The use of Digital Image Correlation to monitor delaminations in composite structures

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This thesis is submitted to the University of Surrey for the degree of Doctor of Philosophy

2018

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Abstract

The range of applications for composite materials is growing, but understanding of the effect of defects is limited, as is the ability to detect them. Versatile non-destructive testing (NDT) techniques, that can be deployed rapidly and reliably, to detect and monitor damage in composite components are vital to the continued growth of this sector.

This research investigates the application of Digital Image Correlation (DIC) as an NDT technique for monitoring delamination defects in Fibre Reinforced Polymer (FRP) composites. The research has matched physical experiments with Finite Element (FE) modelling. Four types of glass-fibre reinforced epoxy matrix composite structural elements were designed and manufactured to assess this application of DIC. The first two types of structural elements were flat coupons containing fully embedded delaminations, artificially introduced using two different methods. It was found that by placing these specimens in three-point bending, near surface delaminations, one ply below the surface being monitored, would cause a plateau in the surface strains. This plateau in strains was used to measure the embedded defect sizes. The size of the delamination was consistently overestimated from the interpretation of the strain fields. This was improved with the assistance of FE modelling to identify the relationship between the feature and the delamination. Pulse thermography was found to be a better technique for measuring the size of these defects.

The third type of specimen was a flat coupon containing a milled-slot, which was fatigued to grow a delamination at the foot of the milled slot, and the delamination measured visually. For this specimen, the DIC results showed good correlation with the visually determined delamination lengths with an empirical fit applied to the strain results. Both lock-in thermography and pulse thermography were used to measure the delamination size of the same specimens and showed reasonable correlation with the visually determined delamination lengths.

Finally, tubular specimens containing embedded PTFE delamination-defects were fatigued at different ratios of tension and torsion. DIC of the specimens loaded at the fatigue load ratio at which the delaminations were grown could not be used to quantify the size of the delaminations.

The work has shown that DIC can be used to monitor delaminations in some structural elements, however the type of loading needs to be considered to ensure sufficient influence on the surface strains to enable strain features that can be used to measure the size of delamination.
Acknowledgements

I would like to thank my academic supervisors, Prof. A. D. Crocombe, Prof. S. L. Ogin, Dr D. A. Jesson as well as my industrial supervisor Mr M. R. L. Gower for their guidance, supervision and support that made this research possible. I would also like to thank Dr M. Poole and Mr P. Haynes for their assistance in the manufacturing and testing of the specimens.

I would also like to thank my supervisors at the University of Padua, Prof. M. Quaresimin and Dr. P. Carraro, for their guidance and insight for the tubular specimen research during my three-month Erasmus exchange.

I am grateful to the University of Surrey, EPSRC and NPL for sponsoring this work which allowed me to explore an extremely interesting field of research.

Finally, I would like to express my appreciation of my family and friends for their continued encouragement and support.
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Chapter 1. Introduction

1 Introduction

1.1 Background

Composite materials are being increasingly used in industry for structural applications due to their advantages over traditional materials. These advantages include a higher resistance to corrosion compared with metals and high specific strength and stiffness (Le Cahain et al., 2015). The fibre tows in FRP laminates are often woven to produce fabric. Woven fabrics used in FRPs are a type of textile composites, which have many applications in a large number of industries, including space, marine, automotive and off-shore due to the advantages over unidirectional laminated composites (Wang et al., 2017). Compared with other types of textile fabrics, 2D woven are most commonly used in composites due to the relatively lower cost and easy fabrication. However, components produced using fibre-reinforced polymer (FRP) composites have comparatively high manufacturing costs and, due to the non-homogeneous nature of the material, multiple modes of failure which can be initiated through mechanical damage, fatigue or even during manufacturing (Greenhalgh, 2009). The more damage development in composites is understood, the less components in industry are overdesigned, increasing weight savings and reducing the cost. Detecting damage in composite materials is more complex than homogenous materials due to the anisotropy and the potential for damage to occur inside the material, not on the surface where it is visible. To address the issue of damage detection in composite materials, Non-Destructive Testing (NDT) techniques have been developed and adopted. Current commonly used NDT techniques include variations of ultrasonic inspection, acoustography, radiographic inspection, shearography, thermography and others.

Digital Image Correlation (DIC) is an optical technique that monitors full-field deformation of surfaces of structures under load. The rapid improvement in the ready applicability of DIC suggests that it may also be a candidate as an NDT technique by identifying unexpected deformation fields on a surface. The use of DIC to detect damage in composite materials is currently in its infancy. The advantage of this technique is its versatility, allowing for components of any size to be inspected in-situ, imaging a component before and after loading. Many of the other techniques described are less flexible in terms of the scale of component to be investigated and the need for a laboratory environment.
1.2 Aims and objectives

The overall theme of this thesis is to investigate the application of Digital Image Correlation (DIC) as an NDT technique to detect delaminations in woven FRP composites. Due to the lack of development in this application of DIC, this work is focused on determining its feasibility. To deliver this aim, the following objectives were set:

- To design and manufacture representative structural elements in which delamination defects can be introduced and/or grown.
- To load the specimens without propagating the damage, while still producing enough strain to identify any strain features relevant to delaminations.
- To use Finite Element Analysis (FEA) to help interpret the DIC strain results and to reinforce the experimental findings.
- To compare the modelled and measured strain fields and assess the damage size from strain perturbations using DIC. The basic concept was to identify features in the strain distribution which can be used to quantify the size and shape of the delaminations.
- To do the above on a range of structural elements with different methods of introducing delamination damage only, to assess general applicability of the technique.

A secondary aim of this study was to develop these representative structural elements and monitor delamination defects using DIC as well as with other NDT techniques to compare the effectiveness of DIC as an NDT technique with existing methods.

1.3 Thesis overview

The thesis is structured as follows: Chapter 2 reviews key literature on composite specimen manufacturing as well as on NDT techniques being used to detect delaminations. Chapter 3 describes the experimental methods used to manufacture, mechanically test and observe the delaminations as well as the modelling methodology for all four types of specimens. Chapters 4 and 5 describe the experimental findings of specimens in three-point bending with fully embedded delaminations placed one ply below the surface being monitored. Chapter 6 describes the experimental findings of the milled-slot specimen where delaminations were grown in a controlled manner using fatigue. This has been investigated two plies below the surface being investigated, as well as four plies. Chapter 7 outlines work predicting the direction of delamination growth of tubular specimens under tension/torsion loading. The concluding remarks and suggestions for future work are summarised in Chapter 8.
The majority of the work was undertaken at the University of Surrey and at the National Physical Laboratory. A three-month placement at the University of Padua was organised to enable the testing of the tubular specimens.

1.4 Novelty

This thesis includes a number of novel features and contributions to the state of art. Primarily this revolves around the design of the representative structural elements used in this project. The following lists the novel aspects of this project:

- The use of a polymer insert between plies during the manufacturing process along with a stress-raiser to cause a debond between the insert and adjacent plies to simulate the presence of a delamination in the cured laminate once fatigued.
- The design and creation of the milled-slot specimen produced to generate delamination growth within the specimen through fatigue loading.
- The design and manufacturing of the tubular specimen with the embedded PTFE/stress-raiser delamination.

Based on these structural elements, this thesis details a comparison of the sizing of the designed defects with DIC as well as thermographic NDT techniques, including pulse thermography, lock-in thermography and passive lock-in thermography. The application of different techniques to monitor the same designed defect allowed for direct comparisons of the effectiveness of these techniques to be made.
2 Literature review

2.1 Introduction

As the applications for composite materials in industry grows, it is becoming increasingly necessary to develop NDT techniques that can be easily, rapidly and reliably deployed. This thesis focuses on the detection of delamination defects in woven glass fabric composite structural elements using DIC. The project involves the manufacturing of representative and reproducible structural elements in which delamination defects can be readily created, as well as investigating how well different NDT techniques detect these defects.

As the project involves the manufacture, NDT, and numerical modelling of the different structural elements, the primary focus of this chapter is to outline and summarise the research undertaken in these areas. This chapter starts by describing the type of materials used in this work. The use of a woven fabric was encouraged at the start of the project to link up with a connected project at the National Physical Laboratory (NPL), the collaborative company. Even so, this chapter includes a review of different types of composites used to produce specimens to investigate NDT techniques. The next section looks at methods for manufacturing structural elements for the purpose of evaluating NDT techniques. This is followed by sections on different NDT techniques as well as the finite element analysis modelling techniques used to represent delaminations in composite structures. This review assumes the reader has a general understanding of composite materials. For more general information on composite materials, the reader is referred to Hull and Clyne (1996).

2.2 Woven Glass Fibre-Reinforced Polymers

2.2.1 Introduction

Composite laminates, mainly Carbon Fibre-Reinforced Polymers (CFRP) and Glass Fibre-Reinforced Polymers (GFRP) manufactured using multiple layers of woven fabrics are material systems that are used in a number of industries. A woven fabric consists of fibres bundled into yarns (or fibre tows) which are interlaced in a pattern. If the woven fabrics contain any interlaminar reinforcement (in the through-thickness direction) they are known as 3D fabrics, which have out-of-plane reinforcements to mitigate delaminations. In this work only 2D woven fabrics have been considered as delaminations are the type of damage that is being investigated and the use of composites comprising of 2D woven fabrics is more established in industry. Figure 2-1 shows three common types of fabric weave. The plain weave is the simplest; each yarn is laid over one orthogonal yarn and under the next. In the 5-
Chapter 2. Literature review

harness satin (5HS) weave each yarn is laid over four orthogonal yarns and then under one. Similarly, for the 8-harness satin (8HS) weave, each yarn is laid over seven orthogonal yarns and under one.

A composite laminate is formed using layers of fabric that are impregnated with resin and then cured. The advantage of using a satin weave over a plane weave is the drapability of the fabric. From the different types of weaves studied, Rozant et al. (2000) showed the 8HS weave fabric has the highest drapeability, meaning that it is easier to form a complex shape compared with a number of different weaves.

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2.2.2 Types of damage in woven FRPs

Fibre-Reinforced Polymers (FRPs) exhibit a number of damage mechanisms. These can be grouped into 3 categories: micro-scale, meso-scale and macro-scale (Renard and Thionnet, 2006). Micro-scale damage includes matrix cracking, the debonding of fibres from the matrix and fibre failure within the yarns. Meso-scale considers damage on a ply-by-ply basis in the laminate, including interlaminar damage, or delaminations. Finally, at the macro-scale, interactions of micro-scale and meso-scale damage accumulate, leading to the failure of the yarns and large delaminations.

Delaminations are the separation or debonding of a ply from an adjacent ply due to a low strength in the through-thickness direction of the laminate due to a lack of reinforcement. Delaminations are indicators of complete component failure as, while the strength of FRPs is fibre dominated, the low shear strength between the plies can lead to the growth of delaminations resulting in plies debonding and not transferring loads through the laminate, leading to stress concentrations and eventually...
component failure. For this reason, the detection and growth monitoring of delaminations in FRP components is essential. There are three main types of delaminations that can be distinguished from one another based on where the delaminations are situated in a structural element as summarised in Figure 2-2. This distinction between the different types of delamination is made as, under load, the stability of delamination growth is a concern; near surface delaminations have a tendency to buckle, which has a compromising effect on the structural health. Near surface delaminations are associated with increased instability, and are of higher concern with respect to actual components than delaminations situated well within a structure.

![Figure 2-2: Three types of delaminations: (a) internal, (b) near-surface and (c) multiple cracking (Bolotin, 1996)](image)

2.3 Structural elements for NDT

2.3.1 Introduction

The design of composite components is usually based on tests performed on structural elements before moving on to tests on full-scale structures. This is commonly represented with a testing pyramid, such as the one shown in Figure 2-3. As with testing materials at the coupon level to assess their applicability to a more complex structure, establishing the proficiency of an NDT technique in detecting defects requires the design of a coupon or structural element in which a defect can be introduced in a reproducible manner. This enables the comparison of different techniques and a basis for establishing the resolution of the techniques before applying them to specimens higher up in the pyramid.
In evaluating different NDT techniques to assess their effectiveness in the measurement of the size and growth of delaminations, representative structural elements need to be manufactured in which delaminations can be introduced and grown. In the design and manufacture of a structural element for the purposes of evaluating NDT techniques, it is imperative to consider the ease of manufacture as this directly relates to how reproducible the specimens are. To ensure that the testing can be easily reproduced, different material systems, specimen design and manufacturing techniques are evaluated, as well as how the damage is inserted.

This section evaluates the different materials and structural elements that are used in studies on delamination assessments in FRP laminates. Many different material systems and specimens have been designed and manufactured for the purposes of evaluating NDT techniques. There is a wide use of CFRP and GFRP. Structural elements include flat coupons, T-sections, lap joints, sandwich panels and tubes.

2.3.2 Flat coupons

As indicated in Figure 2-3, the use of flat coupons is the most common structural element used in investigating the use of NDT techniques to detect defects. These coupons have defects introduced to them either in the manufacturing stage or after the panel has been manufactured.

Out of all of the material systems available, unidirectional (UD) CFRP panels with a quasi-isotropic layup are the most common. Gaudenzi et al. (2014) manufactured flat coupons made from 16 layers
[+45/0/-45/90]_{2S} of unidirectional carbon UD300 reinforced M10 epoxy resin, resulting in an overall thickness of 4 mm. This layup was selected to reduce the difference in the flexural stiffness between adjacent plies. The damage was introduced using several different methods. Initially, flat bottom holes were used to simulate damage. Sheets of polyethylene release film were also used to validate the NDT technique used in the study. The main focus of this paper was detecting damage caused by low velocity impact which generates different types of damage, including delaminations. De Angelis et al. (2015) uses the same CFRP test plates [+45/0/-45/90]_{2S} with a total thickness of 4 mm. In this study flat bottom holes were also used to simulate delaminations while monitoring the specimens on the surface where the holes are not visible. This study also considers low velocity impact to create damage. Similar materials were used by Maio et al. (2016), where flat panels made out of 8 layers [+45/-45/0/90]_{S}, of carbon/epoxy pre-preg were manufactured by hand lay-up resulting in an average laminate thickness of 1.6 mm. To simulate the presence of a delamination, a PTFE disk was inserted two plies deep from the surface being monitored using the NDT techniques being investigated in the study. De Angelis et al. (2012) used CFRP test plates made with 8 unidirectional layers, [0, ±45, 90]_{S}, with a total thickness of 4 mm. In this study, flat bottom holes were used to simulate delamination defects in the investigation, using digital shearography as an NDT technique. Devivier et al. (2010) used a 32 ply CFRP quasi-isotropic layup for a study on delaminations in composites under bending. There is also literature on the use of quasi-isotropic GFRP panels when manufacturing specimens for the use of investigating delamination defects in composite structural elements. Short et al. (2001) conducted a study on the effect of delamination size and geometry on the compressive failure of flat composites. In this study, GFRP panels [0/+45/-45/0]_{S} made out of unidirectional plies were used. These panels were manufactured using hand lay-up and cured using a vacuum bag method.

Cross-ply CFRP panels have also been used in studies. Pinto et al. (2014) focused on the evaluation of an NDT technique on a flat panel, but also manufactured a structural element in the shape of a wing. The material system used was CFRP made with T700 UD carbon fibre prepreg and a [0/90]_{S} stacking sequence. This work used single sheets of PTFE to simulate the presence of delaminations.

Purely UD CFRP laminates have also been used in studies. Schorer and Sause (2015) used flat coupons made out of 8 layers of UD carbon/epoxy prepreg, producing specimens with a nominal thickness of 1.76 mm, as shown in Figure 2-4. These laminates contained only UD plies with the fibres oriented in the direction of the tensile loading. The study looked at the use of 3D DIC as an NDT technique. To obtain strain measurements, the specimens were mechanically loaded: as all of the tensile loading occurs along the fibre direction, it is unlikely for damage other than the inserted defects to develop unintentionally. While this UD layup is suitable for this work, other types of mechanical loading may cause unintended damage.
The use of fabrics in the manufacture of panels for delamination investigations is an area that needs more work. There are few studies in which the use of fabrics have been used instead of UD plies, which is understandable due to the fact that laminates containing fabrics, as opposed to unidirectional fibres, are more resistant to splitting and delaminations (Kim and Sham, 2000). However, studies where the delaminations are simulated using methods other than fatigue induced damage have considered the use of fabrics. Pawar and Peters (2013) investigated the detection of impact damage in composite laminates using pulsed phase thermography. In this work, 12-layer CFRP laminates were manufactured out of twill weave plies made out of Advanced Composites LTM22/CF0300 carbon fibre epoxy prepreg. In a study investigating the detection of flat bottom holes using the local defect resonances obtained from laser Doppler vibrometry, Hettler et al. (2017) used a GFRP laminate manufactured out of plain weave [0/90] plies.

2.3.3 Tubular specimens

While flat coupons are the most common types of specimens used in investigating delaminations in composites, tubular specimens have also been used in the literature. The applications for tubular components produced from FRP composites is growing. These are being seen in the automotive and aerospace industries and more commonly now in bicycle frames. In terms of using tubes for structural elements for the purpose of investigating NDT techniques, the benefit is allowing the monitoring of damage growth without the interaction of free edges. These specimens also allow the application of pure shear loads in the form of torsion to be applied as well as biaxial loads, i.e. a combination of tension and torsion. The manufacturing of composite tubular specimens for studies investigating damage have a tendency to manufacture the specimens using winding machines on mandrels. Rheinfurth et al. (2011) and Schmidt et al. (2012) used free wound E-glass tube specimens produced using a winding machine. In both studies, the tubes were manufactured with eight layers with a symmetric layup of [0/45/90/-45]. This was infused with RIM135/RIM137 epoxy resin and hardener using Resin Transfer Moulding (RTM). The damage was fatigue induced in Rheinfurth et al. (2011)
and impact induced in Schmidt et al. (2012). Hack et al. (2015) manufactured cylinders using UTS50 carbon fibres reinforced with XB 3515/5021 BD resin. The non-symmetric layup was specified as being [0₃, -45₁₄, +45₆]. This layup was chosen to initiate damage at the ±45° interface when the specimen was placed in torsion.

In a different study characterising damaged tubular composites a number of NDT and structural health monitoring (SHM) techniques, Chandarana et al. (2017) manufactured hollow composite cylinders using unidirectional pre-preg carbon fibre (Toray T700) for the 0° plies and unidirectional pre-preg E-glass fibres oriented in the 90° to produce a [0/90/0/90/0] layup. In this study, the damage was introduced (after the tubes were cured) by low velocity impact. Chen et al. (2011) manufactured tubes with a [0/90]₉ cross-ply GFRP layup containing embedded Fibre Bragg Grating (FBG) sensors. This study, and many others, do not detail the manufacturing process.

Other methods of manufacturing tubular specimens were investigated as well. In a study by Jung et al. (2009), where the energy absorption and ultimate bending moments of hybrid aluminium GFRP square tubes was investigated, the square tubes were manufactured using the technique shown in Figure 2-5. The aluminium square tube was enveloped with Bondex 206 adhesive film and wrapped by the GFRP prepreg to the required number of layers. The wrapped aluminium/GFRP tube was then placed inside an aluminium mould, which was kept separated by silicone rubber plates. The mould was tightened to uniformly consolidate the GFRP prepreg. The whole set-up was then cured as specified by the providers of the GFRP material system.

![Figure 2-5: Manufacturing process for the hybrid aluminium GFRP square tubes. (a) Stacking of the prepreg and adhesive film. (b) Aluminium mould assembly and silicon rubber dividers (Jung et al., 2009)

2.3.4 Other types of structures

Other, less common, structures have been investigated as well. These include T-sections, sandwich panels and lap-joints. A T-section is a structural element one tier above the coupon level in the testing
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pyramid (Figure 2-3). As such there are fewer examples in literature of the use of T-sections in the evaluation of NDT techniques. Ooijevaar et al. (2010) used a [0/90]_{4s} T-section made out of 16 layers of unidirectional carbon AS4D reinforced polyetherketoneketone (PEKK). To join the two composite plates to make the T-beam a PEKK injection moulded filler was used as a connection. A schematic of this design is shown in Figure 2-6a. This design was chosen to create a structural element with a high bending rigidity and a low torsional rigidity. The delamination was created by placing a 100 mm long, 0.1 mm thick polyimid film under the T-joint during the manufacturing process. The position of the delamination is shown in the schematics of the T-Beam in Figure 2-6b. The T-beams were cured in an autoclave.

Sandwich panels are a type of structural element that is heavily investigated due to the applications of composite sandwich structures in industry. Scarponi and Briotti (1997) subjected sandwich panels to impact and fatigue loads to create delaminations for the purpose of investigating the damage with ultrasonic NDT techniques. Hettler et al. (2017) also looked at the capabilities of an ultrasonic technique in characterising delaminations and debonds. The sandwich panels used in the study were used to investigate the debonds, placed between the sandwich panel and CFRP laminate as shown in Figure 2-7.

Figure 2-6: Schematics of T-Beam specimen. (a) pictorial view before delamination and (b) side view of the delaminated T-beam (Ooijevaar et al., 2010)
Lap joints have primarily been used to investigate the performance of adhesive bonds. Tighe et al. (2015) used thermography and ultrasonics to detect kissing bonds between the CFRP and the adhesive in the lap joint specimens tested. Three different methods of creating the debond were investigated using PTFE inserts, silicone grease and mould release. Kumar et al. (2013) used DIC to investigate kissing bonds in GFRP adhesive lap joints. In this work, ethylene tetrafluoroethylene (ETFE) inserts were used to simulate the debond.

2.3.5 Summary

A number of different structural elements have been used in several studies involving damage in composite materials and NDT. The vast majority of these have been flat coupons. This is due to the ease of manufacture, as well as the ease in inserting controlled damage into the specimens. Papers containing tubular structural elements tended not to mention the manufacturing process. The damage in these was induced by fatigue or impact, rather than the use of an insert.

Other types of structural elements included sandwich panels, T-sections and lap joints, but with these more complex structural elements, the damage investigated tended to lean towards failure of the adhesive joint, rather than embedded delaminations. While investigating these types of specimens, and how DIC could be used to investigate debonds between adhesively bonded structures, these types of structures increase the complexity and resources required to manufacture the specimens.

Unidirectional CFRP in a quasi-isotropic layup was the most commonly used type of material. The majority of materials investigated were prepreg materials, which could be due to the ease of laying up the material in the correct configurations as well as the placement of inserts to simulate damage. The use of fabrics in these types of studies are limited, but not unheard of. The next section gives an overview of the methods of creating delamination defects into FRP composites.
2.4 Introducing delamination defects in composites

2.4.1 Introduction

A number of methods exist for artificially creating artificial delamination defects in a composite laminate. This section provides more detail on the application of the methods of simulating and creating damage, specifically delaminations, in composite materials which were introduced in the previous section. These methods include: the insertion of polymer sheets, impact, the use of flat bottom holes, and other methods such as the use of pressurised air, drilling holes and complex inserts.

2.4.2 Insertion of polymer sheets

The most common way to create a reproducible defect to simulate the presence of a delamination in a composite structural element is the insertion of a polymer sheet between two plies, prior to curing the laminate during the manufacturing process, in order to prevent uniform consolidation of the composite, which should cause (or at the least simulate) delamination (Pinto et al., 2014). The most common insert is a chemically non-reactive polymer such as Teflon (PTFE).

The use of PTFE to simulate a delamination seems to have varied success in different studies. Shahverdi et al. (2011) investigated the fracture behaviour of pultruded adhesively bonded joints using Double Cantilever Beam (DCB) specimens manufactured with an existing pre-crack. The pre-crack was introduced in the manufacturing procedure of the specimen by placing a 0.05 mm thick Teflon film between the adhesive layer and the upper arm of the DCB. While this method seemed to work with the crack tip at the edge of the specimen, the paper indicates that placing the pre-crack deeper in the pultruded material did not ensure the initiation of the crack at the desired depth, meaning it did not behave well as a pre-crack when embedded. Nilsson et al. (2001b) studied the behaviour of carbon fibre/epoxy composite laminates loaded in compression with embedded artificial delamination defects. The 60 mm diameter delamination defects were created by inserting 10 μm thick Teflon (PTFE) film during the manufacture of the laminate between the desired plies. The testing produced delamination growth as a result of placing the thin composite laminate under compression loading. The paper notes that delamination buckling was difficult to achieve in many panels, as the delaminations did not open properly. In these cases, a perturbation load close to the global buckling load of the structure was applied to open the delamination. Another example showing the limitations of just using Teflon as an insert to simulate cracking or delamination is the study by Sarens et al. (2010). This study investigated the use of shearography and laser doppler vibromatic scanning to detect the presence of non-bonded contact defects such as delamination defects. The defects were simulated using 20 mm diameter Teflon inserts with a thickness of 10 μm between the 2nd and 3rd ply below the surface being investigated. To ensure the insert acted as a delamination, the opening of the
Chapter 2. Literature review

delamination was enhanced by impacting the plate above the film by a falling steel ball with a diameter of 25 mm.

Maio et al. (2016) investigated the use of ultrasonic phased array and IR thermography in detecting a PTFE disk two plies below the surface of a flat CFRP panel corresponding to a depth of 0.4 mm. The position of the PTFE insert is shown in Figure 2-8. Most investigations of NDT techniques have used fully embedded delamination inserts such as this one.

![Figure 2-8: Schematic of the (a) top view of specimen, (b) section view of the position of the defect (Maio et al., 2016)](image)

The use of PTFE to simulate delaminations as pre-cracks is so well established in the literature, that most standards for testing that require delamination pre-cracks suggest the use of PTFE. The American Society for Testing and Materials (ASTM) standard for testing the mode I interlaminar fracture toughness of unidirectional fibre-reinforced polymer matrix composites recommends the use of a thin sheet of PTFE to produce the initial crack (ASTM, 2014). This technique is also recommended for determining the mode II fracture toughness (ASTM D7905/D7905M-14, 2014) and for determining the mixed mode I-mode II fracture toughness of unidirectional FRP-matrix composites (ASTM D6671M, 2006).

Pérez et al. (2014) presents the effects of artificially induced delamination defects as well as low velocity impact damage on the vibrational response of a CFRP panel. The artificial delamination inserts were created by placing a piece of polyimide film of unspecified thickness in between the desired plies before consolidating and curing the panels in an autoclave. When comparing the influence of the artificial delamination and the impact introduced damage, it was concluded that the inserts had less of an effect on the damage tolerance of the coupons than the impact damage (Pérez et al., 2014). The polyimide technique for introducing an artificial delamination was also used by Ooijevaar et al. (2010).
Le Cahain et al. (2015) compared a range of insert materials, including: 5 μm steel shims, 12.7 μm PTFE films, 20 μm Flouro ethylene propylene (FEP) films, 15 μm ETFE films and 12.7 μm Kapton films as the insert materials in both glass fibre epoxy and carbon fibre epoxy laminates. The results indicate that only the steel shim and PTFE consistently act as a delamination in both the composites tested (Le Cahain et al., 2015). However, this is also probably dependent on the thickness of the inserts as well. The thickness of the inserts is a factor that has not been investigated in detail in literature. The standards recommend sheets with a thickness of 25 μm or less but in the descriptions the most detail given is that it should be a “thin” film. There are many instances in the literature where the insert is larger than 25 μm (Deivier et al., 2010; Ling et al., 2005; Shahverdi et al., 2011). There are some studies where the thickness of the inserts is changed or not recorded. For instance in a study investigating embedded flaws used to control interlaminar crack growth and through-thickness crack branching in composite laminates, Orifici et al. (2014) manufactured DCB specimens out of carbon/epoxy VTM-264 prepreg with various layups. The delaminations were simulated with sheets of ETFE. 25 μm and 13 μm sheets were used interchangeably. In this study each ply had a nominal thickness of 0.22 mm and there were no reported differences in the results due to the thickness of the inserts (Orifici et al., 2014). The exception may be foam inserts which are inherently thicker. Pawar and Peters (2013) used Rohacell foam inserts with a thickness of 3 mm in CFRP laminates with twill weave woven fabric. The reason for using foam inserts was to simulate the effects of barely visible impact damage (BVID) as the purpose of this work was to evaluate a thermographic NDT technique in detecting impact damage in composite laminates.

2.4.3 Impact

Impact is commonly used to create damage in structural elements to analyse NDT techniques. Damage to composite components used in industry is likely to be caused by impact, making it the most realistic form of damage to detect. There is a distinction to be made between Low-Velocity Impact (LVI) and High-Velocity Impact (HVI). The works investigated in this review all investigate LVI, with energy in the range of 5-25 J, as HVI tests tend to cause more complex damage interactions. A good example of LVI is the impact from gravel and debris on aircraft structures (Gaudenzi et al., 2014). HVI better represents impact from bird strikes or ballistic impacts. LVI mainly produces damage such as matrix cracking and delaminations with limited fibre breakage (Abrate, 1991). The main restricting factors in using impact to assess how well an NDT technique can detect and monitor a delamination is that multiple delaminations are likely to be produced at the same position at various depths (Gaudenzi et al., 2014; Senthil et al., 2013; Shen et al., 2001) as shown in Figure 2-9a. This is further complicated with other modes of damage occurring as shown in Figure 2-9b.
2.4.4 Flat bottom holes

Flat bottom holes are reported in literature as a method of simulating damage in a flat laminate after it has been cured. The holes are milled into the specimens on the opposite surface to the one being monitored using an NDT technique. An example of a panel with flat bottom holes is shown in Figure 2-10. The use of flat bottom holes in composites specimens is generally to evaluate thermographic techniques as it assumes delaminations completely block the conduction of thermal energy to the laminate below where the delaminated region is (Chatterjee et al., 2011; Pickering and Almond, 2008; Winfree and Zalameda, 2003) (see section 2.5.5). This method guarantees that the hole acts as a defect when evaluating NDT techniques, whereas polymer inserts can have issues where the inserts bond with the laminate during cure (see section 2.4.2). Optical techniques have also been evaluated in the literature using composite panels with flat bottom holes. De Angelis et al. (2012) used flat bottom holes to simulate delamination defects in a study concerned with using digital shearography to detect and characterise defects in composite panels. Flat bottom holes have also been used in ultrasonic NDT methods. Hettler et al. (2017) uses local defect resonance to detect and characterise flat bottom holes in a composite laminate.
2.4.5 Other methods

Ekenel & Myers (2009) investigated fatigue loading of CFRP strengthened concrete beams. The effect of delaminations in the CFRP panels was studied. The delaminations were artificially inserted by injecting a small amount of pressurised air beneath the fabric in the appropriate layer immediately after the application of the final layer of the epoxy resin. Insignificant delamination growth occurred during testing, however the delamination presence in the CFRP did significantly decrease the stiffness of the entire reinforced concrete beam.

Schorer & Sause (2015) simulated the presence of delaminations by creating “pocket” delaminations by the introduction of a double layered ETFE foil with a thickness of 25 µm. The delamination insert was consolidated by sealing the insert by welding the edges using a hot wire processing technique. Nilsson et al. (2001a) also attempted a stacked insert technique. In this work two pieces of 7.5 µm thick polyimide film were placed between the plies where the delamination was to be simulated. To prevent adhesion, a thin layer of Teflon was sprayed between the two pieces of polyimide. This technique did not guarantee the simulation of a delamination as in several tests the two films did not separate properly. As part of a study to investigate the capabilities of a number of NDT techniques to detect damage in composite materials, Gower et al. (2016) detailed the design and manufacture of methods to create delamination defects in FRP composites. A more elaborate pocket delamination was manufactured using two pieces of heat resistant tape to seal two PTFE inserts as detailed in Figure 2-11. Also, in this work, natural defect artefacts (NDAs) were created using impact as well as by milling a notch into a flat coupon and placing it under tension as shown in Figure 2-12.

![Figure 2-11: Schematic of the pocket delamination insert using heat resistant tape and PTFE](Gower et al., 2016)
Sereshk and Bidhendi (2016) drilled holes into a CFRP panel, producing natural delaminations. Delaminations are a well-known result of drilling into 2D FRP panels, as the weak interlaminar strength of these types of material is likely to cause plies to debond in the area around the drilled hole due to the machining forces (Davim and Pedro, 2003). Figure 2-13 shows 10 mm holes drilled into the CFRP panels and the resultant delamination damage (Sereshk and Bidhendi, 2016).

2.4.6 Summary

The use of polymer inserts is the most common method used to simulate a delamination for experimental testing. This is probably due to the ease of reproducing specimens with the same delamination sizes. Flat bottom holes, drilled into the back-face of a flat coupon, is an easy method to simulate the presence of a delamination compared with methods involving placing polymer sheets between plies during manufacturing. However, this method cannot be used as a method for simulating delaminations if the specimens need to be mechanically loaded, as the removal of material will result in a significant change in mechanical behaviour when compared to a conventionally delaminated specimen. These specimens are primarily used for investigating thermographic techniques as in theory, a real delamination should act as an air pocket, interrupting the transmission of thermal
energy from the front-face to the back-face of the material. For this application, the removal of the material from the back-face emulates a delamination.

In the Schorer and Sause (2015) study, a pocket delamination insert was developed using two pieces of ETFE. Similarly, Gower et al. (2016) used the design from an earlier study (Broughton et al., 1999) to create more elaborate pocket delamination inserts. In these works, the pocket delaminations successfully emulated delaminations. This approach by Gower et al. (2016) was adopted for the initial investigations of the capabilities of DIC as an NDT technique in this thesis (see Chapter 4).

NDAs produced by impact do include delaminations, however it is widely reported that impact also produces other damage mechanisms. The notched tensile specimen produced delaminations by mechanically loading of the flat coupon (Gower et al., 2016). This method has many advantages over other methods of producing damage, as producing flat coupons and milling a slot through the width of the specimen is an easy way to produce a specimen, which when loaded, grows delaminations at the depth of the notch. This method was adopted and further developed for work in this thesis (see Chapter 6).
2.5 Detection and characterisation of delamination defects in composite structures

2.5.1 Introduction

As the main objective of the project involved the need for a NDT method to detect and measure the presence of cracks, this section summarises the research investigating the different methods available.

