CRANFIELD UNIVERSITY

Leigh Dunn

Investigating accidents involving aircraft manufactured from polymer composite materials

School of Engineering

PhD
Academic Year: 2009 - 2013

Supervisors: Prof. Graham Braithwaite & Dr. Matthew Greaves
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ABSTRACT

This thesis looks into the examination of polymer composite wreckage from the perspective of the aircraft accident investigator. It develops an understanding of the process of wreckage examination as well as identifying the potential for visual and macroscopic interpretation of polymer composite aircraft wreckage.

The in-field examination of aircraft wreckage, and subsequent interpretations of material failures, can be a significant part of an aircraft accident investigation. As the use of composite materials in aircraft construction increases, the understanding of how macroscopic failure characteristics of composite materials may aid the field investigator is becoming of increasing importance.

The first phase of this research project was to explore how investigation practitioners conduct wreckage examinations. Four accident investigation case studies were examined. The analysis of the case studies provided a framework of the wreckage examination process.

Subsequently, a literature survey was conducted to establish the current level of knowledge on the visual and macroscopic interpretation of polymer composite failures. Relevant literature was identified and a compendium of visual and macroscopic characteristics was created.

Two full-scale polymer composite wing structures were loaded statically, in an upward bending direction, until each wing structure fractured and separated. The wing structures were subsequently examined for the existence of failure characteristics. The examination revealed that whilst characteristics were present, the fragmentation of the structure destroyed valuable evidence.

A hypothetical accident scenario utilising the fractured wing structures was developed, which UK government accident investigators subsequently investigated. This provided refinement to the investigative framework and suggested further guidance on the interpretation of polymer composite failures by accident investigators.

Keywords: Fractography, Reconstruction, Failure Analysis, Fracture, Mishap

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"*If I have seen further it is by standing on the shoulders of giants" – Isaac Newton, 1676*

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LIST OF ABBREVIATIONS

AAIB	Air Accidents Investigation Branch
ADREP	Accident/Incident Data Reporting
AIBN	Accident Investigation Board Norway
ASC	Aviation Safety Council
ASI	Air Safety Investigator
ATSB	Australian Transport Safety Bureau
BEA	Bureau d'Enquêtes et d'Analyses pour la sécurité de l’aviation civile
BFU	Bundesstelle für Flugunfalluntersuchung
BVID	Barely Visible Impact Damage
CAA	Civil Aviation Authority
CAIAC	Comisión de Investigación de Accidentes e Incidentes de Aviación Civil
CFP	Carbon Fibre Polymer
CFRP	Carbon Fibre Reinforced Polymer
CIS	Commonwealth of Independent States
CSAIC	Cranfield Safety and Accident Investigation Centre
CT	Computed Tomography
CVR	Cockpit Voice Recorder
DCB	Double Cantilever Beam
DOA	Department of Agriculture
DOE	Department of Energy

ESCC	Environmental Stress Corrosion Cracking
ENF	End Notched Flexure
FAA	Federal Aviation Authority
FALN	Failure Analysis Logic Network
FOQA	Flight Operations Quality Assurance
FRP	Fibre Reinforced Polymer
GA	General Aviation
GFRE	Glass Fibre Reinforced Epoxy
GFRP	Glass Fibre Reinforced Plastic
GPWS	Ground Proximity Warning Systems
HMSO	Her Majesty's Stationary Office
HSE	Health and Safety Executive
ICAO	International Civil Aviation Organisation
ISASI	International Society of Air Safety Investigators
LOC	Loss of Consciousness
MilAAIB	Military Air Accident Investigation Branch
MN	Mega-Newton
MOD	Ministry of Defence
MOT	Ministry of Transport
NASA	North Atlantic Space Authority
NDE	Non-Destructive Examination
NIAR	National Institute for Aeronautical Research

NTSB	National Transportation Safety Board
PEEK	Polyether ether ketone
PIP	Planned Investigation Program
PTSD	Post-Traumatic Stress Disorder
QI	Quasi-Isotropic
RAE	Royal Aeronautical Establishment
SEM	Scanning Electron Microscope
SME	Subject Matter Expert
TCAS	Traffic Collision Avoidance System
TSB	Transport Safety Board
TSI	Transport Safety Investigator
UD	Uni-Directional
UK	United Kingdom
UN	United Nations
US	United States
USAF	United States Air Force
USSR	Union of Soviet Socialist Republics
VMC	Visible Meteorological Conditions

1 INTRODUCTION

1.1 Introduction to research

With unstable fuel prices and an increasing awareness of broader environmental issues, such as noise and emissions, the offer of commercial aircraft which provide new levels of fuel efficiency and a reduced environmental impact is of increasing importance to airlines, consumers and the broader community (King, 2007). Whilst developments in commercial aircraft design to meet such requirements have encapsulated many elements of aircraft architecture, it is expected that “most new aircraft will feature primary structures of advanced materials such as composite” (Apffelstaedt, Langhans and Gollnick, 2009: 12).

The commercial air transport industry has already seen the introduction of the Boeing 787, an aircraft that entered commercial service in 2011 and contains 50% composite material content by structural weight (Brosius, 2007). Furthermore, the growth in usage of polymer composite materials for airframe manufacture is evident in other aircraft categories such as business jets, rotorcraft, military and light aircraft. It is apparent that the aerospace industry is undergoing a transition whereby polymer composite materials are replacing aluminium alloys as the material of choice for airframe construction.

This transfer to polymer composite materials has been promoted by the offer of significant advantages over traditional aluminium alloy structures. Examples include better fatigue resistance, higher strength to weight ratio and a greater corrosion resistance. This transition is not without its disadvantages however. The aviation industry has much experience in aluminium alloy as an airframe material. Fatigue, a significant form of degradation in aluminium alloy structures, is relatively well understood with the initial recognition of the problem dating back to the early 1800’s (Schütz, 1996). Development of our understanding of fatigue has been promoted by the occurrence of catastrophic accidents (Schijve, 2003). A survey, albeit conducted between the years of 1934 and

1979, by Campbell (1981), revealed that 306 accidents had been attributed to metal fatigue resulting in some 1803 fatalities.

It is reasonable to suggest that the above mentioned statistics are entirely dependent on the investigation identifying metal fatigue in these accident aircraft. In essence, the ability of aircraft accident investigators to recognise either the physical presence or symptoms of fatigue failure, is crucial in increasing our understanding of the phenomenon, and hence our ability to prevent future occurrence. It is recognised, however, that the established experience and understanding by accident investigators regarding the failure modes of aircraft constructed of aluminium alloy is not necessarily transferrable to that of polymer composite materials.

Consider the differences in properties between the two material groups. Metallic materials, such as aluminium alloys, can provide a valuable source of information during an investigation. For ductile metals, plastic deformation of the material during failure creates a visual record of the events that had unfolded. Furthermore, metals typically allow the macroscopic differentiation between progressive (e.g. fatigue) and static (e.g. overload) fracture surfaces. The ability of an investigator to differentiate between these two failure modes can be critical to an investigation.

Composite materials however, are brittle, behave differently, and contain complex fracture surfaces. Moreover, whilst composite materials have a higher level of resistance to traditional degrading factors such as fatigue, they have introduced new failure modes such as compression after impact, a condition which can significantly reduce the strength of a composite structure. This is unlike metals which have no similar failure mode and hence there is little experience within the investigation industry on recognising failures which are generally unique to composite materials.

Whilst it is recognised that the investigation process is not necessarily reliant on a single source of evidence but is, instead, a complex process that encapsulates a variety of information sources. It would also be questionable to suggest that other sources of evidence could substitute the requirement for a wreckage investigation. The investigation community is entering a period where composite materials are increasingly dominating aircraft construction yet the experience in understanding new failure modes in aircraft wreckage is still in its infancy. By increasing knowledge on failure mode recognition, an opportunity exists to increase the information that can be retrieved by the investigator from aircraft wreckage. In turn this increases the ability to learn from accidents and hence promotes flight safety through accident reduction. There is therefore an urgent need for research aimed at assisting aircraft accident investigator practitioners in the examination of composite material aircraft wreckage.

Procedures for the examination of aircraft wreckage are relatively mature. According to the International Civil Aviation Organisation (ICAO) Manual of Aircraft Accident Investigation (ICAO, 1970: III-5-1), the detailed examination of the aircraft wreckage, known as the ‘Structures Investigation’, “covers the investigating and reporting upon the airframe of the aircraft. This includes primary and secondary structure, lift and control surfaces”. It includes the examination of the aircraft wreckage at the accident site and a subsequent examination in a secure environment where the investigation and reconstruction can occur at a controlled pace.

Evidently, there are several procedures for aircraft wreckage examination, but currently a theoretical approach is somewhat anecdotal. An understanding has been suggested through personal experience or training literature. One such example was presented by Heaslip (1973) as the Planned Investigation Program (PIP) (figure 1-1). This sequenced the process of investigation using prominent activities conducted during a major investigation. Additionally, the process path and associated relationships were highlighted between the activities. It was created by the Canadian Ministry of Transport (MOT) and was designed with the purpose of creating a structured plan for the investigation of a major accident. This is in contrast to techniques involved in the examination of wreckage, where a rich, predominantly practitioner led, understanding exists. Information is widely available covering areas such as methods of evidence preservation, photographic techniques, factors that influence failures, and, as previously mentioned, recognition of metallic failures; but not composite failures.

It is apparent therefore that in order for this research to assist the investigation practitioner during the examination of composite material aircraft wreckage, an understanding of the context in which the wreckage examination is undertaken has to be made.

In contrast to the practitioner led approach as mentioned above, academically derived knowledge on the understanding of polymer composite material failure features has received greater attention. Polymer composite fractography (the study of fracture surfaces), gained interest in the late 1970's with work being undertaken by the UK Royal Aeronautical Establishment (RAE) and the US Wright Laboratory. Currently, a substantial qualitative understanding of the features present on polymer composite fracture surfaces has been characterised. This includes the identification of modes of failure, locating origins of fracture and identifying degradation or in-service damage.

This is not without limitations for investigation practitioners as the characterisation has predominantly focused on the laboratory based controlled fracture of small test specimens. There is hence somewhat of a disparity between the conditions in which the knowledge has been produced, and the context and scope of the accident investigation wreckage examination. For example, there may be significant differences between the loading environment in which an aircraft wing failed in-flight compared to that of laboratory failed test coupons. This may be present in not only the global loading on the wing but also the load distribution within the structure and the change in the distribution as the failure progresses. Academically, there is a dearth of research focussed on the controlled failure and post fracture separation of a large aircraft structure, with the purpose of identifying the failure features present in the separated structure. Moreover, there is a distinct absence of scientific research in examining such failed specimens with a view to understanding the failures within the context of the accident investigation practitioner.

In summary, there is now a critical need for research to support the examination of polymer composite aircraft wreckage by investigation practitioners. It has been shown that whilst knowledge of polymer composite failure characteristics is mature, there has been a lack of research applying these within the context of the accident investigation practitioner. The challenge is therefore to determine whether current knowledge on polymer composite fractography can be successfully applied within the context and scope of accident investigation.

The research aims and objectives are presented in the next section.

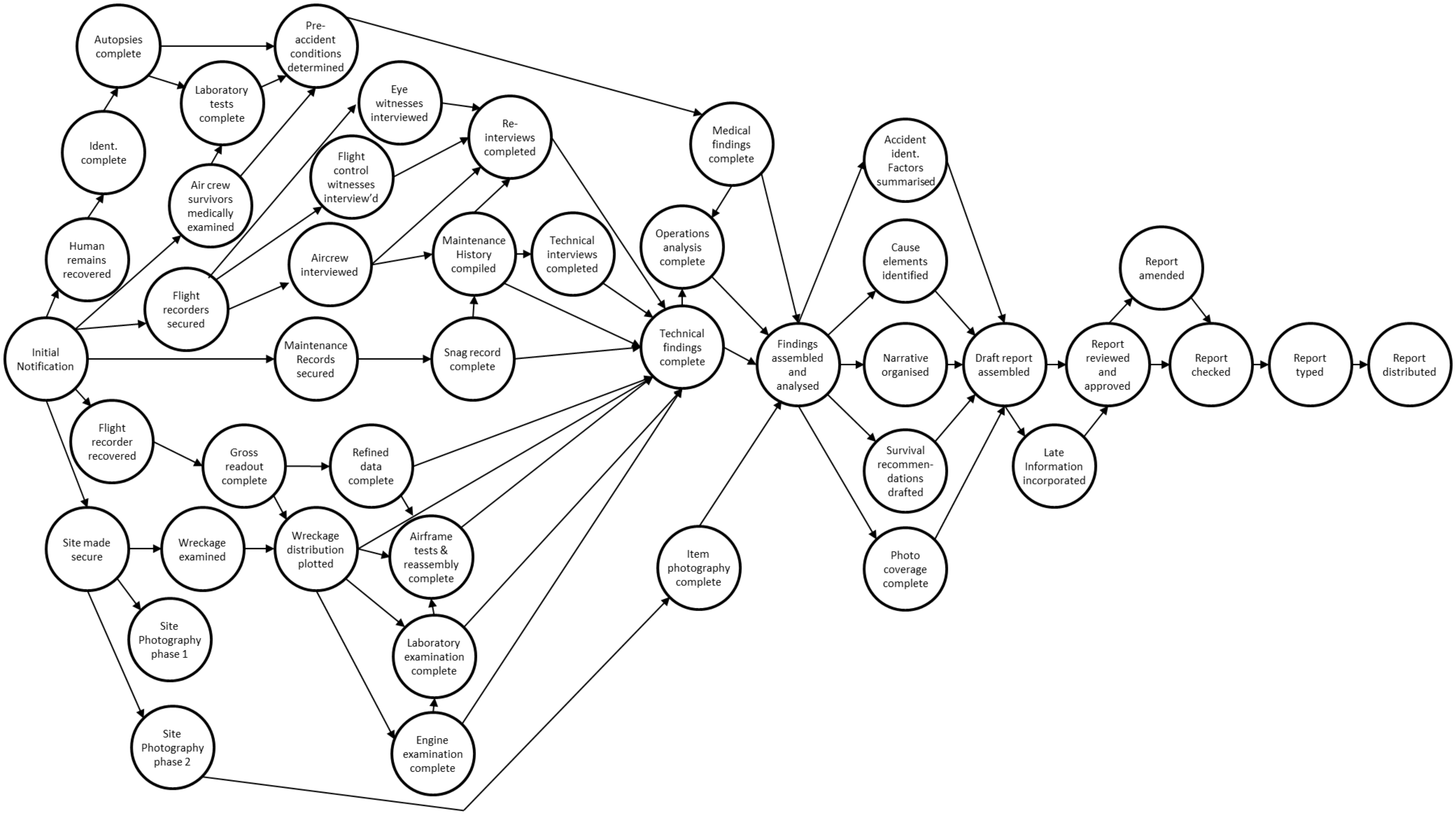


Figure 1-1 – Planned Investigation Program (PIP) (redrawn from Heaslip, 1973)

1.2 Research Aims & Objectives

1.2.1 Overall aim

To determine if known visual and macroscopic failure features of polymer composite materials can assist the accident investigation practitioner in conducting wreckage investigations and structural investigations.

1.2.2 Objectives

1. Explore how accident investigation practitioners conduct wreckage investigations and structural investigations of composite aircraft during the accident investigation process.
2. Identify in literature the current understanding of visual and macroscopic failure recognition of polymer composites. Accumulate information on the individual failure recognition characteristics that show potential for use by the investigator practitioner.
3. Design, conduct and evaluate a study to determine whether these failure characteristics exist in aircraft wreckage and determine whether they can assist the accident investigation process.
4. Design, conduct and evaluate a study to determine how accident investigation practitioners currently use failure characteristics to assist the accident investigation process.

1.3 Research programme

1.3.1 Objective 1

Phase 1 of the research is devoted to answering Objective 1 and is presented in Chapter 4. The purpose of phase 1 is to explore how accident investigators conduct wreckage investigations and structural investigations involving an aircraft of polymer composite construction. This phase utilises case study research methodology, focussing on four case studies of investigations determined to be of significance to this research. Case study evidence is collected via semi-structured interviews of investigators and forensic specialists, documentary evidence, and artefact evidence. The outcome of this phase is a defined understanding of the wreckage and structures examination process in an investigation involving polymer composite wreckage.

1.3.2 Objective 2

Phase 2 of the research is devoted to answering Objective 2 and is presented in Chapter 5. The purpose of phase 2 is to locate and review literature that is focussed on the visual and macroscopic failure characteristics of polymer composite materials. The outcome of this phase is a set of failure features that show potential for use during the wreckage investigation and structural investigation processes, and hence are suitable for subsequent trial in Objective 3.

1.3.3 Objective 3

Phases 3a and 3b of the research are devoted to answering Objective 3 and are presented in Chapter 6. The purpose of phase 3a is to design and conduct a testing programme whereby realistic simulated wreckage is created. The purpose of phase 3b is then to evaluate the failure features as identified in Objective 2 against the simulated wreckage. The outcome of this Objective is an understanding of the identification of failure features within the context of wreckage investigation and structural investigation processes.

1.3.4 Objective 4

Phase 4 of the research is devoted to answering Objective 4 and is presented in Chapter 7. The purpose of phase 4 is to design, conduct and evaluate a study whereby the existing capabilities of accident investigators in conducting wreckage investigations and structural investigations of polymer composite wreckage can be assessed. This phase utilises a simulated investigation method whereby the participants undertake a simulated investigation. The polymer composite wreckage is that which was created in phase 3a of the research programme. The outcome of this Objective is an understanding of the existing capabilities of accident investigators to identify failure features within the context of the wreckage investigation and structural investigation processes.

1.4 Contribution to knowledge

This research presents three main contributions to knowledge. The first is an academically derived concept of the wreckage investigation and structural investigation in aircraft accident investigations. The literature review (Chapter 3) has identified that there has been significant research effort in understanding the theory of accident causation and models of analysis. However, there is a paucity of research in understanding how the inner processes of an investigation are conducted and how these fit into the wider accident investigation process.

The second is in accumulating known visual and macroscopic failure features of polymer composite materials, which are oriented for application within the wreckage investigation and structural investigation processes of General Aviation (GA) aircraft accidents. Historically the visual and macroscopic failure features of polymer composite materials have been collated on numerous occasions, with a recent and significant contribution being completed by Greenhalgh (2009). However, these have been primarily aimed at the forensic or fractographic specialists' perspective. Thus, the significant contribution emanates from the assembly of the information within the requirements of the investigation practitioner and the needs of the investigation process.

The final contribution to knowledge is in understanding the application of failure characteristics from both the accident investigators perspective and the potential from the current understanding as identified in literature. It has been a unique opportunity to gain access to the investigation community and to conduct research directly with investigation practitioners.

Additionally it has been a rare opportunity to conduct a large-scale fracture and separation of a complex aircraft structure. The generation of understanding on failure modes and failure characteristics of polymer composite materials has been built up over decades of fracturing predominantly coupon-sized pieces. This research has provided a unique opportunity to conduct the fracturing and separation of a large multifaceted aircraft structure as a means to recreate fracture features in a complex aerostructure.

This research has the benefit of offering a contribution to knowledge to both the accident investigation practitioners and to the academic community.

1.5 Thesis structure

This report consists of 8 chapters (Figure 1-2). The individual chapters are outlined below:

Chapter 2 reviews the context behind accident investigation and polymer composite materials. It identifies the interaction between both areas and the challenges that polymer composite materials bring to the accident investigation community.

Chapter 3 provides an in-depth review into both the historic and current research efforts in understanding the investigation process. It highlights the current state of the art and the research issues associated with the wreckage investigation and structural investigation of polymer composite wreckage. This chapter provides a foundation from which primary research is conducted.

Chapter 4 presents the first phase of the research programme. It describes the process of case study research and presents the four cases undertaken. The results are then discussed presenting key findings on the process of examination of the wreckage, and the effect polymer composite materials have on the investigation.

Chapter 5 presents the second phase of the research programme. Findings from phase 1 of the research programme are discussed to generate a foundation on how visual interpretation of polymer composite materials can assist in the investigation process. A literature survey is conducted to identify macroscopic and visual failure characteristics of polymer composites and to understand the potential for assistance to the investigation.

Chapter 6 presents the third phase of the research programme. It presents the process and procedures by which simulated aircraft wreckage was created. It discusses the selection of an appropriate specimen, the design of the fracturing programme, the procedures followed, and the results from the fracturing programme. It then presents the process whereby the failure characteristics of the fractured specimens were examined. Finally the results of the examination of the fractured specimen are summarised with the results from the literature survey on visual and macroscopic failure features (chapter 5).

Chapter 7 presents the final phase of the research programme. Firstly it discusses the simulated investigation methodology that was used as a basis to conduct a simulated investigation with experienced practitioners. Having completed the simulation, the results are discussed in two sections. Firstly, the results from how the investigators conducted the investigation are examined (process). Finally, results on what the investigators identified during the examination are discussed (failure features).

Chapter 8 provides a conclusion to this thesis by discussing: the research findings against the research aim, the contributions to knowledge, and the limitations of the research programme and findings. It finally presents areas for future research that have been created specifically by this research.

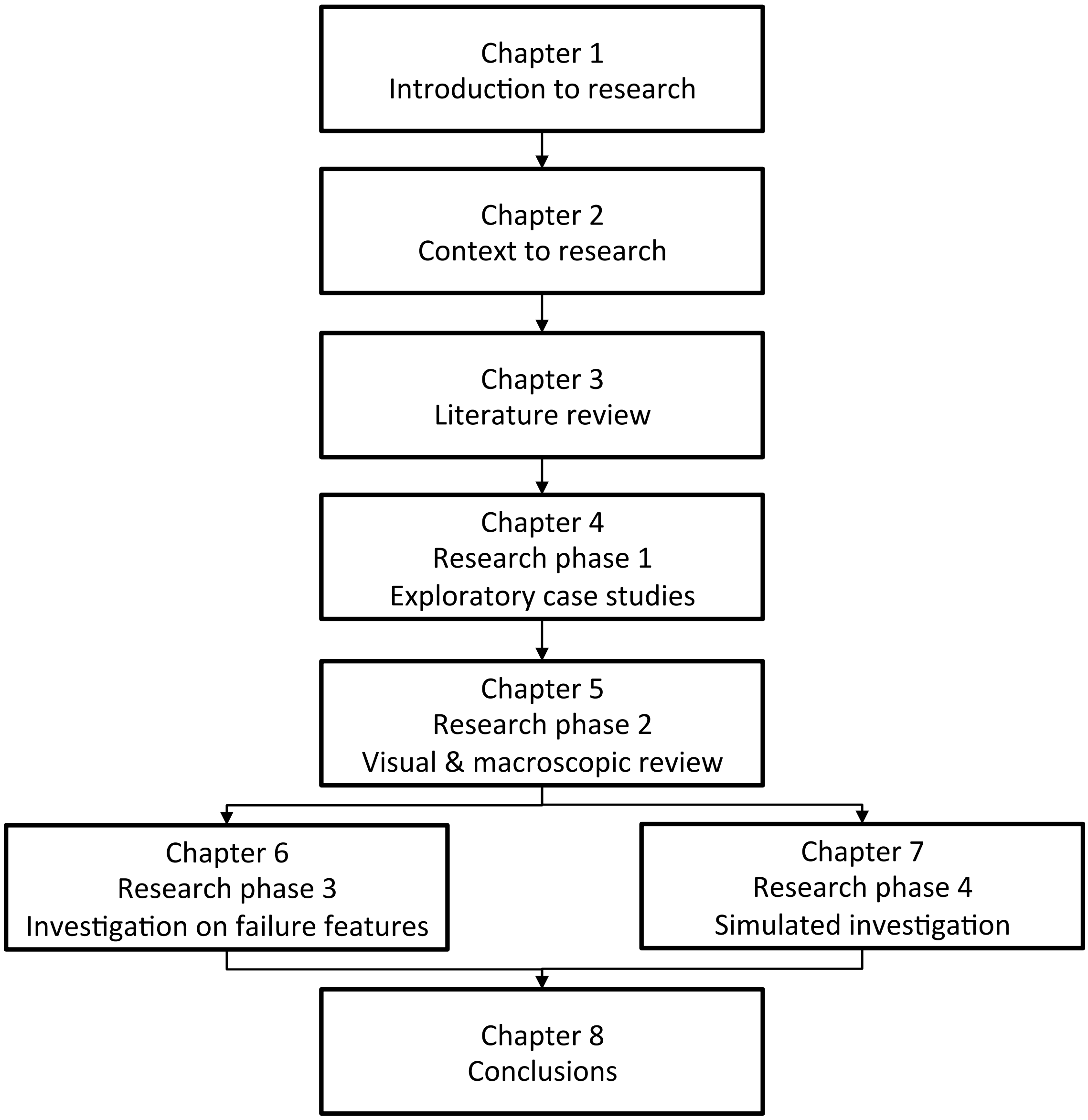
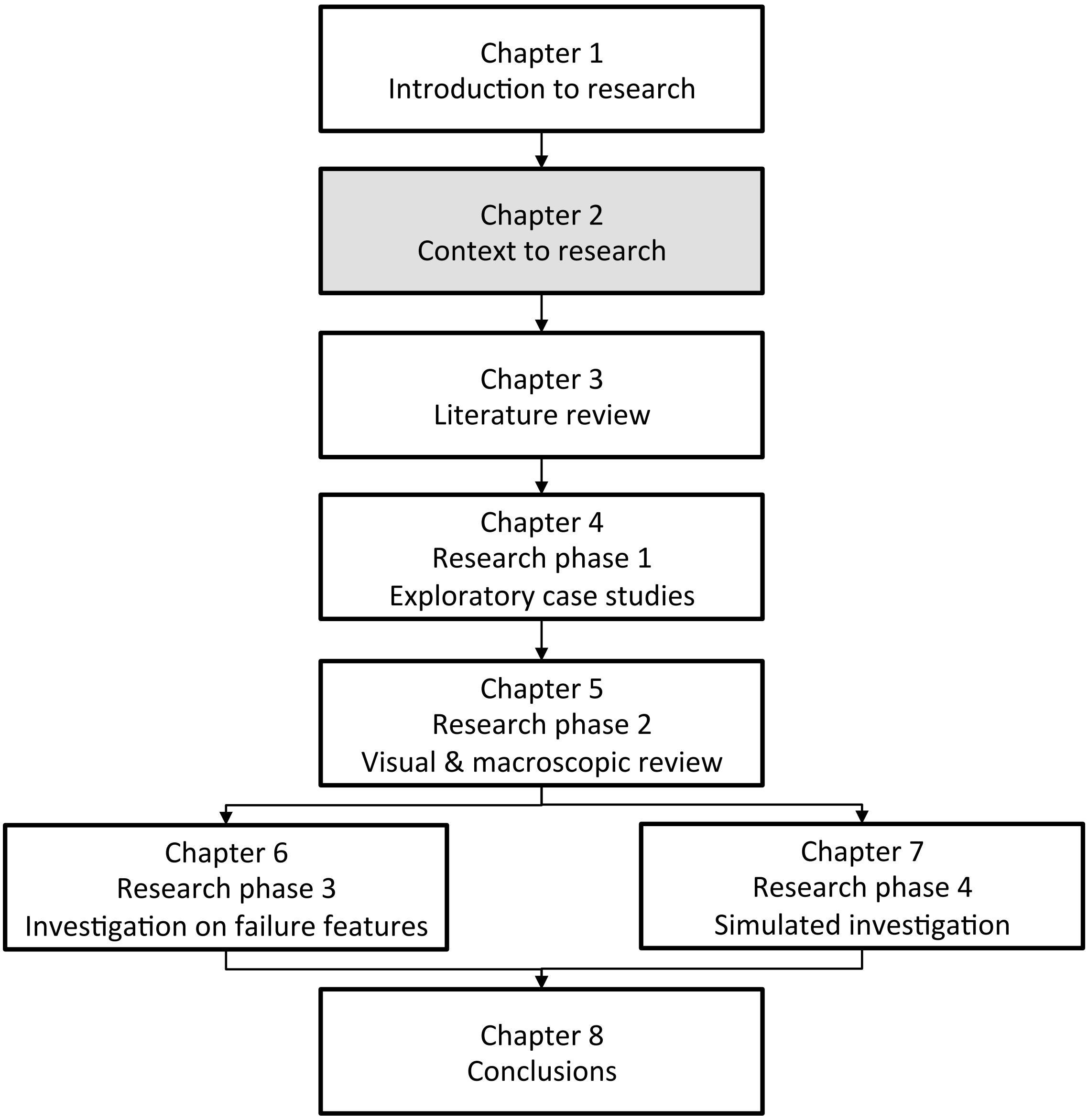


Figure 1-2 – Thesis outline (source: author)

2 CONTEXT TO RESEARCH



This chapter presents the context of the research by providing introductions into the fields of accident investigation and polymer composite materials. Initially, the discussion emphasises the importance of aircraft accident investigation as a means to improve flight safety (Sections 2.1 & 2.2). Subsequently, an introduction into composite materials is presented (Section 2.3), and an overview of the growth rate of composite materials in aircraft construction is given (Section 2.4).

2.1 The need to investigate accidents

The investigation of accidents is essential to the field of safety management (Braithwaite and Greaves, 2009) and is essential to accident prevention (Lindberg, Hansson & Rollenhagen, 2010). There are many reasons why an aircraft accident could be investigated. These include: to apportion blame or liability; for purposes of research; to provide closure to the friends and families; and, most importantly, to prevent reoccurrence (see Ferry, 1988).

The philosophy of accident investigation to prevent reoccurrence is enshrined into the standards and practices placed onto state investigation agencies worldwide. The International Civil Aviation Organisation (ICAO) implemented standards and recommended practices for aircraft accident inquiries in 1944 during the adoption of Annex 13 of the Convention on International Civil Aviation (ICAO, 2010). At the time of writing there are 191 member states (ICAO, 2013) contracted to ICAO, all sharing the principle aim of investigating accidents which, as written by ICAO (2010), is:

> *"The sole objective of the investigation of an accident or incident shall be the prevention of accidents and incidents. It is not the purpose of this activity to apportion blame or liability."*

This objective is replicated in accident investigation mission statements (e.g. AAIB, 2013), with agency independence from regulators and political interference adding further prominence to the conducting of impartial investigations.

Moreover, ICAO (2005), state: *"Through the discipline of 'flight safety', the frequency and severity of aviation occurrence have declined significantly".* This is widely supported were it is acknowledged that accident rates for scheduled operations has stabilised to historic low levels (Matthews, 2004; Davis, Johnson & Stepanek, 2008; ICAO, 2008).

Perhaps the most basic need for investigation is to reduce the 'cost' of accidents. Whilst this has been explained in terms of a monetary cost (Ferry, 1988; Čokorilo, Gvozdenović, Vasov & Mirosavljević, 2010), the most significant cost of accidents is the loss of life. The UK CAA reported that during the period of 1998-2007 there was a total 8,038 fatalities from accidents involving large passenger and cargo transport aircraft (CAA, 2008). However, this information excludes fatalities related to other categories of aviation, where especially in developed countries, fatalities relating to General Aviation (GA) may be substantially higher. For example, between the years of 2007-2010, fatalities within the US occurring within the GA sector accounted for 92% (496 fatalities), 87% (494 fatalities), 89% (475 fatalities) & 96% (451 fatalities) respectively of all aviation related fatalities (table 2-1). Furthermore, this difference is reflected in the volume of accidents were the GA sector accounts for circa 95% of all accidents during this period.

Sector	2007			2008			2009			2010		
	Number of Accidents		Fatalities	Number of Accidents		Fatalities	Number of Accidents		Fatalities	Number of Accidents		Fatalities
	Total	Fatal		Total	Fatal		Total	Fatal		Total	Fatal	
Total U.S. Civil Aviation	1745	303	540	1659	297	566	1554	276	535	1500	275	470
Part 121	28	1	1	28	2	3	30	2	52	28	1	2
Part 135	65	14	43	65	20	69	49	2	17	37	6	17
Part 1- General Aviation	1652	288	496	1567	275	494	1477	273	475	1435	268	451

Table 2-1 – Total accidents, fatal accidents, and fatalities for major segments of U.S. civil aviation (adapted from NTSB, 2013; NTSB, 2013a)

2.2 A change in technology

There is a wealth of information available providing either statistical analysis of accident rates, trends, detailed categorisation of accidents, or sources for accident reports. For example, accident investigation agencies publish accident reports and national and regional aviation authorities publish accident statistics. Additionally, statistical data also comes from research articles, manufacturers, consultancy firms. Whilst there is a wealth of data available, the accuracy and comparability of the data and statistics are debatable. Davis *et al* (2008) present a discussion on this debate, as well as presenting accident statistics within the US.

Annex 13 to the Chicago convention requires that all accidents involving aircraft over 2,250kg are reported to ICAO (ICAO, 2010). Subsequently, the information is stored within ICAO's ADREP database such that safety information can be shared amongst member states (DIT, 2013). The taxonomy of ADREP (ICAO, 2006) separates aircraft into four categories, namely:

- Commercial Air Transport
- General Aviation
- Aerial Work, and
- State Flights

Within each of these categories are further sub-categories, which provide hierarchical levels of types of operations contained within the category (see ICAO, 2006).

Through the ADREP database, ICAO provides statistics on historic accident rates for scheduled operations (scheduled operations being a sub-category of the commercial transport taxonomy). The accident rate since 1945 is presented in figure 2-1 (ICAO, 2002). Although not illustrated in figure 2-1, ICAO statistics show that accidents involving fatalities are down to 0.1 fatalities per 100 million miles (ICAO, 2008a).

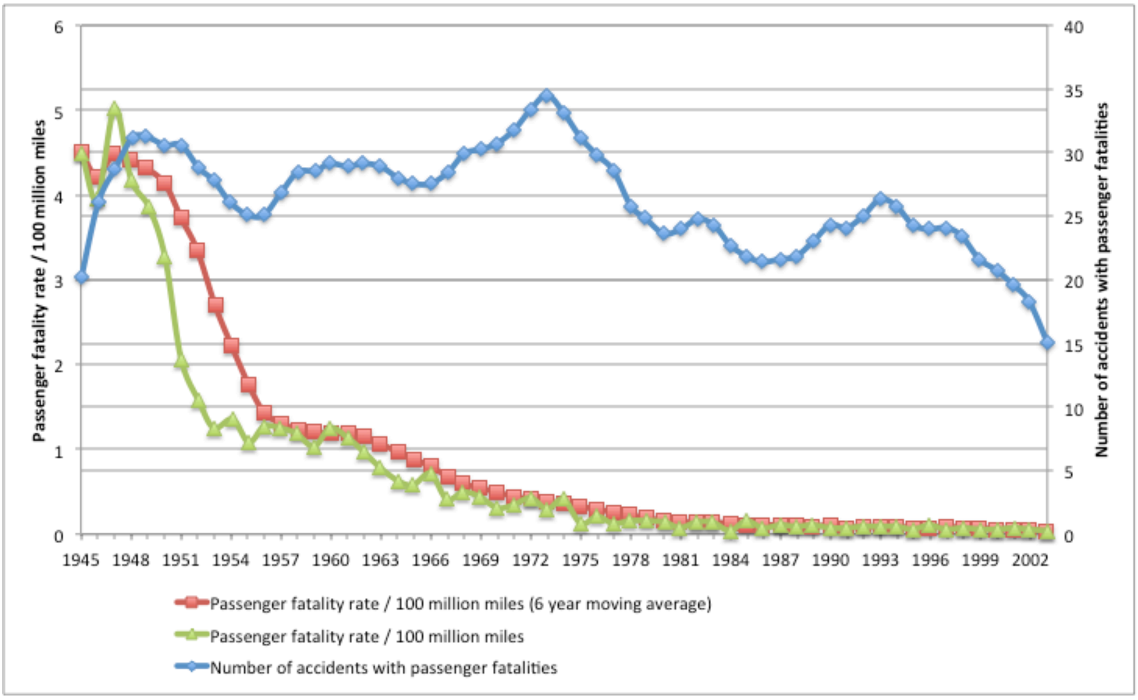


Figure 2-1 – Passenger fatality rate / number of accidents, scheduled ops, excluding USSR/CIS (redrawn from ICAO, 2002)

Matthews (2004) and Del Gandio (2009) suggest that the overall reduction is linked to evolution of the industry with the implementation of new technology being a significant factor. Ground Proximity Warning Systems (GPWS), Traffic Collision Avoidance Systems (TCAS) and Flight Operations Quality Assurance (FOQA), and fleet turnover are a few examples quoted (Mathews, 2004; Del Gandio, 2009). Matthews (2004) illustrates this by incorporating the introduction of safety features into a timeline of accident rates, figure 2-2. He discusses, by quoting Boeing and Airbus data, that when reviewing accident rates per generation of jet, the latter generations statistically have a lower accident rate (figure 2-3).

