Evaluation of Drilling Damage in Carbon Fibre Reinforced Plastic (CFRP) and Glass Fibre Reinforced Plastic (GFRP) Composites

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This thesis endeavours to investigate the damage caused to CFRP and GFRP laminates during drilling. The drilling parameters including feed rate, rotational cutting speed and drill bit type will be varied and an assessment of the damage around each hole will allow an analysis of the most favourable drilling parameters. The effect of variations in fabric type and ply orientation will also be investigated to evaluate the conditions required to minimise delaminations in composites. It is important to be able to make an assessment of the damage caused by drilling as even small delaminations can significantly reduce the structural integrity of a component. A range of different methods will be employed to locate and evaluate delaminations in the laminate including backlight, sectioning, visual inspection and ultrasonic inspection. The small area of delamination caused by drilling, poses a challenge in determining the most accurate method of testing. The methods used are evaluated against one another to identify the most suitable. Ultrasonic testing has been held in high regard for achieving superior results in comparison with other non-destructive techniques in the location and evaluation of delaminations in composites. The ultrasonic testing system at UNSW@ADFA is required to be upgraded for use in producing C-scan images of the delaminations in composites. This thesis will aim to provide guidance for the upgrade and use of the Ultrasonic testing system, a comparison between different techniques used to locate delaminations and the effect of drilling parameter variation on drilling damage in CFRP and GFRP.

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Nomenclature

\[ D = \text{Diameter of hole [mm]} \]
\[ D_{\text{max}} = \text{Maximum delamination diameter [mm]} \]
\[ DF = \text{Delamination Factor} \]
\[ \delta D = \text{Uncertainty of the diameter of the hole [mm]} \]
\[ \delta D_{\text{max}} = \text{Uncertainty of the maximum delamination diameter [mm]} \]
\[ \delta DF = \text{Uncertainty of the calculation of the delamination factor} \]

I. Introduction

A. Purpose

Composite materials provide many advantageous properties for manufacturing use in the aerospace industry. They are becoming increasingly popular since their introduction in the 1960s for use in military aircraft. Due to composites having a high strength to weight ratio they are beginning to overtake conventional aviation materials such as aluminium alloys. There is a constant requirement to enhance the performance of aircraft which deploys the need for high performance structural materials. As composites are a relatively new technology further research is needed to provide a better understanding of their causes of failure. Processes such as drilling are known to produce delaminations in composite materials and hence reduce the structural integrity of the laminate. Delaminations do not occur in conventional aviation materials such as aluminum and these new failure modes are required to have accurate and reliable methods of detection. Even small hidden flaws in the laminate can cause catastrophic failure. As mechanical bonding of composite laminates is undertaken in the aviation industry, an understanding of the effect of varying drilling parameters on a composite material is important. This thesis will look at damage caused by drilling parameters including rotational cutting speed, feed rate, drilling with and without backing support and variation of drill bit type in both CFRP and GFRP laminates. In order to determine the extent of damage caused by varying the drilling parameters, different inspection methods are employed. These methods include ultrasonic scanning, backlighting, liquid penetrant method, sectioning and visual inspection.

B. Objectives

The main objective is to investigate the effect of various drilling parameters on damage caused by drilling in GFRP and CFRP laminates. The following sub-objectives will be used to complete the main objective:
- Investigate the extent of damage caused by various rotational speeds
- Investigate the extent of damage caused by various feed rates
- Investigate the extent of damage caused by a support backing
- Investigate the extent of damage caused by absence of a support backing
- Use various techniques of ultrasonic testing, backlighting, liquid penetrant method and sectioning to provide information about the structural integrity of laminate
- Repair ultrasonic C-scan testing system

C. Approach

There is an increasing need for further research concerning the effect of drilling of composite material. The aviation industry is further developing aircraft such as the Boeing 787 Dreamliner which is using composite material to replace the conventional aluminium frame. This thesis will look at the extent of damage that variations of rotational speed, drill bit type and feed rate of the drill will cause to the composite laminate. The influence of composite layup during drilling will be investigated through the stacking sequence of different ply
orientations. The effect of different types of woven cloth including twill weave, harness satin and plain weave will also be investigated during the drilling process. To simulate a composite panel on an aircraft, drilling was completed with and without a backing support to assess the damage on components where only one sided access is available. As the damage caused by the variations of ply orientation, woven cloth type, drilling parameters and backing support were compared, the most favourable drilling parameters are able to be determined for different conditions. This allows informed decisions to be made with regard to choosing the most advantageous parameters in order to preserve the structural integrity of the workpiece during drilling.

The experimentation will determine the best methods to locate and analyse the delaminations in composite laminates. The methods available include, automated and handheld Ultrasonic testing, backlighting, liquid penetrant method and sectioning. In order to utilise the automated ultrasonic testing method, an upgrade of the equipment is required. This upgrade will also prove beneficial to UNSW@ADFA as it will be made available for future research.

II. Literature Survey

A. Principles of Ultrasonics

Composite materials have provided a new avenue of approach for lightweight construction. Composites such as GFRP and CFRP are attractive materials in the aviation industry due to the high strength-to-weight ratio, high stiffness-to-weight ratio, fatigue and corrosion resistance and good thermal and acoustic insulation (Hasiotis et al. 2007). However composites are susceptible to hidden delaminations which can be sustained during manufacture or service. These hidden delaminations will affect the toughness and strength of the material and hence this develops a need for reliable non-destructive detection methods. One of the most common methods used in the detection of delaminations in composite materials is Ultrasonic Testing.

Ultrasonic inspection measures the high frequency sound waves passing through a material which are introduced at the surface. Electronically controlled sound pulses travel through the material and are converted back to an electronic signal at certain points (Grandt 2004). These points indicate the reflection and refraction of sound waves at boundaries. The boundaries include the surface at which the transducer introduces the pulse into the material, the opposite side of the material and delaminations in the material. The high frequency sound waves are sensitive to changes in acoustic impedance in the material and therefore can pick up delaminations in composites due to the air gap that is created. Interpreting the electronic signals at the boundaries through voltage peaks on a screen allows the operator to establish if any voids or inclusions exist. This type of data representation is called an A-scan and is shown in Fig. 1.

The sound waves are introduced into the material using Ultrasonic Transducers whose operation is based on the piezoelectric effect. Transducers contain a crystal or ceramic shown as the ‘active element’ in Fig. 2, which becomes compressed and deformed when a high frequency electric voltage is applied. This causes the crystal to transmit a pressure wave into the material. The pressure waves bounce off the surface boundaries and any flaws that are in their propagation path. The return pressure wave is received by the transducer and hits the internal crystals producing an electric voltage which is registered on a screen and produces an A-scan image. The ‘backing’ absorbs the energy radiating from the active element and controls the vibration of the transducer (Olympus 2006). When the acoustic impedance of the backing and the active material are equal, the result is a heavily damped transducer that had a good resolution but lower signal amplitude (Olympus 2006). The ‘wear plate’ protects the transducer active element from the outside surroundings, as it comes into contact with the surface of the material during contact ultrasonic testing.
It is important to choose the most suitable transducer for the job based on the shape, type and thickness of the composite material. The sound field of the transducer is shown in Fig. 3. The near field and the far field make up the two zones of the sound field. The near field is directly ahead of the transducer and the amplitude of the sound waves goes through a sequence of minima and maxima values. At the end of the near field distance “N”, the amplitude reaches its maximum (Olympus 2006). This point is the natural focus of the transducer. The near field distance is a function of the transducer diameter, the frequency of the transducer and the velocity of sound in the composite material. The diameter of the beam continues to increase further away from the transducer. As the beam diameter increases, the sensitivity of the transducer decreases. As the beam diameter decreases, the energy that is reflected by a flaw becomes larger. As the last signal maximum occurs at the focal point, the transducer is unable to be focused at a further distance. If the thickness of the sample to be tested is known, a probe with a specific focal length can be manufactured.

When choosing the correct type of transducer, consideration needs to be given to the techniques used during ultrasonic testing. Ultrasonic transducers can be manufactured to contain both the transducer and receiver in the same probe. These transducers are called ‘Dual Element Transducers’ and consist of two crystal elements separated by an acoustic barrier in the same case. Dual Element Transducers are used for the ‘Pulse-Echo’ technique. The pulse echo technique introduces the pulse at the surface of the material. The pulse is then reflected off the bottom surface of the test sample or a flaw that is present and returns the pulse to the transducer at the surface as shown in Fig. 4a. Figure 4b shows a second method that can be used called “Through Transmission”. The Through Transmission technique requires a transmitting transducer on one side of the test material and a receiving transducer on the opposite side of the material.

The pulse-echo technique is useful when only single sided access to the material is available; this is often the case in the aviation industry. The Pulse-echo technique not only gives the size and shape of the delamination but also gives a physical location and the depth of the delamination. Through transmission is used in high attenuation materials, such as composites, as the beam only passes through the material once. Through transmission provides information about the size, shape and planar view of the delamination; however it lacks the ability to provide information on the depth of the delamination. Composites are non-homogeneous and have very high sound damping, therefore the through transmission technique is beneficial (Hillger 2000). However, Pulse-echo technique is commonly used by researchers to identify and determine the depth of delaminations in composite materials (Lee et al. 2009; Wooh & Wei 1999).

Transducer selection is also influenced by the way in which the transducer will physically be used during testing. There are two techniques used in ultrasonic testing which include the contact method and the automated immersion method. The contact method requires the transducer to be in contact with the surface of the material and the scanning is commonly completed by hand. Contact transducers are equipped with a wear resistance face which prolongs the life of the probe. A coupling material is used between the sample and the probe to allow the sound energy to be transmitted. A coupling material, usually a viscous fluid such as oil is used to ensure there is a seal between the test sample and the transducer. Couplants are necessary as an interface of air and the test sample produces an acoustic mismatch. Even a small air gap will cause the beam to be 100% reflected at the air-test material interface (Haller & Khuri-Yakub 1992). There are different angles of transducers that are available.