NDT techniques can be combined, such as Infra-Red Thermography (IRT) with ultrasonic testing, to complement one another to improve the detection and characterisation of defects (Aldave et al., 2013). While a combination of different techniques can enhance the results, at this stage individual techniques have been investigated.

2.5.2 Overview of available NDT techniques

A review of the non-destructive evaluation of composites was conducted by Ibrahim (2014). This review considered many older reviews together with recent studies using different NDT techniques to detect and characterise defects in composite structures. Included in that review are the application of a number of NDT techniques consisting of vibration analysis, strain monitoring, ultrasonics, acoustic emission (AE), ground penetrating radar (GPR), microwave, terahertz spectroscopy, infrared thermography, optical interferometry, radiography, X-ray tomography, neutron techniques, nuclear magnetic resonance (NMR) imaging and electrical techniques. Table 2-1 shows the key findings from the review for each NDT technique applied to each type of structure. The structures include polymer matrix composites (PMC), honeycomb sandwich structures, foam sandwich structures, ceramic matrix composites (CMC), metal matrix composites (MMC) and fibre metal laminates (FML). In the table, the applicability of each technique for each type of specimen is reviewed, and given a rating out of three stars, assigned from the perspective of the reviewer. From this review, it is shown that the detection and characterisation of delaminations in solid PMC laminates is best done using ultrasonic inspection techniques, as these techniques have the capabilities of detecting and characterising delaminations both close to the surface and deeper within the laminate.

There is an overwhelming amount of literature on all of these techniques and types of specimens, therefore, to simplify this chapter, the applicability of different techniques on flat coupons has been prioritised. Also, as the primary purpose of this thesis was to investigate the use of DIC to monitor delaminations, full-field NDT techniques were prioritised.
Table 2-1: A summary of the applicability of NDT techniques to different types of thick-section composites. The defects each technique is most capable of detecting are listed with a rating on the reliability of the technique to detect the specific defect: The empty star is the ability to detect defects near the surface. The filled star is the ability to detect and characterise defects near the surface. Two stars is for defects not close to the surface, empty for the ability to detect and filled for the ability to characterise. Half-filled stars indicates limitations. (Ibrahim, 2014)

<table>
<thead>
<tr>
<th>Solid PMC Laminates</th>
<th>Honeycomb sandwich</th>
<th>Foam sandwich</th>
<th>CMC</th>
<th>MMC</th>
<th>FML</th>
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<tr>
<td><strong>Vibrational</strong></td>
<td>Delam★★</td>
<td>Skin-to-core disbond★★</td>
<td>Delam★★</td>
<td>Delam★★</td>
<td>Delam★★ DISbond★★</td>
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<tr>
<td><strong>Strain Sensing</strong></td>
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<tr>
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<td>Disbond★★</td>
<td>Skin-to-core disbond★★</td>
<td>Void★★</td>
<td>Delam★★</td>
<td>Delam★★</td>
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<td><strong>Ultrasound</strong></td>
<td>Delam★★ Void★★</td>
<td>Skin-to-core disbond★★</td>
<td>Void★★</td>
<td>Porosity★★</td>
<td>Cracking★★</td>
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<td>Fibre V.★★</td>
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<td>Delam★★</td>
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<tr>
<td><strong>AE/Acousto-UT</strong></td>
<td>Fibre failure★★</td>
<td>Node failure★★</td>
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<td>Cracking★★</td>
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<td>Moisture★★</td>
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<td>Fibre V.★★</td>
<td>Inclusions★★</td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
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<td><strong>Thermography</strong></td>
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<td>Skin-to-core disbond★★</td>
<td>Voids★★</td>
<td>Delam★★</td>
<td>Cracking★★</td>
</tr>
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<td></td>
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<td>Core-crush★★</td>
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<td>Water★★ Bondlines★★</td>
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<td></td>
<td>Cracking★★</td>
</tr>
</tbody>
</table>

Of these techniques, not all are suitable in the current context. The following sections summarise the current usage of key techniques for NDT of composites, with a particular focus on the ability to evaluate delamination.
2.5.3 Digital image correlation (DIC)

DIC is a relatively new concept, first conceived at the University of South Carolina in the early 1980s (Zhu et al., 2011). Sutton, et al., (1983) introduced an improved digital correlation method for determining full-field in-plane deformations on an object surface. This work is the basis for the development of DIC into the well-established commercial offerings that are available today. The use of a stereo pair of cameras to obtain three-dimensional data was first presented by Kahn-Jetter and Chu (1990) and Luo et al. (1993). This extension of the DIC technique allows for the measurement of out of plane deformations.

DIC works by acquiring high resolution digital images of a surface while it is deforming under an incremental load and evaluating the changes in the characteristics to obtain full-field deformation data. Initially, a reference image is taken of the surface of the structure without a load to compare to the images of the same surface under load. The differences in patterns on the surface between the deformed images and the reference images are calculated by correlating sets of pixels (called subsets) in both. To ensure good results, high contrast speckle patterns are usually applied to the surface being monitored (described in more detail in Chapter 3). This speckle pattern has a requirement of being non-periodic, as repeating textures may lead to misinterpretation problems, i.e. subsets being confused for one another (Kumar et al., 2013). A number of studies have been conducted on the speckle pattern and subset size (Crammond et al., 2013; Pan et al., 2008; Yaofeng and Pang, 2007). For more information regarding DIC, refer to literature such as Sutton et al. (2009).

Using DIC, studies have been conducted on measuring the mechanical properties of different materials, monitoring the fatigue and breakup of materials and also for high temperature objects (Zhu et al., 2011). In terms of NDT, Coburn & Slevin (1995) used digital correlation to detect damage in thermally stressed ceramics. Work done by NPL demonstrated that DIC has the potential to be used as an NDT tool for measuring deformation and cracking in concrete structures (McCormick and Lord, 2010). Vanniamparambil et al. (2013) conducted a study on the damage detection capabilities of a number of methods, including DIC, on seven-wire strands and concrete masonry wall. In the detection of damage in composite materials, there have been very few studies. Kumar et al. (2013) used DIC to detect dry contact kissing bonds in composite adhesive lap joints. Kashfuddoja & Ramji (2013) used DIC to analyse a CFRP panel containing an adhesively bonded patch repair in tension. Figure 2-14 displays a schematic of the DIC set up used to look at the surface of interest with the equipment. The damage initiation and progression in both a notched and repaired panel was successfully monitored using this technique by observing the full-field strain data. The DIC results displayed highly localised strains around the edges of the patch. All full-field strain variations obtained from the testing were
compared with FEA and found to be in good agreement. In another study, Kashfuddoja et al. (2014) looked at the characterisation of a CFRP panel using DIC.

![Figure 2-14: Schematic diagram of 3D-DIC setup (Kashfuddoja and Ramji, 2013)](image)

Schorer & Sause (2015) conducted a study on identifying failure mechanisms in CFRP laminates using 3D DIC. This study included the detection of fibre breakage in different plies, delaminations between different ply interfaces and inter-fibre cracks running through the 8-ply laminate. Specimens with embedded artificial defects were placed in tension with the DIC equipment monitoring the surface to which the defects were the closest to (Schorer and Sause, 2015). As this method revolves around the effect of defects on the strain behaviour of the surface being investigated, the data was evaluated as a strain difference at certain load level, $i$, by equation 2.1.

$$\Delta \varepsilon_i = \overline{\varepsilon}_{\text{defect}} - \overline{\varepsilon}_{\text{global}}$$

(2.1)

Where

$$\overline{\varepsilon}_{\text{defect}} = \frac{1}{m} \sum_{j=1}^{m} \varepsilon_j$$

(2.2)

And

$$\overline{\varepsilon}_{\text{global}} = \frac{1}{n} \sum_{k=1}^{n} \varepsilon_k$$

(2.3)

In equation 2.2, $m$ is the number of data points in the strain field with the highest strain due to the stress concentrations caused by the defect. In equation 2.3, $n$ is the total number of subsets used in the post processing of the global strain field. Using these equations, the results were evaluated by plotting the change in strains (equation 2.1) divided by the applied stress as a function of the predefined delamination size as shown in Figure 2-15.
The results from the paper indicate that the DIC is a promising technique to assess different failure types in composite laminates. Further work is required to reduce the background noise in the data and to improve the ability to assess different defect sizes and depths of the defect from the surface being monitored.

2.5.4 Ultrasonic inspection

As identified in the review by Ibrahim (2014) ultrasonic inspection techniques are the most well established techniques for the detection of delaminations in FRP panels. Ultrasonic Testing (UT) techniques are acoustic techniques that measure either the reflection or transmission of pulsed elastic waves. The general principle behind the technique is to use electroacoustic transducers to generate ultrasonic waves and transmit them through the material that is being inspected (Gaudenzi et al., 2014). A receiving transducer is placed either on the same side as the transmitting transducer (to measure the reflected waves), or on the other side of the specimen (for transmission based ultrasonic inspection). In either case, the waves interact with the structure and get reflected, refracted and diffracted. For more information on ultrasonic techniques, refer to literature such as Krautkrämer et al. (1977).

Ultrasonic inspection has been applied in a number of studies. The most common form of ultrasonic inspection is the C-scan. Ultrasonic C-scans provide plan type views of the specimen being tested. It enables cross-sections of the specimen to be viewed displaying 2D images of the defects as well. Figure 2-16 shows a schematic view of a defect within a test piece. The work of Nilsson et al. (2001a) makes use of acoustic emissions to detect the onset of damage growth during the compression loading of the test coupons. To monitor the crack growth the coupons were dismounted after each load sequence and analysed using ultrasonic C-scan. This method enabled them to investigate the effect of the depth of the defect within the laminate on the direction of growth. In a study comparing
thermographic techniques to ultrasonic techniques in detecting delaminations in composite panels, Gaudenzi et al. (2014) used an ultrasonic C-scan method to detect circular embedded delamination inserts in a composite panel. The C-scans are shown in Figure 2-17.

Figure 2-16: Ultrasonic C-scan diagram (NDT Resource Center, n.d.)

In a study comparing the effects of artificially introduced delamination damage using a polyimide film and real damage induced by impact, Pérez et al. (2014) examined the test coupons after manufacturing using non-destructive ultrasonic phased array testing to evaluate the compaction of the coupons as well as the presence of pores, defects and delamination defects. The method involved the use of both B- and C-scans which proved to show good agreement with the size of the delaminations detected and the actual size of the artificial delamination inserts used in the specimens.

Figure 2-17: Two C-scans of the same CFRP panel with multiple embedded delaminations at different depths. The Two images are of opposite surfaces being investigated (Gaudenzi et al., 2014)

Ultrasonics may be one of the more promising NDT techniques for detecting delaminations, however, there are some disadvantages with the technique. The transducers require coupling with the specimen. Scarponi and Briotti (1997) found that indentations from the impact used to generate defects caused signal losses due to the uncoupling of the transducers with the material. In some cases,
immersion baths are used to immerse the specimen in water to couple the high frequency waves. This impedes in-situ applications of the technique (Rheinfurth et al., 2011). Furthermore, the technique is not full-field and requires accurate 3D mapping to characterise defects in a structure.

2.5.5 Infrared thermography

Infrared thermography refers to any technique that monitors the emitted infrared emissions from the surface of a specimen. Figure 2-18 shows a schematic of different thermography methods: pulse thermography (PT), step thermography (ST), lock-in thermography (LIT) and vibrothermography (VT) (Castanedo et al., 2011). For all of these techniques, the specimen is stimulated by an energy input. The most common inputs are thermal, optical, mechanical or electromagnetic. Generally, thermography based on optical energy excitation is considered to be active, and is an external input, whilst mechanical excitation is passive thermography based on internal heating of the specimen. Similarly, electromagnetism can be used to induce heating through the generation of eddy currents (in electrically conducting materials).

All thermographic techniques rely on the thermal response of the specimen undergoing the excitation to be affected by the presence of defects. Specifically, pulse thermography makes use of the fact that the surface temperature of a thick homogenous solid as a response to a uniform instantaneous heating can be defined by the one-dimensional heat diffusion equation (Shepard, 2003):

\[
\frac{\partial^2 T}{\partial z^2} - \frac{1}{\alpha} \frac{\partial T}{\partial t} = 0
\]

Where \( T \) is temperature, \( t \) is time, \( z \) is the through-thickness coordinate, and \( \alpha \) is the thermal diffusivity coefficient of the material determined from the thermal conductivity, heat capacity and density of the material. Equation 2.4 assumes the lateral thermal diffusion components (x and y components) cancel out in a defect-free sample. The equation does not hold true for a void or a defect resulting in a boundary. Defect detection using pulse thermography is the identification of areas where the one-dimensional assumption breaks down.

For optical infrared thermography techniques, there are two modes in which the inspection can be done; transmission or reflection. While transmission IRT has a tendency to produce more accurate results (Chandarana et al., 2017), it is less practical as it requires access to both sides of the structural element and other difficulties are present when the structural element has a complex shape. Reflective IRT on the other hand has the advantage of ease of set-up and only requires one-sided access.
Gaudenzi et al. (2014) conducted a study on how different NDT techniques evaluate damage in a CFRP panel. Damage was induced into the panel using low velocity impact tests as well as flat bottom holes drilled into the surface not being monitored. The study observed the damage using active thermography, Sonic Infrared Thermography (SIR), as well as an ultrasonic phased array. The active thermography used in this work included lock-in thermography and transient thermography (TT). TT involves the heating of a specimen with a long duration pulse of thermal energy, followed by monitoring the subsequent cooling of the surface being investigated with a thermal camera to observe the emitted Infrared (IR) waves. Lock-in thermography is performed by monitoring the surface of the specimen while it is undergoing thermal excitation that is modulated with a sinusoidal waveform. This is described in more detail in chapter 3 (see section 3.6). Figure 2-19 shows the results of lock-in thermography conducted at two different frequencies, 0.1 Hz and 0.04 Hz, as applied to a CFRP panel with flat bottom holes. From these results it can be seen that the flat bottom hole defects can be detected using this technique. However, these types of defects are not representative of a real type of damage observed in composite materials, as described in section 2.2.2.
Specimens containing defects from low velocity impact were also evaluated using LIT. Figure 2-20 shows the results of this investigation with three coloured dots located in the impact area and one in the undamaged area (red). These results show that for damage induced by low velocity impact, there is a clear difference in the IR emissions observed between the impacted area and outside. This demonstrates that the damaged areas can be identified using this technique, however as impact does not cause just one type of damage, the damage being monitored is likely to be a combination of defects caused by the impact.

Maio et al. (2016) compared the detection of a delamination in a composite panel using lock-in thermography and pulse-echo ultrasonic C-scan. In the detection of the PTFE insert using the two NDT
techniques, the insert can be identified, as well as an outer ring surrounding the known position of the insert. Figure 2-21a shows the C-scan results where the colour represents the amplitude of the signal output. Figure 2-21b shows the phase image of the specimen taken at a lock-in frequency of 0.70 Hz. The outer ring is associated with the disbonded area as shown in Figure 2-22.

![C-scan and Lock-in thermography](image)

*Figure 2-21: The embedded PTFE insert detected using (a) C-scan and (b) Lock-in thermography (Maio et al., 2016)*

![Schematic of the embedded Teflon insert](image)

*Figure 2-22: Schematic of the embedded Teflon insert in the interface of two plies (Maio et al., 2016)*

In a study on the through-thickness identification of impact damage in composite laminates using pulsed phase thermography (PPT), Pawar & Peters (2013) validated the detection capabilities of the NDT method using foam inserts to simulate delaminations between plies at different depths. In the investigation, the panel containing delamination inserts of different sizes and different depths was investigated using pulse thermography. The results from this test are shown in Figure 2-23 and it can be seen that there is a window of time over which the thermal contrast between the area containing the defect and the non-defective area is highest, meaning the thermogram at the peak absolute contrast would enable the best characterisation of the defect from the rest of the thermograms in this test.
In PPT, the sample is heated by either a long or a short flash of light. The IR data collected by the thermal camera is inspected in the frequency domain, working on the theory that an ideal Dirac pulse contains frequency components. These frequencies can be individually extracted and analysed using Fourier analysis (Pickering and Almond, 2008).

In a study comparing the damage detection capabilities of pulsed thermography and lock-in thermography, Chatterjee et al. (2011) compared the mathematically processed amplitude and phase images of flat bottom holes in CFRP panels with pulsed thermography results. In this work, the pulsed images were enhanced with an algorithm developed by Shepard (2003), called the time series reconstruction (TSR) algorithm. This method works by fitting the cooling curve after the pulse with a logarithmic polynomial derived from the one-dimensional heat diffusion equation (Shepard, 2003). This method works by using the one-dimensional model to accurately predict the thermographic response with respect to time for a defect free sample. TSR compares deviations in the defect-free predicted behaviour in the logarithmic domain to the time history of each pixel of the acquired thermograms. This patented method is widely used in a range of applications, (Balageas et al., 2015; Chatterjee et al., 2011; Omar and Zhou, 2008; Shepard, 2003) however in a comparison of pulse thermography processing routines, Omar and Zhou (2008) showed that the defect depth predictions by TSR had a standard deviation of approximately 15%.

2.5.6 Fibre Bragg grating (FBG) sensors

The review of different NDT techniques used for composite materials inspection by Ibrahim (2014) suggests that strain monitoring does not necessarily detect damage in composites, but gives an indication of damage locations based on the effect the damage has on the strain response of the...
surface being monitored under load. As DIC makes use of surface deformations, post-processed into strain contours, this section investigates another strain based structural health monitoring technique; FBG sensors.

FBG sensors are being increasingly used in the structural health monitoring (SHM) of composite structures because of a number of advantages over conventional NDT techniques. Most damage detection methods are visual or are localised methods such as ultrasonic methods. These require that the approximate location of the damage is known prior to being inspected (Gouve et al., 2008). This is overcome by embedding FBGs in the composite during manufacturing for health monitoring of composite components (Rito, 2015). This method either needs the use of many FBGs or knowledge of where damage is most likely to occur. A number of studies have been done on the detection of delaminations in composite structures using FBGs. Rong et al. (2011) did a study on a CFRP panel with the delaminations placed between the 4th and 5th ply from the surface on which the FBG is installed. The panel, with an embedded PTFE insert, was placed in three-point bending, allowing the measurement of delaminations by reading the strain on the surface of the specimens using FBG sensors.

This work was based on Ling et al. (2005) where GFRP panels with embedded FBGs were loaded in three-point bending with PTFE inserts placed between two plies to simulate a delamination. Different specimens were tested with the insert placed between different plies. A table summarizing these can be found in Appendix A (Table A-1). Figure 2-24a shows the composite panel in the three-point bending fixture. The delamination insert is through width and runs from the edge to 55 mm into the specimen (dimension “a” in the schematic), with the edge being between the supporting roller and the loading roller. The strain readings from the FBG were used to characterise the delaminations. These strain readings are shown in Figure 2-24b. For most cases, there are abrupt changes in strain at the delamination tip. Similar results were found by Rong et al. (2011), where the main differences in the experiments were the specimen materials, the FBG being surface mounted and the insert being embedded.
These strain profiles along the optical fibres provide information that can be used to translate strain data along a line into a size measurement of delaminations. The same principles have been used in this thesis, by extracting surface strain data along a linear path, the position and size of delaminations of specimens in three-point bending can be identified (see Chapter 4).

2.5.7 Other optical methods

Optical methods are a relatively new type of NDT technique that have been investigated. These methods are full-field and give a visual representation of the condition of the structural element or component being tested (Restivo et al., 2008). These techniques include reflection photoelasticity, geometric moiré, holographic interferometry, laser speckle shearography and speckle pattern interferometry (Cloud, 1995). From these listed techniques, digital speckle shearography (DSS) and digital speckle pattern interferometry (DSPI) are the most popular for NDT applications (Restivo et al., 2008). These methods are very sensitive and are sometimes used for three-dimensional stress or strain analysis. This section looks at the applications of optical methods other than DIC for the non-destructive evaluation of structures. Zhu et al. (2011) reviews a number of optical NDT techniques, however this section only gives a short overview of digital shearography.

Shearography (speckle pattern shearing interferometry) is an interferometric measurement technique that uses coherent laser illumination (Hung et al., 2009). The method works by using a laser light source to illuminate the surface being inspected. This expanded laser is reflected off the surface and is scattered due to the optically rough surface of the specimen. The scattered laser light wave fronts are sheared and recorded by the CCD camera as shown in Figure 2-25. This results in a speckle pattern unique to the surface of the specimen in the unloaded state. When the specimen is loaded, the speckle
pattern from the reflected laser light changes due to the deformations in the optically rough surface of the specimen. Specimens are usually loaded using pressurisation, partial vacuum, acoustics and thermal shock excitation (De Angelis et al., 2012).

![Figure 2-25: Schematic of digital shearography (Hung et al., 2009)](image)

While shearography is a proven method, endorsed by the Federal Aviation Administration (FAA) for inspecting delaminations and other damage in aircraft tires (Hung et al., 2009), it is a complex technique, the results of which can be difficult to interpret. The technique is also sensitive to disturbances such as vibrations (Devivier et al., 2010). The technique, being full-field and similar to DIC, would be an ideal method to compare NDT capabilities with, however due to limited resources, this was not pursued.

A summary of key literature used in this section are listed in Table 2-2. The table summarises the type of coupons/specimens used in the literature, detailing the type of FRP and method of inserting the type of defect that was being monitored. The table also includes the methods used to non-destructively assess the damage in the material being investigated.
<table>
<thead>
<tr>
<th>Type of specimen</th>
<th>Reference</th>
<th>Type of FRP</th>
<th>Method of inserting defect</th>
<th>Type of NDT / Structural health monitoring technique</th>
</tr>
</thead>
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<td>Flat coupon</td>
<td>Gower et al. (2016)</td>
<td>UD CFRP: SE84LV prepreg, UD GFRP: 913G prepreg, Quadraxial GFRP: FGE111/20LV, UD GFRP: MTM®28</td>
<td>Delamination from notch, pocket delamination inserts (PTFE), flat bottom holes, impact</td>
<td>Ultrasomics, Microwave inspection, active thermography</td>
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<td>Gaudenzi et al. (2014)</td>
<td>UD CFRP: UD300/M10 epoxy</td>
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<td>CFRP</td>
<td>Flat bottom holes</td>
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<td>De Angelis et al. (2015)</td>
<td>UD CFRP</td>
<td>Flat bottom holes, Impact</td>
<td>Ultrasomics, SIR, Lock-in thermography, digital shearography</td>
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<td>Deflectometry</td>
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<td>PTFE insert</td>
<td>Embedded SMA heat source thermography, Ultrasomics, shearography</td>
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<td>(Kim and Sham, 2000)</td>
<td>Multiple CFRP, woven and UD</td>
<td>Impact</td>
<td>Ultrasomics</td>
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<td>Pawar and Peters (2013)</td>
<td>Woven CFRP: LTM22/CFO300 prepreg</td>
<td>Polymer foam inserts, impact</td>
<td>Pulsed Phase Thermography (PPT)</td>
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<td>UD CFRP prepreg</td>
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<td>Type of NDT / Structural health monitoring technique</td>
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<td>Air pockets</td>
<td>Pulse thermography, PPT</td>
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<tr>
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<td>Graphite epoxy</td>
<td>Air pockets (by making impressions)</td>
<td>Pulse thermography</td>
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<td>Ultrasonics</td>
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<tr>
<td>Flat coupon</td>
<td>Battams and Dulieu-Barton (2016)</td>
<td>UD CFRP: SE84LV</td>
<td>Fatigue</td>
<td>Lock-in thermography, TSA, DIC and combinations</td>
</tr>
<tr>
<td>Flat coupon</td>
<td>Ekenel &amp; Myers (2009)</td>
<td>CFRP (fabric)</td>
<td>Air pockets</td>
<td>None</td>
</tr>
<tr>
<td>Flat coupon, sandwich panel</td>
<td>Hettler et al. (2017)</td>
<td>GFRP flat plate, CFRP foam sandwich</td>
<td>Flat bottom holes</td>
<td>Ultrasonics, Local Defect Resonance (LDR)</td>
</tr>
<tr>
<td>Flat coupon, sandwich panel</td>
<td>Scarponi and Briotti (1997)</td>
<td>Woven CFRP: T400/HMF834, AS-4/PEEK, foam core: SynCore</td>
<td>Impact and fatigue</td>
<td>Ultrasonics</td>
</tr>
<tr>
<td>Type of specimen</td>
<td>Reference</td>
<td>Type of FRP</td>
<td>Method of inserting defect</td>
<td>Type of NDT / Structural health monitoring technique</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------</td>
<td>-----------------------------------</td>
<td>--------------------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>Tube</td>
<td>Rheinfurth et al. (2011)</td>
<td>GFRP: OC111A/(RIM135 / RIMH137)</td>
<td>Fatigue</td>
<td>Thermal imaging</td>
</tr>
<tr>
<td>Tube</td>
<td>Schmidt et al. (2012)</td>
<td>GFRP: OC111A/(RIM135 / RIMH137)</td>
<td>Impact</td>
<td>Thermal imaging</td>
</tr>
<tr>
<td>Tube</td>
<td>Chandarana et al. (2017)</td>
<td>CFRP/GFRP</td>
<td>Impact</td>
<td>Acoustic emission, pulse thermography</td>
</tr>
<tr>
<td>Tube</td>
<td>Chen et al. (2011)</td>
<td>GFRP</td>
<td>None</td>
<td>FBG sensors</td>
</tr>
<tr>
<td>Tube</td>
<td>Hack et al. (2015)</td>
<td>CFRP: UTS50 F24 24K 1600tex fibres, XB3515/S021</td>
<td>Layup designed to initiate failure under torsion</td>
<td>Infra-red thermography, Thermoelastic stress analysis (TSA)</td>
</tr>
<tr>
<td>T-section</td>
<td>Ooijevaar et al. (2010)</td>
<td>UD CFRP: AS4D reinforced PEKK</td>
<td>Polymide film</td>
<td>Vibration based using laser vibrometer</td>
</tr>
<tr>
<td>Lap joint</td>
<td>Tighe et al. (2015)</td>
<td>CFRP: SE84LV prepreg</td>
<td>Debond: PTFE insert, mould release, silicone grease</td>
<td>PPT, ultrasons</td>
</tr>
<tr>
<td>Lap joint</td>
<td>Kumar et al. (2013)</td>
<td>GFRP: LY556/HY 951</td>
<td>Debond: ETE</td>
<td>Ultrasons, Digital Image Correlation (DIC)</td>
</tr>
<tr>
<td>Adhesively bonded pultruded joints</td>
<td>Shahverdi et al. (2011)</td>
<td>GFRP: CSM, woven fabric and UD</td>
<td>PTFE insert initiation (DCB)</td>
<td>None (visual inspection)</td>
</tr>
<tr>
<td>Sandwich panel, flat coupon</td>
<td>Aldave et al. (2013)</td>
<td>GFRP, CFRP, PGE</td>
<td>PTFE insert, film and metal inserts</td>
<td>Lock-in thermography</td>
</tr>
</tbody>
</table>

2.6 Finite Element Analysis of FRP structures

2.6.1 Introduction

Finite Element Analysis (FEA) has been used in this thesis to model the experimental specimens tested. This served two main purposes; predicting the behaviour of the specimens under load and to compare the full-field strain contours from the DIC results with the FEA strain contours of the representative models. A number of commercially available FE packages exist, of which Abaqus and ANSYS are the two most commonly used in literature. Both of these packages have the capability of modelling composite material behaviour.

The basic concept behind FEA is to break up structures into smaller, simple structures connected by a network of nodes. The set of elements is known as the mesh. By breaking down the structure into finite elements, each element is analysed, given the applied load and boundary conditions applied on the model, separately using mathematical equations. The individual behaviour of each element is
combined to predict the overall behaviour of the full structure. This section describes the numerical modelling methods used for the analysis of FRP structures. The focus is on the research undertaken regarding the modelling techniques of quasi-isotropic composites.

2.6.2 Modelling delaminations in composite laminates

The modelling of composite structures can be done on multiple scales: micro-scale, meso-scale and macro-scale. Figure 2-26 shows the differences in these scales, with micro-scale ranging from modelling the individual fibres to individual yarns to produce micro-level repeated unit cells (RUCs). The meso-scale models the architecture of yarn systems and matrix. Finally, macro-scale models composite beams as homogenous systems with anisotropic properties. This section investigates how different studies have approached modelling FRPs and how they have modelled pre-existing delaminations. This area was investigated due to the applicability of comparing numerical models with experimental specimens within which there is a delamination of a known size.

![Figure 2-26: Multiple scales of FE modelling for a 3D orthogonal woven composite (Jia et al., 2013)](image)

The effects of the curing stresses on delamination crack growth behaviour was investigated by Pradhan & Panda (2006a) using the commercially available FE package ANSYS 7.0 to generate 3D models of a composite laminate. The models used eight-noded layered solid elements, where each node has three degrees of freedom (Solid 46). In modelling the layers of the composite laminate, each ply was assumed to be a homogeneous anisotropic material, the properties of which were modelled using orthotropic material properties for individual layers. Experimental evidence showed delaminations usually being located in thin, resin-rich regions between two adjacent plies. Hence, this resin rich region was modelled between the plies where the delaminations were to be placed and the delamination was assumed to be embedded within the resin rich region. The interlaminar matrix region was assumed to have a thickness one-tenth the thickness of a ply. The modelled laminate was split up into three sublaminates. The top and bottom sublaminates were the graphite/epoxy laminates where each sublaminate was one element thick. The middle sublamine was the resin-rich interface
modelled as two separate layers with identical isotropic properties. This interface layer was modelled with two elements through the thickness. The delamination was simulated by removing elements from the interface layer, making the shape of the delamination (Pradhan and Panda, 2006a). Figure 2-27 shows the model of the laminate containing the centrally located elliptical delamination.

Figure 2-27: 3D FE model of a laminate containing an elliptical delamination (Pradhan and Panda, 2006a)

Nilsson et al. (2001a, 2001b) used 4 noded isoparametric shell elements to model a thin CFRP panel in compression using the commercially available FE-code ADINA. In these studies, the plies above and below the delamination were modelled as separate shell elements. For areas where the plies were not delaminated, the displacement field of the lower ply was constrained nodewise to the upper ply. The nodes in the delaminated areas of upper and lower plies with the same in-plane coordinates were joined with a linear elastic spring definition (Nilsson et al., 2001a). While this paper used shell elements, it was found in the literature that to capture localised behaviour, multiple layers of brick elements through the thickness of the material are required to make an accurate analysis (Senthil et al., 2013). This is in order to have enough nodes between the modelled defect to avoid singularities from having a large effect on the overall results.

In the study on the identification of failure mechanisms in composite laminates using 3D DIC (see section 2.5.3), Schorer & Sause (2015) created 3D models of the specimens that were tested using the commercially available FE package Comsol Multiphysics. Each individual ply was modelled with homogenous unidirectional material properties oriented as the experimental specimens were. The embedded delamination inserts were modelled with the out-of-plane stiffness corresponding to the elastic properties of the ETFE inserts used. The in-plane stiffness was set to zero. These inserts were modelled with the same dimensions as the EFTE pocket inserts used (see section 2.3.2).

2.6.3 FEA/DIC comparisons

The research paper by Kashfuddoja and Ramji (2013) mentioned in section 2.5 described the use of linear static 3D FEA models on ANSYS using solid 20 noded 186 elements. The FE models were used to
provide full-field strain contours of the specimens being tested in tension. These results were compared with the full-field strain contours obtained from the DIC equipment and found to be in good agreement. Schorer & Sause (2015) directly compared the strain contour from FEA (Comsol Multiphysics) with DIC strains of a flat composite coupon under tension. Figure 2-28a shows the strain contours obtained from the DIC which correspond with the predicted strain contours in Figure 2-28b.

![Figure 2-28: DIC (a) and FEA (b) strain contours of CFRP panel with embedded delamination defect one ply below surface under applied tension of 695 MPa (Schorer & Sause, 2015)](image)

2.6.4 Damage modelling

The majority of the FEA undertaken in this thesis is linear elastic without the need for damage criteria as the purpose was to evaluate surface strains in structures for a given load (within the elastic region) to compare with DIC results. However, work was done on predicting the direction of delamination growth (see Chapter 7), which required a study of common methods for damage modelling in composites.

Because of the complexity of fibre-reinforced polymers, and the numerous ways they can fail, as discussed in section 2.2.2, analysing structures made from these materials can pose numerous challenges. Delaminations, which are caused by stresses acting on relatively weak interlaminar interfaces with respect to the rest of the laminate, are one of the most common type of failure modes.

With regard to the prediction of delamination crack growth, failure criteria based on critical interlaminar stresses do not predict the thickness dependence of delamination onset. For this reason, the strain energy release rate (SERR) appears to be the most useful parameter for predicting the growth of a delamination (O’Brien, 1982).

In the FEA of composite structures, linear elastic fracture mechanics (LEFM) is a very common approach to predict crack growth. In short, LEFM considers that if there is a crack in a structure under load, it will grow when the strain energy release rate (SERR) exceeds the fracture toughness of the
material. LEFM requires an initial crack to be defined and assumes the size of the fracture process zone is negligible (Yuan and Fish, 2016).

Works that investigated the prediction of delamination growth have been investigated. In both papers by Pradhan and Panda (2006a, 2006b), LEFM has been used to model the growth of elliptical delaminations. In these studies, SERR methods are used to indicate delamination growth and propagation behaviour. This method works by using the three components of SERR, $G_I$, $G_{II}$ and $G_{III}$ to assess delamination growth (Pradhan and Panda, 2006a). Each component relates to the different modes of crack growth as shown in Figure 2-29. Due to the inherent complications of composite laminates, closed-form expressions to determine the components are not possible. Therefore, there have been many studies on the finite element evaluation of the components of SERR. Pradhan and Panda (2006a) used the modified crack-closure integral method of Rybicki and Kanninen (1977), which is based on the virtual crack extension method (Irwin, 1957). It is important to note that many mode mixity formulas neglect the effect of mode III ($G_{III}$). This is an acceptable assumption to make for embedded delaminations as the mode III component is usually very small (Nilsson et al., 2001a).