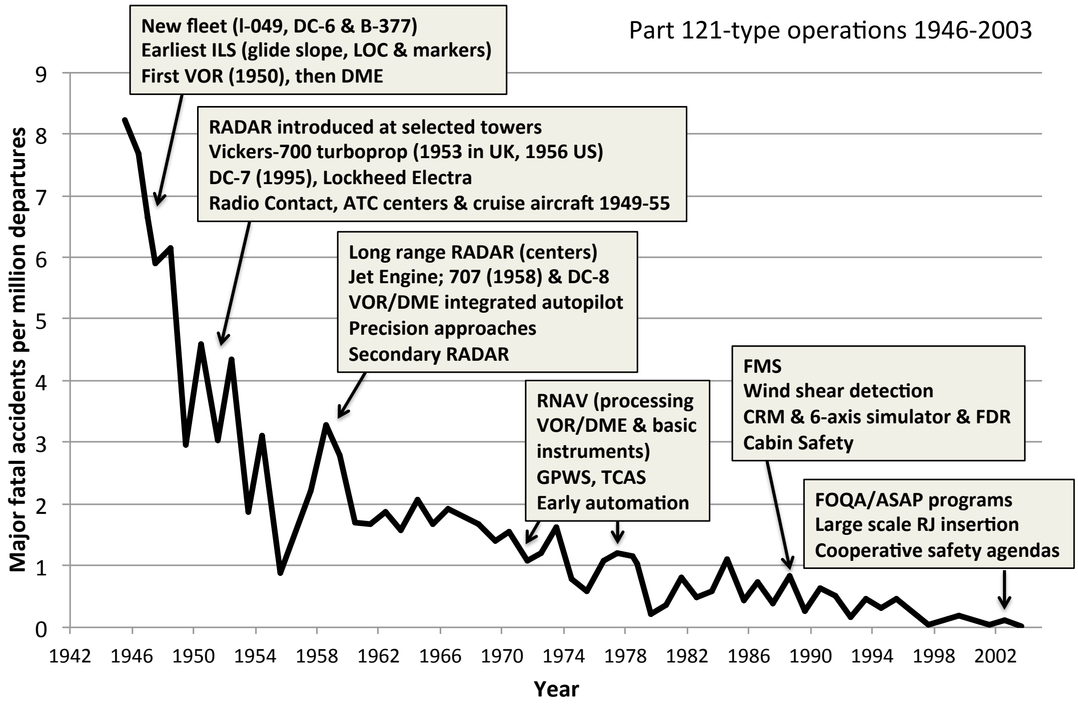


Figure 2-2 – Selected safety innovations and major fatal accidents per million departures. US data. (redrawn from Matthews, 2004)

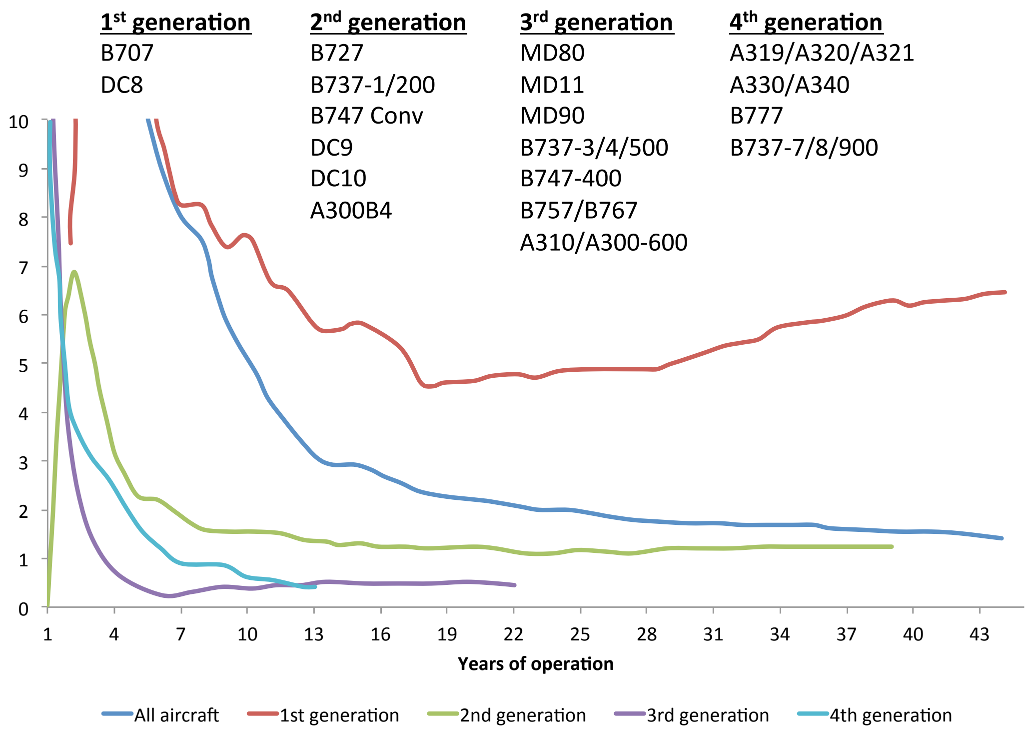


Figure 2-3 – Number of accidents per generation of jet (redrawn from Matthews, 2004)

A key argument for this continued reduction due to technological change is the ability to learn from accidents. In referring to the Comet accidents of 1954 (HMSO, 1955), Matthews (2004) suggests:

> *"These events led to what many people recognize as the birth of modern accident investigation. Investigators in the U.K. employed the scientific method in various experiments to establish that the Comets in fact had broken up in flight. The U.K. investigators established that, as the Comet operated at unprecedented altitudes, the aircraft's frame expanded and contracted during every pressurization cycle, which caused metal fatigue. Designs changed abruptly to avoid points of added stress, such as sharp corners or square openings, and included fewer but stronger joints. The next generation of commercial jets, such as the Boeing 707 and the DC-8, were the primary beneficiaries of this knowledge"*

Whilst this is plausible, when considering the technological move from metallic structures to polymer composite structures, the argument becomes weaker. It is recognised that composite materials have a higher level of resistance to traditional degrading factors such as fatigue and corrosion (Armstrong, Bevan & Cole, 2005). However, it is also recognised that the materials are fundamentally different and introduce new failure modes such as compression after impact, a condition that can reduce the compressive strength of a composite structure by 70% (Davies & Olsson, 2004). It is therefore acceptable to question as to whether the continued link between new technology and reduced accident rates can be sustained during periods where new technology replaces old technology, rather than evolving current technologies. Moreover, if the introduction of new materials is not supported by an ability to understand and recognise new failure modes then the learning curve may once again be dominated by learning through accident investigations. As Walker (1965) suggested back in 1965:

> *"Research into aircraft structural fatigue in the last twenty years or so has not only led to the prevention of many fatigue accidents, but has also meant that they are more likely to be discovered and recognized when*

they have unfortunately occurred. The result has been some misleading statistics, since, while the designer has been reducing the true accident rate from fatigue, the accident investigator has virtually been increasing it."

Moreover, numerous authors have presented reviews referring to a direct relationship between accident investigations of aircraft constructed from metallic materials and our growth in understanding of structural integrity (Wanhill, 2003: Schijve, 1994; Goranson, 1993).

The investigations and the resultant understanding in structural integrity are illustrated in table 2-2.

Year	Aircraft Failure	Influence, follow-up
1954	DeHavilland Comet; 2 aircraft crashed owing to fuselage explosion	General awareness of finite aircraft fatigue life as an important issue for passenger safety. Attention drawn to full-scale fatigue testing
1969	F-111; wing failure due to undetected material flaw	Aircraft should be damage-tolerant. Fatigue cracking due to initial damage should be considered
1977	Boeing 707; tailplane lost owing to fatigue failure in spar	Old aircraft become more fatigue critical, *geriatric aircraft*
1988	Boeing 737; aircraft lost part of fuselage skin structure owing to multiple fatigue cracks in skin splices	Multiple-site damage (MSD) can occur in *ageing aircraft*, especially in lap joints of the pressurised structure

Table 2-2 – Milestones of structural integrity through accident investigations (redrawn from Schijve, 1994)

It is also stressed by Wanhill (2003), when referring to composite materials, that the current development of aircraft structural integrity has been predominantly based on experience with metallic structures.

2.3 Composite materials

The definition of a composite material is described differently between texts however they tend to follow a common theme. To be classified as a composite, the material must consist of at least two distinctly different constituent materials (Greenhalgh, 2009; Hull & Clyne, 1996; Matthews and Rawlings, 1994). Moreover, the constituents must be physically and chemically different (Matthews & Rawlings, 1994), and the resultant combination must have superior properties to the constituents alone (Greenhalgh, 2009; Matthews & Rawlings, 1994). As a result, the combination of materials to create a composite structure offers a form, which can provide greater strength for a lower equivalent density (figure 2-4).

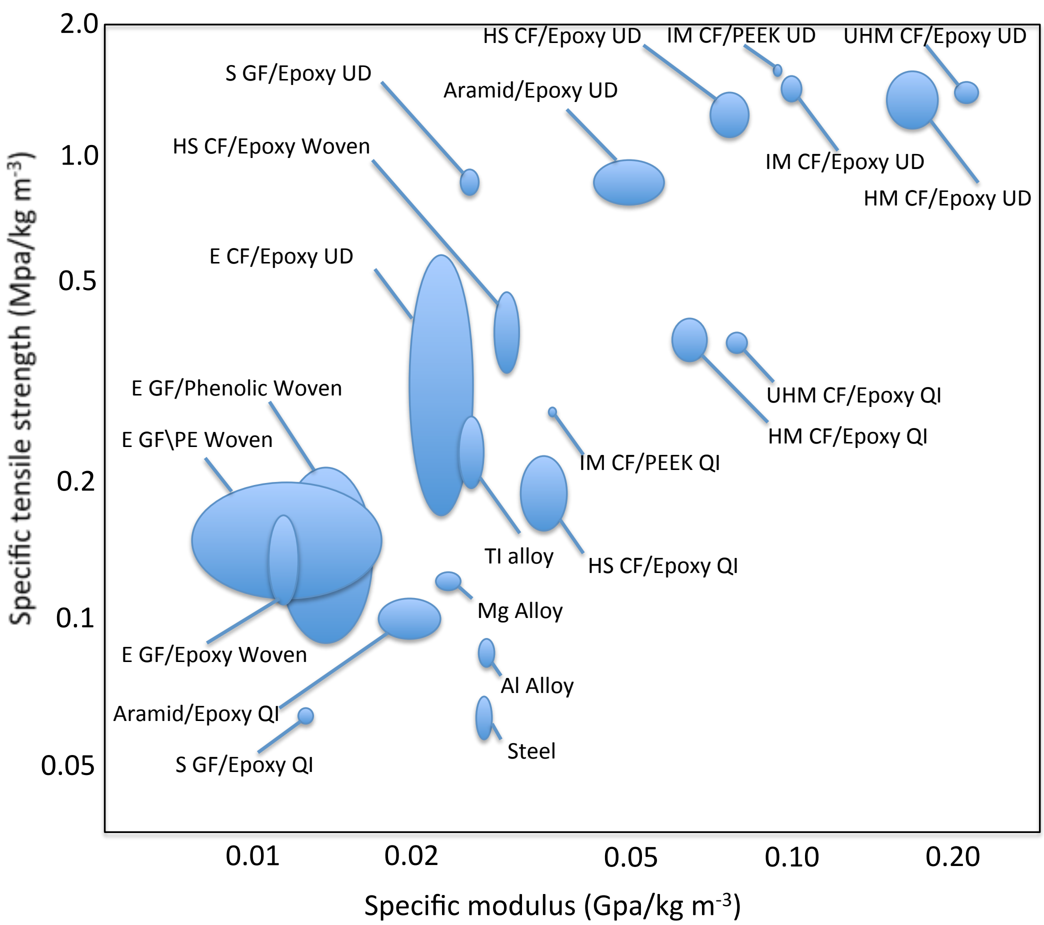


Figure 2-4 – Specific tensile strength vs. specific stiffness, for metallic and Unidirectional (UD), Quasi-isotropic (QI), and woven composite materials. (redrawn from Greenhalgh, 2009)

A composite material consists of a reinforcement phase (e.g. fibre), a matrix (e.g. epoxy) and an interface (i.e. the fibre matrix bond) (Greenhalgh, 2009; Hull & Clyne, 1996). The interface is not a physical constituent, but is a significant factor in the failure characteristics of a composite material. Additionally, unlike typical isotropic materials, the architecture of the internal reinforcing fibres plays a significant role in the material properties.

Figure 2-5 illustrates the classification of conventional polymer composite materials based on reinforcement type. Non-conventional polymer composites (which are not illustrated in figure 2-5) include 3D architectures where additional reinforcement is placed in the z-direction, through braiding or knitting (Greenhalgh, 2009).

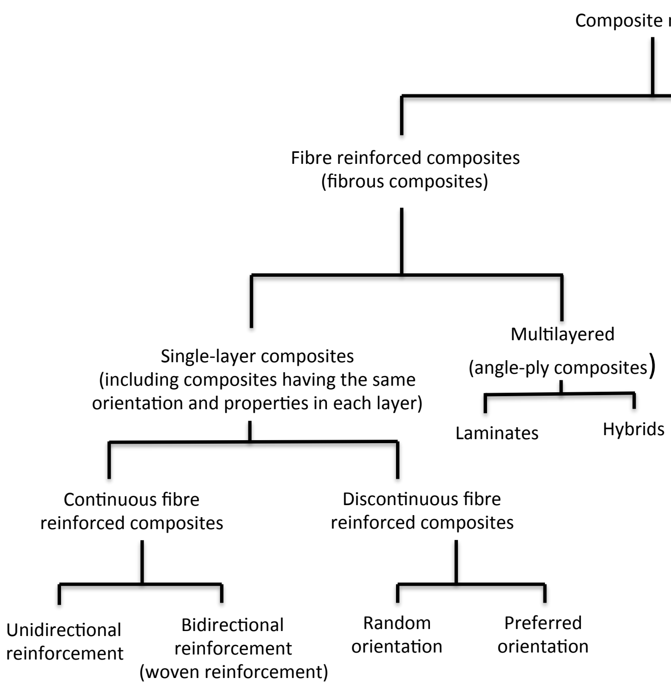


Figure 2-5 – Classification of conventional composite materials (redrawn from Matthews & Rawlings, 1994)

2.3.1 Reinforcements

Reinforcements are generally categorised as being either fibrous or particulate (Matthew & Rawlings, 2004; Campbell, 2010), although other forms such as flake or filled composites have been described (Vinson & Sierakowski, 2002).

Particulate reinforcement is typically used in wear applications (Immarigeon, Holt, Koul, Zhao, Wallace & Beddoes, 1995) with the role of the matrix simply to hold the particulates in solid form (Harris, 1999). Consequently, particulate composites are utilised to introduce unusual properties to the material as opposed to improving the materials strength (Askeland, Green, & Robertson 1996).

A fibrous composite is classified by the length of the fibre being substantially longer than its diameter (Matthews & Rawlings, 2004). The classification between discontinuous fibres and continuous fibres is a length to diameter ratio of thirty (Greenhalgh, 2009). Above thirty and the reinforcement is deemed as continuous. Unlike particulate reinforcements, most fibrous reinforcements are designed to apply improved strength and stiffness (Askeland *et al*, 1996), with the reinforcement architecture dictating how effectively the fibres carry the load (Greenhalgh, 2009). Consequently, if the orientation of the fibres is misaligned, the efficiency of the load carrying capability of the material may also be reduced (Hoskins & Baker, 1986).

Furthermore, continuous fibres are sub-categorised into differing fabric configurations. Typical reinforcement types include woven, unidirectional and roving (figure 2-6).

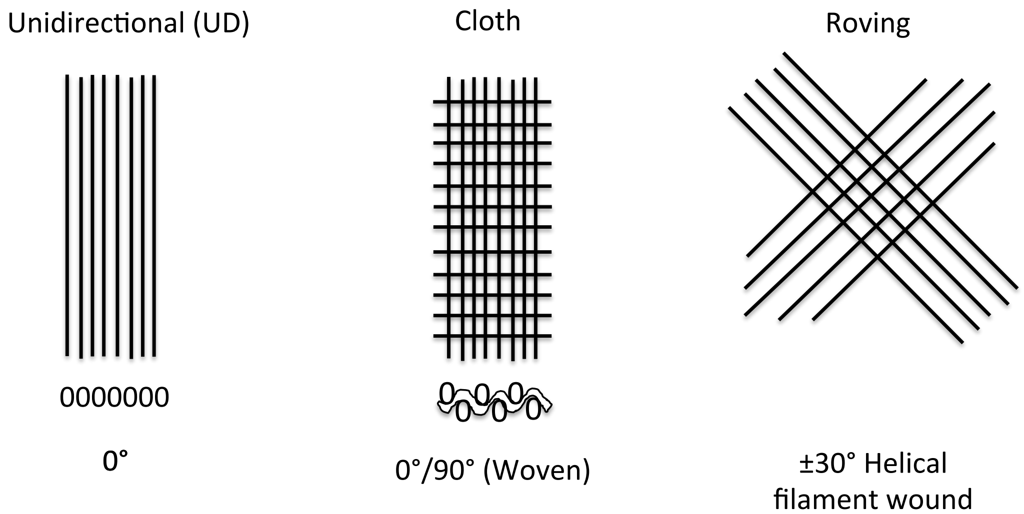


Figure 2-6 – Typical continuous reinforcement types (redrawn from Campbell, 2010)

In high performance composite components typical for aerospace structures, continuous fibre fabrics are typically stacked in layers (Hull & Clyne, 1996). Campbell (2010) suggests that where the layers are orientated in the same direction, the laminae combine to form a lamina, and where the laminae are combined in differing predefined orientations, the form is termed a laminate (figure 2-7).

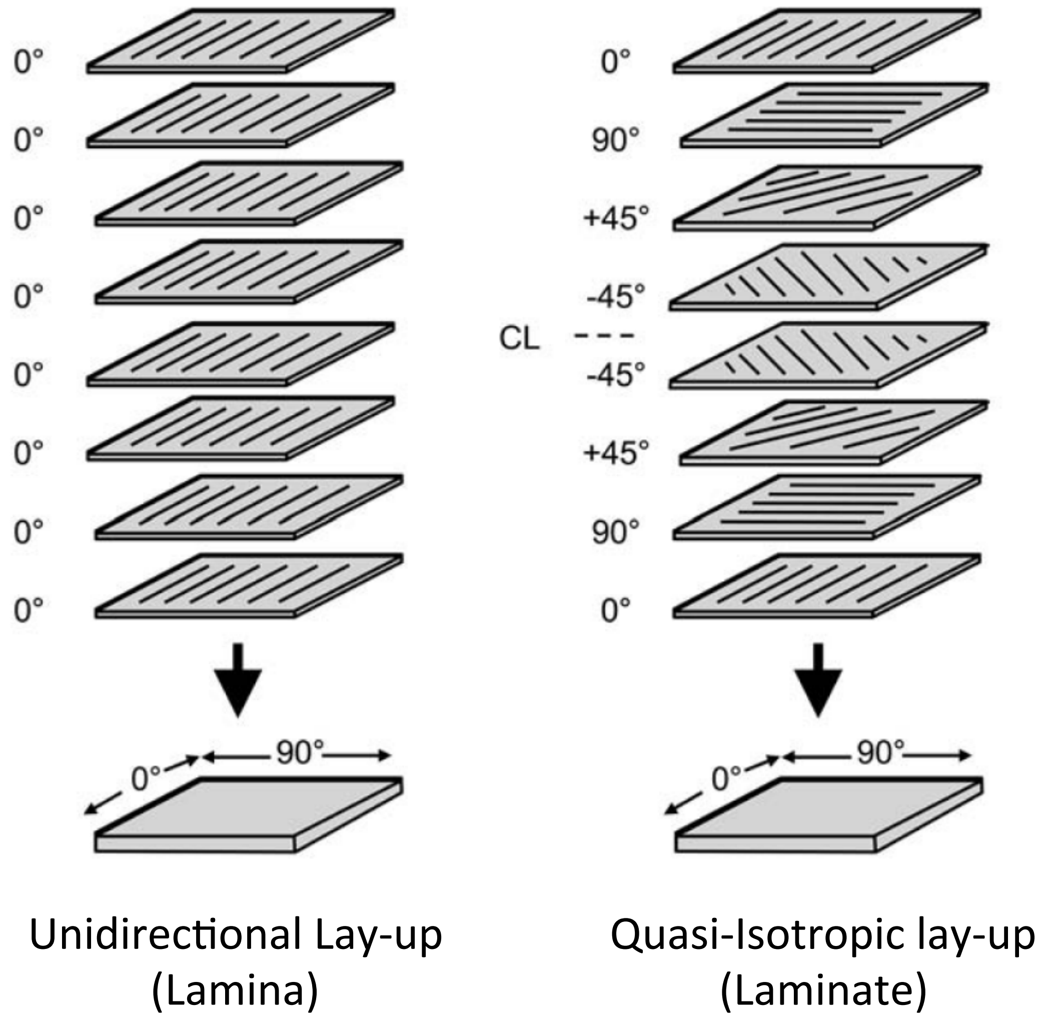


Figure 2-7 - Lamina and laminate lay-ups (Campbell, 2010)

The development of composite materials has led to a large variation in the types available, the types of matrices available, and the possible combinations between (figure 2-8). However, the most common forms of fibres utilised in continuous composites are glass, carbon and aramid, with most common matrices applicable to these fibres being polymers (Greenhalgh, 2009). Of these, the most important combination to aerospace applications is Carbon / Epoxy (Baker, Dutton, Kelly, 2004).

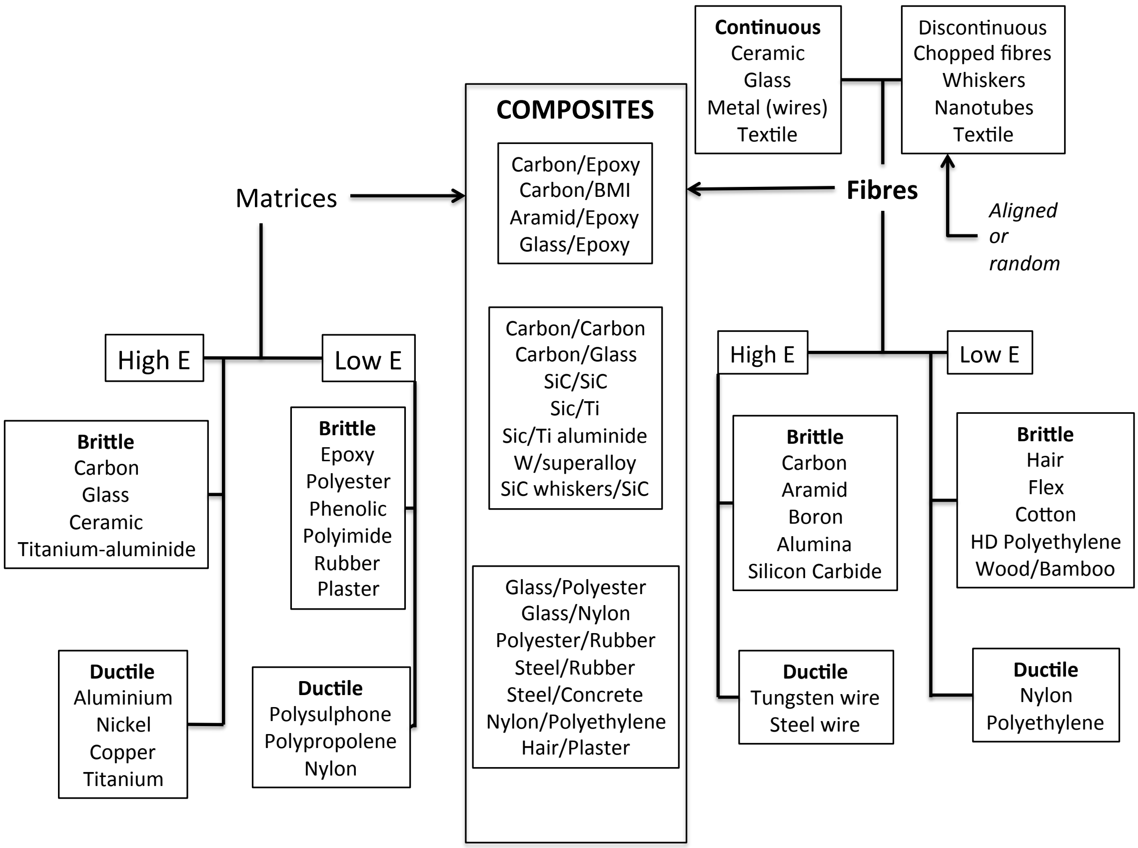


Figure 2-8 – Classification of composites according to fibre and matrix properties (redrawn from Baker, Dutton & Kelly, 2004)

2.3.2 Matrices

The primary role of the matrix is to transfer the loading applied to the structure to the fibres, protect the fibres from damage, inhibit the propagation of cracks, and to hold the fibres into the preferred orientation (Askeland *et al*, 1996; Harris, 1999). Polymer matrixes are the largest class consisting of either thermoplastics or thermosets (Greenhalgh, 2009). Thermosets are typically brittle materials (Hull & Clyne, 1996) with epoxy being used almost exclusively for space, aircraft, and high performance applications (Greenhalgh, 2009). Conversely, thermoplastics are ductile and undergo plastic deformation during failure (Hull & Clyne, 1996).

Property	Thermosets		Thermoplastics		
	Epoxy resins	Polyester resins	Nylon 6.6	Polypropylene	PEEK
Melting Temperature (°C)	-	-	265	164	334
Distortion Temperature (°C)	50-200	50-110	120-150	80-120	150-200
Shrinkage on curing (%)	1-2	4-8	-	-	-
Water absorption (24h @ 20°C) (%)	0.1-0.4	0.1-0.3	1.3	0.03	0.1
Chemical resistance	Good, attacked by strong acids	Attacked by strong acids and alkalis	Good, attacked by strong acids	Excellent	Excellent

Table 2-3 – Environmental and dimensional properties of thermosets and thermoplastics (redrawn from Hull & Clyne, 1996).

2.4 The growth in polymer composite materials in aircraft construction

Composite materials are not new. Composite materials, in the form of mud and straw building blocks, were being used by ancient civilisations (Matthews & Rawlings, 2004). However, with the advent of advanced fibre types such as glass, Kevlar and carbon, and the corresponding development of matrices (Vinson & Sierakowski, 2002), polymer composites have increasingly become attractive to the aerospace industry as an alternative to traditional metallic structures (ASM, 2001). Furthermore, composite materials are relatively early within their maturity cycle (figure 2-9) hence are undergoing significant advancement and variations in designs. However, due to the high cost of material qualification, aircraft manufacturers tend to select early generation materials (Baker et al, 2004).

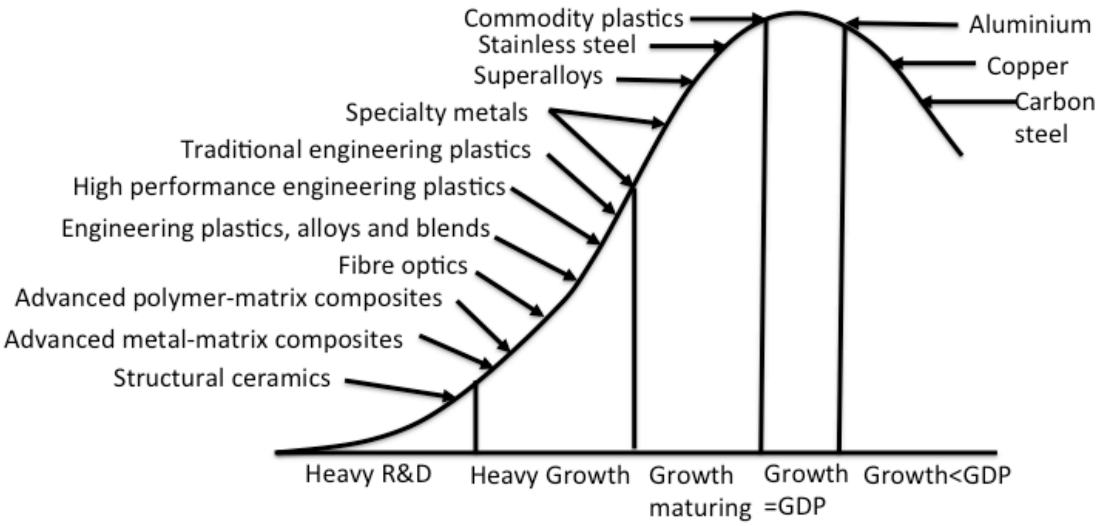


Figure 2-9 – State of materials maturity (redrawn from Vinson & Sierakowski, 2002)

Similarly, the use of polymer composite materials in aircraft design is not new. De Bruyne (1937) published a paper to the Royal Aeronautical Society discussing the application of plastic materials in aircraft construction. Within the publication, the use of reinforcement was discussed as a method to increase material properties. A breakthrough in the use of polymer composite materials for aircraft construction came in c1950 when, for the first time, a polymer composite primary structure outperformed a metallic equivalent (McMullen, 1984). Furthermore, it was as early as 1957 when the FS-24 Phönix, a sailplane constructed almost entirely from a glass fibre reinforced polyester resin and balsa sandwich, first flew (Deutsches Museum, 2013).

It is only in recent years that composite materials have taken prominence in new commercial aircraft designs. The Boeing 787, which first flew in December 2009, contains approximately 50% composite material by structural weight with the aluminium content being 20% (figure 2-10) (Brosius, 2007). In contrast the Boeing 777, which first flew in June 1994, contains 12% composite materials and 50% aluminium.

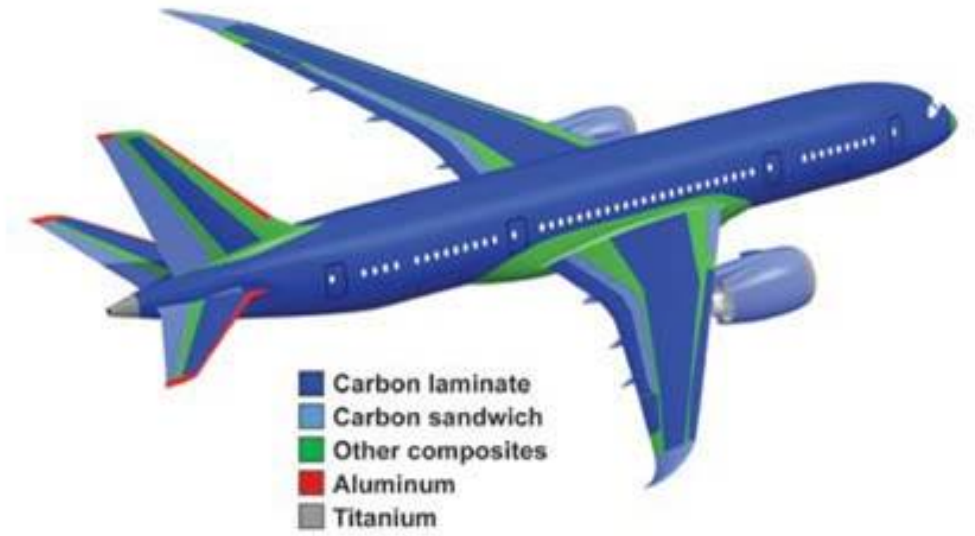


Figure 2-10 - Boeing 787 composite profile (FAA, 2012b)

Furthermore, the Airbus A380, which first flew in 2005 (Airbus, 2013) contains 25% composite structure as a percentage of total structural weight (figure 2-11). And the Airbus A350 is expected to contain 53% composite material by structural weight (Airbus, 2013a).

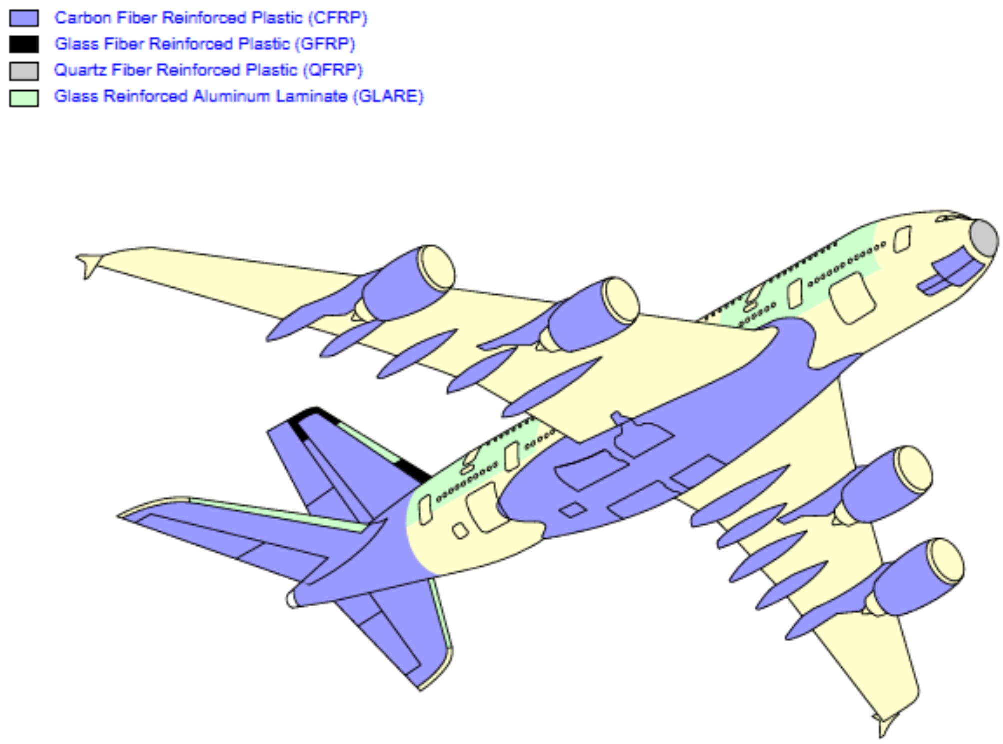


Figure 2-11 – Composite content of the Airbus A380 (Airbus, 2008)

Moreover, there are significant differences in the construction between the aircraft. For example, the fuselage for the Boeing 787 is manufactured from carbon fibre in multiple barrel sections (Marsh, 2006). The upper fuselage of the A380 is constructed of fibre-metal laminate panels (Marsh, 2006). The A350 is constructed of carbon fibre panels fixed to the airframe in a manner similar to the attachment of traditional metallic fuselage skins (Spirit, 2011).

Whilst this recent milestone marks a transition from metallic materials to polymer composites as the material of choice (Rakow & Pettinger, 2007), composite materials have been used in secondary structures of large transport aircraft since the 1970's (ASM, 2001) (figure 2-12). The first certification of an all-composite primary structure occurred in 1985, when an all-composite vertical stabiliser was installed on the Airbus A310-300 (ASM, 2001).

