The use of a CFBG sensor for detecting damage in composite laminates and adhesively bonded joints

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Abstract

Reliable in-situ damage detection techniques which can determine the existence and location of damage in composite materials and structures are critical for the effective use of these materials. In this work, embedded chirped fibre Bragg grating (CFBG) sensors have been shown to be successful for both detection and location of matrix cracks in composite laminates and disbond detection in bonded composite joints. In all the cases, the CFBG reflection spectra were predicted using commercial software and agreed well with the experimental results.

In the matrix cracking work, single matrix cracks in cross-ply GFRP (glass fibre reinforced plastic) laminates were detected and located using a CFBG sensor embedded within the $0^\circ$ plies, near the $0/90$ interface. The CFBG sensor showed an approximately sinusoidal variation of the intensity of the reflected spectrum at the position of the crack, enabling both crack development and crack position to be identified. It was shown that the precise position of the cracks does not correspond with the bottom of a dip in the reflected spectrum, as has previously been thought.

Disbond initiation and progression from either end of a composite bonded joint was monitored by embedding the CFBG sensor in one of the GFRP adherends, with the low wavelength end of the sensor positioned at the cut end of the adherend. A shift in the low wavelength end of the spectrum to lower wavelengths indicated disbond initiation and movement of a perturbation in the reflected spectrum towards higher wavelengths indicated disbond propagation. In a related fashion, disbond initiation and propagation was detected from the high-wavelength end of the spectrum (adjacent to the other cut end of the adherend). With the aid of a parametric study based on a closed-form solution for the strain field in the bonded joint (available in the literature), it has been shown that the sensitivity of the CFBG sensor in detecting the disbond depends mainly on the position of the sensor within the adherend and the strain distribution in the adherend. Finally, artificial manufacturing defects were introduced into GFRP-GFRP bonded joints using Teflon inserts and it has been demonstrated that the location of the defects is possible using the CFBG technique.
Author’s Publications


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To my husband Sakthivel and son Kabilan
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1.1. COMPOSITE MATERIAL: AN INTRODUCTION

Polymer matrix composite materials are increasingly being used for different types of structures. For example in aerospace, they are widely used for radome, wing leading- and trailing-edge panels and stabilisers. The new Boeing B787 is incorporating composite material in the fuselage, a first for commercial jets, and will be using more than 50% (by weight) of composite material (see Figure 1.1) [Seattlepi news]. In the marine area, Mirabella V is the world’s largest single-masted yacht made with composite materials weighing 740 tonnes and measuring 75 metres in length. In the automobile sector, Ford produced a car almost entirely from carbon fibre composite in 1979. In the energy production sector, the largest wind turbine blade manufactured by LM Glasfiber is made of composite materials and produces 5 MW power.

Composite materials essentially consist of two main constituents: a low modulus, low strength matrix material and a high stiffness, high strength reinforcements. These distinct phases are combined on a macroscopic scale to produce a heterogeneous composite with desirable characteristics that exceed those of the individual components. Matrices include metals, ceramics and plastics and they serve to bind the fibres together, transfer...
loads to the fibers and protect them against environmental attack and damage due to handling. Reinforcements are the principal load-bearing elements. Reinforcements basically come in three forms: particulate, discontinuous fibers and continuous fibers. Composite’s properties are best in the direction of the fibers. Perpendicular to the fibers the matrix properties dominate because load must be transferred by the matrix. As most structures are not loaded in a single direction, even though one direction may dominate, it is necessary to orient fibers in multiple directions. This is accomplished by stacking multiple plies together called a laminate. The type of composites that are used for advanced applications such as marine, aircraft, automobile application, as well as load bearing structural parts, are continuous long fiber polymer matrix composite laminates and therefore those are the ones that are going to be highlighted in this thesis.

Cross-ply composite laminates, with individual plies at angles of 0° and 90°, often exhibits several distinguishing modes of deterioration such as transverse matrix cracks, delamination and debonding of fibres preceding final fracture under loading. Matrix cracking is the first stage of damages and though it is not catastrophic in nature, its presence can influence the overall mechanical behaviour of the structure [Mahi et al., 1995; Berglund et al.,1992]. The existence and multiplication of matrix cracks can degrade the life of the structure by introducing other more severe damage such as delamination and fibre breakage [Berglund et al., 1992; Guild et al., 1993].

Joining composite to composite and composite to metal using adhesives are an attractive alternative to mechanical fasteners and are increasingly accepted in safety critical applications, such as those in automotive and aerospace structures. Adhesive bonding of composite structures is considered superior to mechanical fasteners for cost saving, weight reduction and the stress distributed over the entire bond area [Baker et al., 2004; Adams and Comyn, 2000]. The serious concern with these adhesively bonded joints is disbond initiation and growth in either quasi-static loading or cyclic (fatigue) loading. As the structural demands on these joints have increased, the need for reliable NDE (non destructive evaluation) techniques and knowledge of damage tolerance has also increased.

1.2. OBJECTIVES OF PRESENT WORK

Determining the existence, location and extent of damage in such composite materials is of great importance. Inspection of such structures in the past has been based mainly on conventional non-destructive evaluation techniques. These techniques are often
difficult to use for in-service inspection of large components and they do not necessarily provide a quantitative measure as to the extent of the damage. Consequently new techniques are sought and structural health monitoring (SHM) of composite structures using fibre Bragg grating (FBG) sensors is a promising and cost-effective solution compared to regularly scheduled inspections. It is an advantage that such sensors can provide information on the health of the structure not only during the in-service life of the structure, but also during its manufacture.

Fibre Bragg grating sensors with a uniform grating spacing have been used to detect various types of damage in composite materials and structures. Much research has been done to detect the transverse matrix crack, the earliest form of macroscopic damage in composite laminates, by the use of a uniform FBG but it is observed that they could not identify the exact location of this damage [Okabe et al., 2004]. Furthermore uniform FBGs were also used to detect disbond in bonded joints and repairs [McKenzie et al., 2000; Jones et al., 2002; Li et al., 2004; Herzsberg et al., 2005; Marioli-Riga et al., 2005; Takeda et al., 2004; Minakuchi et al., 2007], but this method cannot easily detect both the initiation and the growth of a disbond. For these reasons the recent work has utilised an embedded chirped FBG (CFBG) sensor, whose grating period increases linearly along the length of the grating thereby producing broad range of wavelength, for the detection and location of the transverse crack in the laminated composites and the initiation and propagation of disbond in the single lap bonded joint. The work was also extended to the detection of a defect caused during manufacturing of the bonded joint. Experimental, analytical and modelling studies were undertaken for the in situ detection of damage in composite materials with the great potential of CFBG sensors demonstrated in order to obtain information on the presence of damage, its size, and its location.

1.3. THESIS STRUCTURE

The structure of the thesis is as follows: Chapter 2 is the literature review which gives an insight into the damage in composite materials and structures, in particular to transverse matrix cracking in laminated composites and disbond in single lap bonded joints; non-optical damage detection methods and optical techniques with the main focus on FBG and CFBG sensors for the damage detection. Chapter 3 gives information on the background theories of the study undertaken and the tool used for the studies. Chapter 4 describes the material fabrication and methods of experimentation. Chapters 5, 6 and 7
relate to the main experimental studies conducted in this work and each provides the results and discussion of the experiments, modelling and predictions. Chapter 8 reports on the parametric study undertaken to determine the factors affecting the sensitivity of the sensor in locating the defect. Chapter 9 presents the work undertaken to detect the manufacturing defect in bonded joints. Finally Chapter 10 summarises the major conclusions from the study and then presents the direction for further work in this area.
2.1. INTRODUCTION

Fibre reinforced polymer (FRP) composites are finding increased usage in structural applications, in particular for aerospace, marine, construction and automotive purposes. Figure 2.1 represents the usage of polymer matrix composites over the past few decades by aircraft companies including Airbus and Boeing [EATS 2007 report]. One of the critical issues in these applications is the long term behaviour of FRP laminate/structures and the associated damage and failure mechanisms under quasi-static or fatigue loading. In this chapter a brief review of the existing literature concerning damage and damage detection in cross-ply composite laminates, particularly transverse matrix cracking damage in cross-ply laminates, and damage in composite bonded joints, particularly disbonding is presented. In the next section, matrix cracking damage is introduced followed by an introduction to adhesively bonded joint damage in the subsequent section.

![Figure 2.1: Usage of composite materials in various aircraft over the past few decades [EATS 2007 report].](image-url)
2.2. DAMAGE IN COMPOSITE MATERIALS AND BONDED STRUCTURES:

2.2.1. Matrix cracking damage

A composite laminate can display three major macroscopic damage modes: matrix cracking in 90° plies, delamination between 0° and 90° plies and fibre fracture [Berthelot et al., 1996; Mahi et al., 1995; Berglund et al., 1992; Garrett and Bailey, 1977; Wang, 1984]. Figure 2.2 shows the various damage modes occurring in cross-ply composite laminates. Of these, matrix cracking is generally the first type of damage observed easily and it has been much studied, particularly in cross-ply composite laminates [Mahi et al., 1995; Berglund et al., 1992]. As the transverse cracks are easily visible in transparent glass-fibre reinforced epoxy laminates, many studies on transverse cracking development have concentrated on these laminates [Parvizi et al., 1978; Ogin et al., 1985]. The transverse cracks initiate when the applied strain is above a threshold value and this threshold strain value depends upon the transverse ply thickness, stacking sequence and the material properties of the laminate [Berglund et al., 1992; Garrett and Bailey, 1977]. Garret and Bailey (1977), for example, have shown that the threshold strain value for initiating the transverse cracks is lower for a 2.6 mm transverse ply thickness than for a 0.75 mm thick transverse ply with the same 0° plies.

Different crack growth behaviour was observed in cross-ply laminates under quasi-static or fatigue loading. In the case of quasi-static tensile loading, cracks initiate at the free edges of the specimen for thick transverse plies and propagate instantaneously along the thickness and width of the transverse ply [Berthelot et al., 1996]. Parvizi et al. (1978) observed that in thin transverse cross-ply laminates, the cracks initiate at the free edges of the specimen but grow slowly with increasing strain before finally spanning the full width of the transverse ply. Garrett and Bailey (1977) observed that, under quasi-static loading for glass fibre reinforced polyester specimens; the crack spacing was uniform and decreased as the applied stress increased. The crack density increased until it reached a limiting value which depends on the transverse ply thickness at higher applied stress. Wang (1984) suggested in work on carbon cross-ply laminates, that there is no saturation stage for the crack density as was observed for glass fibre laminates, and that the fracture of the 0° plies at high strain interrupts the development of additional transverse cracks.
In the case of fatigue loading, transverse cracks initiate from the free edges in thick transverse plies and grow slowly across the width of the specimen as the number of cycle is increased [Berthelot et al., 1996; Boniface and Ogin, 1989]. The crack density increases with increasing cycles [Berthelot et al., 1996] and the crack growth rate is a function of the stresses in the fatigue cycles, with higher stress leading to higher growth rate [Boniface and Ogin, 1989]. The crack density not only depends on factors such as the number of cycles, laminate lay-ups, stress amplitude, but also on the temperature. Sun et al (2003), for example studied cross-ply laminates in fatigue (tension-tension) loading at both room (24° C) and high (149° C) temperatures with a stress ratio of R=0.5 at 4 Hz. They observed that the crack density increases rapidly at higher temperature leading to a lower life compared to the laminate, at the same normalised stress level, at room temperature. The crack spacing is not uniform in fatigue loading as observed in static loading; see Figure 2.3 [Berthelot et al., 1996; Boniface and Ogin, 1989]. Boniface and Ogin (1989) observed that the crack growth rate decreases with decreasing crack spacing and there occurs crack arrest when the crack spacing is reduced to about half the transverse ply thickness.

The development of transverse cracks either under quasi-static loading or fatigue loading causes residual strain to develop upon unloading (i.e. a permanent small spacing
extension of the specimen occurs) [Bassani et al., 1998] and results in a lowering of the material properties such as stiffness [Berthelot et al., 1996; Ogin et al., 1985; Tong et al., 1997]. For example, Bassani et al. (1998) observed a residual strain of 85 με for a single matrix crack, with increasing residual strain as the crack density increases. In case of stiffness reduction, the stiffness of the specimen decreased progressively when the transverse cracks developed. Ogin et al (1985) have shown three stages of the stiffness reduction in a [0/90] laminate, the first stage being an initial rapid modulus reduction followed by much slower reduction and finally rapid fall off just prior to failure. The amount of reduction depends on the transverse ply thickness, the stacking sequence and the material properties. For example, Garrett and Bailey (1977) observed a greater stiffness reduction for a glass fibre laminate with a thicker transverse ply (0/90/0) than a laminate with thinner transverse ply (0/90/0). Berthelot et al. (1996) reported that the stiffness reduction in a glass epoxy laminate is more than that for a carbon epoxy laminate due to a large ratio of transverse ply modulus to longitudinal ply modulus. Mahi et al. (1995) studied the influence of stacking sequence by finite element analysis on the stiffness reduction for a (0/90), specimen where the total thickness for each ply was the same but the specimen differ in their 90° ply arrangements. The authors observed that the stiffness reduction starts within the first hundred cycles for the (0/90), but only at about $10^3$ to $10^4$ cycles for the (0/90/0),. Moreover the stiffness reduction was more for the (0/90), at about 0.5% compared to the (0/90/0), at about 0.15%.

Though the presence of matrix cracks does not lead to catastrophic failure, they do promote secondary damage modes in composites such as delamination and fibre breakage [Berglund et al., 1992; Guild et al., 1993; Takeda at al., 2007]. Transverse cracking also provides an easier pathway for moisture ingress [Berthelot, 2003]. Moreover matrix cracking is often used as the design criteria for certain critical applications such as (i) fluid and/or pressure vessel design, and (ii) the design of aerospace structures. In these applications, the presence of matrix cracks constitutes failure since the structural integrity of the structure is compromised by the matrix cracking. Matrix cracks in pipes/pressure vessels can lead to leaks and, in composite laminates, to delamination and fibre fracture. Hence, early detection of damage could avoid complications and it would be beneficial to have an in-situ continuous monitoring system which would monitor the growth and location of the damage in a composite structure.
2.2.2. Damage in adhesively bonded composite joints:

Adhesive bonding is the most common means of forming joint used in composite manufacturing and maintenance (repair). The advantages of an adhesive joint over the other mechanical joints [Barnes and Pashby, 2000; Baker et al., 2004; Adams and Comyn, 2000] include:

i. ability to join dissimilar materials thereby avoiding galvanic corrosion
ii. continuous bond formed such that stronger and stiffer structures are often produced
iii. reduced weight and part count
iv. more uniform stress distribution achieved on loading thereby avoiding local stress concentrations
v. small areas bonded accurately and large areas bonded without inducing stresses
vi. no/little finishing is required
vii. smooth appearance as there are no protruding fasteners such as screws, rivets, and spot-welding marks, and
viii. does not distort the components being joined

Composite-composite or composite-metal bonded joints have found applications in various areas from high technology industries such as aerospace, marine, and automotive to traditional industries such as construction, sports, health and packaging [Barnes et al., 2000; Baher et al., 2004; Marcadona et al., 2006; Adams and Wake, 1984]. Adhesively bonded FRP composite are also widely used in the repair and rehabilitation of steel buildings and bridges [Matta et al., 2006] and as patches for repair of aircraft structures [Koh et al., 2003; Chiu et al., 2000]. With this wide increase in the usage of adhesive bonding, various methods for the evaluation and testing of the structural integrity and quality of bonded joints have been widely investigated and developed. The major factors affecting the integrity of the adhesive bonded joints include geometry/material of the adherends/adhesive, load magnitude/direction, fatigue properties and varying environments [Papini et al., 1994, Ashford et al., 2001]. There are many different joint geometry (see figure 2.4), among which the most commonly used are single-lap joints, double-lap joints, scarf joints and step-lap joints [Baker et al., 2004]. Of particular importance to this work is the behaviour of single lap joints and the stresses developed in single lap joints are explained in Chapter 3.
Defects and damage in adhesive joints occurs either at the adherend-adhesive interface or within the adhesive layer itself, during manufacturing or in-service. For example in the yachts used in the America cup races, whose hull and mast are made of CFRP sandwich composites, the critical damage is caused by skin-core debonding and debonding between structural members [Murayama et al., 2003]. Moreover, QinetiQ (2006) has reported that, in a survey conducted in the European Framework IV project ‘MONITOR’ to determine the damage forms that the end users are of most concerned about in composite structures, 59% of end users have reported for disbond detection (these end users are in aerospace, defense, research organizations and manufacturers). Hence, the majority of nondestructive testing performed on bonded structures is aimed at detecting disbonding and other forms of defect such as voids or porosity [Summerscales, 1990]. The term disbond here is defined as a separation of the composite material from another material to which it has been adhesively bonded such that it will not transfer load from the adherend to another through the adhesive.

Disbond during manufacturing could occur due to the presence of contaminants on the adherend, inclusion of release film, poor process control and poor release procedure. Disbonding during service could be due to impact, fatigue loading and environmental degradation. Disbonds provide a site for fatigue crack propagation and hence will lead to premature failure in structures [Adams and Wake, 1984]. The disbond also allows moisture to penetrate into the joint [Schindel et al., 1997]. Hence, a reliable non-destructive
inspection technique which could detect the initiation and growth of the disbond failure at an early stage would be effective.

2.3. NON-OPTICAL DAMAGE DETECTION METHODS IN COMPOSITE MATERIALS AND STRUCTURES:

Damage detection in composite materials and in adhesively bonded composite joints is extremely important and it still often remains a difficult problem to detect damage easily. Damage such as matrix cracks and delamination within the composite, and disbonding within joints, are difficult to detect and yet can potentially lead to catastrophic failure. For adhesively bonded structures, damage is even more difficult to detect due to the complexities of geometric details and loading. Being able to definitively detect damage is an area that needs further research for obvious reasons related to safety, performance, and cost [Baker et al., 2004]. Types of non destructive testing (NDT) for composite materials and bonded joints originated from the processes developed for investigating metallic materials. However composite materials being heterogeneous, anisotropic in mechanical and physical properties, having poor electrical conductivity and low thermal conductivity has the consequence that only a few methods used for metallic structures in industry are applicable to composite structures.

2.3.1. Cross-ply matrix cracking damage detection

Damage in crossply composite laminates, particularly matrix cracking, has been studied by various means. For example, visual methods have often been used to detect matrix cracking in glass fibre reinforced composite components if they are transparent [Ogin et al. 1985; Ussorio, 2006] although this method is not suited for opaque composites such as carbon composites (of course, matrix cracking detection using a visual technique is not possible for structures that are painted). The edge replication technique [Ogin et al., 1985] and optical microscopy [Berglund et al., 1992, Tong et al., 1997] have been used to determine crack density in composites. These techniques are ideal only for laboratory specimens and cannot be used for larger structures. They suffer from the fact that the load must be interrupted periodically and the component has to be removed from the testing regime for each measurement which further adds to the time required to complete a test. Removing the specimen may induce artifacts in the results due to alignment problems in re-gripping the specimen. Transverse cracks was also evaluated indirectly by measuring
residual strain, stiffness reduction and Poisson's ratio reduction for the laminate [Ogin et al., 1985; Tong et al., 1997; Bassam et al., 1998]. Other direct experimental NDT techniques used for damage detection in composite laminate with different sensitivity levels are dye penetrant X-ray radiography, ultrasonics and acoustic emission [Sun et al., 2003; Noh et al., 2002; Crossman et al., 1980; Prosser et al., 1995; Jong, 2006; Summerscales, 1990; Gorman, 1991].

Penetrant-enhanced X-radiography, which utilizes a radio-opaque liquid (e.g. Zinc iodide, di-iodomethane) to infiltrate the examined area, was used to detect matrix cracks in composites [Sun et al., 2003, Noh et al., 2002; Crossman et al., 1980]. The main drawback of this technique is that it can resolve only damage connected to the surface, while internal defects (impossible to fill with the dye) may remain undetected [Maslov et al., 2000]. The other drawbacks include large and costly equipment, cannot be used for in-situ inspections (needs the component to be removed for inspection), requires access to both sides of the surface in order to emit and collect the X-ray radiation and there is a danger of radiation exposure.

Through-transmission or pulse-echo ultrasonic techniques [Maslov et al., 2000; Noh et al., 2002] are most sensitive to flaws that lie parallel to the surface (e.g. delaminations), but cannot detect damages lying perpendicular to the surface (matrix cracks) because the cracks do not offer a wide enough reflecting surface as delaminations. The ultrasonic polar backscattering technique [Gorman, 1991] was successfully used to detect transverse cracks running parallel to the fibre direction, in specimens manufactured with simple lamination sequences, when loaded in tension. In the polar back scattering technique the transducer was oriented at an angle to the tested surface so as to acquire the energy backscattered from damage, and the high-frequency mechanical oscillations were used for the detection of damage mechanisms. The drawback in these techniques include the fact that water usually needs to be used as a couplant, often needs access to both sides of the structure, cannot be used for in-situ inspections and needs expert interpretation.

Acoustic emission [Prosser et al., 1995 (a); Prosser et al., 1995 (b); Jong, 2006] involves the detection of the energy released by the material whilst under stress where cracking events are detected using acoustic receivers such as microphones or piezoelectric sensors. The method proves very efficient for monitoring structures in service but a precise identification of the size, shape and location of any flaws is not possible in composite materials due to their anisotropy. Moreover, the data produced can be complicated to
interpret and, for thinner laminates, the AE signals from cracks are not always detected successfully [Prosser et al., 1995 (b)].

2.3.2. Damage detection in adhesively bonded composite joints:

Damage detection techniques for adhesively bonded joints and repairs also include ultrasonic, acoustic emission, radiography and thermography techniques [Adams and Drinkwater, 1997; Lowe et al., 2000; Thomas et al., 1998; Meola et al., 2004]. Of the various methods available for monitoring the integrity of bonded composite joints, ultrasonic methods are generally regarded as potentially the most useful [Adams and Drinkwater, 1997]. Conventional ultrasound C-scan is time-consuming and expensive, with the result that emphasis has been placed on developing techniques that extend the range over which a given transducer can detect damage, though some types of debonding (e.g. kissing bonds and interlayer defects) are difficult to detect with these techniques. The other main problem with conventional ultrasonic methods is the need for a liquid couplant between the transducer and test structure. This often makes ultrasonic methods cumbersome, since the test object must be immersed in a water bath (which is not a practical option for aircraft), and some materials (such as polymer-based composites) can be affected or damaged through absorption of the liquid. As a result, various non-contact ultrasonic transducers such as air and laser ultrasonic have been investigated for the detection of disbond in bonded joints [Schindel et al., 1997; Adams and Drinkwater, 1997]. However these ultrasonic techniques also have the limitations of the time, require direct access to joint area and require skilled labour [Lowe et al., 2000].

Acoustic emission (AE) techniques are used to detect the damage in the bonded joints by positioning piezoelectric transducers on the surface of the structure to record the stress waves emitted by the damage. For example, Matta et al (2006) studied the use of acoustic emission signals to monitor disbond in the CFRP-steel bonded joints under load using two acoustic piezoelectric transducers operating at a frequency of 200-750 kHz. They noted that the acoustic parameters such as signal counts, amplitude and energy increased significantly once the disbond initiated, and continued until the CFRP patches separated from the steel bar. They concluded that these acoustic emission parameters provided valuable data for correlating acoustic emission signals and bond damage progression. The analysis of the acoustic emission data also provided the basic information for identifying
the damaged area location. The disadvantage of the technique lies in the complexity and accuracy of data interpretation.

An example of the use of a thermographic technique is by heating one surface of a bonded structure and observing the temperature rise of the opposite face. The areas of disbond which resist the transfer of heat, show as cool areas [Thomas et al., 1998]. Alternatively, if the heated face is scanned, disbands will show as hot areas. Temperature sensing is normally detected with a scanned infrared camera. The success of using the thermographic technique depends on the thermal characteristics of the material (thermal conductivity and thermal diffusivity) and there is a limitation on the depth of the damage and the resulting size resolution.

Backface strain measurement is another technique for monitoring disbond growth [Crocombe et al., 2002]. Crocombe et al (2002) used this technique to monitor disbond growth caused during fatigue loading in an Al-GFRP bonded joint. In this technique, the strain is measured by locating a strain gauge on the exposed adherend surface (backface) adjacent to the site of the adhesive damage in the bonded joint. The technique was based on the strain distribution in single lap joints and detected the fatigue crack initiation by the increase in local strain. This technique has the potential to determine both the fatigue crack initiation and the position of the crack initiation. But the limitations arise from the lack of a convenient backface in many joint configurations.