**Figure 3. Sound field of a transducer**
(Olympus 2006)

**Figure 4. Schematic of Ultrasonic techniques: a) pulse echo technique; b) through transmission technique**
which allow access into samples with changing geometries. As the composite samples used in this thesis are of flat plate design, angles probes are not required.

During the automated immersion method both the transducer and the test material are submerged. The water acts as a coupling material which maintains the ultrasonic contact between the probe and the test material. Immersion testing is advantageous for components that can be removed from structures and are not susceptible to water damage. Automated immersion scanning reduces the operator variables and has the ability to provide information to create a planar image of the test material and its condition. The automated immersion method is limited to relatively flat test samples to ensure that the transducer remains a constant distance from the sample. The constant distance from the probe to the test material is important when high resolution C-scan images are required as each probe is given a focal length in water (Halmshaw 1987). Immersion probes have a wear face that is matched to the impedance of water. A large number of researchers choose immersion testing for thin laminates as it provides uniform coupling and has high frequency capabilities for fine focusing (Razek et al. 2005; Kazys & Svilainis 1997).

Ultrasonic C-scans have the ability to detect discontinuities that are perpendicular to the ultrasonic beam. Planar images called C-scans use the time of flight data from the ultrasonic flaw detector to display the depths of flaws in a material. The variations in colour indicate the different depths of the material and so the exact location of the flaw can be determined. C-scans are widely used for delamination analysis of composite materials as they provide information about the structural integrity of the composite in three dimensions, whereas A-scans and B-scans only provide 1D and 2D images respectively (de Fretas & de Carvalho 2005).

**B. Previous Research**

The need for accurate and reliable results in the detection of delaminations in composite materials using ultrasonic methods has fuelled the continuing research and analysis to improve test equipment. Unlike metals, composite laminates give very little notice before failure occurs. Therefore it is important to locate small, hidden delaminations to maintain the structural integrity of the composite laminate. To determine that ultrasonic flaw detection methods and equipment are providing useful and accurate information they are required to be calibrated. Calibration involves using composite samples made with artificial delaminations to determine the limits of the equipment with regards to detecting the depth and size of delaminations.

The ultrasonic method has proven to be the most effective non-destructive testing (NDT) technique for use with composite material flaw detection. As summarised in Table 1, a comparison between the different techniques shows that the ultrasonic method will provide an indication for all types of composite defects.

**Table 1: Composite defects which can be detected by different techniques** *(Cawley & Adams 1988)*

<table>
<thead>
<tr>
<th>DEFECT TYPE</th>
<th>Ultrasonics</th>
<th>Radiography</th>
<th>Eddy Current</th>
<th>Acoustic Emission</th>
<th>Thermography</th>
<th>Optical Holography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voids, porosity</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Disbonds</td>
<td>Yes</td>
<td>Some</td>
<td>Some</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Delaminations</td>
<td>Yes</td>
<td>Some</td>
<td>Some</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Impact damage</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Resin variations</td>
<td>Yes</td>
<td></td>
<td>Some</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broken fibres</td>
<td>Yes</td>
<td>Some</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Fibre misalignment</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resin cracks</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cure variations</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclusions</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Delaminations are common failure modes in CFRP and GFRP and are sensitive to faults in manufacturing (Mikulik et al. 2008; Thouless et al. 1989; Suemasu & Osamu 1996). The most common causes of delaminations in composite materials include drilling and impact damage. Both of these causes are common in an aviation environment where tools may be dropped on a composite wing or joining using mechanical fasteners is required. The most dangerous types of delaminations are hidden delaminations which are not visible from the
As composite materials are a relatively new technology, NDT methods need to be further enhanced to provide reliable and accurate information about the structural integrity of the component.

UNSW@ADFA has the hardware for an Automated Ultrasonic Scanning System. The hardware consists of an immersion bath, an ultrasonic flaw detector with a Cathode Ray Tube (CRT) screen, a National Instruments Data Acquisition Device (NIDAQ) and a scanning frame controlled by a microprocessor with a console display showing the position of the test head as shown in Fig. 5. A large amount of effort has been directed towards increasing the reliability of automated NDT methods in order to increase the reliability of test results. As Ultrasonic testing has proven to be the most effective method of detecting delaminations in composite materials, the School of Engineering and Information Technology at UNSW@ADFA will benefit greatly from a functioning automated ultrasonic scanning system. The components are required to be linked to a computer in order to obtain and process the information received during testing. The issues associated with the development of an automated ultrasonic scanning system include the age and reliability of the components and the ability to create an interface between the old components and a new computer.

To test the limits to which a system can provide accurate and reliable results for the detection of delaminations in composites, calibration tests need to be undertaken. A number of studies have been conducted in the failure predictions of composite materials, using Teflon inserts to create artificial delaminations (Milette et al. 1995; Nageswaran et al. 2005). Teflon is a non-stick material which is placed in between the plies of carbon fibre and glass fibre during layup and is good for simulating delaminations in laminated composites.

C. Material Layup

Various layup of CFRP and GFRP can be used to reduce the chances of delaminations forming in structural components. Studies (Short 2002; Ng & Kumnick 2006) compare specimens of unidirectional layers stacked together in different orientations as shown in Fig. 6. The cross-ply laminates are more robust in comparison to a unidirectional laminate. In a unidirectional 0° layup the strength of the composite is highest in the direction of the fibre. In the layup shown in Fig. 6, the strength is lower in the 0° direction when compared to a unidirectional layup as the strength is distributed over different orientations. Hence this provides a lower strength in the fibre direction and a more robust structure. Carbon fibre and glass fibre also come in a woven cloth which is

Figure 5. Ultrasonic C-scan equipment: a) NIDAQ; b) Veriscan microprocessor and monitor; c) Immersion bath and frame; d) Krautkramer Ultrasonic flaw detector

Figure 6. A laminate made up of 4 plies of different orientations
produced by interlacing fibres in the ‘warp’ and ‘fill’ direction. The warp direction runs the entire length of the roll of material and the fill direction runs perpendicular to this. The mechanical interlocking of the fibres governs the reliability of the cloth. There are various patterns of the weave which each possess different material properties. The woven cloths available at UNSW@ADFA include twill weave, plain weave and a harness satin style as shown in Fig. 7. In terms of yarn slippage and fabric distortion the plain weave is very stable, however, is difficult to drape. The twill weave consists of fibres passing over two bundles of fibres and under two bundles. It is more flexible and will conform more readily to simple contours and is slightly less stable than the plain weave. The 5-harness satin weave is similar to a twill weave however it incorporates fewer intersections of warp and fill. It is constructed with one warp yarn interlocking over four and under one filling yarn and is a very tight weave. The 5-harness satin fits well to contours and, due to its high fabric count, provides maximum strength to composites that it reinforces (Peters 1998). The pattern of the weave, weight and alignment of fibres have a direct influence on the mechanical properties of the material.

![Figure 7. Various commonly used weave architectures: a) Plain weave; b) 2x2 twill weave; c) 5-harness satin (Baker et al. 2004)](image)

There are two manual methods that use fabric to construct CFRP and GFRP laminates; wet lay-up method and prepreg method. The wet lay-up method uses dry fabric which is manually saturated with liquid resin during the layup where the layers are stacked on top of each other to reach the required thickness (Strong 1989). Once all the plies have been stacked the layup is prepared for curing. A vacuum bag is applied over the surface of the layup and sealed to a mould. This allows pressure to be applied during cure which compresses the plies together and pushes out any gases and liquids, such as air and water that may be trapped in the layup or generated during curing (Baker et al. 2004). This also bleeds out any excess resin. A schematic of a vacuum bag layup is shown in Fig. 8. The release film is a smooth non stick film constructed from fluoropolymers, placed over the workpiece. It is used to bleed out any excess air or resin and may have small holes in it. The breather fabric is a light material which has the ability to transmit gases under pressure. It allows the gases to flow from the workpiece to the vacuum fitting. The bleeder fabric is a thin absorbent cloth with is used to soak up excess resin. The tool is a heavy metal sheet which provides a smooth surface for the workpiece. The vacuum bag is a rubber material which moulds to the shape of the workpiece during cure. The wet layup method itself is simple. However, variations in resin viscosity and thickness across the layers will cause imperfections in the final laminate. The prepreg method is more precise and produces a more superior product than the wet layup method (Strong 1989). The prepreg material has been pre-impregnated with resin and slightly cured to increase viscosity. Less resin used and it employs a simpler fibre handling procedure. The curing procedure for prepreg materials requires vacuum bagging and heating.

**D. Drilling of Composites**

As the use of composites in the aviation industry has grown in recent years, there has been a greater need for mechanical fastening of composites which requires drilling. Examples of the increasing need for mechanical fastening include field situations where adhesive bonding is not feasible due to time and environmental
constraints and the increasing need to bond materials such as aluminium to CFRP or GFRP. Drilling composites can be difficult due to their non-homogeneous nature and the fact that their reinforcements are very abrasive. Therefore drilling in composite material can cause damage to the composite materials if the correct parameters are not used due to their low interlaminar strength.

The most common cause of drilling damage includes delaminations, fibre pull out, peel up and push out damage and thermal damage. Delaminations cause separation between the plies due to failure in the adhesive bond. Figure 9 shows the different delamination models caused by the cutting force of a drill exceeding the bonding strength between the layers. The cutting force can be understood in terms of two components. These are the axial force and the torque force. The axial force produces vertical stress in the through thickness direction of the laminate and is the most influential factor in causing delaminations (Jin et al. 2008). ‘Type A’ breakage is caused by the axial force from the drill and ‘type B’ breakage is caused by the shear stress generated by the torque of the drill. The combination of shear and axial forces cause delaminations during the drilling of composites.