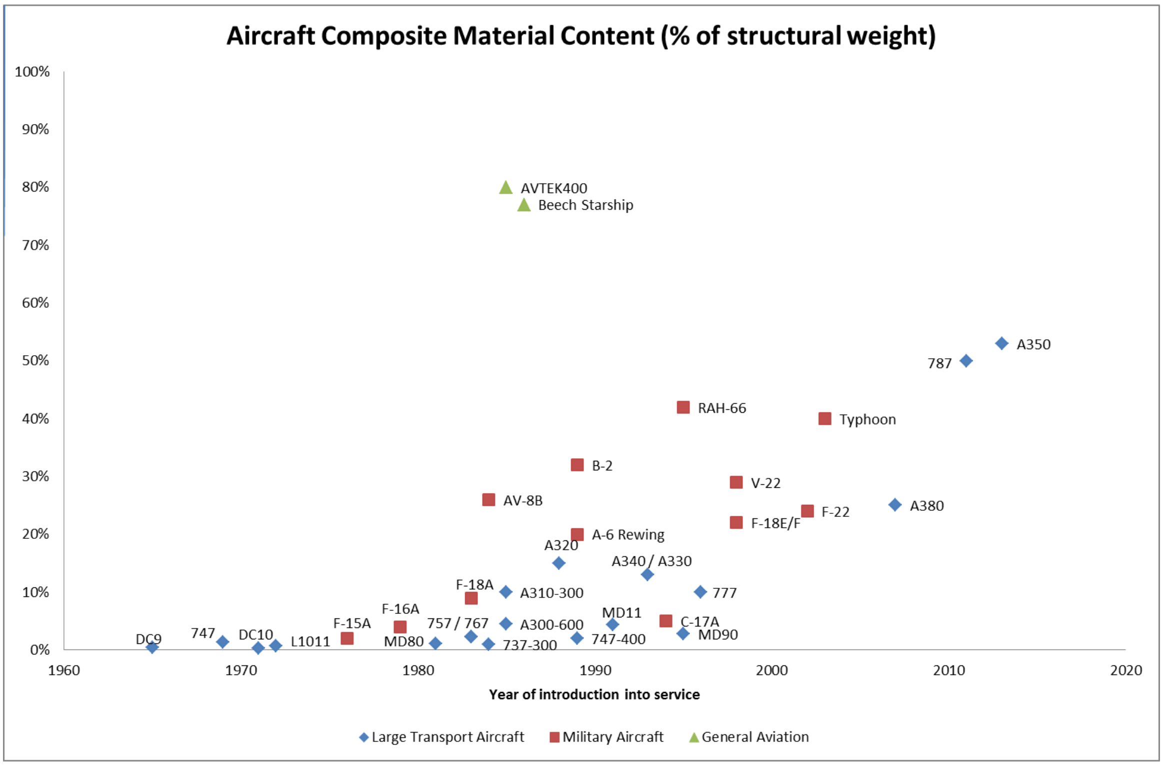


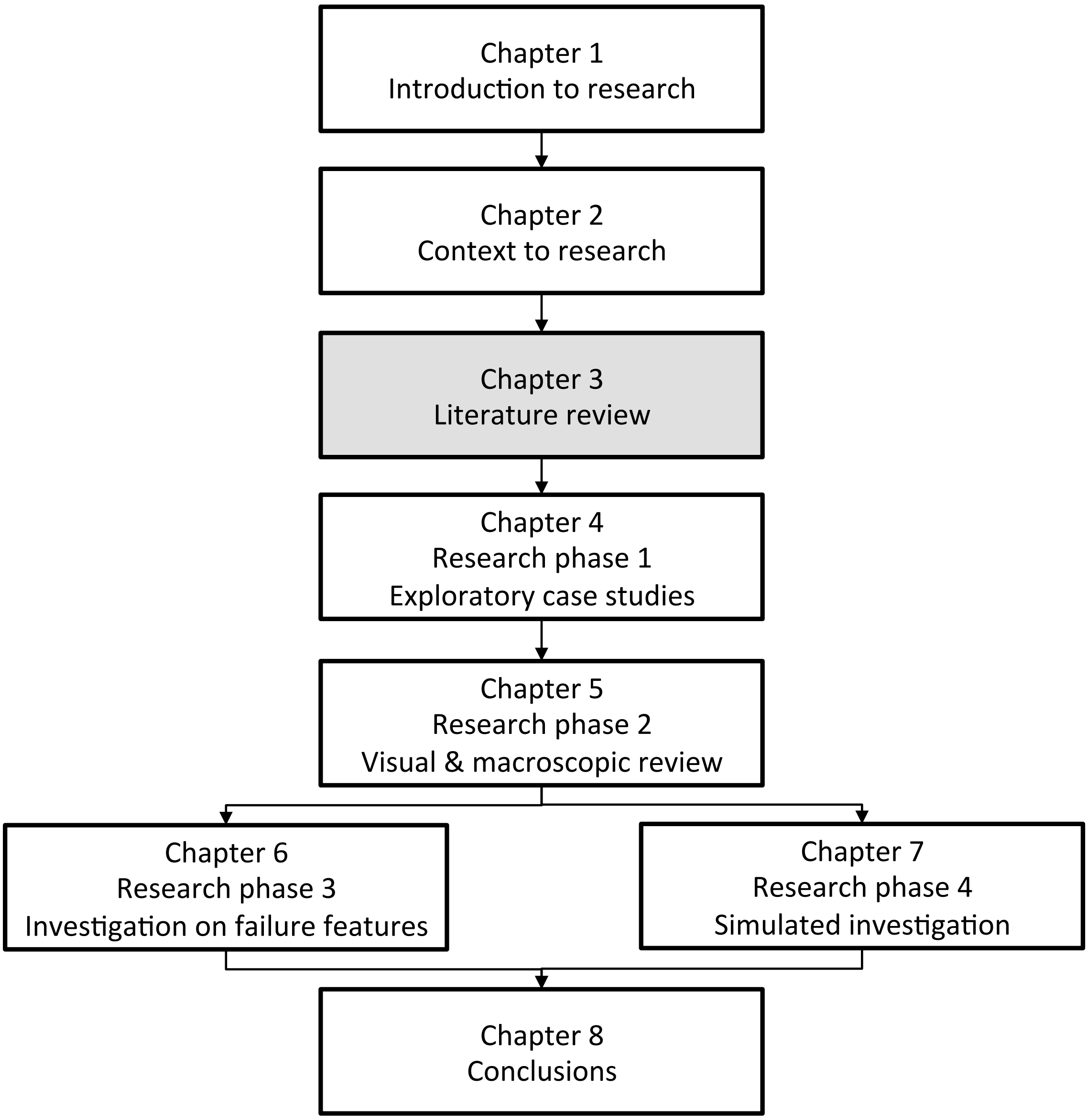
Figure 2-12 – Growth in aircraft composite content (Kelly & Zweben, 2000; Deo, Starnes & Holzwarth, 2002)

For example the fuselage of the A380 contains GLARE, the Boeing 787 fuselage is of filament wound carbon fibre and the A350 fuselage is constructed of carbon fibre panels. These differences in design may complicate the investigation of composite material accidents.

2.5 Summary

This chapter has shown the importance of aircraft accident investigation in promoting flight safety. It has also demonstrated that there is currently undergoing a change in the preference of polymer composite materials over metallic materials, for future airframe construction. Whilst the most notable developments are within large civil transport aircraft, the change is also occurring in other sectors including military and GA. It is also suggested that traditionally, technological advancements have generally improved flight safety. It has been suggested that composite materials may improve flight safety as they offer distinct advantages in fatigue and corrosion resistance. The do present issues however as they have new failure modes and they do not have the history of learning and development associated with metallic materials.

3 LITERATURE REVIEW



The purpose of this research is to assist aircraft accident investigators in conducting the examination of polymer composite aircraft wreckage. The intention of this chapter is to: explore previous work in this area, to determine the underlying principles related to the conducting of a wreckage examination and, to identify current research issues. These intentions are achieved by discussing the following:

1. The wreckage examination (section 3.2)

2. The investigation process (section 3.3)
3. Research conducted to assist the field investigator in examining polymer composite materials (section 3.4)

3.1 Introduction

The literature review was conducted to identify literature that has made a significant contribution to knowledge in the fields of investigation and wreckage examination. It became apparent that there was a dearth of academic research located within peer-reviewed journals. Of the publications that were discovered, they were generally orientated to discussing experience gained from specific investigations (e.g. Clark, 2005; Fox, Schultheisz, Reeder, 2005).

Furthermore, whilst there was a wealth of academic interest in understanding accident analysis, theory and causation, there was a dearth of research orientated to understand the investigation process, which would be appropriate to the examination of wreckage.

Hence a significant portion of the literature reviewed focussed on material from within the investigation community, including accident investigation manuals, reports and published works by investigators.

3.2 Investigation of wreckage

The examination of aircraft wreckage is an important aspect of accident investigation. Through conducting a wreckage examination, the investigator may be able to differentiate between pre-impact and post-impact failures, and also gain an understanding of the aircraft dynamics at impact (Walker, 1965). Moreover, when considering premature structural failures, it is the responsibility of the investigator to recognise a ‘suspicious’ component and subsequently send for forensic analysis (Wood and Sweginnis, 2006). This identification however is a complex process that requires skill from the investigator.

This complexity is sometimes exacerbated when access to or recovery of the wreckage is restricted. For example, the Transportation Safety Board (TSB) of

Canada (TSB, 1991) summarise the factors that are likely to influence wreckage recovery as:

- The likelihood of finding any significant evidence
- The benefit to the investigation
- The potential to further advance aviation safety
- The possibility of organising an effective search
- The probability of a successful search
- The feasibility of recovering the wreckage
- The extent of public interest
- The total cost of the search and retrieval process compared to the benefit to aviation safety
- The likelihood of reliable cost–sharing between the owners, operators, insurance companies and the TSB.

The TSB (1991) go one further to state:

> *"You can usually adequately examine the wreckage in situ at the site, and need to only bring back selected components for detailed examination and analysis."*

Whilst this view is not identical to all investigation agencies, it is similar to policies by Australian Transport Safety Bureau (ATSB) (Macaulay, 2010), and Accident Investigation Board of Norway (AIBN) (Nørstegård, 2010).

The examination of aircraft wreckage primarily occurs in two phases. The first phase concerns the examination of the wreckage at the scene of the accident. Initially, this will entail a walk through the wreckage to gain an understanding and provide perspective of the accident (Wood & Sweginnis, 2006). This preliminary overview will provide information from which the investigator can start to develop hypothesis surrounding the accident (Carver, 1987).

During the wreckage examination phase, the initial tasks are focused on recording the accident scene, collecting perishable evidence, plotting the wreckage, and developing a plan (Wood & Sweginnis, 2006; ICAO 1970).

The examination of the wreckage during this phase will provide indications of (ICAO, 1970):

- The direction, angle and speed of descent
- Whether it was a controlled or uncontrolled descent
- Whether the engines were under power at the time of impact
- Whether the aircraft was structurally intact at the point of first impact

Furthermore, cursory examination of the fractures will be able to provide indications as to whether a component failed in overload (Heaslip, 1973) and hence understand the breakup of the airframe during the impact sequence.

Structural failure is a significant factor in many aircraft accidents (Wood & Sweginnis, 2006). ICAO (1970) defines a structures examination as *"the investigation and reporting upon the airframe of the aircraft. This includes primary and secondary structure, lift and control surfaces".* If a structural failure is suspected, then it is likely that a second phase of detailed wreckage examination will be conducted (Carver, 1987).

Typically, the most convincing evidence of an in-flight structural failure is in the wreckage distribution (Wood & Sweginnis, 2006). This is not always the case however, as in-flight structural failures can also result in contained or non-separating failures (ICAO, 1970), where the fractured components are 'carried' to the location of impact. ICAO (1970) describes these occurrences as *"by far the more difficult to investigate".*

Carver (1987) summarise the charter of an investigator when conducting a structural investigation as follows:

> *"To do your job as an investigator it is not necessary for you to be the final authority on why and how aircraft parts failed in a mishap. You need to understand the fundamentals of failure analysis, to be able to recognize anomalous failures—things that just don't look right, that didn't fail the way you would expect them to—and to know where and how to go to find out what caused these failures. There are always people available to assist you in determining why a piece of metal failed. Your*

job is to determine which failed pieces of metal are important; to preserve the evidence which these parts represent so that a true determination of the causes of failure can be made; to consult the failure analysis experts who can make that determination: and then to use the information they give you to determine the cause of the mishap, to prevent future mishaps."

There is, however, an important variation in the wreckage examination that is not investigator centred, rather, dependent on the resources deployed to the investigation and on the aircraft under investigation. Importantly, both of these factors are significantly influenced by the operating category of the aircraft.

When considering the scope of aircraft utilisation, ranging, for example, from light sports aircraft to large commercial air transport aircraft, it is reasonable that the types of composite material may also have a wide variation. This would typically vary from the use of hand laid, wet resin saturated, room temperature cured fiberglass used in light sports aircraft and gliders, to machine laid, autoclave cured, pre-impregnated carbon fibre (prepreg) used in larger transport aircraft (Abbott, 2000). This suggests that, to a certain degree, there is potentially a variation in the design and manufacture of the airframe, depending on the type of aircraft. For example, R. Abbott (Abbott, 2000) when discussing Glass Fibre Reinforced Epoxy (GFRE), suggests that the use of GFRE is suited to primary structures in small light aircraft, but it has a use on large commercial aircraft limited to items such as fairings and trailing edges.

Furthermore, there are typically differing investigation protocols depending on the nature of the accident. For example, according to Sarsfield, Stanley, Lebow, Ettedgui, and Henning (2000), the US NTSB has five different investigation categories.

*"**Major investigation**. This usually entails an accident involving a commercial airliner or cargo aircraft. The Washington headquarters of the NTSB, through the OAS dispatches a "goteam" of investigators to handle the investigation of such an accident.*

Major investigation, regional office. *This is a less serious air accident in which significant safety issues have been identified. It is handled by one of the NTSB's six regional offices, at least at the outset. Some nonfatal airline accidents and most small commuter airline accidents fall into this category.*

Field investigation. *This is an airline accident or incident with no fatalities (such as an incident involving air turbulence) or a GA accident. The investigation is conducted by the nearest regional office and at least one investigator goes to the site of the accident. A small number of field investigations involving GA aircraft are complex and grow to rival headquarters-led investigations.*

Limited investigation. *A limited investigation, sometimes called a "desk investigation," is conducted subsequent to an event involving GA aircraft. This investigation is carried out by U.S. mail or over the telephone.*

Delegated investigation. *These investigations are delegated to the FAA. They include accidents involving rotorcraft, amateur built aircraft, restricted category aircraft, and all fixed wing aircraft that have a certificated maximum gross takeoff weight of 12,000 pounds or less, unless fatalities occurred, the aircraft was operated as an "air taxi," or the accident involved a midair collision. The FAA is directed to report the facts, conditions, and circumstances of the accident to the NTSB; if necessary, the Safety Board may determine the probable cause.*

According to the NTSB major investigation manual (NTSB, 2002), when a major investigation occurs, the investigation team may contain over one hundred technical specialists from over a dozen parties. This party system is established to allow *"the NTSB to leverage its limited resources and personnel by bringing into an investigation technical expertise from the aircraft manufacturers or airlines, professional organizations… During the field investigation and throughout the fact-finding process, party representatives play a significant role in evaluating physical evidence from the crash and developing a complete and accurate factual record of the accident."* (Sarsfield *et al,* 2000). When commenting on the difference in the resources, and hence role, that an investigator would have when investigating a typical GA accident compared to that of a major investigation, Sarsfield *et al* goes on further to state:

> *"In the field, the Air Safety Investigator (ASI) dispatched from a regional office usually works alone and investigations do not receive extensive support from the OAS in Washington. Field investigations are also usually much smaller in scope, making only occasional use of the Safety Board's headquarters-based laboratories facilities."*

This difference in deployed resources between a major investigation and one involving a GA type accident is not limited to the NTSB. A similar difference is described in the UK AAIB operations manual (AAIB, 2008).

It is therefore evident that whilst there will be similarities in the wreckage examination of large commercial transport aircraft and that of GA aircraft, there is also the potential for some significant differences. These differences can be related to the typical types of construction identified on site or the expected support, in terms of technical expertise and resources, provided to the investigator during the investigation. It can therefore be expected, although this is not assured, that during an investigation involving a typical GA aircraft, there is likely to be an increased emphasis placed on the field investigator to conduct the wreckage examination and hence to conduct the visual examination of the composite structure. Moreover, there is likely to be less resource to support further in-depth examination unless the part in question had already been identified as of significance to the investigation.

3.2.1 The knowledge and skills to conduct a wreckage examination

As previously stated, it is not an expectation that the accident investigator should be a metallurgist as all formal confirmations of failures come from the laboratory (Wood & Sweginnis, 2006). However, a basic knowledge of metallurgy is of importance. For example, the accident investigator chooses the specimens to be sent to the laboratory and they must liaise with the failure analyst and interpret the information gained within the context of the whole accident (Wood & Sweginnis, 2006; Kar, 1992). Moreover as Noon (2009) suggests:

> *"Some evidence may be misinterpreted by the investigator. Perhaps its significance is overlooked, overvalued, or not understood properly at all. For example, the significance of material fatigue may not be properly evaluated if the investigators cannot recognize what a fatigue fracture looks like."*

Packer & Morin, (1974) describe a similar instance where, without the understanding of the wider context of the accident, a false analysis from a laboratory examination occurred. Additionally, an understanding of an accident sequence may come from the interpretation of fracture surfaces and characteristics of the failed component. As Walker (1965) states,

> *"The study of fractures usually has an important place in accident investigation. Many of these fractures have a conventional form and are readily recognized by engineers with a text-book knowledge of what might be termed metallurgical specimens."*

ICAO circular 298 AN/172 (ICAO, 2003) *"training guidelines for aircraft accident investigators"* represents standards for the training of aircraft accident investigators (ICAO, 2003). Within this circular the following is given as accident investigation course guidelines in structural examination training (ICAO, 2003):

> *"As the basis for the examination of the wreckage, the study of structures is an area of prime interest to the investigator. The study of structures should comprise metallurgy, fibre reinforced plastics and timber structures, stress analysis and the strength of these materials. It should also include the various modes of failure and the characteristics of such failures in the materials used in aircraft structures. The methods of failure analysis, reconstruction of areas of interest in the airframe, and the evidence of the various modes of failure are important considerations. The various types of flight controls and landing gear structures should also be studied under this heading. This section of the syllabus should*

cover the advanced equipment used in the study of failure mechanisms, the preparation of samples for examination by such equipment, and the methods for comparative testing of similar materials. The study of structures also provides a platform for introducing the means of wreckage trajectory analysis. Every effort should be made to provide examples of the various failure modes in materials used in aircraft construction."

It is evident that the identification of composite material failure modes is a requirement of the investigator. Moreover, it is recognised that the investigators understanding of composite failures lags behind that of metallics (Wood and Sweginnis, 2006; Rakow & Pettinger, 2007; Taylor, 2007).

3.2.2 The examination of material failures within aircraft accident investigation

Whilst the accident investigation community has a long history with the structural failure of metallic materials, including the understanding and identification of failure modes, the situation with composite materials is different. An understanding of the challenges that composite materials present to the accident investigation community was described by Fox, Schultheisz and Reeder (2005). Fox and Schultheisz were both NTSB staff working within the materials laboratory and the paper published relates to the structural investigation of American Airlines Flight 587. Within this paper the authors state:

"For most common airplane structural metals, visual inspection or low-power magnification is often sufficient to determine fracture mechanism and direction. For metals, the fracture plane, surface roughness, radial marks, chevrons, shear lips, and general deformation when present all provide macroscopic clues to the fracture mechanisms, direction of fracture propagation, and relative motion of mating surfaces. Preexisting cracks in metals often show staining or changes in color associated with corrosion. Using these clues, large areas of damaged structure can be examined relatively quickly by an experienced investigator to identify fracture origins and areas requiring closer inspection."

They go on to state:

> *"Visual clues to preexisting fractures, such as flat fracture features with curving boundaries or staining from corrosion that can be readily observed in structural metals, generally are not readily visible in composites. Furthermore, the visual cues to fracture propagation directions that are sometimes apparent in composite structures, such as crack branching in translaminar fractures (fractures that break fibers) or banding in delaminations (fractures between layers), were not apparent in many of the fractures of interest."*

It is therefore apparent that when looking for visual characteristics within a composite material, the investigation noted that there was a lack of known visual characteristics, and of those that were known, not all were visible on the structure.

However, the identification and reporting on simple failure characteristics to support the reconstruction of the accident sequence has appeared in numerous accident investigation reports.

For example, during the investigation of a Glaser Dirks DG-400 all composite sailplane, the field investigator reported (NTSB, 2009)

> *"Examination of the wing spar carry though revealed that the left wing bottom spar cap fracture surface exhibited a flat face, and carbon fibers that were bent and buckled in a manner consistent with compression loading. The upper spar cap fracture surface was jagged with carbon fiber ends extending at different lengths, consistent with tension loading."*

In addition, a series of Schempp-Hirth Duo Discus wing failures were investigated by the BFU (BFU, 2006) and BEA (BEA, 2003) (figure 3-1). The investigators conducted visual examination of the bonding surfaces and fracture surfaces to identify insufficient bonding and failure modes.

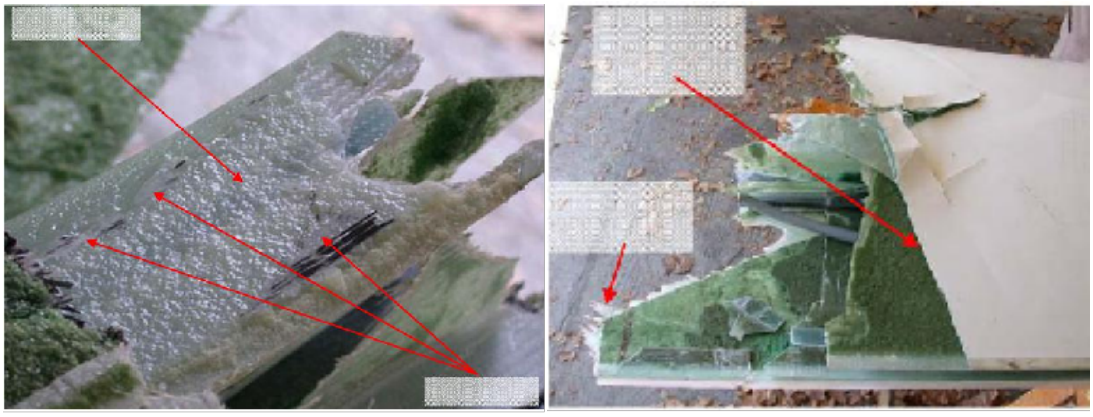


Figure 3-1 – Images from BEA investigation report depicting visual characteristics (BEA, 2003).

In 2002 Qinetiq, who provide forensic analysis of structural failures to the UK AAIB, observed that the top three metallic failure mechanisms were Fatigue (55%), Corrosion (16%) and Overload (14%), (Findlay & Harrison, 2002). This result is perhaps not surprising since typically the fatigue limit of light alloys can be as little as 10% of the ultimate static strength (Greenhalgh, 2009). This experience has provided an understanding to the accident investigation community as to how metallic aircraft can fail prematurely. Composites, on the other hand, are relatively fatigue resistant, and any significant fatigue crack growth may not develop until 60% of static failure stress (Greenhalgh, 2009). Moreover, delamination is a failure mechanism that is considered a significant issue for laminate composite materials but one which does not affect traditional aluminium materials. Delamination involves the subsurface separation of plies of a laminate and may be initiated by relatively low energy impacts. The full extent of such damage may remain barely visible under visual examination. Thus early detection is reliant on Non-Destructive Evaluation (NDE). Ransom, Glaessgen, Raju, Knight and Reeder (2008), however, have recently questioned the effectiveness of NDE inspections claiming that *"Nondestructive evaluation (NDE) techniques of complex structures are generally inadequate to detect damage during typical in-service inspections".*

The understanding of metallic failure modes and how to make a preliminary visual identification has benefited from decades of failures and subsequent investigations. In the case of metal fatigue, Wanhill (2003) discusses advances in the knowledge of fatigue linked to notable aircraft accidents such as: the Comet disasters of 1954, which gave a general awareness of finite aircraft fatigue life, the F-111 wing failure in 1969 which highlighted aircraft should be damage tolerant, the Dan Air 707 accident in 1977 which presented the fatigue of geriatric aircraft, and the Aloha Airlines 737 accident in 1988 highlighting multiple site fatigue damage. Unfortunately this accrued knowledge and understanding of metallic failures cannot necessarily be transferred to the understanding of composite material failures due to key differences between metallics and composite materials (Wanhill, 2003). In the case of metallics, a suspect fatigue initiated failure may be visibly identified by beach marks and the presence of two distinctly different fracture zones (ICAO, 1970). These visual clues can also provide the investigator with an indication as to the initiation site. In the case of composites, visual examination of most failure modes can be complicated through a substantial increase in the number of fracture surfaces, a general difficulty in visual identification, a high susceptibility to post fracture damage and the lack of any significant permanent deformation (Greenhalgh, 2009). In the case of the latter, the permanent deformation of metallic structures can provide valuable clues as to what was occurring to the aircraft prior to or at the time of impact. For example Frank Taylor (1998), in his paper discussing the wreckage analysis of a DC-9 being operated by Itavia that crashed off Ustica, discusses how the permanent deformation of the aircraft structure can be used to determine the break up sequence and to locate the most probable position of an explosive device. An absence of this 'recording' of evidence may have major implications on accidents where evidence from alternative sources is limited.

Accident investigation literature, which includes the explanation of metallic failure characteristics and subsequent identification features, is dominated by sketches produced by Thomas Gavin. These sketches have been used within accident investigation training media for many decades, e.g. Cranfield University's Applied Aircraft Accident Investigation course, ICAO's manual of accident investigation (ICAO 1970; ICAO 2008), the book titled "Aircraft Accident and Investigation" by Wood and Sweginnis (2006), and a publication titled “Aircraft Accident Reconstruction and Litigation”, by McCormick and Papadakis (2003).

3.2.3 The visual and macroscopic failure characteristics of polymer composite materials

The visual examination of a failed component is usually the first step in a failure investigation and has been suggested as the most important step (ASM, 2001). In many cases the visual examination can be enough to determine the cause of failure (Stumpff, 2001; Kar, 1992a) and a subsequent in-depth investigation is conducted to confirm or contradict the initial finding (Greenhalgh, 2009). Moreover, a successful in-depth failure investigation has been conducted solely using low magnification techniques (Purslow, 1984), albeit this has relied on the expertise of the analyst in interpreting the findings.

Generally a visual examination can provide a considerable amount of information such as identification of the sequence of failure, determination of crack growth directions, identification of the failure initiation site and identification of failure modes (ASM, 2001; Purslow, 1981). Although the visual examination can be fruitful, it is seldom a replacement for high magnification examination. In fact, the most widely used method of studying fracture surfaces is through the use of the Scanning Electron Microscope (SEM) (Roulin-Moloney, 1989).

Some of the most seminal work on identifying the visual and macroscopic characteristics of composite failures appeared in the 1980’s, although there were numerous publications before this time. During this period the development of a handbook began in 1984 (Stumpff & Snide, 1986) and was presented in numerous volumes and updates (Smith & Grove, 1987; Hua & Yamashita, 1989; Kar, 1992; Kar, 1992a; Kar, 1992b; Kar, 1992c; Walker, 1997)). The purpose of the handbook was to visually record the fracture surfaces of composite materials that had failed under differing conditions. This began the compilation of an atlas of fractographs much in a similar fashion as had been conducted within the metals field (e.g. ASM, 1987). It was later realised that this would be an impractical task due to the vast variations in possible fracture surfaces and thus, as Greenhalgh (2009) suggests *"the approach pursued by most fractographers has been to understand the mechanisms and relate them to the fracture morphologies".*

Whilst this argument applied to predominantly microscopic fracture characterisation, the same fundamental issues appear from a visual and macroscopic perspective. When a metallic material fails, the failure is usually restricted to one or a limited number of fracture planes. When a composite material fails, whether it a unidirectional material or a multi-directional laminate material, the failure is likely to result in a significant amount of energy being absorbed through multiple fractures (Greenhalgh, 2009). Moreover, the fracture characteristics are influenced by additional factors that do not occur to metallic materials. For example, the fracture characteristics of a composite material are dependent on (Modified from: Greenhalgh, 2005; Srivastava, 1989):

- The material, including the fibre, the matrix and the interface
- The architecture
- The form of loading applied (e.g. compression, tension, etc.)
- The fracture plane (e.g. translaminar, interlaminar, etc.)
- The nature of loading (e.g. static, dynamic, or cyclic)
- The influence of degradation mechanisms.

It is thus likely that similar issues will appear during the visual and macroscopic interpretation of polymer composite materials. This would be likely to have ramifications on transferring knowledge to the field investigator. The argument previously mentioned suggests that an understanding of mechanisms and principles of failure will be necessary in order to confidently identify the failure mechanism. This is in contrast to the current transfer of understanding on metallic failures to accident investigators where current accident investigation training literature predominantly focuses on visual representations of the failure surfaces. For example, McCormick and Papadakis (2003), in their publication title "Aircraft Accident Reconstruction and Litigation", present a chapter on metallic failures that is based on pictorial representations of failure modes with little reference to the mechanisms.

Whilst there has been a significant development in the understanding of visual and macroscopic interpretations of composite failures, there also lacks discussions on the current status and future requirements for identification. Rather, the visual and macroscopic interpretation is generally treated as a precursor to the higher magnification examination. One of the first publications, which tackled the issue of visual and macroscopic interpretation, was during the development of the handbook by Kar (1992). There were six major tasks in the construction of the handbook, with the first task being to create "procedural guidelines for field investigation techniques". Whilst the procedures included handling, transportation and health and safety risks, the handbook also presented visual identification techniques (table 3-1) and a framework for field procedures (figure 3-2). However, in summarising the current knowledge, Kar (1992b) suggested:

> *"The ability to define fracture types at the macroscopic level can often be the most valuable capability for many investigators, particularly for those performing field investigations. When examining a failed composite structure, the investigator must assess the nature and direction of the applied load, identify the significance and time of fracture, and select portions of the structure for laboratory analyses. Visual examination alone can often provide sufficient information to answer these questions. However, this extremely valuable capability is very much in its infancy compared to the metals field."*

<table>
<tr><th>Mode</th><th>Environment Condition</th><th>Macroscopic Fracture features</th></tr>
<tr><td rowspan="5">Interlaminar Tension Dominated</td><td rowspan="2">Low temperature / Dry</td><td>Smooth Glassy fracture surface</td></tr>
<tr><td>Major portion of fracture between plies</td></tr>
<tr><td rowspan="3">Hot or Hot / wet</td><td>Smooth but with loose fibres strewn on surface</td></tr>
<tr><td>A majority of the fracture within plies</td></tr>
<tr><td>May be permanent deformation of the laminate</td></tr>
<tr><td rowspan="5">Interlaminar Shear Dominated</td><td rowspan="2">Low temperature / Dry</td><td>Surface flat, but with “Milky” appearance when held at angle to light</td></tr>
<tr><td>Major portions of fracture between plies</td></tr>
<tr><td rowspan="3">Hot or Hot / wet</td><td>Also exhibits “milky” appearance</td></tr>
<tr><td>Tends to fracture within a ply</td></tr>
<tr><td>Loose fibres on surface</td></tr>
<tr><td>Translaminar tension</td><td>-</td><td>Rough, jagged fracture surface with individual fibres protruding from surface</td></tr>
<tr><td rowspan="2">Translaminar compression</td><td rowspan="2">-</td><td>Extreme surface damage. Large regions of fibres fractured on same plane</td></tr>
<tr><td>Very few, if any, fibres protruding from surface</td></tr>
<tr><td>Translaminar flexure</td><td>-</td><td>Two fairly distinct regions, one exhibiting translaminar tension and the other translaminar compression, the regions being separated by a neutral axis line</td></tr>
</table>

Table 3-1 – “Visual macroscopic fracture surface features” (Kar, 1992a)

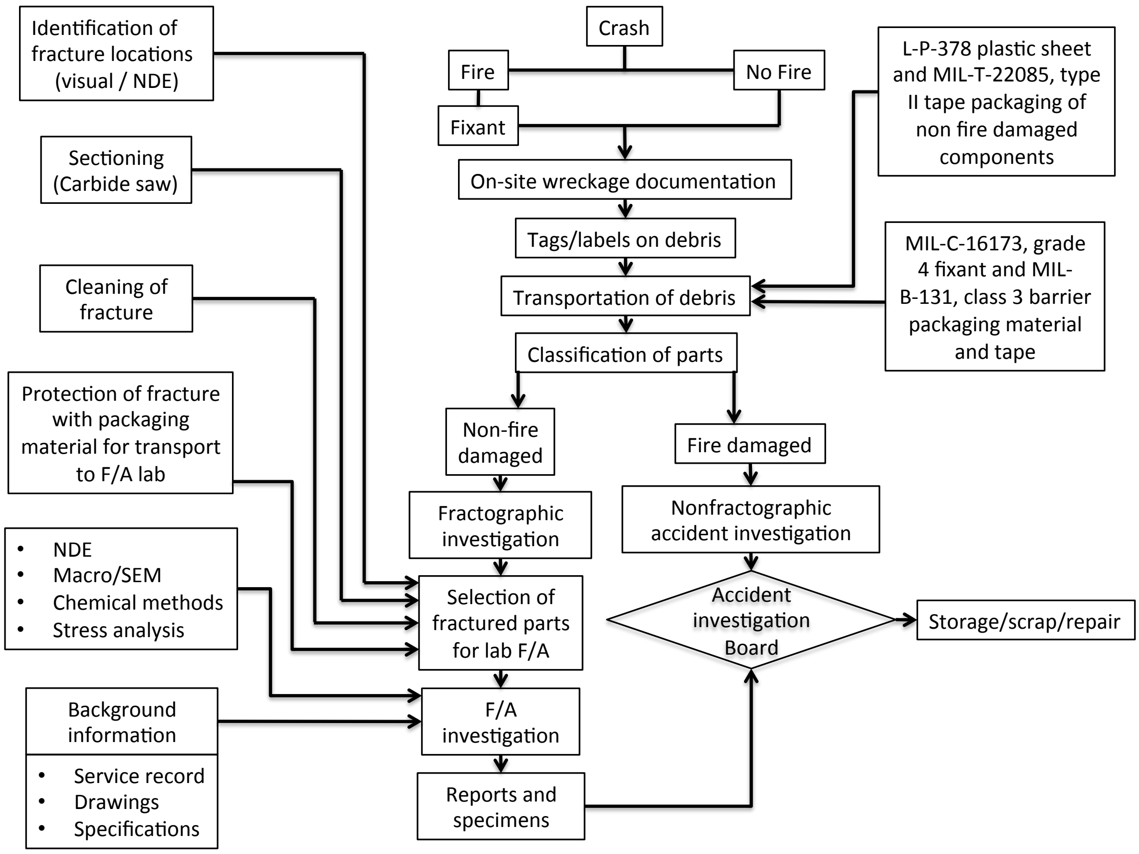


Figure 3-2 – Field Handling Logic Network for composite parts (Kar, 1992b)

It is evident however that table 3-1 was not representative of an overarching academic knowledge of failure characteristics at that time; rather it was based on *"relationships that various investigators have observed"* (Kar, 1992). Aside to the above-mentioned handbook, visual features began to be described in literature most noticeable by Purslow (1981; 1983; 1987; 1986; 1988). However, it was not until Greenhalgh (2009) published his seminal book titled "Failure analysis and fractography of polymer composites", that a significant compendium of visual characteristics was created (although the publication was dominated by high magnification interpretation). Within this publication an alternative table of characteristics was presented (Table 3-2), along with detailed information on the characteristics and mechanisms of a variety of macroscopic features.

	Feature	Implication
Undamaged surfaces	Visible distortion	Possible evidence of sub-surface damage or delamination
	Visible nicks, dents, splits or gouges	Possible crack initiation site. Possible evidence of impact, fretting or wear damage. Direction of impact can be deduced from gouge direction
	Surface blistering or splitting	Internal damage, such as delamination and ply splitting and may indicate instability such as buckling or post-failure damage
	Discolouration or fading	Evidence of exposure to chemicals or ionising radiation
Translaminar fracture surfaces	Radial or chevron features	Emanate from crack initiation site, and show crack propagation direction
	Flat, dull surface	Compression failure or evidence of fretting of surfaces
	Shiny, dark surface	Tensile failure
	Radial steps	Torsion failure; rotation direction deduced from the orientation of steps
	Increasing degree of secondary damage	Growth often in the direction of increasing degree of secondary damage, but may be limited if the fracture or loading mode changes
Intralaminar and interlaminar fracture surfaces	Ribs or tide marks	Slip/stick fracture, and may be an indication of cyclic loading. Propagation from the centre of radius of curvature.
	Dull fracture surface	Either mode II interlaminar shear or surface fretting
	Shiny fracture surface	Mode I interlaminar peel dominated fracture surface
	Fracture surface discolouration	Either post-failure contamination or evidence of corrosion prior to failure
	Change in surface hue	Evidence of a change in fracture mode or crack growth direction

Table 3-2 – "Features to note during a visual examination" (Greenhalgh, 2009)

It was apparent however that despite an increase in understanding, there still existed areas where failure modes could not easily be identified using visual interpretation (Hiley, 1999). Moreover, the interpretation is likely to be subjective in certain situations. Hence, due to the vast array of factors which may influence the fracture surface, much work still can be conducted on understanding the visual characteristics and their occurrence. However, a substantial amount of knowledge has been presented on potential characteristics that may be visually evident.

However, the application of the techniques within the real world failure investigation scenario is rarely discussed. It is therefore impossible to predict the success of visual identification within the field of accident investigation without taking the field into context. For example, the ‘duck test’ (van Wersch, Forshaw and Cartwright, 2009) is an adage of inductive reasoning which describes the use of multiple sources of information to assess the likely outcome, i.e. “if it looks like a duck, swims like a duck and quacks like a duck, then it is probably a duck”. External sources of evidence such as the wreckage distribution, aircraft accident history, witness evidence, etc. may supply the ‘swims’ and ‘quacks’ of the examination, with the visual examination supplying the ‘looks like’. Therefore, it may be plausible that within the field investigation scenario, a probable positive determination, or conversely a probable false determination, may be sufficient to benefit the investigation. Especially, as in the eyes of the field investigator, all confirmations of material failures must come from the laboratory (Wood & Swegginis, 2006).