The NDE techniques, mentioned above, are either expensive, time-consuming, complicated to interpret or difficult to use for complex geometries. For most of these techniques, with the exception of acoustic emission and thermography, the testing must be interrupted and the component must be removed from test setup or from service location to perform the damage evaluation i.e. they are not suitable for on-line damage monitoring. Moreover the key location of the inspection is the edge of the bonded joints and this is almost impossible to achieve with the existing methods, other than optical methods. The challenges for the use NDT in industrial circumstances are provided by a recent high profile case study. After the investigation of the crash of an Airbus A300 (American airlines 587), where the 27-foot high tail fin tore off, the National Transportation Safety Board (NTSB) stated that current inspection methods may be inadequate to spot damage and recommended even tighter non-destructive inspections on aircraft [National transportation report, 2004]. The damage in this A300 had gone undetected despite undergoing its routine inspection involving ultrasonic, eddy current and visual NDI methods such as radiography. Hence,
new in-situ NDI techniques need to be developed, and sensors based on optical fibres may present the way forward.

2.4. OPTICAL DAMAGE DETECTION METHODS IN COMPOSITE MATERIALS AND STRUCTURES

The technique of using optics as a measuring tool has been reported for more than a century but the current technique of optical sensing had its birth only within the past few decades due to the development of low loss, optical fibre waveguides for the telecommunication industries. Recent innovations in fibre optic instruments combined with cost advantages have significantly increased their utility and demand as a sensor in construction, aerospace, healthcare environments and defence and security [Merzbacher et al., 1996, Badcock et al., 1995; Park et al., 2000; Lee et al., 2001; Steward et al., 2003; Kageyama et al., 1998].

2.4.1. Optical fibre sensors (OFS):

The following section provides an introduction to optical fibre sensors before focussing on fibre Bragg gratings (FBG). Fibre optic sensors are one of the fastest growing areas of light-based sensors technologies. They offer significant advantages such as insensitivity to EMI (electro magnetic interference), small size, light weight, non-conductive, fast response and resistance to corrosion [Merzbacher et al., 1996]. In general, fibre optic sensors may be categorised under two headings, extrinsic sensors and intrinsic sensors. Extrinsic sensors are those where the light leaves the feed or transmitting fibre to be changed before it continues to the detector by means of the return or receiving fibre. Intrinsic sensors are different in that the light beam doesn’t leave the optical fibre but is changed whilst still contained within it [Merzbacher et al., 1996]. OFS can be classified based on the optical properties been altered, they are intensity based sensors, interferometric sensors, polarimetric sensors and wavelength based sensors [Merzbacher et al., 1996]. Michelson and Fabry-Perot (F-P) interferometer sensors are typical of interferometric sensors and the fibre Bragg grating is a wavelength based sensor. It is not the intention to write a review of all of the sensors available, but a few will be discussed in this chapter.

The fibre optic sensors are used either surface mounted or embedded to monitor the physical parameters and damage in composites. Though surface mounting sensors have the
ease of installation, the optimum use of these sensors is obtained by embedding the sensor in the composite itself, since they can then provide a more accurate measurement of what is occurring in the material [Betz et al., 2003; Lau et al., 2001]. Betz et al (2003) for example, studied the various methods of attaching the fibre sensors such as surface mounting, structural integration (embedding into the host material) and surface integration (surface mounting but protected by a varnish on the structures) for successful structural monitoring and concluded that the most satisfactory solution suitable for FRP composites is by structural integration.

Embedding sensors could lead to complications and the interaction between the optical fibre and the host composite and has been studied by various authors to try to understand the response of the optical fibre due to embedding and the response of the structure to the presence of the fibre. For long term structural monitoring using an optical fibre sensor, the effect of such sensors on the strength, stiffness and fatigue life of composite is important. Contradictory results, ranging from an improvement to a slight degradation in the mechanical performance of composites have been described [Lau et al., 2001; Okabe et al., 2002; Lee et al., 1995; Benchekchou et al., 1998; Zhang et al., 2003]. The laminate layup, the number of embedded sensors, the embedding direction of the sensors and their type of coating (bare fibre, acrylate coating etc.) influences the results. Lau et al. (2001), for example, observed a reduction in the strength of the composite laminate when the optical fibres were embedded perpendicular to the loading direction. With regards to coatings, Okabe et al (2002) have calculated that the reflection spectrum from coated embedded FBG sensors should be almost the same as the reflection spectrum using uncoated sensors. Lee et al. (1995) observed no significant changes in the strength, stiffness and Poisson’s ratio of GFRP laminates containing embedded optical fibres and observed the same mechanical behavior for unidirectional and cross-ply laminates with different numbers of embedded sensors. However for fatigue loading they observed that fatigue life decreased with an increasing number of embedded optical sensors. In contrast, few authors [Badcock et al., 1995; Benchekchou et al., 1998] showed that embedding optical fibres in composites does not alter the fatigue behavior and that Benchekchou et al. (1998) showed that embedding optical sensors within 0° orientation plies leads to better fatigue behaviour than embedding them within 45° plies. Lee et al. (1995) have also shown that the matrix crack damage accumulation was not affected by the embedded optical fibre both for static loading and for cyclic loading. With some exceptions, overall it can be said...
that the inclusion of a single optical sensor causes no, or only very little strength/stiffness degradation when embedded parallel to the reinforcing fibres [Lau et al., 2001; Zhang and Tai, 2003].

Optical sensors of different types can sense a variety of physical and chemical effects and are used in various industries and a number of applications (see Table 2.1). For example, Culshaw et al (1996) have explored the use of various fibre optic sensors to measure physical and chemical parameters such as strain, temperature, corrosion and pH in the construction industry. Lee (2003) presented a pie chart (Figure 2.5) on the distribution of papers at 15th optical fibre sensor conference, 2003 for various measurands of interest. The majority of OFS sensor use is focused on strain and temperature monitoring studies [Badcock et al., 1995; Lee et al., 2001; Steward et al., 2003; Kageyama et al., 1998; Betz et al., 2003; Lau et al., 2001].

Table 2.1. Use of optical fibre sensors in monitoring composite structures [Culshaw et al., 1996; Badcock et al., 1995; Park et al., 2000; Lee et al., 2001; Steward et al., 2003; Kageyama et al., 1998; Betz et al., 2003; Lau et al., 2001; Rao, 1999]

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<td>Marine</td>
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In addition to measuring physical and chemical parameters, fibre optic sensors have emerged as a recent technique to detect damages in composite laminates/structures. For example, intensity based optical fibre sensor (IBOF) fabricated with two lengths of optical fibres with a reasonable gap between two cleaved ends have been used for fatigue damage detection in a CFRP laminate [Badcock et al., 1995]. The principle of the operation in this IBOF depends on the output intensity change when the gap between the cleaved ends changes due to strain change as the result of damage in the host. Plastic optical fibres sensor, a multi-mode fibre in which core is made of polymer material, were used to detect the damage (transverse cracks) by measuring the optical power loss in unidirectional and cross-ply GFRP laminated composites [Takeda et al., 1999]. In the plastic optical fibre sensor, the optical power decreased linearly as the strain increased before the initiation of transverse cracks, but the optical power decreased nonlinearly when the cracks appeared. Work on polarimetric sensors to detect the transverse crack under quasi-static loading were done by embedding the sensor at 0/90 interface of GFRP coupon [Wang et al., 2006]. Polarimetric fibre optic sensors are highly birefringent (HiBi) fibres which transmits orthogonally polarized components of light with different velocities. The principle of this sensor utilizes the differential delay between the two orthogonally polarized modes propagating in the optical fibre to detect the applied external perturbation of interest (e.g. strain, temperature, pressure etc). A step change in the optical output of the polarimetric sensor is noted by the authors when a transverse crack passed the sensor. With respect to damage detection in bonded joints, surface mounted fibre optic interferometric sensor was
proposed to detect the disbond in a concrete structure, an aluminium plate and a composite plate when repaired by CFRP [Xu et al., 2005]. The principle of detection is that when the quasi-impulse loading is applied to the repaired material containing the surface mounted sensor, the optical phase shift that is proportional to the integral strain along the fibre is different to that of a perfect bond. Integral strain is the total length change that occurs in the optical fibre. There occurs a perturbation in the plot of fibre integral strain vs. load position. The difference depends on the extent of the debonding, the relative position of the debonding and the load applied.

2.4.2. Fibre Bragg gratings (FBG) – uniform and chirped FBG:

A sensing device of considerable current interest in the fibre optic community is the FBG because of its distinguishing advantages over other fibre optic sensors such as self-referencing, smaller size than other FOS and unique wavelength multiplexing capabilities [Lau et al., 2001; Botsis et al., 2005]. Figure 2.6 shows a second pie chart by Lee (2003) on the distribution of papers according to type of optical techniques in the 15th optical fibre sensors (OFS-15) conference in 2003. This pie chart clearly shows the interest in investigating the capabilities of fibre Bragg grating sensors.

A fibre Bragg grating sensor consists of a periodically varying refractive index that is written into the core of a germanium doped single mode optical fibre [Erdogan, 1997; Othonos A, 1997; Kersey et al., 1997]. When a broadband light is coupled into the optical fibre sensor, a reflection peak is obtained, centred on a wavelength called the Bragg-wavelength (see Figure 2.7(a)). The Bragg-wavelength depends on the refractive index and the period of the grating. Further details are provided in Chapter 3. As described in previous sections, such optical sensors can be embedded readily into structures without influencing the mechanical properties of the host material due to their relatively small size [Lau et al., 2001].
FBG sensors are sensitive to both strain and temperature changes and typical strain and temperature sensitivities of FBG sensors at different wavelengths are shown in the Table 2.2 [Rao, 1997]. Changes in strain or temperature will result in a change of the grating period and refractive index of the Bragg grating and hence shift the Bragg wavelength of the reflected light thus providing valuable information for monitoring strain, temperature or damage in structures [Botsis et al., 2005; Lau et al., 2001; Guemes et al., 2002; Kuang et al., 2001; Gebremichael et al., 2005; Takeda et al., 2002; Moyo et al., 2005]. Lau et al. (2001) measured the internal strain of a composite strengthened concrete structure at different locations using a single optical fibre with multiplexed FBG sensors. Some of the real time and in situ applications of FBG sensors for strain and temperature monitoring includes a yacht, *Jacquelinia*, fitted with 60 FBG sensors in its 38 m free standing mast and boom for the long term monitoring of the strain [King., 2001]; *West Mill bridge*, (Oxfordshire, UK), Europe’s first all fibre reinforced road bridge, embedded with 40 ruggedly protected FBGs to monitor traffic loading and environmental temperature at
various locations along the structure [Gebremichael et al., 2005] and the structural health monitoring of various rehabilitated bridge structures in Canada (such as Beddington Trail bridge, Alberta; Salmon River bridge, Nova Scotia; Taylor bridge, Manitoba) using FBG sensors (both surface mounted and embedded) [Tennyson et al., 2001].

FBG sensors have also been used for cure monitoring of composites. For example, Kuang et al (2001) demonstrated the method of monitoring the cure in composites using FBG sensors to monitor the residual strains. They measured the residual strains from the embedded FBG within carbon epoxy and glass epoxy composite and fibre metal laminate by the shift in the peak Bragg wavelength of FBG sensor. The peak wavelength shifted towards the higher wavelength in unidirectional, quasi-isotropic and angle ply laminates but the shift towards lower wavelength in cross-ply laminates due to various matrix shrinkage during polymerization and thermal shrinkage during cooling based on their stacking sequence. They also observed a single well defined peak of FBG spectra for carbon fibre/epoxy unidirectional [0/45(FBG)/0] laminate, but splitting of the FBG spectra into multiple peaks, and broadening of the width of the FBG spectra, in angle ply glass fibre/epoxy [(45/-45)2(FBG)/(45/-45)] laminate composites. They suggested that the splitting of FBG spectra in the angle ply composite is due to the non-uniform loading. It is likely that this is giving rise to a birefringence effect. In addition to these, uniform FBGs are used for monitoring damage in composite materials and structures and these are presented in the next section.

In addition to uniform FBG sensors, there are other types of FBG sensors [Erdogan, 1997; Othonos A, 1997; Kersey et al., 1997], of which the chirped FBG (CFBG) is used in this work. Unlike the uniform FBG, whose grating period is constant throughout, the chirped FBG has a grating period which changes linearly with position (Figure 2.7). This linear change in the grating period reflects a different wavelength at different points along the fibre length and hence reflections occur over a spectral band of wavelength (further details are given in Chapter 3). This relationship between the reflected spectrum and physical distance along the sensor is very useful for investigating the position of changes in strain, temperature, pressure and damage.
Tjin et al (2003) used CFBG sensors embedded in composites to sense and locate local pressures in the range 0 - 30 N along the length of sensor. The effect of pressure was observed from the change in shape of the CFBG reflected spectrum (dips and peaks) at a certain wavelength. The shape change at the certain wavelength showed an increased reflectivity when the magnitude of applied pressure was increased and the shape change at certain wavelength varied linearly with the point of application of the pressure. This effect was used by Swart et al (2005) to monitor the magnitude and the position of oesophageal pressures in a medical application using CFBG sensor. Nand et al (2006) demonstrated the use of CFBG sensors for detecting and positioning a localised temperature change. The temperature change was identified and located from the change in the shape of the reflection spectrum (reduction in reflectance at shorter wavelengths and the corresponding increase in reflectance at longer wavelengths) at a particular wavelength. Gillooly et al (2004) presented a surface mounted CFBG sensor as a wear sensor. There is a reduction in
the bandwidth of the reflected spectrum due to abrasive removal of the gratings with the higher spacings. Hence this sensor can be employed in monitoring the wear on a car brake, the wear in combustible environments such as those in the oil and gas industry etc. Recently a CFBG sensor was proposed as a self-temperature referenced strain sensor in non isothermal thermoset processing by partially embedding the CFBG sensor in a thermoset resin [Cusano et al., 2006]. The embedded part of the sensor monitors both the temperature and the strain during curing of the resin while the free part of the sensor monitors only the temperature changes. A number of papers have been concerned with the use of CFBGs for monitoring damage in composite materials and structures and these are presented in the next section.

2.4.3. DAMAGE DETECTION USING FBG

2.4.3.1. Damage in composite laminate

FBGs are currently the most widely studied type of fibre optical sensors. Two diameters of uniform FBG sensors have been used: normal diameter FBG and small diameter FBG sensors. The core, cladding and outer diameter of the normal diameter FBG are 9 μm, 125 μm and 250 μm respectively and the core, cladding and outer diameter of the small diameter FBG sensors are 6.5 μm, 40 μm and 52 μm respectively [Okabe et al., 2002]. Both diameter sensors have been used for monitoring damage in composite materials such as transverse cracks and delaminations [Ussorio et al., 2006; Takeda et al., 2002; Okabe et al., 2000; Okabe et al., 2002; Murayama et al., 2003; Takeda et al., 2007]. Okabe et al (2002) have suggested that using small diameter FBG sensors will minimise any mechanical property variation due to the embedding of sensors. Considering the results using normal diameter sensors, multiple transverse cracks in CFRP were detected by embedding uncoated normal diameter FBG in the 0° ply close to the 0/90 interface. They observed the FBG reflection spectrum upon increasing tensile stresses and noted the distortion, i.e. broadening and some extra peaks, in the FBG reflection spectrum as the transverse crack density is increased by tensile strain (see Figure 2.8). As the crack density approached saturation, the spectrum became narrower with one single peak. These changes are due to the non-uniform strain distribution caused by the transverse cracks.
Ussorio et al (2006) have demonstrated that it is possible to detect a single transverse crack in a crossply GFRP laminate by embedding the FBG sensors at the 0/90° interface. A single transverse ply crack was grown by fatigue loading and the FBG reflection spectra due to the crack showed a broadening of the spectra and secondary peaks on the higher wavelength side. The enhanced strain field due to the matrix crack increased the strain local to the crack plane. Consequently, additional reflections at higher wavelengths are produced from this region of the FBG (see Figure 2.9), in addition to the reflections from the parts of the FBG which do not experience the enhanced strain.

Normal diameter uniform FBG sensors have also been used to detect delamination in composite laminates. For example, Takeda and his colleagues (2005) embedded a 10 mm
FBG sensor in a CFRP cross-ply laminate within 0° ply and close to 0/90 interface. A notch was introduced in the CFRP laminate and one end of the FBG sensor was positioned near the notch tip. Upon quasi-static loading, splits and transverse cracks occurred at the lower strain at the notch tip and on increased strain the delamination starts to appear at the notch tip. They recorded the reflection spectrum at 0.1% strain intervals with the load held constant and noted that the form of the FBG spectrum was changed as the damage occurred. When the initial damage occurs (splits and transverse cracks), the reflection spectrum becomes broad and had some low intensity peaks at the longer wavelength due to the non-uniform strain distribution caused by the cracks. After the delamination was initiated from the crack tip, peaks with high intensity appeared at longer wavelengths because the longitudinal strain is high in the delaminated region.

The results using small diameter FBG [Okabe et al., 2000] embedded in the 0° ply for transverse crack detection in cross-ply CFRP laminate by quasi-static loading, showed that under loaded conditions the spectrum became broader, showed some peaks on the long wavelength side and the intensity of the highest peak became smaller as the transverse crack density (ρ) increased due to the non-uniform strain distribution caused by the transverse cracks. However, they noted that under unloaded conditions, the spectra recovered its height but the form of the reflection spectrum was not recovered completely. This disturbance in the spectra after unloading is due to the non-uniform thermal residual strain distribution. The reflection spectra recorded by the authors after transverse cracking under loaded conditions and unloaded condition are shown in Figure 2.10 and Figure 2.11 respectively. For delamination detection, Takeda et al (2002) embedded a small diameter FBG in 0/90 interface of CFRP cross-ply laminate. For the delamination onset from the crack tip, a notch was introduced. One end of the sensor is placed near the tip of the transverse crack grown from the notch. Quasi-static bending load with a four-point bending device was applied and the reflection spectrum was recorded after unloading. They noted that the form of the FBG spectrum was changed as the delamination initiates and increases in length due to the non-uniform strain distribution. When there was only a transverse crack (i.e. before the occurrence of the delamination), the reflection spectrum had only one sharp narrow peak. After the delamination was initiated from the crack tip, another peak appeared at longer wavelength due to higher strain in the delamination region. The intensity of the longer wavelength peak increased relatively with an increase of the delamination length.
Chapter 2

LITERATURE REVIEW

Figure 2.10: Reflection spectra measured at various values of tensile strain (ε) data (A)–(E) [Okabe et al., 2002]

(A) ε = 0.00%, ρ = 0.0cm⁻¹
(B) ε = 0.25%, ρ = 0.0cm⁻¹
(C) ε = 0.43%, ρ = 6.5cm⁻¹
(D) ε = 0.80%, ρ = 11.0cm⁻¹
(E) ε = 1.19%, ρ = 13.0cm⁻¹

Figure 2.11: Reflection spectra measured after unloading. These correspond to the spectra for (A), (C), (D) and (E) [Okabe et al., 2002]

The use of uniform FBG sensors could identify that damage had occurred in the composite laminates, but could not locate the position of the damage. In order to achieve this, a CFBG can be used. For example multiple cracks were identified and also located from the CFBG reflection spectrum [Okabe et al., 2004]. A CFRP cross-ply laminate was embedded with a CFBG sensor in the 0° ply close to the 0/90 interface and the CFBG reflection spectrum was observed upon increasing tensile strain. As the tensile strain was increased the crack appears and then the crack density increases. The uniformly increasing grating spacing of the CFBG was interrupted by the strain field of the cracks leading to dips in the CFBG reflection spectrum at certain wavelength and hence both crack development and crack position can be determined. Figure 2.12 shows the reflection spectrum recorded by Okabe et al. (2004) after unloading the specimen containing cracks at various maximum strains. Small diameter CFBG sensors were also employed in a similar way to detect and locate the crack [Okabe et al., 2004]. In this case the dip was narrower as the small diameter CFBG sensor has larger amplitude of index modulation and hence higher spatial resolution.
Figure 2.12: CFBG Reflection spectra measured after unloading of various maximum tensile strain $\varepsilon_{\text{max}}$: (a) $\varepsilon_{\text{max}}=0.0\%$, no crack; (b) $\varepsilon_{\text{max}}=0.875\%$, 1 crack; (c) $\varepsilon_{\text{max}}=0.95\%$, 5 cracks; (d) $\varepsilon_{\text{max}}=0.975\%$, 10 cracks; and (e) $\varepsilon_{\text{max}}=1.05\%$, 21 cracks [Okabe et al., 2004].

Takeda et al (2007) also used CFBG sensors for delamination detection in CFRP laminates. The CFBG sensors were located at 0/90 interface and one end of the sensor was placed at the crack tip. The experiments were performed for two different cases: with the sensors placed with high wavelength end towards the crack tip (Type I) and sensors placed with low wavelength end towards the crack tip (Type II) to detect the delamination, delamination size and the direction of propagation of the delamination. The reflection spectra were measured at various delamination lengths under four point bending test. When there was no delamination, the reflection spectra showed a broad wavelength. When the delamination started from the high wavelength end of the CFBG, the long wavelength side
of the reflection spectrum shifted to longer wavelengths and the broad reflection spectrum was divided into two halves. As the delamination propagated, the division of the spectrum moved to long wavelengths and the longer wavelength shift increased (the spectrum width increased) with the increase in delamination length. This effect is due to the release of thermal residual strain in 0° ply as a result of delamination growth. When the delamination starts and propagates from the low wavelength end of the CFBG, the change in the reflection spectrum was not remarkable but the spectrum width decreased with increase in delamination length. This is because the short wavelength component corresponding to delamination region shifts to longer wavelength due to delamination growth but was superimposed into the longer wavelength end.

Embedded CFBG sensors were also investigated for detection of a combination of damage processes (splits, cracks and delamination) in cross-ply CFRP laminates. For example, Yashiro et al (2007) investigated the effect on the CFBG reflection spectrum of each type of damage process (split, crack and delamination) due to holes in the specimen. They embedded the CFBG sensor close to 0/90 interface and the high wavelength end of CFBG near the hole edge. Quasi-static loading was applied and the reflection spectra were measured at various applied strains while the load was held constant. Before the onset of cracks and delamination, the spectrum was broader with decreased reflectivity at higher wavelengths. This is due to stress concentration around the hole. When the cracks appear, some dips occurred in the reflection spectra at certain wavelengths. This is due to non-uniform stress distribution caused by the transverse cracks. The number of dips increased with the increase in transverse cracks. At the onset of delamination the decreased reflectivity at higher wavelengths was recovered and as the delamination grew, the reflectivity of the region close to the recovered region decreased while the recovered region became broader.

2.4.3.2. Damage in adhesive bonded joint / patch repairs:

FBG sensors have been used by many authors [McKenzie et al., 2000; Jones et al., 2002; Li et al., 2004; Herzsberg et al., 2005; Marioli-Riga et al., 2005; Takeda et al., 2004; Minakuchi et al., 2007] as either surface mounted, embedded within composites or placed in the adhesive layer, to detect defects in adhesively bonded joints or adhesive bonded patch repairs. Jones, Galea and colleagues [McKenzie et al., 2000; Jones et al., 2002] demonstrated that it is possible to monitor the disbond growth using an array of
surface-mounted uniform FBG sensors in the aluminium skin of a honeycomb sandwich panel that had been repaired with a boron/epoxy patch. The possibility of monitoring disbonds through changes in the residual thermal strain of a patch repair because when the patch disbonds, the thermal residual strain is released and the FBG sensor shows this signal change with respect to the input signal (the thermal strain occurs due to the thermal expansion mismatch of a composite patch bonded at elevated temperature to a metal substrate).

Embedded FBGs have also been utilised for the health monitoring of adhesively bonded joints/repairs [Li et al., 2004; Herzsberg et al., 2005; Marioli-Riga et al., 2005; Takeda et al., 2004]. Li et al (2004) used an embedded FBG to detect a disbond in a ship joint. The disbond was artificially introduced using a Teflon film and the sensitivity of the embedded FBGs at various locations along the interface of adhesively bonded composite joints was assessed. Three FBG sensors are embedded between adherend-adhesive interface, with the first sensor along various positions (a) within the disbond region (S1); the second sensor at the edge of the disbond (S2) and the third sensor 30 mm away from the disbond (S3), see Figure 2.13. Three point bending load was applied and the reflection spectra were recorded at every 2 kN interval. The sensor within the disbond region (S1) showed a shift in the peak wavelength towards the lower end, indicating a compressive strain within the disbond region due to the three point loading, and a very slight broadening of the spectra, due to reduced strain gradient. The sensor located at disbond tip (S2) showed a large shift in the peak wavelength, due to severe rise in strain, and a broadening of the spectra, due to the steeper strain gradient. The sensor S3 showed no change as there were no strain changes away from the disbond region. However, to detect the damage size and location, the authors suggest that an optimized sensor array and a sophisticated data processing technique would be required.