![Figure 2-29: The three modes of loading that can be applied to a crack (Anderson, 2005)](image)

The use of cohesive zone models (CZM) are commonly reported in literature to predict delamination initiation and growth. In CZM, a zone is specified as having cohesive elements which a traction-separation relationship defines a degradation mechanism, rather than a stress strain relationship (Yuan and Fish, 2016).
Chapter 2. Literature review

2.7 Summary

This chapter presents an introduction to fibre-reinforced polymer composites using woven fabrics and the manufacturing of representative structural elements for the analysis of NDT techniques, including the insertion of delamination defects. This chapter also presents a review of different techniques currently available for the detection and characterisation of delamination defects in composite panels. On top of this, finite element modelling of composites and damage in composites was investigated.

A review of the literature has shown that flat coupons are the most common structural element when evaluating NDT techniques. Compared with other types of structures, the flat coupon is the easiest to manufacture and to insert representative damage into. Delaminations are primarily simulated by placing polymer inserts between plies during the manufacturing process of the specimens. Variations to this include placing “pocket” delaminations between the plies instead, increasing the thickness of the insert, but ensuring a low friction surface to simulate an ideal delamination. Natural defect artefacts (NDA) such as impact are other common ways of creating delaminations in composites, however this does tend to also induce other damage mechanisms.

Regarding NDT techniques, plenty of literature on the use of ultrasonics has been found. A focus on full-field techniques was made, in which thermography was the most commonly used method for NDT of specimens with delamination defects. Thermography has been shown to be a very cost-effective way of identifying near surface delaminations in the literature. There is little literature on the use of DIC as an NDT technique. This lack of literature is what focused the project on the use of DIC as an NDT technique in the detection of delaminations in composite structures. Techniques, such as surface mounted FBG sensors, that use strain to determine the location and size of defects exist, however similar analysis can be done in full-field using DIC. Along with the potential of the technique as just an NDT technique, the technology enables the monitoring of strain fields to better understand the mechanics of structures under load. The following chapter describes the experimental methodology used to manufacture and test the specimens, as well as outlines the FEA methodology.
3 Methodology

3.1 Introduction

The purpose of the present chapter is to describe the preparation undertaken to perform the experimental tests as well as the numerical modelling. The first section describes the manufacturing of the specimens. This includes the manufacturing methods used to make the GFRP specimens and the methods of inserting defects into the specimens. This is followed by a section on the mechanical testing undertaken and sections on each of the NDT techniques used and how they were applied. Finally, this chapter also provides an overview of the FEA undertaken.

3.2 Specimen Manufacturing

All the composite laminates manufactured consisted of 8-harness satin woven glass fibre fabric (8HS) or 5-harness satin woven glass fibre fabric (5HS), supplied by Fothergill Engineered Fabrics Ltd. This fabric was selected due to the higher drapability these weaves exhibit compared to other weave types (see section 2.2), enabling a flexibility in the design of the structural elements to be manufactured. All specimens, except for the tubular specimens, were impregnated with epoxy resin using a wet/hand lay-up technique, as these specimens could all be cut from flat panels. The tubular specimens were impregnated with a different, less viscous, epoxy resin using Vacuum Assisted Resin Transfer Moulding (VARTM).

3.2.1 Flat panel manufacturing

The epoxy resin was created by mixing the base resin with a hardener and a curing agent. The resin used contained 100 parts of Epoxide Resin 300, 60 parts of Methyl Nadic Anhydride (MNA) hardener and 4 parts of Ancamine K61B curing agent. These were supplied by Kommerling UK Ltd, Fluka Ltd and Air products Ltd., respectively. The fabric and resin were chosen due to the similarity in the refractive indices, resulting in transparency of the material after curing. A transparent material allowed visual confirmation of damage growth under load.

A 16-ply configuration was selected to ensure the specimens undergoing bending had a high enough bending stiffness such that smaller applied displacements would result in sufficiently high strains on the surfaces being monitored using DIC (see section 3.4) based on the predicted surface strain response from the FE models. Two layup configurations were considered. Initially, in order to maintain relevance to a connected project at NPL (the collaborating organisation), a quasi-isotropic laminate layup [(0/90)/(±45)]₄₄ was selected. Of the three main types of structural elements used, only the three-point bend specimens used the 5HS weave and contained ±45° plies. ±45° layers were very
difficult to use in the manufacturing because they distorted easily when handled. As the project progressed, for ease of manufacturing and to ensure the reproducibility of specimens produced from different laminates, the layup was changed to a cross-ply layup [(0/90)]₈s.

The manufacture of the laminate consisted of six steps: (i) cutting the fabric, (ii) creating the delamination inserts, (iii) preparing the resin, (iv) wet/hand lay-up, (v) laminate degassing and (vi) curing the laminate. The method for the manufacturing of the laminate, not including the artificial delamination inserts, was adapted from Rito (2015).

3.2.1.1 Cutting the fabric
The glass fabric was unrolled off the reel onto a clean surface. Due to the high drapability of the fabric, after unrolling, the sides were aligned with a meter ruler and the leading edge was aligned by cutting a thin strip from the leading edge and ensuring the yarns on the 90° side ran parallel to the edge with minimal distortion. The 300 x 300 mm square dimensions were then marked onto the fabric using a sharpie pen with the help of a meter ruler and a set square. The fabric was then carefully cut out using a rotary cutter. The 45° plies were cut by marking out a 424 x 424 mm square and then drawing a 300 x 300 mm square within. The corners of the smaller square being at the centre of the edges of the larger square. The orientation of the fabric was marked at the corner of each cut.

3.2.1.2 Resin preparation
Early trials with the manufacturing process established the amount of resin required. 350 g of epoxide 300 resin was used with any excess being expelled during the process. Due to the relatively large amount of resin, two batches of 175 g were created simultaneously. Each beaker was placed on top of a scale accurate to 0.001 g and 175 g of epoxide 300 resin was poured in. This was then followed by 105 g of MNA hardener and 7 g of Ancamine K61B curing agent to create the three-part resin to the 100:60:4 ratio by weight, as specified by the suppliers. The resin was mixed slowly by hand using a polymer stirrer with the bottom and sides of the beaker submerged in warm water to lower the viscosity of the mixture. The mixing was undertaken for both batches simultaneously and took approximately 30 minutes before the resin was fully homogeneous with the exception of air bubbles; care was taken not to trap air in the mixture by the slow mixing, but some bubbles of air were present. To remove this air, the beakers were placed in a vacuum oven at 60°C with a negative pressure of 1 bar. The mixtures were degassed for 30 minutes.

3.2.1.3 Wet/hand lay-up of laminate
The wet/hand lay-up method requires a stiff flat working surface. Two tempered glass plates, one 300 x 300 mm and another 400 x 400 mm were used in this method. The glass plates were cleaned, waxed and placed in an oven at 90°C. This stage was performed as the resin was being degassed. In addition,
Two steel plates were heated to 90°C in order to lower the viscosity of the resin. The lower the viscosity the easier it was to remove air bubbles. This varied slightly from the method used by Rito (2015).

Once the resin was degassed, one of the steel plates was removed from the oven and placed on the working surface. The larger glass plate was also removed from the oven and placed on top of the metal plate. A PTFE frame was used as an addition to this method in order to assist with the positioning of the fabric pieces and ensure the resin was contained during the rest of the process. A sheet of Melinex® (approximately 400 x 400 mm) was adhered to the frame using tacky tape and placed on top of the glass plate and an amount of resin was poured onto the centre of the sheet as shown in Figure 3-1.

![Figure 3-1: Initial set up of the apparatus required for the wet/hand lay-up manufacturing method including the first pooling of resin](image)

The amount of resin required for each layer was determined by dividing the volume of resin in the beakers by the number of plies. The resin was allowed to spread for a few seconds before the first layer of fabric was carefully laid on top of the resin. A sheet of Melinex® was then placed on top of the fabric and a hand roller was used to slowly spread the resin across the fabric. This is shown in Figure 3-2.

![Figure 3-2: Wet/hand lay-up method: (a) Resin poured in the middle of the frame, (b) fabric placed on top of poured resin inside frame and (c) resin spread through fabric by placing melinex on top and using a roller](image)
The Melinex® was then peeled off slowly to avoid the creation of air bubbles. More resin was then poured on top of the first fabric layer and the second ply was then placed on top. A sheet of Melinex® was used again with the hand roller to spread the resin. This process was repeated until each layer was laid in the frame. A sheet of Melinex® was then placed on top of the laminate and the smaller glass plate placed on top of that.

3.2.1.4 Degassing and curing of the laminate

The second steel plate, heated to 90°C, was removed from the oven and placed in the vacuum chamber. The laminate, two glass plates on either side, was then placed inside the vacuum chamber on top of the steel plate. The pressure in the chamber was then reduced to negative 1 bar and left for an hour. The laminate was removed and placed on the working surface. The laminate had a large number of small bubbles of air trapped in the excess resin. These bubbles were removed by slowly rolling excess resin away from the laminate through the edges after removing the top glass plate. Care was taken not to push too quickly to avoid air bubbles getting trapped inside the laminate.

Finally, the laminate was placed inside the curing oven with the glass plates on either side. A pressure of approximately 12 kPa was applied on the laminate from a large metal plate clamped to the top of the laminate with additional weights placed on top. The laminate was then cured for 3 hours at 100°C after heating at a rate of 2.5°C per minute from room temperature. The laminate was removed after the oven returned to room temperature.

3.2.2 Manufacture of artificial delamination inserts

During the manufacturing process of the laminates, as described in the previous section, inserts were introduced to simulate delaminations. In this work, two main types of artificial delamination inserts were used; pocket delaminations and PTFE/stress-raiser delaminations. The pocket delaminations were the first type of insert used in this work as they were shown to be effective in published work for the purposes of validating C-scan results (Broughton, et al. 1999). This type of insert, having two sealed sheets of PTFE placed between plies, was also thought to be a good candidate technique to simulate a delamination in specimens that would subsequently be mechanically loaded. The PTFE/stress-raiser delamination inserts were designed to create a fully embedded insert that was thinner than the pocket delaminations but that still acted as a delamination while the specimen was under mechanical load. Trials with just a fully embedded sheet of PTFE without a stress raiser proved unsuccessful in simulating a real delamination, therefore a stress raiser was introduced into the manufacturing process in the form of a cut in the top layer of fabric to initiate a debond between the PTFE and the adjacent plies. The concept was to start the delamination with the inserted sheet of PTFE and subsequently grow it into the ply interface generating real delaminations through fatigue loading.
These inserts debonded from the adjacent ply, however growing the delamination further between two plies was unsuccessful (see chapter 5).

3.2.2.1 Pocket delaminations

The pocket delamination inserts were created using Polytetrafluoroethylene (PTFE) sheets sourced from Goodfellow and blue Flashbreaker® 2 tape from Airtech. Two types of differently shaped inserts were manufactured in this work: square and circular. The square pocket delaminations were produced using square hole punches sourced from 1stopsquare.com; 25.4 x 25.4 mm for the PTFE and 31.8 x 31.8 mm for the Flashbreaker® 2 tape. The pocket delamination inserts were manufactured using two square pieces of 0.05 mm thick PTFE film, surrounded and encompassed by two larger pieces of Flashbreaker® 2 adhesive tape such that there was about 3 mm of tape at each edge not adhered to the PTFE, as shown schematically in Figure 3-3. The two pieces of tape were then adhered to one another, carefully aligning the PTFE pieces to be fully in contact. The resulting pocket delamination insert was then consolidated using a hand roller to ensure the two pieces of PTFE were sealed. This arrangement ensured that the two surfaces of the PTFE film in contact were free to slide relative to each other, producing an artificial delamination with extremely low friction between the PTFE surfaces.

The circular pocket delaminations were made similarly. Two circular discs of PTFE were cut using a 25 mm hole punch sourced from Buck and Hickman. A 28 mm hole punch was used to cut the Flashbreaker® 2 tape. The pieces were brought together creating a 1.5 mm wide border of tape around the PTFE discs, sealing the PTFE within. The resulting inserts produced by this method had a total thickness of ~0.23 mm.

![Figure 3-3: Manufacturing method of the pocket delamination inserts. (a) Two square pieces of PTFE and two larger squares of Flashbreaker® 2 tape. (b) The PTFE is adhered to the tape (c) Both pieces of PTFE/Flashbreaker® 2 tape were superimposed, and the edges of the tape were brought together, sealing the 2 sheets of PTFE.]
3.2.2.2 **PTFE/stress raiser delamination inserts**

The second type of artificial delamination used for the three-point bend specimens consisted of a single square film of 0.05 mm thick PTFE with dimensions of 25.4 x 25.4 mm. As the purpose of this type of insert was to grow a delamination, the ply above the insert was cut before the infusion of resin to provide a stress-raiser. The top ply of the fabric was cut using a rotary cutter across the width at the midpoint of where the PTFE insert would be for each specimen. During the addition of the resin in the hand lay-up technique, the PTFE inserts frequently shifted slightly, causing the cuts in the fabric not to lie perfectly across the centre of the inserts.

The tubular specimens also contained PTFE/stress raiser delamination inserts. These followed the same concept as for the ones used for the three-point bend specimens, however rather than square pieces of PTFE, these were circular. The PTFE disks had a diameter of 10 mm and a 2 mm diameter hole was punched in the fabric to act as a stress-raiser.

3.2.3 **Three-point bend specimen manufacturing**

The primary objective while deciding the geometry of the specimens was to allow the inserts to be fully embedded, thereby avoiding free edge effects, while enabling a range of loading modes to be applied to the specimen. The inserts were placed one ply below the surface being monitored for all three-point bend specimens. Figure 3-4 shows an image of a three-point bend specimen with pocket delamination inserts post manufacture and testing. The three-point bending testing the specimen was designed for is shown in a schematic diagram of the specimen in three-point bending in Figure 3-5.

![Figure 3-4: A specimen containing two square pocket delamination inserts used for testing in tension and three-point bending](image-url)
The three-point bend specimens were made by cutting flat panels containing delamination inserts described in section 3.2.2 into 265 x 70 mm coupons. For specimens containing pocket delaminations, the process described in section 3.2.1 was followed, but before the final ply was placed on to the other plies during the wet/hand lay-up process, the inserts were placed in the appropriate positions. The rest of the process continued as was described in section 3.2.1. As the delamination inserts shifted during the wet/hand lay-up procedure, the square delaminations were at a slight angle, and the inserts were not exactly in the centre (width-wise) of the specimens. An example of a finished specimen is shown in Figure 3-4 and it can be seen that the square delamination on the left had shifted. The specimen was cut to accommodate this, resulting in both inserts being slightly offset from the centre.

For the PTFE/stress-raiser inserts, the PTFE sheets were placed in the same positions as the pocket delaminations were. The top layer of fabric was cut through across the width of the final specimens and overlaid carefully such that the stress-raisers were in contact with the PTFE inserts. The dimension of the test specimen, 265 x 70 mm, were carefully marked out, and cut using a circular diamond saw. The thickness of laminates both with and without inserts was measured to be 4.50 ± 0.10 mm.

3.2.4 Milled-slot specimen manufacturing

As the previous specimens contained inserts to mimic the effect of a delamination, the milled-slot specimens were designed to generate natural delaminations in a specimen without the requirement of an insert. The concept of the specimen was based on a type of specimen used in a previous NDT evaluation (Gower et al., 2016). These specimens were cut from a flat panel produced using the wet/hand lay-up technique as described in section 3.2.1. The laminates were cut into individual specimens 125 x 20 mm and a 2 mm wide slot was milled across the width of the specimen from the top surface along the mid-length position. To ensure the specimens would be gripped in the testing rigs uniformly with minimal slippage, the specimens were end-tabbed with Tufnol® 10G/40 supplied by RS components. As the milled-slot specimen was manufactured out of the GFRP, Tufnol® was selected as the end-tab material due to it also being GFRP, albeit a different system.

The end-tabs were machined to have a length of 40 mm and a width of 20 mm. Four Tufnol® end tabs were used for each milled-slot specimen. The surfaces to be adhered to one another were abraded using sandpaper, as shown in Figure 3-6, then adhered to the specimens using Scotch-Weld™ DP 190 epoxy structural adhesive. Once the adhesive was applied, the specimens were placed in a clamp to apply pressure to the materials being joined. This can be seen in Figure B-1 in Appendix B. The adhesive was left to cure for 48 hours prior to testing. The final specimen gauge-section shown in Figure 3-7a
and schematics of the specimens are shown in plan view and edge view in Figure 3-7b and Figure 3-7c. This method of end-tabbing the specimens proved to successfully bond to the specimen and transfer loads to the gauge section evenly (see Chapter 6). When testing to failure, the specimens consistently failed in the gauge section, and not at the end-tabs.

For the main part of the testing, the slot was milled down from the surface to the approximate depth of the interface between the second and third plies, where the delaminations were to grow, i.e. as each ply has a thickness of approximately 0.28 mm, the slots were milled to a depth of 0.6 mm. Further testing was done on specimens with the milled-slot machined to a depth of 1.1 mm to initiate delamination growth between the fourth and fifth plies. The milling process was done by the University of Surrey workshop, where the milling process was done slowly and with plenty of lubrication to avoid the development of damage during the machining process. Each specimen was visually inspected to ensure no damage was present prior to the testing.

![Figure 3-6: Milled-slot specimen with four pieces of Tufnol® end tabs](image)

![Figure 3-7: (a) Image of a milled-slot specimen gauge area. Schematic of the specimen placed under tension with (b) front view of the specimen and (c) side profile of the specimen. The dotted red line indicates the delamination growth path](image)
3.2.5 Tubular specimen manufacturing

The second type of structural element used in this work was a tubular specimen. In the literature (see section 2.3.3), the majority of studies investigating damage in tubular structural elements manufactured the tubes using filament winding with the damage either fatigue grown or created by impact. Due to the need to introduce damage in a reproducible manner, a novel method of manufacturing the composite tubes was used with an embedded delamination similar to the PTFE/stress raiser insert. The fabric used was the same 8HS glass fabric used for the three-point bend specimens, as the high drapability of the fabric meant it was easy to form onto the mandrel. The manufacturing of the tube was a multi-stage process which is described in this section.

The dimensions of the specimens were determined based on the requirements of the tension-torsion equipment used at the University of Padua (Figure 3-8) which is based on work done by Quaresimin and Carraro (2013). The key differences in the manufactured specimens and the specimens used by Quaresimin and Carraro (2013) was the outer diameter of the tube being 21.5 mm as compared to 22 mm. To overcome this, an added layer of CFRP prepreg was applied to make the outer diameter of the end tab 24 mm, ensuring the specimen fitted in the testing rig. After testing at the University of Padua, it became necessary to re-test the specimens in the UK. For this purpose, the specimens were fitted with cylindrical aluminium end-tabs for testing at Instron in High Wycombe, where the Vee-wedge grips used could accommodate a maximum diameter of 18 mm. The aluminium end-tabs had a length of 75 mm, where 35 mm of this length had a diameter of 18 mm for the Vee-wedge grips, and the remaining 40 mm had a diameter of 18.5 mm to fit inside the tubular specimens. Figure 3-9 shows a Computer Aided Design (CAD) model of a tubular specimen: (a) prior to end-tabbing, (b) after end-tabbing with CFRP prepreg for testing in Italy, and (c) with adapted end-tabs for the testing at the Instron facility in High Wycombe.

![Figure 3-8: Schematic of a composite tube and the end tabs representative of the manufactured tubular specimens](image-url)
To start the manufacturing process of the tubular specimen, the fabric was cut using a rotary cutter, as in section 3.2.1. The entire width, 915 mm, of the supplied roll of fabric was used per batch of tubular specimens made. The fabric was cut to lengths of $L = 258$ mm to account for four rotations of the fabric on the 19 mm diameter mandrel. This was determined based on calculating the average circumference of the four layers using equation 3.1, where $r_i$ and $r_o$ are the inner and outer radii of the tube, respectively.

$$L = 4 \left( \pi \frac{(r_i + r_o)}{2} \right)$$

PTFE/stress-raiser inserts similar to those used in the 3-point bend specimens as described in section 3.2.3 were used. Figure 3-10a shows the spacing of the fabric and the placement of the 2 mm diameter stress-raisers, in the form of a hole in the fabric, and the circular 10 mm diameter PTFE inserts placed directly on top of the stress raiser holes, such that after rolling the fabric on the mandrel, the insert would be between the surface ply and the second ply from the surface. After cutting the fabric to the correct length, the 2 mm diameter stress-raisers were punched in the fabric at a distance of half of the circumference of the final layer, 34 mm, from the leading edge. This length was chosen to ensure the delamination was positioned on the tube opposite to the seam due to the manufacturing method of the tube. This position was the best way to ensure the stresses around the insert were not affected by the seam produced due to this unconventional method of manufacturing tubes.
The circular PTFE pieces, each with a thickness of 0.05 mm, were placed directly on top of the punched holes such that the centre of each PTFE piece and the centre of the circular stress-raiser hole were overlaid. The pieces of PTFE were placed on the side of the fabric dominated with tows running in the X direction, along the width of fabric as shown in Figure 3-10b. The PTFE inserts were adhered to the fabric using a Pritt® stick (a water based solid adhesive) to ensure the insert stayed in the correct position during the rolling and resin infusion.

Initial trials were performed using a 19 mm steel mandrel coated with various release agents, however for these trials the specimens had a tendency to bond to the steel mandrel. Finally, the mandrels were manufactured with Polyvinyl Chloride (PVC) foam containing steel cores to ensure the tubes did not bend during manufacturing. Cylindrical PVC foam mandrels with an external diameter of 19 mm and a length of 1 m were machined by the NPL workshop. The edge of the fabric furthest away from the PTFE inserts was brushed with Gurit PRIME™ 20 epoxy resin mixed with PRIME™ fast hardener at a ratio of 100:26 by weight. The PVC foam mandrel was then placed on the wetted edge of the fabric as shown in Figure 3-11 on the same surface that the PTFE was placed on. The resin was pre-cured for 2-3 hours establishing a bond strong enough to ensure the fabric would not shift during the rolling process.
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The assembled parts were placed on top of plastic shrink wrap, which was then rolled over the exposed mandrel and placed over the top surface of the fabric as shown in Figure 3-12. A cylindrical steel mandrel was placed on top of the shrink wrap next to the PVC foam mandrel. The fabric was rolled onto the PVC foam mandrel by applying pressure between the two mandrels and rotating the mandrels as shown in Figure 3-12b. This resulted in a tight wrap of the fabric on the PVC mandrel. The final edge of the rolled fabric was wetted with Gurit PRIME™ 20 epoxy resin mixed with PRIME™ fast hardener and allowed to cure such that the fabric remained in a tight roll on the mandrel during the infusion process.

Figure 3-11: CAD model of PVC foam mandrel placement on fabric containing the PTFE/stress-raiser delamination inserts during the manufacturing process.

Figure 3-12: Schematic of the rolling procedure for the tubular specimens using shrink wrap and a steel mandrel from (a) the top view and (b) the side view.
The infusion of the fabric tube was performed using the Vacuum Assisted Resin Transfer Moulding (VARTM) technique. Figure 3-13 shows a block diagram of the process. The PVC foam mandrel with the wrapped fabric was placed inside a vacuum bag and sealed using tacky tape. A reinforced tube connected the bag to the beaker containing the resin, in this case Gurit PRIME™ 20 epoxy resin mixed with PRIME™ slow hardener. The other side of the vacuum bag had a tube connecting it to the resin trap which in turn was connected to a vacuum pump which drove the infusion process by creating a pressure of -1 bar. The process was stopped after resin reached the resin trap. The two tubes connected to the vacuum bag were sealed with clips to maintain the vacuum. This was then placed in an oven and cured at 65°C for 7 hours. The cured tube in the sealed vacuum bag is shown in Figure 3-14.

![Figure 3-13: Block diagram of VARTM process used to infuse fabric wrapped around a PVC foam mandrel](image)

![Figure 3-14: Cured composite tube still sealed in release film removed from the oven after the resin infusion process and curing](image)

After removing the vacuum bag, the specimens were cut to lengths of 155 mm, ensuring the PTFE insert was located at the mid-length position as illustrated in Figure 3-10a by the vertical black lines. The PVC foam mandrels together with the steel cores were then machined out of the specimens leaving the tubular composite specimens. The tubes were all end-tabbed with woven CFRP pre-preg to be fitted for testing in at the University of Padova in Italy. The end-tabbing was done by cutting 40 mm wide strips of CFRP pre-preg and wrapping the ends of the specimens until the desired outer diameter of the end-tab was achieved, in this case 24 mm. For testing in the UK, aluminium end-tabs were bonded to the inside of the tube using Scotch-Weld™ DP 190 epoxy structural adhesive as shown.
in the schematics in Figure 3-8 and Figure 3-9. The regions of the end-tabs with a diameter of 18.5 mm were coated with adhesive and placed inside the tubes as shown in Figure 3-15.

Figure 3-15: Tubular specimen with aluminium end-tabs placed inside and left for curing

3.2.6 Summary of test specimens

A number of specimens were created for all aspects of the project. These include specimens manufactured for failure testing, proof of concept and predominantly for NDT. Table 3-1 shows all types of the specimens used for NDT. Most three-point bend specimens were manufactured with two defects. By the nature of the specimen, the milled slot specimens also had two delaminations growing on either side of the milled slot. Each specimen was given a number, and each defect region was labelled accordingly: For the three-point bend specimens, the L designating the defect on the left and R the defect on the right. For the milled slot specimens, the A and the B are for the top and bottom defect regions respectively. The tubular specimens each contained only one defect region.

<table>
<thead>
<tr>
<th>Type of specimen</th>
<th>Defect type</th>
<th>Number of specimens</th>
<th>Defect labelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-point bend</td>
<td>Square pocket delamination</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Three-point bend</td>
<td>Circular pocket delamination</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Three-point bend</td>
<td>Square PTFE/stress-raiser</td>
<td>4</td>
<td>0L, 0R, 1L, 1R, 2L, 2R, 3L, 3R</td>
</tr>
<tr>
<td>Three-point bend</td>
<td>Circular PTFE/stress-raiser</td>
<td>1</td>
<td>CL, CR</td>
</tr>
<tr>
<td>Milled-slot</td>
<td>Natural delamination</td>
<td>7</td>
<td>1A, 1B, 2A, 2B, 3A, 3B, 4A, 4B, 5A, 5B, 6A, 6B, 7A, 7B</td>
</tr>
<tr>
<td>Milled-slot</td>
<td>PTFE</td>
<td>2</td>
<td>P1A, P1B, P2A, P2B</td>
</tr>
<tr>
<td>Tubular</td>
<td>PTFE/stress-raiser</td>
<td>5</td>
<td>TenTen1, TenTen2, TenTor1, TenTor2, TorTor1</td>
</tr>
</tbody>
</table>
3.3 Mechanical testing

All the specimens investigated in this work were mechanically loaded quasi-statically and/or in fatigue. For the quasi-static testing performed while obtaining DIC results, all loads were small to avoid growing damage further as the DIC technique requires the specimen to be deformed during testing. All specimens other than those containing pocket delamination inserts were fatigued to grow delaminations between the PTFE insert and the adjacent ply for specimens containing the PTFE/stress-raiser insert, as well as for the natural delaminations in the milled-slot specimens. Three types of mechanical loading have been used in this work; tension testing, three-point bending and tension/torsion testing.

For all specimens tested, visual images of the specimens were taken. For the most part, a Canon 1300D digital single-lens reflex (DSLR) camera with a 60 mm Canon EF-S macro lens was used to image the specimens. Visual images were taken of the insert regions of the specimens containing PTFE/stress-raiser inserts (see Chapters 5 and 7) and the natural delaminations grown through fatigue testing in the milled-slot specimens (see Chapter 6). These images were used to visually quantify the size of the delaminated regions in the transparent structural elements.

3.3.1 Tension testing

Quasi-static tensile testing was done on the three-point bend specimens containing pocket delamination inserts shown in Figure 3-16a. This was done to establish the best way to determine the position and size of the delaminations simulated through the use of the inserts by monitoring the surface with DIC. The maximum size of grips available for the in-plane tensile loading was 50 mm. Care was taken to ensure the specimen was aligned with the grips by measuring keeping the distances from the edge of the specimen to the edge of the grips constant at 10 mm.

For the milled-slot specimens, the delaminations were grown by placing the specimens under tension-tension fatigue loading with a peak load of 8 kN (i.e. 103 MPa across the milled region, which corresponded to approximately 40% of the quasi-static failure load of the milled specimen), an R-ratio of $R = 0.1$ and a frequency of 5 Hz. This testing was done using an Instron 1341 with a 50 kN loadcell. The same rig was used for most of the quasi-static tension testing of the same specimens for the purposes of acquiring DIC images. The specimens were also quasi-statically loaded in an Instron 5982 machine with a 100 kN loadcell as this rig was the only one with which micro-DIC testing using the stereo-microscope system could be used (see section 3.4.1).
3.3.2 Three-point bending

The three-point bend specimens were designed for the use of 3D DIC as an NDT technique. Since the DIC technique monitors the displacements of the surface being monitored (as described in section 3.4), loading modes that increased the effect of the delaminations on the surface deformations were selected. As discussed in chapter 4, when loading the specimens in tension, fully embedded delamination inserts were not easily detectable. The shear stress state induced by three-point bending results in the delaminations having a greater effect on the surface deformations. Figure 3-17 shows the three-point bending apparatus within the Instron 1185 testing rig. The specimen shown in this figure contains no inserts.
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The three-point bend apparatus spacings is shown in the schematic diagram in Figure 3-5, with the support rollers placed 200 mm apart, and the loading roller positioned to apply a force vertically at the midspan. The loading block was bolted to the crosshead of the Instron machine to ensure the support rollers did not change position relative to the loading roller during testing.

3.3.3 Tension-torsion testing

The tubular specimens were tested at four different ratios of tension and torsion: (i) pure tension, (ii) pure torsion, (iii) 120 MPa tension and 20 MPa torsion and finally (iv) 100 MPa tension and 20 MPa torsion. Each specimen was fatigued with one ratio of tension and torsion with R=0.1 and the fatigue frequency used was 5 Hz. The purpose of this testing was to investigate the directional growth of the embedded defects under the different ratios of tension and torsion. Tubular specimens were also quasi-statically loaded to their respective maximum fatigue loading for the purposes of obtaining DIC strain contour results. The specimens were tested with two different rigs requiring different end-tabs for the specimens. For the testing in Italy, the CFRP prepreg end-tabs were bonded to the ends of the specimen as described in section 3.2.5. As the inside of the tube was hollow, a 40 mm long steel tube with an embedded LED light was placed in either side as shown in Figure 3-18a. The lighting ensured that the DSLR images would be well illuminated as external lighting sources caused glare.

![Figure 3-18](image_url)

*Figure 3-18: Images of a tubular specimen (a) with LED lights placed inside for inner lighting, (b) placed inside the MTS testing rig and (c) placed inside the Instron testing rig*

The tubular specimens were tested in tension and torsion using an MTS 809 Axial/Torsional Test System. Figure 3-18b shows a tubular specimen gripped over the CFRP end-tabs by the MTS rig. The
specimens were designed to ensure compatibility with this testing rig. For testing of specimens under
tension and torsion for the DIC, the equipment used was an Instron ElectroPuls™ E10000 linear-
torsion all-electric dynamic test instrument. The wedge grips used in this rig required smaller diameter
specimens than the specimen, therefore the smaller diameter aluminium end-tabs described in
section 3.2.5 were designed, manufactured and bonded to the inside of the tubes. Figure 3-18c shows
the specimen inside the grips of the Instron rig.

The mechanical testing setups had two main purposes, to grow delaminations through fatigue and to
load the specimens such that the resultant surface strains could be monitored using DIC. As the
purpose of this project was to assess the applicability of detecting delamination damage using DIC,
the following section describes the DIC equipment used and how it was set up for monitoring the
delaminations in the different types of specimens tested.

3.4 3D Digital Image Correlation (DIC)

The DIC technique was used to monitor the deformations on the surface of the specimens under their
respective loading conditions. The surface strains were post processed from the acquired DIC images.
This provided an opportunity to compare strain contours on the surface of the specimen with strain
contours predicted using FEA. For the most part, a standard 3D stereo DIC system was used consisting
of two 9-megapixel Allied Vision Technology Manta cameras, with LINOS MeVis-C 35 mm f/1.6 lenses
used for three-point bend specimens and LINOS Rodagon 80 mm lenses for the milled slot and tubular
specimens. Each camera contains a 2/3” (16.9 mm) chip. For higher magnification DIC images, a stereo
microscope DIC system was used. Both DIC systems were supplied by Correlated Solutions Inc. DIC
requires the setting up of the camera system, calibrating the cameras, the speckling the surfaces of
the specimens being tested, and post processing the acquired DIC images from the testing.

3.4.1 Experimental arrangement for DIC

The setup and positioning of the cameras and lighting depended on the testing environment. In all
types of test environments considered in this work, the goal was to ensure the surface of the specimen
being tested filled the field of view of the cameras to maximise the resolution of the cameras. To do
this, the cameras had to be set up at the required distance from the specimen and the correct lenses
and number of extension rings had to be selected. The reason these two aspects had to be done in
conjunction was because the cameras and lenses did not have an optical zoom built in, leaving less
flexibility in the set-up. Once these factors were determined, the cameras had to be focused; the
aperture of each camera was opened fully and focused on the area of interest. The aperture was then
closed to increase the depth of field until the entire surface being monitored was in a high degree of focus. This was determined using the sigma estimate function on VIC snap, the DIC image acquisition software. The following sections provide an overview of the individual set-ups used for the three-point bend specimens, the tubular specimens and the milled-slot specimens.