3.3 Investigation process

3.3.1 Data, facts, information and evidence

Perusing within the accident investigation literature, the themes of facts, data and evidence appear to be used interchangeably and placed within the same context. They do however have one similarity in that there are no clear definitions within the accident investigation literature to separate each. Distinguishing between them may be inconsequential if it were not for the investigation depending heavily on these from a theoretical point of describing the process of investigation, and from a practical perspective as the investigation is centred on establishing these key aspects. For example, the ICAO (2005) “ICAO Accident Prevention Programme” and ICAO (2010), Annex 13 both refer to the collection of ‘information’. Within Annex 13, ICAO (2010) defines an accident as (emphasis added):

> *“A process conducted for the purpose of accident prevention which includes the gathering and analysis of* ***information****, the drawing of*

conclusions, including the determination of causes and/or contributing factors and, when appropriate, the making of safety recommendations.”

Conversely, in ICAO’s (2008) draft document “Manual of aircraft accident and incident investigation”, the investigation process is referred to as the collection and analysis of ‘**data**’. With the documents predecessor, titled “Manual of aircraft accident investigation” ICAO (1970), referred to the process as (emphasis added):

> *“The fundamental purpose of inquiry into an aircraft accident is to determine the* ***facts****, conditions and circumstances pertaining to the accident with a view to establishing the probable cause thereof…”*

Similar themes appear in other investigation literature, e.g. Ellis (1984), Wood & Swegginnis (2006), and Ferry (1988) with the collection of ‘**evidence**’ being quoted. For example, the term ‘perishable evidence’ is frequently quoted.

However, a clearer understanding of the differences has been suggested within the field of criminal investigation. For example, the Association of Chief Police Officers produced the “Core investigative doctrine”. Within this document, the definitions are extracted from the Criminal Procedure and Investigations Act (1996). Here, the definitions are split into ‘Evidence’ and ‘Material’, with Material including *“material of any kind, including information and objects”.* Both terms are hence drawn from the legal framework from which a criminal investigation is investigated.

An alternative school of thought is presented by the “American Institute of Chemical Engineers” (Safety Center for Chemical Process, 2003). Here, the definition of evidence is given as:

> “*Data on which the investigation team will rely for subsequent analysis, testing, reconstruction, corroboration, and conclusions”.*

Moreover, the US Department of Agriculture suggest that a fact can be defined as (DoA, 2003):

"An actual happening in time or space that is verified, preferably by two or more sources of evidence or proof."

The collection of data, and hence evidence, is directly related to the determination of causes (Carver, 1987). For this reason, the understanding of the forms of evidence available, how it can be identified by the investigator and, how it is gathered in a manner to avoid permanent destruction, is of critical importance to the investigation process.

The potential sources of data or potential evidence are boundless. However, there are general categories from which evidence is generally located. ICAO (2005) proposes that sources of information can be located from either primary or secondary sources. Much like the definitions of primary and secondary research, the primary sources are information which is collected by the investigator and secondary sources are reliant on information that has already been gathered. Within primary and secondary information sources contain sub-sections listing categories which the information appear (Figure 3-3).

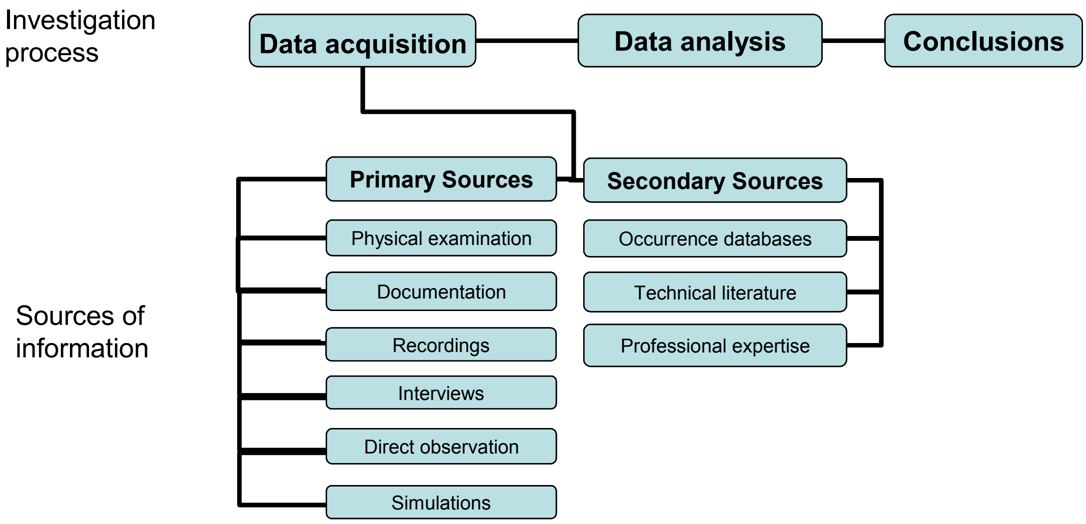


Figure 3-3 - Investigation process with sources of information (redrawn from ICAO, 2005)

Stott (2009), in training literature associated with accident investigator training at Cranfield University, suggests that evidence can be split into: Environment, Equipment, and People.

An alternative approach, which occurs in accident investigation training literature, is to describe the internal investigations and to highlight possible forms of evidence within each category. For example the following has been taken from the ICAO (2008):

- Wreckage investigation
- Organisational investigation
- Operations investigation
- Aircraft operations environment
- Aircraft performance investigation
- Flight recorders
- Reconstruction of wreckage
- Structures investigation
- Mid-air collision investigation
- Fire investigation
- Powerplant investigation
- Systems investigation
- Maintenance investigation
- Helicopter investigation
- Investigating human factors
- Survival, evacuation, search, rescue and fire fighting
- Pathology investigation
- Investigation of explosives sabotage
- Investigating system design issues

This format is present in other investigation publications such as ICAO (1970), Wood & Swegginnis (2006), Carver (1987), McCormick & Papadakis (2003). Whilst this separation may suggest that sources of evidence are linked to individual areas of investigation, this is not necessarily the case. For example, a pathological examination may be conducted to identify how the pilot died and whether a pathological aspect may be causal to the accident. Additionally however, evidence contained with the victim may provide significant information as to the other areas of investigation or to the reconstruction of the accident sequence. Mason (1968), in his book on aviation pathology, describes the location of shrapnel within the victims' bodies, as providing a source of evidence to suggest the probable location of detonation within the aircraft. Furthermore, Folio, Harcke & Luzi (2009) describe the examination of hand and leg injuries to ascertain who was at the controls at the time of the accident.

3.3.2 Investigation framework

The investigation of aircraft accidents is inherently reactive by design. The occurrence of the accident becomes the starting point in which the investigator traces backwards through the sequence of events that occur. It is therefore advantageous to expand the scope of the review to include disciplines outside of aircraft accident investigation, but also where investigations will occur. However, methods of investigations which are conducted primarily to establish blame or liability, such as those in criminal investigations, have been excluded.

3.3.2.1 ATSB Model of safety investigation activities

In discussing analysis, proof and causality in safety investigations, Walker & Bills (2008) present a framework of the activities that are deemed by the authors to occur during the investigation process (figure 3-4). The purpose of the framework was to illustrate the placement of the analysis conducted by the investigator into the activities of the investigation. It is proposed that the analysis is conducted during the majority of the investigation although the purpose of the analysis may change. The model is used within the paper to set the scene for a requirement for an enhanced framework for investigation analysis. It proposes that the analysis conducted is varied and ultimately relies on the judgement of the investigators.

Figure 3-4 – ATSB safety investigation activities overview (redrawn from Walker & Bills, 2008)

3.3.2.2 US Department of Energy

Ferry (1988) presents a seven step process created as a refinement to a model proposed by Johnson (1980). The seven step process is illustrated in figure 3-5 and involves the following steps (Ferry, 1988):

1. *Analyse all available information*
2. *Isolate relevant and irrelevant facts. Develop hypotheses to resolve uncertainties*
3. *Analyse the facts developed to date*
4. *Form conclusions based on what is known and what is not known, and determine serious deficiencies in information.*
5. *Analyse the conclusions for validity*

6. *Make recommendations based on an analysis of the conclusions*
7. *Summarise the entire process*

Figure 3-5 – Seven steps of information collection (Ferry, 1988)

3.3.2.3 Operator, Events & Activity mini-investigation model

Richard Wood (Ferry, 1988), proposes a model whereby the investigation is segregated into individual small scale investigations (figure 3.6). The initial information gathering leads to the development of the operator, events and activity scenarios. These are not restricted to one event each and thus the second phase of the process may contain many more. Each of these stages undergo a mini-investigation, where facts, analysis and conclusion are drawn. The outcome, which may be positive or negative, is then passed to the conclusions summary stage.

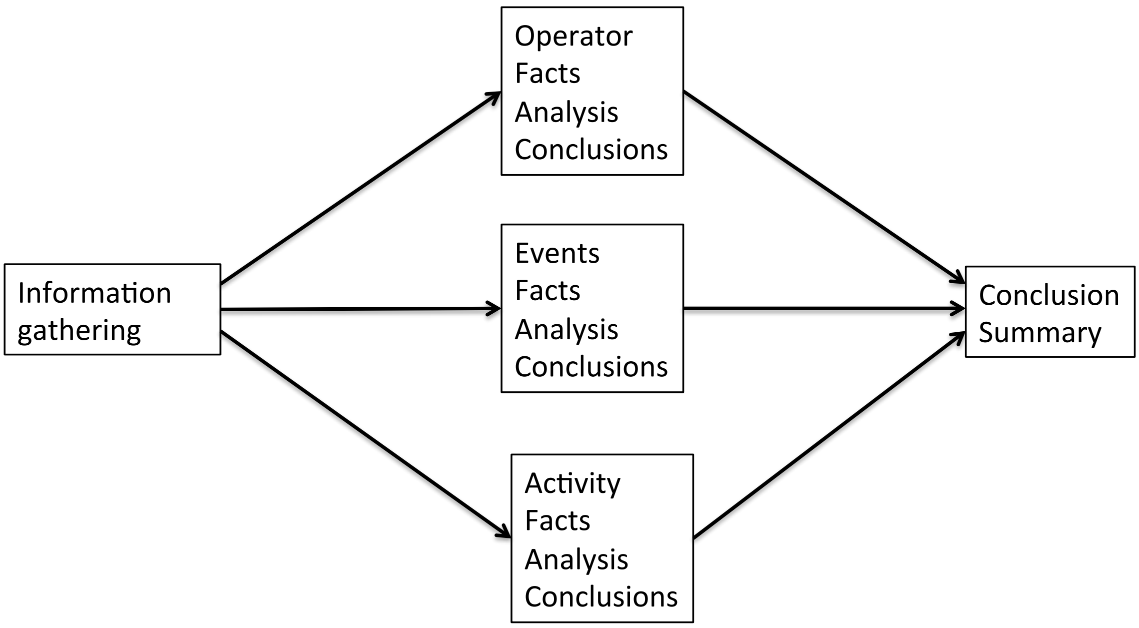


Figure 3-6 – Examination of items of consideration through a facts, analysis, conclusions and process (redrawn from Ferry, 1988)

3.3.2.4 Three phase investigation

A three phase approach to accident investigation is presented by Ferry (1988), DOE (1999), and Sklet (2002), and is illustrated in figure 3-7. The x-axis illustrates the increasing time during an investigation and the movement between the three phases of fact gathering, analysis and report preparation. The y-axis illustrates the investigator effort within each phase.

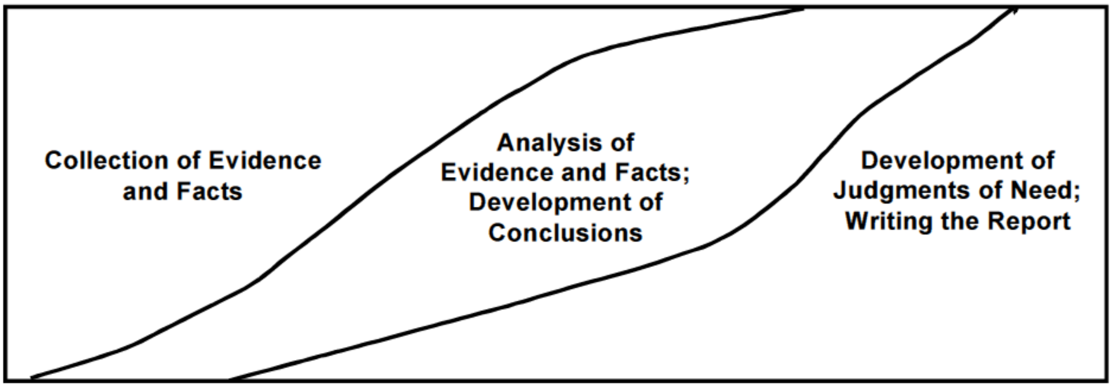


Figure 3-7 – Three phases in an accident investigation (DOE, 1999)

3.3.2.5 ICAO investigation process

ICAO (2008; 2005) presents a three phase approach to the investigation, split into the collection of data, analysis of data, and the presentation of findings (figure 3-8). Although the illustration suggests a stop start process, ICAO suggests that the analysis runs parallel with the collection of data.

The data collection phase initiates with the defining and obtaining of data to the accident. The orientation of the data collection should ensure perishable evidence receives priority. The data collection is not a step process rather the data collected at different stages of the investigation may be combined to validate possible contributing factors.

The data analysis is conducted on the evidence gathered, which in turn produces more data requirements. Following the data analysis the findings are presented.

Figure 3-8 – ICAO Investigation process (redrawn from ICAO, 2008)

3.3.2.6 US Department of Environment process of investigation

The DOE (1999), in their accident investigation workbook, present an overview of the investigation program (figure 3-9). It was latterly presented by Sklet (2002). The diagram illustrates the step-by-step process by which the investigation is conducted. The primary investigation phase includes data gathering, data analysis to determine causal factors, evaluation of causal factors, develop conclusions and judgements of need, and conduct verification analysis. The draft report is created in-parallel with the latter four steps.

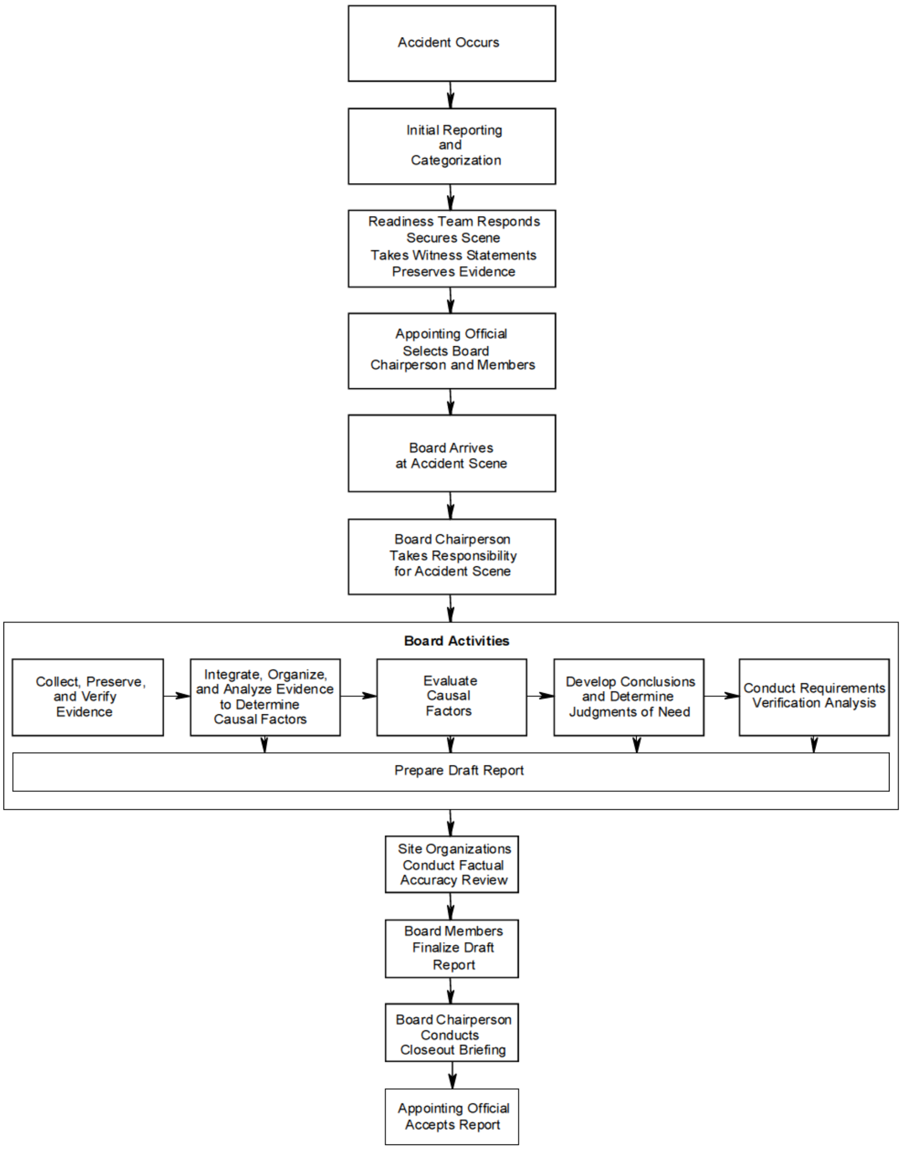


Figure 3-9 – DOE's process for accident investigation (DOE, 1999)

3.3.2.7 Wood & Sweginnis field investigation

Although not created in diagrammatic format, Wood & Sweginnis (2006) present a descriptive guide to the investigation process. They suggest that at its simplest level the investigation consists of data gathering, analysis and conclusions, much like that proposed by ICAO (section 3.3.2.5). They suggest however that the data gathering and analysis stage are conducted using mini-investigations, much like the model proposed by Wood (section 3.3.2.3). They go on further to suggest a list of procedures which are conducted during the initial field investigation, namely:

1) Preparation
    a) Initial coordination
    b) Equipment selection
    c) Technical data
2) Initial actions
    a) Establish a base of operations
    b) Establish liaison with the local authorities
    c) Arrange for security and protection of the wreckage
    d) Determine what has happened so far
    e) Conduct an organisational meeting
    f) Establish safety rules
    g) Conduct an initial walk through of the wreckage
    h) Take initial photographs
    i) Collect perishable evidence
    j) Inventory wreckage
    k) Begin a wreckage diagram
    l) Develop a plan

3.3.2.8 US Department of Agriculture accident investigation process

The US Department of Agriculture (Whitlock, 2005) proposes there are four components which provide a framework for the investigation, namely: Accident sequence, Human factors, Equipment factors, and Environment factors. The model proposed is displayed in figure 3-10 which represents the process from beginning to end of the investigation. The four framework components are essentially mini-processes which aim to gather and analyse the associated facts relevant to the framework component.

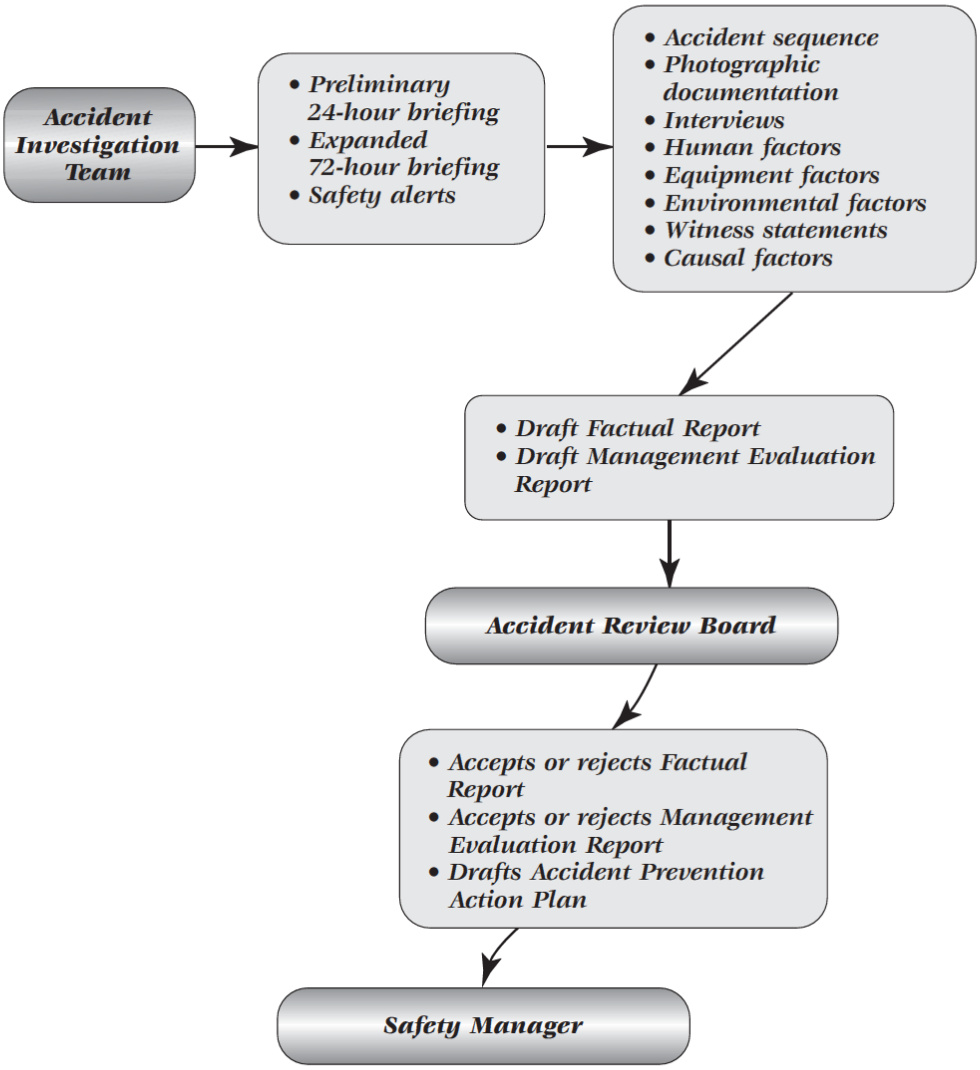


Figure 3-10 – US Department of Agriculture accident investigation process (Whitlock, 2005)

3.3.2.9 Health and Safety Executive (HSE) investigation process

The HSE (Livingston, Jackson, & Priestley, 2001) conducted a review of methodologies and approaches to investigation with the aim of creating a generic process (figure 3-11). In summarising the methodologies review, they state:

"Differences arise however, in the particular emphasis of the techniques. Some focus on management and organisational oversights and omissions while others consider human performance/error problems in more depth."

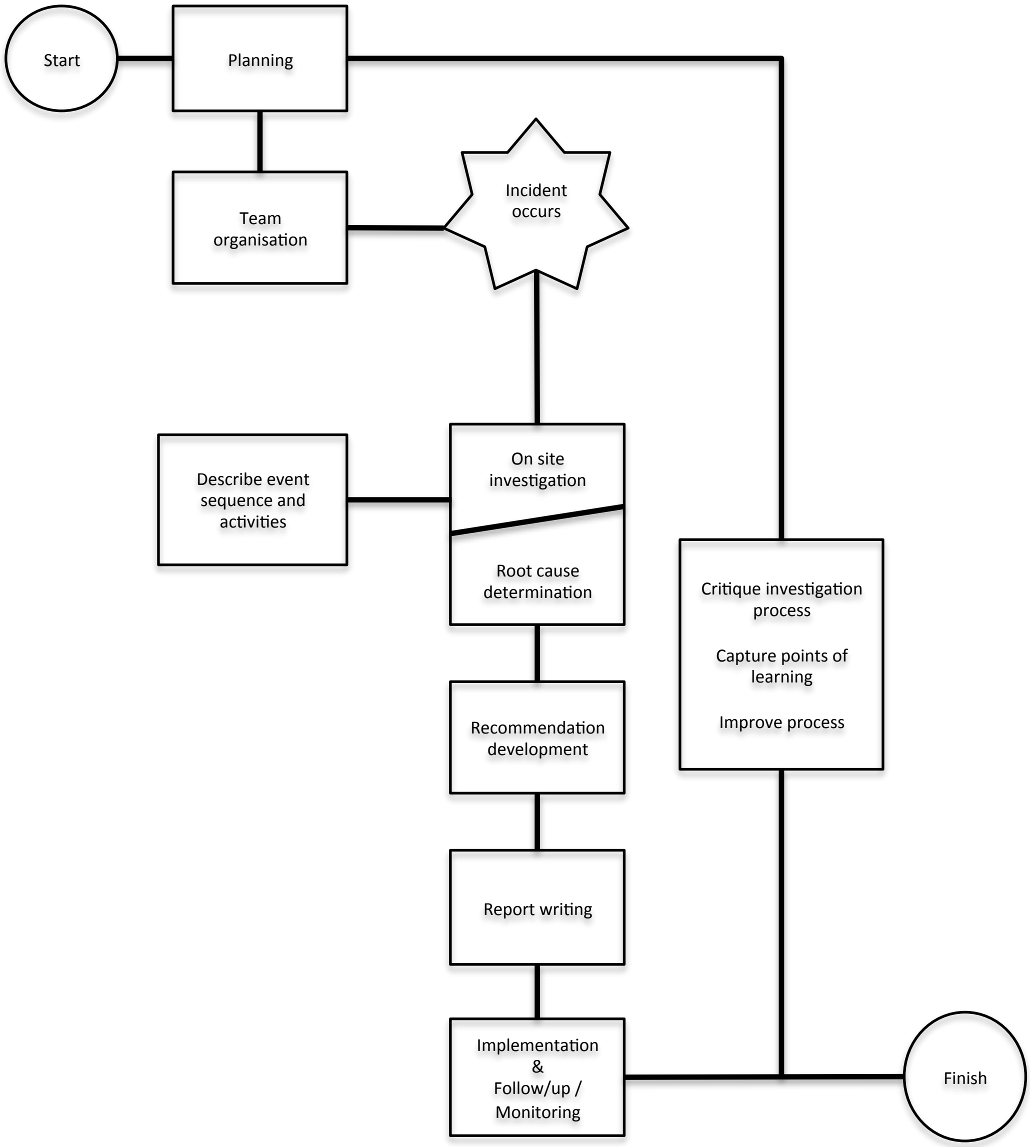


Figure 3-11 – Overview of the incident investigation process (redrawn from Livingston, Jackson, & Priestley, 2001)

3.3.2.10 Summary

The above has introduced a series of models developed to present the accident investigation process. Whilst they have covered different fields, similarities in the design and approach can be identified. The following highlights the key differences and commonalities.

- All of the models contain at least three levels to the investigation; the data gathering, the analysis and the conclusions.
- It is accepted that the levels are non-independent; rather there is a degree of overlap between the stages with iterative flow between levels.
- The description of the mechanism by which the individual levels interact and is undertaken by the investigator offers the most variation. Two themes appear. Firstly, the use of mini-investigations which may either be preselected prior to the investigation or selected during the investigation. Secondly, the iteration between facts and analysis as a single, but generic, process.
- Whilst formal analysis methods were referred to and procedures for undertaking the investigation were outlined, the in-field processing of the data was not clearly defined.

Therefore, the next section will focus on understanding methods and models as to how investigators conduct the simultaneous data gathering and data analysis. Formal analysis models were not included in the review, rather generic approaches to the processing of data were identified.

3.3.2.11 The iteration between data analysis and data gathering

American Institute of Chemical Engineers (Safety Center for Chemical Process, 2003) presents a process by which the gathering of data is conducted (figure 3-12). The process is iterative between the analysis and the data being gathered with analysis occurring as soon as the data is identified. The process also includes the formulation and adjustment of scenarios which is being developed during the iterations. Additionally, the data is judged for relevance and for its placement within the wider scenario.

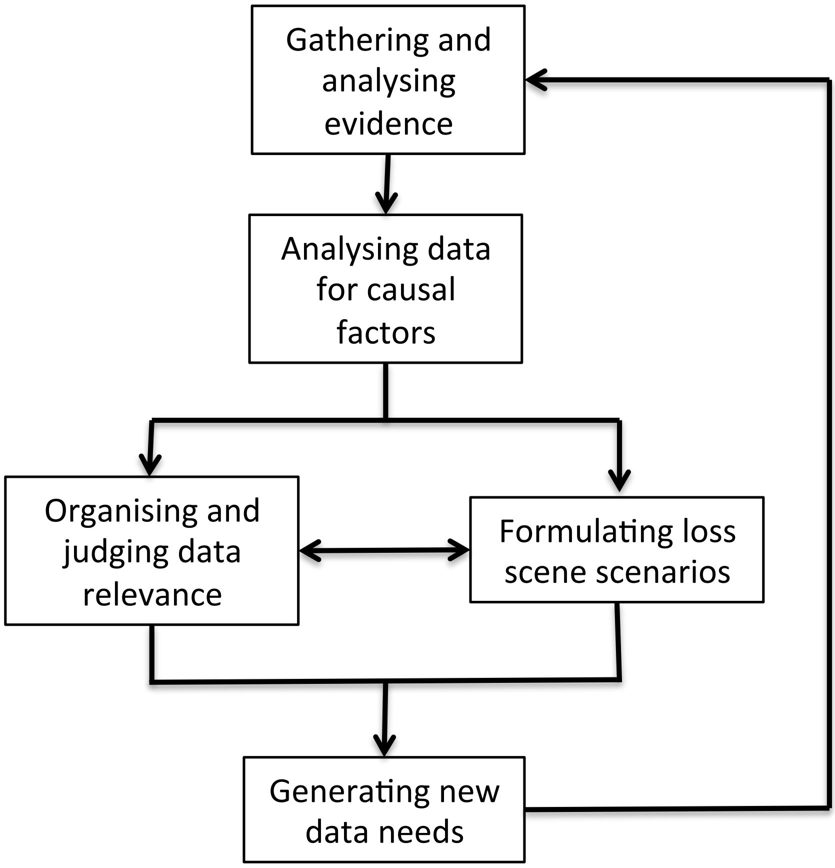


Figure 3-12 – A proposed model for the iteration between data analysis and data gathering (redrawn from Safety Center for Chemical Process, 2003)

3.3.2.12 Reasoning

Although not specific to the data gathering, the Centre for Chemical Process Safety (1992), list three generic approaches for conducting the analysis:

- Deduction approach
- Induction approach
- Morphological approach

The individual approaches are further presented by Sklet (2002). The approaches are described as a means to conduct the generic analysis. For example, as Sklet (2002) suggests, formal analysis techniques can be categorised within the inductive and deductive approaches. For example, Fault Tree Analysis (FTA) is a deductive form of analysis, and failure mode and effects analysis (FMECA) is an inductive form of analysis.

The following definitions are extracted from the second edition of the Center for Chemical Process Safety manual (Safety Center for Chemical Process, 2003).

> *"Deductive Approach—Reasoning from the general to the specific. By postulating that a system or process has failed in a certain way, an attempt is made to determine what modes of system, component, operator, or organizational behavior contributed to the failure."*
>
> *"Inductive Approach—Reasoning from individual cases to a general conclusion by postulating that a system element has failed in a certain way. An attempt is then made to find out what happens to the whole system or process."*
>
> *"Morphological Approach—A structured analysis of an incident directed by insights from historic case studies but not as rigorous as a formal hazard analysis."*

3.3.2.13 Factual exclusion

McCormick & Papadakis (2003) present a series of methods which are described as "being available to sort through the clues". Amongst others, the most prominent methods for the investigator include:

- The differential method
- The hypothetical exclusion method, and
- The factual exclusion method

The differential method is akin to the method presented by Wood (1980) as presented in section 3.3.2.3. This method involves the separation of the investigation into mini-investigations and is utilised by the NTSB for conducting major investigations (NTSB, 2002). The factual exclusion method is described as the method most likely to be utilised during GA accident investigations (McCormick & Papadakis, 2003). The factual exclusion method involves the collection of data sufficient to exclude a scenario or system. The purpose of this method is not to analyse the data to its causal relation, rather to reduce investigative effort in unwarranted areas (McCormick & Papadakis, 2003). The hypothetical exclusion method relies on the formation of hypothetical scenarios which may explain a cause for the accident. The scenarios are then eliminated based on facts, logic and experience.

3.4 Research conducted to assist the field investigator in examining polymer composite materials

The discussion thus far has detailed the importance of accident investigation and the growing challenges that polymer composite materials present to the accident investigator. This section explores research, publications and investigations that have contributed to the field of polymer composite materials in aircraft accident investigation.

3.4.1 NIAR

In 2002 the National Institute for Aviation Research (NIAR) published research into composite failure analysis specifically for the accident investigator (Tomblin & Ng, 2002). The research was conducted by the NIAR, funded by the FAA at the request of the NTSB (Tomblin & Ng, 2002). The research was conducted on the wreckage of a Nimbus 4DM glider that suffered an in-flight breakup over Minden, Nevada. The break-up of the airframe occurred during the recovery phase following a departure from controlled flight whilst manoeuvring in thermal lift conditions. The wings were subject to the research with the research objectives being:

> *"to conduct a failure analysis of a composite structure and determine the tests that are useful for crash investigations and how to avoid pitfalls. The secondary objective was to determine if any anomalies found could have contributed to wing failure"*

The research included the examination of a wing section from a similar Schempp-Hirth Nimbus glider accident (4DT variant) that had occurred in Spain (CIAIAC, 2000), and a sample wing section supplied by Schempp-Hirth.

The research conducted multiple aspects of examining aircraft wreckage as illustrated in figure 3-13.

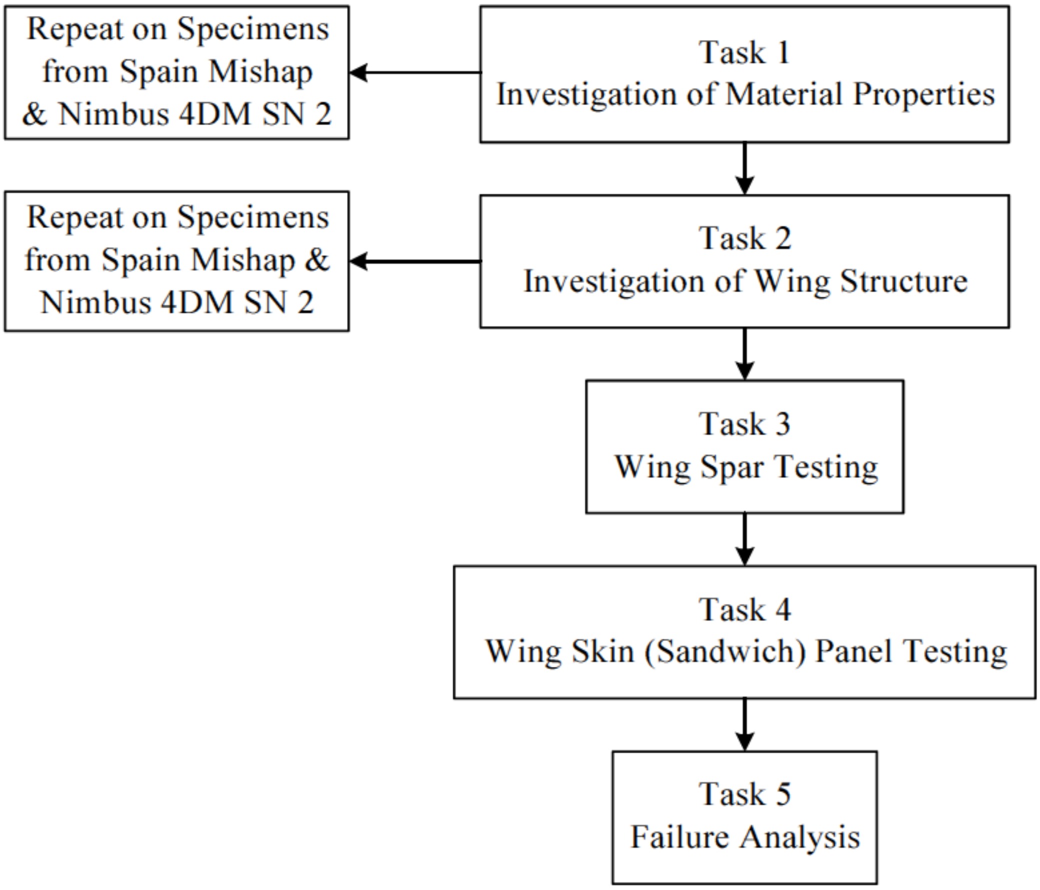


Figure 3-13 – Flow chart of the NIAR investigation of Schempp-Hirth 4DM (registration: N807BB) accident (Tomblin & Ng, 2001)

Whilst the research was very thorough, the majority of the failure analysis techniques demonstrated were orientated to laboratory investigations with significant use of laboratory based equipment and destructive techniques. This is illustrated in table 3-3.