![Figure 2.13](image_url)

Figure 2.13. a) Test specimen with the disbond in the bondline of the bonded joint (b) Sensor location with respect to disbond in the bonded joint [Li et al., 2004]
Apart from normal diameter FBG sensors for damage detection in bonded joints/repairs, small diameter FBG sensors were also used for damage detection by locating them in the adhesive layer [Takeda et al., 2004; Minakuchi et al., 2007]. The form of the reflection spectrum changed as the disbonding length increased. Under no disbond, the FBG reflection spectrum showed a single peak. However, when the disbond reached the FBG sensors another peak appeared at the shorter wavelength. The intensity of the shorter wavelength increased relatively as the disbond length increased [Takeda et al., 2004]. Detection of both disbond and crack propagation in an aluminium plate patched with CFRP was also discussed by Takeda et al (2004). The authors proposed that the appearance of shorter and longer wavelength components to the existing reflection spectrum indicated the existence of a disbond and a crack respectively. Takeda and colleagues [Minakuchi et al., 2007] also proposed the use of an embedded small diameter FBG sensor for disbond detection in a sandwich panel consisting of CFRP face sheet and an aluminium honeycomb core. The small diameter sensor was embedded through a small slit in the adhesive layer between the composite facesheet and honeycomb core during curing. The disbond in the sandwich honeycomb structure was detected by the recovery of the reflection spectrum to its original shape. The reflection spectrum recorded before curing is said to be the original shaped reflection spectrum. On curing, the reflection spectrum was distorted due to the non-uniform strain distribution induced by the formation of a fillet between the core and facesheet. When the disbond occurred, this non-uniform strain was released and hence the reflection spectrum gained its original shape.

SUMMARY:

In this chapter, an overview of matrix cracking in composite laminates and disbonding in adhesively bonded joint/repairs was presented together with various NDT techniques available for damage detection. In the subsequent sections optical fibre sensors and in particular FBG and CFBG sensors are discussed. CFBG sensors are reported to have the ability to indicate the position of the damage, but relatively little research has been undertaken for matrix damage detection using CFBG sensors and more importantly none of the work was performed to study the behaviour and to detect the matrix damage in a GFRP laminate using CFBG sensors. In the case of disbonding in bonded joints, none of the techniques mentioned can both indicate that a disbond has formed and monitor its progression. Both of these areas of damage detection have been studied within this thesis.
In the next chapter, the background theory of matrix damage in a composite laminate, an adhesively bonded joint and a fibre Bragg grating are presented. The tool used to predict the FBG reflection spectrum is also presented in next chapter.
CHAPTER 3

BACKGROUND THEORIES AND TOOLS

3.1. INTRODUCTION

This chapter is aimed at giving an introduction to the theoretical background relevant to the work described in this thesis. In section 3.2, a brief discussion of the stress redistribution in cracked cross-ply laminates is provided. Section 3.3 gives an overview of adhesively bonded joints and the stresses in the single lap bonded joint. In section 3.4, a brief description is given on the theory relevant to fibre Bragg gratings, both uniform and chirped. The computational tool used for the prediction of the FBG reflected spectra, the commercial FBG software, OptiGrating [version 4.2], is discussed in section 3.5.

3.2. MATRIX CRACKING

Matrix cracking detection in the cross-ply laminates is one of the aims of the study and hence it is important to understand the stress distribution for undamaged and damaged laminates. For an undamaged cross-ply composite consisting of a central 90° ply with thickness 2d and an outer 0° ply with thickness d (see Figure 3.1), the longitudinal stresses in the longitudinal plies (\(\sigma_1\)) and transverse plies (\(\sigma_2\)) are given by

\[
\sigma_1 = \sigma \frac{E_1}{E_o} + \sigma_r \quad \text{(eqn. 3.1)}
\]

\[
\sigma_2 = \sigma \frac{E_2}{E_o} + \sigma_r \quad \text{(eqn. 3.2)}
\]

where \(E_1\) is the Young’s modulus parallel to fibres; \(E_2\) is the Young’s modulus perpendicular to fibres; \(\sigma_r\) is the residual thermal stresses arising from the difference in the thermal expansion coefficients in a direction along the fibres \(\alpha_0\) and in a direction perpendicular to the fibres \(\alpha_90\) and \(E_o\) is the composite Young’s modulus parallel to the loading direction.

\(E_o\) is calculated using the equation

\[
E_o = \frac{(bE_1 + dE_2)}{(b + d)} \quad \text{(eqn. 3.3)}
\]
Matrix cracking in the transverse 90° plies is the first macroscopic damaged mode in the cross-ply laminate. The transverse matrix cracking causes the redistribution of mechanical stress and the release of thermal strain in the 90° plies in the cross-ply laminate. To analyse the stress redistribution in a laminate when a transverse matrix crack is present, a shear-lag model is widely used. According to this model, when the transverse ply undergoes matrix cracking parallel to the fibres in this ply and perpendicular to the longitudinal ply in the vicinity of the crack, the transverse ply carries no load and hence it is taken by the adjacent longitudinal plies. Away from the crack, the load is shed back into the transverse ply via shear.

![Figure 3.1. Schematic edge view of a simple cross ply laminate with two consecutive matrix cracks in the transverse ply of (0/90)_s composite [Usarrio, 2004]](image)

The longitudinal stresses of the damaged composite in the longitudinal plies (σ_{1(D)}) and the transverse plies (σ_{2(D)}), with the origin of the co-ordinate at the middle of the transverse ply midway between two cracks spaced 2s (see Figure 3.1), are given by [Boniface et al., 1989]

\[
\sigma_{1(D)} = \sigma \left( 1 + \frac{d}{b} \right) - \frac{d}{b} \left( \sigma \frac{E_2}{E_0} + \sigma_T \right) \left( 1 - \frac{\cosh(\lambda s)}{\cosh(\lambda s)} \right) \tag{eqn. 3.5}
\]

\[
\sigma_{2(D)} = \left( \sigma \frac{E_2}{E_0} + \sigma_T \right) \left( 1 - \frac{\cosh(\lambda x)}{\cosh(\lambda s)} \right) \tag{eqn. 3.6}
\]

The stress redistribution factor, \( \lambda \), is given by

\[
\lambda^2 = \frac{3G(b + d)E_0}{bd^2E_1E_2} \tag{eqn. 3.7}
\]

where \( G \) is the shear modulus of the composite material. Assuming \( \sigma_T = 0 \), the longitudinal stress distribution at the longitudinal plies (\( \sigma_1 \)) and transverse plies (\( \sigma_2 \)) are shown in the Figure 3.2.
Adhesives are being increasingly employed in the assembly of complex components. In particular they are used to replace or augment more traditional joining techniques such as welding and mechanical fastenings. One driving force for the use of adhesives is the wider use of composite materials. Adhesives possess excellent properties and are very cost effective. In structures composed of polymer matrix composite materials, components must be joined such that the overall structure retains its structural integrity while it is performing its intended function which can include both mechanical loads (static and dynamic) and environmental loads (temperature and humidity).

The strength and durability of an adhesively bonded joint is a complex function of the stress concentrations set up by the applied loads and the operating conditions. Although the load capacity of a joint is simply the product of the bonded area and the shear strength of the adhesive, in practical applications a number of variables must be factored in. These include the substrates and the surface finish, the bond thickness, temperature, the joint...
geometry and the environment [Papinini et al., 1994; Ashford et al., 2001]. Of the different joint geometries such as single-lap joints, double-lap joints, scarf joints and step-lap joints, single-lap joints (SLJs) are of much interest and widely studied for two reasons: they are employed extensively in various configurations for a wide range of industrial products and they have simple and convenient test geometry for evaluating adhesively bonded joints.

The simplest model to calculate the adhesive shear stress ($\zeta$) in a single lap joint under load as shown in Figure 3.3, is given by

$$\zeta = \frac{P}{bl}$$

where the applied force is $P$, the overlap length $l$, and width $b$. Here the adherends are assumed rigid and the adhesive may deform only in shear, and hence there will be a uniform shear stress throughout the adhesive. However, this simple model is not valid as the stresses in the adhesive layer are not uniform. The simple lap joint has stress concentrations due to differential shear of the bonded structures and the load eccentricity. The non-uniform deformation of the adhesive layer under loading is known as differential shear. Hence, the adhesive layer will no longer be solely in shear, but will have peeling stresses at the end of the joint.

Figure 3.3. Simple rigid adherend model of single lap joint [Adams and Comyn, 2000]

Figure 3.4. Goland and Reissner bending model [Adams and Comyn, 2000]
Goland and Reissner (1944) took the load eccentricity into account by relating the moment at the adherend ends to the applied load and calculated the stress distribution in the adherend and the adhesive. They assumed the adhesive to be elastic and have the same material property as the adherends. They presented closed form solutions for calculating the stress distribution in the single lap joint for two cases:

a) The adhesive layer is extremely thin and rigid, so that its deformations are of little importance. This is quantified by the condition
\[
\frac{t_a}{E_a} \ll \frac{t}{E}, \quad \frac{t}{G} \ll \frac{t_a}{G_a}
\]
where \(t_a\) and \(E_a\) are the thickness and Young's modulus of the adhesive, respectively; \(t\) and \(E\) are thickness and Young's modulus of the adherend, respectively; \(G_a\) and \(G\) are the shear modulus of adhesive and adherend, respectively. From this analysis, the stress distribution along the adherend can be calculated.

b) The adhesive layer is thick and flexible so that its deformation makes a significant contribution to the stress distribution in the joint. This was quantified by the condition
\[
\frac{t}{E} \ll \frac{t_a}{E_a}, \quad \frac{t}{G} \ll \frac{t_a}{G_a}
\]
From this analysis, the stress distribution along the adhesive can be calculated.

Figure 3.4 illustrates the joint deformation and the adhesive peel stress predicted by the Goland and Reissner model under tensile loading. From the model, it was observed that the adhesive peel stress peaks at the ends of the overlap and the adhesive shear stress varies along the length of the joint with concentrations at the ends. The adherend shear stress was low at the adherend free ends and peaks at the overlap ends. Further details on the stress distribution in the adherend along the overlap length are given in Chapter 8.

3.4. BRAGG GRATING SENSORS

Fibre Bragg grating technology developed rapidly from 1989 when it was shown that gratings could be written into the core of optical fibres using UV light [Othonos, 1997]. Now they are widely adopted in modern optical fibre telecommunications and sensor systems. A phase mask technique was used to fabricate the FBG sensors by our collaborators in Singapore for our application. In the phase mask method the phase mask is used as a diffractive element and the UV light is focused on the optical fibre, which is beneath the phase mask, to produce a permanent refractive index change in the core of the
fibre as shown in Figure 3.5.

![Figure 3.5. Fabrication of FBG sensor using phase mask technique](image)

3.4.1. Bragg grating theory

In this thesis, both uniform and chirped FBG sensors have been used. The fibre Bragg grating sensor is produced as a result of periodic variations in the refractive index of the core of single mode optical fibres. The grating then reflects particular wavelengths and transmits all others. Figure 3.6 shows a schematic of the periodic refractive index change in the core of the optical fibre. The basic principle behind the FBG is that, when broadband light is introduced into the optical fibre containing the FBG, the wavelength that satisfies the Bragg condition (eqn. 3.9) is strongly reflected. This reflected wavelength is called the Bragg wavelength ($\lambda_B$) and the spectrum is not simply a delta function peak because the grating has a finite length. The periodicity of the index variation, called the grating period or the pitch length ($\Lambda$), is related to $\lambda_B$ by the following equation [Kersey et al., 1997]

$$\lambda_B = 2\pi n \Lambda$$

(eqn. 3.9)

where $n$ is the average refractive index of the optical fibre core.

![Figure 3.6. Refractive index change in the core of the optical fibre and its spectral response.](image)
3.4.1.1. Uniform FBG

In a uniform FBG, the grating period changes uniformly and hence when broadband light propagates through the uniform FBG sensor, a single peak Bragg wavelength is reflected. Figure 3.7 shows the optical fibre with a uniform FBG, with its reflected spectrum and transmitted spectrum when the light is passed into the fibre.

![Figure 3.7. Light propagation in uniform FBG [Kersey et al., 1997]](image)

From equation 3.8, it is clear that a shift in the Bragg wavelength would be observed when the grating pitch or the refractive index changes. The grating pitch or the refractive index undergoes changes due to an externally applied load or temperature and the shift in Bragg wavelength can be expressed [Kersey et al., 1997] as:

\[
\Delta \lambda = 2n \Lambda (1 - \frac{\pi^2}{2}[P_{12} - \nu(P_{11} + P_{12})]) \Delta \varepsilon + [\alpha + (\frac{dn}{dT}/n)] \Delta T \quad \text{(eqn. 3.10)}
\]

where \( \varepsilon \) is applied strain, \( P_{11} \) and \( P_{12} \) are Pockel’s strain optic constants, \( \nu \) is Poisson’s ratio, \( \alpha \) is the coefficient of thermal expansion of the fibre material and \( \Delta T \) is the temperature change. Consequently, the theoretical wavelength shift for isothermal conditions when the FBG is uniformly strained is given by [Rao, 1999]:

\[
\Delta \lambda = \lambda_B (1 - \rho_a) \Delta \varepsilon \quad \text{(eqn. 3.11)}
\]

where \( \rho_a \) is the photoelastic coefficient of the fibre (0.22 for silica) and \( \Delta \varepsilon \) is change in the applied longitudinal strain. For a uniform strain, the peak wavelength is shifted according to equation 3.11. Figure 3.8 shows the single peak wavelength shift in the reflection
spectrum as the fibres are uniformly strained. However, for a FBG subjected to non-uniform axial strain under isothermal conditions, the wavelength shift is given by

\[ \Delta \lambda(z) = \lambda_B (1 - \rho_u) \Delta \varepsilon(z) \]  

(eqn. 3.12)

In this case, due to the non-uniform strain, the reflection spectrum is distorted. This phenomenon can be used for damage detection [Okabe et al., 2000; Okabe et al., 2002; Li et al., 2004; Herzsberg et al., 2005].

![Shift in the peak wavelength of uniform FBG as the sensors are strained](image)

Figure 3.8. Shift in the peak wavelength of uniform FBG as the sensors are strained

3.4.1.2. Chirped FBG:

Chirped FBG sensors have a linearly increasing grating period. The Bragg wavelength is different for each different period and hence a spectral band of wavelength is reflected when a broadband light is coupled to the fibre. Thus the reflected wavelength is also related to the position along the grating. Figure 3.9 shows a schematic of how the grating period and the reflection spectrum change for the uniform and the chirped FBG. For a CFBG experiencing a uniform strain, there is a uniform increase in grating period and the whole reflected spectrum is shifted uniformly. The equations to calculate the grating period and the refractive index from the axial strain are given by [Okabe et al., 2004]:

Grating period:

\[ \Lambda(z) = \Lambda_0(z)[1 + \varepsilon(z)] \]  

(eqn. 3.13)

where \( \Lambda_0(z) = \Lambda_c + \Delta \Lambda(z - \frac{L_k}{2}) \)  

(eqn. 3.14)

Refractive index:

\[ n(z) = n_0 - \frac{n_o^3}{2} \{ p_{12} - v(p_{11} + p_{12}) \} \varepsilon(z) \]  

(eqn. 3.15)
where $\Lambda_0$ is the initial grating period, $n_0$ is the initial refractive index, $\Lambda_c$ is the central grating period, $\Delta \Lambda$ is the linear change of the period along the grating, $L_g$ is the grating length and $z$ is the position along the grating from the end with the smallest period. The properties of the chirped FBG used in this work are given in Table 4.2 of Chapter 4. Under non-uniform strain conditions, the grating period at the particular location of the non-uniform strain undergoes changes and hence the reflection spectrum at that region is distorted, with the other parts of the reflection spectrum remaining essentially undisturbed.

![Figure 3.9. Schematic Grating period and reflection spectra of](image)

(a) uniform FBG, and (b) CFBG.

3.5. SPECTRUM PREDICTION SOFTWARE (OPTIGRATING)

A commercially available software package, OptiGrating [version 4.2], was used to predict the reflection spectrum of the optical Bragg grating sensor once the strain distribution was known. In the software, the reflection spectra were predicted by defining parameters such as the index profile of the fibres, the grating shape, the average index change, the grating period chirp, the length, the strain-optic parameters and the thermo-optic parameters. The reflection spectra could then be predicted for the sensor under the unstrained and strained condition. When the prediction was made for strained condition, either the strain distribution experienced by the sensor was defined or the grating period and refractive change due to the strain changes were defined. Once all the parameters were set up, numerical simulations were performed within OptiGrating by inbuilt equations and the grating device characteristics, which include the reflection spectrum and the transmission spectrum, are predicted.
In our study the experimental results from the fibre Bragg grating are compared with the predicted OptiGrating reflection spectrum results. The studies of matrix cracking and disbond detection involved non-uniform strain distribution along the length of the grating. The strain distribution was incorporated into the OptiGrating software and the program was run to predict the spectrum. The parameters used in the software are given in Table 3.1.

**Table 3.1: Parameters used in OptiGrating**

<table>
<thead>
<tr>
<th>Core:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>4.5 μm</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cladding:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>62.5 μm</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.44</td>
</tr>
<tr>
<td>Central wavelength</td>
<td>1.550 μm</td>
</tr>
<tr>
<td>Grating shape</td>
<td>sine</td>
</tr>
<tr>
<td>Average index change</td>
<td>Uniform (0.0005) / From file</td>
</tr>
<tr>
<td>Period chirp</td>
<td>No chirp(if uniform FBG) or Linear (if chirped FBG)</td>
</tr>
<tr>
<td>Total chirp</td>
<td>from file</td>
</tr>
<tr>
<td>Sensor length</td>
<td>10000 μm / 15000 μm / 30000 μm / 45000 μm / 60000 μm</td>
</tr>
</tbody>
</table>

| Index Modulation           | 0.0005/0.0002    |

**Strain-optic parameters of fibre:**

<table>
<thead>
<tr>
<th>Photoelastic coefficients:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{11}</td>
<td>0.113</td>
</tr>
<tr>
<td>P_{12}</td>
<td>0.252</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.16</td>
</tr>
</tbody>
</table>

**Thermo-optic parameters** Not chosen

**Micro-strain** linear / user defined
As mentioned above, for the OptiGrating prediction, there are two methods to incorporate the strain distribution into the software. One method involved entering the strain distribution as an equation which was fitted to the FE results. This equation was entered within the user-defined micro-strain parameter of OptiGrating. The second method was to calculate the modified grating period and refractive index using the equations 3.12 and 3.13 from the strain distribution. The first method was used when the strain profile was simple (as in the matrix crack strain distribution, discussed in Chapter 5). This method was simple, easy to apply and less time consuming when the strain distributions were simple. When the strain profile was complex (as in the disbond damage studies for the bonded joint work), the second method was adopted [Okabe at al., 2004, Takeda et al., 2003]. An equation solver within excel was used to calculate the grating period and refractive index from the strain profile, which made the process of calculation easier. The calculation time was reduced and hence this method was adopted for further studies, when the strain profile was complex.

3.6. SUMMARY

In this chapter some background theory on matrix cracking in composite laminates and stresses in bonded joints has been presented. In addition, theory for the fibre Bragg grating sensors has been discussed and the methods used to predict the spectrum using the OptiGrating software have been described. The next chapter outlines the experimental methods used in the work.
CHAPTER 4
MATERIALS AND METHODS

4.1. INTRODUCTION

The present chapter describes the FBG sensor system used in the experimental work and the methods adopted to carry out the experimental investigations. The first section describes the instruments utilised to build and operate the FBG sensor system and the procedures for obtaining the reflection spectra when investigating either the matrix crack development or disbond detection. The second section is devoted to a description of the manufacturing process for glass fibre/epoxy matrix cross-ply laminates with the embedded sensors. The technique of developing single-lap composite bonded joints, without and with manufacturing defects, is also described within this section. Loading of the specimens including tensile and fatigue loading are described in subsequent sections.

4.2. FBG SENSOR SYSTEM

4.2.1. FBG sensor system arrangement:

The FBG system consists of a broadband light source, a coupler, an optical spectrum analyzer (OSA) and a refractive index matching liquid, which was used to eliminate the unwanted light reflections from the fibre ends. A schematic diagram of the optical arrangement is shown in figure 4.1. All the connections in the system are through single mode optical fibre. The starting point of the system is the broadband light source which is connected to one of the four arms of a 3dB coupler. The second arm, at the same end of the coupler, is connected to an Optical Spectrum Analyser (OSA). The light from the broadband source passes through the coupler and is evenly split into two parts (see Figure 4.2). The FBG sensor embedded within a composite specimen is connected to one of the two arms and the other arm is terminated in a black container of refractive index matching liquid (paraffin was used in this work, this avoided any reflection at the interface between the optical fibre end and the liquid). The light through the other arm is transmitted to the part of the optical fibre which is embedded in the specimen and contains the FBG sensor. This light is partly back-reflected and partly allowed through the grating. The transmitted light is dispersed into a second container of refractive index matching liquid and absorbed
by the black walls of the container.

**Figure 4.1.** Diagram of the FBG system arrangement.

**Figure 4.2.** Optical connections through 3 dB coupler.

The reflected light from the FBG sensor carries the information relevant to the experiment and the light passes through the coupler and is then analysed and recorded using the OSA. All optical connections (i.e. the optical fibres) are stripped, cleaved and spliced. For stripping, chemical stripper (Nitromose) is used. The safety operating procedure while stripping, cleaving and splicing is attached in the Appendix 4A. The optical fibres are spliced using an arc fusion splicer manufactured by Fuji (see Figure 4.3).

4.2.2. ASE broadband source:

The Amplified Spontaneous Emission (ASE) broadband light source used in the study is the JDS Uniphase / AFC Technologies (AFC BBS 15/16, see Figure 4.4). The output power of this source is about 3 mW, distributed over the whole range of the wavelengths between 1520 nm to 1570 nm. The optical connection to the broadband source was made via a front panel FC bulkhead adapter.
This broadband source is classified under the class 3b laser source. Class 3b lasers can present a major hazard through exposure to the direct or reflected laser beams, when there is a direct line-of-sight path to the laser beam or its reflection. Hence safety regulations have to be followed while using the laser. Appendix 4B outlines the laser product specification, laser beam hazards, the safety calculations relevant to the safe operation of this laser and the safety procedures followed.

4.2.3. Optical spectrum Analyser (OSA):

The OSA used in our FBG system arrangement was a Type AQ-1425 (see figure 4.4) manufactured by Ando Electric Co., Ltd., Japan. This instrument detects the intensity of light at each wavelength component. The shape of the intensity vs. wavelength diagram (i.e. the light spectrum) is displayed on the OSA monitor. The way this analysis is carried out by the device is by sweeping over a wavelength range, defined preliminarily by the operator. The control panel in the OSA enables the setting of a series of parameters whose value needs an adjustment to run the analysis of a specific light beam in the most efficient way. The principal parameters for the OSA are:

1. centre wavelength: central value of the wavelength interval to be swept,
2. sweep width: amplitude of the wavelength interval to be swept,
3. resolution: amplitude of the wavelength interval to which a single intensity data point is assigned
4. reference level: noise level for the current analysis

![Figure 4.3: Arc fusion splicer with controller and monitor used to splice the optical fibres](image-url)

---

**Figure 4.3:** Arc fusion splicer with controller and monitor used to splice the optical fibres
Once the centre wavelength and the sweep width have been given a value, the sweep interval is completely defined. The instrument is capable of analysing wavelengths in the range 400nm to 1600nm and the wavelength range used in these experiments is 1525-1575 nm. The resolution used in these experiments was 1 nm. The reference level of the noise was set at -32 dB. All the above listed commands are adjusted by operating on the instrument’s built-in control panel. Once the parameters are setup manually in the OSA, they are remotely controlled by a PC to run the sweep.

4.2.4. Reflection spectrum capturing procedure

To capture the reflected spectrum from the optical sensors for the experiment, the following basic procedure was followed:

- switch on the ASE source
- run a single sweep over the wavelength range through the PC-controlled OSA
- store the analysis data for further processing.

By launching broadband light through the single mode fibre to the FBG, the reflected signal contains all the wavelengths which can be reflected by the FBG. This spectrum was analysed and recorded with a single OSA sweep over the fixed wavelength range. The reflection spectrum data was then stored as an MS-Excel readable file in the form of intensity for 560 data points which correspond to wavelength range. This was converted to intensity against wavelength to be plotted as a spectrum.
4.3. MATERIAL FABRICATION TECHNIQUES:

This thesis contains a study on detecting a matrix crack in composite laminates and disbonds (both service and manufacture) in composite-composite bonded joints using chirped FBGs. The fabrication techniques for both studies are very similar. The process starts with the preparation of the sensors and their incorporation into a GFRP laminate.