3.4.1.1 Three-point bend tests
The three-point bend specimens were monitored first on the compression surface, followed by rearranging the DIC setup to monitor the tension surfaces during testing. Figure 3-19 shows an overview of the setup including the two DIC cameras positioned to obtain data on the compression and tension sides of the specimen under three-point bending. The light source was placed behind the cameras to ensure the surface was well lit. When monitoring the compressive surface, only the area between one of the support rollers and the loading roller could be monitored, as both cameras required a view of the area and the loading roller interfered with the view when attempting to look at either side of the loading roller. When monitoring the tensile surface, the cameras were placed below the specimen as shown in Figure 3-19b. In this case, both delamination inserts could be monitored simultaneously.

![Figure 3-19: DIC setup with Instron machine to obtain three-point bending results for (a) the compressive side of the specimen and (b) for the tension side of the specimen](image)
3.4.1.2 Tension/torsion tests

The tubular specimens were monitored with the stereo DIC equipment to establish if the delamination defects in these specimens could be detected using the strain fields under the same ratios of tension and torsion as was applied in fatigue to grow the damage. The set-up is shown in Figure 3-20. The tension/torsion tests of the tubular specimens were the most difficult to monitor with DIC as the surfaces being investigated were curved. As the 3D DIC system requires both cameras to have the same view but at different angles, the field of view was limited. Another issue with the curved surface was that the lighting caused a glare along a line running down the surface. As the specimen needed to be illuminated from a point where both cameras would have a well-lit view, a line of glare was inevitable.

![Image of DIC setup for monitoring surface deformations of tubular specimens under load](a) (b)

Figure 3-20: DIC set up for monitoring the surface deformations of the tubular specimens under load (a) including the rig, tripod, cameras and light source and (b) closeup of the cameras and specimen in the grips of the rig

3.4.1.3 DIC for the milled-slat specimens

The milled-slat specimens were the simplest of the three types of specimens for monitoring with DIC as the specimens were flat. The cameras were placed on the same horizontal plane as the midpoint of the specimen and angled at approximately 15°. Figure 3-21a shows an image of the setup. For the tensile test, the cameras were placed so that the lenses were parallel to the surface of the specimen and the light source was placed at a slight angle to illuminate the specimen while avoiding glare.

In addition to regular DIC testing, the micro DIC kit was used on these specimens to achieve a higher resolution of the surface strains over particular areas of interest such as the delamination front. The kit consists of two 5-megapixel Allied Vision Technology Manta cameras setup with an Olympus 1.6x
Stereo Microscope. The micro DIC kit (supplied by Correlated Solutions ltd.) was designed to enable DIC for microscopic fields of view. The stereo microscope consists of a series of lenses and mirrors, creating complex optical paths causing significant amounts of geometric distortion. This in turn requires a more detailed calibration as discussed in the next section. The light source for this apparatus was a Fiber-Lite® illuminator. This was needed as the microscope lens needed to be set up too close to the specimen for a conventional lighting source. The set-up with the milled-slot specimen in the Instron machine is shown in Figure 3-21b.

![Figure 3-21: (a) DIC set-up for monitoring the surface deformations on milled-slot specimens under load. (b) Micro DIC set-up for monitoring the surface of a milled-slot specimen close-up](image)

### 3.4.2 DIC Calibration

For all the test methods discussed in the previous section, the cameras had to be calibrated after the DIC system was set up. The principles of the calibration process are the same regardless of the technique, and the method only differs in terms of the equipment used. 3D DIC increases the complexity of the system, however it provided valuable through depth data not possible to obtain with 2D DIC. For the system to acquire data, the images from both cameras needed to be matched by the software. In order to do so, a minimum of 20 pairs of simultaneous images were acquired of a 2D calibration target grid in multiple positions and angles with respect to both of the cameras. Figure 3-22 shows a pair of images taken by the DIC system simultaneously during calibration. The grids have pre-set defined distances between each dot. The software matches these dots to define an origin and the focal planes relative to each camera for each of the sets of images. After calibrating in Vic-3D, the software used for post-processing all the data from the DIC images, the system provides feedback on the quality of the calibration. Provided the feedback indicates that the calibration is above a certain level (calibration score), the hardware is set to collect data from the experiment. Any further movement of the cameras would require recalibration. The calibration score is provided by the Vic-3D
software. This score is established using a model generated using both of the cameras' focal lengths, distortions and perspective, as well as the distance and angles between the cameras and the geometry of the calibration grid. This model is used to project theoretical locations for all the grid points in the images (Simonsen, 2016). These grid points are the black dots seen on the target grid in Figure 3-22. The calibration score given by Vic-3D is based on the distance between the predicted grid point locations and the actual grid point locations in each image.

The calibration procedure for the micro-DIC equipment is similar to the conventional method described above. Instead of regular calibration target grids, this equipment required high precision glass grids mounted in a backlit holder. One set of calibration images is shown in Figure 3-23. Multiple sets of images were taken while manipulating the position of the grid using the grid holder in the testing rig. Due to the high magnification lenses and the series of mirrors resulting in a complicated optical path there is distortion in the images. Therefore, the stereomicroscope DIC requires an additional calibration step to account for this distortion. This is done by using a speckle pattern printed on a flat surface and moving the stage in the X and Y directions individually by about 15% of the field of view while taking sets of images. After calibration, the production of a suitable speckle pattern is a key part of the process.
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For the DIC system to obtain data from the experiment, the program breaks down each image taken during the experiment into square sections known as subsets to allow for the use of a small region for pattern matching (Sutton, Orteu, & Schreier, 2009). To allow these subsets to be identified and matched in all the pairs of images, a random speckle pattern needs to be applied to the surface of the specimen. The speckle pattern had to be applied with an idea of how much of the surface would fill the field of view of the cameras, such that the appropriate pattern density to ensure accurate measurements from DIC can be estimated. The near optimal feature size is between 3 and 6 pixels, a feature being a speckle, and approximately 10-20 speckles per subset (Sutton et al., 2009). Figure 3-24 shows an example of a speckle pattern used on a three-point bend specimen. This speckle pattern was applied by spraying a base matt white layer of acrylic paint from an aerosol can, allowing it to dry and then using an aerosol can with matt black acrylic paint from a distance of approximately one to two meters away until the desired speckle density was achieved. This process had to be restarted if the resulting speckle pattern did not satisfy the criteria for a near optimal feature size specified by Sutton et al. (2009).

![Figure 3-24: Speckle pattern applied using aerosol cans on a milled-slot specimen used in experimental testing including a 5 times zoom of a 3 x 3 grid of 27 pixel subsets](image)

Prior to speckling the surfaces of the specimen, a study was undertaken comparing different speckling techniques to determine which produced the best results. The use of aerosol cans (described above) took the least time to apply on the specimen and produced the best results for conventional 3D DIC. For the micro DIC however, a different speckling technique had to be investigated to produce speckle features that satisfy the near optimal feature size criterion. Numerous techniques and variations were investigated, however the technique that provided the best results was by depositing dry powder (sodium cobalt oxide) with an approximate particle size of 20 microns on the surface being investigated on the specimen (the sodium cobalt oxide was courtesy of E. Jakubczyk). To prevent clumping of the powder, moisture was drawn out of the powder by placing the powder in an oven at
100 °C for a couple hours. The powder was then placed on a fine stainless-steel mesh with a wire diameter of 0.025 mm and 0.039 mm apertures and carefully pushed through into contact with the surface of the specimen to be monitored. Prior to the powder deposition on the specimen surface, the surface was sprayed with a layer of matt white acrylic paint. A comparison of the two speckle patterns are shown in Figure 3-25.

![Figure 3-25: Speckle patterns as observed by micro DIC at a 0.7x zoom using (a) conventional acrylic spray-based speckling and (b) powder deposition speckling](image)

3.4.3 Subset and step size

To obtain full-field strain data, DIC images needed to be postprocessed. There are three main factors that need to be considered to get the best results with the lowest amount of noise; the subset size, the step size and the strain filter size.

After mechanically testing the specimens and obtaining DIC images, the results were postprocessed by dividing the image into subsets. The purpose of a subset is to enable the tracking of specific points on the image. While the analysis is done on each of these points (separated by the step size), the area around the point is used to provide a unique marker in the image which is then tracked during the deformation. The size of the subsets was selected in Vic-3D producing a grid of subsets over the surface; an example is shown in Figure 3-26. The choice of a subset size is one that requires the balancing of a number of factors. In order to obtain a reliable correlation analysis from DIC, the subset size is required to be large enough for each subset to be unique in terms of a distinctive speckle pattern with high contrast speckles on the surface being monitored. For this reason, a large subset size is desirable. However, at the same time, the underlying deformation field is calculated based on the subsets. A larger subset is more prone to larger errors in the approximation of the deformations compared with smaller subsets, for which the underlying deformation field can be accurately...
approximated by first and second order subset shape functions (Pan et al., 2008). In addition, each subset contains only one central data point, meaning data can only be read a minimum of half a subset size away from the edge. For these reasons, a smaller subset size is desirable to ensure a reliable deformation measurement. However, if a subset is too small, correlation issues can occur due to lack of random speckle data in each subset. Too large a subset smooths out details in the deformed area (Kashfuddoja and Ramji, 2013), which is critical in determining the size of defects from the strain contours.

The step size chosen defines the spacing of the pixels being analysed during the correlation (Sutton et al., 2009). A step size of 1 means the software will perform analysis on every pixel individually, while a step size of 2 means the analysis is performed on every other pixel. A subset of 27 x 27 pixels is chosen with a step size of 5 means the software is tracking the deformation of 27 x 27 pixel areas every 5 pixels (the subset at each data point overlap with subsets of other data points). The lower the step size the higher the computational resources required for the analysis.

The method of calculating the strain is similar to how strains are generally determined in FEA. The strain calculation is done using the grid of data points in the images, separated by the step size. The grid contains information on the X, Y and Z positions as well as the U, V, and W displacement vectors of each data point. The analysis considers each data point separately, creating a local mesh of triangles with the surrounding data points. Three data points are used for each triangle. The difference in displacement at each of these points is used to compute a strain tensor for the triangle. This is done for all triangles within the grid of data points. The strains at each data point is then interpolated from
the surrounding triangle strain tensors. Due to the size of the triangles, the calculated strain tensors can be noisy (relatively high or low compared with adjacent triangles). To lower the amount of noise, a strain filter is applied to average the strains over an area.

The strain filter size is a parameter that defines how localised or averaged the strains are postprocessed in the results. The lower the value, the more localised the results. This parameter is defined as the number of pixels over which the virtual strain gauge will be applied at each data point (separated by the step size) (Byrne, 2017). For instance, if the step size was 5 pixels and a strain filter was 15 pixels, the total area over which the strain was calculated is $5 \times 15 = 75$ pixels.

More information on how the software post-processes the data in relation to the strain filter can be found in Byrne (2017). In this project, a strain filter size of 15 was found to be a good compromise on the strain resolution (higher with a smaller strain filter) and the accuracy with less uncertainty (larger strain filter).

In this project, the subset size, step size and strain filter sizes were determined mainly using the speckle pattern on the surface being monitored. Table 3-2 summarises the values of these parameters for each type of specimen tested. The reduction in step size when comparing the parameters used in three-point bending specimen with the milled-slot specimens was adopted due to this change having minimal effects on the noise. The subset sizes were chosen to have at least 10 speckles per subset to obtain data as recommended by Sutton et al. (2009). The tubular specimens had poorer quality speckle patterns which could not be optimised due to restricted testing time (see Chapter 7), therefore the subset size was increased to allow for on average of at least 10 speckles per subset.

<table>
<thead>
<tr>
<th></th>
<th>THREE-POINT BEND</th>
<th>MILLED-SLOT</th>
<th>TUBULAR</th>
</tr>
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<tbody>
<tr>
<td>Subset size (pixels)</td>
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<td>27 x 27</td>
<td>29 x 29</td>
</tr>
<tr>
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<td>7</td>
</tr>
<tr>
<td>Strain filter (pixels)</td>
<td>15</td>
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<td>15</td>
</tr>
</tbody>
</table>

The main focus of the work done in this project has been on the applicability of DIC as an NDT technique in monitoring delaminations in different structural elements. As a basis for comparison, the delaminations in the GFRP specimens were also visually monitored as well as with more established NDT techniques. These NDT techniques were all thermographic techniques, including pulsed thermography, active lock-in thermography and passive lock-in thermography.
3.5 Pulse Thermography

The pulse thermography system, supplied by Quantum Design UK, consisted of a Phoenix Medium Wavelength Infrared (MWIR) 9705 IR camera (FLIR systems) with a resolution of 320 x 256 pixels and two xenon flash lamps with an energy output of 2 kJ. This set up is shown in Figure 3-27. Pulse thermography was used to monitor the inserts and debonds of the inserts in the PTFE/stress-raiser specimens in Chapter 5 as well as in the milled-slot specimens at different stages between the fatigue loading. The specimen surface was pulsed with a high intensity flash of light for a duration of 30 ms. This high intensity flash causes a sudden increase in the temperature of the surface, which decays as the thermal energy is absorbed by conduction through the thickness of the specimen. Defects such as delaminations do not conduct the thermal energy well due to the discontinuity in the material and reflect the thermal energy. This reduces the surface cooling rate adjacent to the defect. By comparing the surface temperature directly above the defect with the surrounding surface over undamaged material, a contrast can be observed which enables the location and size of the defect to be determined.

The equipment was run using the commercial software Mosaiq v3.1 and Echotherm v6 produced by Thermal Wave Imaging (TWI). The raw thermal images are processed using TWI’s patented Thermographic Signal Reconstruction (TSR) method to enhance the presence of defects such as inserts and delaminations. More information on this method can be found in Shepard (2003).
3.6 Lock-in Thermography

The lock-in thermography equipment consisted of a FLIR SC5200 Silver 420M thermal camera with a resolution of 320 x 256 pixels, a frequency generator and two 1 kW halogen lamp. The experimental set-up is shown in Figure 3-28a. Lock-in thermography was used primarily for the milled-slot specimens to monitor the growth of the delaminations produced from the fatigue loading of the specimens. The sample was periodically heated with halogen lamps modulated with a sinusoidal waveform from the function generator that controlled the power to the lamps. The setup of the different components and how they were connected is shown in a schematic in Figure 3-28b. The thermal energy emitted from the halogen lamps is absorbed and phase shifted as the energy wave penetrates the surface of the specimen. When this thermal energy wave is conducted through the material, it is partially reflected when it reaches areas in the specimen where the thermo-physical properties are not homogenous compared with surrounding materials (for example a delamination). This reflected wave interferes with the incoming energy wave from the halogen lamps at the surface of the specimen, which causes interference patterns in the surface temperature. Throughout this process the thermal camera is used to record the IR emissions from the surface of the specimen. The IR emissions recorded from the surface being monitored corresponded to the modulated input signal, from which any interference pattern was attributed to a reflected thermal response from defects.

(a) (b)

Figure 3-28: (a) Image of the specimen, IR camera and lamps and (b) schematic of lock-in thermography experimental set up

To determine a close-to-optimal frequency with which to induce the heating, lock-in testing was carried out at frequencies between 0.070 and 0.080 Hz in steps of 0.002 Hz. Slight differences in the depths of the delamination defects in each specimen tested meant that the frequency used in this range was varied on a specimen by specimen basis. During this work, it was discovered that the
thermal camera tended to lose synchronicity with the frequency generator after a certain number of periods for the testing. For this reason, the duration of each test was limited to 3.5 periods (i.e. approximately 44 to 50 seconds of lock-in testing at the specified frequencies). The extra half period was added to allow the system to eliminate background temperature changes from the analysis.

3.7 Passive lock-in thermography

The passive lock-in thermography experiments were carried out at the University of Padova. The passive lock-in thermography equipment consisted of a FLIR SC7600 MW thermal camera with a resolution of 640 x 612 pixels. The basic concept behind the passive lock-in analysis used in this project is to monitor a surface under mechanical fatigue loading and to record the resulting InfraRed (IR) emissions from the surface of the specimen. This is the same concept as for the lock-in thermography described in the previous section, with the key difference being that the specimen undergoes mechanical rather than thermal excitation. At regular intervals during the fatigue testing for three-point bending and tension/torsion testing, described in section 3.3, the camera recorded the emissions from the surface of the specimen for five periods of the fatigue cycle. Figure 3-29 shows a schematic of passive thermography. The sinusoidal loading is compared with the thermal emissions recorded by the thermal camera. For the undamaged part of the specimen, the response is expected to be 180° out of phase, whereas the damaged zones should have a lower phase shift.

![Figure 3-29: Schematic of passive lock in thermography concept](image)

The three-point bend specimens were placed in the MTS rig as shown in Figure 3-30. The thermal camera could not be setup to look vertically down at the surface of the specimen as the camera would
not fit between the crosshead of the loading rig, however the results shown in Chapter 5 show that the phase results clearly display the delaminated areas in the specimens tested.

![Figure 3-30: IR thermography experimental set-up to detect the delamination in the three-point bend specimen](image)

The tubular specimens were placed in the MTS rig as described in section 3.3.3. The specimen surface nearest to the PTFE insert was monitored with the IR camera focused on the specimen surface immediately above the insert. The DSLR camera was placed next to the IR camera facing the insert in the specimen at a small angle as shown in Figure 3-31. This provided visual monitoring of the damage growth in the tube to compare with the IR thermography results.

![Figure 3-31: IR thermography set-up to monitor IR emissions from tubular specimens under fatigue loading](image)

In all the testing, the common theme in determining the distance from the surface being monitored using all of the full-field techniques was to fill as much of the gauge-section as possible into the view of the cameras while maintaining the focus of the cameras. This could not be done for the images.
taken by the DSLR camera of the tubular specimens, as this was done at the same time as the passive lock-in thermography.

On top of the manufacturing, mechanical testing and delamination monitoring, the volume fractions of the different specimens were determined to ensure the properties of the specimens tested were consistent.

3.8 Volume fraction measurements

The fibre volume fractions of the GFRP specimens used were measured using the resin burn off method (ASTM D3171 - 15, 2010). This was done to ensure the specimens created were produced in a manner that could be reproduced with a uniform fibre volume fraction. This was also done to compare the volume fraction of the material with literature, to validate that the laminates manufactured were done so appropriately. Samples were taken from the laminates and their masses recorded. The samples were then placed in an oven at 600°C for 3 hours to burn off any resin. The remains were then weighed to obtain the mass of fibres from which the volume fraction was calculated. The fibre volume fraction is defined by equation 3.2.

\[ V_f = \frac{v_f}{v_f + v_m} \]  

Where \( V_f \) is the volume fraction of fibres in the composite, \( v_f \) is the volume of fibres and \( v_m \) is the volume of the resin. By knowing the density of the constituent materials; the glass fibre and the epoxy resin, the mass of the samples prior and post resin burn-off were measured using high precision scales and divided by the density to obtain \( v_f \) and \( v_m \). The density of the E-glass fibres in the woven fabrics was taken as 2.56 g/cm³ (Kyriazoglou and Guild, 2005) and the epoxy system used in all specimens other than the tubular specimens was taken as 1.21 g/cm³ (Belmonte et al., 2001).

The density of the cured Gurit Prime 20LV resin system used is stated in the product data sheet is 1.144 g/cm³ and 1.153 g/cm³ for the system using the slow and fast hardener respectively (Gurit, 2017). As the manufacturing method used a combination of both but was predominantly infused with the matrix using the slow hardener, the density of the slow hardener was assumed.

Both types of three-point bend specimen as well as the milled-slot specimens were manufactured using the wet/hand layup technique as described in section 3.2.1. For the three-point bend specimens, the average volume fraction was found to be 0.403 ± 0.006, which is consistent with the paper from which the manufacturing technique of the laminates was adapted from, which stated a fibre volume fraction of 40% (Rito, 2015). The laminates from which the milled-slot specimens were created were
found to have an average volume fraction of 0.402 ± 0.015. These specimens were produced from a larger number of laminates, therefore the variation in volume fraction compared with the three-point bend specimens is understandable.

The tubular specimens were produced using VARTM and a different epoxy resin as described in section 3.2.5. From the range of samples tested, the volume fraction of the tubular specimens was found to be 0.385 ± 0.053. The novel manufacturing method of the tubular specimens, created to enable the placement of PTFE/stress-raiser inserts within the specimens, allowed for a lot of air bubbles to get trapped in the specimens. Tables summarising the measurements and calculations are shown in Appendix B: Table B-2 for three-point bend specimens, Table B-3 for milled-slot specimens and Table B-4 for tubular specimens.

3.9 Finite Element Analysis

Throughout the project, the FEA software used was Abaqus/Standard version 6.14. The purpose of FEA is to break down complex geometric models into simple elements to provide an approximate solution given certain boundary conditions. The results can be dependent on the number of elements that are used in the model which is why for each model created, a mesh independence study was conducted to ensure the results converged with respect to the meshes used.

Finite Element Analysis was used in this work with two main purposes. The first was to model all the structural elements considered prior to manufacturing and physical testing to assist in the design of viable specimens under different load cases under which the surface strains would indicate the position and size of the delamination. The second was to obtain surface strain predictions for specimens with pre-defined damage based on experimental specimens to compare with DIC results to identify methods of quantifying delamination sizes based on surface strains.

The geometries of the FE models were based on the experimental specimens. As with most numerical modelling, assumptions had to be made to simplify the model. As the modelling was macro-scale, one general assumption was that the anisotropic properties of each ply were distributed evenly, i.e. each ply was modelled as having a uniform thickness and no variation in the directional orthotropic properties. Details of each model are given in the relevant results chapters along with the mesh independence studies. The mechanical properties of the cured 8HS weave glass fabric infused with epoxy resin are shown in Table 5-1 (Kyriazoglou & Guild, 2005). Apart from the weave, the 5HS weave fabric properties were identical to the 8HS weave glass fabric. For this reason, the same properties were used when modelling the three-point bending specimens which used the 5HS weave fabric. The
properties of the Flashbreaker®2 tape were also needed to model the effects of the embedded insert on the different responses to the load cases. These mechanical properties could not be found, instead the properties of generic Polyethylene Terephthalate (PET) were used. The properties of PTFE were also used in the models of these specimen (see Chapter 4) as well as in the models of the PTFE/stress-raiser specimens (see Chapter 5). The PTFE/Stress-raiser models and the tubular specimen models also used the properties of epoxy resin, which acted as the stress-raiser. These properties are summarised in Table 3-4.

**Table 3-3: Material properties of a woven (0°,90°), 8HS weave epoxy laminate (Kyriazoglou and Guild, 2005)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Young’s Modulus / $E_x$</td>
<td>21.0 GPa</td>
</tr>
<tr>
<td>Transverse Young’s Modulus / $E_y$</td>
<td>21.0 GPa</td>
</tr>
<tr>
<td>Through-thickness Young’s Modulus / $E_z$</td>
<td>8.55 GPa</td>
</tr>
<tr>
<td>Shear Modulus / $G_{xy}$</td>
<td>3.70 GPa</td>
</tr>
<tr>
<td>Shear Modulus / $G_{xz}$</td>
<td>3.50 GPa</td>
</tr>
<tr>
<td>Shear Modulus / $G_{yz}$</td>
<td>3.50 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio / $\nu_{xy}$</td>
<td>0.183</td>
</tr>
<tr>
<td>Poisson’s ratio / $\nu_{xz}$</td>
<td>0.0305</td>
</tr>
<tr>
<td>Poisson’s ratio / $\nu_{yz}$</td>
<td>0.0750</td>
</tr>
</tbody>
</table>

**Table 3-4: Isotropic mechanical properties of PET (Goodfellow, n.d.), PTFE (Goodfellow, n.d.) and cured epoxide resin 300**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PET</th>
<th>PTFE</th>
<th>Epoxy resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus / $E$</td>
<td>3.0 GPa</td>
<td>0.80 GPa</td>
<td>3.8 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio / $\nu$</td>
<td>0.40</td>
<td>0.46</td>
<td>0.37</td>
</tr>
</tbody>
</table>

A number of assumptions have been made throughout the project. The thickness of each specimen was averaged for each individual model, and it was assumed that each ply had the same thickness; the thickness of the modelled plies was the average measured laminate thickness divided by the number of plies. In the modelling of the different specimens, an effort was made to ensure the meshes produced would be uniform on a ply-by-ply basis, such that each node on a shared surface of a ply would have a corresponding node with the same spatial position on the adjacent ply. This was achieved in all types of specimens modelled by extruding the geometry of features such as delamination inserts, milled sections, and stress-raisers through the thickness of the specimen into
layers that do not contain the said feature. Assumptions and simplifications made specific to each individual type of specimen modelled is discussed in the relevant results chapter.

3.10 Concluding remarks

Three main different structural elements were manufactured, mechanically tested, inspected with NDT techniques and modelled using FEA. These included the three-point bend specimens, the milled-slot specimens and the tubular specimens.

The specimens were manufactured in-house using 8HS or 5HS weave glass fabric impregnated with epoxide 300 resin using the wet/hand lay-up technique, with the exception of the tubular specimens which use the Gurit Prime 20 epoxy resin and is manufactured using VARTM.

Quasi-static loading was performed to elastically deform the specimens for monitoring the delaminations using DIC. For all specimens other than the three-point bend specimens, fatigue testing was used to grow delaminations, which were subsequently analysed using DIC and/or thermography techniques.

The FE models were created based on the geometry of the experimental specimens. The models were run using only 3D solid brick elements, C3D8R reduced integration brick elements for models with bending, and C3D8 full integration elements for models without applied bending.
4 Monitoring of pocket delamination specimens

4.1 Introduction

This chapter presents the results related to the finite element analysis (FEA) and experimental work undertaken on the three-point bend specimens containing the PTFE/Flashbreaker®2 inserts, referred to henceforth as pocket delamination inserts. This type of insert was chosen to simulate a delamination by ensuring two very low friction surfaces were in contact between two adjacent plies. By creating wide specimens with fully embedded inserts, the capabilities of DIC as an NDT technique to detect delaminations could be assessed. The purpose of the work presented in this chapter was to investigate a method to quantify the size of the delaminations using the DIC technique. The inserts were only placed one ply below the surface of interest during the manufacture as described in section 3.2.2.1. This was done to ensure that the delamination would have the largest effect on the specimen surface strains, minimising the effect of experimental noise on the resolution.

4.2 Finite-element modelling

The FEA methodology used in this work has been introduced in Chapter 3 (section 3.9). Several assumptions have been made in order to simplify the models. Each ply has been modelled as a homogenous section with orthotropic material properties and is given its respective orientation; the laminate having a layup of [(0/90), (±45)]_s as described in Chapter 3 (section 3.2.1). The material properties of a woven ply are specified in Table 3-3 in the previous chapter.

The specimens were modelled as two separate parts, with the pocket delamination located one ply below the surface being monitored. In other words, the interface containing the insert was what separated the two parts of the model, i.e. one part consisting of a single woven ply and the other part consisting of fifteen woven plies. These two parts were constrained to one another using tie constraints apart from the regions where the delamination was placed.

The geometry of the inserts was based on the dimensions of the inserts measured prior to inserting them in the laminate during the wet/hand lay-up process (see section 3.2). The sides of the simulated delamination area in the square insert were measured to be 25.4 mm, while the circular PTFE inserts had a diameter of 25 mm. The inserts shifted during the wet/hand layup procedure, so the position of the inserts within the specimens was measured after cutting the specimens from the cured laminate. The FE models had to be modified to take the geometric variations into account. The delamination...
defect inserts were modelled by partitioning the contacting faces of the two plies on either side of the delamination in the shape of the delamination and these areas were not “tied” together in the contact definitions. The areas were also specified to not penetrate one another by applying a frictionless contact condition between them.

The thickness of the inserts was not initially considered in the modelling. However due to a lack of agreement between the DIC and FEA results when the specimen was tested in tension, the thickness of the inserts was later considered and modelled with the properties of the Flashbreaker®2 tape and the PTFE used. This provided much better correlation between the results as shown in section 4.3. Microscopy of the cross-section of a specimen containing an insert was undertaken to confirm the thickness of the inserts in the cured laminate (see Appendix C, Figure C-3). Based on the measurements of the inserts prior to the manufacturing of the specimens and the microscopy, the thickness of the modelled pocket delamination inserts was 0.243 mm of which 0.10 mm is the thickness of the two sheets of PTFE. In the FE model this thickness of the insert was “taken” from the surrounding two plies. The insert was modelled by partitioning the surrounding plies in the region of the delamination. The delamination partition was given the properties of the Flashbreaker®2 tape and PTFE, Table 3-4 in the previous chapter. The geometry of a modelled specimen as well as the properties of the assigned sections is shown in Figure 4-1.

This method of accommodating the thickness of the insert resulted in locally thin regions in the two adjacent plies. The reduced thickness of the plies was compensated by increasing the fibre volume
fraction of the regions of the plies directly above and below the insert in order to maintain the strength of the plies due to the macro-scale modelling of the ply. It was assumed that the volume fraction of the matrix reduced by the same ratio as the thickness is reduced in these localised regions, increasing the volume fraction of the fibres in the composite from 40% to 64.5%. The values for the Young’s moduli of the plies surrounding the insert were obtained using the rule of mixtures, Equation 4.1, where \( E_C \) is the Young’s modulus of the composite, \( V_f \) is the volume fraction of fibres, \( E_f \) is the Young’s modulus of the fibres, \( V_m \) is the volume fraction of the matrix and \( E_m \) is the Young’s modulus of the matrix.

\[
E_C = V_f E_f + V_m E_m
\]  
(4.1)

The adjusted values used are displayed in Table 4-1. As the shear moduli and the Poisson’s ratios of orthotropic materials cannot be determined through the rule of mixtures, the values were kept the same as for the 40% fibre volume fraction material. The effect of varying the shear moduli on the surface strain results by the same ratios as the increase in elastic moduli was investigated (i.e. increasing the shear modulus by approximately 60%) and found to be negligible.

<table>
<thead>
<tr>
<th>Parameter / unit</th>
<th>Original Value</th>
<th>High ( V_f ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Young’s Modulus / ( E_x )</td>
<td>21 GPa</td>
<td>34 GPa</td>
</tr>
<tr>
<td>Transverse Young’s Modulus / ( E_y )</td>
<td>21 GPa</td>
<td>34 GPa</td>
</tr>
<tr>
<td>Through-thickness Young’s Modulus / ( E_z )</td>
<td>8.55 GPa</td>
<td>9.9 GPa</td>
</tr>
<tr>
<td>Shear Modulus / ( G_{xy} )</td>
<td>3.7 GPa</td>
<td>~</td>
</tr>
<tr>
<td>Shear Modulus / ( G_{xz} )</td>
<td>3.5 GPa</td>
<td>~</td>
</tr>
<tr>
<td>Shear Modulus / ( G_{yz} )</td>
<td>3.5 GPa</td>
<td>~</td>
</tr>
<tr>
<td>Poisson’s ratio / ( \nu_{xy} )</td>
<td>0.183</td>
<td>~</td>
</tr>
<tr>
<td>Poisson’s ratio / ( \nu_{xz} )</td>
<td>0.0305</td>
<td>~</td>
</tr>
<tr>
<td>Poisson’s ratio / ( \nu_{yz} )</td>
<td>0.075</td>
<td>~</td>
</tr>
</tbody>
</table>

4.2.1 Boundary conditions and element type

The FE models were assigned boundary conditions to apply the same loading conditions as the experimental specimens. For tension testing, the nodes on one of the end surfaces were constrained to a reference point in the loading direction only, with an applied load of 8180 N as shown in Figure 4-2a. Figure 4-2b shows the opposite face on the model assigned with a boundary condition
restraining any displacement of the nodes on the surface in the loading direction. This simulated the testing described in section 4.3.

![Figure 4-2](image)

(a) The applied load on the reference point constrained to the nodes on the top surface of the model in the X direction only. (b) The boundary condition applied on the bottom surface of the model, restraining any movement in the X direction only.

To model the specimens in three-point bending, boundary conditions representing the support rollers were placed 200 mm apart, and the load was applied to a single master node, constrained in the through thickness direction with slave nodes on a line to represent the loading roller. The two outer purple lines in Figure 4-1 show the location of the boundary conditions applied through partitioned lines on the bottom surface of the models. They were simply supported by only restricting motion in the through-thickness (Z) direction. The middle purple line shows the path along which the slave nodes are constrained to the master node to simulate the uniform distribution of force through the loading roller.

The models all use solid continuum elements; in this case, first order eight node brick elements with reduced integration C3D8R and hourglass control. These elements were chosen as opposed to eight node brick elements C3D8 as there is a tendency for first order fully integrated elements to shear lock when subjected to bending, as the numerical formulation of the elements causes shear strains that do not exist. This type of shear is known as “parasitic shear” which causes these elements to be too stiff in bending (Dassault Systemes, 2014). For the most part, each ply was modelled as being one element thick. This was not the case for the top two plies containing the pocket delamination. These plies were three elements thick.

4.2.2 Mesh assessment

The effect of the size of the elements in the FE models on the accuracy of the results was assessed through a mesh independence study. The method involves using the same model multiple times with differently defined grid spacing to produce meshes ranging from very coarse to very fine. The model
was placed under three-point bending with a load of 275 N applied along the nodes specified as the loading roller (see previous section). A reference node was chosen between the 2nd and 3rd ply halfway between a support roller and the loading roller as shown in Figure 4-3. The position of the node was kept constant as it was placed in the position of a partition in the model. The reference node was used for comparing results from the various mesh refinements. The position of the node was kept as a constant regardless of the mesh. The results of the study are displayed in Figure 4-4. From the results, the values for both the Von-Mises stresses and displacement converge after approximately 100,000 elements. In this chapter, models with approximately 400,000 elements were used, as shown in Figure 4-5, with each element having dimensions of approximately 1 x 1 x 0.30 mm where the insert was not present.

![Reference node](image)

**Figure 4-3:** Position of the reference node used in the mesh independence study for the three-point bend specimen models containing pocket delaminations

![Graph](image)

**Figure 4-4:** The result from the mesh independence study of the 5 HS weave specimen in three-point bending
4.3 Tension loading

A specimen containing pocket delamination inserts was tested in tension to assess if it were possible to detect fully embedded delaminations in flat composite specimens under tension. This was the first load-case attempted due to the ease of monitoring the surface using DIC in this arrangement, allowing for the conventional set up of the cameras as shown in section 3.4. In the experimental testing, the specimen was gradually loaded to a fixed displacement of 0.4 mm in an Instron machine with a 100 kN load cell. This resulted in a load of 8180 N being applied through the specimen.