Fibre pull out generates delamination where weak adhesive bonds exist. This occurs when the fibres are not cut when drilled but are pulled out of the matrix leaving a gap in the laminate which creates a roughness defect on the surface of the hole. Peel up damage occurs at the entry hole and push out damage occurs at exit of the drilled hole as shown in Fig. 10. A push out delamination is generated where the point loading of the drill bit exceeds the interlaminar bond strength. A peel-up delamination occurs at the entrance hole and is caused by the drill abrading the laminate surface and pulling the abraded material away along the flute. This forces the material to spiral up before it is machined completely.

![Figure 9. Breakage models of laminates](Jin et al. 2008)

Thermal damage in the laminate occurs when heat is generated from the friction between the fibres and the cutting edge of the drill. The length of time that the drill engages with the composite laminate directly correlates to the amount of thermal damage. It is suggested that a low feed rate will increase the amount of thermal damage during drilling (Singh et al. 2004)

There are numerous factors to consider when attempting to reduce the damage caused by drilling in composites. These are:
- Feed rate,
- Rotational cutting speed,
- Support of the sample during drilling,
- Layup,
- Type of cloth,
- Thickness of sample,
- Type of drill bit,
- Condition of drill bit, and
- Cooling of drilled area.

Previous results have suggested revolutions per minute (RPM) of the drill and the feed speed are the most significant parameters during the drilling of GFRP composites (Marques et al. 2006; Quan & Zhong 2009; Hochen et al. 1992; Mohd Ariffin et al. 2009). Both visual inspection and ultrasonic inspection have been used to look at the delaminations caused by drilling in composite laminates (Hasiotis et al. 2007; Quan 2009; Tsao 2008). Visible damage of holes drilled in CFRP at different feed rates is shown in Fig. 11. It is evident from visual inspection that the holes drilled with a higher feed rate produced more damage to the laminate. The high feed rates of the drill cause large delaminations and burring around the holes as the large thrust force damages the interlaminar integrity of the plies before they are completely cut. A low feed rate is recommended when
drilling in conjunction with a high rotational cutting speed. However, as thermal damage can also occur with a low feed rate, a balance needs to be established where minimal delaminations are caused with minimal thermal damage during the drilling process.

The type of woven cloth, the thickness of the laminate and the backing support provided during drilling are factors that will not necessarily always be flexible to change. In the aviation industry drilling of composites may occur on a panel with access to only one side and the thickness of the laminate is chosen with the weight of the aircraft in mind. However, an assessment can be made on choosing the ideal drilling parameters for each specific situation. Research has shown that woven cloths are much less susceptible to splintering during drilling and many experiments employ quasi-isotropic layups of unidirectional fibres due to the different fibre orientations which provide a more robust structure (Campbell 2006; Davim 2010).

![Figure 11. The effect of feed rate on exit holes in CFRP: a) high feed rate; b) low feed rate (Quan 2009)](image)

When selecting a drill bit for optimum drilling results, it is recommended that the drill bits have a large positive rake angle (angle between tool face and vertical), as shown in Fig. 12, without becoming so large that the cutting edge gets very thin and dulls quickly (Strong 1989). This allows the drill to penetrate the material with lower force and reduces the heat generated from friction. The large positive rake angle pushes the fibres apart as opposed to a smaller angle which forces the fibres to collect in front of the drill and increases the cutting forces and heat (Strong 1989).

Together, experiments and theory show that drilling in thin composites causes more laminate damage than using thicker composites (Shuaib et al. 2004; Jin et al. 2008). Figure 13 shows the disfigurement process in the drilling of a composite laminate. At the entrance, the sample edge is thin and the resistance to the drilling torque is weak which produces shear stress and causes peel-up. The drill produces a downwards force on the undrilled lamina of the component which is thick in comparison to the drilled part. In comparison with the shear stress causing peel up, the axial stress is small. A thinner laminate will possess a greater axial stress as the undrilled part will also be relatively thin. As the drill moves deeper into the laminate, the undrilled part of the sample becomes thinner and the resistance against the axial force decreases. The increased axial force causes larger amounts of burring and disfigurements on a thinner laminate in comparison to a laminate with more plies (Jin et al. 2008).

![Figure 12. Rake angle of a twist drill (Timings 2002)](image)

The damage around the holes is characterised by a delamination factor [DF]. This is the ratio of the diameter of the maximum delamination zone [Dmax] to the diameter of the hole [D]. Equation (1) gives a numerical value to compare the degree of delamination caused when altering different drill bit diameters. Figure 14 shows a diagram used for the calculation of the delamination factor.

\[
DF = \frac{D_{\text{max}}}{D}
\]  

(1)
As previously identified a higher rotation rate of the drill bit used in conjunction with a lower feed rate produces better hole quality. However the heat accumulation at the drill tip is an issue and is overcome by the use of a water soluble coolant pumped through a cold air blast unit when drilling composite materials (Peters 1998; Quan & Zhong 2009; Jawaid et al.1992).

The way a composite sample is supported during the drilling affects the severity of the delaminations. Research recommends (Jin et al. 2008) that while drilling CFRP is it useful to place a backing material or dab glue at the exit area or bottom of the composite sample. This increases the strength of the fibres in the laminate and reduces the occurrence of delaminations and burrs.

It is not only the health and reliability of the composite component that needs to be taken into account when drilling. It is also the wear on the drill bit which requires monitoring and changing. A worn drill bit can cause more damage to the composite material (i.e. severe burring effect) along with increasing the final manufacturing costs due to constant changing of the drill bit.

III. Preparation Method

A. Upgrade of Ultrasonic Equipment

The aim of the upgrade of the Ultrasonic system is to provide UNSW@ADFA with a working Ultrasonic system incorporating new software that has the ability to produce C-scan images. The C-scan images must be of high enough resolution to detect small delaminations in composite materials.

The initial requirement of the upgrade was to determine if and how each of the components worked. In order to test the capability of the Krauterkramer Ultrasonic Flaw detector, an aluminium step block shown in Fig. 15 was used. Using the handheld pulse echo method with oil as a couplant, the ability of the machine to pick up changes in depth as the probe was moved along the test piece was assessed. Using a 15mHz, 0.325in transducer it was verified that the ultrasonic flaw detector was functioning correctly. The Veriscan microcontroller and monitor require an input of the size of the area needed to be scanned, the scanning speed and the number of increments the mechanical frame should move. The size of the test sample is simply its length and width which have scanning limits between 10cm and 100cm. The transducer needs to be positioned at the point (0,0) on the sample material and begins to scan in the y-direction. Once the transducer reaches the specified length in the y-direction, it moves one increment in the x-direction and continues scanning in the y-direction. The scanning speed has a range of 1 to 99. The length of time that the transducer spends at each point on sample material is governed by the scanning speed. However the Veriscan user manual did not provide information on what the numerical range of speed represents. This proved problematic when differentiating from which point on the workpiece the data had been sampled by the ultrasonic flaw detector. The number of increments ranges from 1 – 10.

Again the user manual fails to mention the length of the increments, ΔL, which will be determined by sectioning the voltage raw data output. The voltage data output should show a distinct change in value when the transducer moves over the increment ΔL. As the sampling rate and the number of samples in the increment are known the distance ΔL can be determined.

Once each component was verified to be working correctly, the second stage of the process required the data to be extracted from the ultrasonic flaw detector during scanning. A 50-pole connection socket is located at the back of the ultrasonic flaw detector and provides a voltage output at each pole corresponding to a function of the flaw detector. An image of the 50-pole connection socket is shown in Fig. 16. To extract the data from the ultrasonic flaw detector a 50-pole plug shown in Fig. 17, is connected to the socket. Using the pin-code diagram and
function table in Appendix A, wires were soldered to the appropriate pins to obtain an analogue output voltage. The significant pins are 9, 10, 17 and 18 which correspond to the initial pulse, the DC voltage proportional to echo height in the gate and two instrument grounds respectively. The connections from the pins are wired to the analogue channels of the National Instruments DAQ device. The DAQ device is connected via a USB cable to a laptop which provides the capability to download the voltage data output from the ultrasonic flaw detector.

In order to verify that the voltage output corresponds to the data that is being obtained from the test sample a program called LabVIEW is used. LabVIEW is a graphical programming environment which has the ability to develop advanced measurement, test and control systems using graphical icons to create block diagrams. It acts as the interface between the Ultrasonic flaw detector and the laptop and provides data analysis and visualisation. By connecting the wires from pins 10 (echo height) and 17 (ground), to a channel and a ground respectively on the analog input of the DAQ device, the voltage values from the Ultrasonic flaw detector can be monitored on the laptop using the waveform graph shown in Fig. 18. By moving the transducer along the aluminium step block, the voltage output of the echo height should vary and be able to be observed on the waveform graph.

Once the connection has been verified to be producing the correct voltage output, a program is required to capture and collate the data. Figure 19 shows the block diagram and the user input window of the LabVIEW program that was constructed to collate the received voltage data. The number of samples, the scan rate and the time out are all counters with user input required. The number of samples depicts the amount of data points that are sampled over a set time. The scan rate or the sampling rate is the frequency at which the points are sampled and a schematic is shown in Fig. 20. For example if the user inputs a value of 500 for the scan rate, 500 samples will be taken every second. Therefore every \( \frac{1}{500} \) of a second one sample is taken. As the number of samples is increased, more data points are collected close together which increases the resolution of an image when it is plotted using the data points. The voltage is collated by the DAQ assistant and exported in an Excel format and on a waveform graph. The waveform graph allows visual monitoring of the output voltages. The table in Excel will contain a column of numerical values which correspond to the voltage values sampled at each of the points.

Once the speed and increment distance is determined from the raw voltage data, the position in x and y coordinates of the mechanical frame at each point can be determined. In order to plot a planar image of the test material the x and y positions and the amplitude of the voltage will be used in a Matlab code. The Matlab code needs to have the ability to determine if there are any voltage peaks between the initial pulse and the first echo which indicate a flaw in the test material. The highest voltage amplitude in the sampled data indicates the maximum amplitude of the initial pulse. The corresponding time of the peak can be calculated from the sampling rate. Similarly, the maximum amplitude and time of the first echo can be determined from the numerical data. As shown in Fig. 21, once the time of the initial peak (\( t_i \)) and the first echo (\( t_e \)) is known the change in time between the peaks (\( \Delta t \)) can be determined. The Matlab code is required to determine which of the sample times are close to the initial peak time and the first echo time. Once the time difference is determined, the position in the x and y coordinates of the mechanical frame at that point can be calculated.