4.3.1. Sensor preparation

Both uniform FBG sensors and chirped FBG sensors were used in this work. The uniform FBGs were 10mm long having a nominal Bragg wavelength of 1550 nm. The CFBGs used were of various lengths (15 mm, 30 mm, 45 mm and 60 mm) written into the core of a commercial single mode optical fibre. All the CFBG sensors had the same spectral bandwidth, having a full width at the half-maximum (FWHM) of the reflected spectrum of 20 nm, and hence the sensors had different chirp rates (Table 4.1). The CFBG sensors were supplied by the School of Electrical and Electronic Engineering, Nanyang Technological University (NTU), Singapore. Table 4.2 shows the optical and thermo-mechanical properties of CFBG sensors [Okabe et al., 2004].

Table 4.1: Grating length of CFBG sensors used and chirp rates

<table>
<thead>
<tr>
<th>Grating length, mm</th>
<th>Chirp rate, nm/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>30</td>
<td>4.5</td>
</tr>
<tr>
<td>45</td>
<td>3</td>
</tr>
<tr>
<td>60</td>
<td>2.25</td>
</tr>
</tbody>
</table>

The entire length of the optical fibre provided by NTU was coated with an acrylate resin, except for a short length of 70 to 80 mm. In this uncoated region of the optical fibre segments, the Bragg grating was written. The position of Bragg grating was provided by NTU in terms of the start from the uncoated region (e.g. 12 mm from the left of the beginning of the bare fibre). Hence the position of the Bragg grating would be determined to an accuracy of approximately 1 mm. The length of stripped fibre was not recoated after the gratings were fabricated, which enabled direct contact with the epoxy matrix during the manufacturing process of the composite specimens. The total length of the optical fibre in which a few mm of the Bragg grating was written, supplied by NTU, was very long.
(approximately 700 mm) and hence it was shortened to embed within the 200 mm long GFRP coupons. The splices were arranged to be within the coupon to shield them from breakage. The first operation executed, after the sensor was ready for embedment, was to record the reflected spectrum of the free sensor under unloaded conditions. This was done to obtain a spectrum which served as a reference for comparison with the spectra after embedding in the composite.

Table 4.2: Properties of chirped FBG sensor [Okabe et al., 2004]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson’s ratio $v_f$</td>
<td>0.16</td>
</tr>
<tr>
<td>Thermal expansion coefficient $(x10^{-6} \text{C}^{-1})$, $\alpha$</td>
<td>0.5</td>
</tr>
<tr>
<td>Strain optic coefficients</td>
<td></td>
</tr>
<tr>
<td>$p_{11}$</td>
<td>0.113</td>
</tr>
<tr>
<td>$p_{12}$</td>
<td>0.252</td>
</tr>
<tr>
<td>Initial average refractive index $n_0$</td>
<td>1.449</td>
</tr>
<tr>
<td>Refractive index of cladding $n_c$</td>
<td>1.444</td>
</tr>
<tr>
<td>Index modulation $\Delta n$</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

4.3.2. Laminate manufacture with embedded sensors

Continuous E-glass fibre-reinforced epoxy resin crossply laminates with different lay-ups, were used for various studies as shown in Table 4.3. The use of curly brackets ({{}}) shows the interface where the FBG or CFBG sensor was embedded.

Table 4.3. Lay-ups of the laminates manufactured for the study.

<table>
<thead>
<tr>
<th>Study</th>
<th>Lay-up</th>
<th>Thickness of each ply, mm</th>
<th>Total laminate thickness, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix cracking</td>
<td>$\left(0 / {\text{FBG/CFBG}} / 90_4 / 0\right)$</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>Bonded joints</td>
<td>$\left(0_2 / {\text{CFBG}} / 90 / 0_6 \right)_s$</td>
<td>0.25</td>
<td>4.5</td>
</tr>
</tbody>
</table>

The production of GFRP coupons with embedded FBG sensors required several steps. The GFRP laminates were manufactured by a wet impregnation technique using E-
glass fibres and an epoxy resin matrix. The following description, which applies to the 
\((0/\{\text{CFBG}\}/90/0\delta)_{s}\) laminates, was used in a simpler form for the \((0/\{\text{FBG/CFBG}\}/90/0)\) laminate. A dry preform was constructed by winding glass fibres (600 TEX) around a steel frame (dimensions 450 mm x 450 mm). Figure 4.5 shows the winding of glass fibres onto the steel frame. The inner 0° plies are wound first and the frame was then rotated through 90° to wind the 90° plies. The number of 0° plies and 90° plies depends on the study mentioned in table 4.3. The frame was then removed and two 5 mm wide, thin Perspex strips were bolted to the winding frame. Incorporation of the FBG or CFBG sensors into the laminate was carried out as follows. FBG/CFBG sensors were to be placed near the outer 0/90 interface along 0° ply direction. Hence the sensors were positioned in the desired locations by gluing the optical fibres onto Perspex strips perpendicular to 90° plies. The 0° ply fibres were finally wound to form the outer longitudinal plies. The fibres at the composite specimen ends were given an additional silicone rubber coating over the length to prevent fibre breakage at these locations during fabrication and handling of the specimens. The embedded portion of the silicone coating will not affect experimental results, as it is located far from the gauge length in every specimen.

![Steel frame Glass fibre](Image)

**Figure 4.5:** Photograph of winding machine; process of winding the glass fibres onto the steel frame is shown

The fibre preform was now ready for impregnation. A tri-component epoxy resin (weight composition: 100 parts of Biphenyl A Epichlorohydrin resin 300; 60 parts of MNA hardener; 4 parts of Ancamine K61B catalyster) were mixed in a beaker and degassed at 60° C in a vacuum oven. The liquid resin was introduced manually on one side of the reinforcement stack and vacuumed for approximately 20 minutes to assist in drawing resin through the fibres and removing any air bubble content in the laminate. The procedure was
repeated to the other side of the reinforcement stack. Care was taken to remove the air bubbles from the preform and hence manual removing of air bubbles was also carried out by squeezing the resin in all directions by a thin plate. The laminate was cured in an air circulating oven for 3 hr at 100 °C under a pressure of 100 kPa.

4.3.3. Matrix cracking coupon specimens:

To produce coupon specimens for the matrix cracking study, coupons with dimensions 220 mm x 20 mm containing the sensors were cut from the crossply laminate. 1 mm thick aluminium end tabs, of length 20 mm, were bonded to the specimens using 3M-490 structural adhesive. In Figure 4.6, the GFRP coupon with an embedded 45 mm CFBG sensor, is shown schematically and Figure 4.7 shows the location of the optical fibre in the GFRP coupon and the side view of the location of the optical fibre within one of the longitudinal plies near the 0/90 interface respectively. Figure 4.8 is a micrograph of a portion of the cross-section of a specimen showing the optical fibre location in the laminate at the 0/90 interface with the optical fibre located within the 0° fibres.

![Figure 4.6](image1.png)

**Figure 4.6.** Schematic of GFRP coupon with the embedded CFBG sensor (Top view)

![Figure 4.7](image2.png)

**Figure 4.7** Location of CFBG sensor in GFRP crossply laminate within 0-ply, at 0/90 interface.
Figure 4.8: Micrograph of a portion of the cross-section of a specimen (0/90/0) crossply laminate showing the optical fibre location at 0/90 interface along 0°. 

The Perspex strips which were used to locate the optical fibres during the fabrication stage remain embedded in the coupons, but within the grip area and well away from the gauge length of the coupons. This laminate fabrication procedure introduces a small, though unknown, tensile pre-strain into the optical fibre which can vary from specimen to specimen. With a chirped FBG, this pre-strain simply shifts the entire reflected spectrum uniformly to slightly longer wavelengths. The optical transparency of the GFRP laminates provided an advantage in the study of matrix damage and the development of disbonding damage between the composite-composite adherends, as the damage development can be photographed for direct comparison with the sensor measurements.

4.3.4. Single lap composite-composite bonded joint coupon specimens:

Coupon specimens with dimensions 220 mm x 20 mm containing the sensors of various lengths were cut from the (0_2 / {CFBG}/90/0_8), lay-up cross-ply laminate. For the bonded joint studies the coupon is called an adherend. A number of studies were undertaken using CFBG sensors to monitor disbonds adjacent to the low-wavelength or high-wavelength end of the sensor. For the detection of the disbond adjacent to the low-wavelength end of a bonded joint, CFBG sensors of various lengths (15, 30, 45 and 60 mm) were used and for the study of disbond detection adjacent to the high-wavelength end a CFBG sensor length equal to the overlap length of the bonded joint (i.e. 60 mm) was used. The adherends were cut so that the low wavelength end of the CFBG sensor terminated at the cut end of the adherend. For this to be possible, it was necessary to discriminate between the low and high wavelength end of the sensor and to locate the end of the sensor.
This was done by applying a simple through-thickness load using a small finger-tightened clamp mounted onto the coupon; this loading produces a perturbation in the reflected spectrum which enables the low-wavelength end of the sensor to be identified, as shown in Figure 4.9. This loading procedure was continued to identify the lower wavelength end of the sensor and it was identified within an accuracy of 1 mm. The adherends prepared in this way with embedded sensors, were 120-130 mm in length depending on the position of the low wavelength end of the sensor in the laminate.

![Figure 4.9](image)

**Figure 4.9:** (a) Schematic of a GFRP coupon with embedded CFBG sensor showing the two positions used to apply a through-thickness compressive load to identify the low-wavelength and high-wavelength end of the sensor; (b) superposition of typical CFBG reflection spectra obtained when a GFRP coupon was loaded at positions 1 and 2.

Prior to bonding, the adherends were cleaned with acetone and the bonding surface was abraded with a fine silicon carbide sheet. The adherend with the embedded sensor was bonded to the second adherend without an optical sensor using an adhesive (Araldite AV119), a one-part heat-cured epoxy adhesive supplied by Huntsman, UK. AV119 adhesive was chosen as it is popular in aerospace industry and also produces a transparent joint when used with the transparent GFRP adherends in this investigation. This is valuable for monitoring and recording the propagation of the disbond during the tests for a direct
comparison with the measurements made using the CFBG. The mechanical properties of AV119 are given in Table 4.4 [Broughton et al., 1999].

**Table 4.4: Properties of adhesive AV119 at room temperature [Broughton et al., 1999]**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear modulus (GPa)</td>
<td>1.07 ± 0.04</td>
</tr>
<tr>
<td>Shear strength (MPa)</td>
<td>47.6 ± 2.9</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>3.05</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.4</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>70</td>
</tr>
</tbody>
</table>

Figure 4.10: (a) Schematic diagram of the single-lap composite-composite bonded joints with the sensor embedded in one of the adherends. (b) Edge view of the joint with exaggerated adhesive thickness and wire spacer, showing 60 mm CFBG sensor embedded in the adherend; the low-wavelength end of the CFBG sensor terminating at the end of one adherend.
Chapter 4

MATERIALS AND METHODS

The adherend containing the CFBG sensor was positioned such that the sensor was close to the bondline but approximately 0.5 mm from the adhesive bondline as the CFBG sensors were embedded near the first 0/90 interface. A uniform thickness of adhesive between the adherends was achieved by using aluminium wires with a diameter of 0.40 mm as spacers and the bond was formed under light pressure in a finger-tightened spring-loaded jig. The overlap length of the bonded joints was 60 mm. The joint was cured at 120° C for 1 hour. Figure 4.10 (a) and (b) shows the single-lap composite-composite bonded joints with the sensor embedded in one of the adherends and the edge view of the joint with 60 mm long CFBG sensor in one of the adherend respectively. In the Figure 4.10 (b), the low-wavelength end of the CFBG sensor terminating at the end of one adherend is also shown. Aluminum end tabs, length 20 mm, were bonded to the specimens using 3M-490 structural adhesive. Now the single lap GFRP-GFRP bonded joint with dimensions 120x20 mm and 60 mm overlap was ready for testing. For the detection of disbond from the low-wavelength end of bonded joint, CFBG sensors of various lengths (15, 30, 45 and 60 mm) were used and for the study of disbond detection adjacent to the high wavelength end, a CFBG sensor of length equal to the overlap length of the bonded joint (i.e. 60 mm) was used.

4.3.5. Single lap composite-composite bonded joint with manufacturing defect:

The process of preparation of single lap composite–composite joints with manufacturing defects (artificial disbonds) is similar to the process explained in section 4.3.4 except for the insertion of a defect using Teflon (PTFE). A piece of Teflon with dimensions 12 mm long, 25 mm wide and 0.25 mm thickness was inserted at the centre of the overlap length. The size of the Teflon characterized the disbond size. The Teflon acted as a spacer to provide the required thickness, so there was no need to use the aluminium spacer wire. Hence the thickness of adhesive would be the thickness of the Teflon insertion (i.e. 0.25 mm thick adhesive layer). The bonding was then continued as before using elevated temperature epoxy adhesive AV119, and the joints were cured at 120° C for 1 hour. In Figure 4.11 (a) the edge view of the bonded joint with the disbond due to the Teflon insertion in the bond line is shown. Figure 4.11(b) shows the transparent image of the GFRP bonded joint with the 12 mm Teflon insert within the bondline at the centre of the overlap. The dimensions of the bonded joint were 120 x 20 mm with an overlap length of 60 mm.
Figure 4.11 (a) Edge view of the GFRP-GFRP bonded joint with the Teflon in the adhesive bondline. (b) transparent image of bonded joint with 12 mm Teflon insert (artificial disbond) within the bondline at the centre of the overlap (Plan view).

4.4. MECHANICAL TESTING

4.4.1: Quasi-static tests for matrix cracking damage detection

Firstly, quasi-static tensile tests were carried out using an Instron 1341 computer-controlled servo-hydraulic testing machine (Figure 4.12) at room temperature in a temperature-controlled laboratory on the specimens with embedded uniform FBGs and chirped FBGs. The specimens were subjected to simple unidirectional loading and the reflected spectra were recorded with the specimen unloaded and under various tensile strains. The parameter controlled in the loading process was the longitudinal strain of the specimens, measured using an extensometer with the gauge length of 50 mm attached using an elastic band to the surface of the coupon. The strain loading steps were increased in increments of 0.05% longitudinal strain. The specimens were strained up to 0.3 %. The reflection spectra for these undamaged specimens were recorded at these strains to compare with the reflection spectra obtained for the specimen after the initiation of a matrix crack. The results were also used to calculate the strain sensitivity of the sensors having different lengths.

For the study of the response of the FBG/CFBG sensor to matrix cracking damage, matrix cracking was manually initiated in the transverse ply of the specimen adjacent to the
FBG sensor and grown by fatigue cycling. Since the location of the FBG/CFBG sensor within the coupon was already known (see section 4.3.1), a single matrix crack in the transverse ply at a location adjacent to the grating length was initiated. Work by Boniface et al (1991) has shown that the transverse ply cracks can be grown in a controlled fashion under fatigue loading by carving a notch. Hence a crack was initiated by introducing a notch in the 2 mm thick transverse ply using a scalpel blade. The crack was grown as a fatigue crack by running tensile fatigue cycles with a peak strain of 0.15%, an R-value of 0.1 at a frequency of 5Hz. Care was taken not to destroy the longitudinal ply. The crack grew slowly, as a fatigue crack, across the specimen. Fatigue cycling was continued until the crack grew past the sensor location and across the full width of the coupon. The cracked specimen was again subjected to quasi-static tensile load applied in increasing discrete longitudinal strain steps of 0.05% and the FBG/CFBG reflection spectra were recorded for the cracked coupons both unloaded and at various values of strain. The response of the CFBG to the presence of two cracks was tested in a similar way.

![Instron computer-controlled servo hydraulic testing machine used for the test.](image)

**Fig 4.12.** Instron computer-controlled servo hydraulic testing machine used for the test.

4.4.2. Fatigue tests for disbond detection in bonded joints:

The single lap GFRP-GFRP bonded joints, prepared by the process described in section 4.3.4, were subjected to fatigue cycling to initiate and propagate a disbond. The end-tabs of the bonded single-lap joints were gripped within the standard wedge grips of an Instron 1341 servo hydraulic testing machine and subjected to fatigue cycles of either a
peak load of 8 kN, and an R-value (i.e. $\sigma_{\text{min}}/\sigma_{\text{max}}$) of 0.1, using a sinusoidal waveform with a frequency of 5 Hz or a peak load of 11 kN (corresponding to an adherend tensile stress of 122 MPa) an R-value (i.e. $\sigma_{\text{min}}/\sigma_{\text{max}}$) of 0.1 and frequency of 3 Hz was adopted. A digital camera was set up to record the growth of disbond. The cyclic loading was performed until the bonded joints completely disbonded. Loading was interrupted at increasing numbers of cycles in order (a) to record the position of the growing disbond front in the transparent lap joint using an in situ digital camera, and (b) to record the reflected spectrum of the CFBG sensor with the joint under no load and a constant load of 5 kN (equivalent to an adherend tensile stress of 55 MPa). This experimentation was performed for bonded joints with various lengths of CFBG to detect the disbond initiating adjacent to lower wavelength end of the CFBG sensor. Additional sets of experiments for bonded joints with CFBG lengths equal to the overlap length investigated the possibility of detecting disbond initiating adjacent to higher wavelength end of the CFBG sensor.

4.4.3. Tensile test for manufacturing defect detection in bonded joints

The experiments were carried out to determine the possibility of CFBG sensors detecting any manufacturing defects in bonded joints. The bonded joints made with an artificial manufacturing defect using Teflon insertion, as mentioned in section 4.3.5, were subjected to tensile loading using the Instron servo-hydraulic machine. The reflection spectra were recorded under unloaded conditions to form a reference spectrum and at various levels of increasing load at an interval of 1 kN. The load was applied manually using the load adjusting control on the hydraulic machine. The reflection spectra recorded at unloaded and loaded condition are then compared.

4.5. SUMMARY

In this chapter, firstly FBG instrumentation and the procedure to capture the reflection spectrum were discussed. It was then followed by the description of the fabrication techniques of the composite laminate with embedded FBG or CFBG sensors for matrix cracking studies and single lap bonded joints with and without artificial disbonds for service and manufacturing disbond detection studies. Lastly the testing procedures to detect a matrix crack in composite laminate and service or manufacturing disbonds in bonded joint
is discussed. In the next chapter, the results obtained for the matrix crack detection using FBG and CFBG sensors are discussed.
CHAPTER 5
MATRIX CRACKING DETECTION IN GFRP CROSS-PLY LAMINATE

5.1. INTRODUCTION
The present chapter deals with the results obtained from optical fibre sensors, based on fibre Bragg gratings (FBG), embedded in a cross-ply GFRP laminate to detect single matrix cracks, the earliest form of macroscopic damage in composite laminates. In this chapter both uniform and chirped FBG sensors were used to detect single matrix cracks. The simulation of the reflection spectra with the aid of a stress transfer model is also presented.

5.2. RESPONSE OF UNIFORM AND CHIRPED FBG SENSORS TO APPLIED STRAIN
The chapter begins by investigating the strain response of the uniform and chirped FBGs. Experiments were conducted to investigate the response of free sensors and those sensors embedded in laminates at various strain levels. No cracks were present in the cross-ply laminate during these experiments.

Before the uniform or chirped FBGs were embedded into the laminate the reflection spectra of the free sensors were taken to form the reference. Figure 5.1 shows the reflected spectrum recorded from a 10 mm uniform FBG sensor before it was embedded into the composite laminate. There is a single peak wavelength corresponding to the Bragg wavelength reflected from the uniform FBG sensor. The same procedure was followed for recording the reflection spectrum of the chirped FBG sensor. In Figure 5.2, the reflected spectrum obtained from a free chirped FBG is shown. A spectral band of wavelength is reflected by the chirped FBG.
After recording the reflection spectrum of both uniform and chirped free sensors, they were embedded in the cross-ply GFRP laminate and the reflection spectra were recorded. For details of the embedment procedures refer to Chapter 4. Figure 5.3 shows the comparison of reflection spectrum before and after embedment of the uniform FBG. A shift in the reflection spectra to a lower wavelength after embedment in the cross-ply laminate is observed. This is explained as follows: The cross-ply laminate is cured at elevated temperature and when they are cooled to room temperature the difference in the CTE of 0° and 90° ply produces a residual thermal strain. The CTE of the 90° ply is greater than the CTE of the 0° ply, and hence the expansion is constrained by each other. As a result the 90° ply undergoes tensile strain and the 0° ply undergoes balancing compressive strain. Hence the optical FBG sensor embedded in the 0° ply experiences a compression, thereby the grating period is decreased and the reflected Bragg wavelength is shifted to lower wavelengths.
The cross-ply laminate with the embedded uniform FBG sensors were then subjected to tensile loading as discussed in Chapter 4, section 4.4.1. The reflection spectra were recorded with the coupon unloaded and at various increasing strain conditions with the longitudinal strain increased in steps of 0.05%. The reflection spectra obtained from a uniform FBG are shown in Figure 5.4. As expected the main peak Bragg wavelength is shifted to higher wavelengths as the strain is increased. But the shape of the spectrum remains largely unchanged during the shift to higher wavelengths and the spectrum has an approximately symmetrical shape about one main peak. The Bragg wavelength depends on the pitch length and an increase in pitch length as a consequence of a uniform strain produces an increase in Bragg wavelength so that the spectra are shifted to higher wavelengths. The sensitivity of the uniform FBG sensor is calculated by plotting the peak wavelength shift in relation to the applied strain (Figure 5.5). From the plot, the sensitivity of the uniform FBG sensor embedded in a cross-ply laminate is $1.24 \times 10^{-3}$ nm / με. This value is similar to the sensitivity value reported by Ussorio et al, 2004.
Figure 5.4. Reflected spectra of an embedded FBG at different strain levels

Figure 5.5. Bragg wavelength shift from uniform FBGs as a function of applied strain

The same procedure of recording the reflected spectra before and after embedding the chirped FBG sensor and quasi-static loading were performed and the results are shown in Figure 5.6 and 5.7. Again the compressive strain in the 0° ply shortens the pitch length and hence the whole of the wavelength range in the reflection spectra is shifted to lower wavelengths after embedment, as shown in Figure 5.6. The coupons were then subjected to increasing strains and the reflection spectra are shifted uniformly to higher wavelengths in proportion to the strain, as observed for the uniform FBG (see Figure 5.7). This is because the uniform strain applied increases the period of the chirped grating along the grating length, thereby shifting the reflected wavelengths to higher values for all locations along the grating.

The reflected spectra shown in Figure 5.7 at various strains are for a chirped FBG of 30 mm length. Various lengths of CFBG were used and the same experiments were
performed for all the lengths of CFBG (i.e. for 15, 30, 45 and 60 mm) and the shift in the centre wavelength at various strains were plotted and are shown in Figure 5.8. The centre wavelength is the half of wavelength measured at full width at half the maximum (FWHM) of the reflected spectra. The strain sensitivity of the 15, 30, 45 and 60 mm CFBG sensors were calculated to be $1.07 \times 10^{-3}$ nm / $\mu$e, $1.10 \times 10^{-3}$ nm / $\mu$e, $1.08 \times 10^{-3}$ nm / $\mu$e and $1.13 \times 10^{-3}$ nm / $\mu$e respectively. Overall the strain sensitivity of the CFBG sensors after embedment in GFRP cross-ply laminate was approximately $1.1 \times 10^{-3}$ nm / $\mu$e for central wavelength of 1549 nm (unstrained).

![Figure 5.6. Comparison of chirped FBG reflection spectrum before and after embedment in cross-ply laminate.](image)

![Figure 5.7. Reflected spectra of an embedded chirped FBG at different strain levels](image)
5.3. RESPONSE OF UNIFORM FBG SENSORS TO MATRIX CRACKING

In order to determine the response of a uniform FBG embedded in a cross-ply laminate to a single matrix crack, a crack was deliberately introduced at the location of the FBG sensor. The technique of introducing the crack was described in Chapter 4. Reflected spectra were recorded after crack growth with the specimen unloaded and at various strain levels. Figure 5.9 shows the unloaded reflected spectra of the coupon with fully developed matrix crack and at 0.1%, 0.2% and 0.3% strain.

In the reflected spectra after matrix cracking, the peak in the spectrum remains at the same wavelength as the undamaged reflection spectrum, but the shape of the reflected spectrum becomes asymmetrical for all strains. The spectrum is skewed towards the long wavelength side of the main peak and one or more distinct side peaks appear on the long wavelength side of the spectrum at higher strains. The intensity of the spectrum also decreases over the increased strain. These results are similar to the results shown by Ussorio et al (2006). In order to study the response of the sensors to the crack, a side by side comparison with the uncracked coupons is shown in Figure 5.10. Figure 5.10 shows the reflected spectra before and after single transverse ply cracking at unloaded and 0.3% strained conditions.
Figure 5.9. Reflected spectra of uniform FBG after cracking at various strain conditions

Figure 5.10. Reflected spectra of uniform FBG at unloaded and 0.3 % strain for (a) coupon before transverse matrix cracking (b) coupon after transverse matrix cracking

From the changes in the reflection spectrum, the presence of the crack could be identified. But as reported by Okabe et al (2004), though this technique provides information on the presence of crack, further details on the location of the crack are unable to be provided. In order to obtain quantitative information both on the presence and location of the crack, the response of chirped FBG to matrix cracks were studied; as the reflected spectrum from the CFBG is a function of the position along the grating.