Task	Method	Purpose	Destructive?	Specialist Equipment?
1	Differential Scanning Calorimetry (DSC)	Level of cure	Y	Y
	Dynamic Mechanical Analysis (DMA)	Determine Tg	Y	Y
	Resin content		Y	Y
	Void content		Y	Y
2	Ply Burn-off	Layup	Y	Y
3	Tension	Confirmation of spar cap mechanical properties	Y	Y
	Compression		Y	Y
	Flatwise Tension		Y	Y
	Spar cap cross-sectional area		Y	Y
	Three-point bend test		Y	Y
4	Compression	Confirmation of wing skin mechanical properties	Y	Y
	Four-point bend test		Y	Y
5	Visual examination	Identification of load directions	N	N
	Microscopic examination		Y	Y

Table 3-3 – Methods utilised in the NIAR investigation of Schempp-Hirth 4DM (registration: N807BB) accident) (Source Author)

Wood and Sweginnis (2006) stress it is the role of the laboratory to confirm failures and not that of the field investigator. Thus whilst techniques that are destructive of evidence or which require specialist equipment are of interest to the investigation, they offer little practical use to the field investigator. The research did however discuss the use of visual techniques in identifying the failure mode of the main spar caps. Unfortunately the details of the characteristics identified to determine the failure mode were not given, although the accident wing fractures were compared to reference failures created from the additional specimens. Furthermore, the purpose of identification was specifically to identify compression and tension failure mechanisms and thus was limited in scope and observation.

Based on the released information, it is therefore reasonable to suggest that whilst this research utilised methods which are likely to assist the investigation, the scope of assistance to the field investigator was limited.

3.4.2 ATSB - "Fibre composite aircraft – capability and safety"

In 2007 the Australian Transport Safety Bureau (ATSB) released a report titled "Fibre composite aircraft – capability and safety" (Taylor, 2007). The purpose of the report was primarily as a foundation to highlight: the prevalence of composite aircraft in Australia and projected growth, the structural areas in which polymer composite materials are utilised, load behaviour and reparability, and the health and safety aspects of responding to polymer composite aircraft accidents.

Whilst the report does discuss the failure characteristics of polymer composite materials, the understanding is founded on the work of Rakow & Pettinger (2006) (discussed in 3.4.3). The report does recognise the issues that composite materials present to the investigator with respect to the recognition of failure characteristics, stating:

> *"…it is inherently more difficult for Transport Safety Investigators (TSIs) to analyse failed composite structures and clearly determine what types of loads were involved"*

The report goes on further to describe failure characteristics relating to simple failure modes and presents an argument, stating:

> *"On a macroscopic scale, fibre composite structures that have failed in tension show no common characteristics that indicate that a tension load was the cause of the failure"*

This argument is based on a paper published by Ginty & Chamis (1987), although the report cites Rakow and Pettinger, (2006). The experiment undertaken by Ginty & Chamis (1987) was the tensile loading to failure of numerous test coupons. The test comprised of coupons with the orientations of +/-15°, +/-45°, +/-30° and 0° (figure 3-14).

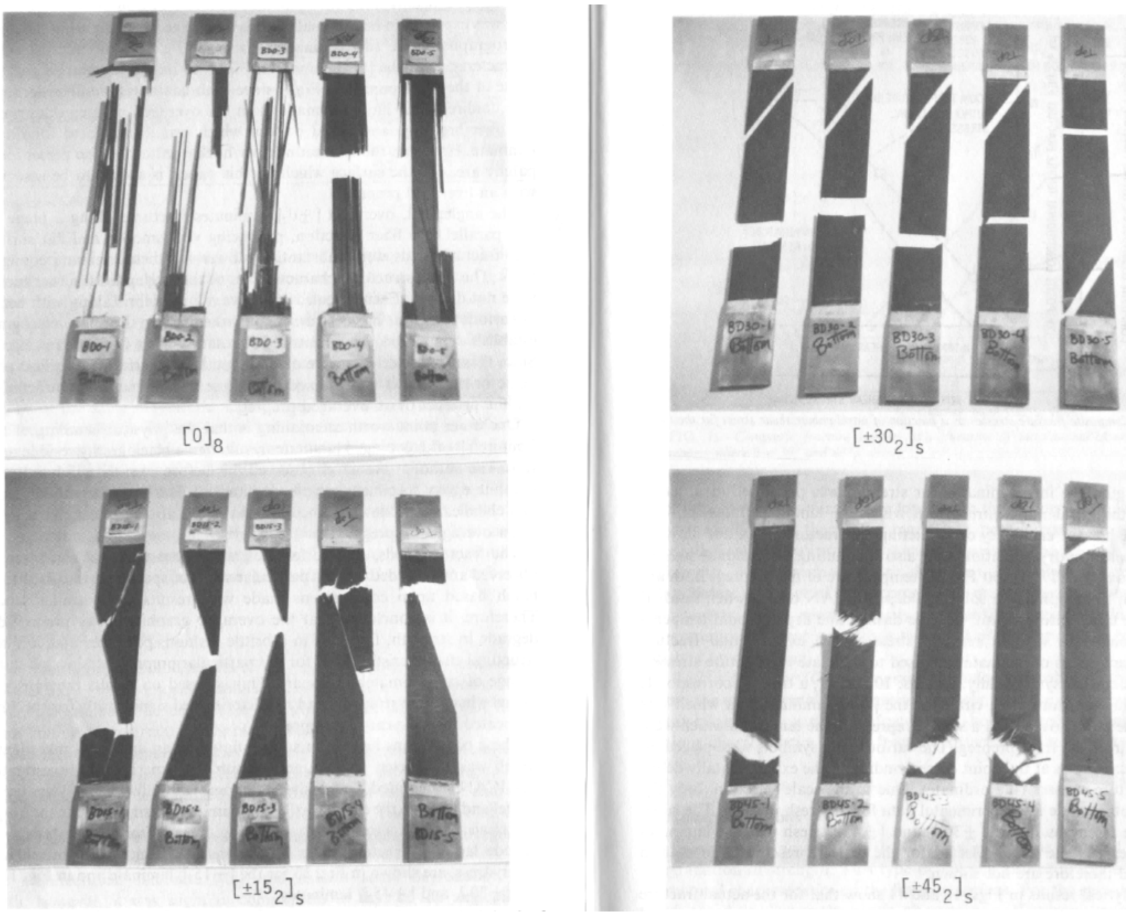


Figure 3-14 - Fractured unnotched graphite/epoxy specimens (Ginty & Chamis, 1987)

The perspective presented by the ATSB report was that the image shows "carbon fibre reinforced plastic (CFRP) samples that failed under exactly the same tension force, yet show a huge variety in failure patterns." (ATSB, 2007). The conclusion that macroscopically, tensile failures show no common characteristic was not produced by Ginty & Chamis (1987).

It appears rather, that the images demonstrate that the fracture behaviour of the composite is strongly influenced by the architecture of the laminate. Moreover, Stumpff and Snide (1986) conducted tensile failure of 0° and +/-45° specimens and reported macroscopic characteristics associated with the tensile failures. It is thus apparent that whilst the specimens may appear different, there may be characteristics associated with the failure to assist in the macroscopic identification of the failure.

Consequently, it appears that whilst the understanding of failure characteristics is recognised as an issue within the accident investigation community, there appears to be a disparity between the understandings of the academic community.

3.4.3 Exponent: Failure analysis of composites – a manual for aircraft accident investigators

In 2007, Exponent, an engineering and scientific consultancy, released a manual for aircraft accident investigators on failure analysis of composites (Rakow & Pettinger, 2007). The manual follows a well-received seminar presentation to the International Society of Air Safety Investigators (ISASI) (Rakow & Pettinger, 2006). The information contained within the manual has subsequently been inserted into ICAO's draft document titled "Manual of aircraft accident and incident investigation" (ICAO, 2008).

Exponent, an engineering and scientific consulting company, produced the manual to

> *"...summarize some of the fundamental concepts related to the failure analysis of fiber-reinforced composites, as applicable to the investigation of aircraft accidents"* (Rakow and Pettinger, 2007)

Whilst it is not the purpose of the manual to present the methods available to a field investigator to examine fractured composite materials, this is a subject which appears on numerous occasions. Specifically, reference is made to:

- Rough appearance of tensile failures
- Apparent difference in zones within a flexural failure
- Difference in shear and peel failure characteristics in impact
- Global and local buckling modes of compression loaded sandwich structures
- Adherend failure modes in bonded composites
- Failure modes of mechanically fastened composites
- Recognition of composite repairs and indications of poor repair

However, caution in the visual interpretation of failures is suggested to the reader as:

> *"With variations in fiber orientation, and variations in imperfection, each failed specimen has a unique appearance, even though they all failed under tension. This is one of the challenges of analysing failed composites."*

The document continues stating:

> *"In many cases, this challenge can be addressed by microscopically analysing the failure surfaces to identify common features that indicate failure in tension."*

Whilst both statements are correct, it fails to fully consider the case for visual interpretation of the specimens but rather suggests that the challenges presented by visual interpretation can be overcome by microscopic interpretation. For example, metallic materials have been known to fail in both a ductile manner and a brittle manner, with both providing different failure characteristics (Wood & Swegginis, 2006). Yet it is accepted within the accident investigation community that a tensile failure of both a ductile material and a brittle material can be visually identified (Wood & Swiggennis, 2006; ICAO, 1970; ICAO, 2008; McCormick & Papadakis, 2003). Moreover, the understanding of the difference in brittle and ductile failure characteristics can assist the investigator in materials that have failed not as expected and thus provide a useful line of enquiry. For example, a brittle metallic material that has failed in a ductile manner may suggest severe temperature had been applied to that material.

It is therefore apparent that the communication of knowledge on fundamental principles on the failure analysis of composite materials has been well received by the accident investigation community. Moreover, the publication has provided basic information on the visual recognition of some failure characteristics. It is apparent however that the current understanding of the potential for visual characteristic use in accident investigation is instead inclined towards that of microscopic examination. Furthermore, additional visual characteristics that have been identified by the academic community (chapter 5) have not been discussed and thus allow potential for an expansion of the application. This therefore suggests that a logical next step would be to study whether the visual interpretation can be expanded and implemented within the field investigation process.

3.4.4 American Airlines flight 587

On the 12th Nov 2001 an Airbus Industrie A300-605R operated by American Airlines crashed into Belle Harbor, Queens, a residential borough of New York City, following the in-flight separation of the vertical stabiliser and rudder from the aircraft (NTSB, 2004). The separation of the vertical stabiliser occurred at the main attachment points to the aircraft fuselage, notably the separation occurred at a series of lugs manufactured from Carbon Fibre Reinforced Polymer (CFRP). This accident represents the first major structural failure of a primary aircraft component manufactured from a composite material on a commercial aircraft (Fox *et al*, 2005). All 260 persons on board the aircraft and 5 on the ground were fatally injured. Whilst a significant proportion of the airframe was consumed in the ensuring fire, the fractured sections of the attachment lugs, which remained attached to the fuselage, survived with limited fire and impact damage. The vertical stabiliser, which also contained fractured CFRP attachment lug sections, was recovered from Jamaica Bay.

In addition to the reports released by the NTSB, details of the investigation have appeared frequently within the academic literature (i.e. Greenhalgh, 2009; Raju, Glaessgen, Mason, Krishnamurthy, Davila, 2007; Fox *et al*, 2005; Winfree, Winfree, Madaras, Cramer, Howell, Hodges, Seebo, Grainger, 2005; Murphy, O'Callaghan, Fox, Ilcewicz, Starnes, 2005).

Whilst the in-depth failure analysis of the composite materials by the NTSB, Airbus and NASA dominate the discussions, Fox *et al* (2005) discussed the macroscopic fracture modes and features. Specifically, delaminations, translaminar fracture, fracture geometry, features of bearing damage, and the presence of witness marks were mentioned as visible features. Furthermore, the report goes on to interpret the features to suggest probable loading at failure (e.g. *"rough fracture features consistent with overstress fracture in primarily tensile loading"*). The identification of a loading condition at failure is also examined whilst considering the location of the lug on the structure. Thus, whilst the authors do not specifically state a probable failure scenario from the macroscopic evidence alone, an interpretation of the most probable failure scenario can be gained from the macroscopic evidence presented. For example, the macroscopic evidence suggested that the right side of the vertical stabiliser failed in primarily tensile failure, whilst the left side failed in tension with evidence of a bending load to the left and to the aft.

Whilst this macroscopic interpretation is presented in this paper as a precursor to a detailed failure investigation, it does demonstrate the level of information on failure mode that can be gleaned from an initial visual / macroscopic examination.

3.4.5 The failure examination of composite structures using visual and macroscopic examination

In 1984, Purslow, whom had by this time published a number of papers, presented a paper on conducting a comprehensive failure examination using low magnification optical microscopy. The specimen examined was a Carbon fibre reinforced I-beam simulating an aerospace component (Purslow, 1984). Although this paper was not orientated towards the field investigation of polymer composites, it was to demonstrate that a failure analysis could be successfully conducted using relatively low magnification techniques. The component being examined was 'blind', although the visible loading points were likely to provide an indication as to the loading mechanism. However, the examination was tasked with establishing the initiating fracture through tracing the sequence of fracturing and the identification if individual failure modes. Therefore, whilst the loading points may provide an indication as to how the component would have been loaded, it would not provide an indication as to where the fracture initiated. During the examination the low magnification characteristics identified included:

- Visual differences in the peel / shear boundary

- Cusp formation due to misaligned fibres between plies
- Texture and hue differences to distinguish between failure modes
- Post fracture abrasion, visible as featureless surfaces
- Crack spacing to indicate fracture stress, reduced crack spacing equals higher stress
- Crack sequencing
- Translaminar compression failure
- Translaminar flexural failure due to local buckling

The above example suggests that a comprehensive examination of an aerospace structure can be undertaken using visual and low magnification examination. However, the examination was conducted based on the author having “considerable experience in composites fractography using an SEM” (Purlsow, 1984) and involved the dissection of the structure to access areas. It is reasonable to assume that both of these aspects will not be considerations for a field investigator.

3.5 Summary

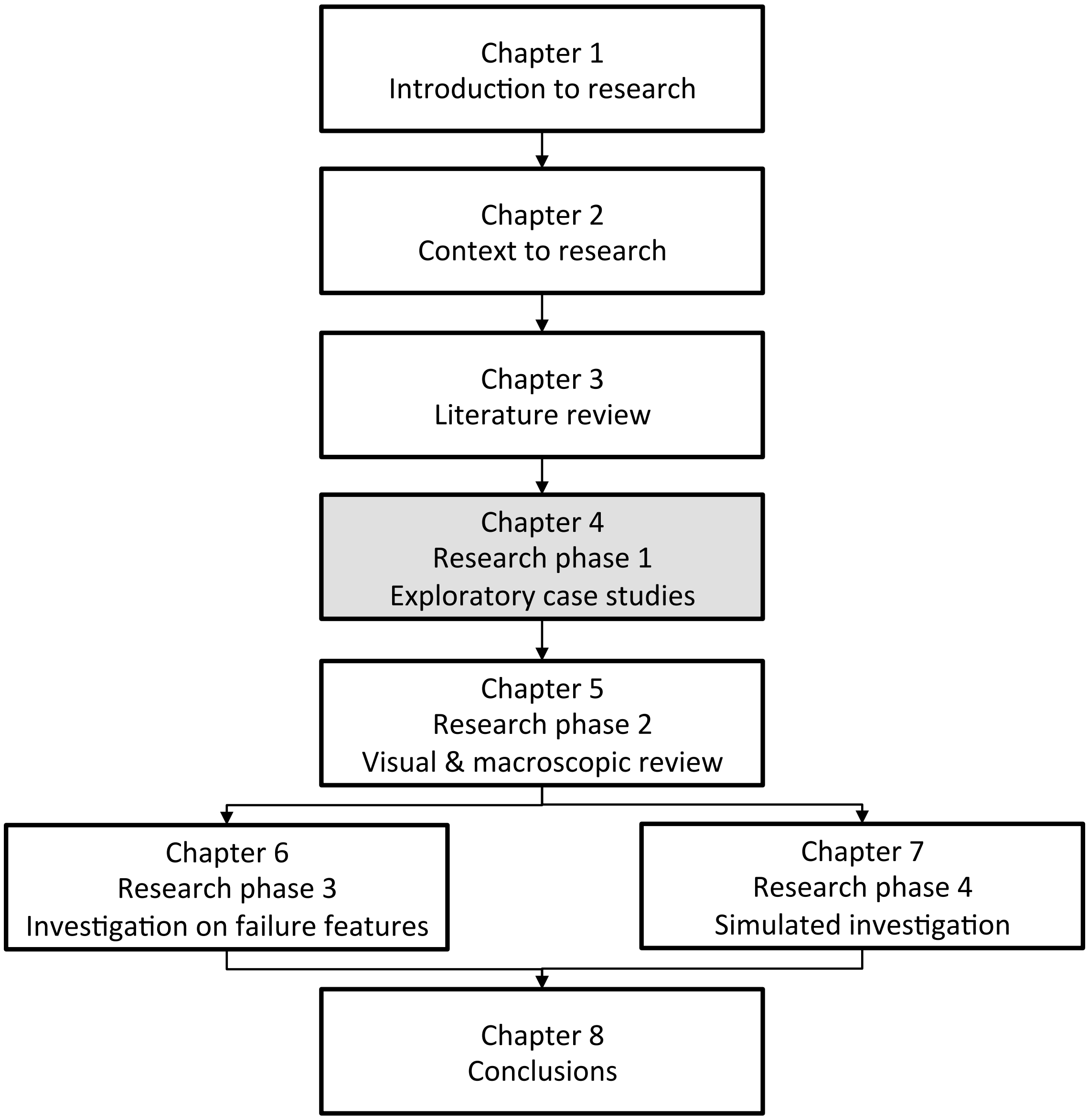
This chapter has reviewed literature dealing directly with the visual examination of polymer composite materials, and the processes surrounding such examination in the context of accident investigation. It is apparent from the literature review that there is a substantial understanding of the visual interpretation of metallic failures in aircraft accident investigation. This knowledge, and demonstrations of its use, is ingrained into publications directly related to aircraft accident investigations, including training manuals aimed at the field investigator. The same, however, cannot be said for polymer composite materials. It is apparent that the academic literature has established a fundamental knowledge on the visual interpretation of polymer composite materials. Whilst this knowledge is not complete, it provides a level of understanding from which, with due care and understanding, failure modes and sequences can be identified. However, there is a dearth of literature, both academic and non-academic, which discusses the examination of composite materials from the perspective of the field aircraft accident investigator.

Moreover, there is a lack of a documented understanding of the processes by which a field investigator would conduct the wreckage examination, whether it is for metallic components or those of polymer composite construction. Therefore, the literature has emphasised that research focussed on the application of visual and macroscopic polymer composite failure identification can assist the field practitioner and provide a valuable contribution to academic understanding. Furthermore, the literature has suggested that to achieve this an understanding of the processes and framework within which the application will be applied must also be understood.

Furthermore, it is apparent that the research should be focussed on the role of the investigation practitioner conducting the wreckage examination in support of a GA type accident investigation. This focus will concentrate the research effort whilst making a practical contribution to the investigation practitioner. It is still likely however that this focus will not remove the potential for the knowledge transfer to examinations of structures from large commercial transport aircraft.

This chapter has therefore provided a foundation from which the subsequent phases of primary research can be conducted. Specifically, it has provided a background to the examination techniques of polymer composite materials in aircraft accident investigation and on current investigative frameworks. This hence leads to the first phase of the research programme, which is discussed in the next chapter.

4 EXPLORATORY STUDY ON THE INVESTIGATION OF COMPOSITE AIRCRAFT ACCIDENTS



This chapter explores how accident investigation practitioners investigate aircraft accidents involving aircraft of polymer composite construction. It aims to explore the process of wreckage examination such that a foundation for the research can established. The chapter commences by discussing and presenting the appropriate research method (section 4.1). It then presents the design of the study (sections 4.2 to 4.8) touching on subjects such as the data collection protocol, case selection and ethical considerations. The pilot study is then presented (section 4.9) which covers pilot case engagement, substantive issues identified and methodological adaptations to the primary protocol. The execution of the case studies is then presented by describing the descriptions of the cases (section 4.10). Finally, the analysis is presented (section 4.11 to 4.12).

4.1 Research Design and Methodology

It is important that the strategy and methods employed must be appropriate for the research questions (Robson, 2002). With many different research methods available, it is necessary for the researcher to understand which research method is most suitable for answering the research questions, and hence objectives posed.

The objective of this phase is to explore how aircraft accident investigation practitioners conduct an investigation involving an aircraft of polymer composite construction, and to determine what issues polymer composite materials present. To meet this objective it will be necessary to examine how and why aircraft accident investigation practitioners examine the wreckage of the aircraft and how they conduct the wider structural investigation. This will include identifying methods or techniques that are utilised by the practitioner in identifying failure features. One way to select a methodology is to replicate, or perhaps draw on, methodologies presented in the research literature. However in this case, there is very little academic literature on which to draw.

Yin (2009), in arguing against a “common misconception” amongst some scientists that research methods should be “arrayed hierarchically”, suggests that instead, three conditions form the basis for methodology selection. The conditions suggested are based on 1) the form of the research question, 2) the extent to which the investigator has control over behavioural events, and 3) the focus on contemporary (as opposed to historical) events. Table 4-1 presents Yin’s proposal.

Method	Form of research question	Requires control of behavioural events?	Focuses on contemporary events?
Experiment	How, why?	Yes	Yes
Survey	Who, what where, how many, how much?	No	Yes
Archival Analysis	Who, what where, how many, how much?	No	Yes/No
History	How, why?	No	No
Case Study	How, why?	No	Yes

Table 4-1 – Relevant situations for different research methods (redrawn from Yin, 2009)

According to table 4-1 the most suitable methodology for conducting the first phase of the research programme is through the use of case studies. This is because, 1) the research objective focusses predominantly on “how and why” questions, 2) the research objective is a contemporary problem, and 3) by removing the need for control of behavioural events, the research can be focussed within the real world and thus be more appropriate to the research objectives. Figure 4-1 presents the case study method as proposed by (Yin, 2009).

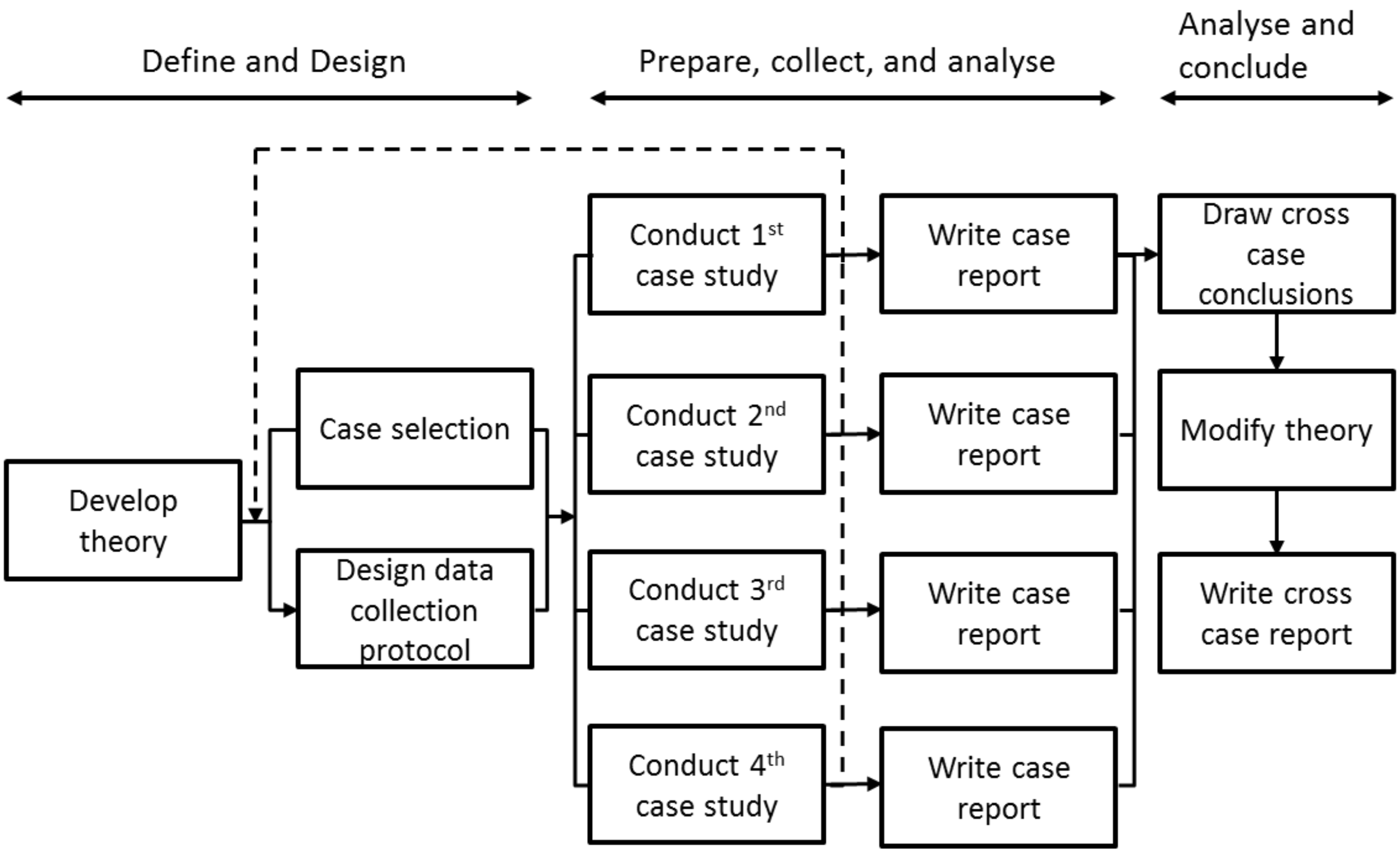


Figure 4-1 – Case study Method – (redrawn from Yin 2009)

4.2 Data collection protocol

The data collection protocol as developed by Yin (2009) contains the instruments, procedures and rules which promote high academic reliability. At the core of the protocol is a set of questions reflecting the study focus and lines of enquiry to be undertaken by the researcher. Yin (2009) in discussing data collection for case study research proposes that the creation of research questions is necessary to ensure that data collection follows the path of intended exploration. Furthermore, the formation of research questions also has the added benefit of assisting in the creation of prompts for interviews and subsequent lines of enquiry.

Research questions are dependent on the requirements of the specific study and for this study have been split into the typologies of 1) “science” and 2) the “art and craft” of investigations. These typologies have been discussed in literature as providing a means for understanding investigative practice and are further discussed in the following sections.

The formation of research questions is presented in the proceeding sections (4.2.1 & 4.2.2). Following which the generation of the data collection protocol is continued by discussing the procedures centred on case selection and execution.

4.2.1 Establishing case study questions on the “science” of investigation

The use of “science” as a facet within aircraft accident investigation has frequently been discussed within both academic and non-academic literature. An understanding of the term “science” is perhaps best understood through the amalgamation of two suggestions from prominent academic figures in the field of accident investigation. The first is from Braithwaite (2008) who suggests that the “science” of investigation includes the technical aspects. The second is from Roed-Larsen and Stoop (2012) who refer to scientifically based methods. Further clarification, identified within the field of investigation, suggests that the science of investigation includes “scientific approaches, social sciences, the use of physical evidence, investigative interviewing, and managing the investigative process" (Tong, Bryant & Horvath, 2009). It should also be noted that the principle of "science" within an investigation can also involve the use of scientific principles and the scientific method, where the investigation "is posited as inquisitorial in nature, seeking after the truth, emphasising evidence and promoting hypothesis testing" (Tong, Bryant & Horvath, 2009).

Table 4-2 was generated, by the author, as a supplement to those methods presented in chapter 3.3. It provides a list of scientific concepts or methodologies that have been identified as relevant to the investigation process, or to the examination of polymer composite materials. Additionally, tables 4-3 and 4-4 present an overview, as suggested by Kar (1992) & Greenhalgh (2009) respectively, of the failure characteristics to note during the visual examination of polymer composite material failures. These processes and techniques were considered as a necessary basis for the generation of lines of enquiry that may link the practice of the investigator to existing scientific principles.

Process	Key steps
Basic Failure analysis Safety Center for Chemical Process, (2003)	1. Evaluate conditions at the failure site 2. Perform a preliminary assessment of the component. 3. Preserve "fragile" data 4. If needed, perform more detailed component assessment. 5. If needed, perform more detailed component analysis. 6. If needed, test under simulated conditions. 7. Determine failure mechanism and explore root causes.
Field Handling Logic Network for Composite Parts Kar, (1992)	1. On-Site Wreckage Documentation 2. Tags/Labels on Debris 3. Transportation of Debris 4. Classification of Parts 5. Selection of fractured parts for lab failure analysis, (inc. identification, sectioning, cleaning, protection) 6. Failure analysis (NDE, Macro/SEM, chemical, Stress Analysis, Background) 7. Report and Specimens
Failure analysis logic network (FALN) for determining sources of failure in composite parts ASM, (2003)	1. Obtain background and service history 2. Non Destructive Examination 3. Material configuration and verification 4. Fractography 5. Define (origin, mode, environment, contaminants, defects, damage & Stress Analysis)
General procedure for a failure analysis Greenhalgh (2009)	1. Identify aims and objectives 2. Collate background information 3. Label specimens and construct assembly diagram 4. Visual inspection 5. Non-destructive inspection 6. Photography
DOE process for investigation - board activities DOE (1999)	1. Collect, preserve, and verify evidence 2. Integrate, organise, and analyse evidence to determine causal factors 3. Develop conclusions and determine judgments of need 4. Conduct requirements verification analysis 5. Prepare draft report
Three phases in an accident investigation DOE (1999)	1. Collection of evidence and facts 2. Analysis of evidence and facts; Development of conclusions 3. Development of judgments of need; Writing the report
Iteration between data analysis & data gathering Safety Center for Chemical Process (2003)	1. Gathering and Analysing Evidence 2. Analysing data for causal factors 3a. Organizing & judging data relevance and 3b. Formulating loss scene scenarios 4. Generating new data needs
The scientific method Wilson, Dell, & Anderson (1993)	1. Define the issue 2. Propose a hypothesis 3. Gather data 4. Test the hypothesis 5. Develop conclusions

Table 4-2 - investigative procedures, methodologies and techniques

	Feature	Implication
Undamaged surfaces	Visible distortion	Possible evidence of sub-surface damage or delamination
	Visible nicks, dents, splits or gouges	Possible crack initiation site. Possible evidence of impact, fretting or wear damage. Direction of impact can be deduced from gouge direction
	Surface blistering or splitting	Internal damage, such as delamination and ply splitting and may indicate instability such as buckling or post-failure damage
	Discolouration or fading	Evidence of exposure to chemicals or ionising radiation
Translaminar fracture surfaces	Radial or chevron features	Emanate from crack initiation site, and show crack propagation direction
	Flat, dull surface	Compression failure or evidence of fretting of surfaces
	Shiny, dark surface	Tensile failure
	Radial steps	Torsion failure; rotation direction deduced from the orientation of steps
	Increasing degree of secondary damage	Growth often in the direction of increasing degree of secondary damage, but may be limited if the fracture or loading mode changes
Intralaminar and interlaminar fracture surfaces	Ribs or tide marks	Slip/stick fracture, and may be an indication of cyclic loading. Propagation from the centre of radius of curvature.
	Dull fracture surface	Either mode II interlaminar shear or surface fretting
	Shiny fracture surface	Mode I interlaminar peel dominated fracture surface
	Fracture surface discolouration	Either post-failure contamination or evidence of corrosion prior to failure
	Change in surface hue	Evidence of a change in fracture mode or crack growth direction

Table 4-3 – "Features to note during a visual examination" (redrawn from Greenhalgh, 2009)

Mode	Environment Condition	Macroscopic Fracture features
Interlaminar Tension Dominated	Low temperature / Dry	Smooth Glassy fracture surface
		Major portion of fracture between plies
	Hot or Hot / wet	Smooth but with loose fibres strewn on surface
		A majority of the fracture within plies
		May be permanent deformation of the laminate
Interlaminar Shear Dominated	Low temperature / Dry	Surface flat, but with "Milky" appearance when held at angle to light
		Major portions of fracture between plies
	Hot or Hot / wet	Also exhibits "milky" appearance
		Tends to fracture within a ply
		Loose fibres on surface
Translaminar tension	-	Rough, jagged fracture surface with individual fibres protruding from surface
Translaminar compression	-	Extreme surface damage. Large regions of fibres fractured on same plane
		Very few, if any, fibres protruding from surface
Translaminar flexure	-	Two fairly distinct regions, one exhibiting translaminar tension and the other translaminar compression, the regions being separated by a neutral axis line

Table 4-4 – "Visual macroscopic fracture surface features" (redrawn from Kar, 1992)

4.2.2 Establishing case study questions on the "art and craft" of investigation

The "art" of investigation has been described by Braithwaite (2008) as "the less tangible aspects" of an investigation. A further definition is suggested by Tong, Bryant & Horvath, (2009), where they describe "art" as "intuition, and instinctive feelings [of the investigator] regarding problem-solving in an investigative capacity", like a craft where the "art" is developed through on the job learning and experience. They further describe this "art" as the investigators "ability to separate the false from the genuine" with creative and effective lines of enquiry being established through an ability to instinctively 'read' a situation, scenario or interviewee. It is interesting to note that this artistic ability to 'read' is frequently referred to in aircraft accident investigation literature when describing the examination of wreckage:

> "The story is written in the wreckage; you have to learn how to read the bent metal" – Sam Taylor USAF (From McCormick & Papadakis, 2003);
>
> "I am a professional tin-kicker, I go out there hunting down the clues, and the only way to do that is to roll the wreckage over and rummage through it to see what it's going to tell us" – Gregory Feith, senior air safety investigator with the NTSB (From Faith, 1996)
>
> "Give them a piece of wreckage and they will read it like another person would read a book. Give them a heap of wreckage and they will be kept busy and contented for weeks". – P. B. Walker CBE, Senior Consultant to the Director and Chief Scientific Officer, RAE Farnborough. (Walker, 1965)
>
> "The summation….. The bent metal speaks" - M.P. Papadakis (From McCormick & Papadakis, 2003)

Whilst it would be plausible to discuss further the psychological reasoning and meaning behind the investigators "art" it would also be out of the scope of this research.

A review of literature surrounding investigation in practice was thus conducted to identify areas which, although not highlighted in academic literature as having formal relationships with wreckage and structural examination, presented views or possibilities as having such an influence. This resulted in a framework from which exploration can be conducted.

The created framework for research questions is illustrated in table 4-5. This highlights the regions of exploration to guide the case studies during both the conducting of the study and as a basis for the questioning of the participant during the semi-structured interviews. As the primary purpose of this phase of the research is exploratory, then the initial approach is expected to be highly flexible (Robson, 2002). Subsequently, the framework was utilised as a basis from which the exploratory should be conducted, and not as a binding scope to which the data collection should be restricted to.

Element	Areas for exploration
Background to accident	Overview, Sequence of events, Sequence of investigation, resources, scale
Evidence	Availability, types, interrelationship with wreckage and structural examination, strengths, weaknesses
Tools, methods, techniques	Checklists, stop rules, evidence saturation, discounted scenarios
Agency	Background, standard practices (including methods and methodologies), procedures, management
Practitioner(s)	Background, preferential practices (including methods and methodologies), training, experience, hindsight
Preliminary response	Preparation, background information gathering
Site evaluation	Prioritisation, evolution
Preliminary component assessment	Formal Tools, methods, techniques, resources, context,
Post wreckage examination	Selection, procedures, decisions, rationale, influence on investigation progression
Post recovery structural assessments	Formal Tools, methods, techniques, parties, resources, limitations
Post recovery structural testing and analysis	Formal Tools, methods, techniques, parties, resources, limitations
Conclusions	Sequence and timing of conclusions / Airworthiness Directives, etc., overall analysis, reflection, problems, obstacles, interferences, influence, pressures, challenges

Table 4-5 – Areas of exploration as identified form chapters 4.2.1 & 4.2.2

4.3 Ethical considerations

Prior to data collection the ethical impact of this research program was considered. The following section discusses the approach taken. It starts by discussing how an understanding of the potential risks to the participants was established, and finishes by presenting the process by which ethical approval was acquired.