The delamination defects in the FE models initially did not include the thickness of the inserts used in the experimental testing. Only the original properties of the 8 HS weave epoxy plies, shown in Table 4-1, were used. The results from these initial models showed that an applied uniaxial tensile load produced a uniform strain across the entire surface of the specimen, as the unconstrained “defect” region did not interrupt the load transfer in the specimen. For an applied load of 8180 N, the load used experimentally, a longitudinal strain of 0.00145 was produced across the entire surface of the specimen. Consequently, these results were identical to a model with no delamination. This was not the case experimentally (from DIC) and so the FE models were revisited to include the properties of the Flashbreaker®2 tape and PTFE sheets used in the manufacture of the pocket delamination inserts as outlined in section 4.2.

Figure 4-6 shows the strain contour results from the FE model of the specimen with the pocket delamination properties included. The longitudinal strain contours in Figure 4-6a clearly display the presence of the defect due to the strain perturbations at either end of the insert. Similar perturbations of higher magnitude are seen in the DIC results; however, these are located directly above the insert and not at the insert ends as predicted by the FEA. The shear strains are approximately zero, as expected due to the panel being placed in simple tension. In the DIC results, the strain concentrations
at the upper edge of the figure are as a result of the grips used, which did not span across the entire specimen width.

![FEA and DIC strain contours of a specimen containing PTFE/Flashbreaker®2 pocket delamination inserts in tension (8180N) (a) Longitudinal strain $\varepsilon_{yy}$ (b) shear strain $\varepsilon_{xy}$. The outer dashed square indicates the location of the pocket delamination insert. The inner dashed square outlines the area of the insert in which the delamination is simulated. To further analyse these results, the longitudinal surface strains along a path running across the mid-width of the specimen was extracted from both the FEA and the DIC results. These results are shown in Figure 4-7a along with a schematic of the specimen under load (Figure 4-7b). The orange blocks in the schematic represent the hydraulic grips being used to apply the tensile load to the specimen, the blue squares being the area above the artificial delamination defect inserts and the dashed red line represents the data path used to produce the chart. The results from the FEA model (dashed black line) show a strain of 0.00145 along the data path except for the region containing the insert. This is also the case for the DIC results (solid black line), except for near the grips of the testing rig, where the interaction with the grips caused a higher strain. The simulated delamination, being the interface between the two sealed sheets of PTFE, had a width and length of 25.4 mm. This dimension can be seen in the FEA results by measuring the distance between the two slight dips in strains at each end of the delamination, as shown by the distance between the blue markers in Figure 4-7a. By measuring the distance between the dips between the two peaks at either end of the delamination in the DIC results, shown by the red markers, a dimension of 23.5 mm was measured. The major difference between the DIC and FEA results is on the surface of the ply directly above the delamination. In the
DIC results, there appears to be large oscillations in the strain. In the FE model, the strains in this region remain constant, but at a higher value than the far-field strain. A model was run without the higher fibre volume fraction properties to account for the decreased thickness in the plies due to the presence of the insert, this produced the same result, except with an even higher strain along this region. This is shown by the grey dashed line plot in the figure.

Figure 4-7: (a) Comparison of FEA and DIC longitudinal strains of a specimen containing a pocket delamination at a tensile load of 8180 N. The grey dashed line is the strain data from a FEA model not taking into account the thickness reduction on the strength of the plies. The data is extracted along the dashed line on the schematic in (b), starting from the edge of the top grip.

Schorer and Sause (2015) carried out some similar work, discussed in Chapter 2. In their work it was shown that it was possible to detect a similar type of pocket delamination (two sealed sheets of ETFE) in tension. Similar perturbations in strain can be seen in the DIC results (Figure 4-8a), located inside the region of the insert, similar to the DIC results shown in Figure 4-6a. In their FEA modelling (Figure 4-8b), the region of the delamination is shown to have a higher strain than the surrounding no defect regions.

Figure 4-8: DIC (a) and FEA (b) strain contours of CFRP panel with embedded delamination defect one ply below surface under applied tension of 695 MPa (Schorer & Sause, 2015)
As the results from the FEA analysis outlined in this section indicated that only a delamination caused by the interruptive presence of an insert would be visible from the surface strains of a specimen under tension, and not a natural delamination, three-point bending was investigated.

### 4.4 Linear elastic three-point bending loading

The modelling and testing of specimens at levels of loading where delaminations would not grow is considered in this section. The purpose of this section is to demonstrate the correlation between the FE modelling and the DIC experimental data for testing the pocket delamination specimens in three-point bending and to assess whether the defects were detectable from the surface strains. Subsequently, the growth of the defects is considered. Quasi-static three-point bend testing was carried out as described in section 3.4.1, with the delaminations located one ply below the surface being monitored.

#### 4.4.1 FEA results – compression surface

A comparison of the longitudinal compressive surface strains along a data path running along the mid-width of the specimen (as shown in schematic Figure 4-9a) containing the delamination modelled with and without considering the insert thickness, as well as modelled with no defect is shown in Figure 4-9b. In these models the specimen is under an applied load of 275 N, which was 25% of the static failure load of the laminate in three-point bending. The data path interrogated is illustrated by the dashed line in the schematic in the figure. The no defect model demonstrates a linear decrease (increase in magnitude) of the longitudinal strains between the support roller and the loading roller. This same behaviour is seen in the models including the defect, however, over the length of the delamination there is a plateau in the longitudinal strains between the support roller and the loading roller. This phenomenon occurs as the delaminated region acts as a thin plate, 1/16th the thickness of the surrounding material, that is isolated from the bulk of the laminate below it. While this plateau does not have a uniform strain, the increase in the compressive strain is much smaller than that of the non-damaged specimen when moving towards the loading roller.

Figure 4-9c and Figure 4-9d show the longitudinal and shear strain respectively, on a data path running across the width of the specimen halfway between the loading and support roller (see schematic Figure 4-9a). In all models, the shear strain at the mid-width of the specimen is 0. It can be seen that the shear strains in the ‘no defect’ model and the two models with defects do not vary, apart from the region of the insert. The defect model results show peaks near the edges of the insert. In the longitudinal strains along the width (Figure 4-9c), the differences in the longitudinal strains along the
transverse data path for models considering the presence of a delamination (black), the presence of an insert (red) and no defect are shown. The no defect model clearly shows the effects of anticlastic bending. In the defect models, this behaviour is affected by the effect of the delamination, causing an abrupt change in strains. It is important to emphasise that the model is based on an experimental specimen, and as such the middle of the insert is not located halfway between the loading and support roller, but rather, for this specimen, shifted 3.3 mm towards the support roller. From Figure 4-9b the longitudinal strain at the middle of the insert would be the same as if modelled with no defect (the plateau strain value), meaning the presence of the defect would be indistinguishable from the longitudinal strain data along a data line running along the mid-length of the insert. However, as in Figure 4-9c the data line is 3.3 mm away from this mid-point (closer to the loading roller), the strain profile of the defect and non-defect specimen are different.

The magnitude of the change in shear strains due to the presence of the defect is similar to the magnitude of the change in longitudinal strains when compared with the non-defect model along the same path. This comparison between the longitudinal and in-plane shear strains was made to assess which one would be better to consider for NDT purposes.

Figure 4-9: (a) Schematic of paths of data extracted from FE model of three-point bending. (b) Comparisons of longitudinal surface strain with (red) and without (black) modelling the insert thickness as well as a specimen without any damage or insert (green) along the length of the specimen and (c) across the width. (d) Comparisons of shear surface strains. (275 N)
From these figures, it is clear that modelling the thickness of the inserts has far less an impact in three point bending than it does for tension loading as discussed in section 4.3. In the modelling, there are small singularities at either ends of the insert with the GFRP, Flashbreaker®2 tape and high fibre volume fraction GFRP properties. The plateau of the strain was not significantly affected by how the insert was modelled. Based on these observations, the experimental specimens were tested while monitoring the compression surface of the three-point bend using DIC to compare with the FEA.

4.4.2 DIC results – compression surface

All three-point bend testing was carried out on an Instron 1185 using a 5 kN load cell. The load was applied to the testing by controlling the displacement of the loading roller, loading to 4 mm at a rate of 2 mm/minute. The DIC setup was placed in timed capture mode to take a set of pictures every 2 seconds. The experimental results shown in the remainder of this section were all taken at 4 mm displacement, with the resulting loads taken from the Instron machine.

4.4.2.1 No defect specimen

No defect specimens were tested to compare the longitudinal and in-plane shear strain contours from DIC with the contours produced by FEA. The model has an applied load of 275 N to match the experimental data. Figure 4-10 shows the longitudinal and shear strain contours of the compressive surface from FEA (top) and DIC (bottom). The contours and legends were matched to allow for easier comparisons. Figure 4-10a shows the longitudinal strain contours from the FE model (top) and DIC results (bottom). Figure 4-10b shows the in-plane strain contours from the FE model (top) and DIC results (bottom). The FEA results in Figure 4-10a show that along the width of the specimen the strains are slightly curved due to the effects of anticlastic bending. This effect is not apparent on the DIC results due to the limited strain resolution of the technique. The shear strain DIC contours in Figure 4-10b are a lot noisier due to the lower magnitude of the values compared with the longitudinal strain results.

Figure 4-11b and Figure 4-11c compare the extracted longitudinal strains (from the results shown in Figure 4-10a) obtained from the DIC results as well as the FEA results along the length and width of the specimen, as shown in the schematic in Figure 4-11a. While this specimen does not contain a defect, the schematic includes the inserts as the data paths were placed in the same positions for the specimens containing defects (see section 4.4.2.2). The DIC results are plotted with the solid lines, while the FEA results are plotted with dashed lines. In Figure 4-11c, transverse data paths were chosen along the length of the specimen. The black data path ran along the mid-length of the location where the insert in the corresponding defect specimen was, while the red and green data paths were placed 8 mm on either side of the black data line. The purple data line was selected as a reference. Overall
both the DIC and FEA results generally agree with one another but with some key differences. The FEA shows a smooth linear increase in the magnitude of the longitudinal strains after the support roller. While the DIC result displays a similar linear increase, the noise in the data produces minor variations in strain values.

![FEA and DIC results](image)

**Figure 4-10**: Strain contours of the compression surface of a no defect 5 HS weave epoxy specimen in three-point bending. (a) Longitudinal strain and (b) shear strain (275 N)

![Data paths](image)

**Figure 4-11**: Comparison of longitudinal strains along no defect FE model and no defect specimen DIC results (a) along the dashed data paths illustrated in the schematic. The results are plotted together (b) along the length of the specimen, and (c) along the width. (275 N)

Similarly, through-width data paths were extracted from the shear strain results. These results can be seen in Appendix C, Figure C-4. The DIC results show a large amount of noise for the shear strain data. While the magnitude of the strains is broadly consistent, the contours are very difficult to interpret, which might make this strain component a poor candidate for damage detection.
4.4.2.2 Square shaped delamination specimen

A specimen containing square-shaped pocket delamination inserts between the two plies closest to the compressive surface was manufactured to assess the behaviour of the delamination defect on the surface strains. The modelling of this type of defect in the laminate is described in section 4.2. The comparison of surface strains for this specimen is shown in Figure 4-12. As with the results from the no defect specimen, the DIC results contain some noise, although the overall strain distribution is similar to the FEA results. In these strain contours, the edges of the simulated delamination region are highlighted with the dashed white lines. From these strain contours alone, the presence of the delamination is visible from the strain irregularities when compared to the results for specimens containing no defect detailed in the previous section (directly compared with Figure 4-10).

![Figure 4-12: Strain contours of the compression surface of a 5 HS weave epoxy specimen containing a pocket delamination in three-point bending. (a) Longitudinal strain and (b) shear strain (275 N)](image)

Data paths in the same position as those in the previous section (section 4.4.2.1) were placed to generate graphs of the surface strains vs. position along the data paths directly comparable to the no defect specimen results in Figure 4-11. Figure 4-13 shows the FEA and DIC strains along the various data paths shown in the schematic included in Figure 4-13a. From these results it can be deduced that even though the noise in the data is substantial, the size of the delamination can be estimated from the DIC results. The size estimates, based on the strain data, can be made by assuming that the length over which the longitudinal strain remains relatively constant along the X position (i.e. between points X1 and X2 in Figure 4-13b) is the length of the delamination, while the width can be deduced from the transverse data lines (i.e. between points Y1 and Y2 in Figure 4-13c). The measured length of the delamination from the DIC results in Figure 4-13b was determined from the two blue markers, X1 and X2, placed. This length was observed to be 0.2 mm smaller than the simulated delamination length.
Chapter 4. Monitoring of pocket delamination specimens

The width measurements were undertaken on the two data paths in which the change in longitudinal strain along the delamination was clear. These measurements were from the local troughs and peaks before and after the change in strains (points Y1, Y2, Y3 and Y4 in Figure 4-13c), which proved to overestimate the size of the delamination by 8.1 mm and 10.7 mm. As observed in section 4.4.1, the closer the data path along the width of the specimen was to the centre of the insert, the lower the change in strains over the insert as shown by the black line in Figure 4-13c. The shear strains along these data paths (Figure 4-13d) show a shear strain concentration at the edges of the delamination. Using the peaks in the shear strains as markers (points S1 and S2 for DIC, S3 and S4 for FEA), it was observed that the FEA results underestimated the size of the delamination by 2.0 mm, while the DIC results overestimated it by 1.7 mm. These peaks are clearly visible in the contours shown in Figure 4-12b. As the shear strains provide a better measurement of the width of the simulated delamination, they can be used in conjunction with the longitudinal strain contours to provide reasonable estimates of defect size. The shear strains along the other data lines can be seen in Appendix C, Figure C-5. The data along the red and green data paths are in close agreement with the black data path (refer to schematic in Figure C-5 or Figure 4-13a).

Figure 4-13: Comparison of longitudinal surface strains along square defect FE model and square defect specimen DIC results (a) along the dashed data paths illustrated in the schematic. The results are plotted together (b) along the length of the specimen, and (c) along the width. (d) The shear strains along the mid width are also shown (275 N)
Chapter 4. Monitoring of pocket delamination specimens

The DIC and FEA data paths were manually selected. An example of how this was done is shown in Figure D-22 in Appendix D. Care was taken to try to match the position of the data paths, however inevitably there is a difference in the paths defined on the DIC and the FEA data which will give rise to some discrepancies between the two techniques.

4.4.2.3 Circular delamination specimen

Specimens with circular delaminations between the first and second plies from the compressive surface were manufactured to assess the difference the shape of the delamination insert makes on the strain contours. The diameter of the simulated delamination in these inserts was 25 mm. The thickness of the pocket delamination inserts and the resulting volume fraction differences were included in this model as well. Figure 4-14a shows the longitudinal strain contour for the FE model and DIC results, and Figure 4-14b shows the in-plane shear strain contour. As in the previous section, the outline of the position of the insert has been indicated using a dashed white line. The longitudinal strain contours observable from the DIC results in Figure 4-14a show major fluctuations in the strain at the edge of the delamination closer to the loading roller, indicating a phenomenon that did not occur with the square shaped delamination. Apart from this fluctuation in strains, the presence of the plateau in longitudinal strains remains the key identifier for the length measurement of the delamination, as shown by the FE results in Figure 4-14a and Figure 4-15b.

Figure 4-14: Strain contours of the compression surface of a 5 HS weave epoxy specimen containing a circular pocket delamination in three-point bending. (a) Longitudinal strain and (b) shear strain (250 N)

Figure 4-15 shows the strains extracted along the data paths illustrated in the schematic (in Figure 4-15a) from the contour results shown in Figure 4-14. The shear strain results from DIC shown in Figure 4-14b and Figure 4-15d indicate the edges of the delamination insert, however there was too much noise to determine the width of the delamination from the shear strains. The longitudinal strains along the width do, on first appearance, show the same characteristics as for the square delamination,
however the data path closest to the loading roller shows a large increase in the compressive strains in DIC. This is the purple region inside the outline of the insert shown in the DIC contour in Figure 4-14a. The black transverse data line ran through the centre of the insert. This should mean that the longitudinal strains remain relatively constant as shown in the FE results in Figure 4-15c, however the DIC results did not show this. These two observations indicate a minor local buckling of the ply above the defect. In an attempt to measure the delaminations without causing this local buckling, placing the defect next to the tension surface of the three-point bend was investigated, i.e. flipping the specimen in the three-point bend and changing the position of the DIC cameras.

Figure 4-15: Comparison of surface strains along the compression surface of the FE model (dashed lines) and DIC results (solid lines) of the circular pocket delamination specimen in three-point bending (a) along the length of the specimen and (b) across the width. (250 N)

4.4.3 DIC results – tension surface

Initial investigations on monitoring the tension surface of the three-point bend specimen proved to produce poor results. These results are shown in Figure C-8 and Figure C-9, Appendix C. The adaptation of the set up to include extensions of the blocks containing the support rollers as shown in Figure B-2 (in Appendix B) proved to produce better results. The full-field FEA and DIC strain contours
are shown in Figure 4-16. Loading the specimens with the inserts 1 ply below the tension surface of the three-point bend specimen and monitoring that surface with DIC produced the same plateau in strains along the length of the simulated delamination as shown in Figure 4-17b. In this specimen, the delamination length was underestimated by 4.8 mm. It is important to note that the selection of the points in which the markers are placed can be affected by the noise of the strain at the edges of the plateau regions. While selecting the markers at the peak of the first noise related variation in strain in the plateau, approximately at X = -48.4 mm, rather than at the edge of the plateau at X = -54.3 mm, the size of the delamination was measured to be 14.3 mm rather than 20.2 mm. In either case, the FEA strain field suggested the delamination should be 25.4 mm.

Figure 4-16: Strain contours of the tension surface of a 5 HS weave epoxy specimen containing a circular pocket delamination in three-point bending. (a) Longitudinal strain and (b) shear strain (266 N)

Figure 4-17: (a) Schematic of a circular defect specimen on the tension side of a three-point bend with the data path highlighted. (b) Comparison of the longitudinal surface strains along the tension surface of the FE model (dashed line) and DIC results (solid line) data path (266 N)
The longitudinal strains along the transverse data paths suggested defect widths of 25.8 mm and 24.7 mm at the data lines closest and furthest from the loading roller, respectively. As the defect was circular, the defect widths at these sections were expected to be lower than the diameter of the insert. These measurements have been influenced by the location of the strain changes as shown by the FEA. There would have been a lot more uncertainty in the selection of the markers in the DIC results without the FEA results. These measurements corresponded to visual measurements of 19.2 mm at the position of the data lines as illustrated in the schematic in Figure 4-18. The longitudinal DIC strain along the transverse data path across the middle of the delamination remained relatively constant through the delamination as expected, however there was a large perturbation with a change of strain of approximately 0.0003 at one of the edges. Figure C-10 in Appendix C shows the shear strains along the transverse data paths. Only the path closest to the loading roller had low enough noise to identify the peaks at the edges of the delamination.

4.5 Three-point bending to failure

Specimens containing the pocket delamination inserts were tested to failure while monitoring the surface closest to the inserts with DIC. This was done to investigate the local buckling of the material with the insert closest to the compression surface as seen in section 4.4.2.3. This work was also done to investigate if the delamination would grow any further into the material under quasi-static three-point bending. Testing was carried out on specimens containing square pocket delamination inserts, considering both when the inserts are closest to the compression side (Test 4) as well as the tension side (Test 1). A specimen containing no inserts was tested as well (Test 5). Testing specimens
containing circular inserts (Test 2 and Test 3) was only done with the inserts nearest the tension side of the three-point bend specimen. The load displacement diagram in Figure 4-19 shows the data from all the tests to failure. From these results, the general behaviour of the specimens is fairly consistent, with linear elastic behaviour in all specimens up to approximately 720 N and failure of the material occurring above between approximately 1 - 1.1 kN.

![Figure 4-19: Load/displacement diagram of 5HS weave epoxy specimens loaded to failure.](image)

4.5.1 Compression surface

Comparing tests four (square defects) and five (no defect) in Figure 4-19, the specimen containing the insert showed an overall increase in deflection and ultimate strength compared with the no defect specimen, which could be due to the presence of unintended damage in the no defect specimen or differences in the specimens due to the manufacturing (a slight misalignment of the plies). It is also important to note that the no defect specimen was created from a laminate produced earlier than the laminate containing the damaged specimen, meaning there were possible variations in properties. Measurements indicate an average thickness 0.2 mm (~4%) lower for the no defect specimen.

The load-displacement response for the specimen containing a defect showed a small but sharp decrease in load just before the displacement of the loading roller reached 15 mm, approximately 720 N. DIC data was collected every second during the testing, producing a set of before and after strain contours of the specimen during this blip. The set of images are displayed in Figure 4-20. Figure 4-20a shows longitudinal strain contours consistent with the non-destructive testing discussed earlier in this chapter, but at much higher strain values due to the higher load. Figure 4-20b shows a local buckling effect occurring on the ply above the delamination insert. The shear strain contours are displayed in Appendix C in Figure C-11.
Chapter 4. Monitoring of pocket delamination specimens

The overall effect of this local delamination did not seem to have a large effect on the overall performance of the specimen, however this could also have accounted for the higher ultimate strength and deflection compared with the no defect specimen.

Figure 4-21 shows the longitudinal strains taken along the data path at intervals of approximately 200 N during the destructive testing of test 4, the specimen containing the square pocket delaminations. The occurrence of buckling in the surface caused a large spike in the strains over the centre of the delamination, dominating the strain profile over the insert. At the highest load, the middle of the specimen was displaced by almost 30 mm, which resulted in large errors in the DIC measurement due to the surface of the specimen going out of focus as the applied load deformed the specimen past the depth of field of the cameras. The longitudinal strain contours at each interval can be seen in the Appendix C, Figure C-12 to Figure C-16.
Figure 4-21: (a) Schematic compression surface of a square defect specimen and the dashed data path. (b) Longitudinal strains from the longitudinal data path on the DIC strain contours at different applied loads during the three-point bending of the 5 HS weave epoxy specimen with square delamination defects

4.5.2 Tension surface results

Figure 4-22 shows the longitudinal strains on the data path of a specimen containing two square pocket delamination inserts, close to the tension side of the three-point bend specimen, as obtained with DIC at ~200 N intervals up until failure. On the tension side, the plateau effect of the delamination can be seen at any applied load. However, depending on the load, the length of the plateau varies. The average distance over which the plateau in strains occurs over the left sided delamination is 25.7 mm with a standard deviation of 2.9 mm. The largest is at the highest load, measuring 29.5 mm. From this data alone, it would suggest the delamination grew after the failure of the specimen, however visual inspections of the laminate proved otherwise. Similar observations can be made for the defect on the right side. The crack growth could not be seen visually for any of the delamination defects in the specimen.
Chapter 4. Monitoring of pocket delamination specimens

Figure 4-22: Longitudinal strains from the through length longitudinal data path on the DIC strain contours at different applied loads during the three-point bending of the 5 HS weave epoxy specimen with square delamination defects

Similar results for the other two specimens can be found in Appendix C, one with one circular defect and no damage on the other side of the loading roller (Figure C-17), and the other with two circular defects (Figure C-18). As for the square delamination specimen, the defects within these specimens were detectable from the surface strain contours, however there appeared to be no growth of the defect both visually and in the plotted results.

4.6 Concluding remarks

This chapter investigated, for the first time, the monitoring of a fully embedded artificial delamination in a 5HS glass fibre weave epoxy laminate using DIC. It was found that detecting the delamination while the specimen was placed in tensile loading was possible, however the FEA modelling suggested this was only due to the insert and would not be the case for a natural delamination. In three-point bending however, regardless of how the insert was modelled, a characteristic plateau in the strains over the delaminated region suggested that this was the better loading condition with which to investigate the use of DIC.

Due to the method used to simulate a delamination, the PTFE/Flashbreaker®2 combination, the delamination sizes investigated were fixed to the two dimensions initially used for the square and circular delamination inserts. Tests on specimens containing this pocket delamination insert have shown that the DIC can be used to detect delaminations in panels when subjected to three-point
bending, however quantifying the size of these delaminations has not been further investigated due to uncertainties due to the slight mismatches in overlapping of the two pieces of PTFE and other complications arising from using these relatively high thickness inserts.

As this study has shown that the plateau in strains can be detected using DIC on the tension side of the three-point bend specimens without incurring the possibility of local buckling over the insert, the next chapter considers growing a delamination in the same type of specimen with a key difference; a single sheet PTFE defect used instead of the pocket delamination. This was done to reduce the thickness of the insert, creating an embedded debond region that acted as a delamination. Following on from the quasi-static test to failure results, fatigue testing was considered to promote the growth of delamination damage without the initiation of other types of composite material damage such as fibre breakage.
5 Monitoring delaminations in PTFE/stress-raiser specimens

5.1 Introduction

The specimens manufactured with the PTFE/Flashbreaker®2 pocket delaminations investigated in the previous chapter resulted in specimens containing a low friction interface between two sealed sheets of PTFE embedded within the laminate. This method of simulating a delamination in the composite specimens demonstrated the ability of DIC to detect delaminations under three-point bending. Following on from this work, an investigation was carried out to create a more realistic fully embedded delamination within the specimens that could be grown. As the PTFE/Flashbreaker®2 artificial delaminations could not be grown either under quasi-static or fatigue loading, a second type of defect was developed.

In the literature, a single layer of PTFE is commonly used to simulate the presence of a delamination, see chapter 2 (section 2.4). In the work presented in this chapter, the PTFE approach was used with the addition of a stress-raiser in the form of a cut introduced into the top layer of the glass fabric prior to manufacturing the laminate, as described in chapter 3 (section 3.2.2). For specimens containing this type of artificial delamination, the testing was done with the delamination near to the tensile face of the laminate to avoid buckling of the material above the delamination.

In this chapter, the finite element modelling of the tested specimens is discussed, as well as the DIC, pulse thermography and passive lock-in thermography results. Finally, the growth of the delaminations in a specimen with circular PTFE inserts and hole-punched stress-raisers is investigated leading into the work on the tubular specimens in the next chapter.

5.2 Finite-element modelling generation

The FE models created for the specimens tested in this chapter are based on the models created in the previous chapter. A few assumptions and simplifications have been made to the FE models to reduce complexity such that the models were less numerically intensive. These assumptions and simplifications include the project-wide simplifications mentioned in chapter 3 (section 3.9) those from the previous chapter, and some new ones which are discussed below.
Chapter 5. Monitoring delaminations in PTFE/stress-raiser specimens

5.2.1 Model design and boundary conditions

Due to the manufacturing method described in chapter 3, the position of the PTFE inserts moved within the specimen, meaning the cured specimens had variations in the position of the inserts. In addition, if the PTFE insert moved width-wise relative to the cut in the fabric acting as a stress-raiser, the specimens had to be prepared to ensure the embedded inserts were not too close to the edge in order to avoid any free edge effects. Because of all these variations in the position of the insert and the extent of the stress-raiser across the width of the specimens, each specimen tested was modelled individually based on visual measurements of specimens. The position and sizes of the PTFE inserts within the transparent specimens were measured visually and modelled accordingly. The same was done for the position of the stress-raisers, however assumptions were made over the width of the stress-raiser (i.e. the gap size in the fabric cut) as this varied both within and between specimens. The stress-raiser was created by cutting the top layer of fabric but keeping the two cut pieces of fabric together. During the curing process, the cut in the fabric tended to widen to approximately 1-4 mm. This was measured for each specimen and modelled by partitioning the width of the stress-raiser into the top face and extruding the partition down through the entire laminate. This partitioned section on the top layer was specified as having the properties of the epoxy matrix resin. The partitions for the PTFE and stress-raisers were extruded through the thickness of the laminates to ensure the meshes produced would be uniform on a ply-by-ply basis such that each node on a shared surface of a ply would have a corresponding node with the same spatial position on the adjacent ply.

Table 3-1 in Chapter 3 outlines the different specimens used. Specimen 0 was the initial proof of concept specimen. The testing of specimens 1-3 was undertaken after the results from specimen 0 demonstrated through testing that the insert did act as a delamination after fatigue testing (see section 5.3). Figure D-19 in Appendix D shows close-up images of the PTFE inserts and stress raisers along with the delaminated regions.

The geometry of an FE model representing a specimen (specimen 1) is shown in Figure 5-1. The properties of the various sections have been colour coded where beige indicates regions with GFRP properties, red regions with the adjusted higher V\text{f} properties shown in Table 5-1, green stress-raisers with epoxy properties and blue PTFE inserts. The dashed lines in Figure 5-1a show the positions of the partitions made to extract data to compare with DIC results (see section 5.3). The remaining lines are partitions made to create the boundary conditions for the support rollers and to apply the load across the width of the specimen at the midpoint to represent the loading roller.
In modelling these specimens, the assumption from the previous chapter of the insert thickness being partitioned from the adjacent plies is used. A cross-section of a specimen is shown in Figure D-20 in Appendix D. It was difficult to determine how much resin the inclusion of the PTFE insert displaced in each ply during the manufacturing, however it is likely that the insert displaces more resin in the adjacent plies than the other fourteen plies.

As in the previous chapter, the inserts were modelled by partitioning cells into the adjacent plies at half the thickness of the PTFE sheet, such that the full thickness, 0.05 mm, would be positioned as it was on the experimental specimens. This partitioned cell was specified as having the properties of PTFE (Table 3-4). The volume of the plies from which these cells were partitioned was given adjusted high fibre volume fraction (\(V_f\)) material properties taking the original \(V_f\) as 0.4, to account for the reduction in thickness of the plies. As in the last chapter, these adjusted properties were determined using the rule of mixtures (see section 4.2) and are shown in Table 5-1. Only the elastic moduli were adjusted, the Poisson’s ratios and shear moduli were not adjusted. Variations in the shear moduli were investigated, however these did not change the results in the mesh assessment and surface strain data.
in any way. The meshing of the FE models was investigated to ensure the results had converged with respect to the density of the mesh.

In the experimental specimens, the inserts were initially bonded with weak secondary bonds to the adjacent plies (see section 5.3). After the fatigue loading, the bond was broken on one interface between the PTFE and the ply, sometimes on both interfaces (see specimen 3L in Figure D-19 in Appendix D). This means that in the physical specimens the delamination runs between the PTFE insert and the adjacent ply. In most cases, the entire shared surfaces of the top ply and the adjacent ply were constrained to one another with a tie constraint apart from where the insert was present. Specimens in which the insert had not fully debonded from the adjacent ply (see section 5.3) were constrained in the regions where the bond was still present. This modelled the inability for these surfaces to transfer load from one part to the other over the region of the insert.

Table 5-1: Material properties of a woven (0°,90°), 8HS weave epoxy laminate and the adjusted properties of the higher volume fraction regions

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<th>Parameter</th>
<th>Value</th>
<th>Adjusted high Vf value</th>
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<td>Longitudinal Young’s Modulus / Eₓ</td>
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<td>24.8 GPa</td>
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<tr>
<td>Transverse Young’s Modulus / Eᵧ</td>
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<td>24.8 GPa</td>
</tr>
<tr>
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<td>9.61 GPa</td>
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<td>~</td>
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<td>Shear Modulus / Gₒᵧ</td>
<td>3.50 GPa</td>
<td>~</td>
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<td>~</td>
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</tr>
<tr>
<td>Poisson’s ratio / νₒᵧ</td>
<td>0.075</td>
<td>~</td>
</tr>
</tbody>
</table>

5.2.2 Mesh assessment

The mesh used in the FE models detailed in this chapter was assessed by investigating the effect of mesh density on the output values on a reference node (shown in Figure 5-2). This reference node was placed at a partition to ensure the location on the model stayed fixed regardless of the mesh in a position away from any singularities. Figure 5-3 shows the overall displacement and the Von-Mises stress at the reference node in a model with an applied load of 275 N applied at the position of the loading roller. This study showed that the results at the reference node converge before a total of 100,000 elements in the model. In this chapter, the brick elements had dimensions of approximately
1 x 1 x 0.28 mm. The inserts were modelled with 1 x 1 x 0.025 mm brick elements. These dimensions varied increasingly the closer they were to the irregularly shaped stress-raisers and angled inserts as described in the previous section. The number of elements varied slightly due to the modifications on the positioning of the inserts as described in the previous section on each model, however the total number of elements was approximately 350,000 in all models.

![Figure 5-2: Location of the reference point used in the mesh assessment of the FE models of three-point bend specimens with PTFE inserts and stress-raisers](image)

Figure 5-3: Results taken from the reference node in the mesh assessment study, where the results are plotted against the number of elements used in the model. The results investigated were (a) the overall displacement and (b) the Von-Mises Stress at the node.

5.3 Digital Image Correlation

Specimens with the PTFE/stress-raiser delaminations were subjected to cyclic loading with a peak load of 600 N (R = 0.1) at 2 Hz for 10,000 cycles as described in chapter 3 (section 3.3). The DIC equipment was set up to monitor the tension side of the three-point bend specimen under a load of approximately 275 N, resulting in a maximum displacement of 4 mm. An example of the longitudinal strain contours on one of these specimens is shown in Figure 5-4. By observing the strain contours, the steep strain gradients indicate the presence of delaminations in the positions of the PTFE inserts within the specimen. In this figure, 64 different shades were used, while in the previous chapter, only
16 shades were used, making the differences in strain around the defect visually clearer. It is also important to note that the speckling of the specimens was improved as these specimens were tested later during the project, reducing the amount of noise in the data. In this chapter, the Lagrange and Engineering strains were used interchangeably, as the differences in the two were minimal for $\varepsilon_{xx}$ and $\varepsilon_{yy}$.

**Figure 5-4:** Longitudinal strain contour results from DIC on the tension surface of a specimen containing embedded PTFE inserts and stress-raisers under three-point bending. The dashed black lines indicate the data lines from which the results were extracted.