5.4. RESPONSE OF CHIRPED FBG SENSORS TO MATRIX CRACKING

The coupons with chirped FBG were studied for their response to matrix cracking in the same manner as the coupons with uniform FBG. The crack was deliberately introduced at the desired location and fatigue cycling was run at the peak load and frequency as
reported in Chapter 4. The transverse crack introduced grew slowly across the width of the coupon past the sensor and reached the coupon’s other edge.

After the single crack had grown fully, the reflection spectrum was taken in the unloaded state and at a number of increasing strains. The reflection spectra at various strains were then compared. Figure 5.11 is a photograph of the GFRP coupon with the embedded CFBG sensor after a crack. Figure 5.12 (a) and (b) shows the recorded reflection spectra at various strain levels for 15 mm and 30 mm CFBG lengths respectively.

![Transverse Crack](image)

**Figure 5.11.** GFRP coupon with embedded 30 mm CFBG sensor after a single transverse crack

![Reflection Spectra](image)

**Figure 5.12.** CFBG reflection spectra after single matrix cracking at a number of strain levels for (a) 15 mm and (b) 30 mm CFBG lengths.

The comparison of the reflected spectra after damage for increasing strain conditions showed two differences. The first being the shift of the reflection spectra to higher wavelengths with increasing strains, as expected and as explained in section 5.2.
The second being a characteristic change in the shape of the reflection spectra after the crack. In order to study this in detail, the reflection spectra before and after the single matrix crack were compared, as shown in the Figure 5.13 (a) and (b) for a 15 mm CFBG length coupons under unloaded and 0.1 % strain conditions respectively. In Figure 5.14 (a) and (b) the reflected spectra for a 30 mm CFBG length coupon under unloaded and 0.1 % strain conditions are shown respectively.

![Figure 5.13. Comparison of reflection spectra for a 15 mm CFBG sensor before and after crack for (a) unloaded condition (b) under 0.1 % strain](image1)

![Figure 5.14. Comparison of reflection spectra for a 30 mm CFBG sensor before and after crack for (a) unloaded condition (b) under 0.1 % strain](image2)

From the reflection spectra comparison, it is observed that there is an approximately sinusoidal shape change at a particular location of the reflected spectrum after the crack has passed the sensor. To locate the crack in the reflection spectrum, firstly the location of the crack from the image of the transparent GFRP is identified. The crack location in the transparent GFRP is reported in terms of position from the low wavelength end of the
CFBG sensors as the initial starting position of the low wavelength end of CFBG was known with an accuracy of 1 mm. Then using FWHM in the CFBG reflection spectra as a reference which corresponds to the length of CFBG sensor used, the position of the crack in the image of the transparent GFRP is converted to the position in the reflection spectrum. Fortunately, a position in the sinusoidal shape corresponds to the position of the crack in GFRP.

Another crack was grown in a similar way but away from the first crack in a coupon containing 30 mm CFBG sensor. The first crack in the coupon was approximately at 5 mm from the low wavelength end and the second crack was grown approximately at 20 mm from the low wavelength end, making the crack locations 15 mm apart from each other. The reflected spectrum was then recorded with the coupon containing two cracks, 15 mm apart. The position of the crack in reflection spectra was calculated as mentioned before and is denoted by a vertical line and the uncertainty is indicated by the dotted lines in Figure 5.15. It can be noted that the position of the crack is not at the minimum of the dip. Takeda et al had suggested in their work on matrix crack in CFRP laminates that the position of the crack is at the minimum of the dip [Okabe et al., 2004]. But it could be clearly seen in our case that the position of crack is not at the minimum of the dip, though the uncertainty in the crack position with respect to the CFBG makes a firm conclusion impossible. The modelling, described in section 5.5, sheds further light on this issue and indicates the exact position of the crack with respect to the perturbation in the reflection spectrum.

![Figure 5.15. Reflection spectra in a 30 mm CFBG containing two cracks, 15 mm apart. Long vertical line denotes the position of the crack and the small dotted line denotes the uncertainty in locating the position of crack.](image-url)
To study how the characteristic shape change in the reflected spectra was related to the crack position, the spectra were predicted using a stress transfer model and OptiGrating, version 4.2. A stress transfer model was required to provide the strain distribution in the composite laminate in the vicinity of crack. In the section below, the strain distribution due to the transverse crack was obtained from the McCartney’s stress transfer model [McCartney, 1998] and the prediction of reflected spectra using the strain distribution from the model is discussed.

5.5. MODELLING AND PREDICTION

McCartney’s stress transfer model [McCartney, 1998] was used to provide the strain distribution due to a crack in the composite laminate and McCartney carried out the relevant calculations for this work. The mechanical properties used in the calculation are shown in Table 5.1. The strain distribution for an unloaded coupon in the 0° ply at a distance of 62.5 μm (i.e. half the optical fibre diameter) from the 0/90 interface, for a single crack in the 90° ply was predicted and is shown in Figure 5.16. The strain distribution shown in Figure 5.16 is for an unloaded coupon, with the zero on the x-axis representing the physical location of the crack. The strains are compressive in the 0° ply due to the thermal strains arising from the much smaller coefficient of thermal expansion parallel to the 0° fibres within a ply than in the transverse directions. Consequently, during cooling from the cure temperature, tensile strains develop in the 90° plies and balancing compressive strains in the 0° plies. In the plane of the crack, the thermal strain is relaxed, with the consequence that the compressive strain in the 0° ply is reduced, although as a result of the redistribution of strain in the vicinity of the crack, the strain is not reduced to zero.

The reflection spectra were then predicted using the OptiGrating software. As described in Chapter 3, the OptiGrating software requires the strain to be input as a function of distance. The stress transfer result in Figure 5.16 is well represented by a Lorentzian function:

\[ \varepsilon = \varepsilon_0 + \frac{2A}{\pi} \frac{w}{4(x-x_c)^2 + w^2} \]  

(eqn. 5.1)

with \( \varepsilon_0 = -0.00247\% \), \( x_c = 0 \) mm (crack position), \( w = 0.78 \) (distribution width) and \( A = 0.0023 \% \) (amplitude), where \( x \) is the distance along the grating. For the prediction of the CFBG reflected spectra for a 15 mm CFBG length using the OptiGrating software, the
properties mentioned in Chapter 3 have been used, with an index modulation, $\Delta n$, of 0.0005. The reflection spectra in the vicinity of crack using the Lorentzian fit to accurate stress transfer predicted for the index modulation 0.0005 are shown in Figure 5.17 (a). Okabe et al (2004) when modeling the reflected CFBG spectra due to transverse ply cracking in carbon fibre/epoxy resin cross-ply laminates, suggested that a better fit to the reflected spectrum could be obtained by optimizing the index of modulation, $\Delta n$. Figure 5.17(b) shows that a better fit can indeed be obtained by changing the value of $\Delta n$, in this case to 0.0002. In particular, the sinusoidal variation of the spectrum in the vicinity of the crack is now well-represented.

**Table 5.1. GFRP lamina properties [Ussorio et al., 2004]**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Young’s modulus, $E_1$ (GPa)</td>
<td>43</td>
</tr>
<tr>
<td>Transverse Young’s modulus, $E_2$ (GPa)</td>
<td>13</td>
</tr>
<tr>
<td>Transverse (through-thickness) Young’s modulus, $E_3$ (GPa)</td>
<td>13</td>
</tr>
<tr>
<td>Shear modulus, $G_{23}$ (GPa)</td>
<td>4.64</td>
</tr>
<tr>
<td>Shear modulus, $G_{12}$ (GPa)</td>
<td>4</td>
</tr>
<tr>
<td>Shear modulus, $G_{13}$ (GPa)</td>
<td>4</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu_{23}$</td>
<td>0.4</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu_{12}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu_{21}$</td>
<td>0.091</td>
</tr>
<tr>
<td>$\alpha_1$ (coefficient of thermal expansion parallel to fibres, $K^{-1}$)</td>
<td>$8.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\alpha_2$ (coefficient of thermal expansion perpendicular to fibres, $K^{-1}$)</td>
<td>$34.3 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\Delta \alpha \Delta T$ ($\Delta \alpha$ is the difference between the coefficients of thermal expansion; $\Delta T$ is the temperature difference between room temperature and the resin ‘lock-on’ temperature during cure)</td>
<td>$3.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$b$, full thickness of outer 0° ply (mm)</td>
<td>0.5</td>
</tr>
<tr>
<td>$d$, half thickness of inner 90° ply (mm)</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 5.16. Predicted strain profile in the $0^\circ$ ply at a distance of 62.5 $\mu$m from the 0/90 interface.

(a)  

(b)  

Figure 5.17. Predicted spectra using the accurate stress transfer predictions for (a) $\Delta n = 0.0005$, and (b) $\Delta n = 0.0002$

(a)  

(b)  

Figure 5.18. Predicted spectra using the modified Lorentzian fit (half amplitude) for (a) $\Delta n = 0.0005$, and (b) $\Delta n = 0.0002$
However, it has to be noted that the stress transfer model has calculated the value of the strains at the position of the optical fibre core without taking into account (a) the replacement of the reinforcing fibres (diameter, 16 μm) and matrix by the optical fibre itself (diameter, 125 μm) and, (b) the possibility of matrix non-linearity. Both of these effects are likely to reduce the local strain magnification experienced by the CFBG sensor. Hence the peak strain in the Lorentzian function was reduced by a factor of 2, while retaining as far as possible the shape predicted by the stress transfer model (Figure 5.16), and the resulting predicted spectrum is shown in Figure 5.18(a) for both index modulation of 0.0005 and 0.0002. The predicted reflection spectra is now in much better agreement with the experimentally measured spectrum for both $\Delta n = 0.0005$ and $\Delta n = 0.0002$. Closer agreement between the simulation and the experiment is found by reducing the value of the peak strain to account for the likely reduction in the strain magnification and at the index modulation of 0.0002. Hence, it appears likely that the detailed predictions of the stress transfer model in the vicinity of the crack are at least as important as modifications to the value of the index modulation, $\Delta n$, for an accurate simulation of the reflected spectra.

To locate the position of the crack, the full width at half maximum (FWHM) is taken as the reference. The FWHM corresponds to the physical length of the CFBG i.e. the sensor length. As the prediction was made for a 15 mm CFBG length with the crack located at 5 mm from the low wavelength end, the FWHM in the reflected spectrum corresponds to 15 mm and the 5 mm location is calculated from the low wavelength end which would provide the exact location of the crack. In all cases of Lorentzian fit and modified Lorentzian fit, the crack position in the simulation (represented by dotted vertical line in all the reflection spectra) is found to be on the lower wavelength side of the deep valley in the reflected spectra, corresponding to distances of up to 1 mm (Figure 5.18(b)). Hence, the simulation confirms that the minimum in the spectrum does not correspond to the precise physical location of the crack, but the cracks lie away from the minimum towards the low wavelength.

The prediction of uniform FBG reflected spectra was also carried out using the modified half amplitude Lorentzian function and the index modulation of 0.0002. Figure 5.19 (a) shows the predicted reflected spectra of uniform FBG before any crack, and Figure 5.19 (b) shows the predicted FBG reflected spectra after the crack under 0% strain. The crack was placed at the 5 mm in the 10 mm length FBG. The FBG reflected spectra before crack development showed a single peak and are symmetrical. After the crack, the
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predicted spectrum is asymmetrical with skewing at the higher wavelength end. The resulting predicted FBG reflected spectrum before and after cracking was in good agreement with the experimental spectrum (Figure 5.10).

![Figure 5.19. Predicted uniform FBG reflected spectra for coupon (a) before crack and (b) after crack using the modified Lorentzian fit (half amplitude) and Δn = 0.0002](image)

5.6. DISCUSSION:

5.6.1. Reflection spectra changes recorded by the uniform FBG:

Reflection spectra recorded for the 10 mm uniform FBG at various strains due to transverse cracking shows broadening on the longer wavelength side of the main peak, and with additional peaks of weaker intensity on the longer wavelength side. The qualitative explanation for these results follows the description given by Ussorio et al [25,93].

When the composite cross-ply laminates are fabricated, due to difference in thermal coefficient of expansion between the 0° ply and 90° ply, thermal strains were locked in. The 0° ply experiences thermal compressive strain, which shifts the reflection spectrum to lower wavelength as shown in Figure 5.3. When the transverse cracks were grown, it locally releases the thermal stresses developed during processing. As a result the compressive thermal strain in the longitudinal ply is relaxed locally (as shown in the strain distribution from the stress transfer model in Figure 5.16). These strain changes due to cracking were localized and occur typically over lengths of about one transverse ply thickness on either side of the crack, in this case over a length of about 4 mm of the Bragg grating. For the remaining 6 mm of the Bragg grating, the grating period is undisturbed by the strain field surrounding the crack. Hence the grating spacing of the FBG sensor embedded in the 0° ply experiences, a) the local increase in strain in the vicinity of crack and b) unchanged strain away from crack. The former contributes to the additional reflections at high wavelengths, producing a skewing of the spectrum in the FBG reflection
spectrum and the latter contributes to the main peak of the spectrum approximately at the same wavelength as the peak for the undamaged coupon. This effect was accentuated when a strain was applied to the composite, since the 0° plies see an enhanced local strain in the plane of the crack because the transverse ply crack has lost its ability to carry load across the crack plane. Hence the peak reflected wavelength remains in its position as in the uncracked strained coupons but the reflection at high wavelength has moved to higher wavelengths thereby broadening the spectrum.

5.6.2. Reflection spectra changes recorded by the Chirped FBG:

In the vicinity of the crack, the reflection spectrum recorded by the CFBG embedded in the composite laminate shows a sinusoidal shape change; first with a fall in intensity followed by a rise and fall to the undisturbed value. This shape change occurs at a particular location, corresponding to the location of the crack. The characteristic shape change in the reflection spectrum is explained as follows.

The non-uniform residual strain distribution due to the crack in the transverse ply produces a sharp narrow peak at the crack location as the compressive strain in the 0° ply is released by the transverse crack in 90° ply, shown in Figure 5.16. This strain distribution disrupts the linear increase of the pitch length of the chirped grating, causing the grating period to change unevenly. This change in the grating period due to the crack (calculated from the equations 3.13 and 3.14) is shown in Figure 5.20.

![Graph showing grating period changes](image)

Figure 5.20. Grating period calculated for the CFBG of 15 mm length from the axial strain before and after crack.
From Figure 5.20, it could be noted that the grating period at the vicinity of the crack changes unevenly but away from the crack it remains the same. At the vicinity of the crack, particular grating periods are lost at a few positions and particular grating periods are gained at other positions compared to grating periods in uncracked specimens. As the density of the grating period corresponds to intensity of the reflected spectrum, any reduction in the grating period density leads to a reduction in the intensity of the reflected spectrum at particular wavelengths and an increase in grating period density leads to an increase in the intensity of the reflected spectrum at other wavelengths. Far from the crack, the strain field in the composite is not disturbed, so that the reflected spectrum retains its undisturbed shape.

5.7. CONCLUSIONS

Uniform and chirped FBG sensors have been embedded within the 0\(^0\) ply of transparent cross-ply GFRP composite coupons and changes to the reflected spectra as a function of strain and crack development have been studied. In the case of a uniform FBG, the spectra of undamaged material have a single peak and a symmetrical shape. After the formation of a crack, the spectra become skewed in shape, with a broadening of the spectra on the higher wavelength side. Secondary peaks in the spectrum on the higher wavelength side become more prominent with increasing applied strain. For the CFBG, a spectral band of wavelengths are reflected and are shifted uniformly to higher wavelength values with increasing strain. For coupons containing a crack, a CFBG shows an approximately sinusoidal variation of the intensity of the reflected spectrum at the position of the crack, enabling both crack development and crack position to be identified. The changes in the spectra of both types of FBG are due to enhanced local strains in the 0 ply due to the development of a crack in the transverse ply. Simulations of the CFBG reflected spectra for the case of a coupon containing a matrix crack are in reasonable agreement with the experimental results, particularly when the strain magnification predicted by a stress transfer model is reduced to account for the presence of the optical fibre and possible matrix non-linearity.

Thus the main conclusions from this part of the study are

- The presence of a crack in a cross-ply laminate could be identified by the embedded uniform FBG sensor at the 0/90 interface from the skewing and broadening of spectra towards the higher wavelength.
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- The effect of identifying the crack in the composite laminate could be enhanced by recording the reflection spectra at increasing strains.
- The presence of the crack could be identified by the chirped FBG from the approximate sinusoidal shape in the reflection spectrum.
- In addition to identifying the cracks, the location of the crack could be predicted with the use of a CFBG from the characteristic change in the CFBG reflected spectrum.
- The location of the crack in the CFBG reflected spectrum is not the minimum of the dip, but at a distance of about 1 mm from the position of the minimum towards the low-wavelength end of the reflected spectrum.
- The spectrum could be predicted from the strain distribution obtained from a stress transfer model with the aid of OptiGrating software and the predicted results agree well with the experimental results.

5.8. SUMMARY

This chapter presented the results and discussion on the response of both uniform and chirped FBG’s to matrix cracking. The advantage of using the chirped FBG lies in the crack identification and crack location. The precise location of the crack in the composite laminate is identified from the reflection spectrum and hence this technique is a new reliable approach for damage detection in composites. In the next chapter, the work was extended to study the disbond detection in composite-composite bonded joints using CFBG sensors. The forthcoming chapter will discuss the detection of disbond initiation and the progression of the disbond when analysing the CFBG reflected spectra.
6.1. INTRODUCTION

A chirped FBG has proved to be successful in determining and locating the damage (a transverse crack) in a composite crossply laminate (details in Chapter 5). For bonded joints, the integrity of the joint during its designed life span is an important factor. Any loss in this integrity in terms of disbond initiation and growth is of major concern and as a result there are a number of potential inspection techniques to detect them. In this chapter, a CFBG sensor embedded in the composite is investigated as a method of detecting the disbond initiation and progression in a bonded joint. It is emphasised that the sensors are embedded in the adherend and not within the bond line which may be a disbond initiator. In the first section, the response of a 45 mm CFBG to the disbond is discussed. Subsequently it is shown that the initiation and progression of a disbond could also be detected by CFBGs of different length, i.e. 15, 30 and 60 mm. The modelling of the strain distribution due to a disbond in a bonded joint is presented along with the prediction of reflection spectra using commercial software for different CFBG lengths. In section 6.5, the experimental results are discussed and finally conclusions are drawn in section 6.6.

6.2. RESPONSE OF 45mm CFBG SENSOR TO DISBOND

Single lap bonded joints with a 45 mm CFBG sensor embedded in one of the composite adherends were manufactured as reported in Chapter 4. The low-wavelength end of the CFBG sensor was adjacent to the cut end of the adherend and the sensors were 0.5 mm from the bond line, as they were embedded at the first 0/90 interface of the (0₂/90/0₆), laminate. The reflection spectrum of the bonded joint before disbond initiation, under unloaded conditions, is shown in Figure 6.1 (a). In this reflected spectra, a small dip at 1552 nm (labelled W) is evident. This dip is due to the wire spacer (aluminium wire of
thickness 0.4 mm) placed to obtain a 0.4 mm adhesive thickness. The reflection spectrum under loaded conditions (5 kN) was recorded and is shown in Figure 6.1 (b). The comparison of the reflection spectra before and after loading shows the shift in the spectra to higher wavelengths due to the increase in all of the grating periods of the CFBG (see the detailed discussion in Chapter 5). The bonded joints were then subjected to fatigue cycling to initiate and grow a disbond. The cyclic loading was interrupted at increasing numbers of cycles in order (a) to record the position of the growing disbond front in the transparent lap joint using an in situ digital camera, and (b) to record the reflected spectrum of the CFBG sensor with the joint subjected to a constant load of 5 kN.

![Figure 6.1](image)

**Figure 6.1.** (a) CFBG reflected spectra from the bonded joint under unloaded condition. The dip (labelled W) at 1552 nm represents the wire spacer kept from achieving the adhesive thickness (b) Comparison of CFBG reflected spectra before and after load.

6.2.1. Detection of disbond initiation

The following section provides a typical example of disbond initiation detection. In this joint, a disbond had initiated at the edge of the free end of the bonded joints after a few thousand fatigue cycles (7500 cycles). The reflection spectrum recorded after the disbond initiation (7500 cycles) and the digital image of the GFRP bonded joint at 7500 cycles with the disbond is shown in Figure 6.2. Comparison of the reflected spectra before disbonding and after disbonding (Figure 6.2(b)) showed a shift in the low wavelength end of the reflection spectrum to lower wavelengths. The other parts of the reflection spectra remain unchanged.
Figure 6.2 (a) GFRP lap joint with a disbond which has just initiated. The wire used to produce a uniform thickness of glue line can be seen at W extending across the centre of the joint. (b) Reflected spectra from the CFBG after 4000 cycles (before disbond) and 7500 (after disbond initiation), showing the wavelength shift.

Figure 6.3 (a) CFBG reflected spectrum showing the shift of the low wavelength end of the spectrum as the disbond extends along its full width. (b) Reflected spectrum recorded at 0 cycles and 9000 cycles; with the dip indicating the disbond front.
At 7500 cycles, the disbond had initiated but not yet grown fully across the specimen width. With increasing cycle number, the disbond grew across the width and at these increasing numbers of fatigue cycles the low wavelength end of the spectra moved towards the lower wavelengths, as shown in Figure 6.3 (a). Once the disbond has fully extended across the bond width, the shift in the spectrum towards lower wavelength was complete. At this point, the end of the disbonding adherend is now fully relaxed and hence the reflected spectrum for the lowest wavelengths (corresponding to the free edge of the adherend) stabilises. In addition to this shift, perturbation or dip develops in the reflection spectrum and Figure 6.3 (b) clearly demonstrates the additional feature (dip at the low wavelength end) that appears on the reflected spectrum after 9000 cycles. The shape of the dip is approximately symmetrical.

6.2.2. Detection of disbond propagation:

With further fatigue cycling, the disbond grew along the length of the bonded joint, as shown in Figure 6.4. The figure shows the digital image of the transparent GFRP joint with a disbond after 9,000, 11,000, 12,000 and 13,200 cycles, when the disbond had extended to points A, B, C and D respectively. It is perfectly feasible for a disbond to initiate at the other end of the bonded joint and indeed such a disbond is evident in Figure 6.4. The reason this disbond had no effect on the reflected spectrum is simple. The CFBG is 45 mm long and is positioned at the lower end of the joint. As the other end of the joint is 60 mm away the disbond would need to progress some 15 mm to have any effect on the spectrum. In this case the disbond from other end has not grown sufficiently for this to occur (the response of the CFBG to disbonding adjacent to the high wavelength end of the sensor will be discussed in Chapter 7). Figures 6.5 (a), (b),(c) and (d) shows the reflection spectra obtained from the CFBG sensor of the disbonded specimen at 9,000 cycles, 11,000 cycles, 12,000 cycles and superposition of the CFBG reflected spectra for 9,000, 11,000, and 12,000 cycles with the disbond A, B and C respectively. The reflection spectra at increasing fatigue cycles shows the perturbation moving to the high wavelength end of the reflection spectrum. From the superposition, the movement of the dip in the spectrum towards high wavelength is very clear.
Figure 6.4. GFRP lap joint with the growth of the disbonds to positions A, B, C and D after 9,000; 11,000; 12,000 and 13,200 cycles, respectively.

Figure 6.5. CFBG spectra after (a) 9,000 cycles, (b) 11,000 cycles, (c) 12,000 cycles and (d) superposition of 9,000, 11,000 and 12,000 cycles spectra showing the movement of the perturbation in the spectrum to higher wavelengths as the disbonds grow.

Initially the minimum of the dip in the reflected spectra was assumed to be the position of the disbonds front. Figure 6.6 shows a plot of the position of the disbonds front.
(from the CFBG spectrum) plotted against the actual disbond front position as measured directly from images of the transparent bonded joint. The error bars indicated in Figure 6.6 represent the uncertainty in identifying both the position of the minimum of the dip in the reflected spectrum and the difficulty of identifying the precise position of the disbond front from images such as those shown in Figures 6.2 and 6.4. Despite these uncertainties, it was noted that the movement of the perturbation in the spectrum is directly related to the disbond position. In order to check the assumption, the reflected spectra were predicted theoretically for known disbond lengths of 5 mm and 10 mm. The relationship between the perturbation in the reflected spectrum and the actual position of the disbond front as physically measured on the transparent specimen was explored and is reported in section 6.4.