![Figure 19. LabVIEW program: a) block diagram; b) waveform graph](image)

![Figure 20. comparison between high and low data sampling rate](image)
to look for changes during $\Delta t$. If there is no flaw, the time distance between the first two peaks will not change. However if a flaw is present it will create a voltage peak between the initial pulse and first echo. The Matlab code needs to be able to recognise the flaw echo as the second peak which has a lower $\Delta t$ from the initial pulse than the first echo. The main function of Matlab code is to produce a C-scan image of the test sample. To do this it is required to plot any value of $\Delta t$ that is lower than the $\Delta t$ between the initial pulse and the first echo in a white colour which will indicate a flaw. A black colour will be used to plot the $\Delta t$ value when there is no flaw. This will produce a dual colour planar image of the test sample. To further refine the image to show depth, the time differences between the voltage peaks will be compared to one another and a colour gradation will be used to identify depth.

B. Calibration Sample Preparation

A calibration sample of 16 ply CFRP with Teflon inserts was prepared. A plain weave carbon fibre cloth was used with a West System brand 105 Epoxy Resin and a 206 Slow Hardener. 16 pieces of 400mm (fill direction) x 200mm (warp direction) woven fabric were cut and weighed. A ratio of 1:1 was used for the cloth weight to resin and hardener weight. The hardener and resin were then combined using 1 part hardener and 6 parts resin. A layer of clear plastic was placed on the table and the first woven cloth was placed on top. A small amount of the resin and hardener mixture was poured onto the cloth and the plastic sheet was folded over the top of the cloth. The mixture was then worked into the woven cloth until the cloth was saturated by the mixture as shown in Fig. 22. After peeling back the plastic sheet, the second layer of woven cloth was placed on top with the warp and fill direction in the same orientation as the first layer. Again a small amount of resin and hardener mixture was poured on to the fabric and worked into the cloth until it was saturated. The Teflon inserts used to create artificial delaminations are shown in Fig. 23. Each Teflon insert had two pieces of Teflon to ensure that there were two non stick surfaces to create an air gap. A, B and C, the variable width Teflon inserts (30mm, 20mm and 10mm) were placed at the same depth between the 8th and 9th piles. This will determine the smallest delamination width that is able to be detected. The same width Teflon inserts, D, E, F and G were placed at different depths in the laminate in order to investigate the depth at which the artificial delaminations can be detected. Teflon insert D was placed between the 2nd and 3rd plies, Teflon insert E was placed between the 4th and 5th plies, Teflon insert F was placed between the 6th and 7th plies and Teflon insert G was placed between the 8th and 9th plies. The wet layup is cured in a vacuum bag at a pressure of -25Kpa for 12 hours. The pressure is monitored using a gauge placed on the valve. In order to check that there is a tight seal around the workpiece, the vacuum is turned off and the pressure gauge is monitored for any change in pressure to indicate a leak. The layup of the vacuum bag is shown in Fig. 24. The bleeder cloth used was an absorbent tear ply and was only used on one side of the workpiece in order to achieve a smooth surface on the other side. This smooth surface is made up of excess resin and is necessary during handheld ultrasonic testing so the probes run smoothly across the surface. In order to ensure that the Teflon inserts had created an air gap between the layers, a 0.03mm feeler gauge was slipped between the two Teflon inserts.
A calibration sample of 8 ply GFRP with Teflon inserts was prepared. A 5-harness satin glass fibre fabric was used along with four 5mm x 5mm Teflon inserts. The glass fibre cloth was cut out and weighed. A West System brand 206 Slow Hardener and a 105 Epoxy Resin at a ratio of 1:6 was used. The calibration sample was laid up with the warp and fill directions having the same orientation in each layer. The resin and hardener mixture is worked into the glass fabric in the same way as the CFRP sample was prepared. As the glass fibre is moderately clear when cured, the numbers 1 to 4 were written on each of the Teflon inserts to denote which plies there were placed between. Number 1 insert was placed between the 1st and 2nd plies, number 2 insert was placed between the 2nd and 3rd plies, number 3 insert was placed between the 3rd and 4th plies and number 4 insert was placed between the 4th and 5th plies. Seven different depths are able to be tested due to the sample being made up of eight layers. If the glass fibre sample is flipped over number 1 insert is seen to be placed between the 7th and 8th layer. The wet layup of the glass fibre is cured in a vacuum bag under the same conditions as the CFRP sample. However the layup in the vacuum bag included an extra tear ply bleeder cloth to soak up excess resin as the glass fibre produced a smooth enough surface for a handheld probe to be moved along. The layup of the vacuum bag and the calibration sample are shown in Fig. 25 and Fig 26 respectively.

C. Wet layup CFRP Samples for Drilling

Five 200mm x 200mm 16 ply samples of CFRP are prepared for drilling. These samples are made with a plain weave carbon fibre cloth and are laid up in the same way as the calibration sample. As these samples are being prepared for drilling no artificial delaminations are incorporated in the layup. The samples are cured in a vacuum bag with a layup as shown in Fig 25.

D. Wet Layup GFRP for Drilling

Two different types of woven cloth, 5-harness satin and plain weave are used to make up drilling samples using the wet layup process. All samples had dimensions of 200mm (warp) x 250mm (fill) and were of different thicknesses. The 5-harness satin was used to layup one 16-ply sample and two 8-ply samples. The plain weave was used to layup one 8-ply sample. Each sample was laid up with the warp and fill directions of each layer in the same orientation. West System brand 206 Slow Hardener and 105 Epoxy Resin was used with a ratio of 1:6. The samples were cured in a vacuum bag at -25kPa for 12 hours with a layup as shown in Fig 25.

E. Prepreg Layup GFRP for Drilling

Two samples of 200mm x 150 mm 8-ply twill weave prepreg glass fibre were prepared. As the material was pre impregnated with resin, it had been stored in the freezer. The roll of prepreg glass fibre is shown in Fig. 27. Before use, the roll of prepreg was thawed for 24 hours. The first sample was laid up with the same orientation of the warp and fill direction for each ply. The warp direction is denoted by the blue tracer lines in the cloth. The second sample was laid up with 4 plies at +45° and the other 4 plies at -45° [+45/+45/+45/+45/-45/-45/-45/-45]. The stacking
sequences of the both samples are shown in Fig. 28. Both samples were laid up in symmetry with warp face to warp face (stacking) between the 4th and 5th plies. The remaining plies were laid up fill face to warp face (nesting).

The curing process used heat and a vacuum bag. The layup of the vacuum bag was the same layup as shown in Fig. 25; however the bleeder used was a perforated plastic so not as much resin could escape. This is because the prepreg material has less excess resin than the wet layup. The prepreg material was cured at a pressure of -25kPa and a temperature of 250°F for 2 hours. The increase in temperature was 5°F per minute from room temperature and the curing did not begin until the temperature reached 250°F. The second stage of the curing process involved reducing the temperature from 250°F to room temperature at a rate of 5°F per minute.

F. Drilling of CFRP

The four samples of 16-ply CFRP were drilled with and without backing and at different RPM and feed rates using a new 2-flute high speed steel twist drill with a 115° point angle and 12mm diameter as shown in Fig. 29. A ‘Hafco Metal Master’ milling machine was used with three set feed rates of 0.13mm/s, 0.08mm/s and 0.04mm/s and an rotational cutting speed range from 60 RPM to 2800 RPM as shown in Fig. 30.

The first three samples of CFRP were drilled without a backing. This was to compare the effect that variations in feed rate and RPM had on the amount of delamination in the CFRP laminates. They were mounted from the edges on two metal blocks and clamped down as shown in Fig. 31. Each sample was drilled with a constant feed rate and varying rotational cutting speed. Sample one was drilled at a constant feed rate of 0.13mm/s and produced five holes with rotational cutting speeds of 2800, 1800, 800, 400 and 60 RPM. Sample two was drilled at a constant feed rate of 0.08mm/s and produced five holes with RPM’s of 2800, 1800, 800, 400 and 60 RPM. Sample three was drilled at a constant feed rate of 0.04mm/s and produced five holes with rotational cutting speeds of 2800, 1800, 800, 400 and 60 RPM.

The fourth sample was drilled with a backing of 20mm thick wood and was clamped down on two metal blocks. This was to provide a comparison between the damage caused by drilling at the same feed rate and rotational speed with and without a backing. Six holes were drilled at different feed rates and rotational cutting speeds. The fastest and slowest rotational cutting speeds were used at each of the feed rates. Two holes were drilled with a feed rate of 0.13mm/s at 2800 RPM and 60 RPM. Two other holes were drilled at 0.08mm/s at 2800 RPM and 60 RPM. The final two holes drilled were at a feed rate of 0.04mm/s at 2800 RPM and 60 RPM.