To quantify the sizes of the delaminations, data lines were extracted along the mid-length of the specimens as well as along the width, 5 mm away from the stress-raisers as shown by the dashed black lines in Figure 5-4. Due to the positioning of the DIC cameras (see section 3.4.1), the surface being monitored is at a skewed angle. Ensuring the position of the longitudinal data line running along the mid-width of the specimen was established by outputting the Y-position contour on the DIC results as demonstrated in Figure D-22a in Appendix D. Similarly, the position of the transverse data lines, running along the width of the specimen, was placed approximately 5 mm away from the stress-raiser towards the loading roller using the X-position contour shown in Figure D-22b in Appendix D. The results extracted along these data lines are the longitudinal strain values in the X and Y directions as shown by the coordinate system in Figure 5-4.

It is important to note that the PTFE inserts were initially bonded to the surrounding composite during the curing of the epoxy resin in the laminate. Figure 5-5a shows an image of the PTFE artificial delamination with a stress-raiser in the transparent laminate before fatigue loading. The DIC image with the specimen under a load of 315 N shows longitudinal tensile surface strains which are in agreement with the surface strains for the surrounding material not containing the insert. The variation in strain along the coupon for these “pre-fatigue” results are shown in Figure 5-6. The strain
increases linearly from about 500 µε near the support rollers, to about 2,800 µε at the centre of the coupon; the mirror-image of this strain distribution occurs for the other half of the specimen. At the location of the cut in the top layer of the fabric there is a small perturbation in the strain for both halves of the coupon.

With this PTFE/stress-raiser insert, it proved possible to grow the delamination under fatigue loading. Figure 5-5b shows the appearance of the delamination after 10,000 fatigue cycles. The delamination initiated at the location of the cut in the fabric and grew at the interface between the PTFE layer and the top layer of the laminate. Interestingly, the delamination did not extend beyond the limits of the PTFE insert, even after 100,000 fatigue cycles. From the visual images only, the increase in the opacity of the material above the insert is indicative of the bond between the PTFE insert and an adjacent ply being broken as the absence of a bond reduces the transparency of the material. Figure 5-5b shows the DIC image at a load of 315 N after fatigue loading, and the surface strains derived from the DIC results for this “post-fatigue” delamination are shown in Figure 5-6. The overall changes in the strains shown in Figure 5-6 correspond to what would be expected for the surface strains in a three-point bend test. However, there are two significant differences. First, there are now large perturbations at the locations of the cuts in the surface fabric of the laminate and, second, there are strain plateaux (i.e. regions of constant strain) which occur in the vicinity of the delamination. The perturbations in the strain values occur where the fabric was cut is due to the higher deformations within this resin-rich region.

Prior to fatigue loading, the insert was fully bonded to the surrounding epoxy and the presence of the PTFE insert could, therefore, not be detected using DIC. However, once the insert debonded from the epoxy due to the fatigue loading, load transfer to the delaminated surface ply was no longer possible and the surface ply above the defect remained at a constant level of strain, thus producing the plateaux observed in the strain profiles. These plateaux are similar to the plateaux seen for the PTFE/Flashbreaker®2 results in chapter 4. Consequently, it can be concluded that the delaminations growing from the PTFE/stress-raiser act as real delaminations, producing the same effects on the surface strains as the PTFE/Flashbreaker®2 delaminations, with the added advantage that this second type of artificial delamination grows under fatigue loading. The artificial delamination shown in Figure 5-5 corresponds to the X-position of about 140 mm in the strain results in Figure 5-6.
Figure 5-5: Images of the surface directly above a typical specimen with a PTFE insert and a cut fabric stress-raiser (a) pre-fatigue and (b) post fatigue

Figure 5-6: Comparison of DIC longitudinal strains along the centre line of the specimen with the PTFE/stress-raiser artificial delamination both before and after the growth of the delamination (“pre-fatigue” and “post-fatigue”)

The DIC results and corresponding FEA model results (both taken along the longitudinal data line in Figure 5-4) are shown in Figure 5-7a. Figure 5-7b shows the results along a transverse data line running across the width of the specimen closer over the position of the insert as shown by the transverse dashed lines in Figure 5-4. As in the DIC results for the three-point bend specimens containing the
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PTFE/Flashbeaker®2 pocket delaminations in the previous chapter, the distance along the data line over which the plateaux in strains is present can be quantified to determine the size of the delamination. The main difference between the results in these specimens compared with the pocket delamination specimens is the presence of the spike in strains at the position of the stress-raiser caused by the cut in the top layer of fabric.

Two approaches were investigated for interpreting the strain data along the data paths. The first was to select the markers based on where the strain profiles deviated from the expected undamaged strain profile, for example the positions over the inserts in Figure 5-6. The other approach was to use the FEA model to assist in the positioning of the markers on the curves. The first approach allows for the characterisation of the size of the delamination purely from DIC results, without prior bias of the size of the delamination from FEA models. Both approaches are shown for quantifying the delamination length in Figure 5-7a. The first approach uses positions X1 and X2 determined by selecting the points at which the expected linear change in strain along the position along the X-axis is no longer linear. The length of the defect was measured by subtracting the position along the X-axis at X2 from X1.

The second approach uses FEA to estimate the expected small increase of strain over the delaminated region and apply marker X3 on the curve at the same increase in strains compared with X1 as for the corresponding two points in the FEA (shown by the blue markers in Figure 5-7a). The X position at X3 is subtracted from that at X1 to obtain the length of the delamination.

Initially, measuring the length of the plateau between the green markers in Figure 5-7a, for specimen 2R this was 23.4 mm. While this method underpredicted the size of the delamination, it was also inconsistent on a specimen by specimen basis as only a small number of tested specimens demonstrated a plateau with low enough noise to position the markers with confidence. Therefore, the approach using a clear marker at X1 as the starting point and X3 as an estimate based on the FEA was adopted.

Only the first approach was used to quantify the size of delamination from the strain results for the width of the specimen. This is shown in Figure 5-7b. The positions Y1 and Y2 are determined by selecting the points prior to the dip leading into the plateaux of strains. These points were selected as they act as markers that occur on all transverse data lines in all specimens containing delaminations. The size of the delamination along the data line is then calculated by subtracting Y2 from Y1. For the FE models, subtracting these two points resulted in very good correlation with the visually determined delamination sizes, however from the DIC results the value was consistently larger. A comparison of the width measurements for all delaminated inserts using visual measurements, FEA and DIC strain contour results are shown in Figure 5-8.
Chapter 5. Monitoring delaminations in PTFE/stress-raiser specimens

Figure 5-7: Longitudinal strains along data lines on three-point bend specimen 2R containing an embedded PTFE/stress-raiser insert. The strain values were extracted along (a) the length of the specimen where the origin of the X-axis is the position of the loading roller, and (b) the width of the specimen 5 mm from an insert stress-raiser closer to the loading roller.

Figure 5-8: A comparison of the delamination sizes taken from data lines from the tension surface of the specimens along the width.

In some instances, the de-bonding of the PTFE inserts from the adjacent ply did not extend throughout the insert after 10,000 cycles of fatigue, or even after the 100,000 cycles applied to specimen 0L. The images used for the visual measurements of the delaminations in every specimen after the fatigue testing are shown in Figure D-19 in Appendix D. The visual measurements along the mid-width of specimen 0L are shown in Figure 5-9a. This includes the length measurement of the insert as well as
the de-bonded region. The corresponding DIC and FEA longitudinal strain data along the longitudinal data line, such as the one in Figure 5-4, are shown in Figure 5-9b. The approach using only DIC results gave a delamination length approximately 26-39% larger than the delamination length compared with the FEA and visual measurements of the same delamination along the same data line. Most specimens contained fully de-bonded inserts along the data lines. The partially de-bonded inserts, 0L, 3L and 3R have a curved de-bond front, meaning the data line must have the same position for the DIC results and the visual measurements. The FEA models had to be adjusted to include this curved front as well by excluding the nodes in the bonded region in the delaminated region definition as described in section 5.2.1. A comparison of the length measurements for all delaminated inserts using visual measurements, FEA and DIC strain contour results is shown in Figure 5-10. Both results using the DIC only approach as well as the FEA assisted approach are shown in this figure.

Figure 5-9: (a) Image of three-point bend specimen insert 0L containing a partially grown delamination to the left of the stress-raiser along with the visually determined lengths of the delamination and the insert along the dashed black line. (b) The measured sizes of the delamination and insert along the aforementioned dashed black line using the DIC and FEA strain results.

The visual measurements were made by photographing the specimens above the insert such that the two edges of the specimen running parallel to the length were included in the image. Using ImageJ image processing software, the width of the specimen was measured in pixels, which was compared
with the measured width using a Vernier calliper. From this, the length of a pixel was determined to be approximately 21.6 µm. This varied slightly (±0.5 µm) due to the set-up used to take the images with a DSLR camera being kept at a fixed distance from the specimens for all image acquisitions.

The DIC approach that uses FEA to assist in the positioning of the markers proved to overestimate the delamination length less, approximately by 9-19%. However, the FE assisted approach only effected the placement of the X3 markers and not the X1 markers (see Figure 5-7a), which in this approach was reserved for the consistent feature in these plots. X1 was selected as the peak prior to the trough into the plateau. More work could be done on the FEA assisted approach to better estimate the delamination size, however the scope of this work is to determine the application of DIC as an NDT technique. As such, further analysis is only included for the DIC only approach.

An empirical correction factor was calculated by averaging the differences between the DIC measured delamination sizes and the delamination sizes determined using visual images post processed using ImageJ software. This difference for the width measurements was consistently between approximately 6-8 mm except for specimens 1L and 1R. These results were excluded from the calculation of the mean empirical correction factor. For the length measurements, the difference was between 7-9 mm. The DIC strain results were reduced by the mean empirical correction factor, 7.70 mm to give the adjusted measured delamination sizes using the DIC strain contours. A summary of the measured delamination sizes for each specimen and the adjustment is shown in Table D-5 in Appendix D. A plot of the measured sizes of the delaminations using the adjusted DIC longitudinal strain results against the visually determined sizes of the delaminations is shown in Figure 5-11. The DIC measurement errors were based on the standard deviation of the differences in the visual measurement and the DIC measurement. The values can be seen in Table D-5 in Appendix D. The average difference in the visual and DIC measurements after subtracting the correction factor was
0.52 mm with a standard deviation of 2.51 mm. The errors in the visual measurement were based on the pixel error. As one pixel represented approximately 0.022 mm in the images, and the dimension measured was based on two points in the image, the error is ±0.044 mm.

![Figure 5-11: Comparison of measured delamination sizes from DIC strain results and the visually determined delamination sizes. The dotted line represents the ideal relationship](image)

As a basis for comparison, a more established NDT technique, pulse thermography, was also used to determine the size of the delaminations in these specimens. This technique was chosen due to the ease of obtaining results, its prevalence in industry and because it is like the DIC technique in the sense that it is also a full-field technique.

5.4 Pulse thermography

The output of a pulse thermography test consists of a series of thermal images. In this work, after the pulse from the xenon flash lamp, the camera recorded the IR emissions from the surface of the specimen at a rate of 50 Hz. The technique is described in chapter 3 (section 3.5). As described in literature (Sun, 2013), a defect at a certain depth, \( z \), can be resolved by considering the thermal image taken at time, \( t \) according to Equation 5.1.

\[
t = \frac{z^2}{\pi \alpha}
\]  

(5.1)

Here, \( \alpha \) is the thermal diffusivity of the material, taken to be constant. The effective thermal diffusivity of the material was determined using a Netzsch LFA 467 HyperFlash light flash apparatus (NETZSC, ...
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2017). The instrument is still in the process of validation at the NPL. Nevertheless, two 12.5 mm
diameter discs of 4 ply [(0/90)]_{2S} 5HS weave epoxy specimens with an approximate thickness of 1.1
mm were tested to obtain the thermal diffusivity value. These discs were coated with graphite prior
to the experiment to reduce the reflection of the surface of the discs. The result of this experiment is
shown in Figure 5-12. The two specimens tested have a slightly different value of thermal diffusivity,
approximately 1.5%, however the uncertainty of the measurement is stated as being approximately
4%, meaning this variation is to be expected. Based on these results, the value of $\alpha$ has been assumed
to be 0.196 mm$^2$ s$^{-1}$. It is important to note that this technique for determining the thermal diffusivity
of a material assumes the material is homogeneous and isotropic, which fibre reinforced polymers are
not. For this reason, the value used is an effective thermal diffusivity.

![Figure 5-12: Two sets of thermal diffusivity measurements of 5HS weave epoxy laminate](image)

As the defect depth in these specimens was known to be between the first and second ply at a depth
of approximately $z = 0.28$ mm, using equation 5.1, the time $t$ at which the pulse thermography should
show the results most clearly should be $t \approx 0.13$ s, i.e. between the 6$^{th}$ and 7$^{th}$, frame after the flash.
A number of different methods for determining the value of $t$ have been discussed in the literature
(Krankenhagen and Maierhofer, 2014; Sun, 2013), however these varied significantly and did not
correspond to the highest contrast thermogram. Instead of using these equations, to establish the
time after the thermal pulse excitation after which the delamination insert would show the highest
contrast in the heat amplitude compared with a no defect region, reference points were placed on a
specimen (3L). This specimen was selected as approximately 60% of the PTFE insert region contained
the de-bonded PTFE, while the remaining area was still bonded to the adjacent plies. The average heat
amplitude was extracted from three areas on the specimen for thirty seconds after the pulse as shown
in Figure 5-13a. Three reference areas were selected; away from the insert in the no defect region
(blue), in the bonded PTFE region (black) and in the debonded PTFE region (red). Care was taken to
ensure each reference point was placed away from other noticeable defects such as the stress-raiser
and visible voids. The extracted values of the heat amplitude are shown in Figure 5-13b. These values are unitless and are related to the wavelength of the infrared emissions from the surface. These data were extracted using Thermal Wave Imaging (TWI) software Echotherm v6, while the thermograms used in determining the sizes of the inserts and delaminations in this section were acquired and analysed using TWI software Mosaix v3.1. From these results the highest contrast between the defect region and no defect region occurs within the first 2-5 frames (0.04 – 0.10 s) after the flash. At this timeframe however, there was a lot of noise from the weave in the top layer. The clearest results occurred in the second peak in the difference between the de-bonded region and the no defect region, shown by the dashed red line in Figure 5-13b. The contrast is an absolute value established by subtracting the heat amplitude of the region of interest by the no-defect region. This peak occurred at approximately 0.5 s, i.e. 25 frames after the pulse with a contrast of 86 in the heat amplitude output. All analysis in this chapter was done on thermograms at this frame. While the contrast is higher from 0-0.12 s, the thermograms at this range were heavily affected by noise from the weave of the fabric in the top layer. A comparison of two thermograms taken from the same test at 0.08 s and 0.50 s after the pulse can be seen in Figure D-23 in Appendix D.

Figure 5-13: (a) The first derivative of heat amplitude with respect to time of three-point bend specimen 3L containing a PTFE/stress-raiser insert. Three reference regions highlighted; no defect region (blue), bonded PTFE region (black) and unbonded PTFE region (red). (b) Extracted heat amplitude averaged within the reference regions plotted against time and the contrast in the average heat amplitude in the PTFE regions and the no defect region plotted with dashed lines, red for the debonded PTFE region and black for the bonded PTFE region.
Chapter 5. Monitoring delaminations in PTFE/stress-raiser specimens

The Thermal Signal Reconstructed (TSR) results, discussed in chapter 3 (section 3.5) were used on both delamination inserts in each three-point bend specimens 1-3. Figure 5-14a shows the thermogram for specimen 3L with the borders of the bonded and de-bonded regions of the PTFE insert highlighted by dashed black lines. The grey scale values were extracted along the red dashed line, from which the dimension of the insert was measured as shown in Figure 5-14b. The borders of the separate regions are shown much more clearly in Figure 5-15 where the contrast was enhanced on image processing software ImageJ. The length and width of the PTFE inserts were measured using ImageJ as shown by the red dashed lines in Figure 5-15 as was done for the visual measurements described in the previous section. The dashed lines in these figures have been drawn based on data in the images, where changes in the grey scale indicate the boundary of the insert as well as the bonded and unbonded regions. The grey scale values varied on a specimen by specimen basis, however the outline of the insert is clearly visible. It is important to note that the data lines in which the measurements were taken were parallel to the specimen edges rather than the insert edges, as was done for the results in the previous section. In the few cases where the inserts were only partially de-bonded, the length of the de-bonded region was also measured in both the thermograms and from the visual images. The final sizes of the inserts and delaminations measured using this technique are shown in Figure 5-16 compared with the visually determined sizes for the same specimens. The errors in the measurement were based on the pixel errors. As before, the visual measurements have a pixel error of 0.022 mm. The pixel error on the thermograms is much higher due to the low resolution of the thermal camera. The length of one pixel in the thermogram is approximately 0.30 mm. The X and Y error bars in Figure 5-16 are ±0.044 mm and ±0.60 mm respectively due to the data lines starting and ending at two different points in the images.

Figure 5-14: (a) Pulse thermography TSR result of specimen 3L with the outline of PTFE insert, debonded region and stress-raiser highlighted by dashed lines. (b) Extracted grey scale values along the position of the red dashed line with the start and end of the insert region marked by the blue markers.
Figure 5-15: Pulse thermography TSR results of specimen 3L with enhanced contrast and the measured insert lengths along the X and Y axes with respect to the specimen edges. The red dashed lines indicate the measured dimension.

Figure 5-16: Comparison of measured delamination sizes from pulse thermography results and the visually determined delamination sizes. The dotted line represents the ideal relationship. (a) includes all inserts and delamination sizes measured, (b) only includes the measured PTFE inserts and not the debonded regions.

These results have less deviation than the DIC results in the previous section. This can be attributed to the clearer edges of the delaminations in the thermograms compared with the change in strains from the DIC contours. The method of measuring the delamination lengths from the thermograms was also much more like the method used to obtain the sizes from the high-resolution images which are used as the control in both of these experiments.

This method of determining the size of the delamination could not be used on specimens 0L and 0R, as the thermal response from the stress-raisers dominated the thermograms. These specimens were part of the coupon that was originally tested, having undergone over 100,000 cycles of three-point bending fatigue in an attempt to grow the delaminations further into the specimen. The other specimens only underwent 10,000 cycles of fatigue to grow the de-bonded PTFE delaminations. The thermograms of these specimens can be seen in Figure D-24 in Appendix D.

5.5 Passive lock-in thermography

Further to this work using Pulsed Thermography, discussed in the previous section, the use of passive thermography to monitor the inserts in these specimens as the de-bonding was occurring was investigated. This was done on specimens 0L and 0R as well as on a separate batch of specimens produced with the same type of inserts and stress-raisers.
A short investigation on the detection of the PTFE/stress-raiser delamination specimens was conducted as a proof of concept. Three-point bend specimens were tested in a different laboratory and a small modification was included in the manufacturing of the specimens to ensure the inserts did not shift during the manufacturing process described in chapter 3, section 3.2. The inserts were adhered to the underside of the top layer aligned with the cuts in the fabric using Pritt stick adhesive as was done on the tubular specimens. While this did not present a problem for the tubular specimens (see chapter 7) or the circular PTFE insert three-point bend specimen (see section 5.6), the PTFE inserts in these three-point bend specimens generally did not de-bond from the adjacent ply during fatigue loading. One insert in a three-point bend specimen was an exception, the phase results of which are shown in Figure 5-17. The bonded parts of the PTFE insert were not detectable using the phase results from this technique. The un-bonded regions of the inserts are shown very clearly with a low phase shift compared with the no defect regions. These three-point bending tests were carried out with the inserts closer to the compression surface as described in chapter 3 (section 3.3.2). Specimen 0R could not be analysed due to a glare on the surface of the specimen. This can be seen in Figure D-25 in Appendix D.

Figure 5-17: In test image and passive lock-in thermography results of three-point bend specimen with PTFE/stress-raiser type delaminations. (a) after initial growth of delamination and (b) after subsequent delamination growth
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5.6 Circular PTFE defects and stress-raisers

Three-point bend specimens were created with circular PTFE inserts and hole punched stress-raisers in the surface layer of the fabric (a similar approach was used for the tubular specimens, see chapter 7). The bend specimens were manufactured using the same technique outlined in Chapter 3 (section 3.2.2). As with the specimens used in section 5.5, Pritt stick adhesive was used to adhere the specimens to the top ply containing the stress-raiser, ensuring the position of the stress-raiser remains at the centre of the PTFE insert. The diameters of the stress-raisers were chosen to have a similar ratio to the circular PTFE insert as used in the tubular specimen.

5.6.1 Fatigue damage growth and visual inspection

The delaminations produced by this type of specimen under three-point bending fatigue did not grow the delaminations across the PTFE inserts as with the specimens investigated in sections 5.3 and 5.4. These types of delamination had a directional property, growing from the stress-raiser towards the edges of the specimens nearest the loading roller and support rollers as shown in Figure 5-19. In both cases, the growth of the delaminations did not grow throughout the PTFE insert, leaving some regions of PTFE still bonded to adjacent plies. As these delaminations did not have a uniform edge, the length of the delamination after 10,000 cycles of three-point bending fatigue was determined from the data line running through the midpoint of the inserts rather than from a data line running along the mid-
width of the coupon. The shape of the delamination made it difficult to establish the length of the defect that would be shown in the DIC. The outer dimensions in Figure 5-19 are the measured insert lengths, while the inner dimensions are the measured lengths of the delaminated regions. Slight variations in the position of the data line resulted in different delamination lengths as shown in Figure 5-20, where the defect length was measured to be 19.14 mm along the mid plane, however changing the position of the data line by 2.5 mm to the edge of the stress-raiser resulted in a measurement of 16.23 mm. The type of delamination produced by this specimen is more like a delamination that would occur in the in-service life of a composite component, with uneven edges.

![Figure 5-19: Image of three-point bend specimen containing circular PTFE inserts and hole punch stress-raisers; (a) Left sided insert with an 8 mm diameter stress-raiser and (b) Right sided insert with a 5 mm diameter stress-raiser](image)

![Figure 5-20: Greyscale image of the right sided circular PTFE insert with enhanced contrast showing the lengths of the delaminations grown using fatigue loading](image)
5.6.2 Digital Image Correlation

The DIC set-up for this specimen was identical as for the specimens containing the square PTFE insert delaminations described earlier in this chapter. The longitudinal strain contours are shown in Figure 5-21a. The mid points of the highly strained circular regions were assumed to be the mid points of the stress-raisers in the positioning of the longitudinal data line, the plot of which is shown in Figure 5-21b with the measurements of the lengths of the delaminations from these plots using the technique discussed in section 5.3. The data lines for the widths were positioned such that they coincided with the largest low strain areas (purple in Figure 5-21a) adjacent to the stress-raisers. Figure 5-21c shows the extracted data and the measurements of the delaminations along these data lines.

\[(a)\]

Figure 5-21: (a) DIC longitudinal strain contour results of three-point bend specimen containing circular PTFE inserts and stress-raisers with the data lines indicated by the black dashed lines. (b) Plot of data extracted from longitudinal data line and (c) plots extracted from transverse data lines.

Subtracting the correction factor of 7.60 mm determined from the previous set of experiments, the measured length of the two delaminations were 21.63 mm and 16.17 mm for the left and right side of the coupon, respectively. The width measurements are 14.16 mm and 5.10 mm respectively. A
comparison of these DIC delamination size measurements with the visually determined delamination sizes is shown in Figure 5-22. Due to the variation in the visual measurements of the irregularly shaped delaminations along what was thought to be the same data path as the DIC measurements, the errors were calculated using the standard deviation of the measurements based on a mean value. This mean value was based on measurements from three data lines as shown in Figure 5-20. As the error in the visual measurements was based on the approximation of the DIC paths, the DIC measurement errors were based on the standard deviation of the differences in the visual measurement and the DIC measurement, as was done in section 5.3.

![Figure 5-22: Comparison of measured delamination sizes from DIC strain results and the visually determined delamination sizes. The dotted line represents the ideal relationship](image)

5.6.3 Pulse thermography

Pulse thermography was conducted on the same specimen containing the circular PTFE inserts and stress-raisers. As these inserts were at the same depth as the square PTFE insert specimens, thermal images analysed were acquired 0.5 s after the pulse, as was determined in section 5.4. Figure 5-23 shows these thermograms for the left-side and right-side specimens within the coupon. Comparisons of the measured dimensions were investigated as in the previous section. The results are shown in Figure 5-24, containing both the measurements of the PTFE insert and of the de-bonded region. The specimen in Figure 5-23a had a dip in the surface on the right side of the delamination obscuring the edge of the delamination, this measurement was omitted from the results. From these results it is apparent that all the length measurements are overestimated using pulse thermography, and all the width measurements are underestimated. This is probably due to a distortion in the acquired image, as shown by the curved specimen edges in the thermograms in Figure 5-23.

The thermograms in Figure 5-23 detects the PTFE insert, the de-bonded region referred to in this chapter as delaminations as well as the presence of the Pritt stick adhesive used to adhere the PTFE
insert to the fabric. The adhesive was applied to the PTFE insert which was moved around on the fabric to ensure it was located directly under the stress-raiser. This resulting pattern is shown in the thermograms as lighter areas as the adhesive affects the thermal conduction of the pulse through the thickness of the specimen.

![Image](image.jpg)

**Figure 5-23:** Pulse thermography TSR result of the three-point bend specimen containing circular PTFE inserts and stress-raisers. (a) Left sided insert with an 8 mm diameter stress-raiser and (b) right sided insert with a 5 mm diameter stress-raiser. The results on the left have been annotated to show the region effected by the Pritt stick adhesive and the insert.

![Graph](graph.png)

**Figure 5-24:** Comparison of measured delamination sizes from pulse thermography results and the visually determined delamination sizes. The dotted line represents the ideal relationship.

### 5.7 Concluding remarks

The three-point bend specimens containing a single sheet of PTFE and a stress-raiser in the form of cut fabric were non-destructively tested using DIC and pulse thermography. Passive lock-in thermography was also briefly investigated as a proof of concept. It was observed that including a PTFE insert does not on its own simulate a delamination, as the insert bonded with the adjacent plies
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during the curing of the laminate. While this bond transferred load, it had a weak interface that could be debonded with fatigue loading.

By extracting data lines along the specimen, the size of the delaminations were measured using DIC results by the characteristic plateaux in the longitudinal strains as discovered in the previous chapter. Two approaches were investigated for analysing this data. One approach measured the delamination by observing the distance between the two points at which the strain profile differed from a no defect specimen under the same loading conditions. This method tended to overpredict the dimension being measured by an average of 7.60 mm. After applying a correction factor, most of measurements taken were within 2 mm of the visually determined size measurement of the same defect.

Pulse thermography was investigated as a more established full-field NDT technique. The same type of measurements were made after first determining the frame after the thermal pulse in which the delaminated regions would present the highest contrast in the thermograms with the no defect part of the specimens. This technique proved to be able to detect the both the bonded and de-bonded regions of the PTFE insert. The results show it is more reliable in the monitoring of these defects than using DIC. The use of passive lock-in thermography was shown to be a valid technique in detecting only the de-bonded regions of the PTFE. This was only briefly investigated, but as a proof of concept the technique demonstrated that the de-bonded regions have a lower phase shift than the 180° out a phase non-damaged zones.

While the method used in this chapter to introduce a delamination into the composite panel proved to be successful to a certain extent, the “designer” delaminations created only simulated the effects of a delamination in the regions of the insert. Further growth of the fully embedded delaminations within the specimens proved unsuccessful. As these delaminations are between the PTFE insert and an adjacent ply, the simulated delamination is not fully representative of a real delamination. As such, the milled-slot specimens were created to generate “natural” delaminations and all the interactions between the delaminated surfaces, the results of which are discussed in chapter 6.

An investigation into the growth of this de-bond delamination in circular PTFE inserts with circular stress-raisers was investigated in this chapter. The growth of the de-bond delamination during the three-point bend fatiguing of the specimens within the interface between the PTFE insert and the adjacent ply had a directional property to it, growing in the direction of the loading and support rollers. This prompted the investigation into predicting the directional growth of delaminations in a structural element that could be introduced to different types of loading conditions. This resulted in the design of the tubular specimens to be loaded at different ratios of tension and torsion. The results of this investigation are presented in chapter 7.
6 Monitoring delaminations in milled-slot specimens

6.1 Introduction

In this chapter, the results of experimental testing and FEA of milled-slot specimens are presented. These specimens were designed to generate natural delaminations without the need for inserts. The milled-slot specimens are fatigued to grow delaminations as described in chapter 3 (section 3.3.1). Specimens containing milled slots were loaded in quasi-static tension to establish the safe testing loads for the specimens. Failure was found to initiate above 12 kN on one of the three tested specimens, so testing was limited to a maximum of 8 kN, approximately 66.7% of the failure initiation load for the specimens. The load-displacement curves can be seen in Figure E-26 in Appendix E.

The results of monitoring delamination lengths between each interval of fatigue cycling of the milled-slot specimens are presented, comparing the delamination lengths as determined by visual observations with the experimentally determined delamination lengths using 3D DIC, lock-in thermography (LIT) and pulse thermography (PT), respectively. The specimens were monitored for each interval of fatigue testing. All three techniques were affected by the edges of the specimens; the thermographic techniques due to thermal energy losses and DIC due to the size of the subsets and the integration point positions on the surface as described in chapter 3 (section 3.4). To minimize the variations in the delamination fronts in the milled-slot specimens, when determining the lengths of the delaminations, the data were analysed only along the mid-line of the specimen.

6.2 Controlled natural delamination growth

The growth of the delaminations in the milled-slot specimens though tension-tension fatigue loading (8 kN, R = 0.1, 5 Hz) was monitored visually by taking images of the specimens using a Canon 1300D digital single-lens reflex (DSLR) camera with a 60 mm Canon EF-S macro lens. As the specimens were transparent, the delaminations appeared in the images as lighter areas. The change in the opacity of the specimens over the delaminated region occurs as the delamination damage mechanism changes the refractive index of the material, meaning areas in which there was damage had a higher opacity. Figure 6-1a shows images taken of one of the specimens after 100, 1000 and 3000 fatigue cycles, where the delaminations have grown from approximately 1.7 mm to 4.2 mm. Figure 6-1b shows a plot of the delamination length along the mid-line of the specimen, measured from the edge of the milled-slot, as a function of the number of fatigue cycles. After an initial period of rapid growth over about
the first 500 cycles, the delaminations then grew at an approximately linear rate of about 0.8 µm / cycle. It is not clear why the delaminations in coupon 4 (i.e. 4A and 4B) were larger than the other specimens. This is possibly due to the depth of the milled slot being closer to the interface of the plies than for the other three specimens. Further investigation is required but for the work reported here (which is solely concerned with the NDT techniques), different delamination growth rates are not a concern.

![Figure 6-1: (a) Digital images of a milled-slot specimen after different numbers of fatigue cycles. These images show the full width and length of specimen 1 (20 mm wide), showing delaminations A and B on either side of the milled slot; (b) Delamination lengths determined visually along the mid-line of the milled-slot specimens as a function of the number of fatigue cycles.](image)

6.3 Finite element analysis

As with the other chapters in which DIC was used, FEA was undertaken to compare the theoretical surface strains with the experimentally determined surface strains. The general outline of the modelling and the material properties used has been detailed in chapter 3 (section 3.9). The models created used C3D8 eight node linear brick elements.

6.3.1 Geometry and boundary conditions

As these specimens were loaded in tension, only the gauge area of the specimens was modelled, and the boundary conditions and loadings were defined by applying these on the end faces. Figure 6-2a shows the area where the displacement boundary condition y=0 is applied. The load is applied on a single node tied to the nodes on the opposite surface, shown in Figure 6-2b.

All of the models created for these specimens were made in two parts, separated by the interface of the layer in which the delamination was to be modelled, i.e. the top two layers are modelled as one
part, and the remaining 14 layers as another. These two parts are joined by tie constraint. Any delaminated regions being modelled were not tied together, meaning no load was transferred between the regions where the delaminations were present.

![Figure 6.2](image1.png)

**Figure 6-2:** FE model of milled-slot specimen where in (a) the red area is where the boundary condition is defined and (b) the nodes over which the applied load is distributed.

The models were created on a specimen by specimen basis where each measured delamination length was defined using a partition. In the example shown in Figure 6-3, only the first iteration of delamination growth from fatigue is modelled. The highlighted red areas are the regions that are tied. The multiple areas represent the different lengths of delamination that were modelled using this single model for one of the specimens.

![Figure 6.3](image2.png)

**Figure 6-3:** FE model of the milled-slot specimen where the highlighted red regions indicate the areas where a ply is tie constrained to the adjacent ply from: (a) a top view and (b) a side view
6.3.2 Mesh assessment

As in the previous results chapters, the meshing of the FE models was investigated to ensure the results had converged with respect to mesh density. The reference node was placed on the surface of the model at the edge above the delamination front. This position was selected as the model was partitioned to define the delamination length: the partition forces the node to stay in the same position regardless of the mesh densities defined. The meshed model and the position of the reference node used in the mesh assessment study is shown in Figure 6-4. The FE model was run with a number of different mesh densities, from which the Von-Mises stress and total displacement at the reference node were recorded. These values were plotted against the total number of elements in the model to produce the charts shown in Figure 6-5. While the stresses converge after approximately 150,000 elements, the displacements seem to converge for models with far fewer elements. All FE models used a minimum of 150,000 elements in the work in this chapter, giving the smallest element size in the mesh refined regions as 0.5 x 0.1 x 0.1 mm.

\[\text{Figure 6-4: Mesh of a milled-slot specimen FE model with the position of the reference node used in the mesh assessment indicated}\]

\[\text{Figure 6-5: Results taken from the reference node in the mesh assessment study, where the results are plotted against the number of elements used in the model. The results investigated were (a) the Von-Mises Stress and (b) the overall displacement of the node}\]
Initially the models were created with each ply being one element thick, however this resulted in a singularity that affected the longitudinal surface strain adjacent to the delamination edge. Figure 6-6 shows the surface strain from two FE models modelling a milled-slot specimen with a delamination length of 2 mm. The two models are identical apart from the number of elements used to model the ply thicknesses of the top two plies above the delamination. In one case, only one element was used (red), and in the other three elements (black) was used. While the results were considered to have converged due to the monitoring of the stresses and displacements of the reference node (located above the delamination edge), the presence of the singularity at the edge of the delaminated region between the second and third ply had a large influence on the surface strains with only two elements separating it from the surface. All FE models of the milled-slot specimens contain three elements per ply thickness for the plies above the delaminated region.