Figure 6.6. Disbond front measured from the position of the minimum of the dip in the reflected CFBG spectra plotted against the disbond front position measured from photographs of the joint

After the modelling and the prediction of the reflected spectra due to disbond of known lengths was completed, it was noted that the minimum of the large dip is not the actual position of the disbond front. The disbond front is located about 1.5 mm away from the minimum in the reflected spectrum, towards the low wavelength end of the CFBG sensor (see later; section 6.4). The plot of the position of the disbond front obtained from the CFBG spectra, corrected for the actual position of the disbond front in relation to the minimum of the dip in the spectrum, against the measured position of the disbond front
obtained from images of the bonded joint is shown in Figure 6.7. From the figure, it is evident that the disbond front could be located to within about ± 2 mm.

![Disbond length comparison](image)

Figure 6.7. Comparison of the disbond length obtained using the CFBG measurements (after the corrections) with the disbond length measured from photographs of the bonded joint.

6.3. RESPONSE OF 15, 30 AND 60 mm CFBG SENSORS TO DISBONDING

In the previous section, it was shown that the disbond initiation and growth from one end of the adherend could be detected using a 45 mm CFBG sensor embedded in one of the adherends. In this section, the same experiments were performed on various CFBG sensors with lengths of 15, 30 and 60 mm and their responses to the disbond in the bonded joints were studied. A fatigue load with a peak value of 8 kN, R value 0.1 and frequency of 5 Hz were applied. All of the CFBGs have the same bandwidth of 20 nm which means that they have different chirp rates as discussed in Chapter 4.

When the disbond occurs in the bonded joint containing a 15 mm or 30 mm or 60 mm CFBG sensor, the reflected spectra shows the shift in the low wavelength end of the reflected spectrum to lower wavelengths as reported for the 45 mm sensor, discussed earlier. This shift in the wavelength is an indication of disbond initiation. Figure 6.8 and Figure 6.9 shows the comparison of reflected spectra from 15 mm CFBG before and after disbonding and the reflected spectra from 60 mm CFBG sensor before and after disbonding respectively.
obtained from images of the bonded joint is shown in Figure 6.7. From the figure, it is evident that the disbond front could be located to within about ±2 mm.

![Figure 6.7. Comparison of the disbond length obtained using the CFBG measurements (after the corrections) with the disbond length measured from photographs of the bonded joint.](image)

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The same procedure was adopted to monitor the disbond progression for the 15 mm, 30 mm and 60 mm CFBG sensor lengths as was previously undertaken for the 45 mm sensors. Figure 6.10 shows image of transparent GFRP-GFRP bonded joint containing the 15 mm CFBG sensor after 14,000, 15,000, 17,000 and 19,000 cycles, with the arrows indicating the position of the sensor in relation to the growing disbond front. In Figure 6.11, the reflected spectra from 15 mm CFBG sensor for 12,000, 14,000 and 15,000 cycles are superimposed to study the variation of the spectra due to disbond growth. The superposition of the reflected spectra from the 30 mm CFBG sensor for 12,000, 13,000 and 14,000 cycles are also shown in Figure 6.12. As with 45 mm sensor, progression of the disbond front for the 15 mm and 30 mm CFBG sensors is characterised by a distinct perturbation in the spectrum which moves to higher wavelengths as the disbond front grows. However, the shape of the perturbation for the 15 mm, 30 mm and 60 mm sensor is
different to the symmetric dip in the spectrum found for a 45 mm sensor. For the 45 mm sensor, the perturbation appears as a small rise and then a gentler fall in the reflected intensity, followed by a small rise. Additionally, the shapes are again different for the 30 mm and 60 mm CFBGs, as is evident in Figures 6.12 and 5.13 respectively. These differences in the shape of perturbation in the reflected spectra for different sensor lengths are explored in Section 6.4.3, below.

Figure 6.10. Image of transparent GrFp-GFRP bonded joint with 15 mm CFBG sensor after 14,000, 15,000, 17,000 and 19,000 cycles

Figure 6.11. Reflected spectra from 15 mm CFBG sensor due to disbonds corresponding to 12,000, 14,000 and 15,000 cycles
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Figure 6.12. Reflected spectra from 30 mm CFBG sensor due to disbonds corresponding to 12,000, 13,000 and 14,000 cycles.

Figure 6.13. Reflected spectra from 60 mm CFBG sensor showing the shape of the perturbation due to disbond.

The prediction of the reflection spectra for the four different CFBG sensor lengths (see section 6.4.3) also predicted the shape differences of the perturbations. The shapes of the predicted spectra were in good agreement with the differences seen in the experimental results for the different sensor lengths. In all cases, the actual position of the disbond front is found to be slightly towards the low-wavelength end of the spectrum compared to the position of the minimum of the perturbation. The actual positions of the disbond front were corrected with the aid of the predictions and the CFBG sensor results and were plotted against the measured disbond front from photographs. Figure 6.14 shows the comparison of the in situ photographic measurement of disbond front position with the CFBG sensor determination of disbond front position for sensor lengths of 15 mm, 30 mm, 45 mm and 60...
mm. Overall, the disbond front position could be measured with an accuracy of about ±2 mm with the CFBG.

Figure 6.14. Comparison of disbond front position obtained using CFBG sensors of various lengths (15, 30, 45, 60 mm) with in situ photographic measurements of the disbond front. The dotted line would be the line of perfect agreement between the two measurements.

6.4. MODELLING AND PREDICTION

6.4.1. FE modelling:

A 2D finite-element (FE) modelling was undertaken by my colleague Yannick Rech [private communication] using ABAQUS to predict the approximate longitudinal strain distribution at the position of the sensor (0.5 mm from the bondline) when a disbond between the two adherends has grown to any given length. Using this strain profile, the reflected spectra were predicted in order to understand the effect of disbond to CFBG sensor. The optical fibre was not included explicitly in the model, but the strains have been extracted from the FE model at the position of the sensor. The properties used in the modelling are summarised in Table 4.4 (Chapter 4) and Table 5.1 (Chapter 5) for the isotropic (adhesive) and orthotropic (composite) materials respectively. The mesh size used was 0.1 mm x 0.1 mm. Figure 6.14 shows the FE strain distribution of the adhesively bonded joint at one end of the adherend (around the low strain region of the optical fibre) loaded to 5 kN. The white bands are the 90° ply regions and the position of the optical fibre is at the interface of the first 0° and 90° ply (near to the bondline). Hence, moving from the lower 0/90 interface in the upper adherend (shown arrowed in Figure 6.15), there is 0.5 mm of the 0° ply (upper adherend), then the more compliant adhesive, then the 0° ply of the
second adherend, before reaching the first 0/90 interface in the second adherend. It can be seen from the colour plot and the colour key that the longitudinal direct strains (E11), at the optical fibre position near the free end of the adherend, are low. As the load transfers from the lower (loaded) adherend through the adhesive to the upper adherend, the strains in the upper adherend begins to increase with increasing distance from the end of the adherend.

![Figure 6.15. Strain distribution in the region of the end of one adherend for a joint without a disbond. The white bands are the positions of the 90° plies](image)

The strains along the centreline at the position of the optical fibre were extracted from the FE results and are plotted as shown in Figure 6.16. In Figure 6.16, the axial strain along the 60 mm joint with no disbond and when loaded to 5 kN, is shown. The strain is shown as a function of distance from the end of the adherend which contains the embedded CFBG sensor. At the free end of the adherend the longitudinal strains are low. There is a compressive strain at the start which may be due to the bending effect in the single lap joint. As the load transfers from the lower (loaded) adherend through the adhesive to the upper adherend, the strains in the upper adherend containing the sensor begin to increase with increasing distance from the end of the adherend and reach a plateau region after about 5 mm. The plateau region is, of course, the result of no load transfer at the centre of the long joint. The strains then increase again as the other end of the overlap is approached and the load transfer process begins again with loads transferred from the lower adherend.
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The modelling was then extended to the 60 mm bonded joints including disbond lengths of 5 mm and 10 mm. The 2D FE models were run with the disbond positioned on the lower adhesive-adherend interface, which is consistent with the observed experimental disbond path. Figure 6.17 shows a schematic of the adherends (one of the adherends has the embedded with the CFBG sensor) with a disbond used in the modelling and the corresponding FE results for the strain distribution for the case of a 10 mm disbond. The path of the optical fibre runs just below the marked 0/90 interface. The maximum strain shown in the figure has been limited and the region coloured grey indicates strains above this set value. It can be seen that the right hand “free” part of the upper adherend experiences low values of strain. This lower strain extends for the length of disbond region except around the disbond front. Around the disbond front, there is a small rise and fall in the strain (perturbation), before rising to a plateau value. Meshes with element sizes significantly smaller than the distance of these perturbations from the overlap end (0.1 mm and 0.05 mm) showed that these perturbations were a characteristic feature of the strain field within the adherend. The perturbation in the disbanded cases was made more complicated by the interaction of the disbond front strain field and the load transfer strain field.

Figure 6.16. Strain experienced by the bonded joint of 60 mm overlap length, under no disbond and loaded (5 kN) condition.
Figure 6.17. Magnified view of the strain distribution towards the end of one adherend derived from the finite-element analysis.

Figure 6.18 shows the strain distribution, extracted at the position of the optical fibre from the FE model, within the first 20 mm of the 60 mm overlap region for three cases: no disbond, a disbond 5 mm in length and a disbond 10 mm in length. For the "no disbond" case, the data show the trend described above, i.e. starting from a low stress near the end of the adherend, increasing to a plateau region after about 5 mm and remaining constant over the one-third of the other overlap end. For the two other cases, the 5 mm disbond and the 10 mm disbond, the trend was similar except for an increase in the unstrained length of the adherend due to the disbond and a small perturbation in the strain distribution at the beginning for each case. The small perturbations for the 5 mm and 10 mm disbonds seen in the figure are not an artefact of the mesh size but are probably due to the complexity of the strain from bending, and the interaction of the disbond strain field with the load transfer field.
Figure 6.18. Strain distribution along the fibre optic centre line position for the cases of no disbond, and disbond lengths of 5 mm and 10 mm derived from the finite-element analysis.

6.4.2. Reflected spectra predictions using OptiGrating

The strain profile obtained due to the disbond from the FE analysis with disbonding (Figure 6.18) was a complex shape. Since the method of approximate fit was used in predicting the reflection spectra from OptiGrating, the complex shape was fitted with three piece-wise continuous functions using Boltzmann sigmoidal and Lorentzian fits. A comparison of the input longitudinal strain distribution after the approximate fit and the strain distribution obtained from the FE analysis (Figure 6.19) show that these are almost identical in advance of the plateau, and differ by no more than 6% in the plateau region where small strain changes are not important with regard to the reflected spectrum. The other parameters used in the OptiGrating prediction are shown in Chapter 3.

The predicted reflection spectra for a 45 mm CFBG sensor obtained using this method of fit to the strain distribution for disbond of 5 mm and 10 mm is shown in Figure 6.20. In these predicted spectra, the actual position of the disbond front in the modelling is shown by a small vertical line. The simulations show that the small perturbation in the strain field in advance of the disbond front produces a small dip in the reflected spectrum which was not seen in the experimental results, possibly because this small dip had a similar magnitude to the noise in the spectrum. The important feature of the predicted spectra is the large dip, which was similar to the experimental results. It is clear from the simulations that the minimum of the large dip was not the actual position of the disbond front but was located about 1.5 mm away from the minimum in the reflected spectrum,
shown by the vertical line in Figures 6.20(a) and 6.20(b), towards the low wavelength end of the CFBG spectrum. Superimposing the two predictions (Figure 6.21), it can be clearly seen that there was a shift in the perturbation towards higher wavelengths due to the disbond growth as was observed in the experimental results.

![Figure 6.19. Comparison of input strain for the optical modelling compared with the FE strain profile](image)

![Figure 6.20. Predicted reflected spectrum for disbond lengths of (a) 5 mm and (b) 10 mm. The position of the disbond front in the model is indicated by a short vertical line in each case.](image)
6.4.3. Shape of the perturbation for different CFBG chirp rates and sensor lengths.

6.4.3.1. Different chirp rates:

The reflection spectra was predicted for the experimentally investigated CFBG lengths of 15, 30 and 60 mm using the strain profile predicted from the FE analysis for disbonding. The sensors had different lengths but the same optical bandwidth was achieved by different chirp rates in the sensors. Figure 6.22 shows the reflected spectra predicted for 15, 30, 45 and 60 mm CFBG lengths when the joint has a 5 mm disbond. It can be seen from the predicted spectra that the shape of the perturbation differs for each CFBG sensor lengths and comparison with figures 6.11, 6.12 and 6.13 shows that there is good agreement between the shape of the predicated spectra and experimental reflection spectra. For each of the CFBG lengths, the position of the disbond front in the modelling is shown by the short vertical line in Figure 6.22 and in all cases, the position of the disbond front is away from the minimum of the dip and towards the low wavelength end. However each spectrum shows a different distance between the minimum of the dip and the actual position of the disbond front, varying from about 0.5 mm for the 15 mm sensor, to about 1.5 mm for the 60 mm sensor.
Figure 6.22. Predicted reflection spectra for a 5 mm disbond for CFBG sensor lengths of (a) 15 mm, (b) 30 mm, (c) 45 mm, and (d) 60 mm (the spectral bandwidth is constant). The position of the disbond front for each case is indicated by the short vertical line on the spectrum.

6.4.3.2. Same chirp rate

The strain profile obtained from the FE analysis at the position of the optical fibre for a disbond of 5 mm was used within OptiGrating to determine the effect of keeping the chirp rate, for the four different CFBG sensor lengths (15, 30, 45 and 60 mm). Figure 6.23 shows predicted spectra for the 15, 30, 45 and 60 mm CFBG sensors assuming the same chirp rate of 3 nm/cm (as the chirp rate was maintained constant for each of the four different lengths the optical bandwidth varied). In the figure the position of the disbond is also indicated by the small vertical line. It can readily be seen from Figure 6.23 that the shape of the perturbation is identical for all four CFBG sensor lengths, demonstrating that it is the chirp rate that determines and characterises the shape of the perturbation. Additionally, with a fixed chirp rate the location of the disbond front is constant.
Figure 6.23. Predicted reflection spectra for a 5 mm disbonds for CFBG sensor lengths of (a) 15 mm, (b) 30 mm, (c) 45 mm, and (d) 60 mm (the chirp rate is constant; hence spectral bandwidth changes). The position of the disbonds front is indicated by a short vertical line on each spectrum.

6.5. DISCUSSION

The experimental observation of the CFBG reflection spectra due to a disbonds in composite-composite bonded joints showed four main results. These are;

1) The shift of the low wavelength end of the CFBG reflection spectrum to lower wavelengths on disbonds initiation.

2) A perturbation in the spectra associated with the disbonds.

3) The movement of the perturbation to higher wavelengths as the disbonds grow.

4) A different shape for the perturbation for different lengths of CFBG.

The reason for the shift to lower wavelengths is as follows. The consequence of the onset of a disbonds is that it unloads the free end of the adherend. Hence, the CFBG sensor is also unloaded locally to the disbonds, which causes a relaxation of the grating spacing. Consequently, the grating spacing is decreased adjacent to the disbonds region, so that reflections at lower wavelengths are seen. No changes occurred to the spectrum at higher
wavelengths, and this is verified by the constant position of the dip in the spectrum due to the position of the wire spacer.

The perturbation in the spectra can be explained as follows. Figure 6.24 shows the changes in grating period as a consequence of the strain distribution shown in Figure 6.18 for the 5 mm disbond. The density of the grating period at any position in the sensor is related to the slope of the grating period/distance curve (Figure 6.24). The density is higher when the slope is lower because the grating period is changing more slowly. The reflected intensity is proportional to the grating density. Hence, in the Figure 6.24, for the “after disbond” case, the intensity is roughly constant up to about 4.5 mm and between 4.5 mm and 5 mm the intensity is enhanced. After 5 mm, the intensity falls because the slope is lower than it was initially and the intensity increases to its plateau value at about 7.5 mm. Hence the intensity perturbation consists of a small rise followed by a dip and then an increase to the plateau value.

The disbond progression is characterised by the shift of the perturbation to higher wavelengths. This is because, as the disbond increases in length, the strain distribution is displaced to new positions corresponding to higher wavelength values in the reflected spectrum and the perturbation moves to higher wavelength following the disbond movement.

![Figure 6.24.](image)

Figure 6.24. Comparison of grating period change before and after disbond along the length of grating for a 5 mm disbond.

The different experimentally determined shapes of the perturbations for different CFBG length values is related to the different chirp rate of the CFBG sensors which was
confirmed by the OptiGrating predictions. Different chirp rates provide different slope gradient in the grating period/distance curve, thereby varying the density of the grating period between 5 mm and 7.5 mm. Hence the perturbation in the reflection spectra is of different shape.

6.6. CONCLUSIONS
The main conclusions from this chapter are:

1) Disbonds occurring during service due to cyclic loading in a composite-composite bonded joint can be detected by embedding a CFBG sensor in one of the composite adherends close to the bondline (in this case 0.5 mm from the bondline) with the CFBG sensor being embedded such that the low wavelength end is adjacent to the free end of the adherend.

2) The shift of the low wavelength end of the reflection spectrum of the CFBG sensor to lower wavelengths is an indication of disbond initiation from the free end of the adherend.

3) The movement of the perturbation in the CFBG reflection spectra to higher wavelengths is an indication of disbond growth from the end of the bonded joint.

4) A combination of finite-element modelling and commercial FBG software enables the actual position of the disbond front to be related to the perturbation in the reflected spectrum. The position of the disbond front does not coincide with the minimum of the perturbation, but is located about 2 mm towards the low wavelength end of the spectrum.

5) The chirp rate of the CFBG sensor plays an important role in the shape of the perturbation. CFBG sensors of different chirp rate show different shapes for the perturbation. CFBG sensors of different lengths but same chirp rate show the same perturbation shape for the same strain distribution.

6) In all cases, despite the different chirp rates, the position of the disbond front is located within about 2 mm, and this precision is likely to dependent on adherend material and sensor location.

6.7. SUMMARY
In this chapter, disbond development from only one end of the bonded joint (from the lower wavelength end of CFBG) has been considered. However, it is perfectly feasible
that the disbond could occur from either end, or indeed both ends, of the bonded joint. As a result the next Chapter will consider the response of a CFBG sensor to a disbond from the other end of the bonded joint (i.e. from the higher wavelength end) and additionally when a disbond occurs at both ends of the joint.
CHAPTER 7

DISBOND DETECTION IN ADHESIVELY BONDED COMPOSITE JOINT FROM THE HIGH WAVELENGTH END OF THE CFBG

7.1. INTRODUCTION

The disbond initiation and progression from one end of the bonded joint, i.e. from the lower wavelength end of the CFBG, could be detected from the reflected spectra of the CFBG (details in Chapter 6). As it is perfectly feasible that the disbond can occur from either end of the bonded joint or indeed both ends of the joint, the work is extended to show that disbond monitoring at either end or both ends of the overlap is possible with a single embedded sensor. In the present chapter, the responses of the higher wavelength end of the CFBG due to the disbond in its end and additionally at both ends are studied and the results and the discussion are presented.

7.2. RESPONSE OF THE 60 mm CFBG SENSOR TO DISBOND

The GFRP-GFRP composite single lap bonded joints were manufactured with a 60 mm overlap as discussed in section 4.2.2. To detect the disbond from the other end using the single CFBG sensor, the CFBG sensor length should extend the full length of the overlap. Hence the 60 mm CFBG length sensor was used for the 60 mm overlap bonded joint with the low wavelength end of CFBG terminating at the cut end of the adherend. Figure 7.1 shows the GFRP-GFRP composite bonded joint with a 60 mm CFBG sensor and the position of the sensor with respect to its grating period. The CFBG reflected spectrum was recorded before the disbond to form a reference spectrum. The bonded joints were then subjected to fatigue loading and the reflection spectra were recorded after every 100 fatigue cycles. The experimental procedures were similar to those employed for the disbond detection from the low wavelength end of the CFBG. The fatigue parameters were the same as those described in Chapter 4. The reflection spectra were all recorded at a load of 5 kN.
and subsequently the images of the transparent GFRP were recorded using the in-situ digital camera.

Figure 7.1. Schematic of a lap joint with a 60 mm length chirped FBG embedded in one adherend, with the low-wavelength end of the sensor adjacent to the adherend end.

After a few thousands cycles, disbonds could initiate at either end. The results of the disbond initiation from the high wavelength end are presented first in this chapter. Figure 7.2 shows (a) the transparent GFRP after 21,000 cycles with the disbond initiated and passing the sensor at the high wavelength end and (b) reflected spectra for a CFBG sensor which extends the full length of a 60 mm bonded joint, both before and after disbond initiation respectively. From the comparison of the reflected spectrum before fatigue cycling (hence before any damage development) and after 21,000 fatigue cycles (by which point a disbond had initiated adjacent to the high-wavelength end of the sensor) it could be noted that there is a shift in the high wavelength end of the CFBG reflected spectrum to higher wavelengths. This is a consequence of disbond initiation.

Figure 7.2. (a) Transparent GFRP-GFRP composite joint with the disbond at the high wavelength end of CFBG (b) CFBG reflection spectra before and after the disbond
Figure 7.4. CFBG reflected spectra showing the shift in the high wavelength to higher wavelength as the disbond extend across the width of the specimen.

Figure 7.5. Recorded CFBG reflection spectra when a disbond grows adjacent to the high wavelength end of the sensor after (a) 25000 cycles (b) 34000 cycles (c) 44000 cycles and (d) 51000 cycles. The dip in the spectrum caused by the disbond front is indicated by the arrow; the dip moves to lower wavelengths as the disbond grows with continued fatigue cycling.

In order to understand the effect of the disbond on the CFBG reflection spectrum, modelling work was undertaken and is discussed in the next section (section 7.3). This
modelling was done using the FEA package ABAQUS (to predict the strain distribution in a composite bonded joint due to disbond at the sensor position under loaded conditions) and the CFBG reflected spectra were predicted using OptiGrating. The modelling also established the relationship between the dip in the spectrum and the actual position of the disbond front. It was observed in the prediction that the position of the disbond was not the minimum of the dip in the reflection spectrum, but to the left of the dip and about 1.5 mm away from the dip. This correction has been used to locate the position of the disbond front from the CFBG spectra as the disbond front extends during fatigue cycling. The disbond front position was taken from the in-situ image of the bonded joint at the location of the optical fibre. Figure 7.6 shows the comparison of the position of the disbond front obtained from the CFBG reflection spectra with measurements of the disbond front position obtained directly from photographs, for two specimens. There is a good correlation between these measurements, which suggests that the disbond front position at the high-wavelength end can be measured to within about ±2 mm.

Figure 7.6. Comparison of the disbond front position measured using a sensor of 60 mm with the disbond front position measured directly from photographs. Here, the disbond is growing adjacent to the high-wavelength end of the sensor. The dotted line would be the line of perfect agreement between these measurements.

In addition to the response of the CFBG sensors to the disbond from the high wavelength end of the bonded joints, the simultaneous initiation of disbond at both ends of the bonded joint is shown in Figure 7.7. Figure 7.7 (a) shows the in-situ image of the GFRP
bonded joint with a disbond propagating from both ends of the bonded joint and Figure 7.7(b) shows the CFBG reflected spectrum. As shown in chapter 6, when the disbond initiates adjacent to the low wavelength end of the sensor, the low wavelength end of the reflected spectrum shifts to lower wavelengths and a dip is also observed relating to the disbond front. When the disbond initiates adjacent to the higher wavelength end of the sensor, the high wavelength end of the reflected spectrum shifts to higher wavelengths. Hence the initiation of debonding at both ends of the overlap can be detected.

Figure 7.7(a) insitu image of the GFRP bonded joint with the disbond propagated from both ends of the bonded joint (b) comparison of CFBG reflected spectra before disbond and after the disbond occurred at both ends of the bonded joint.

7.3. MODELLING AND PREDICTIONS

In Chapter 6, the reflected spectra predicted from OptiGrating with the aid of a 2-D ABAQUS FE model for the disbond at one end of the bonded joint (i.e. the lower wavelength end) were discussed. The FE modelling predicted the axial strain experienced by the optical fibre with the bonded joint under a tensile load of 5kN as a consequence of the disbond from the free end. Similar predictions of the reflected spectra for a disbond growing adjacent to higher wavelength end were undertaken, as follows. The FE modelling using ABAQUS with the disbond at the high wavelength end was carried by Capell [private communication], and the longitudinal strain at the position of the optical fibre sensor has been evaluated using an extension of the 2D analysis used previously [details in section 6.3]. Here the disbond was placed at the adherend–adhesive interface with the continuing adherend containing the CFBG sensor (note the high wavelength end of the sensor is now
adjacent to the disbond). Figure 7.8 shows the FE model for a disbond of length 10 mm; the location of the optical fibre is indicated by an arrow although the optical fibre is not included in the model. The longitudinal strain, (EI1) occurring at the position of the centre line of the optical fibre, and parallel to the length of the optical fibre, was extracted from the FE model and plotted as shown in Figure 7.9. The figure shows the strain distribution at the position of the optical fibre (a) before disbonding, and (b) for a disbond of length 10 mm adjacent to the high-wavelength end of the sensor (the applied load for the FE analysis was 5 kN, as in previous cases). The distance along the joint in figure is measured from the low-wavelength end of the CFBG sensor which is adjacent to the cut end of the adherend, with the disbond occurring at the high wavelength end of the bond overlap length.