The fifth sample was used to look at the effect of the worn drill bit to determine if using the same drill bit for all the holes caused greater damage to the last holes that were drilled. The sample was clamped down without a backing on two metal blocks. Two different feed rates of 0.13mm/s and 0.04mm/s were used at the same rotational cutting speed of 1800RPM. These holes could be compared with previously drilled holes to identify any differences in the damage caused by drilling.
G. Drilling of GFRP

The 16-ply sample and the 8-ply sample of 5-harness satin wet layup GFRP and the two 8-ply samples of twill weave prepreg GFRP were drilled using the “Hafco Metal Master” milling machine without any backing. A high speed steel 2-flute twist drill with 115° point angle and a 2-flute slot drill, both with diameters of 12 mm were used during the drilling process. An image of the slot drill is shown in Fig. 32. The samples were mounted on two metal blocks and clamped down in the same way as the CFRP samples. The 16 ply wet layup sample was drilled first using both the slot drill and the twist drill. The rotational speed and the feed rate were varied in a similar fashion to the CFRP sample. The variation of the rotational cutting speed and the feed rate of the drill allow an assessment of the impact of the drilling parameters on the amount of delamination caused by drilling. Eleven holes were drilled into the 16-ply GFRP sample. The first nine holes were drilled with the twist drill. The first three holes were drilled at a constant feed rate of 0.13mm/s at rotational speeds of 2800, 1800 and 60 RPM. The next three holes were drilled at a constant feed rate of 0.08mm/s at rotational speeds of 2800, 1800 and 60 RPM. Another three holes were drilled at a constant speed of 0.04mm/s at rotational speeds of 2800, 1800 and 60 RPM. The final two holes were drilled with the slot drill at the highest and lowest feed rates and the fastest and slowest rotational speeds. The first hole drilled with the slot drill had a rotational cutting speed of 60RPM with a feed rate of 0.04mm/s. The second hole drilled with the slot drill had a rotational cutting speed of 2800RPM and a feed rate of 0.13mm/s.

The 8-ply 5-harness satin wet layup sample was drilled with both the twist drill and the slot drill. The sample was clamped down on two metal blocks in the same way as the 16-ply 5-harness satin wet layup sample. Eleven holes were drilled using the same drill bits, rotational speeds and feed rates as detailed for the 16-ply wet layup sample. The purpose of using an 8-ply sample was to compare the effect of doubling the thickness of the laminate on the damage caused by drilling.

Both prepreg GFRP layups were drilled without backing using the milling machine. The samples were clamped unto two metal blocks as shown in Fig. 33. Six holes were drilled in each sample using both the twist drill and the slot drill. Sample one had a 0° orientation between the plies and sample two had ±45° orientation of the plies. Both samples were drilled with the same combination of rotational speeds and feed rates with the same drill bit types. This allowed a comparison to be made between different layups whilst keeping the drilling parameters constant. The first four holes were drilled with the twist drill. The first two holes were drilled at a maximum feed rate of 0.13mm/s at 60 and 2800 RPM. The next two holes were drilled at the minimum feed rate of 0.04mm/s at 60 RPM. The final two holes were drilled with a slot drill. One hole was drilled at a feed rate of 0.13mm/s at a rotational speed of 2800 RPM and the other hole was drilled at a feed rate of 0.04mm/s at a rotational speed of 60 RPM.

The final two samples of 8-ply GFRP were prepared using the wet layup method. Sample one used a plain weave fabric and sample two was made up of a 5-harness satin. Both were drilled using a different milling machine to the other samples due to the unavailability of the original machine. The maximum and minimum feed rates of the milling machine were 9.2mm/s and 0.13mm/s respectively. The rotational speeds varied from a minimum of 90 RPM to 2000RPM and had set values on the machine. The samples had a backing of a 20mm thick wooden block and were clamped down along all of the edges of the sample to ensure that there was no separation between the backing and the workpiece during drilling. Eleven holes were drilled in sample one with the plain weave fabric, nine with the twist drill and two with the slot drill. Using the twist drill the first three holes were drilled with the highest constant feed rate of 9.17mm/s at rotational speeds of 2000 RPM, 1280 RPM and 90 RPM. The next three holes were drilled at a constant feed rate of 4.17mm/s at rotational speeds of 2000 RPM, 1280 RPM and 90 RPM. The final three holes that were drilled with the twist drill, were drilled with a constant feed rate of 0.13mm/s at rotational speeds of 2000 RPM, 1280 RPM and 90 RPM. The final two holes were drilled with the slot drill, one at 9.17mm/s with a rotational speed of 2000 RPM and the other at 0.13mm/s with a rotational speed of 90 RPM. The same drilling conditions were used for the second sample with a 5-
harness satin weave. The same combination of drilling parameters used to drill sample one were used to drill the second sample. This allowed a comparison of the effect of the different woven cloths on the damage cause by drilling.

H. Method of Evaluation of CFRP

The calibration sample of CFRP was used to calibrate the handheld ultrasonic flaw detector as shown in Fig. 34. The probe used was an Olympus 10MHz, 0.25 inch diameter immersion probe. This probe is a dual transducer and was selected for use in the automated immersion scanner. However a ‘Panametrics’ Propylene-Glycol couplant was used to ensure that there was no air gap between the wear plate of the transducer and the sample. Propylene-Glycol is a good general purpose couplant and is recommended by Olympus for use on smooth surfaces. It is easily washed off with water, does not cause any damage to the composite material and does not evaporate quickly.

Using the smooth side of the laminate, the probe and couplant was placed on the laminate over a section without any artificial delaminations. An initial pulse showed up on the screen, however no echo pulses were visible on the screen. As the gain was increased so that the initial pulse height was greater than 100% of the screen, no echo pulses were visible, however the noise from the probe increased in amplitude. As the probe was moved over delamination A the initial pulse disappeared and the screen only displayed noise. A conclusion was made that sample was so thin that it was in the near field of the beam from the probe. To overcome this, a 20mm Perspex block was placed in between the probe and the CFRP sample. Couplant was used between the sample and the Perspex block as well as between the probe and the Perspex block to ensure that there were no air gaps. The probe was placed over a section of the smooth side of the laminate which did not contain any artificial delaminations. A gain of 48dB was used to set the initial pulse to 80% of the screen height and at a range of 50mm three back echoes are visible as shown in Fig. 35. As the probe was moved over the delaminations, no peaks were visible between the back echoes. Due the plies being very thin and the distance between the peaks on the screen being very small it is possible that the echo from the artificial delamination was so close to the initial peak that they appeared as one peak. By changing the range to 10mm the peaks were enlarged on the screen as shown in Fig. 36. The peaks are not as sharp and have the appearance of rolling hills. When the probe was moved onto a section with an artificial delamination, it can be seen that the echo from the delamination is merged with the initial pulse. An example is shown in Fig. 37 as the probe is moved over Teflon insert E. The inability of the transducer to separate the peaks is due to the sample being in the far zone of the beam. As the beam width increases the peaks on the screen become less defined. To resolve this, a transducer with a higher frequency could be used or a focused probe with the focal length specific for the thickness laminate.

Every artificial delamination except C was able to be detected. Delamination C had a width of 10mm which is equivalent to 0.39 inches. As the diameter of the probe is 0.25inches it was very difficult to place the probe within the boundaries of the artificial delamination. This caused an edge effect where the edge of the delamination and the edge the hole interfered with the results causing numerous peaks to appear on the CRT screen. This made it impossible to allow identification of the flaw echo. Hence the smallest delamination width and length that the transducer and ultrasonic machine can pick up must be greater than 10mm or 0.39 inches.

Appendix B shows the ultrasonic A-scan results for the CFRP sample testing from both the smooth side and the rough side. The rough side was tested using the same method as the smooth side. As the probe was moved over the artificial delaminations there was a change in the peaks which indicates that there was a change in
acoustic impedance. As indicated by scanning the smooth side of the laminate, the deeper the Teflon insert in the sample, the greater the distance between the initial peak and the flaw echo. Hence when scanning from the opposite side where the Teflon inserts are further from the surface the flaw echo should appear further away from the initial peak. This was true for the artificial delaminations D, E, F and G whose depths from the surface could be differentiated. However delaminations A, B and C, which were at the same depth should have displayed similar initial and flaw echo peak positions. This was not the case and differences in the results could be likened to inconsistencies such as excess resin and in the layup process of the CFRP laminate. This result was consistent with the results obtained from scanning the smooth side of the laminate. As the delamination between the 14th and 15th ply was able to be detected, the handheld ultrasonic method was deemed suitable for use throughout the experiment as the maximum laminate thickness used is 16 plies.

The drilled sample of 16-ply CFRP was tested using the ultrasonic flaw detector. However no delaminations could be detected. This was due to the delaminations being too small and too close to the edge of the hole causing an edge effect. Therefore the samples were sectioned through the drilled holes using a diamond tipped saw to view any delamination damage around the hole as shown in the schematic in Fig. 38. The sectioned samples were placed under a ‘Stemi SV8’ microscope where the surface of the drilled holes was inspected at different magnifications ranging from eight-times to twenty-times.

In an attempt to highlight any fibre pull out and delaminations in the images produced by the microscope, the liquid penetrant method was used. The liquid penetrant method involves cleaning the surface of the hole with a solvent, applying a red dye to the surface and leaving for 20 minutes, removing the red dye with water and solvent and applying a developer. After washing off the red dye from the surface, any red dye that has been left behind in holes and gaps caused by fibre pull out and delaminations is brought to the surface by the white developer. The solvent, red dye and developer are shown in Fig. 39.

1. Method of Evaluation of GFRP

Evaluation of the calibration sample of the GFRP was conducted using the handheld ultrasonic method. Similar to the CFRP calibration sample, a Perspex block was used with ‘Panametrics’ Propylene-Glycol couplant between the laminate and the transducer. The transducer used was an Olympus immersion dual transducer with a frequency of 10mHz and a 0.25 inch diameter. Setting the initial peak height to 80% of the screen height, the 8-ply thick sample was tested from both sides to determine the depth at which the artificial Teflon inserts could be detected. The A-scan results obtained from the CRT screen are shown in Appendix C. Due to the diverging beam from the transducer the voltage peaks are not sharp and the flaw echoes are not well defined. Teflon insert number 1 which is located between the 7th and 8th plies produced a single peak without a back echo or flaw echo. At this depth in the CFRP, the artificial delamination was visible as a voltage peak on the CRT screen. As an artificial delamination close to the surface produces only a single peak, an explanation could be that there was a real delamination close to the surface which was not visible. Hence the artificial delamination could not be detected.