![Figure 6-6: Longitudinal strain FEA results on the surface near the delamination for two identical models where the only difference is the number of elements in the through-thickness direction](image)

6.4 Digital Image Correlation

DIC requires the specimens to be mechanically loaded to measure the resultant surface strains. These surface strains have been shown to provide an indication of the position and size of delaminations in the previous chapters on fully embedded delaminations in three-point bending (see Chapters 4 and 5). The milled-slot specimens were created to enable the growth of delaminations without the use of inserts. This was done at the expense of no longer observing fully embedded delaminations, but
delaminations with three free edges. As such the determination of delamination sizes devolved to just determining the length of the delaminations starting from the edge of the milled slot.

6.4.1 Results and comparisons with FEA

Four specimens containing two growing delaminations each (on either side of the milled-slot) were loaded for DIC measurements. Figure 6-7 shows the DIC longitudinal strain results (i.e. parallel to the loading direction) for milled-slot specimen 1; data for delamination 1A, for example, have been extracted along the dotted line. It is important to note that the DIC results within about 1 mm of the edge of the milled-slot were omitted due to high errors caused by the subsets of speckles used in post-processing the DIC results picking up data from the recessed surface of the milled-slot.

100 – 1.7 mm  
1000 – 3.0 mm  
3000 – 4.2 mm

Figure 6-7: DIC longitudinal strain results of specimen 1 at different delamination lengths. The data line extracted for delamination 1A is shown as a dotted black line for delamination lengths of 1.7 mm, 3.0 mm and 4.2 mm.

For a complete delamination, in the sense that there is no fibre bridging between the faces of the delaminated material, the regions on the surface of the specimen above the delamination should show zero strain, as no load would be transferred to the material above the delamination. This is demonstrated in the FEA results; Figure 6-8a shows the surface strain of one side of the test specimen, and Figure 6-8b shows a screenshot of the FE model. The flap of material above the delamination undergoes some bending which physically separates the two delaminated surfaces, and there is a minimum point at the trough of compressive surface strain which occurs very close to the modelled delamination length. However, for the delamination grown in fatigue between the two plies of the woven fabric composite, bridging occurs (this would occur for quasi-static loading as well). As a consequence, some longitudinal strain is still carried by the flap. A comparison of the strain derived from the DIC data and the FE model is shown in Figure 6-8c.
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Figure 6-8: (a) FE model surface strains over a schematic of a specimen. (b) FE image of bending surface, with the displacements magnified by 20. (c) Comparison of the FE model surface strains, for a delamination length of 3.6 mm, assuming no fibre bridging, and the actual strains as measured using the DIC.

To measure the length of the delaminations using the DIC measurements, a calibration was made. It was found empirically that there is a reasonably good correlation between the minimum in the FE predicted strain profile and the visually measured delamination length at a DIC longitudinal strain of $\varepsilon = 0.0015$. This is shown by the dotted line in Figure 6-9b, and this close correlation is illustrated in...
Figure 6-8c. Consequently, for all delaminations, the DIC-measured delamination lengths were found using the y-position distances corresponding to a strain of $\varepsilon = 0.0015$, when the specimens were loaded to 8 kN. A plot of the DIC-measured delamination lengths as a function of the delamination lengths measured from photographs of the transparent laminates is shown in Figure 6-10; there is reasonable agreement between the two measurements.

By modelling the bridging fibres of the delaminations it would be possible to understand how the strains along the surface change at the delamination front, such that that the empirical method used for extracting the delamination lengths from the DIC strain distribution can be avoided. In an effort to do so, the differences in the FE and the DIC curves, most importantly the lack of the dip in strains adjacent to the delamination edge, was investigated further.

The dip in strains was ruled out as an artefact from the FE models by increasing the mesh density in the through thickness direction as discussed in section 6.3.2. This characteristic dip has a length of approximately 1 mm in the FE models with the magnitude of the trough approximately being -0.001 strain and located 0.2 mm behind the delamination front (i.e. further from the milled slot). The lack of this dip in the DIC results was considered to be either, or a combination of, the lack of resolution in the DIC technique and the effects of fibre bridging between the two delaminated surfaces not being taken into account in the FEA.
6.4.2 Micro-DIC investigation of delamination edge

To further investigate if this was an issue with the resolution of the technique, a higher resolution DIC test was undertaken using the micro-DIC system described in chapter 3 (section 3.4). The field of view was reduced from including the whole surface of the milled-slot specimen to approximately 6 x 6 mm focused on the area over which the delamination edges were known to be present from visual observations. As the micro-DIC was a much higher resolution technique, the speckles applied to the surface had to be made finer than for the regular DIC. Multiple techniques were trialled with varying success, but the technique using powder deposition on the surface of the specimen see chapter 3 (section 3.4) was the one used. Even so, only the lowest magnification of the equipment was used, and the subsets had to be increased in size to accommodate the new speckles and to reduce noise in the data. For these results a subset size of 55 x 55 pixels was used with a step size of 7 pixels and a strain filter of 15. Numerous trials did not provide evidence that the lack of the characteristic dip in strains in the DIC results was due to a lack of resolution. Figure 6-11 shows the micro DIC results focused on the delamination fronts for two slightly different delamination lengths.

![Figure 6-11: Micro-DIC results of milled-slot specimens over the surface where the delamination edge is present 4.0 mm and 4.1 mm away from the edge of the milled slot.](image)

Due to the added complexity of the micro-DIC system, including the relatively high translational movement for a given magnification, the fine speckling and difficulties in the calibration of the equipment, there is limited confidence in these results. There is a high amount of noise in the data which is not diminished significantly with an increase in subset size, step size and strain filter size. This is indicative of an issue with the set-up of the experiment itself. The level of user support available for the micro-DIC kit was minimal compared with the regular DIC, and for a technique with added variables to consider (such as the distortion of images due to the series of mirrors and lenses) it was
difficult to improve the results without much more significant time resources allocated to the development of the operational procedure. Regardless, the general trend of a slope upwards without much evidence of a dip in strains with a trough magnitude of -0.001 strain was found.

6.4.3 Milled-slot specimens containing PTFE inserts

Due to the lack of evidence for the dip in strains in the milled-slot specimens, further investigations were made into the mechanics of the milled-slot specimen by creating specimens containing a ‘perfect’ delamination without the complications of fibre bridging. This was achieved by introducing a strip of PTFE running through the width of the specimens between the 2nd and 3rd plies during the manufacturing of the laminates. These specimens were loaded in quasi-static tension just as the other milled-slot specimens were, and monitored with DIC in an identical manner, using the same apparatus, camera distances and sizes of extension rings. Following these tests, the longitudinal strain data were extracted along the mid-width starting from the edge of the milled-slot. This strain was recorded at 8 kN and plotted along with the respective FE models of the delamination insert lengths in Figure 6-12.

In this figure four different delaminations were monitored where the length of the PTFE insert is assumed to be the delamination length and was measured visually. The DIC results are plotted with solid lines, while the FE models for each specimen are plotted with dashed lines. From these results it can be concluded that the lack of the characteristic dip in strains must be due to fibre bridging (absent when using the PTFE insert).

![Figure 6-12: Longitudinal strain profiles along the mid-width of milled-slot specimens containing PTFE inserts to simulate the presence of a delamination between the 2nd and 3rd ply from the surface being monitored. The applied load is approximately 8 kN. Solid lines are DIC results, dashed lines are results from the FE models of the specimens.](image-url)
There are three main differences in the results from the FE models and the DIC result it simulated. Firstly, towards the edge of the milled slot prior to the trough in strains indicating the edge of the delamination (labelled as the delaminated region in Figure 6-13) the FE predicted no significant strain increase leading up to the delamination. This was not the case for the DIC results, as there is a noticeable strain in this region indicating that load was being transferred to the delaminated region. This load was most likely due to the acrylic paint used for the speckling of the specimens connecting the recessed part of the specimen (inside of the milled slot) to the edge of the milled slot. This thin connection of paint was enough to transfer some load to the delaminated region, causing resistance in the opening of the flap, creating a small tension on the surface. This is supported by comparing the FE models with the DIC results at an applied load of 3 kN, shown further ahead in this section, where the effects of the closing force being applied on the delaminated flap from the acrylic paint is more apparent.

The second difference is the position of the dip in strains and the shifts in the slopes of the curve between the dip and the levelled-out portion of the curve (labelled as the dip in strain and slope regions in Figure 6-13). The magnitude of the dips for all four specimens shown are overestimated by the FE models. However, this is most probably related to the load being transferred by the painted surface. In all cases except the 6.66 mm long delamination, the position of the dip in strains and the following slopes in the slope region is shifted to the right when comparing the DIC and FEA results, indicating that the delamination is larger than the modelled delamination. As the delamination in the specimens is defined by the size of the PTFE insert, this indicated that the delamination had grown during the quasi-static loading from 0 – 8 kN as it was being recorded by DIC. After two consecutive
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DIC tests, the speckles on the specimens were removed using methanol and imaged. These images show natural delamination growth, having developed from the edge of the PTFE insert (see Figure 6-14). This is supported by comparing the result with an applied load of 3 kN where the difference in the shifts of the slope regions were diminished (shown further ahead in this section). The final difference is the last strain value over the non-damaged part of the specimen. The finite element models underestimate this with the applied load at 8 kN, however it is overestimated with the applied load at 3 kN.

Figure 6-14: PTFE milled-slot specimen after two loadings from 0 – 8 kN for DIC measurements.

The inclusion of the PTFE inserts resulted in an interesting observation. The secondary bond between the PTFE and one of the adjacent plies needed to be broken prior to testing, as otherwise the load was transferred through the bond at low loads. This phenomenon suggests that simply including a single piece of PTFE to simulate the presence of a delamination is not something that simulates the presence of a delamination for the material system used under mechanical loads. This supports the same observation made for the three-point bend specimens containing the PTFE insert and the stress-raiser, see chapter 4. To avoid the load transfer through the PTFE insert, the secondary bond between the PTFE and an adjacent ply was broken by carefully inserting a razor into the slot and gently prying until the opacity of the material above the insert changed as shown in Figure 6-15. This reduction in the transparency of the material indicates that the bond has broken. This razor separation has been used on the specimens discussed above, the results of which are shown in Figure 6-12.

Figure 6-15: A milled-slot specimen (a) before and (b) after releasing the secondary bond between the PTFE insert and an adjacent ply.
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Two milled-slot specimens with PTFE inserts were tested without releasing the weak bond between the PTFE and the adjacent plies. Figure 6-16a shows one of the delaminations in one of these specimens, demonstrating the effect of the bond between the PTFE and adjacent plies. Comparing it with a similarly sized PTFE insert milled-slot specimen shown in Figure 6-16b (where separation had been induced), it is clear that load is transferred through the bond to the supposedly delaminated region unless the bond is broken. With loads 3 kN and under, the bond transfers enough load that the characteristic dip in strains is no longer noticeable. This effect diminishes at higher loads however as the secondary bond breaks under the testing loads.

To better understand the growth of the “natural” delaminations, one of the PTFE milled-slot specimens was fatigued to grow the natural delaminations from the edge of the PTFE insert. Figure 6-17 shows the longitudinal DIC strains of a milled-slot specimen containing a PTFE insert of length 3.8 mm starting from the edge of the milled slot. It is important to remember that the initial results for just the 3.8 mm PTFE delamination is affected by further growth of the natural delamination during the quasi-static loading in which the DIC data are obtained.
The further growth of the “natural” delamination shows that as the delamination grows, the dip in strains stays at the edge of the insert and the trough reduces in magnitude but is wider. A change in slope is also identifiable. From these results it can be seen that the size of the delamination can be estimated for these specimens by the change in slope rather than by the shifting of the slope.

6.4.4 Increased depth of milled slot analysis

After the analysis of all the milled-slot specimens with the slot depth being two plies, approximately 0.56 mm, an investigation into monitoring the delamination growth in specimens containing the milled slot depth of four plies, i.e. approximately 1.12 mm, was conducted using DIC. Growth of these delaminations was only monitored using visual images and DIC. No analysis was conducted with any other NDT technique. Other than in this subsection, the delamination depth was approximately 0.56 mm.

This work was carried out on three specimens, each containing two delaminations. The specimens were fatigued at 6.86 kN with an R value of 0.1 at 5 Hz and monitored at intervals using DIC when the specimen was quasi-statically loaded to 6.86 kN. The visually measured delamination sizes along the mid-width of the specimens at each interval of fatigue loading are shown in Figure E-27 in Appendix E. Similarly, the FEA and DIC results of specimen 5A are shown in Figure E-28 and Figure E-29 in Appendix E. To better interpret this data, Figure 6-18 shows the longitudinal strains plotted against the Y distance from the edge of the milled slot of one of the specimens at different stages in the fatigue loading. The visually measured delamination lengths along the mid-width of the specimens for each of these curves are shown by the red markers.
Figure 6-18: Longitudinal strain contours along the mid-width of milled-slot specimen 5A with a deep milled slot at different stages in the fatigue loading. The red markers indicate the visually measured delamination sizes at each curve.

Based on the results from Figure 6-18, the strain used as an empirical fit for the deep milled-slot specimen was 0.00075. The corresponding Y distance from the edge of the milled slot at a strain value of 0.00075 was extracted for each specimen at each interval of fatigue loading. This is plotted against the visually determined delamination sizes in Figure 6-19. As with the results for the specimens with the milled slot being two plies deep in Figure 6-10 in section 6.4.1, there is a good correlation between these results. In these results, there are two major outliers from the trend, both from the DIC measurements of specimen 7B. By looking at the longitudinal strain Vs. Y position plot, the reason for the two outliers is due to distribution of shear along the delaminated Y position transferring load, resulting in a non-uniform slope region. This is shown in Figure E-30 in Appendix E.

Figure 6-19: A comparison of the actual delamination length in the deep milled-slot specimens measured from visual observations with the delamination lengths determined from the DIC results. The dashed line indicates the ideal relationship.
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The shifts in the slope regions in Figure 6-18 are relatively uniform. As the slope region of the longitudinal strain vs. Y position plots are more uniform above a strain of 0.001, to better quantify the delamination growth monitoring capabilities of DIC on these specimens, the Y position at a strain of 0.0015 was extracted from these data and the change in delamination size between consecutive DIC readings is plotted against the change in delamination size measured visually as shown in Figure 6-21. However, this amplifies the errors as the error is cumulative.

![Figure 6-20](image)

**Figure 6-20**: A comparison of the change in delamination length in the deep milled-slot specimens measured from visual observations with the change in delamination lengths determined from the DIC results. The dashed line indicates the ideal relationship.

### 6.5 Lock-in Thermography

Throughout the growth of the delaminations in the milled-slot specimens described in section 6.2, the delamination sizes were monitored using lock-in thermography (LIT). Lock-in thermography produces two main types of outputs; amplitude and phase images as discussed in chapter 3 (section 3.6). In this work, the phase images have been used because the phase lag caused by the delaminations in the thermal response indicates the location and size of the delaminations. Figure 6-21a shows the grey-scale phase image of one of the specimens with a delamination length of 4.2 mm. In order to determine the delamination length, the grey-scale values were extracted along the mid-line of the specimen, starting from the edge of the milled slot; in Figure 6-21b, the beginning of the delamination, i.e. the edge of the milled slot, is indicated by the blue line. The grey-scale value is initially high close to the milled slot and decays to a mean value after about 11 pixels, which corresponds to a physical distance of approximately 4.95 mm. The length over which the grey-scale values decay to a mean value away from the delamination has been found to be a good measure of the length of the delamination. Analysing all of the LIT results for all of the delamination lengths in this way (see Figure
6-22) shows that there is a reasonable correlation between the LIT-measured delamination length and the lengths measured from the photographs.

The lock-in thermography technique required multiple runs of the testing at different frequencies to detect damage at different depths. Once a broad range of frequencies had been analysed in moderate steps (in this case steps of 0.1 Hz), the results with suspected delaminations need to be re-analysed at smaller frequency steps; 0.02 Hz, followed by even finer steps of 0.002 Hz to determine the size of the delamination. This was a lengthy process as each test lasted approximately one minute, and between each test the specimens had to be cooled back to room temperature. As the approximate depth of the defects was known, for monitoring the growth of a delamination, the frequency once determined, was kept within a ±0.01 Hz range. The phase result which demonstrated the highest contrast of the delaminated region was used to determine the delamination length.

Figure 6-21: (a) LIT results of 4.5 mm long delamination in a milled-slot specimen. Data extracted along the dotted red line i.e. the mid-line of the coupon. (b) Decay of the grey-scale values to the mean away from the delamination.
6.6 Pulse thermography

Pulse thermography was used to determine the delamination sizes at each interval of the delamination growth through fatigue. The output of a pulse thermography test consists of a series of thermal images. As done in chapter 5, a value of $t = 2.44$ s has been used in this work based on an investigation into the differences of the apparent temperature over a delaminated region in a damaged specimen and a non-damaged region. Figure 6-23 shows the results of this investigation for a milled-slot specimen containing a PTFE insert that simulated the presence of a delamination. From Figure 6-23a it can be seen that the temperature contrast was highest between one and three seconds after the pulse. When considering the rate of change of heat amplitude with respect to time (Figure 6-23b), the highest contrast between the damaged and non-damaged zone was found to occur at 0.8 seconds and over a range between 8 and 15 seconds. The second derivative of heat amplitude with respect to time however displayed the peak being at approximately 2.4 seconds.
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Figure 6.23: Temperature-time curve of a milled-slot specimen containing a PTFE insert to simulate a delamination at two reference points: over the PTFE insert delamination (red) and a non-damaged region (blue). The X-axis remains time for all three curves, the Y-axis is as follows: (a) Raw temperature data with noise reduction, (b) first derivative of heat amplitude with respect to time (1D), and (c) second derivative of heat amplitude with respect to time (2D). (d) displays the 2D thermogram of the specimen with the reference points indicated as well as the edge of the PTFE insert (yellow).

In pulse thermography, complications arise because of specimen edges where extra thermal losses occur. Due to the proximity of the delaminations to the edges of the slot in the specimen, the delaminations were difficult to resolve. However, using the second derivative of the heat amplitude with respect to time increased the contrast when comparing non-damaged and damaged regions. Even so, the milled-slot specimens in which the delaminations were grown through fatigue (without the PTFE insert) did need to be compared with a non-damaged specimen to detect the presence of
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the delaminations. Figure 6-24 shows two thermograms (second derivative of heat amplitude with respect to time) of the same milled-slot specimen, one without any damage grown, and one after fatiguing the specimen until the delaminations reached an average length of approximately 6 mm. From the thermal image of the non-damaged specimen (Figure 6-24a) the effects of the milled slot edges on the surface temperature is apparent. This is also shown for the damaged specimen (Figure 6-24b), however the presence of the delamination is dominated by the effects of the milled slot.

![Figure 6-24: Second derivative of heat amplitude with respect to time PT results at t = 2.44 of a milled-slot specimen (a) prior to any induced damage and (b) after fatigue testing growing delaminations to an average length of 6.1 mm and 5.8 mm above and below the milled slot respectively](image)

Having both the results of the specimens prior to damage and at each stage of delamination growth, further improvement was found by subtracting the second derivative image of the undamaged specimen from the second derivative image for the damaged specimen; an example of this subtraction is shown in Figure 6-25a. By extracting a data line starting from the edge of the milled slot, the length of the delamination can be determined as shown in Figure 6-25b, using a similar procedure to that described for LIT above. Using this approach, the results for all the delaminations considered in this work are shown in Figure 6-26. In a small number of cases, the delaminations could not be resolved using the technique described above and have been omitted from the figure.
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Figure 6-25: (a) PT results of 4.2 mm long delamination in a milled-slot specimen and the post processing done to highlight damage. Data extracted from dotted red line. (b) Results from the data line determining the length of the delamination as measured from PT.

Figure 6-26: A comparison of the actual delamination length in the milled-slot specimens measured from visual observations with the delamination lengths determined from the PT results. The dashed line indicates the ideal relationship.
6.7 Concluding remarks

The three NDT techniques considered, i.e. DIC, LIT and PT, demonstrated the ability to measure the length of growing delaminations in milled-slot specimens. For DIC, an empirical fit (required as a consequence of bridging fibres in the milled-slot delamination), enabled a reasonably good correlation to be made between the measured delamination length and the actual length. An investigation into the differences in the longitudinal strain contours for the experimental specimens and the FE models was conducted. No evidence of the characteristic dip in strains associated with the position of the delamination front was found experimentally for the milled-slot specimens. The presence of the dip in strains was shown not to be an artefact of the FE model by the creation of the milled-slot specimen containing a strip of PTFE. These specimens demonstrated that the dip in strains exist at the edge of the PTFE simulated delamination. Further growth of this delamination through fatigue loading resulted in observations of changes in the strain profile, matching the same type of changes the original milled-slot specimen; shifts in the slope region but not the position of the trough.

Both thermography techniques were not affected to the same extent by the presence of fibre-bridging and showed reasonable correlations between the thermography-measured delamination lengths and the visually observed (i.e. photographed) delaminations, with LIT showing less scatter in the results than PT. However, it is important to note that there are difficulties when measuring delamination lengths close to the edges of the specimen using these techniques. For the milled-slot specimens, the DIC results showed the least amount of scatter of the three techniques, showing that for specimens with edges, DIC is a more accurate technique in determining the delamination sizes when monitoring delamination growth.

PT required the analysis of a specimen with a delamination at a known depth from the surface being monitored. This technique required the least amount of setting up and the results were obtained relatively quickly, however this technique also required the most post processing of the data in order to determine delamination sizes. For the milled-slot specimens containing edges which interact with the thermal absorption and emissions, overwhelming the reduced conduction from presence of a defect, it proved difficult to determine the delamination sizes. For specimens such as these, a pristine specimen needs to be investigated prior to one with damage to subtract the effects of the edges.

Doubling the depth of the delaminations in these specimens had an effect on the longitudinal strain vs. position from the edge of the milled slot plots. The magnitude of the slope region was diminished due to the lower testing loads, and the effects of fibre bridging were more pronounced in the delaminated regions of some specimens. It was still possible to successfully determine the
delamination sizes using the same type of empirical fit as the milled-slot specimens with the delaminations two plies below the surface.
7 A brief investigation into delamination growth in tubular specimens

7.1 Introduction

The creation of the “designer delamination” in Chapter 5 by placing a PTFE insert between two plies and including a stress-raiser from which a debonding between the interface of the PTFE and an adjacent ply grew through fatigue loading led to the question on which direction the delamination will grow given different loading conditions. In turn, this led to investigating different ratios of tension and torsion applied on a tube with the same type of embedded defect to monitor the directional growth of the delamination. With these tubular specimens the defects were circular with a circular stress-raiser of smaller diameter lying on top of the defect taking the form of a circular hole in the top composite ply (more details on this are given later in this chapter).

A limited amount of experimental work was done with the tubular specimens, loaded in fatigue such that the growth of delaminations in the tubes could be monitored with passive lock-in thermography as described in chapter 3 (section 3.7). DIC results were taken after fatigue of the specimens to establish if the directional delamination growth could be detected using the technique and to investigate the application of the DIC as an NDT technique on a non-flat structural element under operational loading. A representative FEA model was created following the design of the experimental tubular specimens. The models, using the Virtual Crack Closure Technique (VCCT), investigated the relationship between the ratio of tension and torsion and the angle of most likely delamination growth from the centre of the stress-raiser.

To investigate different ratios of tension and torsion, the different loading conditions have been given a “shear ratio”, being the ratio of shear loading to the combined shear and tensile loading. i.e. a specimen under a shear ratio of 0% is purely in tension, conversely, a specimen under a shear ratio of 100% is purely in shear (torsion).

7.2 Mechanical testing and delamination growth monitoring

Prior to any mechanical testing of specimens containing the stress-raiser and PTFE inserts, undamaged specimens were loaded in quasi-static tension as well as quasi-static torsion to determine the loads at which failure occurs in the undamaged specimens. In tension the failure load of the specimens was found to be approximately 18 kN (225 MPa). The ultimate torque load was found to be approximately 43 Nm (60 MPa). The force displacement plots can be seen in Appendix F in Figure F-31. Due to a lack
in resources, only four fatigue load cases were investigated; 100 MPa tension only, 20 MPa torsion only and a mixed load case with 120 MPa tension and 20 MPa torsion followed by another mixed load case with 100 MPa tension and 20 MPa torsion. For all fatigue testing, an R value of 0.1 was used and the testing was done at a frequency of 5 Hz. More testing was planned, however due to the difficulty in producing the specimens and machining the foam mandrel out as described in chapter 3 (section 3.2.5), a limited number of testable specimens were available for this work. As such, this work should be considered a proof of concept rather than a detailed investigation.

7.2.1 Tension loading

Two specimens were fatigue loaded in tension only with no torsion component (shear ratio: 0%) to investigate the direction of delamination growth. The specimens were loaded to 100 MPa with R = 0.1 at 5 Hz. Visual images were taken at the same time as recording the infrared emissions from the surface of the specimen over five periods of fatigue loading from the thermal camera as described in chapter 3 (section 3.7). The visual images in the top row of Figure 7-1 show the progression of damage in the area that contained the insert and stress-raiser. This damage appeared to be matrix cracks initiating in the epoxy rich stress-raiser region. The debonding of the PTFE from the adjacent ply can be seen in these images. The initiation of damage can be seen in the first second of testing shown in Figure 7-1a. After the first 500 cycles, i.e. 100 seconds of testing at 5 Hz, the damage looks to have propagated in the loading direction on either side of the stress-raiser. This delamination growth is shown more clearly after 400,000 cycles of fatigue loading as shown by the slightly shaded regions in Figure 7-1c. As the thermal energy observed is induced was a result of mechanical excitation, regions of low stress produce less thermal energy compared with regions under higher stress. The heat amplitude results are not sensitive to the delaminations, but rather indicate the amount of stress in the specimen. Therefore, the phase results have been used to quantify the direction of delamination growth, and the heat amplitude to verify the regions of low stress. It is important to note that due to the setup of the DSLR camera and the thermal camera, the perspective of the visual image is at an angle to the insert, while the thermal camera is placed so that the insert is directly facing the camera.
Chapter 7. A brief investigation into delamination growth in tubular specimens

Quantifying the delamination size is difficult using the phase thermograms on tubular specimens as the non-damaged regions are within a range of approximately 160-180° phase shift, appearing to be affected by the weave of the fabric. In theory, the non-damaged region of the tested specimen should be 180° out of phase from the excitation frequency, while the zones containing damage of any sort should have a lower phase shift. From the results in Figure 7-1, this variation in phase shift is reduced to approximately 155-170° in the delaminated region. More damage can be seen near the stress-raiser; however, this was due to other types of damage (not delaminations). This is shown in Figure 7-2a. In Figure 7-2b, a phase image of the second tubular specimen tested in tension is shown. In these results the lower phase shift areas appear to be focused in the loading direction on either ends of the stress-raiser, i.e. low stress regions, however damage seems to have grown in the high stress regions as well (perpendicular to loading direction). For the first specimen (Figure 7-2a) taking the slightly reduced phase shift area directly above and below the stress-raiser as the delaminated regions, it was estimated that the upper delamination grew at an angle of approximately 1° and the bottom
delamination grew at 177°. The measured angles are largely influenced by the interpretation of the delaminated region. Visual inspection of the specimen after testing showed the debonding of the PTFE from the adjacent ply propagated into actual delamination growth in this specimen, which is supported by the extension of the slightly lower phase shifted region which stretches past the estimated location of the insert. Another issue with this method is defining the location of the centre of the stress-raiser and the PTFE insert. As the stress-raiser and insert were designed to be circular and have diameters of approximately 2 mm and 10 mm, respectively, this was included in the figure as a visual guide, but the exact location cannot be determined from images from the thermal camera.

![Figure 7-2: Phase thermograms of tubular specimens under tension (a) first specimen after 400,000 fatigue cycles and (b) the second specimen after 100,000 fatigue cycles. Black outlines of the approximate position of the stress-raiser and PTFE insert have been included as a visual aid.](image)

7.2.2 Torsion loading

A specimen was fatigue loaded at 20 MPa (R=0.1, 5 Hz) in pure torsion without any tension loading (shear ratio: 100%) while being monitored by the same set up as for the tension loaded specimens described in the section above. The visual images, phase thermograms and heat amplitude thermograms are shown in Figure 7-3 at different stages of the fatigue loading. The visual images for this specimen do not show the damage clearly as the specimen contained voids near the surface, obscuring the view of the insert. Nevertheless, the phase results demonstrated that the delamination growth occurred diagonally to the axis of the specimen in Figure 7-3a and Figure 7-3b. In an attempt to grow the damage further, the load was increased to a peak torsion of 28 MPa for 120,000 cycles as shown in Figure 7-3c, however at that level of loading other forms of damage occurred in the specimen obscuring the delamination. The heat amplitude results indicate a uniform distribution of low thermal amplitude directly above the insert, with no specific direction after the delamination was grown in Figure 7-3b.
Chapter 7. A brief investigation into delamination growth in tubular specimens

Figure 7-3: From top to bottom: Visual images, phase thermograms, and heat amplitude thermograms of tubular specimen under torsion fatigue loading (a) during the first second of testing, (b) after 420,000 cycles of fatigue loading with a peak torsion of 20 MPa and (c) after an additional 120,000 cycles at a peak torsion of 28 MPa

Considering the phase results during the first second of testing as well as after 420,000 cycles of fatigue loading at a maximum load of 20 MPa, the growth of the delaminations occurred diagonally to the axis of the tube. This is shown in Figure 7-4 in which outlines of estimates of the position of the stress-raiser and the insert have been included. From drawing a line running from the estimated position of the centre of the stress-raiser through the delaminated region shown in the phase image, an estimate for the angle of delamination growth was made. During the first five periods of testing (Figure 7-4a), i.e. the first second of testing, the delaminations grew at angles of approximately 134° and 334°. For the phase image taken during the last five periods of testing at 20 MPa fatigue loading (Figure 7-4b), the estimated delamination growths occurred at 135° and 317°.
Chapter 7. A brief investigation into delamination growth in tubular specimens

Figure 7-4: Phase thermograms of a tubular specimen under torsion (a) during the first second of testing and (b) the same specimen after 420,000 fatigue cycles. Black outlines of the approximate position of the stress-raiser and PTFE insert have been included as a visual aid.

7.2.3 Tension-Torsion

Two different ratios of tension and torsion were tested experimentally. Both cases were tension dominated. The first ratio was 120 MPa tension and 20 MPa torsion (shear ratio: 14.3%) followed by a second specimen with 100 MPa tension and 20 MPa torsion (shear ratio: 16.7%). Both the tension and torsion were applied to the specimens so that the components of applied tension and torsion reached their maximum values at the same time. In all cases, the R value was 0.1 and the frequency of the fatigue testing was 5 Hz. For the first ratio of tension-torsion, the damage initiated in the low stress region on the circumference around the stress-raiser, as shown in Figure 7-5a. However, as the damage propagated it grew in an off-axis direction as seen in Figure 7-5b and Figure 7-5c. The phase results for the specimen at a shear ratio of 16.7% during the first second of testing (Figure 7-6a) indicate the damage initiates at approximately 336°. The further growth in Figure 7-6b occurs at 8°. It is also interesting to note that the delamination was concentrated at the top part of the insert, and not at the bottom part. The specimen catastrophically failed after 40,000 cycles of fatigue, which prompted the lowering of the tension component of the fatigue to avoid the catastrophic failure in the second specimen.
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Figure 7-5: From top to bottom: Visual images, phase thermograms, and heat amplitude thermograms of the first tubular specimen under tension-torsion fatigue loading with a shear ratio of 14.3%(a) during the first second of testing, (b) after 500 cycles of fatigue loading and (c) after 40,000 cycles.

Figure 7-6: Phase thermograms of the first tubular specimen under tension and torsion fatigue loading (a) during the first second of testing and (b) the same specimen after 40,000 fatigue cycles. Black outlines of the approximate position of the stress-raiser and PTFE insert have been included as a visual aid.
At the second ratio of tension and torsion, corresponding to a shear ratio of 16.7%, the damage initiated in the low stress areas of the specimen; both above and below in mirrored locations around the circumference of the stress-raiser as shown in Figure 7-7a. Further analysis on the phase results indicated that the damage initiated at 154° and 345°. The damage propagated at an angle of approximately 8° from the centre of the stress-raiser, just as with the first specimen. It is important to note that the measured angles from the phase results are influenced by the estimated position of the stress-raiser.
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Figure 7-8: Phase thermograms of the second tubular specimen under tension and torsion fatigue loading (a) during the first second of testing and (b) the same specimen after 122,000 fatigue cycles. Black outlines of the approximate position of the stress-raiser and PTFE insert have been included as a visual aid.

