro 6.0: the TO FILE object containing the transaction instructing the PC to store the OSA reading into a user-defined file.

Figure B.5. VEE-Pro 6.0: the XY-TRACE object.
The program is completed by connecting an "XY-TRACE" object to the DIRECT I/O object used for the PC to read the data from the OSA. This element is not strictly necessary with regard to the correct execution of the spectrum acquisition procedure, but it is useful for the operator to monitor the control process. If the spectrum acquisition procedure runs correctly, the XY-TRACE diagram of the same spectrum is plotted on the OSA screen. An example of a light spectrum visualised by this object is shown in Fig. B.5.

The x-axis scale of the plot does not represent the real wavelength scale. This is due to the way the OSA stores the measurement data. In fact, the only figures that the instrument provides represent the intensity values (y-axis) of the spectrum: as said, they build up an array of 560 elements. Therefore, the values of the x-axis in the XY-TRACE plot are just the ordinals defining the positions of each data point in the array.

The task of correlating each intensity value to the corresponding wavelength is a task for the operator. This task is carried out within the MS-Excel package when processing the measurement data. In particular, the operation consists of building a new column of 560 points representing the real wavelength values. The first and the last value of this column are coincident with the extremes of the wavelength range swept in the measurement by the OSA. Between these two extreme values, the remaining 558 points are inserted, each one being the limit between two adjacent wavelength intervals. The full set of 560 intervals builds up the whole swept wavelength range. The column so obtained defines the x-axis values of the spectrum diagram, which can now be plotted correctly.

In Fig. B.6 the whole spectrum acquisition program is shown. It is possible to see the lines representing the connections between the objects. These connections define the sequence of operations in the procedure, i.e. the structure of the control process. Highlighted by the pointed ellipse and arrow at the top are the VEE buttons to be triggered by the operator to start, pause and stop the program run.

Fully disconnected from the procedure is a "BUS I/O MONITOR" object. It is a complementary object used to quickly check the format of the data exchanged by the instrument and the PC. This is useful in case any faults occurred in the interpretation of OSA-
borne data by the PC.

Figure B.6. VEE-Pro 6.0: full view of the spectrum acquisition program.
The program assembly shown in Fig. B.6 is the screen which VEE makes visible when the program is still under construction or needs to be modified. However, the VEE package gives the operator the possibility to have on the PC screen a user-friendly interface, in which the only elements present are: (i) the plot showing the test data and (ii) the buttons needed to assign the file name for data storage. Such an interface is shown in Fig. B.7. This is the screen to be used by the operator after the programming activity has come to an end and when the program is to be run. The operator inputs the desired file name and triggers the "RUN" button on the top of the screen to start the program. While the program is running the data acquired by the OSA can be monitored on the XY-plot monitor. In case it is needed, the program can be paused, stopped and resumed by clicking the corresponding buttons on the top of the screen.
At the beginning of each program run, a new file name has to be input for data storage. If the file name is not changed, the program stores the new data in the same file and the old data are lost.

The data acquisition system described here enables each FBG spectrum to be acquired in a time of 11 seconds.