![Figure 38. Schematic of sectioned drilled hole. The red lines indicate where delaminations were expected to be seen](image_url)

![Figure 39. From left to right; solvent, red dye and developer](image_url)

![Figure 40. Stemi SV8 microscope with sectioned GFRP sample](image_url)
The ultrasonic handheld method was used to evaluate the drilled GFRP samples. However as the delaminations caused by the drill were small the transducer was not able to detect them due to interference from the edge effect. Therefore the backlighting method was used to inspect all the GFRP samples.

The backlighting method involved placing a strobe light behind the GFRP samples to create an outline of the hidden delaminations in the laminate. The maximum diameters of the delaminations were measured with a digital Vernier Calliper. This measurement was divided by the diameter of the hole allowing comparisons to be made between the sizes of the delaminations caused by different diameter drill bits. The delamination factors for each of the holes were compared to determine which drilling parameters were most detrimental to the health of the laminate. An analysis of the damage at the entry and exit holes of the laminate was made by a visual inspection. The visual examinations compared the extent of burried edges, thermal damage, uncut fibres and the propagation of the peel up and push out between the drilled holes.

After using the backlighting method, the 16-ply 5-harness satin GFRP sample was sectioned using a diamond tipped saw. A ‘Stemi SV8’ microscope as shown in Fig.40 was used to evaluate the damage caused by the drill to the surface of the hole. The magnification was varied from eight-times to twenty-times.

IV. Results

A. Analysis and Evaluation

The objectives of the analysis of the delamination of the laminate samples are to provide a series of favourable drilling parameters based on the drilling conditions. The drilling conditions include the use of a backing, the orientation plies in the laminate and the type of woven cloth used. Constraints in the aircraft industry such as only one side of a composite laminate being accessible, are simulated by drilling without a backing. A comparison between the drilled samples will provide results for favourable drilling parameters under different conditions. The various conditions are as follows:

- Comparison between the damage due to different thicknesses of the laminate
- Comparison between the amount of damage with and without backing
- Comparison between the damage due to different woven cloth (5-harness satin, twill weave and plain weave)
- Comparison between different layup of material (0° and ±45°)

The damage is assessed on the extent to which the delamination has propagated and on the condition of the entry and exit holes. From this assessment the favourable drilling parameters at different conditions are able to be determined. All raw data for the analysis of the drilled samples are shown in Appendix D.

B. Ultrasonic C-scan

The use of the initial program in LabVIEW produced a numerical column of data in Excel which was incomprehensible. As the probe was manually moved across the aluminum step block the numerical values were only differed very slightly and there was no initial high voltage to indicate the initial peak. In order to check if the voltage data output was delivering the correct data, the Data Acquisition Assistant in LabVIEW was used to view the real time data as shown in Fig. 41. The assistant shows in real time, the output voltage from one channel. The mode is continuous so the voltage data is continuously being taken. The rate in hertz is the frequency at which sampling occurs, so the greater the number, the higher the sampling frequency. The number of samples to read is set to 1000 which asks the Data Acquisition Assistant to take 1000 samples and store them in an Excel spread sheet. The wire from pin 10 which corresponded to the echo height was joined to the analogue channel ‘i0’ which is the channel selected to read the live data from the Data Acquisition Assistant. As the probe was moved along the aluminum step block the Amplitude vs. Samples Chart did not not change. The expectation was to view the same voltage peaks from the back echos that were shown on the CRT screen of the ultrasonic flaw detector. It was concluded that the chart view was just noise as, upon removal of the probe from the step block, the voltage did not change program such as

Figure 41. Screenshot of Data Acquisition Assistant: Real time peaks from Ultrasonic flaw detector
Matlab which is compatible with NIDAQs to try and interpret the voltage data. However due to time constraints this part of the thesis could not be pursued any further.

C. Analysis of CFRP

The damage caused by the drill was evaluated under the microscope and images are shown in Appendix E. Due to the thickness of the 16-ply samples there was very little damage caused by the drill. The strength of the laminate in the through thickness direction was high and opposed the axial force induced by the drill. Therefore the drilling process did not produce visible peel up or push out around the drilled hole. The disadvantage of using CFRP is that it does not transmit light so the only way to view hidden delaminations is through ultrasonic testing. As the equipment was unable to detect small delaminations, the CFRP laminates were unable to be tested using the ultrasonic method. It was very difficult to quantify the amount of damage caused by the drilling as there was very little delamination in the CFRP laminate. The three different feed rates (0.13mm/s, 0.08mm/s and 0.04mm/s) can be differentiated due to the smoothness and thickness of the cut. At the same rotational speed it can be seen that the surface of the drill hole has finer cuts and a smoother surface with the low RPM of 0.04mm/s. As the feed rate increases the drill moves faster through the laminate and hence takes bigger cuts. The decrease in RPM at all three feed rates showed a greater damage at the exit holes. There is visible fibre pull out on the surface of the holes. However the densities of fibre pull out for each of the holes were very similar. Overall there was very little variation in the damage caused by the different drilling rotational speeds and feed rates in the 16-ply CFRP laminate drilled without a backing support. Based on the roughness of the cut and the damage caused at the exit holes, a low rotational speed (less than 1800 RPM) is not favourable. It was noted that the high feed rates produce a rougher cut and hence are not as favourable as the lower feed rates. The images are compared with the CFRP laminate which was drilled without a backing using the same combination of feed rates and rotational speeds. Figure 42 shows a comparison between the laminate drilled without backing the laminate drilled with backing. It can be seen that the laminate closer to the exit hole are being bent by the axial force of the drill. Smoother and straighter cuts were produced with a support backing against the laminate. The effect of the worn drill bit was tested after twenty-one holes were drilled to determine if the damage to the holes was worse. When placed under the microscope and compared to the hole previously drilled at the same feed rate and rotational speed, there was no visible difference between the two holes. The purpose of this is to ensure that the final hole drilled, produces a delamination due to the changing drilling parameters such as feed rate and rotational speed and not due to the wear of the drill bit. Hence effect of the worn drill bit can be neglected when drilling approximately 20 holes with the same drill bit.

The liquid penetrant method was used in an attempt to make any delaminations stand out against the black carbon fibre. However the cut surface of the hole was very absorbent and the red dye showed up over the entire surface when the developer was used. Hence an attempt to use the liquid penetrant method was unsuccessful.

Figure 42. Comparison between CFRP laminate at 0.13mm/s @ 2800 RPM: a) without backing support; b) with backing support

D. Analysis of Wet Layup GFRP

The images of the entry and exit holes, the sectioned samples using the microscope and the delaminations viewed using the backlight are shown in Appendix F.

There was minimal damage caused by the drill on the 16-ply GFRP sample. A very small circle of delamination was visible around the holes that were drilled with the twist drill which were of similar size for all the holes. The holes that were drilled with the twist drill at the lowest feed rate of 0.04mm/s at 2800 RPM and 1800 RPM produced a greater fibre push out at the exit hole. The fibres were pushed out rather than cut with the drill causing delamination in the lamina close to the exit. The holes that were drilled with the twist drill at 60 RPM also produced burred exit holes. The cleanest holes were produced by high feed rates of 0.13 mm/s and 0.8 mm/s at high rotational speeds of 2800 RPM and 1800 RPM. The entry holes had very small pull up and the amount of damage could not be differentiated between the holes.

However using the slot drill on the 16-ply GFRP sample produced the cleanest entry holes and the largest delamination at the exit hole. The large delamination in the plies closest to the exit hole could be due to the larger distribution of axial force generated by the drill. A comparison between the slot drill end configuration and the twist drill end configuration is shown in Fig. 43.
The axial force of the slot drill is distributed over a larger area as the face of the drill sits flush with the laminate. As the thrust force pushes down on the uncut piles, the larger area of the drill face causes the delaminations to propagate out from the hole. In comparison to the slot drill, the twist drill has a much smaller area (chisel edge) which meets the laminate first, where the thrust force is concentrated. As the thrust force from the chisel edge pushes down on the uncut plies, the delamination area does not propagate as far as the slot drill. Hence the twist drill produced less delamination in the plies closest to the exit surface of the laminate. As the force created by the slot drill was being distributed over a larger area, the slot drill produced cleaner entry holes in comparison to the twist drill.

The holes that were drilled with the twist drill had a small amount of fibres that were pushed out at the exit, but when using the slot drill a large area was delaminated at the exit hole. An exit hole at the same feed rate and rotational speed for a slot and twist drill is shown in Fig. 44. It can be seen that the slot drill causes a much larger delamination in the GFRP laminate than the twist drill.

The 16-ply GFRP laminate was analysed under the microscope to look at the surface damage of the hole. There is a significantly lower amount of fibre pull out in the GFRP holes in comparison to the CFRP holes. However a direct comparison between the CFRP and GFRP laminates cannot be made due to the different type of woven fabric used in their manufacture. The slight delaminations that were visible around the hole when using the backlight was verified when the sample was sectioned and viewed under the microscope at 8x magnification. The delaminations are of similar size for each hole and are visible on the edge of the drilled hole as shown in Fig. 45. Again it was very difficult to find any difference between the surfaces of each drilled hole to determine the most favourable drilling parameters. At the lowest rotational speed of 60RPM there are noticeable black burn marks on the surface of the drilled hole at all three feed rates. Due to the very low rotational cutting speed, the heat from the friction generated by the drill bit has caused thermal damage in the laminate. It was difficult to analyse the damage caused by the drill on the 16-ply laminate due to the minimal damage around the drilled hole. Overall the low rotational speed of 60 RPM produced thermal damage on the surface of the drilled hole and produced burred exit holes. The low feed rate of 0.04mm/s was not favourable due to the extent of burring.
at the exit of the hole. The slot drill produced the worst exit hole delaminations and the cleanest entry holes at combinations of the highest feed rate at the highest rotational cutting speed and the and lowest feed rates at the lowest rotational speed in comparison to the twist drill.