4.3.1 Psychological harm

By their nature, aircraft accidents have the potential to create severe emotional pressure on those who are working in the proximity. It is not unusual that during a field investigation the investigators are exposed to scenes of severe trauma, devastation and periods of heightened emotional stress. Whilst this phase of the research project is a reflection on the investigation and thus will not occur during the actual field investigation phase, consideration has to be made on what the implications are for revisiting the 'event'. This is especially true as it is acknowledged that the onset of emotional stress can occur some months after the investigation as a result of a triggering event (AAIB, 2008).

The potential for accident investigators to suffer from psychological trauma from exposure to accident investigations has been frequently cited in literature, including sources such as; (Coarsey-Rader, 1995; Braithwaite, 2006), International Civil Aviation Organisation (ICAO) guidelines on investigator training (ICAO, 2003), and internal investigation manuals (AAIB, 2008).

In discussing the psychological risk to accident investigators, the ICAO, who provides international standards and recommended practices for the investigation of aircraft accidents, states:

> "After past disasters, there have been reports of rescue workers suffering from Post-traumatic Stress Disorder (PTSD), causing sleep disturbance, intrusive thoughts and flashbacks. There is little available evidence to confirm such symptoms amongst accident investigators, suggesting that the psychological impact poses less of a risk to investigators than once thought. However, this more satisfactory outcome may be due to the

> success of existing safety personnel management practices. These include effective selection processes, the establishment of professionalism at both an individual and team level (including good work practices) and effective peer support.” ICAO (Draft - 2008)

Moreover, due to legislative protection (EU, 2010) particular aspects which have been acknowledged to heighten emotional stress for investigators are not covered in data collection. These included Cockpit Voice Recorder (CVR) readout, interviewing of bereaved relatives, interviewing of survivors and on-site trauma (Coarsey-Rader, 1995). As these are not identified as critical sources of data to this research project, no adverse effects are expected.

Even though it is expected that the risks of inducing psychological stress to either the participants or the researcher are no greater than that which would be considered normal to day-to-day activities, it has been decided that cases will only be chosen from organisations that operate an internal support process that reduces psychological stress and provides counselling and assistance.

4.3.2 Harm to career

A goal of this phase in the research is to collect information on the process that an investigator would have undertaken during the examination of the aircraft wreckage. This will involve the collection of documents relating to the investigation and the conducting of interviews with the investigator. To achieve this it is anticipated that the relationship between Cranfield University and the investigation community will be a factor in creating trust between the participant and the researcher. It is therefore imperative that the integrity and professionalism of the researcher be maintained.

4.3.3 Freedom of participation

Agreement to participate was solely at the discretion of the participant and was entirely voluntary. A briefing prior to data collection ensured that the participant may decline to answer any questions that they would prefer not to answer and withdraw at any time of the research project without prejudice. To avoid the possibility of coercion from persons that may influence the participant, the potential participant was contacted in the first instance where practicable, rather than their line manager.

4.3.4 Confidentiality, anonymity and data security

The Data Protection Act 1998 provides legal requirements for the handling of information relating to identifiable individuals. This includes the obtaining, holding, use of, or disclosure of such information (HMSO, 1998). It was determined that the collection of personal data as defined in the Act will not provide additional benefit to the research. Therefore, the collection of personal data was excluded from data collection, and hence the provisions of the Data Protection Act were not applicable. It was believed however that security measures that were presented in the Act offered best practice and thus were adopted as a matter of course.

4.3.5 Ethics approval

Application for ethics approval from Cranfield University's Science & Engineering Research Ethics Committee (SEREC) was sought and approved under the low risk project process.

The research was designed and conducted to ensure compliance with the mission statements and aims of the university and of the agencies from which data collection is sought.

4.4 Ensuring academic rigour

Like all research methods, case study research must be conducted to ensure the highest standards in research quality are met. Yin (2009) suggests that in exploratory case study research there are three tests which are commonly used to establish research quality. These are: construct validity, external validity and reliability. To counter these threats case study tactics are encouraged (Yin, 2009; Cook, & Campbell, 1979; Stake, 1995; Stebbins, 2001) which serve to demonstrate credibility in the interpretation and analysis.

Table 4-6 illustrates each of these threats to research quality and presents the tactics and subsequent actions taken by the researcher to lessen any threats.

Threat	Case Study Tactic	Phase of research	Action taken
Construct validity	Data triangulation	Data collection	Triangulation of evidence from interviews, documentary evidence and physical artefacts
	Chain of evidence	Data collection	Interview data recorded and transcribed. Artefacts photographed. Sources of evidence entered into a database. Evidence chain recorded using links within the database.
	Participant review of case report	Analysis write-up	Draft of procedures and findings submitted to participants for review
External validity	Use of replication logic	Research design	Replication logic used such that ideas can be tested between cases.
Reliability	Use case study protocol	Data collection	Protocol developed highlighting key decisions and reasoning. Consistency in data collection procedures, research questions and initial lines of enquiry maintained between cases.
	Develop case study database	Data collection	Interview transcripts, documents, and physical artefacts recorded within a bespoke database, identifying evidence and findings.

Table 4-6 – Tactics to respond to perceived threats to validity and reliability (Modified from Yin, 2009)

4.5 Number of cases to be studied

An important consideration in case study design is in determining whether to use a single case or multiple cases (Yin, 2009) (multiple case designs are also referred to as collective case studies, e.g. Stake,(1995)). Whilst both designs can be used in answering exploratory studies, there are particular situations where one of the designs is likely to be of greater benefit to the study. The use of multiple cases has many advantages and disadvantages over a single case but perhaps the most prominent advantage relates to the increased strength of the analysis (Yin, 2009) and the ability to conduct individual case analysis as well as cross case analysis (Yin, 2009; Eisenhardt, 1989). As Herriott & Firestone (1983) observe;

> "These multisite qualitative studies address the same research question in a number of settings using similar data collection and analysis procedures in each setting. They consciously seek to permit cross-site comparison without necessarily sacrificing within-site understanding."

Having chosen a multiple case study design, the next step is to determine the required number of cases. When considering literal replication, Yin (2009) suggests the number of cases depends upon the desired certainty required within the results. A figure of 2 or 3 literal replications (cases) is relevant where the theory is relatively straightforward, and 5 or 6 replications where the theory is more subtle. Eisenhardt (1989) expand on this to suggest that when considering building theory from case study research;

> "With fewer than 4 cases, it is often difficult to generate theory with much complexity, and its empirical grounding is likely to be unconvincing, unless the case has several mini-cases within it"

Eisenhardt (1989) however also suggests that ideally the number of cases should be based on "Theoretical saturation", a process where theory development is minimal as new cases are added. This in turn may suggest that the number of cases to be studied need not be determined in advanced. On a more practical note, Creswell (1998) suggests, "Typically, however, the researcher chooses no more than four cases".

A multiple case study consisting of four cases was thus chosen for study.

4.6 Case selection criteria

As is suggested by Seawright and Gerring (2008), encompassing variation in case selection is likely to enhance the representativeness and thus assist in generalisation. Thus to ensure the cases were focused and appropriate to the research aims, selection criteria were generated. Common features were created to ensure the cases remained focussed to the research aim and variations were created to ensure the generalisation of the case study results and to test certain propositions about the possible effect of case characteristics on the investigation and polymer composite examination process.

4.6.1 Wreckage pattern as a means to suspect in-flight structural failure

When considering whether a structural failure of an aircraft has occurred, the wreckage distribution of the aircraft can provide significant clues to the sequence of failure and the initiating location of the failure (ICAO, 1970; ICAO, 2008, Carver, 1987; Wood & Sweginnis, 2006). It is almost always (ICAO, 1970) the circumstance that during a structural failure the major component of the aircraft will separate from the aircraft. In this instance the component of initial structural failure, will be located some distance from the main wreckage either along the flight path in the case of a low altitude breakup or in a reasonably predictable location from a high altitude breakup. Furthermore, there is reference to (e.g. ICAO, 1970; ICAO, 2008, Carver, 1987; Wood & Sweginnis, 2006) and development of (e.g. Greaves, 2010) trajectory analysis as a means to "trace trajectories from the wreckage to the original flight path. The concept is to identify which part came off first, and thereby identify the primary failure" (Carver, 1987). Investigations of significant public interest that involved detailed wreckage distribution and trajectory analysis include Pan Am flight 103 which suffered an in-flight break up caused by the detonation of an explosive device (AAIB, 1990), and TWA flight 800 which suffered an in-flight breakup following ignition of fuel vapours in the centre wing fuel tank (NTSB, 1996).

Wreckage distribution can have such a key implication in the initial stages of an investigation involving an aircraft that has suffered an in-flight structural failure, it warrants being a key variable in case selection. Thus it was decided to design the case selection such that varying degrees of in-flight breakup were considered, as follows:

- Wreckage distribution localised to immediate impact area – i.e. wreckage distribution does not support an in-flight breakup scenario
- Limited wreckage distribution with unreliable wreckage pattern – i.e. wreckage distribution cannot be used to determine whether an in-flight breakup occurred
- In-flight breakup observable from wreckage distribution – i.e. wreckage distribution supports an in-flight breakup scenario

4.6.2 Basic types of in-flight structural failure

Whilst there are perhaps an infinite number of mechanisms by which an aircraft may suffer a structural failure, they can generally be characterised into a few fundamental categories. ASM International categorise these failures as: 1) design deficiencies, 2) material defects, 3) manufacturing / installation defects, and 4) service life anomalies (ASM, 2001). Greenhalgh (2009) further elaborates on the category of design deficiencies to emphasise the inclusion of overload failures which, although strictly not design deficiencies, are a failure of a system to accommodate a loading that it was not designed for.

Within the accident investigation literature the categorisation is orientated differently. Emphasis is given to the context of the investigation rather than categorising the cause of the structural failure. ICAO (1970) suggests that "major component failures result from either, 1) inadequate design strength, or 2) excessive loads imposed upon the component or 3) deterioration of static strength through fatigue or corrosion". This categorisation is retained, although it excludes references to specific causes or mechanisms (e.g. inadequate design, fatigue & corrosion), in the production of the USAF investigation manual (Carver, 1987) with the categories being, 1) Overstressed structure, 2) Understrength structure, 3) Degradation of strength. Latterly, Wood and Sweginnis (2006) however suggest that the categories are, 1) underload, 2) overload and, 3) aeroelastic phenomenon, with suggestion that the usual category of deterioration of strength is in fact a form of underload, however the classification of aeroelastic failure deserving a category in its own right.

The literature on classifying structural failures as presented above, demonstrates an existence of categories or generic reasons for structural failure. Although there are alternate theories, it has been demonstrated that key characteristics exist. These are (1) overload and (2) underload with the latter having multiple sub categories with the most prominent being (1) Design inadequacy (2) Degradation of strength (3) Aerodynamic phenomenon. It was thus decided that during case selection these factors should become a variable (see table 4-7).

4.6.3 Variation in case selection

Lastly, case screening was set to cover, where possible, a variation of demographic criteria such as:

- The selection of different investigation agencies for each case
- The selection of cases which occurred in regions of the world that have a significant general aviation population, and
- The selection of cases which involve different investigators

4.6.4 Common features of the cases

All cases chosen were to have four common attributes which were considered necessary to be considered as a potential case. These are categorised as: investigative requirements, airframe material, data prevalence and investigation status, and are discussed in more detail.

Firstly, the investigation must have contained a structural examination of composite wreckage by the field investigator which made a meaningful contribution to the investigation, including:

- Interpretations of composite failures considered or conducted by the field investigator,
- An investigative need for wreckage examination,

- Examination conducted in the field and/or within a facility external to where specialist examination techniques would be available (brought in and follow-on specialist examinations are permitted).

Secondly, cases will be restricted to include accidents that have involved composite structures, where either the primary failure in the accident sequence is related to a composite structure, or where the aircraft is predominantly manufactured from composite materials.

Thirdly, cases were chosen on the basis of the anticipated prevalence of data. George & Bennett (2005) suggest that cases should not be selected because they are easily reached using readily available data, and thus an initial case screening was designed such that it would allow cases to be chosen that would be most viable at providing quality research data whilst preventing cases being chosen that would not provide substance in answering the research questions.

Finally, whilst access to the early stages of current investigations would potentially allow a richer data set as the data can be queried and recorded in real time, there are significant issues that make this impractical. Some of the most relevant and significant issues being:

- There would have to be the potential for an extended research period as the time-frame for the completion of the investigation is unknown.
- It could not be guaranteed that the participant would be able to support the research through the period of investigation. Due to this additional case would have to be included to cover those which could not be completed.
- The degree of structural examination within each case would not be known and thus a higher number of cases would have to be studied to account for those that subsequently are determined to be unsuitable for study.
- There would be an unknown variation in the circumstances of the accident. Hence a higher number of cases would have to be selected to prevent limitations on the generalisation of the findings

- Accidents are not pre-planned events and thus access to a sufficient number of cases within the time frame of this research may turn out to be impossible.

Thus it was decided to study past, but contemporary, events. This allows the researcher to quantify the most suitable cases for study and select those that have the greatest opportunity to add significance to the study.

4.7 Case screening and engagement

As there were potentially numerous qualifying cases, a case screening process was established to ensure appropriate cases were chosen that would likely provide the greatest chance of realising the research objectives. Initially an internet based search was undertaken to highlight potential cases using accident reports as a basis for determining suitability. It was felt that this initial step presented several weaknesses in case selection, namely; 1) there was no inclusion of accidents which had occurred recently and thus no reports had yet been released, and 2) it didn't provide details as to the richness and scope of data available. For example, whilst interviews and documentary evidence were sources of evidence, further evidence may be available which could enhance the case study such as physical artefacts and documentary evidence. The scope of these evidence sources may not become identified until contact with the participant had been made.

The second step was initiated through informal engagement with the accident investigation agencies and investigators that had been identified as potential cases. This step was facilitated by Cranfield University's Safety and Accident Investigation Centre's (CSAIC) close ties to the investigation community.

Following the identification of possible cases, informal requests were made to the accident investigators for participation in the research through telephone calls and informal face-to-face discussion. If the investigator expressed interest in participating in the research then formal letters were sent to the investigator inviting participation in the research program.

Four formal acceptances to participate were received, aligning with the desired number of cases as discussed in chapter 4.5. Additionally, the cases were aligned well with the case selection criteria and offered access to rich data and scenario variation (See table 4-7). Three different investigation agencies were involved covering three countries and two continents. All three countries have a significant GA population that includes aircraft of polymer composite construction.

Case selection criteria		Case 1	Case 2	Case 3	Case 4
Wreckage distribution	Wreckage distribution localised to primary impact area	✓	✗	✗	✗
	Limited wreckage distribution with unreliable wreckage pattern	✗	✓	✗	✗
	In-flight breakup observable from wreckage distribution	✗	✗	✓	✓
Categories of structural failure	Overload	✓	✓	✓	✓
	Underload - Degradation of strength	✗	✓	✓	✗
	Underload - aeroelastic phenomenon	✗	✗	✓	✓
	Underload - Design inadequacy	✗	✗	✗	✓

Table 4-7 - Comparison of case studies against case selection criteria

4.8 The use of anonymous case identities

It is commonly accepted that the most desirable position when conducting case studies is to disclose the identities of the case and of the participants within the boundaries of ethical considerations. Conversely, there are legitimate reasons concerning why case studies should be kept anonymous. Gibbert, Ruigrok and Wicki (2008) in their creation of a framework for an investigation into methodological rigor of case studies, suggest that a significant aspect of reliability is ensuring the availability of collected documentation, including interview transcripts, and the disclosure of the case identities. Through presenting anonymous cases, restrictions are placed on the ability for the case information to be reviewed, re-gathered or retested and thus placing questions on the validity of the case study.

To overcome the shortcomings of complete anonymity, Yin (2009) suggests three compromises between protection of the case participants and of ensuring information is available to support research rigour, namely;

- anonymity of the individuals, and thus identification of the case,
- naming cases and participants but avoiding attributing particular comments, and
- presenting only the cross case analysis and thus avoiding individual case reports.

After careful consideration however it was felt that due to the nature of the research topic, presenting anonymous cases and participants is essential for the success of the research programme. The resultant impact on perceived research reliability and the effectiveness of particular case study tactics has been accepted as a limitation.

4.9 Case study pilot test

Good preparation for conducting case study research is not confined to the following of established methods, techniques and procedures. It involves establishing the desired skill set on the part of the case study investigator (Yin, 2003).

The case for the pilot study was selected based on three principles as proposed by Yin (2009); convenience, access and geographic proximity. These principles are suggested as they allow a less structured, more prolonged relationship which might not otherwise be found in the real world (Yin, 2009). This provides a greater opportunity for developing the case study protocol, refining lines of enquiry and for the researcher to practice the skills required, repetitively if necessary.

Whilst a pilot case was chosen such that it was appropriate to the case selection criteria of the primary study, this was not the only area for consideration. Selection was based on the capacity for the researcher to practice data collection through interview and documentary sources. The case chosen was of a military helicopter accident which contained a small quantity of polymer composite structure. The participant of the pilot study was one of a team of investigators despatched to conduct the investigation.

The pilot study provided important information from which the primary study would be conducted. Methodologically the pilot study provided an important opportunity for the researcher to trial interview techniques, the data collection protocol and the ordering of the procedures. One aspect that was not included in the pilot test was the discussion of the documentary evidence with the participant during the interview. This created a lost opportunity during data triangulation as visual evidence, such as images, was identified potentially to assist the participant in eliciting information during discussion. Whilst the documentary evidence assisted in understanding the participants' perspective, it could also be used on its own as a source of evidence. The data collection protocol was adapted to include the use of visual cues during the semi-structured interview and hence the documentary data collection preceded the interview.

4.10 Case descriptions

4.10.1 Case 1 – Structural damage due to flight into terrain

During daylight hours and whilst operating during a pre-planned flight, a single engine light aircraft failed to recover from a pilot induced descent and impacted the ground. There was no evidence identified within the investigation to suggest that the aircraft had suffered any structural breakup or failure of any polymer composite structures prior to impact with the ground.

Prior to impact the aircraft was descending, with a rolling motion, in a near vertical attitude. The aircraft failed to return to the horizontal and continued in a descending rolling motion until impacting the ground in a nose down attitude.

Upon impact the airframe was significantly disrupted. The all-composite wings from the aircraft suffered significant damage from the impact with significant fragmentation of the leading edge, bonding failure of the spar / skin interface and numerous diagonal fractures on the wing skin. The wreckage spread was contained within a relatively small area close to the primary impact location.

The aircraft design incorporated a significant proportion of carbon fibre composite materials located throughout the wing, empennage and fuselage. The wing, which had suffered significant damage upon impact, included unidirectional carbon fibre spar caps between carbon fibre laminate shear webs, and a skin which consisted of both honeycomb and foam sandwich structures using woven carbon fibre laminates.

The investigation concluded that there were multiple contributing factors to the accident, none of which included the failure of a structure manufactured from composite materials.

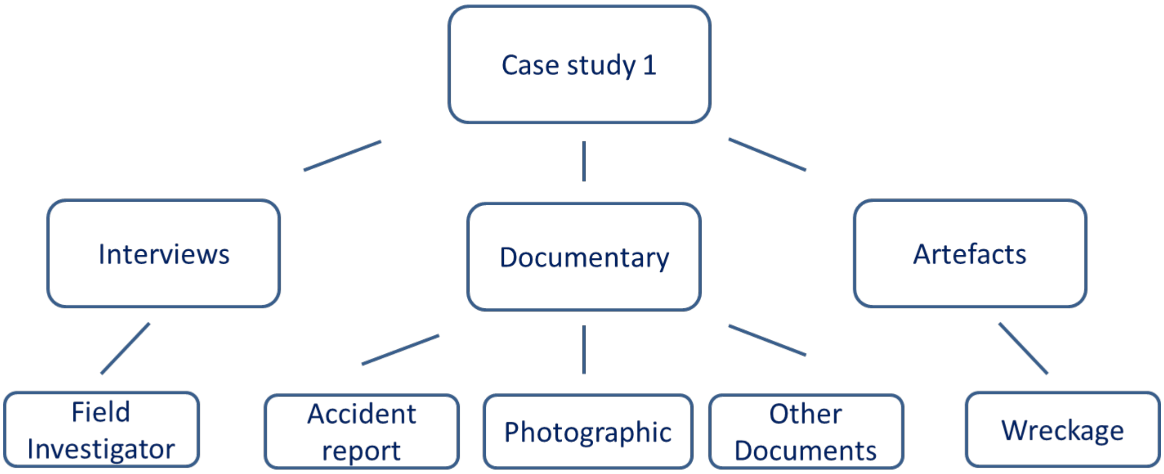


Figure 4-2 – Sources of case study evidence from case study 1 (Source: Author)

4.10.2 Case 2 – Premature in-flight failure of a flight critical composite structure

During daylight hours, and whilst operating during a routine flight in weather conditions permitting flight to operate under Visual Meteorological Conditions (VMC), an aircraft experienced the in-flight failure and separation of segments from a flight critical component constructed of polymer composite materials. The aircraft subsequently conducted an emergency descent and landing. The aircraft suffered additional impact damage as a result of the aircraft coming to rest.

The component which failed was constructed using unidirectional glass fibre rovings and multi directional glass fibre laminates among other non-polymer composite materials.

The investigation concluded that the polymer composite component had suffered a progressive premature failure which had initiated from a manufacturing defect in a glass fibre composite roving.

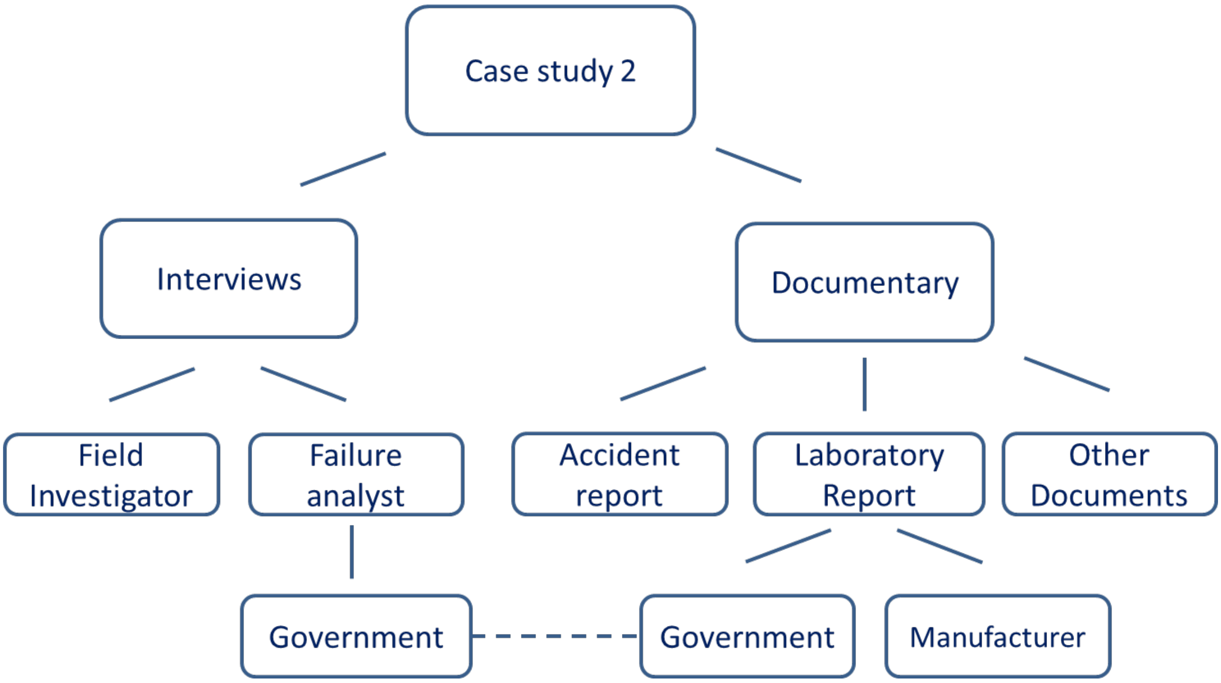


Figure 4-3 – Sources of case study evidence from case study 2 (Source: Author)

4.10.3 Case 3 – In-flight breakup initiated by a premature structural failure

During daylight hours a single engine light aircraft experienced an in-flight structural failure of a flight critical structure being manufactured from both polymer composite and metallic materials. As a result of the failure the aircraft suffered an in-flight breakup following which the aircraft impacted the ground.

The accident occurred whilst the aircraft was travelling in wings level flight with indications of a slight descending attitude. The aircraft was seen to oscillate violently which coincided with the initial breakup of the airframe. Shortly following the initial breakup the airframe catastrophically failed, separating into multiple sections. The wreckage trail was spread over some distance and confirmed that an in-flight structural failure had occurred.

The aircraft was manufactured predominantly from glass fibre polymer composite materials, utilising both unidirectional and woven laminates. The aircraft was a homebuilt kit aircraft designed such that the builder constructed the aircraft. The manufacturer of the aircraft would supply the aircraft in a kit form.

The investigation concluded that the accident sequence initiated due to the premature failure of an incorrectly assembled load bearing structure. The load bearing structure was manufactured from both metallic and polymer composite materials.

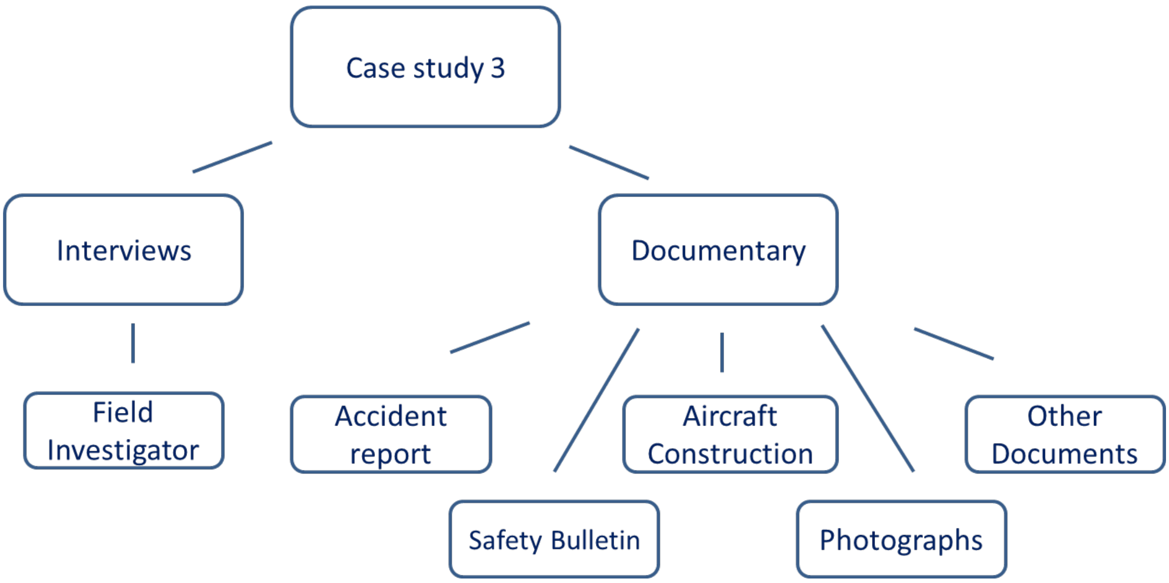


Figure 4-4 – Sources of case study evidence from case study 3 (Source: Author)

4.10.4 Case 4 – Structural failure due to aeroelastic overload

During daylight hours and whilst operating under Visual Meteorological Conditions (VMC), an aircraft experienced an in-flight failure and separation of sections of the control surfaces on the horizontal stabiliser. The aircraft became uncontrollable and descended impacting the ground at a high speed and shallow angle. The airframe subsequently suffered substantial fragmentation as a result of the impact. A fire ensued in the primary impact area which destroyed a significant proportion of the polymer composite wreckage. There were two primary locations of wreckage, the first being the main impact site and the second being further back along the flight path. This second wreckage location contained the flight controls from the horizontal stabiliser. The existence of the separate wreckage zones confirmed that an in-flight structural failure had occurred.

A substantial quantity of the aircraft structure and parts of the aircraft control system were manufactured from carbon fibre and glass fibre composite materials. This included the airframe and flight controls.

The investigation concluded that the accident aircraft had suffered an aeroelastic overload which resulted in the aircraft becoming uncontrollable.

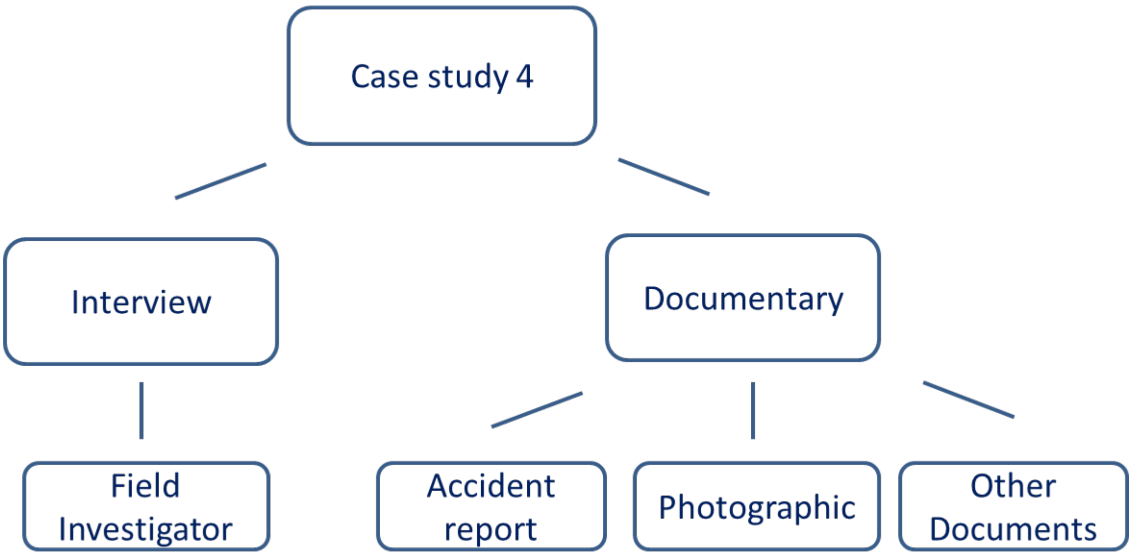


Figure 4-5 – Sources of case study evidence from case study 4 (Source: Author)

4.11 Data analysis methods

Case study analysis is flexible and occurs during data collection allowing the researcher to adjust and pursue new lines of enquiry as the data is collected

(Bickman, Rog & Hedrick, 1998; Leedy & Ormrod, 2010). Moreover, the bulk of the analysis occurs following completion of the data collection where examining, categorizing, tabulating, or otherwise recombining the evidence is used to address the research questions posed in the study (Yin, 2009). Notwithstanding, analysing case study evidence is one of the least developed and most difficult aspects of conducting case studies. As Yin (2009) suggests:

> *"much depends on a [researchers] own style of rigorous empirical thinking, along with sufficient presentation of evidence and careful consideration of alternative interpretations"*

Therefore it is proposed by Yin (2009) that the researcher should focus on creating a research strategy whereby a generic approach to data analysis is established. Yin further suggests four general strategies, namely; relying on theoretical propositions, developing a case description, using both qualitative and quantitative data, and examining rival explanations.

The strategy of relying on theoretical propositions places emphasis on the research propositions, questions or hypothesis, to guide the data analysis. Whilst in this exploratory study the conceptual framework is relatively poor, and thus generated hypotheses would be weak, the study has been created based on a framework from which direction and research questions were generated.

Analysis tactics are subsequently utilised within the generic strategy to assist in making conclusions backed by evidence and replication. Analysis methods or tactics used for case study analysis, whether for qualitative or quantitative data, are frequently presented in literature. Analysis methods such as "description" (Creswell, 1998), "categorical aggregation" (Stake, 1995), "direct interpretation" (Stake, 1995), "patterns" (Yin, 2009; Stake, 1995), "naturalistic generalisations" (Stake, 1995), "explanation building" (Yin, 2009), "time-series analysis" (Yin, 2009), "logic models" (Yin, 2009) and "cross case synthesis" (Yin, 2009) have been presented. Furthermore, Miles & Huberman (1998) suggest a generic framework for the analysis of qualitative data which is particularly valuable for case studies (Robson, 2002). Within this context the analysis of data consists of three parallel activities, namely data reduction, data display, and conclusion drawing and verification.

4.12 Analysis

Data analysis occurred simultaneously with the data collection. For this reason the first forms of data obtained were documentary such as accident reports and operating procedures. This analysis of documentary evidence prior to the interview was especially critical as data extraction during the interview was dependent on the questioning by the researcher.

Initially, the documentary evidence was reduced through the creation of a document sheet, and the formation of memos. The memos were kept separate from the document such that they could be cross-analysed, although traceability to the original source was maintained. The memos were focussed on extracting key data relevant to the data collection framework (tables 4.2, 4.3, 4.4 & 4.5), and to highlight the patterns and themes as recognised by the researcher. The use of theoretical propositions to guide the analysis is suggested by Yin (2009) as the most preferred strategy for case study analysis.

Upon completion of the interviews, a session summary sheet was created and the images and artefacts summarised in narrative form. The audio-recording was subsequently transcribed. The audio-transcription summary sheet, image narratives and artefact narratives were subsequently reduced into memos in the same form as that of the documentary evidence.

'Within-case' analysis was conducted using the reduced data and summary sheets to identify overarching themes and to identify the significance of single events through direct interpretation. Additionally, the investigative procedures, methodologies and techniques frameworks as detailed in table 4-2 were formatted into data displays. The displays were populated with supporting evidence from each case. As the displays were developed, they were analysed for themes and patterns.

Subsequently, the individual case themes and processes were cross analysed to identify reoccurring patterns or trends. A cross-case summary was created which displayed the findings, the chain of evidence and the sources of evidence for triangulation. The subsequent cross case findings were scrutinised for conflicting evidence.

Whilst the cases were being conducted and analysed, consideration was also made for the strength of theory generation based on the number of cases studied and the quality of data obtained. It is currently acknowledged that four literal replications are suitable for the requirements of this research (Chapter 4.5). However, it is also accepted that more cases may be required if the generation of theory is subtle or if theoretical saturation is not reached. Key considerations for approximate saturation can be split into aspects internal to the case, such as the data sampling within the case and the breadth and depth of material obtained, (Mills, 2010), and those specific to multiple cases such as minimal theoretical development as new cases are added (Eisendhart, 1989).

Based on these factors it was decided that no additional cases would be required. Specifically the quantity and quality of data obtained within each case was significant as was the within case data triangulation. Additionally, the theory development as each new case was incorporated became minimal with the theory generated being strengthened by less evidence of rival explanations.

4.12.1 Finding 1

The investigation process of all case studies showed sequencing comparable to four phases; the initiation phase, the convergence phase, the detailed investigation phase and the concluding phase.