For the “no disbond” case in Figure 7.9, the strain in the adherend at the position of the sensor increases as load is transferred from the upper adherend, increasing to a plateau region about 5 mm from the end of the adherend. At the other end of the overlap length, the strain in the same adherend increases as the load is shed from the termination of the other adherend. It should be noted that the small perturbations in the strain are not artifacts of the mesh size, but probably arise as a consequence of the complex strains induced by bending of the asymmetric joint under load. For the disbond length of 10 mm adjacent to the high wavelength end of the CFBG sensor, the strain at the lower and middle portion of the overlap is similar to the strain in the “no disbond” case. However, as the higher end of the overlap is approached the strain begins to increase and reaches a peak value adjacent to the disbond front (at 50 mm). For the remaining portion of the overlap i.e. for remaining 10 mm, the strain reduces due to the disbond. Again, the complexity of the strain field is due to the interaction between the flexure of the joint, the disbond strain field and the load transfer strain field. However, it is the rapid change in strain due to the load-transfer between the adherends which is the most important feature of the strain distribution with regard to the reflected CFBG spectrum. The strain distribution shown in Figure 7.9 was used to predict the reflected spectra using the OptiGrating software and the method of modification of the refractive index and grating period as a consequence of the strain profile. The parameters used in the prediction are discussed in Chapter 3.
Figure 7.8. FE model showing the strain distribution in the region of the end of one adherend for a composite bonded joint with a disbond of 10 mm.

(a)  

(b)  

Figure 7.9. (a) Schematic of disbond growing at the interface between the adhesive and the lower adherend (b) Finite-element prediction of the strain distribution at the centreline position of the optical fibre for the cases of no disbond, and a disbond of 10 mm adjacent to the high-wavelength end of the sensor.
Figure 7.10. The predicted CFBG reflected spectrum for a disbond of length 10 mm adjacent to the high-wavelength end of the sensor. The position of the disbond front is indicated by the short vertical line at about 1550 nm.

Figure 7.10 shows the predicted reflected spectrum using the strain distribution for a disbond of 10 mm. The predicted spectrum has a sharp dip at the higher wavelength end which is very similar in shape to the experimental results (see Figure 7.5). In Figure 7.10, the position of the disbond front in relation to the reflected spectrum is indicated by a small vertical line. It can be seen that the position of the disbond front corresponds to the beginning of the dip in the reflection spectrum i.e. the position of the disbond front is, again, not at the minimum of the perturbation but about 1.5 mm towards the low-wavelength end of the sensor.

7.4. DISCUSSION

The shift of the high wavelength end of the CFBG reflected spectrum to the higher wavelength end (Figure 7.4) can be explained as follows. For the disbond occurring adjacent to the high wavelength end of the CFBG sensor, the disbond enhances the load locally in the adherend which contains the embedded sensor. The consequence is that this adherend experiences an enhanced strain, which leads locally to an increased spacing for the gratings of the CFBG sensor near to the sensor end, and hence the reflected spectrum here shifts to higher wavelengths.
Figure 7.11. Comparison of grating period change before and after disbond along the length of grating

The dip in the spectrum is explained as follows. As mentioned earlier, the intensity of the reflected spectrum of a chirped grating is related to the local density of the grating period and Figure 7.11 shows the grating period changes along the sensor length before and after disbonding. In the “before disbond” case the grating period changes gradually along the distance thereby giving a constant intensity. For the “after disbond” case, the grating period remains unchanged until 40 mm and there is a rapid increase in the grating period from about 40 mm to 50 mm corresponding to reduced intensity in the reflected spectrum as the density of grating spacings at any particular wavelength decreases in front of the disbond (i.e. when the joint is still bonded). Behind the disbond front the grating period changes much more slowly and hence there is an enhanced intensity.

The movement of the dip in the reflected spectrum is due to the movement of grating period density from high wavelength to low wavelength as the disbond propagates.

7.5. CONCLUSIONS

The main conclusions drawn from this chapter are

- A single chirped fibre Bragg grating sensor can be used to monitor the disbond at either end, or both ends, of an adhesively bonded single-lap joint, with the sensor embedded within one adherend, with the low-wavelength end of the sensor at the cut end of the adherend and with the sensor extending the full length of the joint.
• Disbond initiation adjacent to either the low-wavelength or high-wavelength end of the sensor is indicated by a shift in the low wavelength end of the spectrum to lower wavelengths (for disbonding adjacent to the low-wavelength end) or a shift in the high wavelength end of the spectrum to higher wavelengths (for disbonding adjacent to the high-wavelength end of the sensor).

• Disbond propagation from the high wavelength end is indicated by the movement of a perturbation in the reflected spectrum to lower wavelengths which corresponds to the progression of the disbond front and a combination of finite-element modelling and commercial FBG software has enabled the position of the disbond front to be related to the perturbation in the reflected spectrum.

• In this work, the position of the disbond front can be located with a precision of about 2 mm, but in general this is likely to depend both on the adherend materials and on the position of the sensor in relation to the disbond location.

7.6. SUMMARY

In this chapter, a novel optical technique using a single CFBG sensor for monitoring the disbond from either end or both ends of the composite bonded joints has been presented. In the next chapter the sensitivity of the sensor in locating the disbond front in a bonded joint is explored.
Chapter 8

PARAMETRIC STUDIES OF THE SENSITIVITY OF THE CFBG SENSORS

8.1. INTRODUCTION

FE modeling to predict the strain distribution in the bonded joints at the location of the optical fibre due to disbonding was discussed in Chapters 6 and 7. In order to conduct a parametric study on various factors which can affect the sensitivity of the CFBG sensor in locating the defects in a bonded joint, analytical modelling was undertaken. A closed form solution for the stresses in the adherends is available in the literature and this has been used in the parametric study. Using an analytical solution enables many configurations to be investigated quite easily. Four cases have been considered: 1) CFBG sensor location within an adherend; 2) adherend thickness; 3) adherend material; and 4) sensor located at the surface of an adherend.

8.2. PARAMETRIC MODEL

In this study the closed-form solution of Goland and Reissner (1944) has been used. The Goland and Reissner model provides the stress distribution in a single lap joint taking into account the eccentricity of the load path. The joint design used in the paper of Goland and Reissner is shown in Figure 8.1. The analysis is for identical adherends of equal thickness and the width of the adherend is greater than the thickness of the adherend.

Goland and Reissner’s paper has three parts. In the first part, the bending moment and the transverse shear force at the overlap edge of two identical adherends are determined using a cylindrical plate bending model. The second part of the work determined the stress distribution along the overlap length in the adherend for a thin, rigid adhesive layer. This analysis gives acceptable results when the following relationship is satisfied:

\[
\frac{t_a}{E_a} \ll \frac{t}{E}, \quad \frac{t_a}{G_a} \ll \frac{t}{G}
\]  

(eqn. 8.1)
where \( t_a \) and \( E_a \) are the thickness and Young’s modulus of the adhesive respectively; \( t \) and \( E \) are thickness and Young’s modulus of the adherend respectively; \( G_a \) and \( G \) are the shear modulus of adhesive and adherend respectively. In this approximation, it was considered that when the adhesive layer is very thin, the stress distribution in the adhesive has no significant effect on the stresses in the joint and hence the overlap is considered as a single deformed body with the same material properties as the adherends. The same assumption was valid for a non-flexible rigid adhesive even when the adhesive layer is thick. The third part of the study is the most widely used since it provides the stress distribution in the adhesive layer of the joint when the adhesive layer is thick and flexible i.e. when the following relation is satisfied.

\[
\frac{t}{E} \ll \frac{t_a}{E_a}, \quad \frac{t}{G} \ll \frac{t_a}{G_a}
\]

(eqn. 8.2)

where \( t_a \) and \( E_a \) are the thickness and Young’s modulus of the adhesive respectively; \( t \) and \( E \) are thickness and Young’s modulus of the adherend respectively; \( G_a \) and \( G \) are the shear modulus of adhesive and adherend respectively.

In our study, although \( \frac{t_a}{E_a} \approx \frac{t}{E} \), we have \( \frac{t_a}{G_a} \ll \frac{t}{G} \), thereby the first approximation condition is partly met. Moreover the other condition of relative thinness of adhesive layer is completely met and hence the first approximation stress distribution results were considered. The results for calculating the stress distribution in the adherend (not in the adhesive) along the overlap length gives the axial stress in the adherend at a particular location:

\[
\sigma_y = \frac{P}{2} + \sum_{n=1}^{\infty} (A_n + B_n) \left\{ \frac{1}{2} e^{a(y-c)} (a(y-c)^2) \right\} \cos \alpha x
\]

(eqn. 8.3)

where \( x \) is a coordinate with its origin at the upper surface of the joint and in the direction of joint thickness, \( y \) is the coordinate with its origin in the midpoint of the overlap length.
and in the direction of the joint length, $p$ is the tensile stress, $2c$ is the overlap length, and $t$ is the thickness of the adherend (see Figure 8.2).

The factor $A_n + B_n$ in the equation 8.3 is given by

$$A_n + B_n = \frac{4p}{n\pi} \left\{ \left( \frac{12k}{n\pi} \right) \left[ \cos\left( \frac{n\pi}{2} \right) - \cos n\pi \right] - (3k + 1)\sin\left( \frac{n\pi}{2} \right) \right\}$$

(eqns. 8.4)

where $k$ (the bending moment factor) $= \frac{E}{t \sqrt{E}}$.

![Figure 8.2. Schematic of bonded joint with very thin adhesive layer, the notations used in the model are shown.](image)

8.3. SCOPE OF THE PARAMETRIC ANALYSIS

The equation to calculate the axial stress (eqn. 8.3) was programmed into a spreadsheet for rapid evaluation of the stress $\sigma_y$ for the sum over $n=1$ to $\infty$ for particular values of the other parameters (the visual basic macro is shown in Appendix 8 A). When $A_n + B_n$ converged, the stresses are obtained. The stress obtained from the calculation is then converted to strain, to obtain the strain distribution. The parameters used for the calculations are shown in Table 8.1.

The strain distribution along the 60 mm overlap of the joint at 4 mm from the surface of the upper adherend when the bonded joint was loaded by 5 kN was calculated for three cases: (1) no disbond; (2) 5 mm disbond; and (3) 10 mm disbond. The optical sensor is positioned 0.5 mm from the adhesive bond line and hence 4 mm from the surface of upper adherend was taken. For the no disbond case, the overlap was taken to be 60 mm. However to calculate the strain profile for the disbonded SLJ (5 mm and 10 mm disbond) the overlap was considered to be reduced by 5 mm or 10 mm respectively (i.e. the overlap $2c$ was taken to be 50 mm and 40 mm respectively). The approximation appears justified because the effect of the disbond is to unload the adherend in the disbonded region meaning that the overlap bonded length would be reduced.
### Table 8.1. Parameters used in the modelling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlap length (2c), mm</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>50 (5 mm disbond on one end)</td>
</tr>
<tr>
<td></td>
<td>40 (10 mm disbond on one end)</td>
</tr>
<tr>
<td>Tensile load, N</td>
<td>5000</td>
</tr>
<tr>
<td>Tensile stress (p)</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>(varies as load and thickness of adherend varies)</td>
</tr>
<tr>
<td>Thickness of one adherend (t), mm, (which is half the thickness of the adhesive plus thickness of one adherend)</td>
<td>4.7</td>
</tr>
<tr>
<td>Young’s modulus of the GFRP adherend material (E), MPa</td>
<td>43000</td>
</tr>
<tr>
<td>y (distance along length), mm</td>
<td>Varies from -30 to +30</td>
</tr>
<tr>
<td>x (distance across thickness), mm, (here: position of the optical fibre from the surface of the adherend)</td>
<td>4</td>
</tr>
</tbody>
</table>

8.3.1. Comparison of the closed-form solution with FE results:

In this section, a comparison is made between the strain distribution obtained from the FE modeling and the closed form solution, and also of the resulting predicted spectra. The strain distribution from the overlap end for a 60 mm overlap at the location of the optical fibre (4 mm from the upper surface of the joint) when loaded to 5 kN were calculated and the result is shown in Figure 8.3 together with the FE result. In both cases, only half of the overlap length is shown. At the free end of the adherend, the longitudinal strain is low. As the load transfers from the lower adherend through the adhesive to the upper adherend, the strains in the upper adherend (containing the sensor) begins to increase with increasing distance from the end of the adherend and reach a plateau region about 10 mm from the adherend end. There is a small overshoot in the longitudinal strain before it settles to the plateau region value. This overshoot is due to the bending produced by the offset of the joint under load; the plateau region is due to no load transfer at the centre of the 60 mm joint. Similar effects are observed in the FE modelling result, except that the prediction of the overshoot in strain is much smaller. The larger overshoot in the strain
from the analytical model may be due to the assumption in analytical modelling that the material properties of the adhesive and the adherend are taken to be exactly the same. This is an approximation that cannot be avoided when using these expressions.

Figure 8.3. Comparison of strain distribution at the position of optical fibre obtained from FE modelling and closed form analytical modelling.

The longitudinal strain distributions for disbond lengths of 0 mm, 5 mm and 10 mm are shown in Figure 8.4, together with the FE results. Interestingly, there is better agreement between the analytical and FE results for the strain profile as the disbond length increases. The strain distribution for 5 mm disbond obtained from the analytical modelling and from the FE results were used to predict the reflected spectra with the aid of the OptiGrating software, using the method of modification of the refractive index and grating period as a consequence of the strain profile. The CFBG sensor of 45 mm with the chirp rate of 3nm/cm was used for all the calculations. The results are shown in Figure 8.5 and at a higher magnification in Figure 8.6. It is interesting to note that the reflection spectrum obtained from the analytical strain profile shows the dip at the same position as shown by the reflection spectrum obtained from FE strain profile and both are similar to the experimental reflection spectra results shown in Chapter 6. As discussed in Chapter 6, perturbation in the CFBG reflection spectra is essentially due to rapid change in the strain at the disbond front, and both the FE modeling and the closed form solution show a similar rapid change in strain at this position.
Figure 8.4. Comparison of strain distribution at the position of optical fibre for three cases, no disbond, 5 mm disbond and 10 mm disbond obtained from FE modelling and analytical modelling.

Figure 8.5. Comparison of predicted CFBG reflection spectrum obtained by using analytical modelling and FE modelling for a 5 mm disbonded single lap joint.
Figure 8.6. Magnified view of the predicted CFBG reflection spectrum using analytical modelling and FE modelling showing the perturbation due to disbond in the single lap bonded joint.

Having shown that the closed form and FE based results are very similar for the spectra predictions, a parametric study was undertaken using the analytical modeling for the cases of (i) CFBG sensor locations; (ii) adherend thickness and (iii) adherend materials. The study was also extended to thin GFRP coupons with the sensors located at the surface of the adherend.

8.4. PARAMETRIC STUDY RESULTS

8.4.1. Effect of CFBG sensor location

The first parametric study investigated the effect of varying the CFBG sensor location through the thickness of the adherend. The sensor was located at four positions for the study: on the surface (i.e. x=0 mm), and also at x =2 mm; 3 mm and 4 mm (Figure 8.2). It should be remembered that the x coordinate originates from the surface of the upper adherend. Figure 8.7 shows the strain distribution for a disbond which has initiated and grown to a length of 5 mm. The strain distribution obtained due to the 5 mm disbond found to vary across the thickness. It can be seen from Figure 8.7 that when the CFBG sensor is located at the surface of the 4.5 mm thick adherend, the rate of increase of strain in the disbond front is smaller than for x values located closer to the bondline. The position of disbond front is represented as short vertical line in the reflection spectra. Changes in the strain distributions change the shape and the size of the perturbation in the predicted CFBG reflection spectra as shown in Figure 8.8.
Figure 8.7. Strain distribution along the overlap when the sensors are placed at various locations across the thickness of the sample.

- a) CFBG at the surface
- b) CFBG at 2 mm
- c) CFBG at 3 mm
- d) CFBG at 4 mm

Figure 8.8. Predicted reflection spectrum when the sensors are placed (a) at the surface (b) 2 mm from the surface (c) 3 mm from the surface (d) 4 mm from the surface of the specimen.
If the CFBG sensors were placed on the surface of the 4.5 mm adherend (i.e. retrofitted to detect the disbonding) the reflection spectrum predicted shows very little change (Figure 8.8 (a)). When the sensor is placed at 2 mm from the surface of the 4.5 mm thick adherend, a small dip is predicted and as the sensor is brought closer to the bondline, the sensitivity of the sensor in locating the disbond increases and the dip due to the disbond becomes deeper. Moreover the shape of the dip varies as the CFBGs are positioned at various locations through the thickness of the adherend as shown in Figure 8.9.

These results can be explained as follows. The depth of a perturbation in the reflected spectrum depends on the rate of change of strain with distance, and for positions closer to the bondline (i.e. closer to the disbond) the slope of the strain was steep. This steeper slope leads to a greater reduction in the local density of the grating period and hence a greater reduction in the reflected intensity.

![Figure 8.9. Comparison of the size and shape of the dip in the predicted CFBG reflected spectra due to a disbond in a single lap bonded joint when the sensors are placed at various locations through the thickness of the sample.](image-url)

8.4.2. Effect of adherend thickness and material:

The next step in the parametric study was to study the response of the CFBG sensor for (a) decreasing adherend thickness and (b) different adherend materials. The adherend thickness used in the previous analyses was 4.5 mm. In aerospace applications, the thickness of the composite adherends used would be smaller and the adherends could also be CFRP. Hence the parametric study was extended to 1 mm, 2 mm, 3 mm, and 4 mm
thick GFRP adherends and then the use of a CFRP adherend was investigated.

![Graph showing strain distribution](image)

Figure 8.10: Strain distribution in GFRP coupon of various thicknesses loaded at 5 kN and CFBG placed at 0.5 mm from the bondline

First, GFRP-GFRP bonded joints of various thicknesses were loaded to 5 kN and the CFBG sensors were located 0.5 mm from the bondline (i.e. for 1 mm, 2 mm, 3 mm, 4 mm and 4.5 mm thick adherends, the CFBG sensors are located at 0.5 mm, 1.5 mm, 2.5 mm, 3.5 mm and 4 mm from the free surface of the upper adherend respectively). The strain distribution for the disbond length of 5 mm obtained for these various thicknesses is shown in Figure 8.10. Not surprisingly, the strain of the plateau in the distribution reduces with increasing adherend thickness. In addition, the slope of the strain-distance distribution became less steep as the thickness of the adherend was increased. The predicted reflection spectra for theses distributions are shown in Figure 8.11. The CFBG sensor placed at 0.5 mm from the bondline in 1 mm thick adherend shows a broad and deep dip at the position of the disbond as shown in Figure 8.11 (a). For increasing adherend thickness, the dip in the CFBG reflected spectra becomes less deep and also narrower (Figure 8.11(b) and (c)). The superposition of these CFBG reflection spectrums, as shown in Figure 8.11 (d), clearly shows the change in the depth and width of the dip for various adherend thicknesses. It can be noted that the shape of the dip at all these thickness remained the same and symmetrical. The depth and the width of the dip in the reflection spectra depends on the slope and extent of the slope along the distance respectively.
Next, the possibility of detecting a disbond in high modulus CFRP materials was investigated. Initially a study on 4.5 mm thick CFRP adherend loaded to 5 kN was made as the experimental study are for 4.5 mm thick GFRP adherend loaded to 5 kN. Unidirectional T800H/3631 CFRP laminate with the Young’s modulus of 148 GPa [Okabe et al, 2004] was chosen for the study. The other parameters were maintained constant and a comparison of the strain distributions for the GFRP and CFRP adherends are plotted in Figure 8.12. Figure 8.12 shows the comparison of strain along the overlap length at the position 0.5 mm from bondline for a GFRP adherend and a CFRP adherend. Since the load was maintained constant and the Young’s modulus of the CFRP is higher than the GFRP, the plateau strain over the length of the overlap was reduced. The CFRP strain distribution rises less steeply with distance and as a result the reflection spectrum predicted from these strain distributions shows a smaller perturbation at the position of disbond for the CFRP coupon.
compared to the GFRP coupon (Figure 8.13).

![Comparison of strain distribution for 4.5 mm thick GFRP and CFRP coupons at the position of 0.5 mm from the bondline loaded at 5 kN.](image)

Figure 8.12. Comparison of strain distribution for 4.5 mm thick GFRP and CFRP coupons at the position of 0.5 mm from the bondline loaded at 5 kN.

Of more importance is the use of thinner CFRP adherends and hence the investigation is extended to 1 mm and 2 mm CFRP adherends loaded to 5 kN. Figure 8.14 shows the strain distribution for various thickness CFRP adherends and Figure 8.15 shows the predicted reflection spectra for these strain profiles. The CFRP strain distribution for 1 mm thick CFRP rises more steeply with distance compared to 2mm and 4.5 mm thick CFRP and as a result the reflection spectrum predicted from these strain distributions shows a deeper perturbation for a 1 mm thick CFRP adherent at the position of disbond, compared to 2 mm and 4.5 mm thick coupon. Increasing the load applied to the CFRP adherend to 17.2 kN, produces the same strain distribution in the CFRP adherend as in GFRP adherend and hence produces the same reflected spectra (Figure 8.16).
Figure 8.13. Predicted reflected spectrum due to disbond for 4.5 mm thick GFRP and CFRP coupon loaded at 5 kN.

Figure 8.14. Strain distribution in various thickness CFRP adherend at the position of 0.5 mm from the bondline loaded to 5 kN.
Chapter 8  PARAMETRIC STUDY ON THE SENSITIVITY OF THE CFBG SENSORS

Figure 8.15. Predicted reflected spectrum due to disbond for a) 1 mm thick CFRP b) 2 mm thick CFRP and c) superposition of 1 mm, 2 mm and 4.5 mm thick CFRP adherend loaded at 5 kN.

Figure 8.16. Predicted reflected spectrum due to disbond for 4.5 mm thick GFRP loaded at 5 kN and 4.5 mm thick CFRP coupon loaded at 17.2 kN.
8.4.3. Surface mounting of CFBG sensor:

In section 8.4.1, the possibility of locating a disbond when a sensor was mounted on the surface of a 4.5 mm GFRP adherend was investigated and it was found that the sensor would provide no clear information on the disbond. In the next section (section 8.4.2), it was noted that for a thin GFRP adherend, a CFBG placed close to the bondline could clearly indicate the position of a disbond. Hence in this section, the possibility of mounting the CFBG sensor on the surface is explored.

![Strain distribution at the surface of the adherend for 1 mm, 2 mm, 3 mm and 4 mm thick GFRP coupons with a disbond loaded at 5 kN.](image)

Figure 8.17. Strain distribution at the surface of the adherend for 1 mm, 2 mm, 3 mm and 4 mm thick GFRP coupons with a disbond loaded at 5 kN.

An analytical model has been investigated for the CFBG placed on the surface (i.e. $x=0$ mm) for a 1 mm, 2 mm, 3 mm and 4 mm thick GFRP adherend. In each case, the adherend is loaded at 5 kN with a disbond of 5 mm. The other parameters are maintained the same as shown in Table 8.1. Figure 8.17 shows the strain distribution along the length of overlap at the surface of the adherend for the various adherend thicknesses. It can be seen that the slope of the strain-distance curve, is steeper for thinner specimens. The CFBG reflection spectra predicted using these strain profiles are shown in Figure 8.18 and the thinner specimen shows a clear dip at the position of the disbond. Hence, these results suggest that surface mounting of CFBG sensors is possible for disbond detection and is most likely to be successful with thinner adherends.
Figure 8.18. Predicted reflected spectrum due to disbond when CFBG placed at the surface of a) 1 mm adherend, b) 2 mm adherend, c) 3 mm adherend and d) 4 mm adherend, loaded at 5 kN

8.5. CONCLUSIONS

The conclusions which can be drawn from this Chapter are as follows:

1) The predicted CFBG reflection spectra obtained using Goland and Reissner solution for the adherend strains are similar to the predicted CFBG reflected spectra using from FE strain modeling.

2) The sensitivity of the CFBG sensor to detect and locate the disbond with a thick adherend depends on the position of the sensors through the thickness of the adherend. A CFBG sensor placed closer to the bondline detects a disbond in a single lap bonded joint more easily.

3) The sensitivity of the CFBG sensor to detect and locate the disbond depends mainly on (i) the strain distribution in the adherend and (ii) the position of the sensor with respect to the bondline.
4) Disbond in a thin adherend could be detected using a CFBG sensor mounted on the surface. This would open up a new technology of retrofitting a CFBG sensor system for disbond detection in thin bonded joints.