The 8-ply 5-harness satin GFRP sample that was drilled without a backing produced a larger amount of delamination overall in comparison with the 16-ply GFRP sample. This was due to the reduction in thickness of the laminate which reduced the available strength to oppose the axial thrust force created by the drill. Due to the cloth being a 5-harness satin there are more fibres in the warp direction than the fill. Delaminations propagate in the fibre direction and in the case of a woven cloth, delaminations propagate in the direction with the greatest amount of fibres. This is evident when looking at the delaminations at the exit and entry holes, as the fibres are peeled up and pushed out in the warp direction. From visual inspection of the entry holes that were drilled with the twist drill, the feed rates of 0.13mm/s and 0.08mm/s produced the worst pull up at both high and low rotational speeds and a similar level of damage at the exit holes. The twist drill with the combination of the low feed rate of 0.04mm/s and low rotational speed of 60 RPM also produced large peel up at the entry hole and large push out at the exit hole. In order to further differentiate the damage caused by the drilling parameters, back lighting was used to look at the internal delaminations. Figure 46 shows a graphical representation of the delamination factor of each hole drilled with the twist drill with respect to the feed rate and rotational speed. From the graph it can be seen that the highest rotational speed and the lowest feed rate produced the smallest delaminations.

The 8-ply sample that was drilled with the slot drill produced the same result as the 16-ply sample. The entry hole was clean and exit hole was burred with delaminations close to the surface. A graphical representation of the amount of delamination caused by the slot drill and the twist drill at the same rotational speeds and feed rates is shown in Fig. 47.

The analysis of the results for the 8-ply sample concluded that low feed rates with high RPM produce clean entry and exit holes with minimum delamination. A thinner laminate produces larger amounts of delamination when drilled and the slot drill produced a larger amount of delamination closer to the exit hole than a twist drill.

C. Analysis of Prepreg Layup GFRP

The two prepreg 8-ply GFRP laminates at ±45° and 0° layup orientation produced similar damage results. The 0° layup produced significant peel up at the entry of the holes that were drilled with a twist drill at a high feed rate of 0.13mm/s at rotational speeds of 60 RPM and 2800 RPM. Significant peel up was also evident at the hole that was drilled at a low feed rate of 0.04mm/s at a rotational speed of 60 RPM. Consistent with the results of the 8-ply wet layup, the highest rotational speed, 2800 RPM, and the lowest feed rate, 0.04mm/s using the twist drill, produced the cleanest entry hole with barely visible damage. All the holes drilled by the twist drill produced fibre push out at the exit holes. Using the back lighting, the hidden delaminations around each hole were visible. The holes that were drilled with the slot drill produced very clean entry holes,
however also produced large delaminations in the plies close to the exit hole and fibre breakage at the exit hole. The delamination around the drilled holes propagates in the warp direction due to the majority of fibres running in the warp direction on that side of the woven cloth.

The ±45° layup of GFRP produced delaminations of similar size to the 0° prepreg layup. The trends in the delaminations caused by the twist drill and the combination of high rotational speed and high feed rate are consistent with the trends observed in the 0° prepreg layup. Again the slot drill produced clean entry holes and large delaminations in the plies closer to the exit of the hole. Figure 48 shows a graphical representation which compares the damage caused by the ±45° prepreg layup, the 0° prepreg layup and the 0° wet layup. The low feed rates and high rotational speeds produced the lowest delamination factor in all three cases.

The wet layup, made up of a 5-harness satin has a higher strand density than the twill weave prepreg samples. The 5-harness satin produced the lowest delamination factor for each hole drilled using the twist drill. This may be due to the 5-harness satin having a higher number of weaves per centimetre which produces a fabric which holds together better than the twill weave fabric.

In all cases the delaminations separated the plies and propagated in the direction which had the greatest fibre count. From the results obtained from the three 8-ply samples, the material parameter which plays a prominent part in the delamination caused by drilling is the fibre density or the number of weaves per centimetre. As can be seen from the graph the wet layup of GFRP has the lowest delamination factor at each of the combinations of feed rate and rotational speed.

The drilling parameters had a constant trend between the three 8-ply GFRP samples. As the feed rate increased at a high rotational speed of the drill, the delamination factor increased. At a low rotational speed and decreasing feed rate the delamination factor decreased. Therefore the different layups and fabric types did not cause a change in the trends of the drilling parameters. The increase in feed rate has a greater effect on the 5-harness satin at a high rotational speed (2800RPM) than it does on the twill weave fabric. However the delamination factor is still less than the delamination factor in the twill weave fabric. The increase in feed rate at a low rotational speed (60RPM) does not cause as great an increase in the delamination factor of the 5-harness satin sample as it does at a high rotational speed (2800RPM). This shows that although the 5-harness satin is sensitive to changes in feed rate at high rotational speeds, it has a low sensitivity to changes in feed rate at low rotational speeds. Both the 0° and ±45° prepreg layup responded similarly to variations in feed rate and rotational speed as shown by the gradient of the line joining the two points on the graph. The average value of the delamination factor for the ±45° twist weave prepreg was slightly higher than that of the 0° twist weave prepreg.

A comparison between the two prepreg samples which are both made up of a twill weave fabric, allows an evaluation of the effect of different ply orientation on the delamination caused by drilling. As can be seen from the graph the ±45° prepreg sample produced slightly higher delamination factors than the 0° prepreg sample at the same combination of rotational speed and feed rate. The difference between the delamination factors obtained from the 0° and ±45° prepreg samples is quite small and the tests should be repeated to verify and confirm the results.

The layup of the prepreg samples did not affect the delamination size as greatly as the type of fabric used. Previous research (Kelly 1994; Taggart &
Schwan 1987) has shown that varying the ply orientation has increased the strength of the laminate in compression and tensile testing and made it more robust. Therefore the expected results were that the ±45° sample would produce the lowest delamination factor in comparison to the 0° layup. The layup may not have played a prominent part in the size of the delamination generated through drilling, due to the drill generating an axial force in the through thickness direction. As the force was acting in the axial direction and the purpose of the varying ply orientation was to increase the strength in the fibre direction, the drill producing a force perpendicular to the fibre direction was not significantly affected by the orientation of the plies.

A possible reason for the higher delamination factor in the ±45° sample could be that four +45° plies were stacked on top of each other and then four -45° were stacked on top of those plies. As there were only four plies of the same orientation as compared to eight in the 0° layup, the bonding strength in the fibre direction was less and the delaminations propagated further.

In both prepreg GFRP samples the slot drill produced larger delaminations than the twist drill. A comparison between the slot and twist drill delamination factors is presented in Fig 49.

D. Analysis of Wet Layup GFRP with Backing

The 8-ply plain weave and a 5-harness satin GFRP samples produced similar results.

The trends observed with respect to varying the drilling parameters of drill bit type, rotational speed and feed rate in the GFRP samples drilled without a backing were not replicated in the sample drilled with a backing. A direct comparison of the feed rates and rotational speeds could not be made due to the settings on the two different milling machines not corresponding. However a general observation of altering feed rates, rotational speed and drill bit types can be examined.

A graphical representation of the delamination factor for both samples using the twist drill is shown in Fig. 50. The 8-ply 5-harness satin produced the smallest amount of delamination at the higher feed rates of 4.17mm/s and 9.17mm/s at the highest rotational speeds of 2000 RPM and 1280 RPM. The trend with increasing feed rate for rotational speeds of 1280 RPM and 2000 RPM is very similar, possibly due to the rotational speeds being close in value. The lowest rotational speed of 90 RPM produced the smallest delaminations at the lowest feed rate and as feed rate increased the delaminations worsened. The largest delamination factor was caused by a high feed rate of 9.17mm/s and a low rotational speed of 90 RPM.

Figure 51 shows images of the worst peel up damage caused to the laminate. The worst peel up was caused...
by a rotational speed of 90 RPM at 9.17 mm/s and 4.17 mm/s. The only other drilling parameters that caused a visible peel up damage were a combination of a feed rate of 0.13 mm/s and rotational speeds of 2000 RPM and 1280 RPM. The three holes that were drilled at 0.13 mm/s were the only holes that produced visible push out damage. As can be seen from Fig. 51, holes A and B do not have any sharp burred edges when compared with holes C and D. From running a finger around the inside of holes A and B, it became evident that the surface of the hole was only soft fibres without resin. In contrast the surface of holes C and D still maintained the resin matrix and fibres and maintained a roughened texture. An explanation for the soft fabric in holes A and B could be the low rotational cutting speed generating a large amount of friction. As the rotational speed is slow, the drill bit is constantly rubbing the surface of the hole generating heat which may have burnt or rubbed the resin matrix of the glass fibres. This explanation is feasible as the drill bit was extremely hot on completion of drilling and caused the wooden backing to start smoking during drilling.

The feed rate of 0.13 mm/s was used for both samples of 8-ply harness satin drilled with and without backing support at similar rotational speeds. The 8-ply harness satin sample that was drilled without a backing at a feed rate of 0.13 mm/s at 1800 RPM was compared to the 8-ply harness satin sample that was drilled with a backing at a rotational speed of 2000 RPM. Although the sample drilled with a backing used a rotational speed of 2000 RPM, by observing the effect of changing the rotational speed in Fig. 50 by 720 RPM, a difference in rotational speed of 200 RPM should not produce any change in delamination results around the hole. A comparison between the holes is shown in Fig. 52. The hole drilled without a backing produced large peel up, however the fibre and resin matrix had not separated and had created an abrasive surface around the hole. The push out delaminations and thermal damage was greater in the sample drilled with a backing. A possible reason that the sample that was drilled with a backing caused thermal damage to the laminate could be the lack of airflow underneath the laminate due to the wooden support. However further research is needed to verify this claim.