7.3 Digital Image Correlation

A brief investigation was conducted on the use of DIC to detect damage in the tubular specimens containing the fully grown delaminations under the same loading conditions but applied quasi-statically rather than in fatigue. Very limited resources were allocated to this testing due to the availability of the testing rig at the Instron headquarters. All the testing was done within one working day. This meant that the speckling of the specimens was done beforehand without a method of assessing the quality of the speckles in the lighting conditions in which the testing was to be done. Three specimens were tested, the longitudinal strain contours of which are shown for the tension loaded specimen in Figure 7-9a, torsion loaded specimen in Figure 7-9b and the tension torsion specimen in Figure 7-9c. In all the specimens, the adhesive bond between the end-tabs and specimens failed before reaching the desired load. Regardless, the loads up until the failure of the end-tabs transferred enough load to obtain usable strain contours. The strain results from loading the tubular specimens proved not to be useful as an NDT technique, as the strain profile is dominated by the presence of the stress-raiser, obscuring any strain abnormalities that could be attributed to the grown delaminations.
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Figure 7-9: DIC longitudinal strain results of the tubular specimens containing the PTFE-stress-raiser inserts. The specimens are loaded (a) 5.1 kN in tension, (b) 5.6 Nm in torque and (c) 3 kN and 5.4 Nm in torque

7.4 Finite Element Analysis

Modelling of progressive damage growth under fatigue loading is computationally expensive. Instead of pursuing this, the models were loaded quasi-statically and the virtual crack closure technique (VCCT) was used to monitor the distribution of the energy release rate around the perimeter of the circular stress-raiser. This was undertaken by considering the effective energy release rate ratio (EFENRRTR) field output in Abaqus. This method combines all three modes of the energy release rates and the critical energy release rates into “equivalent” values using the Benzeggagh-Kenane law (Benzeggagh and Kenane, 1996).

\[
EFENRRTR = \frac{G_{\text{equiv}}}{G_{\text{equivC}}}
\]

Where

\[
G_{\text{equivC}} = G_{IC} + (G_{IIC} - G_{IC})\left(\frac{G_{II} + G_{III}}{G_{I} + G_{II} + G_{III}}\right)^\eta
\]

A small parametric study, in which the value of \(\eta\) was varied between 0.5 and 2 demonstrated no change in the predicted angle at which the maximum EFENRRTR values were found for the various load cases. Thus, a value of the exponent \(\eta\) was taken as 1. The values of the critical energy release rates were investigated by final year undergraduate students. \(G_{IC}\) and \(G_{IIC}\) were determined to be 0.445 kJ/m\(^2\) (Pimenta-Richardson, 2017) and 1.837 kJ/m\(^2\) (Cashmore, 2017), respectively. In this work, \(G_{IIC}\) was taken to be equal to \(G_{IIC}\). These values were scaled by a factor of 1000 to ensure the EFENRRTR remained below 1 (to prevent the VCCT inducing crack propagation). For the purposes of this
investigation, the position along the circumference of the stress-raiser where the EFENRRTR values are highest are considered as being the likely direction for delamination growth.

7.4.1 Geometry and boundary conditions

Modelling the geometry of the tubular specimens in Abaqus proved difficult. The model was based on the geometry of the design for the tubes shown in Chapter 3 (section 3.2.5). As with the other specimens investigated in the other chapters, the model was created in two parts; the top ply and the remaining three plies, at the interface of which the delaminated region is defined.

Each ply was modelled as a homogeneous material with orthotropic material properties, as defined in chapter 3 (section 3.9). While the resin used in the material system is Gurit Prime 20LV, as opposed to the Shell epikote 828 (formerly known as Epoxide 300) for which the properties have been characterised, for the purposes of this study the minor changes in properties between the two epoxy resins should not have a large effect on the results of the FEA investigation.

Initially, the tubes were modelled with the geometry of the specimens prepared for testing, as shown in Chapter 3. The model is shown in Figure 7-10a with the position of the boundary condition being the bottom surface and the load applied to a central reference node to which the nodes on the top were constrained in the Y direction axially as well as rotationally about the Y axis. These models proved difficult to create geometrically due to the need to define the position of the insert and stress-raiser on curved surfaces. The models also proved very difficult to mesh uniformly. To better understand the effects of torsion on the directional growth of delamination defects without any of the issues introduced by modelling the geometry as a tube, a representative model was created as a plate with the same length as the tube, the width being the average circumference of the tube and the thickness the wall thickness of the tube. This model is shown in Figure 7-10b. To representatively model the effects of torsion on a tube, pure shear was applied to the flat plate. To apply the measured torque from the experiments on the flat model, the torque, T, was converted into the shear stress, $\tau$, using equation 7.1.

$$\tau = \frac{Tr}{J} \quad (7.1)$$

Where $r$ is defined as the mean radius (halfway between the outer and inner radius of the tube, $r_o$ and $r_i$, respectively) and the polar moment of inertia, $J$, which for a hollow circular cross-section is defined as per equation 7.2.

$$J = \frac{\pi}{2}(r_o^4 - r_i^4) \quad (7.2)$$
The calculated shear stress was then divided by the area of the cross-section of the tube to give the average force which was applied to the reference point, constrained to the top surface of the flat tube model.

![Diagram of FEA model of tubular specimen](image)

**Figure 7-10:** Geometry of the FEA model of the tubular specimen containing a PTFE insert and a stress-raiser; (a) with the actual geometry of a tube and (b) as a representative flat plate

Pure shear was achieved in the modelling of the flat plate by using tie constraint definitions on the two outer surfaces (pink and red edges in Figure 7-10b). This effectively modelled a flat plate where the displacements on the left edge where the same as those on the corresponding point on the right edge. Without this constraint, bending would have been introduced on application of the applied shear load. For clarification, Figure F-32 in Appendix F shows the displacements in the Y direction of a flat plate with homogenous properties under a shear displacement with and without the tie constraint definitions.

### 7.4.2 Mesh assessment

The effect of the mesh density on the results was assessed by conducting a mesh refinement study. The model used C3D8 full integration brick elements. The variation in the von-Mises stress and displacement (magnitude) were recorded at the reference node, the red dot in Figure 7-11, for the model under a tensile load of 7200 N and a shear load of 2546.5 N. The position of the reference node was chosen to be at a location away from the stress-raiser and the edges which were tie constrained to one another to avoid singularities where the results would not be expected to converge with the mesh refinement. The results of this mesh assessment are shown in Figure 7-12 in which the results converge after approximately 100,000 elements. In this work the mesh around the circumference of the stress-raiser contained 360 nodes, one for each degree of arc. To achieve this and maintain a well
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meshed model, the mesh was refined such that the model contained approximately 450,000 elements. As such, the position of the maximum EFENRRTR values are accurate to the nearest degree and this was considered reasonable.

![Figure 7-11: Position of reference point used for mesh assessment](image)

**Figure 7-11:** Position of reference point used for mesh assessment

![Figure 7-12: The values of Von-Mises stress and displacement at the reference node with respect to the number of elements in the FE model](image)

**Figure 7-12:** The values of Von-Mises stress and displacement at the reference node with respect to the number of elements in the FE model

7.4.3 Results

The FE model was run with different ratios of applied tensile and shear forces distributed across the top surface of the specimen. Figure 7-13 shows polar plots of the ratios of mode I, mode II and mode III energy release rates with the respective critical energy release rates, as well as the EFENRRTR values for the model placed in pure tension loading of 10 kN (Figure 7-13a), pure shear loading of 10 kN (Figure 7-13b) and equal measures of tension and shear loading of 10 kN and 10 kN(Figure 7-13c). The EFENRRTR values for all three loading conditions are combined in Figure 7-13d. It is important to note that while the FE models were loaded anti-clockwise, the test specimens had the load applied to them in the clockwise direction meaning for the cases in which torsion was applied, the experimental angles of delamination growth have been mirrored along the length of the specimen in the comparisons with the FE model.
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Figure 7-13: Polar plots of the Mode I, Mode II, Mode III and effective energy release rate as ratios to the critical energy release rates (EFENRRTR) around the edge of the stress-raiser in the tubular specimen model under (a) tension, (b) 50% tension and 50% shear and (c) shear. (d) shows the EFENRRTR values for the three cases. The percentage in the legend refers to how much of the load is shear.

Considering the maxima of each mode’s individual ratio of energy release rate ratios to the critical energy release rates, it can be observed that the maximum for mode III is offset by approximately 45° when compared to the maxima in mode I and mode II. As a result, the curve of the EFENRRTR around the circumference of the stress-raiser becomes wider with shallower maxima as the contribution of mode III increases, such as when there is more shear. Models with a shear ratio of 71.4% or more have a total of four peaks in EFENRRTR around the circumference of the stress-raiser, whereas for the load cases tested below this shear ratio, there are a total of two peaks. An example of this is shown in Figure 7-14a where the EFENRRTR values are plotted along the circumference with the two maxima highlighted by the markers. The model was under 10 kN tension and 2 kN shear (shear ratio: 16.7%). The two sets of mirrored peaks in the data for the high shear ratio (83.3%) load case are shown in Figure 7-14b. Both sets of data are shown in polar plot form as well as in a rectangular-axes plot to highlight the position of the peaks in EFENRRTR.
In pure tension the delaminations in the test specimen grew at 359° and 183° (1° and 177° for clockwise loading, see section 7.2.1). Slight singularities at the 0°, 90°, 180° and 270° positions resulted in the maxima in EFENRTRR in the tension model being at 359° and 1° as well as 179° and 181°. The direction of the delamination growth in the tested specimen is very close to the predicted directions. The largest deviation is for the lower end of the specimen, where the experimental results indicated growth at 183°, whereas ignoring the perturbation in EFENRTRR caused by the singularity, the expected delamination growth would be 180°.

In mixed tension and torsion with a shear ratio of 16.7%, the delaminations in the experimental specimen grew at 15° and 206° (345° and 154° for clockwise loading) with further delamination growth at 352° (8° for clockwise loading). The initiation was predicted to be at 11° and 191° from the FEA model. The modelling only considered damage initiation and not propagation, however it was expected that the damage would propagate in the same direction as the damage initiation.

In pure torsion, the delaminations in the experimental specimen grew at 26° and 226° (334° and 134° for clockwise loading) during the first second of testing (see section 7.2.2). After 420,000 cycles of testing, the delamination appeared to have grown at 43° and 225° (317° and 135° for clockwise loading). Using the maximum EFENRTRR it was estimated the damage would grow at 0°, 90°, 180° and 270° around the circumference of the stress-raiser. The experimental data indicate that the damage
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grows in the directions where the mode I and mode II energy release rate ratios were highest, rather than where the EFENRTR (established using the BK law) maxima were, as these were influenced by the mode III results which had a tendency to be 45° different to the mode I and mode II results as seen in Figure 7-13.

A number of load cases were investigated, the angles at which the resultant maxima of the energy release rate ratios for each mode as well as for all modes using the BK law were plotted in Figure 7-15 against the shear ratio. For each of these plots, there is a mirrored maximum 180° along the circumference of the stress-raiser.

7.5 Concluding remarks

A brief investigation on predicting the direction of delamination growth in GFRP tubes with embedded circular PTFE inserts and circular stress-raisers was discussed in this chapter. A manufacturing method was created to produce the tubes, successfully integrating the inserts and stress-raisers to the structure during the manufacturing. The specimens were tested under tension, torsion and combined tension-torsion fatigue to grow the debond between the PTFE and an adjacent ply to compare with the FEA results. Because of the difficulty in producing tubular specimens and a lack of access to resources to continue this investigation, this chapter outlines the preliminary work done in the investigation of predicting the directional growth of delaminations in tubes under tension/torsion fatigue. More testing of specimens is required before making any solid conclusions on the direction of delamination growth in the tubular specimens under different ratios of tension and torsion. The following conclusions are based on the observations made from the limited experimental work.
The FEA models used the BK law to calculate the effective energy release rate ratio (EFENRRTR) around the circumference of the stress-raiser. When considering the position at the circumference of the stress-raiser with the highest EFENRRTR value to be the direction in which the delamination would grow given a high enough load, the experimental tension results, obtained from analysing the phase results of passive lock-in thermography, proved to be within 3° of the predicted angles. Two ratios of tension/torsion were investigated, however due to the layup of the specimen and the resultant behaviour of the tube in torsion, only tension dominated load-cases were investigated. In both specimens, the damage grew at an angle between the pure tension and torsion specimens, however as with the other two load cases, definite conclusions could not be made as the analysis is too dependent on the estimates of where the stress-raiser is positioned in the phase results of the thermography. The initiation of the delamination was close to the predicted direction for damage grown using the EFENRRTR around the circumference of the stress-raiser, however further fatiguing of both mixed tension/torsion specimen exhibited damage growth not as predicted. In pure torsion, the delaminations grew 45° away from what was predicted on FEA using the maxima of EFENRRTR around the circumference of the stress-raiser (delamination front). The tested specimen grew at 135° and 317°. These angles of damage growth corresponded better to the individual energy release rate ratios of mode I and mode II, while mode III was 45° out compared to these. To draw any conclusions would require more detailed modelling and the testing of more specimens, however it would seem likely that the delamination growth may be much more mode I and mode II dominated than the FEA predicted using the BK law and the EFENRRTR with the given parameters. A further study on the mode III critical energy release rate ratio may improve the model.

The use of DIC as an NDT technique for this type of specimen under the loads at which the damage was grown was found not to be a valid technique for detecting damage in these specimens. The strains were dominated by the effect of the stress-raiser. While the results showed the damage grew in the areas of the specimen under low strain, this on its own is not indicative of delamination growth, but rather the expected strain distribution around a circular stress-raiser under the various load cases. The use of DIC to monitor the delaminations in these specimens could be revisited by loading the tubes in three-point bending to obtain strain results more consistent with the results from chapter 5.

As this investigation was at a tangent to the objectives set out for the PhD, limited resources were allocated to it. With the growing use of composite tubes in the automotive and sports equipment industries, this area of research may be of future interest and outlines the methods used in creating a representative specimen in which the delamination growth directions can be monitored.
Chapter 8. Concluding remarks and future work

8 Concluding remarks and future work

8.1 Introduction

This thesis has described the investigation of the use of Digital Image Correlation as an NDT technique to detect delaminations in composite structural elements. The work was focused on the development of representative structural elements in which realistic delamination-like defects could be introduced. These structural elements were all mechanically loaded with the surface closest to the delaminated ply interface being monitored using DIC.

All of the composite specimens used in this work were made out of glass fabric impregnated with epoxy resin. The choice of the material system was made to enable the creation of transparent specimens in which the inserted defects could be visually monitored. Two types of inserts were investigated in a flat coupon under three-point bending. First, the specimens were produced with pocket delaminations placed between the top and the adjacent ply to assess what type of strain features indicate the presence of a delamination. Next, a novel method of simulating a fully embedded delamination was created. This method involved the use of a single sheet of PTFE embedded during the manufacturing of the panels, along with a stress-raiser in the form of a cut in the fabric to enable the debonding of the PTFE from the adjacent plies under fatigue loading after cure. Natural defect artefacts were then investigated by creating milled-slot specimens, adapted from literature, and loaded in fatigue to grow delamination damage only. Finally, a brief investigation was conducted on the PTFE/stress-raiser type of delaminations in tubular structures under tension/torsion loading. The main conclusions from each of these investigations is discussed in this chapter, along with suggested work to further this research.

8.2 Conclusions

8.2.1 Introduction

The main aim of this thesis was to investigate the application of DIC as an NDT technique in monitoring delamination defects in FRP composites. Four types of structural elements were designed and manufactured to assess this application of DIC. This application of DIC was found to be successful for three of the four types of structural elements, however in the three-point bend specimens, the size of the delamination was consistently overestimated from the interpretation of the strain fields. Pulse
thermography was found to be a better technique for measuring the size of these defects. The use of DIC surface strain fields was shown to be a better method than both pulse thermography and lock-in thermography, however at this stage the DIC results require an empirical fit based on FE predictions. The following sections outline the conclusions from each area in more detail.

8.2.2 Monitoring of pocket delamination specimens

By creating a flat coupon with a fully embedded simulated delamination, the delamination monitoring capabilities of DIC were investigated to establish the best loading conditions in which the resulting surface strain changes compared with a no defect specimen enabled delamination characterisation. It was found that by placing flat specimens in three-point bending with the delamination inserts between the loading and a support roller resulted in a plateau in strain corresponding to the position of the delamination. Establishing markers in the strain profiles was not further investigated in this part due to uncertainties involving the thickness of the insert, as well as the complexity of the insert.

8.2.3 Monitoring of PTFE/stress-raiser delamination specimens

Three-point bend specimens containing a single sheet of PTFE and a stress-raiser in the form of a cut in the fabric along the width of the specimens were manufactured and tested, monitoring the delamination sizes visually, with DIC and with pulse thermography. The DIC results demonstrated the same plateau in strain feature as with the pocket delamination specimens. The stress-raiser resulted in high local strains under load, which sometimes obscured delamination edges depending on the stress-raiser position. Provided the position of the stress-raiser was not near the delamination edge, this type of specimen was used to establish the placement of markers on the DIC strain profiles from which the delamination size could be established. Two methods of interpreting the strain-position plots were investigated; using FE models based on the delamination sizes interpreted from visual measurements to assist in the placement of markers, and by placing the markers at the points in the strain profiles where the values of strains deviated from the no defect specimen. Both of these methods tended to over-estimate the delamination size, with the non-FEA assisted DIC method having a larger overestimation. The DIC results were given a correction factor and compared with the visual measurements. This proved to have less of a correlation than the pulse thermography results of the same specimens.

The use of passive lock-in thermography (mechanical excitation rather than thermal) was briefly investigated, showing the capabilities of the technique. This technique detected only the de-bonded regions of the PTFE. The investigation demonstrated that the debonded region had a lower phase shift than the 180° out a phase non-damaged zones.
8.2.4 Monitoring of delaminations in milled-slot specimens

Natural defect artefacts were produced using a milled-slot specimen. This specimen was loaded in fatigue to grow delaminations from the root of the milled slot. This proved to be a successful way to produce controlled delamination growth without introducing other failure mechanisms in the specimens. Thus the progress of the controlled delamination growth was monitored visually, using DIC, pulse thermography and lock-in thermography to compare the delamination detection capabilities using these techniques. It was found that, by applying an empirical fit to the strain results, the DIC method proved to be better suited in measuring the delamination lengths than the two thermographic techniques, however this was mainly due to the fact that these specimens contained edges in the vicinity of the delamination, resulting in thermal losses, obscuring the delamination. Even so, the lock-in thermography results proved to have reasonable correlation with the visually measured delamination sizes. The TSR pulse thermography results of damaged specimens had to be subtracted from earlier pulse thermography results where the specimens were still undamaged to enable a reasonable measurement of the delamination length.

In an effort to evaluate the DIC results without the need for the empirical fit, a milled-slot specimen containing a sheet of PTFE at the milled slot depth was created to simulate a perfect delamination without complications such as fibre bridging. This showed that the dip in strain characteristic to the delamination edge observed in the FEA results did exist experimentally, given a perfect delamination.

It was found that increasing the depth of the milled slot still produced a controllable delamination growth in the specimens under fatigue loading. These deeper delaminations were monitored visually and using DIC. The deeper delaminations were more difficult to characterise for a number of reasons. First, the increased depth of the notch meant the applied quasi-static load had to be reduced accordingly to prevent further damage to the specimen during DIC testing. This reduced the size of the slope region in which the empirical fit is applied. Further to this, the effect of fibre bridging is enhanced in these deeper delaminations.

8.2.5 Investigation of delamination growth in tubular specimens

A novel manufacturing method to produce tubular specimens with embedded PTFE inserts was trialled. This method successfully produced tubular specimens suitable for testing in tension and torsion and enabled an investigation into the directional growth of delaminations in tubes under tension/torsion loading. This was achieved due to the PTFE/stress-raiser combination, assuming the debonding of the PTFE from the adjacent plies occurred in the same direction as the growth of real
delaminations in tubes. Unfortunately, there was insufficient time for this investigation to provide any conclusions other than proof of concept.

FE models were produced using VCCT to identify the position along which the circumference of the stress-raiser the delamination would grow given certain ratios of tension and torsion. The models used the Benzeggagh Kenane law, using all three fracture modes to estimate an effective energy release rate, which the model would then use to establish the direction of damage growth. From the specimens tested, it was observed that the FE predictions of the directional growth of the delamination under pure torsion was approximately 45° away along the circumference of the stress-raiser compared with the experimental results. By further investigating the FE prediction, it was found that by considering only the mode I and mode II fracture toughness criteria, the predictions were closer to the experiments. The mode III fracture toughness criteria skewed the results for torsion dominated load cases.

DIC was used to attempt to monitor the delaminations in the tubes under the tension/torsion, however this was not possible due to the stress-raiser dominating the strain profiles near the delaminations.

8.3 Suggestions for future work

The present work has shown that the surface strain profiles measured using DIC can be used to monitor delaminations in GFRP structural elements given certain load-cases. This work is an advance on the application of DIC as an NDT technique for FRP composites. The following are suggestions of areas in which further investigations might lead to additional enhancement of the applications of DIC as an NDT technique.

To further this work directly, the specimens could be tested with the inserts at different depths within the specimens to assess the depth resolution of the technique. This was done for the milled-slot specimen but would pose an interesting investigation for the fully embedded delamination specimens. In addition, expanding this investigation to different composite material systems, such as CFRP, would increase the confidence of the results, and along with the different depth investigations, would enable the development of algorithms with which the empirical fits on the strain profiles could be applied, taking into account the material properties and the applied load.

Further comparisons of the applicability of DIC as an NDT technique to more established techniques such as digital shearography and ultrasonic C-scans would help identify advantages and disadvantages of the technique. In addition, combining DIC with thermography has been done in the literature, but
further investigations on this would enable an assessment of the NDT capabilities of this hybrid technique similar to the analysis undertaken in this thesis.

Looking further ahead, there has been a recent drive to use neural networks to identify patterns in sets of data. This could be applied to the strain contours of structural elements under load to detect delamination defects by identifying strain profile irregularities such as the plateau in strains for the three-point bend specimens.

The investigation into tubular specimens under tension and torsion left unanswered questions. This was due to a lack of experimental work. Further work is suggested on investigating different failure criteria in FEA to establish which best predicts the directional growth of delaminations in tubes under different ratios of tension and torsion. More specimens would also enable certain conclusions on the experimental aspects of the work.
References


References


Pinto, F., Maroun, F.Y., Meo, M., 2014. Material enabled thermography. NDT E Int. 67, 1–9. https://doi.org/10.1016/j.ndteint.2014.06.004


Quaresimin, M., Carraro, P.A., 2013. On the investigation of the biaxial fatigue behaviour of
References

unidirectional composites. Compos. Part B Eng. 54, 200–208. https://doi.org/10.1016/j.compositesb.2013.05.014


List of publications


Ajmal, O. Z., Crocombe, A. D., Gower M. R. L., Jesson, D. A., Ogin, S. L, Detection of delaminations in 5-harness satin GFRP epoxy laminates using DIC, Proceedings of ECCM-17, Munich (Germany), June 2016
## Appendix A: Supporting figures for Chapter 2

Table A-1: Stacking sequences for study by Ling, et al. (2005) where T denotes the position of the PTFE insert and OF denotes the position of the optical fibre (Ling et al., 2005)

<table>
<thead>
<tr>
<th>Case</th>
<th>Stacking sequence</th>
<th>$h_1/h$</th>
<th>$h_2/h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0#</td>
<td>$0_5^c/(OF)/0_5^e$</td>
<td>0 or 1</td>
<td>1 or 0</td>
</tr>
<tr>
<td>1#</td>
<td>$0_5^c/(T)/0_5^c/(OF)/0_5^e$</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>2#</td>
<td>$0_5^c/(T)/0_5^c/(OF)/0_5^e$</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>3#</td>
<td>$0_5^c/(T)/0_5^c/(OF)/0_5^e$</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>4#</td>
<td>$0_5^c/(T)/0_5^c/(OF)/0_5^e$</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>5#</td>
<td>$0_5^c/(T)/0_5^c/(OF)/0_5^e$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>6#</td>
<td>$0_5^c/(T)/0_5^c/(OF)/0_5^e$</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>7#</td>
<td>$0_5^c/(T)/0_5^c/(OF)/0_5^e$</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>8#</td>
<td>$0_5^c/(T)/0_5^c/(OF)/0_5^e$</td>
<td>0.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>
B. Appendix: Supporting figures for Chapter 3

Figure B-1: Two milled-slot specimens placed in clamps while the adhesive bonding the end-tabs cured.

Figure B-2: Image of extensions to support rollers for monitoring the tension side of the three-point bend test.
**Table B-2: Table summarising measurements and calculations to find the fibre volume fraction of the material used in the three-point bend specimens**

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass composite (g)</td>
<td>3.55</td>
<td>3.557</td>
<td>3.503</td>
<td>3.536</td>
</tr>
<tr>
<td>Mass including crucible pre-burn-off (g)</td>
<td>50.966</td>
<td>55.166</td>
<td>54.527</td>
<td>49.18</td>
</tr>
<tr>
<td>Mass including crucible post-burn-off (g)</td>
<td>49.482</td>
<td>53.689</td>
<td>53.097</td>
<td>47.744</td>
</tr>
<tr>
<td>Mass of resin (g)</td>
<td>1.484</td>
<td>1.477</td>
<td>1.43</td>
<td>1.436</td>
</tr>
<tr>
<td>Volume of resin (cm(^3))</td>
<td>1.226</td>
<td>1.221</td>
<td>1.182</td>
<td>1.187</td>
</tr>
<tr>
<td>Mass of Fabric (g)</td>
<td>2.066</td>
<td>2.08</td>
<td>2.073</td>
<td>2.1</td>
</tr>
<tr>
<td>Volume of Fabric (cm(^3))</td>
<td>0.807</td>
<td>0.813</td>
<td>0.810</td>
<td>0.820</td>
</tr>
<tr>
<td>Fibre volume fraction</td>
<td>0.397</td>
<td>0.400</td>
<td>0.407</td>
<td>0.409</td>
</tr>
</tbody>
</table>

**Table B-3: Table summarising measurements and calculations to find the fibre volume fraction of the material used in the milled-slot specimens**

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass composite (g)</td>
<td>3.189</td>
<td>3.188</td>
<td>3.187</td>
<td>2.96</td>
<td>2.872</td>
<td>2.99</td>
</tr>
<tr>
<td>Mass including crucible pre-burn-off (g)</td>
<td>48.101</td>
<td>48.703</td>
<td>48.512</td>
<td>47.445</td>
<td>52.061</td>
<td>51.14</td>
</tr>
<tr>
<td>Mass including crucible post-burn-off (g)</td>
<td>46.757</td>
<td>47.362</td>
<td>47.172</td>
<td>46.296</td>
<td>50.835</td>
<td>49.946</td>
</tr>
<tr>
<td>Mass of resin (g)</td>
<td>1.344</td>
<td>1.341</td>
<td>1.34</td>
<td>1.149</td>
<td>1.226</td>
<td>1.194</td>
</tr>
<tr>
<td>Volume of resin (cm(^3))</td>
<td>1.110744</td>
<td>1.108264</td>
<td>1.107438</td>
<td>0.949587</td>
<td>1.013223</td>
<td>0.986777</td>
</tr>
<tr>
<td>Mass of Fabric (g)</td>
<td>1.845</td>
<td>1.847</td>
<td>1.847</td>
<td>1.811</td>
<td>1.646</td>
<td>1.796</td>
</tr>
<tr>
<td>Volume of Fabric (cm(^3))</td>
<td>0.720703</td>
<td>0.721484</td>
<td>0.721484</td>
<td>0.707422</td>
<td>0.642969</td>
<td>0.701562</td>
</tr>
<tr>
<td>Fibre volume fraction</td>
<td>0.393516</td>
<td>0.394308</td>
<td>0.394486</td>
<td>0.426927</td>
<td>0.388221</td>
<td>0.415534</td>
</tr>
</tbody>
</table>
Table B-4: Table summarising measurements and calculations to find the fibre volume fraction of the material used in the tubular specimens

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
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<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass composite (g)</td>
<td>2.25</td>
<td>2.645</td>
<td>2.582</td>
<td>2.266</td>
</tr>
<tr>
<td>Mass including crucible pre-burn-off (g)</td>
<td>47.159</td>
<td>48.161</td>
<td>47.909</td>
<td>46.782</td>
</tr>
<tr>
<td>Mass including crucible post-burn-off (g)</td>
<td>46.333</td>
<td>46.929</td>
<td>46.709</td>
<td>45.931</td>
</tr>
<tr>
<td>Mass of resin (g)</td>
<td>0.826</td>
<td>1.232</td>
<td>1.2</td>
<td>0.851</td>
</tr>
<tr>
<td>Volume of resin (cm³)</td>
<td>0.722028</td>
<td>1.076923</td>
<td>1.048951</td>
<td>0.743881</td>
</tr>
<tr>
<td>Mass of Fabric (g)</td>
<td>1.424</td>
<td>1.413</td>
<td>1.382</td>
<td>1.415</td>
</tr>
<tr>
<td>Volume of Fabric (cm³)</td>
<td>0.55625</td>
<td>0.551953</td>
<td>0.539844</td>
<td>0.552734</td>
</tr>
<tr>
<td>Fibre volume fraction</td>
<td>0.435156</td>
<td>0.338855</td>
<td>0.339782</td>
<td>0.42629</td>
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</tbody>
</table>
C. Appendix: Supporting figures for Chapter 4

Figure C-3: Microscopy picture of the cross-section of a 3 HS weave epoxy specimen with an embedded pocket delamination defect
Figure C-4: Surface shear strains along the width of a no defect three-point bend specimen. DIC results in solid lines and FEA results in dashed lines. (275 N)

Figure C-5: Surface shear strains along the width of a three-point bend specimen containing a pocket delamination. DIC results in solid lines and FEA results in dashed lines. (275 N)
Figure C-6: Surface shear strains along the width of a three-point bend specimen containing a circular pocket delamination. DIC results in solid lines and FEA results in dashed lines. (250 N)

Figure C-7: Strain contours of the tension surface of a 5 HS weave epoxy specimen containing two square pocket delamination in three-point bending. (a) Longitudinal strain and (b) shear strain (232 N)
Figure C-8: Longitudinal surface strains along the length of the tension surface of a three-point bend on a specimen containing two square pocket delamination inserts. Solid lines are DIC results and dashed lines are FEA results (232 N)

Figure C-9: Longitudinal surface strains along the width of the tension surface of a three-point bend on a specimen containing a square pocket delamination insert. Solid lines are DIC results and dashed lines are FEA results (232 N)
Figure C-10: Shear surface strains along the width of the tension surface of a three-point bend on a specimen containing a circular pocket delamination insert. Solid lines are DIC results and dashed lines are FEA results.

Figure C-11: DIC shear strain contours of 5 HS weave epoxy specimen with square defect at (a) 741.3 N, 14.53 mm and (b) 726.8N, 14.56 mm.
Figure C-12: Compression surface of 5 HS weave epoxy specimen under three-point bending at 200 N, 3.55 mm displacement

Figure C-13: Compression surface of 5 HS weave epoxy specimen under three-point bending at 401 N, 7.16 mm displacement
Figure C-14: Compression surface of 5 HS weave epoxy specimen under three-point bending at 602 N, 11.48 mm displacement

Figure C-15: Compression surface of 5 HS weave epoxy specimen under three-point bending at 801 N, 15.97 mm displacement
Figure C-16: Compression surface of 5 HS weave epoxy specimen under three-point bending at 1002 N, 21.53 mm displacement
Figure C-17: Longitudinal strains from the through length longitudinal data path on the DIC strain contours at different applied loads during the three-point bending of the 5 HS weave epoxy specimen with no damage on the left and circular delamination defect on the right.

Figure C-18: Longitudinal strains from the through length longitudinal data path on the DIC strain contours at different applied loads during the three-point bending of the 5 HS weave epoxy specimen with circular delamination defect.
D. Appendix: Supporting figures for Chapter 5

Figure D-19: High resolution images of three-point bend specimens tested using DIC and pulse thermography
Figure D-20: Microscopy image of the cross-section of a three-point bend specimen containing a PTFE insert

Figure D-21: Effect of FEA mesh density on the surface strains along the surface nearest to the delamination
Figure D-22: The positions of the lines from which the data was extracted from the DIC results. The contours show (a) the $Y$ positions and (b) the $X$ positions from the origin located at the base of the coordinate system shown.
Table D-5: Delamination sizes determined using the strain contours in the DIC results and the systematic adjustment of these compared with the visually determined delamination sizes.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
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<tbody>
<tr>
<td></td>
<td>Specimen</td>
<td>DIC P-P</td>
</tr>
<tr>
<td>0L</td>
<td>25.03</td>
<td>17.43</td>
</tr>
<tr>
<td>0R</td>
<td>32.92</td>
<td>25.32</td>
</tr>
<tr>
<td>1L</td>
<td>35.79</td>
<td>28.19</td>
</tr>
<tr>
<td>1R</td>
<td>35.04</td>
<td>27.44</td>
</tr>
<tr>
<td>2L</td>
<td>31.08</td>
<td>23.48</td>
</tr>
<tr>
<td>2R</td>
<td>32.94</td>
<td>25.34</td>
</tr>
<tr>
<td>3L</td>
<td>24.69</td>
<td>17.09</td>
</tr>
<tr>
<td>3R</td>
<td>34.65</td>
<td>27.05</td>
</tr>
</tbody>
</table>

Figure D-23: A comparison of the TSR noise reduced thermograms at (a) 0.08 s and (b) 0.50 s after the pulse
Figure D-24: Enhanced contrast TSR noise reduced thermograms of specimens (a) 0L and (b) 0R

Figure D-25: Phase results from passive pulse thermography of specimen 0R.
E. Appendix: Supporting figures for Chapter 6

Figure E-26: Load displacement curves for the quasi-static tests to failure of milled-slot specimens

Figure E-27: Delaminations lengths determined visually along the mid-line of the deeper milled-slot specimens as a function of the number of fatigue cycles.

Figure E-28: FEA longitudinal surface strains Vs the displacement along the mid-width of deeper milled-slot specimen 5A starting from the edge of the milled slot for different delamination lengths.
Figure E-29: DIC longitudinal surface strains Vs the displacement along the mid-width of deeper milled-slot specimen 5A starting from the edge of the milled slot for different delamination lengths.

Figure E-30: DIC longitudinal surface strains Vs the displacement along the mid-width of deeper milled-slot specimen 7B starting from the edge of the milled slot for different delamination lengths.
F. Appendix: Supporting figures for chapter 7

Figure F-31: Quasi-static torsion test of two tubular specimens to determine the ultimate torque

Figure F-32: The displacement in the Y direction of a homogeneous block model with an applied shear load to the top surface (a) without constraining the left and right edges to one another causing simple shear and (b) constraining the left and right edges to one another resulting in pure shear.