8.6. SUMMARY

In this Chapter a parametric study has been carried out on various parameters (adherend thickness, material and CFBG location) affecting the sensitivity of CFBG sensors for detecting disbonds. In the next Chapter, the possibility of detecting manufacturing defects using the CFBG sensor technique is explored.
CHAPTER 9

MANUFACTURING DEFECT DETECTION IN AN ADHESIVELY BONDED COMPOSITE JOINT USING THE CFBG SENSOR

9.1. INTRODUCTION

In Chapters 6 and 7 it was demonstrated that it is possible to detect a disbond that initiates during fatigue loading and locate the disbond front using a CFBG sensor. In this chapter, the possibility of detecting a defect introduced during the manufacture of a bonded joint is explored.

9.2. RESPONSE OF CFBG SENSOR TO MANUFACTURING DISBOND

GFRP-GFRP composite single lap bonded joints were manufactured with an artificial disbond. The artificial Teflon insert with dimensions 12 mm long 0.25 mm thick which extends across the full width of the joint was placed at the centre of the joint (see Figure 9.1). As usual, one of the adherends had an embedded CFBG sensor at the interface of the 0° and 90° plies closest to the bond line. CFBG sensors with a length of 60 mm (chirp rate: 2.25 nm/cm) were used with the low wavelength end of CFBG terminating at the cut end of the adherend. The 60 mm sensor extended the full length of the overlap (further fabrication details are presented in Chapter 4).

The reflection spectrum from a 60 mm CFBG sensor recorded unloaded before and after joint manufacture is shown in Figure 9.2. For this particular sensor, the reflected spectrum increases in intensity from the low to the high wavelength end, but this is a characteristic of this particular sensor which does not affect the results. The insert does not process any variation in the reflection spectrum recorded unloaded after manufacture of the bonded joint. The insert length and its position from the low wavelength end of CFBG were measured directly since the bonded joint is transparent. The position of the insert with respect to the reflected spectrum was calculated in the unloaded reflection spectrum using the relationship between the optical bandwidth at full width at half maximum (FWHM) and a...
60 mm sensor length. The location of the disbond length in the reflection spectrum of the unloaded joint is shown in Figure 9.3. But the unloaded spectrum does not give a clear indication of position of disbond defect (shown between two small vertical lines).

Figure 9.1. Bonded joint with 12 mm Teflon insert in the bondline at the centre of the joint.

Figure 9.2. Unloaded reflection spectrum from 60 mm CFBG sensor (a) before bonded (b) after bonded with the artificial disbond.

Figure 9.3. Location of the disbond length in the 60 mm CFBG reflection spectrum of unloaded joint.
The reflection spectra were then recorded with the bonded joint under tensile loads of 5 kN and 9 kN and these are shown in Figure 9.4 and Figure 9.5 respectively. When the bonded joint with the artificial defect was loaded to 5 kN, the CFBG reflection spectrum developed a region of increased intensity which corresponds to the sensor position (see Figure 9.4). This region of increased intensity is clearer when the bonded joint is loaded to 9 kN, as shown in Figure 9.5. It can be seen that the region of enhanced intensity in the reflection spectrum corresponds approximately to the location of the defect. However, to understand the effect of the manufacturing defect on the CFBG reflection spectrum, modelling was undertaken which is discussed in the next section (section 9.3). The modelling was carried out using FEA analysis (to predict the strain distribution in the composite bonded joint due to the disbond) and the CFBG reflected spectra were predicted using OptiGrating.

![Figure 9.4. Reflection spectrum showing the location of the artificial disbond for bonded joint loaded at 5 kN](image)

![Figure 9.5. Reflection spectrum showing the location of the artificial disbond for bonded joint loaded at 9 kN](image)
9.3. MODELLING AND PREDICTIONS

The FE modelling of the strain distribution in the joint as a consequence of the disbond was carried out by my colleague Capell (private communication). A 2D model of GFRP-GFRP bonded joint with a bond defect was modelled in ABAQUS as a void at the interface using the dimensions shown in Figure 9.1. The properties used for the composite and the adhesive were the same as shown in Tables 5.1 and 4.4 respectively. The longitudinal strain was extracted from the model for applied loads of 5 kN and 9 kN, along a line corresponding to the position of the optical fibre within one of the adherends. Figure 9.6 and 9.7 shows the strain extracted from the FE model along the 60 mm overlap for loads of 5 kN and 9 kN. The strain at the end of the overlap of the bonded joint which is adjacent to the low wavelength end of the sensor increases from zero as the load transfer occurs. The strain reaches a plateau region of roughly constant strain as the load is shared equally between the adherends. This plateau region continues until it is disturbed by the defect in the adhesive layer. As there is a void at the adhesive layer (i.e. there is no bond between the adherends), the load cannot be shared equally at the disbond region and load transfer occurs at both disbond ends. However, due to the bending produced by the offset of the joint (see Figure 9.8), the load distribution is complex and the strain experienced is slightly higher at the edge of the disbond closer to the end of the adherend (at A) and lower at the edge of the disbond (at B). This strain distribution is also seen at the same distance from the bondline in the other adherend, except that the lower strain is now seen at A and higher strain is at B. Moving away from the disbond, the strain returns to its plateau value. Reflected spectra were predicted from the strain distribution in Figure 9.6 and 9.7 using the method of modification of the refractive index and grating period as a consequence of the strain profile using the OptiGrating software. Figure 9.9 shows the CFBG predicted spectra for the applied loads of 5 kN and 9 kN. In the predicted reflection spectra an increased intensity can be seen corresponding to the defect position. The rapid strain changes at the ends of the defect lead to decreased intensity in the reflected spectra (small dips) which indicates the position of the defect reasonably well. The position of the defect was found to lie approximately 3 mm away from the minimum of the dip.
Figure 9.6. Strain distribution extracted from FE analysis at the position of optical fiber for the bonded joint with artificial defect was loaded at 5 kN.

Figure 9.7. Strain distribution extracted from FE analysis at the position of optical fiber for the bonded joint with artificial defect was loaded at 9 kN.
9.4. CONCLUSIONS

From this chapter, the following conclusions can be made

(i) A CFBG sensor embedded close to the bond line in one composite adherend can detect and locate a manufacturing defect in a composite bonded joint when the joint is loaded.

(ii) The extent of the defect can be obtained from the length of the enhanced intensity between two dips in the reflection spectrum.
(iii) A Combination of finite-element modelling and commercial FBG software has enabled the position of the manufacturing defect to be related to intensity changes in the reflected spectra.

9.5. SUMMARY

In this chapter, it has been shown that a CFBG sensor can be used to detect and locate a manufacturing defect in a composite bonded joint. Future work could investigate the sensitivity of the technique for different geometric configurations.
10.1. CONCLUSIONS

10.1.1. Introduction:

An optical technique based on embedded chirped fibre Bragg grating sensors has been investigated for matrix damage detection in composite laminates and disbond detection (both manufacturing disbond and in-service disbond) in adhesively bonded composite joints. The material system used in the experiments was an E-glass/epoxy laminate with the sensor embedded in the 0° ply, near the 0/90 interface.

10.1.2. Matrix cracking damage detection in composite laminate:

FBG and CFBG sensors were embedded in cross-ply GFRP coupons and the changes to the reflected spectra due to matrix crack development have been studied. The conclusions drawn from this study are:

- A single matrix crack grown within the transverse ply of the GFRP cross-ply laminate produces an approximately sinusoidal perturbation in the CFBG reflection spectrum. The physical location of the crack corresponding to the perturbation in the CFBG reflected spectrum is not at the minimum of the dip of the perturbation, but at a distance of about 1 mm from the position of the minimum towards the low-wavelength end of the reflected spectrum.

- The spectrum predicted with the aid of a strain distribution obtained from a stress transfer model agrees well with the experimental results.

10.1.3. In-service disbond detection in adhesively bonded joints

A CFBG sensor has been embedded in one GFRP adherend, closer to bond line (about 0.5 mm from the bond line) in a GFRP-GFRP bonded joint. The changes in the CFBG reflected spectrum occurring during fatigue loading and disbond development have been studied and the conclusions drawn from this study are:
Chapter 10 CONCLUSIONS AND FURTHER WORK

- An embedded CFBG sensor can be used to monitor disbonding at either end of an adhesively bonded single-lap joint, with the low-wavelength end of the sensor positioned at the cut end of one adherend. Disbond initiation adjacent to either the low-wavelength or high-wavelength end of the sensor is indicated by a shift in the low wavelength end of the spectrum to lower wavelengths (for disbonding adjacent to the low-wavelength end) or a shift in the high wavelength end of the spectrum to higher wavelengths (for disbonding adjacent to the high-wavelength end of the sensor). Disbond propagation is indicated by the movement of a perturbation in the reflected spectrum which corresponds to the progression of the disbond front: for disbonding from the low-wavelength end, the perturbation moves towards higher wavelengths, and for disbonding at the high-wavelength end, the perturbation moves to lower wavelengths. In all cases, the reflection spectrum is recorded with the joint under a small load (in practice, this could be the self weight of the structure).

- The detailed shape of the perturbation depends upon the CFBG chirp rate, but in all cases a combination of finite-element modelling and commercial FBG software enabled the position of the disbond front to be related to the perturbation in the reflected spectrum. In general, the position of the disbond front could be located with a precision of about 2 mm, but this is likely to depend both on the adherend materials and on the position of the sensor in relation to the disbond location.

- The sensitivity of the embedded CFBG sensor, predicted using OptiGrating with the aid of a closed form analytical solution of strain distribution available in the literature was investigated in a parametric study. The sensitivity was found to depend on the location of the sensor in the adherend with respect to the bond line and the strain distribution in the adherend (which depends upon adherend material and adherend thickness). The study suggested that surface mounted CFBG sensors could detect disbonds in thin adherend, which opens up the possibility of retrofitting a CFBG sensor system for disbond detection in bonded joints with thin adherends.

10.1.4. Manufacturing defect detection in adhesively bonded composite joint

An artificial manufacturing defect was introduced into bonded joint using Teflon inserts and the possibility of detecting the defect using CFBG sensors was studied. The following conclusions can be drawn from this work:
With the joint under load an enhanced intensity in the reflection spectrum indicates the presence of manufacturing defect and the length of the enhanced intensity between two dips in the spectrum provides an indication of the extent of the defect.

The reflection spectrum predicted from a combination of FE modelling of the strain distribution and OptiGrating agrees well with the experimental results and has enabled the position of the manufacturing defect to be related to the intensity changes in the reflected spectra.

10.2. FURTHER WORK

In this work, the response of embedded CFBG sensors for locating disbond in GFRP-GFRP bonded joints is studied. The work could be extended to study the response of embedded CFBG sensors in both CFRP-CFRP bonded joints and in composite-metal bonded joints. Both of these types of joints are of interest in aerospace applications (e.g. a stringer-stiffened panel or carbon-titanium bonded joint). The response of CFBG sensors in other types of joints such as double-lap, scarf joint could be investigated. More complex joints may produce more complex spectra, and it will be important to determine whether a combination of FE modelling of the strain distribution and OptiGrating spectrum prediction still produces theoretical predictions which are in good agreement with experimental measurements. With regards to the manufacturing disbond, probably the most important manufacturing defect is when the disbond is at the end of the adherend overlap and the ability of the CFBG sensor to detect disbonds in this case should be investigated for GFRP-GFRP, CFRP-CFRP and composite-metal adhesively bonded joints.
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Appendix 4A

Safety operating procedure in Stripping, Cleaving and Splicing

- Do not operate the fiber cleaver or fusion splicer unless you have been properly trained.
- Safety glasses must be worn at all times while cleaving fiber.
- The cut ends of optical fiber are dangerous. They are basically glass needles that will penetrate flesh then break off and become nearly impossible to remove. Once in your body it will likely become infected.
- If broken the splinters or scraps can penetrate the skin, and they can be extremely difficult to find and remove. If the fibers enter the eye, they may have to be removed by a doctor.
- Find and dispose of all cut fiber fragments immediately after cutting. Proper disposal means placing them in an approved fiber disposal unit (not a trash can).
- Handle cut fiber fragments with tweezers only.
- It is the operator's responsibility to ensure that no fiber fragments 'escape' and injure someone. If you lose a fiber fragment you must look until you find it or it is sure to stick someone (maybe you a few minutes later).
- Fiber fragments can stick to the cover of the cleaver. Move slowly when opening the cover. Always look on the inside of the cover if you don't see your fragment on the shelf. Fragments can also fall down by the diamond wheel.
- If you can't find your fragment, get more light on the subject and work area. Do not move the cleaver until the fragment has been found. Use a magnifying glass if you need to but find that fragment.
- Do not drop them on the floor where they will stick in carpets or shoes and be carried elsewhere.
- Avoid touching your eyes at any time.
- Keep your work area clean.
- Do not eat or drink anywhere near the work area.
High Power Broadband Light source:

A. Laser product specifications:

1) Wavelength range: 1500-1600 nm (invisible mid infrared region)
2) Beam size: The beam is safely confined within single-mode optical fibre with a mode field diameter of about 9 μm.
3) Beam Divergence: If the output optical cable is not connected, and the beam is allowed to escape into the free space, its divergence is given by the NA (numerical aperture) about 120 mrad (half angle)
4) Maximum power: Less than 80 mW

B. Laser Beam Hazards:

The Eye
The eye is the most sensitive organ and is easily injured by laser beams. The type of injury depends upon the intensity of light, its wavelength, and the tissue being exposed. Damage is by high temperature or photochemical effects. Acute exposures may result in corneal or retinal burns. Cataract formation and retinal damage may result from chronic exposures to laser light. Retinal damage from exposure to wavelengths in the visible and near infrared region is of concern.
Incoherent light can be viewed safely because the light reaching the eye is about a fraction of the output energy and is spread over the entire retina. But the laser radiation is a coherent light. The beam passes through the pupil and focuses on a very small spot on the retina, depositing all its energy in this area. Only visible and near infrared radiation is focused on the retina. Damage to the retina may result in limited or total blindness if the optic nerve or macula region is injured.

The Skin
Skin is also damaged by laser beams. Acute exposure may cause injuries ranging from mild reddening to blistering and charring. Skin cancers may result from chronic exposure to ultraviolet light. The extent and type of damage depends on the amount of energy
deposited and the wavelength of the light. Unlike injury to the eye, acute damage to the skin is usually repairable.

The following chart outlines the biological effects to the eyes and skin at a variety of wavelengths [Laser training course, 2007]

<table>
<thead>
<tr>
<th>Spectral Wavelength</th>
<th>Eye</th>
<th>Skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actinic UV:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultraviolet C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(100-280 nm)</td>
<td>Cornea: photokeratitis</td>
<td>Erythema (sunburn)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skin cancer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aging of skin</td>
</tr>
<tr>
<td>Actinic UV:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultraviolet B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(280-315 nm)</td>
<td>Cornea: photokeratitis</td>
<td>Increased pigmentation</td>
</tr>
<tr>
<td>Near UV:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultraviolet A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(315 - 400 nm)</td>
<td>Lens: photochemical cataracts</td>
<td>Pigment darkening</td>
</tr>
<tr>
<td></td>
<td>Retina: blue light injury</td>
<td>Skin burns</td>
</tr>
<tr>
<td>Visible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(400 nm -700 nm)</td>
<td>Retinal burns: thermal injury</td>
<td>Pigment darkening</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Photosensitive reactions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skin burns</td>
</tr>
<tr>
<td>Infrared A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(760-1400 nm)</td>
<td>Cataracts and retinal burns</td>
<td>Skin burns</td>
</tr>
<tr>
<td>Infrared B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1400-3000 nm)</td>
<td>Cornea: burns</td>
<td>Skin burns</td>
</tr>
<tr>
<td></td>
<td>Aqueous flare (fluorescence)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lens: cataracts</td>
<td></td>
</tr>
<tr>
<td>Infrared C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3000 nm-1.000 nm)</td>
<td>Cornea: burns</td>
<td>Skin burns</td>
</tr>
</tbody>
</table>

From the following table, it could be noted that our broadband source is Infrared B and it affects cornea and lens of the eye and causes skin burns, if improperly used.

C. Laser safety calculations:
The following parameters have to be calculated for the safety use of laser.

1) MPE (Maximum Permissible Exposure):
   It is the radiation level of laser to which a person may be exposed without hazardous effects or adverse biological changes in eye or skin. It is expressed in Irradiance (W/m²) or Radiant Exposure (J/m²). MPE values for direct viewing of the beam and exposure to skin are
tabulated in British standard BS EN60825-1:1994 in table 6 and 8 respectively. Higher the MPE, lower the hazard. It determines the extent of the NOHD.

Depends on:
- Wavelength
- Exposure duration
- Target Organ (separate MPE limits for skin or eye)

2) NOHD (Nominal Ocular Hazard Distance): distance along the unobstructed beam from the laser to the eye, beyond which the applicable MPE is not exceeded.

For Eye:

Basic information:
Broadband laser source of wavelength 1500 -1600 nm, 30 mW output power, initial beam diameter is 9 µm, Beam divergence is 120 milliradians (half angle)

The MPE of eye to laser radiation at 1500-1600 nm is found to be 1000 Wm², when the exposure time is 10 s [Laser safety training, 2007]

\[
NOHD = \sqrt{\frac{4 \times \text{radiant power}}{\pi \times \text{MPE}} - \frac{\text{initial beam diameter}}{\text{beam divergence}}}
\]

where NOHD is in meters, radiant power is in watts, MPE in Wm², initial beam diameter is in meters and beam divergence is in full angle radians.

Taking the datas,

\[
NOHD = \sqrt{\frac{4 \times 0.03}{\pi \times 1000} - \frac{0.000009}{0.240}}
\]

\[= 0.025 \text{ m} = 2.5 \text{ cm}\]

Therefore, if the laser is viewed directly from above 0.025 m, the person is considered safe for the viewing conditions specified.
For Skin:
The MPE of skin to laser radiation at 1500-1600 nm is also found to be 1000 Wm$^{-2}$, when the exposure time is 10 s [ Laser safety training, 2007 ]. Hence HD (hazard distance) for the above datas are also 0.025 m.

D. Safety procedures followed:

1) Access Restriction: As this is a Class IIIb laser, access restrictions are followed to prevent unauthorized personnel from entering the area when the laser is in use. Doors are kept closed when the laser is in operation.

2) Laser Use Area Control: Area control measures are used to minimize laser radiation hazards. The area is posted with the appropriate signage which includes a sign at the doorway indicating the status of a laser system whether it is used or not. Only authorized personnel who have been appropriately trained are allowed to operate the laser.

3) Personal Protective Equipment (PPE):

   Eye Protection

   Eye protection is used for Class IIIb when the lasers are used within the NOHD zone. The laser protective eyewear is used during alignment procedures since most laser accidents occur during this process. Protective eyewear are labeled with the absorption wavelength and optical density (OD) rating at that wavelength.

   Skin Protection

   For skin protection lab coats and gloves are used when working below the HD zone.

E. SOP (Standard Operating Procedure).

   An SOP is written and followed accordingly and is pasted near the laser system for further information. The below details the SOP
Safe Operating Procedure:
The lasers are only to be used by authorised personnel and are housed in a room which requires a 4-digit code access. Occasionally undergraduate project students may also use the laboratory if their project requires. Undergraduates will be assessed for competence before using the equipment; they can be unsupervised though in voice contact, or visited hourly.

Laser and light Sources to be used in the Laboratory:
One broadband source is currently used in the laboratory. When new devices are introduced, the guidelines and the Safe Operating Procedure will be reviewed to ensure that it is still appropriate, and amended if necessary.

<table>
<thead>
<tr>
<th>Light Source Name</th>
<th>Wavelength (nm)</th>
<th>Output Power (mW)</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFC broadband source</td>
<td>1530</td>
<td>80</td>
<td>3B</td>
</tr>
</tbody>
</table>

General Guidelines:
The following general guidelines, as well as the specific safe operating procedure outlined below are followed:

(i) Protective glasses must be worn by anyone in the laboratory at any time that a laser/light source is active.

(ii) No-one must work alone in the laboratory outside office hours.

(iii) All experimental set-ups should be organised to minimise the distance between components of the experiment, to minimise the risk of exposure of the user or others to an exposed light beam.

(iv) All experimental set-ups should be configured to minimise the risk of exposure to either a direct beam, or a reflected beam.

(v) When aligning an experimental set-up, all users should always ensure that low power is used to minimise the risk of accidental exposure to dangerous levels of optical power.
(vi) All users should be aware of the Safe Operating Procedure.

(vii) Any user introducing a visitor(s) must ensure that the visitor(s) is/are aware of the Safe Operating Procedure.

(viii) Never look directly into a laser/light source emission point, whether the beam is emitted into free space or into fibre.

(ix) Never look directly at the reflection of a laser/light source, whether that reflection is produced deliberately by a mirror, or unintentionally by reflection from a surface or device.

(x) Take care when handling/cutting/preparing fibres that you do not accidentally endanger eyes or penetrate skin.

(xi) Take care when handling/cutting/preparing fibres that fragments are not left where they can accidentally endanger eyes or penetrate skin.

(xii) Laser eyewear is easily damaged. Inspection for damage before use should include checking for scratches, pits and previous laser damage, which may show up as bleaching or scorching. If eyewear is known or suspected to have been exposed to excess laser radiation, or if any damage is found on inspection, the eyewear must be replaced.

Inspection of the frame and sidepieces should ensure that they provide at least the same protection as the lens.

Specific Safe Operating Procedure:

- Before switching on a laser or light source, ensure that the “Laser in Use” sign is displayed on the door.
- The user should then select and put on protective eye glasses before turning on any laser or light emission system.
- The user should check that their experimental arrangement is set up in accordance with the general guidelines above, prior to switching on the laser or light source.
- The user should ensure that any other persons in the room are wearing protective eye glasses prior to turning on the laser or light source.
- The user should warn any other persons in the room that a Laser/light source is about to be switched on, prior to switching on.
- No Laser/light source should be left active unnecessarily.
- If it is necessary to leave a Laser/light source active for extended periods, when the user may not be present, (for example, an experiment that runs overnight), then a warning message must always be left indicating that an experiment is in progress.
- Should it be necessary to adjust the components of an experiment in the path of an optical beam, always deactivate* the beam prior to carrying out the adjustment.
- Where an experiment is conducted with optical fibre, ensure that the risk of fibre fracture is minimised. Should fibre fracture occur, ensure that the laser/light source is immediately deactivated* whilst the fibre is replaced, taking care not to expose any user to fragments of broken fibre.

* Deactivation of the beam means that the beam is removed from the area under consideration, perhaps by a beam stop or equivalent, and does not necessarily mean that power to the laser/light source is removed.

Accidents:
Any laser incident or accident must be reported to the Laser Safety Officer and the School Safety Adviser who will report to the Safety Office. Following an incident/accident any equipment must be isolated pending investigation. If ocular exposure has occurred, a full investigation into the cause and nature of the exposure must be undertaken and recorded in full. If there is suspected injury to the eye, the injured person should see a specialist ophthalmologist at the Royal Surrey County Hospital within 24 hours. The injured person should not drive.

The Laser Safety Officer must report any injury to the Occupational Health Department to ensure follow up for the injured person.

If an ophthalmologist is not available at the RSCH, the injured person should be sent within 24 hours to Moorfields Eye Hospital where the medics are experienced in dealing with laser eye injuries.
Details of the laser beam should accompany the casualty to hospital. These should include type of laser system, classification, wavelength and power.

Royal Surrey County Hospital
Accident and Emergency Department open 24 hours a day
Address: Egerton Road, Guildford, GU1
Telephone Number: 01483 571122

Moorfields Eye Hospital
Accident and Emergency Department open 24 hours a day
Address: 162 City Road, London EC1V 12PD
Telephone: 0207253 4696
Location and directions to A&E department available at www.moorfields.co.uk/Locations/CityRoad
Appendix 8A

In this Appendix, the visual basic macro written for the rapid evaluation of the closed form solution of Goland and Reissner’s model is given. Apostrophe (') represents the comments for our understanding, and is not the part of the programme.

The programme is:
Sub stressanalysis()
    'stressanalysis is the name given to the macro'
    x = ActiveCell.Row
    'active cell to be selected to start the analysis'
    y = x - 4
    'cell to input for the analysis'
    z = x + 887
    'cell till the end of analysis'
    Do While Cells(x, 1).Value <> ""
        'start from the active cell and do till it reaches a blank cell'
        Cells(y, 3).Value = Cells(x, 1).Value
        'input the value to other cell'
        Cells(x, 3).Value = Cells(z, 22).Value
        'take the cell value to the other cell'
        x = x + 1
        'go to the next row'
    Loop
    'loop continuation'
End Sub
    'end program'