The 8-ply plain weave cloth produced similar delamination factor trends to the 8-ply 5-harness satin. The drilling parameters that produced the least delaminations were feed rates of 4.17 mm/s and 9.17 mm/s at 2800 RPM and the worst delaminations were produced by a low rotational speed of 90 RPM in combination with a high feed rate of 9.17 mm/s. The delamination factor value recorded at 1280 RPM and 9.17 mm/s is abnormally large. Through observing the trends in the variation of rotational speed for the other GFRP samples, the delamination factor is considered an anomaly which needs to be verified by repeating the tests. This conclusion was based on considering that the difference in rotational speed between 90 RPM and 1280 RPM is more significant than the difference in rotational speed between 2000 RPM and 1280 RPM. Therefore this should produce a delamination factor closer to the value obtained at 2000 RPM which is a similar result to that obtained with the 5-harness satin.

Peel up occurred at the entrance of every hole drilled with the twist drill. Again the high feed rates of 9.17 mm/s and 4.17 mm/s at 90 RPM produced the worst peel up damage followed by the two holes drilled at a constant feed rate of 0.13 mm/s at rotational speeds of 2000 RPM and 1800 RPM.

The plain weave GFRP sample consistently produced a higher delamination factor than the 5-harness satin GFRP at the same feed rates and rotational speeds. During layup it was noted that the plain weave fabric was not as tightly woven as the 5-harness satin and had a lower fibre density. Similar to the twill weave fabric which had a lower fibre density when compared to the 5-harness satin, the plain weave produced larger delaminations around the drilled hole. Hence a high fibre density fabric with a tighter weave produces a laminate with higher through thickness strength.

The slot drill produced the best entry and exit holes with very little peel up and push out when compared to the twist drill. From the drilling results without backing there was a large amount of push out and delamination between the lower plies of the laminate when the slot drill was used. A comparison between the delamination caused by the slot drill with and without backing is shown in Fig. 53.
backing support provided extra through thickness strength that opposed the axial force of the drill and reduced the delamination damage even at the higher feed rate. Using a backing support, the plain weave laminate produced some small delaminations between the plies close to the exit hole. The 5-harness satin produced barely visible push out near the exit hole when drilled with the slot drill.

Overall, the best drill bit type to use when drilling GFRP with a backing is a slot drill. When using a twist drill, the best combination of feed rate and rotational speed is a high feed rate of 4.17mm/s with a rotational speed of 2000 RPM. A fabric with a higher fibre density and tighter weave such as the 5-harness fibre provides better through thickness strength than a plain weave and should be the material of choice when drilling.

V. Uncertainties

The uncertainty in the results which quantify the extent of delaminations in the composite samples is a consequence of:

- The measuring instrument
- The sample being measured
- Operator skill

The measuring instrument used to determine the diameter of the delamination around the drilled was a Vernier Caliper. The Vernier Caliper has a digital display which provides length measurements to two decimal places. Doubt exists about the result of each measurement taken and the uncertainty associated with a digital Vernier Caliper is ±0.01mm. To calculate the delamination factor, the maximum delamination diameter is divided by the hole diameter. Due to the burring around the entry and exit of the holes causing difficulty in measuring the diameter of the hole, the diameter of the drill bit was measured using the Vernier Calipers to be 12.00mm with an uncertainty of 0.01mm. In order to determine the uncertainty of the delamination factor calculations, Eq. (2) is used.

$$\frac{\delta DF}{DF} = \frac{\delta D_{max}}{D} + \frac{\delta D}{D}$$

Solving for ΔDF for each of the holes measured, the uncertainty of the calculation used to determine the delamination factor was equal to ±0.002 when rounded to three decimal places. As this calculated uncertainty is significantly less than the uncertainty of the measured data, it is deemed negligible.

The GFRP and CFRP samples which were manufactured using the wet layup technique had inconsistencies in the laminate. The fabric that was used warped easily so the layup may have included voids where fibres in the cloth had moved apart. During cure the resin and hardener may not have spread evenly throughout the laminate causing varying properties throughout the laminate. Upon measuring the thickness of the laminate samples after cure, they were found to be inconsistent over the sample. Hence as some areas of the sample were slightly thinner than others this would have an effect on the drilling results obtained. The prepreg layup proved to produce a sample with a consistent thickness. Damage trends are evident between samples of wet layup and prepreg layup when varying drilling parameters and hence it was deemed that the feed rate, the rotational cutting speed and the drill bit type were more influential than the slight deviations in thickness of the laminate. This uncertainty provides the best reasoning in observing any anomalies in the results. The variation in thickness of the laminate can be deemed negligible; however repetitions of the experiment should be conducted to reduce the uncertainty.

The measurement process involved reading fine detail by eye when aligning the Vernier Calliper with the delamination diameter. This operator skill contributes to the overall uncertainty in the measurement of the delamination around the hole.

VI. Recommendations

Due to the growing popularity of composites use in the aviation industry an extension of the research in this thesis is recommended to better understand the influence drilling under different conditions has on the structural integrity of the laminate. The tests that have been performed should be repeated numerous times to ensure that the results observed are statistically significant and are not anomalies. Further research is required to determine the cause of soft fibres on the surface of the hole observed in the drilling of the GFRP samples with a backing. The use of a coolant during drilling is recommended to be tested to determine if thermal damage can be minimised. Another method that could be employed to analyse the hidden delamination damage is to take thickness measurements of the laminate over the area which will be drilled. The thickness of the laminate should be measured both before and after it is drilled. If delaminations occur in the laminate during drilling, the plies will separate, causing the thickness of the laminate to increase. Therefore the delaminations can be detected through thickness measurements.
The effect of the type of drill bit was limited in this thesis so for future research it is recommended to use various types of drill tips (i.e. step drill) in order to determine if they can produce holes with less damage than a slot drill. Unidirectional laminates were not used in this thesis and a comparison between a unidirectional cross-ply laminate with a \([0°/90°]\) layup to a plain weave cloth laminate would to determine if the woven cloth has a higher through thickness strength than the unidirectional cross ply even though the fibres are orientated in the same direction.

Developing the ultrasonic C-scan machine software for future use would benefit the school greatly as it provides an automated method to analyse the structural integrity of composite materials with a reduction in operator variables. The recommended probes for future immersion testing of flat composite laminates should have a spherical focus as shown in Fig. 54. The focal target of the probe should be a Flat Plate Focus (FPF) where the lens is manufactured to supply a maximum pulse echo from a flat plate target at the specified focal length. It is recommended that before purchase of specialised probes a test sample of the material is sent to the Olympus laboratories so that qualified technicians are able to recommend the frequency, diameter and focal length of the probe needed for a particular sample. This would enable a more accurate analysis on the 16-ply CFRP and GFRP samples and provide more conclusive results.

VII. Conclusion

This thesis has presented an investigation into the effects that variations in drilling parameters have on CFRP and GFRP laminates. The drilling parameters of feed rate, rotational speed and drill bit type have been varied at various conditions including drilling with and without a backing support, drilling of different woven cloths and the drilling of different ply layups. The most favourable and the least favourable drilling parameters have been selected at each of the various conditions. Through analysis the most influential parameters that cause the worst damage to the laminate are identified. This investigation has made use of various methods of analysis including backlighting, ultrasonic testing and sectioning to investigate the damage caused by drilling in the laminate. In particular ultrasonic testing was a favourable technique as it has been proven to be superior to other methods of analysis in the detection of delaminations in composites. As part of a supporting objective to provide an analysis using ultrasonic testing, an effort was made to upgrade the automated ultrasonic immersion C-scan equipment at UNSW@ADFA.

The contributions of this thesis include:

- Established most favourable and least favourable drilling parameters for CFRP and GFRP laminate drilled without a backing support. Using a twist drill, the combination of high rotational cutting speed (1800 – 2800 RPM) and low feed rate (0.04m/s) produced no detectable delaminations and clean entry and exit holes. The least favourable parameters using a twist drill are a combination of high feed rate (0.13mm/s and 0.08mm/s) and both low and high rotational cutting speeds (60 – 2800 RPM) and using a combination of low feed rate (0.04mm/s) and low rotational cutting speed (60 RPM). Using a slot drill in comparison to the twist drill produced larger delaminations and cleaner entry holes.

- Established most favourable and least favourable drilling parameters for GFRP laminate with a backing support. Using a twist drill, the combination of high feed rate (4.17 – 9.17mm/s) and high rotational cutting speed (1280 – 2000 RPM) were the most favourable drilling parameters as they produced no detectable delaminations and clean entry and exit holes. The least favourable drilling parameters are combinations of high feed rate (4.17 – 9.17 mm/s) and low rotational cutting speeds (90 RPM) and low feed rates (0.13mm/s) at high rotational cutting speeds (1280 – 2000 RPM). The slot drill produced the no detectable delaminations and the cleanest entry and exit holes in comparison to the twist drill and so its use with a backing support is favourable during drilling.

- Established the effect of woven cloth type on drilling parameters. The 5-harness satin fabric provided the greatest resistance to delaminations during drilling followed by the 2x2-twill weave fabric and finally the plain weave fabric.

- Established the effect of different ply orientation of a 2x2-twill weave fabric on drilling parameters. A layup of \([+45°/+45°/+45°/+45°/-45°/-45°/+45°/-45°]\) produced slightly larger delaminations during drilling in comparison to a layup of \([0°/0°/0°/0°/0°/0°/0°/0°]\).

- Established the effect of variation in the thickness of a laminate on drilling parameters. As the thickness of the composite laminate increases, the smaller the delaminations developed during drilling.
• Established the requirements to upgrade the Ultrasonic C-scan equipment at UNSW@ADFA.
  Recommendations are able to be made to continue the upgrade of the equipment. More time and a
  familiarisation with the software programs are required and further testing is needed to interpret the
  voltage data that is being extracted from the ultrasonic flaw detector.

The objectives of this thesis have been achieved in that an investigation of the effect of varying drilling
parameters under different condition was completed and the most favourable drilling parameters were
presented. Although further work in the way of repeating and expanding drilling experiments and
completing the upgrade of the Ultrasonic C-scan machine is required, this thesis provides an overview of
the damage caused by drilling composite laminates. Research in the area of drilling is important as it will
provide solutions to reducing the damage caused during mechanical bonding of composite materials.

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