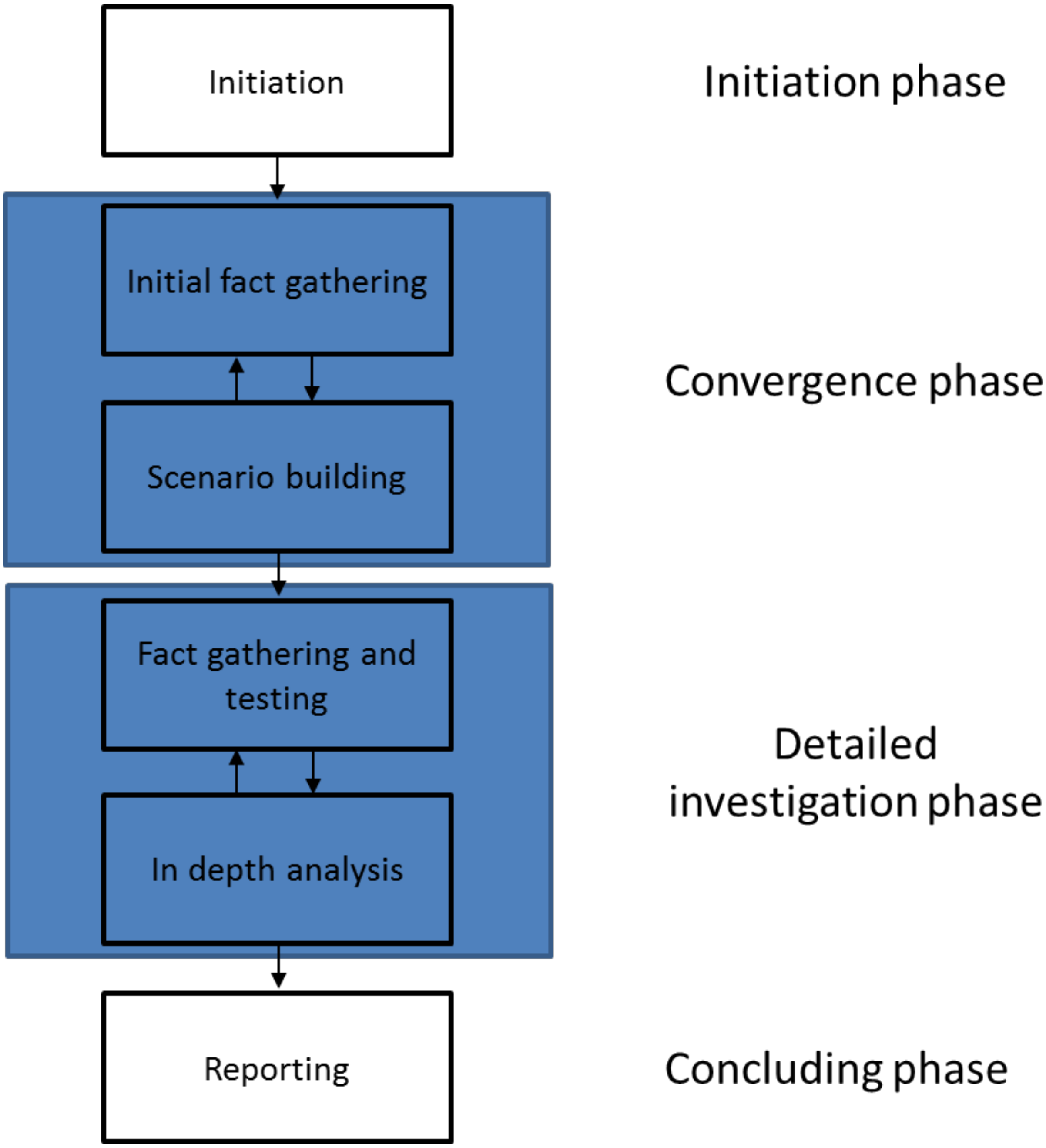


Figure 4-6 – Investigation process model of the wreckage examination process (Source: Author)

1. **The initiation phase**

The initiation phase involves the period between first notification and the time at which the majority of the investigators effort is focussed on fact gathering. Facts may be gathered during this stage but the primary purpose of gathering data concerns acquainting the investigator with the situation. This phase included the following identified steps:

a. Receipt of initial notification

This is a procedural step based on the agencies initial reporting procedure.

b. Initial response

This was both procedural and discretionary, based on investigation agency requirements and investigator judgment. It included stages such as; preparation, recording, risk assessment and kit selection.

The degree of background preparation with regards to the aircraft type was dependent on the information received during the initial notification. It was identified within one case study that the aircraft type was not known during initial notification thus preventing a preliminary information search. Where the aircraft identity was known a brief search is likely to be conducted to gain details on the aircraft and perhaps the aircraft's history.

c. *Site attendance, assessment and stabilisation*

This was a procedural step which started when the investigator arrived at the accident site. It included factors such as site management, liaison, communication, site security, contamination awareness, and prioritisation.

2. The convergence phase

The convergence phase involves the period when the investigator is primarily focussed on initial fact gathering. This phase proceeds the initiation phase and culminates when the investigation enters the detailed investigation. This phase contains two segments which are discussed in the following.

a. Onsite fact preservation, gathering and orientation

The initial focus on the convergence stage of the investigation is in orientating the investigator with the accident site and the preservation of perishable evidence. This phase is predominantly procedural. The preservation of evidence was a procedural step which was likely to have included a checklist approach being conducted from the investigators memory. There was evidence that formal checklists being available within some of the investigation agencies although these served as guides rather than step-by-step instructions. During this phase a site appraisal was conducted to orientate the investigator with the accident site and to generate general hypothesis surrounding the accident.

b. Exploration of facts

This stage marks the point where the hypothesis generation by the investigator tends to move from being predominantly procedurally instigated to increasingly discretionary.

The evidence at the accident site will be recorded, preserved and gathered, with further evidence being gathered outside of the immediate accident site (e.g. witness evidence). This is an analytic and fact gathering stage. As the evidence builds and is analysed, the picture of the accident becomes more distinct. This allows the investigator to focus efforts on areas of the fact gathering which are likely to be more relevant and more fruitful. Through prioritising particular lines of enquiry, more effort can be focused on the relevant areas for investigation. It was apparent that the analysis being conducted at this stage is predominantly undertaken using the investigators "art" or informal analysis techniques, such as informal brainstorming with colleagues.

At the culmination of this phase the investigator will have an understanding of the scope of evidence and would have identified areas which are of key interest to the investigation.

Typically this stage would involve the examining of the wreckage at a visual level to identify abnormal or unusual failures and differentiating between cause and effect within the failures.

The 'exploration of facts' stage occurs throughout the period during which the investigator is conducting the on-site wreckage examination. Depending on the extent of the wreckage examination on-site, it may occur or continue in a secure environment away from the accident site and may include material expertise albeit the expertise will be to assist in the large scale surveying of the wreckage rather than conducting in-depth examinations. It culminates when the wreckage has been surveyed and the key areas of interest in the structure have been identified.

3. Detailed investigation phase

The detailed investigation phase of the aircraft structure occurred during all four case studies with the exception that in only three of the cases studied did the detailed investigation involve structures constructed of polymer composite material.

The detailed investigation phase commenced following the completion of the convergence phase and was finalised when the relevant areas of examination, testing or research, had reached a valid conclusion or the evidence collection had become saturated. This phase differed from the convergence stage as the predominant focus was in detailed examination of specific structural areas. In all cases this involved the use of material experts albeit each to a differing degree. External assistance is likely to be called upon to assist in this examination.

During this stage the wider scenario from the external evidence is largely known and thus there may be fewer external sources of evidence outside of the area of investigation. The exception however is in those areas which are directly related to the area of investigation where further fact gathering is likely to continue, e.g. a flutter investigation is likely to contain a wider area of investigation than just the structural failure.

To accomplish this task the examination typically involves confirmation (fractographic, design, construction, stress analysis, judgement based on location of failure etc.) testing (mechanical, construction, etc.), comparison to existing structures, and further research.

4. The concluding phase

The concluding phase occurred following the completion of the detailed investigation phase and following the finalisation of analysis. This phase primarily focused on the creation of recommendations, communication of findings, formal reporting and release of the investigation report.

4.12.2 Finding 2

The challenges that composite materials presented to the investigation were varied and could not be clearly defined.

In each of the cases there were noted issues that were presented to the investigator as a result of the aircraft structure being constructed of polymer composites. There was no evidence however to suggest that these were detrimental to the investigation. In fact, there was mild evidence suggesting that the use of polymer composites may have assisted in certain circumstances. It was however noted that the issues commented on by the practitioner were in areas perhaps not seen in the selected case studies. Notwithstanding however, the issues may have occurred should the circumstances behind the accident have been different, or the issues were known to the practitioner external to the case study.

It was noted that the fragmentation of the composite reduced the ability of the composite material to assist in identifying the aircraft dynamics at impact. It was commented that in a conventional aluminium structure the permanent gross deformation of the structure may give indications as to the angles and momentum at impact. Whilst this was noted as a difference, it did not hinder the understanding of such conditions. In this case sources of evidence relating to the structure such as ground impact marks, the global deformation of the structure, qualitative degree of composite damage and the deformation of metallic components were all able to provide sufficient evidence to understand the dynamics at impact. In addition, external evidence such as witness, and video evidence was reasonably detailed in all cases and thus assisted in confirmation of the findings based on analysis the wreckage.

Furthermore, in another of the cases studied, the identification of a structural failure was significantly influenced by the evidence external to the examination of the structure. Whilst the investigation had not been hindered by the composite material failure, in this case it is plausible that external evidence was sufficient enough to reduce the need for a high level of composite material failure recognition.

Nevertheless, it could also be postulated that the evidence external to the investigation was ‘filling a void’ having been created by the lack of structural evidence. The identification of impact dynamics through the examination of metallic structures suggests a solution was identified to fill a void in the inability of the composite materials to provide such information. The use of witness evidence to hypothesis a structural failure was significant, but it was proposed by the participant that things may have been different if the witness evidence had not been available.

4.12.3 Finding 3

The wider context of evidence was of significant importance to the wreckage examination and structures examination.

In all cases the wider context of evidence provided significant assistance to the wreckage and structures investigation.

In one case the failure mode was not formally identified during the convergence phase, however the practitioner did note suspicion of the failure area in question. The practitioner noted that particular features provided an indication that was akin to those which could be expected to occur during slow crack propagation rather than a typical fast fracture. This understanding was used to postulate what damage may have occurred during flight and what may have occurred during the impact. There was however significant witness evidence which suggested structural failure in the area in question and thus through triangulation of evidence it was noted that this was a structural area of significant interest for further in-depth investigation.

In a separate case the wreckage distribution played an equally significant role. In this instance the region of primary structural failure separated from the aircraft. Rather than resulting in the in-flight breakup of the aircraft, and hence presenting a continuous wreckage trail, the departure of the structure rendered the aircraft uncontrollable albeit still intact. The aircraft subsequently impacted the ground a distance from the point where the primary failure occurred. This presented the investigator with a significant indication of the structural failure, immediately presenting suspicion to the items which were found at a distance from the main impact location.

4.12.4 Finding 4

In all cases where structural failure was a significant aspect of the investigation, material experts were utilised in examining the wreckage.

In three of the four cases, expertise was sort to assist in the examination of the polymer composite wreckage.

In two of the case studies, expertise was sought during the initial stages of wreckage examination to assist in the early examination of the wreckage. Both of these examinations occurred post wreckage-recovery. In one of these case studies the component was then sent for in-depth laboratory analysis.

In the remaining case study, which involved composite materials examination, expertise was used as confirmatory to the investigator's findings. In this case the advice received from the specialist confirmed that in-depth laboratory analysis would not be required (this was also backed by other evidence suggesting the mode of failure).

4.12.5 Finding 5

In examining composite failures, there were references to visual characteristics which were akin to: gross failure identification, comparative consideration between multiple failures, and individual local fracture examination.

Gross failure identification

The examination of global failures was used by the investigator to understand both the sequence of failure and the failure mechanism of the component. This did not involve the examination of fractures but instead involved understanding the gross failure pattern, or the identification of the 'big picture' as otherwise referred to. An example of this is in one of the case studies where the high degree and multiple regions of damage within a component suggested that a prolonged oscillating failure had occurred rather than a fast single load failure. In all case studies the failure process of large sections of the structure was examined through this method.

Comparative consideration between multiple failures

Here the investigators compared multiple failures against each other with the intention of identifying a failure that is unique against the failure characteristics of the other failures. In one of the case studies the investigator, in visually examining the composite failure area, came to a suspicion that there were two separate zones within the failure sequence. As well as the background evidence gathered, this hypothesis was drawn through the differences in appearance, geometry and profile. In another case study a similar identification was made in four similar load bearing structures. In this instance it was identified that one of the components had failed in a different manner to the remainder.

Local fracture examination

The local fracture examination is the means by which the investigators examine the individual fracture area. In all cases the investigators did not have any procedures or training specifically into the identification of composite failure mechanisms and hence no formal methods were used. In three out of the four case studies, the examination of a fracture surface at a visual level was conducted with the view to making preliminary assessment of the failure mode. In the case where this was not conducted, it was due to the requirement of a polymer composite structural examination having been ruled out at an early stage in the investigation.

In one of the case studies, the investigator utilised the appearance of both the fracture profile and the smooth nature of the fracture as a suspicion of a possible premature failure. This knowledge was gained through general experience with all forms of aircraft structures rather than specific training on composite material failure mode identification. It is important to note that this was used to form the basis for a suspicion rather than to a conclusion of the mode of failure.

In all of the cases that contained a structural examination, the in-depth assessment and verification of the failures was conducted by material experts. In two of the case studies the investigators commented that when examining fracture features from a polymer composite material, the features being looked for would be akin to those found in fractures of wooden materials. They did acknowledge however that they believed that this understanding was not well developed.

It is worth noting however that the recollection of the failure characteristics was dependent on the triggering material, in most cases being photographs of the wreckage, and the ability of the participant to recall from memory. The participants' memory may also be biased towards those features which were of significant interest to the investigation. For these reasons it was not possible to gain an in-depth understanding on the examination of composite materials as it was likely to have been conducted at the time of the initial examination.

4.13 Chapter summary

The exploratory study into the wreckage examination and structural examination of aircraft accidents involving polymer composite aircraft has provided a comprehensive and needed foundation from which further research can be established. The analysis has presented five findings which have been determined through the investigation of four practitioner centric case studies. The results have established an understanding of the process which in turn presents a theory as to 'how' and 'why' the wreckage examination and structural examinations are undertaken. In addition, the findings present observations made regarding key aspects of the investigation of accidents involving polymer composite aircraft.

The understanding provided during this phase suggests that when considering whether known visual and macroscopic failure features of polymer composites can assist the accident investigation practitioner in conducting the wreckage investigation and structural investigation, an understanding has been generated as to:

(1) How they can fit into the investigation process
(2) In what context they will be used, and
(3) Requirements to ensure the selection of failure characteristics will be appropriate

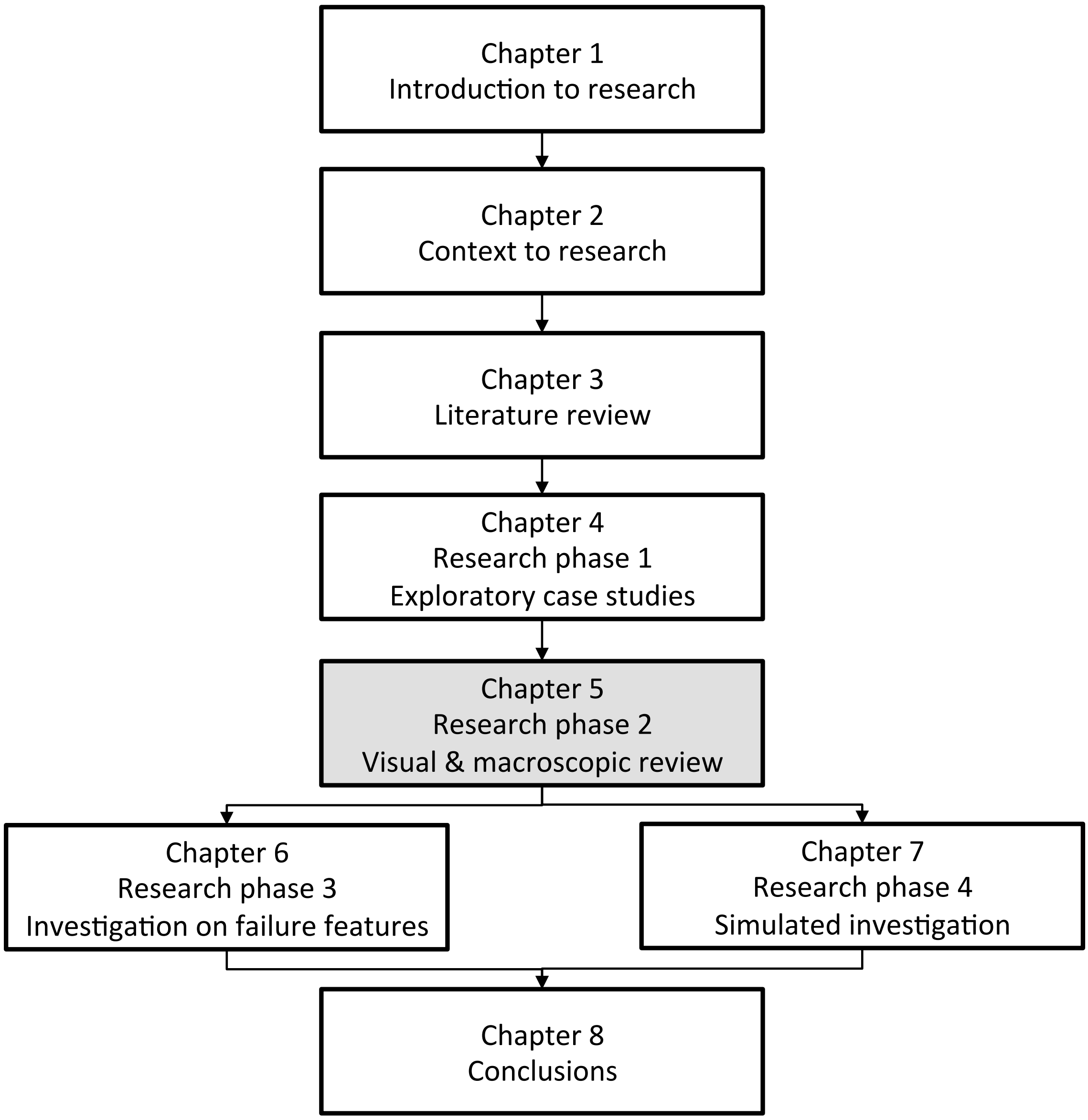
The investigation process as described suggest that the most fitting phase for research efforts aimed at assisting the practitioner is in the convergence phase. Here the addition of new knowledge is likely to assist the investigator in making this stage more effective by providing the practitioner with the additional tools to increase evidence collection and convergence of hypotheses. Additionally it would also assist in extending the capabilities of the 'discretionary investigation' during both the latter part of the convergence phase and the initial in-depth phase. It is thus apparent that the selection of visual and macroscopic examination techniques should fit within the requirements of the convergence stage. Finding one suggests the most prominent considerations as being:

- field deployable,
- assisting in the preservation of evidence,
- methods that can assist in hypothesis generation of the wider accident scenario,
- timely to apply,
- assist in relating cause and effect between failures (i.e. identifying primary failure and secondary failures),
- able to eliminate lines of enquiry as well as identify lines of enquiry,
- identify abnormal or unusual failures,
- consider the wider context behind the failure (e.g. stress concentrations, location of failure), and
- be able to make a preliminary assessment of the failure mode

Additionally, finding 5 has shown that the techniques selection should include those that offer local examination, gross examination and include information regarding the ability to differentiate between failures.

Thus the next phase of research is orientated to review knowledge on visual and macroscopic examination techniques that are relevant to the convergence stage of investigation.

5 SELECTION OF VISUAL AND MACROSCOPIC EXAMINATION OF POLYMER COMPOSITE MATERIALS



The primary aim of this phase is to identify visual and macroscopic examination techniques which are appropriate for potential use by practitioners in conducting the examination of polymer composite aircraft wreckage. To assist in achieving this aim, empirical information gained from the case study phase will be used to establish selection criteria. This will present a scope from which a literature survey can be conducted to identify known visual and macroscopic failure characteristics of polymer composite materials.

This stage of the research programme should not be constrained within the confines of literature on accident investigation. The literature survey was hence expanded to include the areas of fractography and failure analysis. Within these fields information was sought from journal papers, research reports and investigation reports.

5.1 Establishing the scope and objectives of the literature survey

The objective of this phase of the research programme is to identify what visual and macroscopic failure characteristics are appropriate for the examination of polymer composite aircraft wreckage. It was identified during the literature review (chapter 3) that there has been substantial effort in the understanding of composite material failures within the field of fractography and failure analysis. Furthermore, this development has included identifying failure characteristics within the visual and macroscopic range.

The empirical findings from the case studies have established that the visual interpretation of composite wreckage is conducted by the practitioner using predominantly 'discretionary means'. Thus it is likely that the investigators experience is the primary means by which interpretation of the failures is being conducted. This is especially significant during the 'convergence phase' which involves discretionary actions by the practitioner and may not involve the use of external expertise.

It is therefore appropriate that the research method for this phase is to conduct a literature survey to identify visual and macroscopic failure characteristics of polymer composite materials. It is important that the survey is conducted within the findings of the case studies and it will draw information from multiple disciplines.

For the purpose of this research, a failure characteristic is defined as a feature or quality which serves to identify the type of failure.

In order to select appropriate failure characteristics from literature, it is necessary to understand in what context the failure characteristics will be identified and what they will add to the investigation. This can be approached by considering information gained during the case studies phase of this research programme. The following section therefore establishes requirements for failure characteristic search and selection.

5.1.1 Requirements from the case study phase of the research programme

The cases studied in phase one of the research programme provided the researcher with valuable experience of how practitioners conduct the examination of polymer composite wreckage. Moreover the results from the first phase can be used to create practitioner-based criteria to assist in the selection of the characteristics.

Table 5-1 illustrates the findings from the case study phase of the research. The table displays a summary of the findings and suggests the implication that this has on guiding the literature survey. The findings suggest that the literature survey should:

- Exclude features which are only visibly through destructive means
- Be restricted to include only features which are visible below x25 magnification
- Include static overload failures and premature failures involving degradation, design deficiencies and aerodynamic phenomenon.
- Include the influence a degradation mechanism will have on a pristine failure
- Include characteristics which identify fracture origin and fracture propagation
- Include features associated with local fracture identification, comparison between fracture modes and zones, and failures of complex structures
- Consider the wider context of the investigation and evidence collection

Finding	Summary	Implications
1	The investigation process was defined and included 4 phases. Most suitable period of the investigation for the characteristics to be applied is during the convergence stage	*Evidence preservation is a key component:* Include only non-destructive methods
		Examination likely to occur on the accident site: restrict macroscopic characteristics to be those which are identifiable up to x25 magnification. This is consistent with eye loop and lower power magnifying glasses used in field investigation tool kits (ASM, 2001)
		Hypothesis generating stage: Factors that can confirm whether the failure was overload or underload, primary or secondary
		To identify abnormal or unusual failures: Identify how degradation mechanisms influence failure characteristics
		Differentiating between cause and effect: Characteristics which locate fracture origin and propagation.
3	The wider context of evidence was significant to the wreckage examination	Consideration should be made for features which are able to assist in identifying the wider accident scenario, such as identifying the failure sequence.
		Accident investigation literature should assist in the selection of relevant failure mechanisms. Failure sequence characteristics should be selected against accident investigation literature for relevance
5	Practitioners use 3 references to visual identification	Themes identified as local, gross and comparative: Survey should include failure characteristics from all of these themes.

Table 5-1 - Findings from phase 1 of the research programme which defines the scope of the literature search

5.2 Fundamentals

The previous section has discussed the purpose and scope of the literature survey. The results of the survey are now presented, commencing with an overview of key terms and principles.

It should be noted that a seminal text published by Greenhalgh (2009) provided significant direction for the literature survey. This book, titled "Failure analysis and fractography of polymer composites", has hence been cited significantly in this chapter. Whilst this publication provided a foundation for some of the principles discussed in this chapter, the book was not used solely. Rather, the original founding articles were reviewed, additional or conflicting material was sought and links to the accident investigation literature was identified. Furthermore, this literature survey has covered areas and principles which are not presented by the publication.

It is recognised that the failure of a laminate composite can be split generally into three different classes; translaminar, interlaminar and intralaminar (Smith & Grove, 1987). These terms will be utilised within this literature survey and are described below and in figure 5-1 which is based on the definitions presented by Greenhalgh & Hiley (2008).

- Translaminar failure entails fracture of the reinforcing fibres.
- Intralaminar fracture entails through-thickness fracture between the fibres.
- Interlaminar (delamination) entails fracture between the layers. There are three types of interlaminar failure known as Mode I (Peel), Mode II (Shear) and Mode III (Tearing) (figure, 5-2). A combination of modes, i.e. mixed mode, is possible.

The above definitions do not include a definition for a fracture occurring in the same orientation as a delamination but within the ply instead of being located between the plies. The definition as presented by ASM (2003) suggest that this could be described as an intralaminar event for they suggest intralaminar is:

"… an object (for example, voids), event (for example, fracture), or potential field (for example, temperature gradient) existing entirely within a single lamina without reference to any adjacent laminae."

However, for the purposes of this survey this event is referred to as interlaminar failure which is in keeping with the definition as illustrated by Czabaj & Ratcliffe, (2012) (figure 5.3) and described by Greenhalgh (2009) as translaminar and intralaminar failure occurring through the thickness and interlaminar failure occurring in the plane of the laminate.

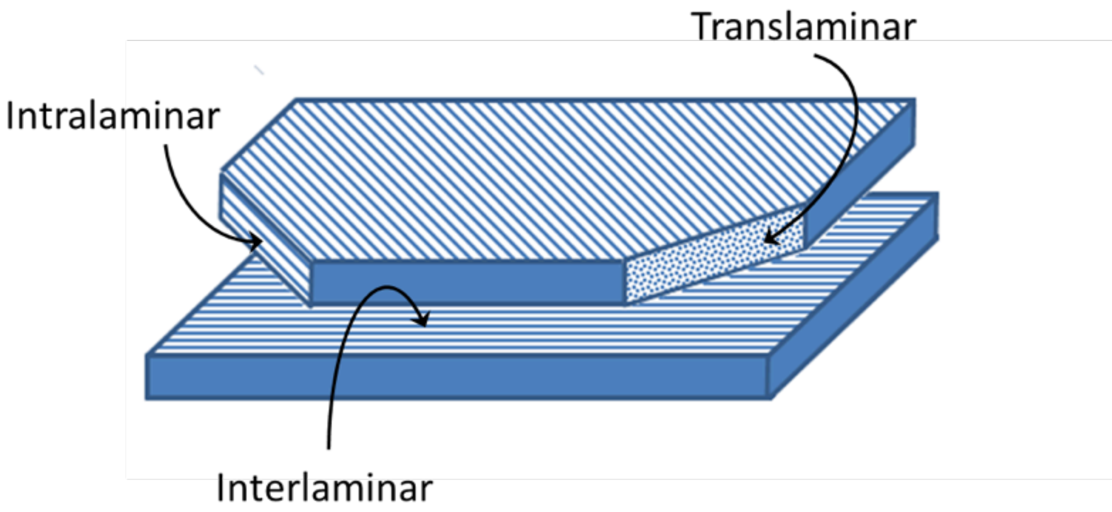


Figure 5-1 – Illustration of translaminar, interlaminar and intralaminar fracture modes. (redrawn from Greenhalgh & Hiley, 2008)

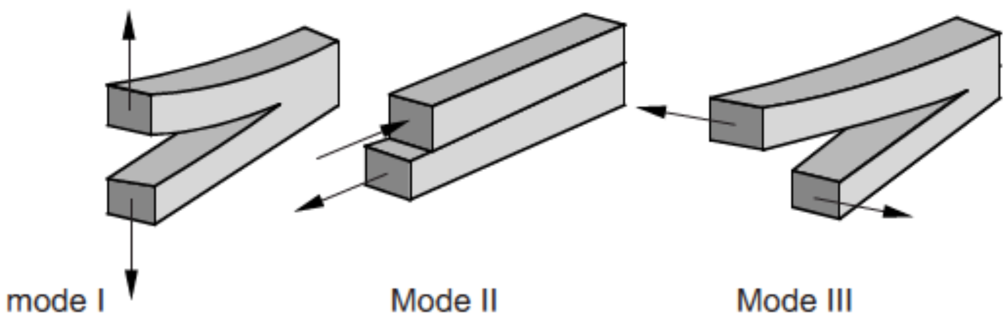


Figure 5-2 – three modes of intralaminar failure (Grellmann & Seidler, 2007)

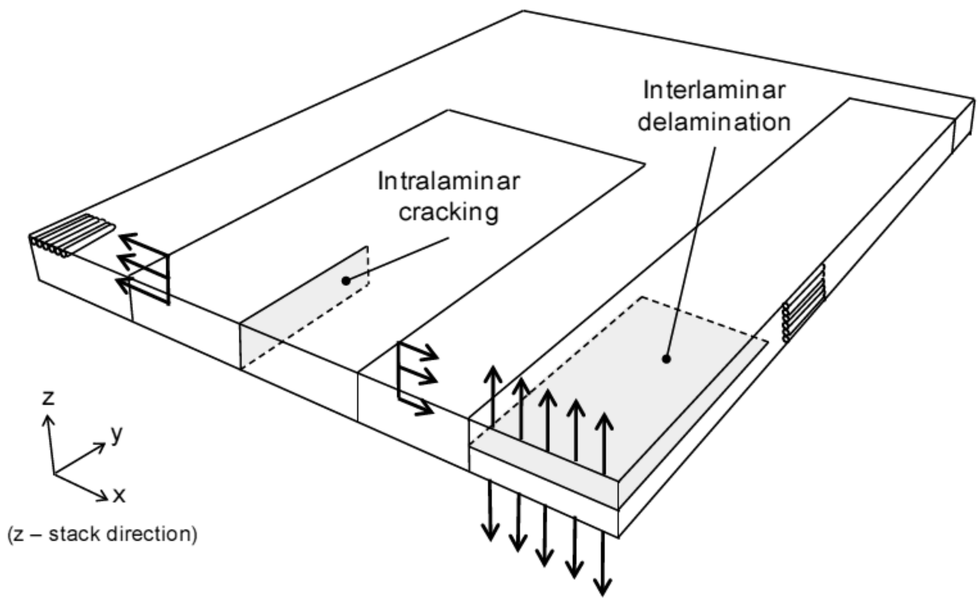


Figure 5-3 - Intralaminar fracture versus interlaminar delamination (Czabaj & Ratcliffe, 2012)

In particular applications, polymer composite materials are designed such that the fibres are preferably orientated according to the direction of the intended load. Thus a unidirectional material that is designed to carry a bending load is likely to fail in translaminar flexural failure under normal loading conditions. An example of this would be the unidirectional monolithic spar caps in glider wings that would typically carry tension or compression loads (Mileshkin, Scott, Wood, Collyer, 1987). The resultant translaminar fracture is also expected to involve secondary damage such as intralaminar splitting. If out-of-plane loads are applied to the same component, then the composite material can be expected to behave in different ways. If for example the load is applied transverse to the intended load direction, then the failure can be expected to initiate due to intralaminar failure and the fracture will be visually different (Ginty & Chamis, 1987). This is a characteristic which can be useful in understanding whether the component failed under anticipated flight loads or due to out of plane loads such as ground impact. Moreover, the understanding of whether a material has failed in a manner that can be associated with in flight loads is recognised within the aircraft accident investigation literature. As Wood & Sweginnis (2006) suggest that in examining a failure the aircraft accident investigator should ask the question:

> *"Was the manner of failure consistent with the way this part was stressed inflight?"*

Unfortunately this principle is not applicable to all components of the airframe as, from the designers perspective, it may not be possible to provide an optimised fibre alignment for a specific component due to manufacturing and certification costs (Baker, Dutton, and Kelly, 2004). In these instances layups of quasi-isotropic alignment may be utilised.

The characteristics as identified during the survey are presented in the following sections.

5.3 Locating fracture origin and fracture propagation

This section discusses features which are associated with characteristics that enable the investigator to locate the fracture origin and fracture propagation direction.

5.3.1 Radials

Radials, or also referred to as ridges (Kar, 1992), are a failure feature which appears to be first described by Purslow (1981). Latterly the identification of radials was repeated in literature both directly through experimentation (Shikhmanter, Eldror & Cina, 1989) and in subject compendiums (Purslow, 1983; Kar, 1992; Greenhalgh, 2009). The morphology by which the radials are created is known as 'mirror, mist and hackles' (a sequence of textures on the fracture surface coincident with increasing roughness as the crack propagates and crack speed increases) with the proportions of each mirror, mist and hackle region being dependent on toughness, loading conditions and environmental factors (Greenhalgh, 2009). This relationship was applied, albeit at a microscopic scale, to the failure examination of glass fibres contained within a main rotor blade by the NTSB (2010). In this instance it was able to provide evidence consistent with low stress fatigue failure.

Radial lines are a phenomenon which is created during fracture growth under brittle axial tension failure of a unidirectional polymer composite. The identification of the characteristic can confirm the propagation direction of the fracture, locate the fracture origin and provide supporting evidence of the failure mode (Purslow, 1981). The characteristics of radials have been described by Purslow (1983) as:

> *“Radiating lines called "radials" can be detected originating at the relatively smooth area. These radials are formed as the fracture propagates along different radii at gradually diverging axial positions causing lines of hills and valleys of increasing magnitude.”*

Figure 5-4 illustrates the fracture surface of a carbon fibre epoxy composite. The initiation point is labelled as “O”. From this illustration the “lines of hills and valleys” can be seen to point towards initiation site. The area immediately surrounding the initiation point is relatively smooth in comparison to outer regions.

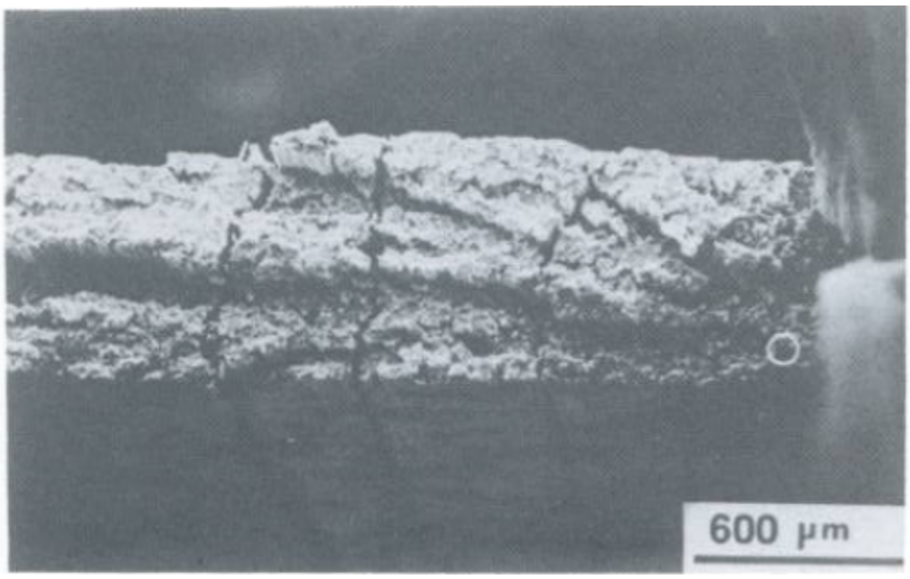


Figure 5-4 – Radial formation during the brittle tension failure of a carbon-fibre/epoxy composite (Shikhmanter *et al*, 1989)

The illustration of this mechanism in literature is typically associated with macroscopic examination under higher magnification.

The phenomenon of ‘mirror, mist and hackles’ can be identified in training literature for aircraft accident investigators. In ICAO’s draft document “Manual of Aircraft accident and Incident Investigation” (ICAO, 2008), and in ICAO’s current document “Manual for aircraft accident investigation” (ICAO, 1970), the phenomenon of hackles is explained as a means to identify the fracture origin of fractures in glass and in plastics. Here ICAO suggests the identification of hackles as “valuable in identifying the origin of the fracture since they always point in the direction of the initial crack”. This is a technique replicated in failure analysis literature (Parrington, 2002; McCoy, 2004).

The significance of identifying radial lines in metallic structures to locate the fracture origin is also expressed in accident investigation training literature. The US Air Force Publication *US Air Force guide to mishap investigation* (Carver, 1987), and *Manual for aircraft accident investigation* (ICAO, 1970) both describe and illustrate the flow of radial lines from the origin of the failure.

The formation of radials is limited to brittle tensile failures in unidirectional materials. Glass fibres generally have a poor fibre/matrix interface so have a tendency to have significant fibre pullout. As a result, the radial features are generally not visible (Greenhalgh, 2009). Similarly, in toughened matrix systems such as thermoplastics, the failure of the material is typically less brittle than that of epoxy. This leads to a failure which contains a higher degree of fibre pullout and as a result the appearance of macroscopic features such as radials may appear to a lesser degree (Purslow, 1988). The fracture origin of failures dominated by significant fibre pullout however, may be distinguished by an area of flat fracture plane at the site of fracture initiation (Greenhalgh, 2009).

5.3.2 Chevron features

The failure feature of Chevrons appears to be first described by Purslow (1981) and is an extension of the radials morphology as described above, albeit it occurs in cross-ply laminates (e.g. 0°/90°) under tensile failure. The mechanism of chevrons was repeated in literature by Purslow (1988) when reporting on the fractographic features of thermoplastics and by Greenhalgh (2009) in the author’s comprehensive subject book. Latterly, chevron formation was reported by Kumar, RaghavendraI, VenkataswamyI & RamachandraII, (2012) in the tensile failure of unidirectional carbon fibre coupons, although it is likely that these features identified would be better described as radials lines.

During loading of the cross-ply laminate, the transverse fibres (90° plies) crack prior to the failure of the 0° load bearing ply (Purslow, 1988). When failure finally occurs on the load bearing plies, the failure occurs at the 0°/90° interface and propagates towards the centre of the 0° load bearing ply with a component towards the global crack growth direction (Purslow, 1981). When the radials converge from the lower face and the upper face of the ply, the result is the formation of apparent chevrons which have been formed from the 'hills and valleys' principle which occurs during radial creation. The chevrons point in the direction of crack propagation (Purlsow, 1981).

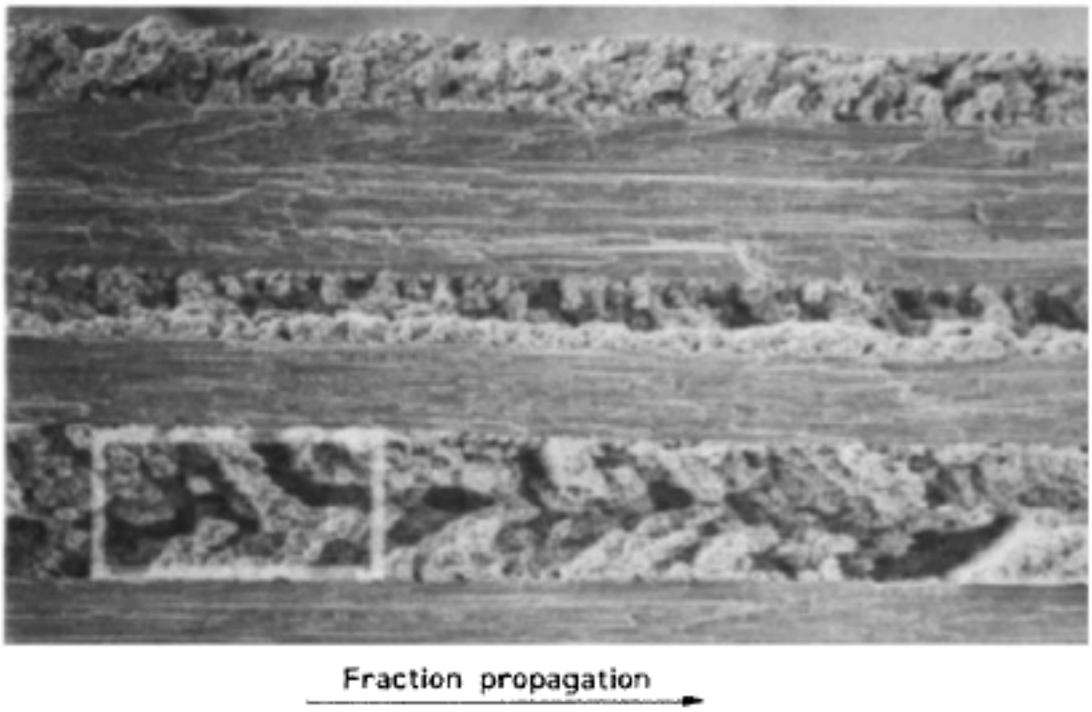


Figure 5-5 - Tension failure of a cross-ply CFRP laminate (x25) (Purslow, 1988)

Chevron (also known as herringbone) features of metallic structures are commonly described in the accident investigation training literature (ICAO, 2008; ICAO, 1970; Wood & Sweginnis, 2006; Carver, 1987; Sander, 2005). The principle of using chevron markings to distinguish the fracture propagation direction and fracture origin are similar, however the chevron formation mechanism which applies to a metallic material is different to polymer composites. In the case of metallic materials the chevrons visibly point towards the origin of the failure. This is converse to the morphology in polymer composites which point in the crack growth direction. The use of metallic chevron patterns as a means of deducing crack growth direction is also evident in accident investigation reports (e.g. AAIB, 2003; AAIB, 1989; ASC, 2002) with perhaps the most high profile use being that of the Sequencing Group of the NTSB to determine the breakup sequence of TWA800 (NTSB, 2000), where the Sequencing Group conducted “detailed visual examinations, occasionally with magnifications up to 30X”.

Similarly to radials, the presence of chevrons is largely dependent on the ply and the matrix to fibre interface strengths as described by Greenhalgh (2009). Materials which have poor fibre-matrix interface strength (e.g. glass fibres) tend to have a higher degree of fibre pullout and hence the chevron features tend not to appear. In this case the fracture origin may be identified by a flat fracture region relative to the surrounding fracture surface (Greenhalgh, 2009). The phenomenon of chevron formation has also been observed to occur, although to a lesser degree, in PEEK (Polyether ether ketone), a toughened thermoplastic matrix (Purslow, 1988). In the case of poor ply interface strength, the plies tends to suffer delamination prior to fracture which leads to a more rugged fracture surface which potentially hinders the formation of chevrons as the presence of delamination tends to lead to the plies fracturing independently (Greenhalgh, 2009). In addition to the failure of cross-ply laminates in axial tension, the formation of chevrons may also appear in the fracture of shear webs of +/-45° loaded under shear stress, where the failure results from the tensile component (Purslow, 1988).

5.3.3 Continuity of fractures

An important phenomenon when considering the sequencing of fractures in composite materials is that a stress concentration associated with an earlier fracture event will influence the crack path of a later fracturing event

(Greenhalgh, 2009). This phenomenon, which is not unique to composites, was first discussed by de Freminville (1914) whilst conducting experiments in metallic structures. It has an important application in composite materials however as the failure of a polymer composite is usually associated with a significant increase in the number of fracture planes and the stiff nature of polymer composites results in a greater range for influence of stress concentrations (Greenhalgh, 2009). The concept of crack sequencing in polymer composites as an aid to failure investigation has been discussed most notably by Purslow (1981; 1984), ASM (2002), Greenhalgh (2005; 2009) and Kumar, et al (2012).

The basic approach, as suggested by Greenhalgh (2009), is to "consider the relative influence of each crack upon the other". Figure 5-6 (ASM, 2001) displays the mating fracture surfaces of an adhesively bonded wing skin and wing spar, showing transverse fractures on both surfaces. As the transverse fractures can be found on both the skin and the mating spar, it can be hypothesised that the transverse cracks must have occurred prior to the delamination. If the delamination had occurred first then it can be expected that the transverse cracks would be absent on one of the surfaces or at least would not have matched in position to the adjacent surface.

Figure 5-6 - mating fracture surfaces of an adhesively bonded wing skin and wing spar showing transverse fractures on both surfaces ~(x0.2) (ASM, 2001)

The influence of a pre-existing crack on a subsequent crack is not limited to stopping crack growth across a boundary, or deviating the crack onto a different plane. Hull (1999) suggests that intersecting cracks can influence each other and thus crack growth direction can be altered such that the cracks converge (figure 5-7). Greenhalgh (2009) suggests that as polymer composite materials are relatively stiff, the distance at which the influence can occur can be reasonably large.

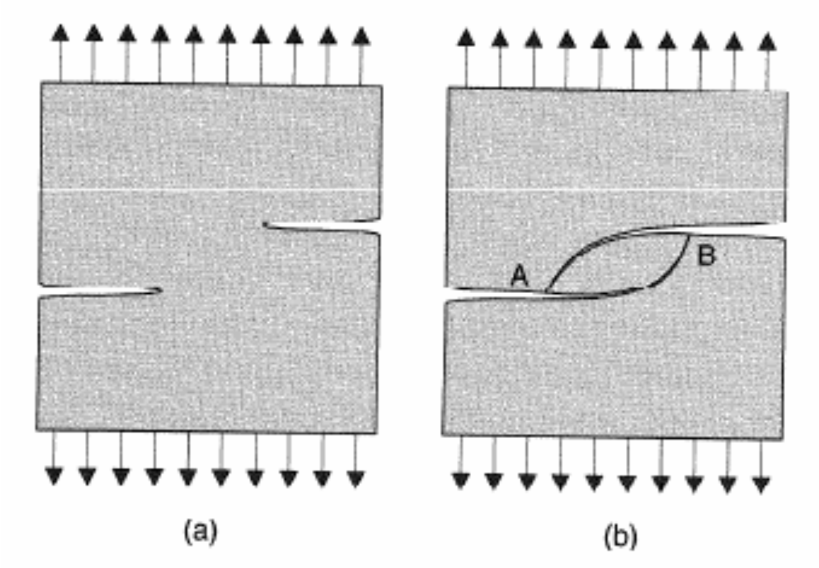


Figure 5-7 – the interaction between pairs of cracks a) the cracks propagate but are not intersecting, b) the stress fields from the crack tips interact thus resulting in the cracks converging (Greenhalgh, 2009).

Whilst there is no evidence of continuity of fractures being discussed in accident investigation training literature, there is evidence of the phenomenon being used, albeit in metallic structures, in major structures investigations (e.g. NTSB, 2000). Furthermore, it should be suggested that whilst the continuity of fractures principle has a strong application in polymer composites, the technique itself is not specific to polymer composite materials.

5.3.4 Compression cracking

The identification of characteristics associated with compression cracking used as a technique to identify the crack propagation direct of a compression-failed polymer composite laminate, was presented by Greenhalgh & Cox (1992). This paper has subsequently been cited in literature with authors (Greenhalgh, Singh, Hughes, Roberts, 1999; Greenhalgh, 1993) reporting the successful use of the technique. Other authors (Tsampas, Greenhalgh, Ankersen, Curtis, 2012; Sivashanker, 2001; Edgren, Asp, Joffe, 2006) have reported the mechanism and its occurrence. Additionally, the technique has been further described by Greenhalgh (2009) and Greenhalgh & Hiley (2008).

Compression cracking is a technique, which utilises the failure pattern of a polymer composite laminate, to provide an indication as to the direction of crack propagation. The technique, as summarised by the founding paper (Greenhalgh & Cox, 1992) is described as:

> *"It has been found that the direction of compression crack propagation in multi-directional carbon-fibre laminates less than 3mm thick can frequently be determined by examination of surface splits around the main fracture. This is done by visualising the splits as 'arrowheads' which generally 'point' to the source of failure, the main translaminar crack forms the shaft of the arrow."*

Figure 5-8. (Greenhalgh & Cox, 1992) shows the mechanism by which the secondary splits are formed and hence the creation of the 'arrowheads'. Image (a) represents the transverse compression growth extending from a defect or notch. In (b) the laminate undergoes secondary splitting in the form of surface ply splits. Image (c) represents the extension of the transverse crack and subsequent increase in secondary splitting. Image (d) shows that as the crack propagates, the secondary splitting extends to the lower section of the transverse compression fracture having been influenced by the inner ply (the image represents a +/-45° layup).

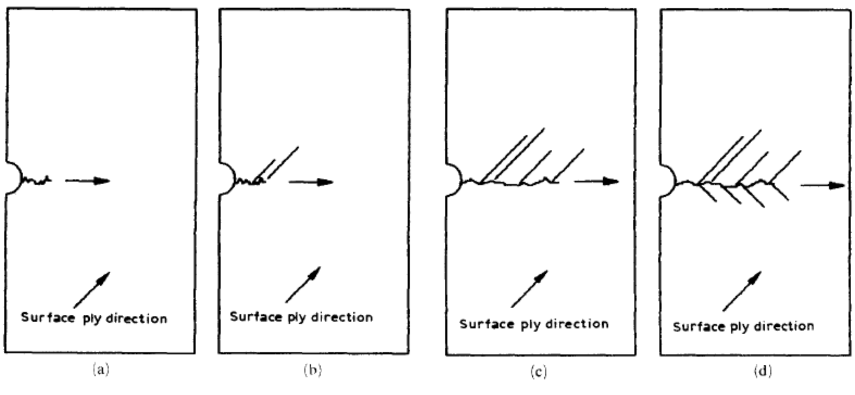


Figure 5-8 - Mechanism of compression crack formation (Greenhalgh & Cox, 1992)

The technique of crack propagation determination through the examination of secondary splits is unique to composite structures and thus has no direct equivalent when considering metallic structures. There is evidence however that the technique has been used successfully in determining crack growth propagation during failure analysis investigations (Greenhalgh & Cox, 2009). Moreover, as highlighted in the preceding sections, there is frequent reference in accident investigation literature to the use of methods to determining crack growth direction.

The technique as applied during the founding paper (Greenhalgh & Cox, 1992) was based on Carbon Fibre laminates with unidirectional ply layup. The technique was found to be useful in examining the compression failure with laminates with outer ply directions of +/-45°, +/+45°, +45°/90° but was hampered with outer plies of +45°/0°. Additionally, the technique can be applied in the examination of woven fibre laminates although the extent of the arrowheads is somewhat reduced (Greenhalgh, 2009).

An important phenomenon which can be seen in images presented in the original paper by Greenhalgh & Cox (1992) (figure 5-9) concerns the effect of compression failure on a specimen that contains pre-existing impact damage. Although the purpose of the image in the article is to demonstrate the formation of compression cracking from each side of the impact area, it also appears to demonstrate the influence of the impact damage on the transverse fracture formation. In this image it can be seen that the primary transverse compression crack meets the lower region of the impact location but is directed around the delaminated area thus forming a visible deviation of the crack path as influenced by the formation of the impact. Potentially this can provide evidence to the investigator in identifying pre-existing impact damage in fractured components.

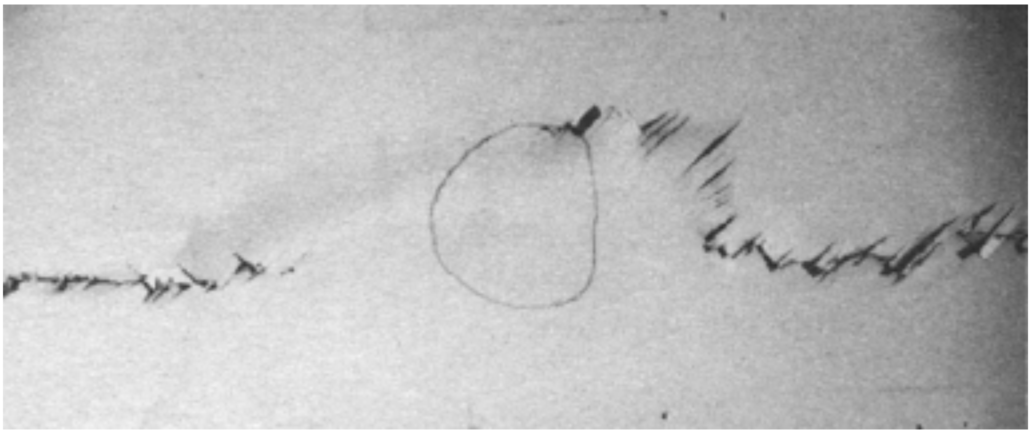


Figure 5-9 - Example of compression cracking in an impacted laminate (Greenhalgh & Cox, 1992)

5.3.5 Tide marks

For delaminated (interlaminar) fracture surfaces, a feature known as ‘tide marks’ can be used to determine the fracture origin and crack growth direction (Purslow, 1986). The phenomenon has been highlighted within the literature widely and has taken names such as ‘ribs’, ‘bands’ or ‘growth rings’. (e.g. ASM, 2001, Greenhalgh, 2009, Purslow, 1986; Purslow, 1987; Greenhalgh 1993).

When a delamination occurs through peel (mode I) or through a combination including peel, a series of visually distinguishable curved bands may form on the delaminated fracture surface as shown in Figure 5-10 (Purslow, 1986).

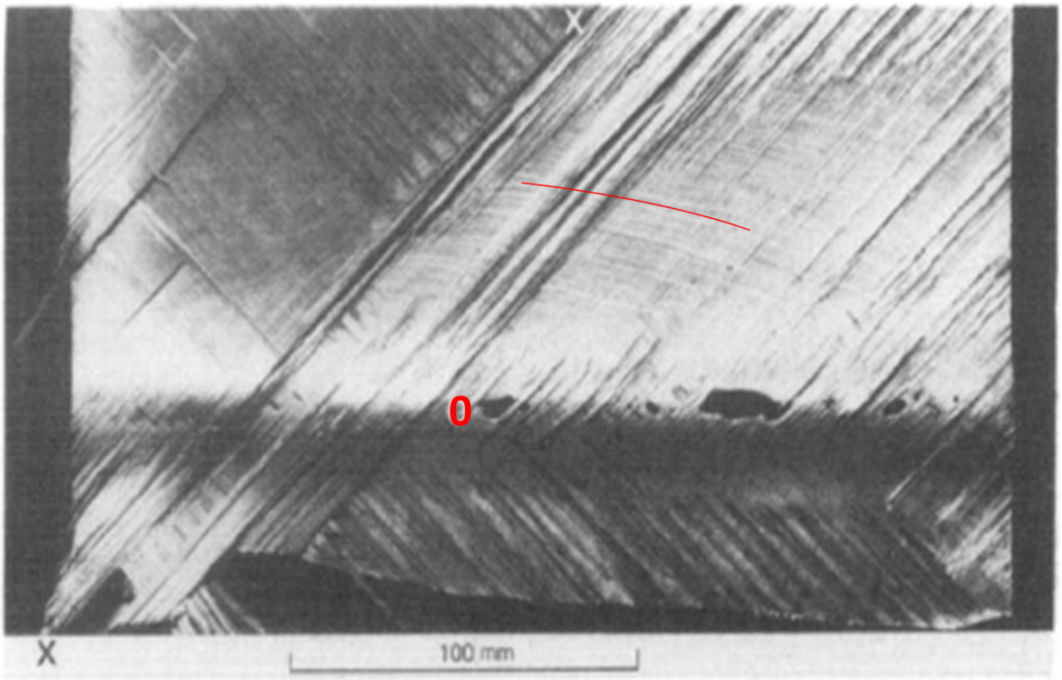


Figure 5-10 – Growth bands during an interlaminar peel failure. The local fracture origin is identified with "0" and the growth bands identified by the red line (modified from Purslow, 1986)

Generally, these tide-mark features are created by changes in crack speed which results in visually apparent light and dark bands on the fracture surface (Greenhalgh, 2009).

The ability to determine the crack growth direction however is not without potential for confusion. Whilst it is accepted that the tidemarks radiate out from the source of failure as demonstrated in figure 5-11, it has been reported also by ASM (2001) that in instances the visually evident banding may suggest crack propagation in the reverse direction, i.e. from the convex side to the concave side. Thus it is possible that depending on the circumstances of the loading, the crack propagation direction can be misleading, other than to state that the crack front travels perpendicular to the tidemarks.

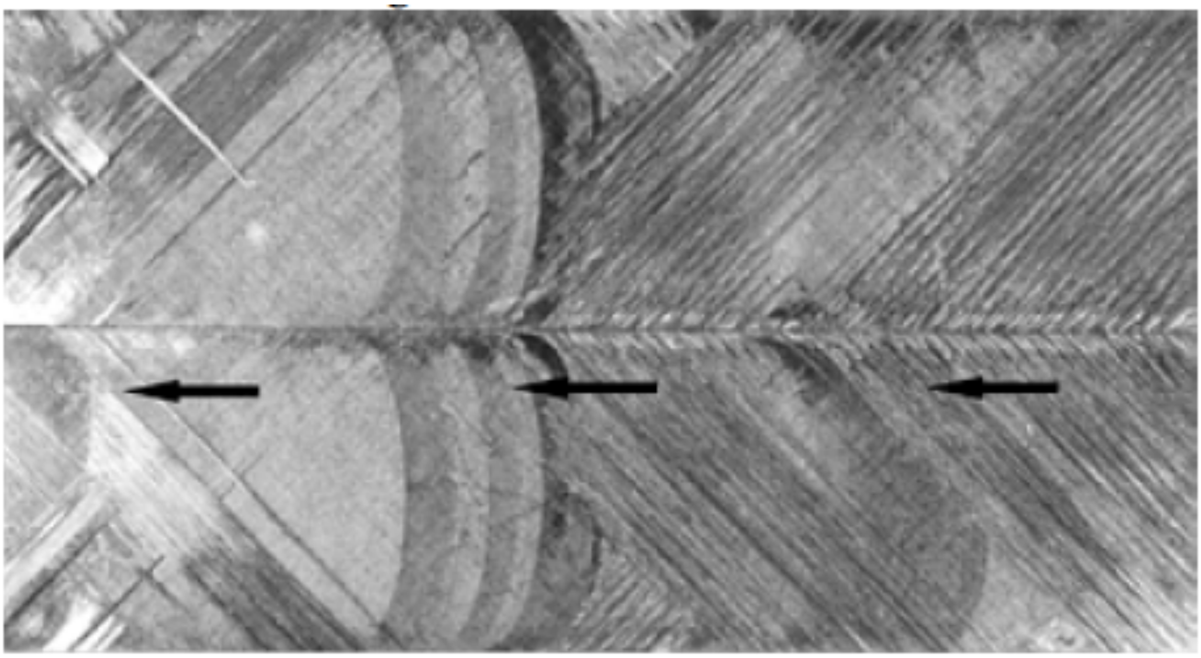


Figure 5-11 - Crack growth direction visible on an interlaminar fracture surface through the formation of bands (ASM, 2001).

Tide marks are not evident visually on all composite materials but are generally visible on toughened thermosets and thermoplastic composites (Greenhalgh, 2009).

5.3.6 Crack bifurcation

The identification of the feature of crack bifurcation was created during research sponsored by the Wright Laboratory to develop the Composite Failure Analysis Handbook (Kar, 1992; Kar 1992a; Kar, 1992b; Kar, 1992c). The technique was re-iterated by ASM (2001) and by Greenhalgh (2009).

Crack bifurcation is a feature that is created during translaminar fracture and is a method which, where evident, can identify the fracture origin and the direction of crack propagation. As a crack propagates through a composite structure, more strain energy becomes available to generate secondary damage and hence a crack is more likely to bifurcate (i.e. transition into two cracks) (Greenhalgh, 2009). Thus the identification of crack bifurcation can be indicative of increasing crack propagation direction. Figure 5-12 illustrates a V-22 Osprey Wing box which failed following upward and aft bending of the outboard ends of the box, so as to create a maximum compressive stress at the upper skin surface (Kar, 1992). The upper surface which is shown in the image subsequently failed in compression buckling (Kar, 1992c). The image identifies the position of a bifurcation in crack propagation and hence suggests that the failure must have initiated prior to this bifurcation point, hence it was concluded that the crack had propagated from the right of the image to the left of the image.

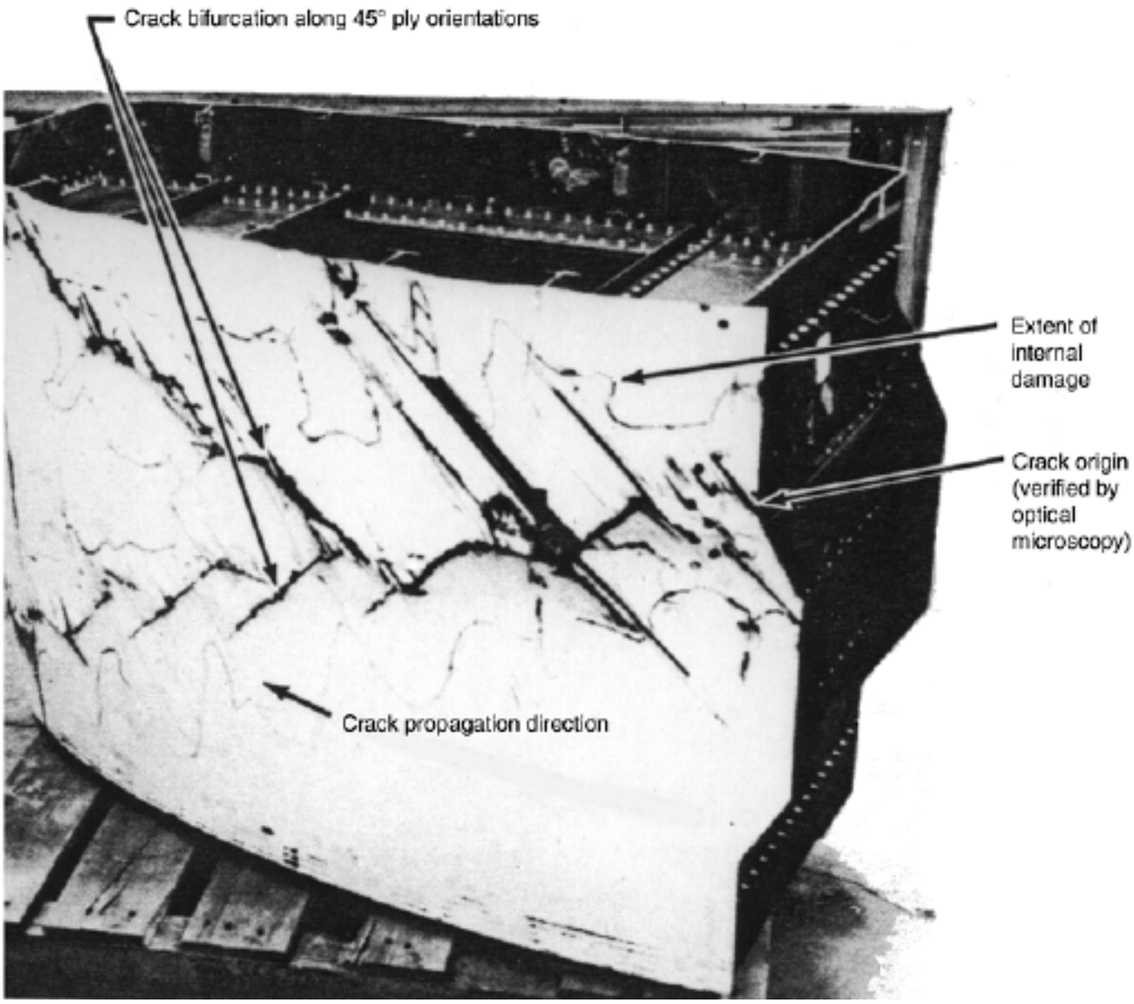


Figure 5-12 - Branched cracks on the upper surface of a graphite-epoxy wing box. The crack branching is indicative of crack growth in the component from right to left (Kar, 1992c)

It is also interesting to note that in figure. 5-12 there are many ply splits which branch out of the primary crack in what appears to be +45° / -45° directions. Figure 5-13 illustrates the top skin of the wing box with the primary crack superimposed in red and the ply splits superimposed in blue. The intersection of the red and blue lines also appears to create arrows. Although it cannot be confirmed without understanding the failure in more detail, it may suggest the existence of compression cracking features.

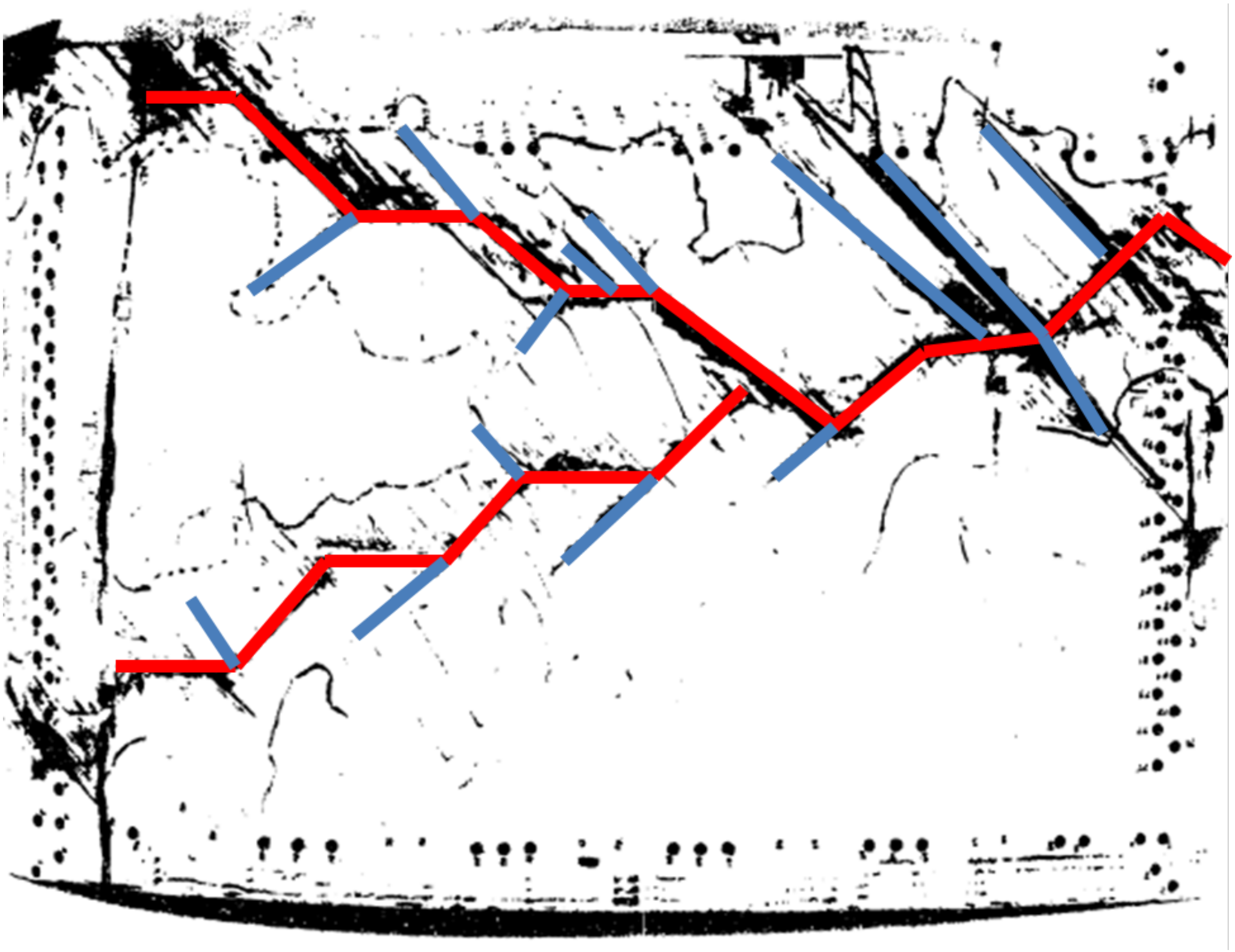


Figure 5-13 – Crack branching on the upper, compressive failed spar box from a V-22 Osprey (modified from Kar, 1992c)

5.3.7 A tendency to follow the 0° interface

The principle behind the tendency for a delamination to follow the 0° interface is first introduced by Purslow (1981). The phenomenon is latterly discussed by Greenhalgh (1993), Greenhalgh & Hiley (2008) and Greenhalgh (2009), with Greenhalgh & Garcia (2004) recreating the phenomenon during experimentation creating the failure of skin-stiffener run-outs.

During delamination crack propagation, a delamination will want to grow parallel to the fibre orientation (Greenhalgh, 1993). To achieve this, the delamination may change from the ply interface at which it originated and move to a different interface before settling at the preferential layer. This mechanism occurs during delamination growth under mode II (shear) or mixed mode (I & II) failure and has the potential to allow visual interpretation of crack growth direction.

As described by Greenhalgh & Hiley (2008), when a delamination propagates within a laminate, the shear forces push the crack front through laminates which have fibres orientated normal to or close to normal to the direction of crack propagation. The plane of delamination will finally settle when a layer has been reached where the fibre orientation is close to parallel to the crack growth direction. The crack front is then restrained from further through-thickness propagation and hence the delamination will continue to propagate on this plane. This shift in fracture plane can usually be identified visually and thus the crack can be traced back to the origin of the failure (Figure 5-14).

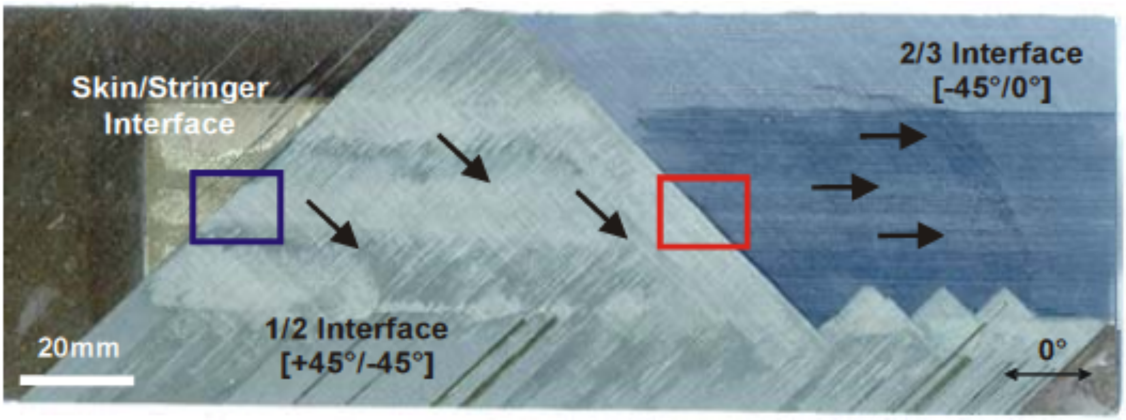


Figure 5-14 – crack growth direction as interpreted through ply propagation of a skin / stiffener delamination (Greenhalgh & Hiley, 2008)

This mechanism has been described as occurring during various situations such as the tensile failure of a skin / stiffener run-out (Greenhalgh & Garcia, 2004) and impact induced delamination (Purlsow, 1981).

5.3.8 Serrations

Although not readily acknowledged within the academic literature, the use of paint film cracking as a means to infer crack growth direction has been cited in two prominent accident investigation training publications (ICAO, 2008; Wood & Sweginnis, 2006). It is proposed by ICAO (2008) that during tearing, a saw toothed pattern is created into the film. The direction of tearing can be gleaned by examining the 'teeth'. Although no detailed means of identifying the features, the use of serrated boundary to determine crack growth direction is recognised in fractographic literature.

Purslow (1987) provides a macroscopic means by which the sequence of failure can be determined when a cross ply laminate has failed in intralaminar shear and peel. In this instance a serrated boundary is created due to the presence of ply splits parallel to the fibre direction and a 45° off-axis load. When the fracture is progressing at 45° to the ply splits, the crack front is separated between a global crack front and the local crack front which is influenced by the ply splits (figure 5-15).

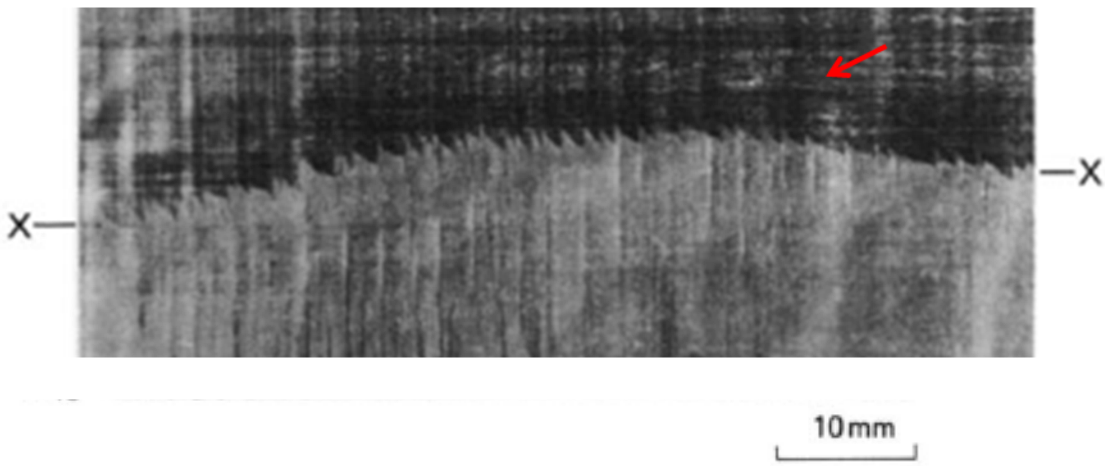


Figure 5-15 – Peel / shear boundary indicating crack propagation direction. Crack growth direction indicated by the red arrow (modified from Purslow, 1987)

5.3.9 Influence of stress raisers

As polymer composites are inherently brittle, failure will always initiate at a stress raiser. A stress raiser can take the form of geometrical features or more subtle features such as damage (e.g. impact) or material defects (e.g. incorrect fabrication) (Greenhalgh, 2009).

5.3.10 Differentiating between different failure zones

In particular instances a failure can leave visually distinct regions of different fracture types. These can be indicative of the failure sequence with each region representing different failure modes during the sequence of failure. Whilst an apparent change in distinctive regions has been used by the investigator to promote suspicion of a failure from which further investigation can be conducted (Chapter 4), it can be used also to provide specific detail into the fracture sequence.

Consider an example given by ASM (2001) as shown in Figure. 5-16. The image shows three different stages in the failure of a helicopter rotor blade, labelled as A, B & C. Each stage is indicative of a different failure mechanism during the failure event. The area labelled “A” depicts the first stage which is a fatigue initiation region. The area labelled “B” depicts a region of translaminar bending failure; and the area labelled “C” depicts an area of fibre crushing during final fracture. Through the identification of such phases in the failure event, a sequence can be hypothesised which may assist in the preliminary understanding of the ‘bigger picture’ surrounding the accident.

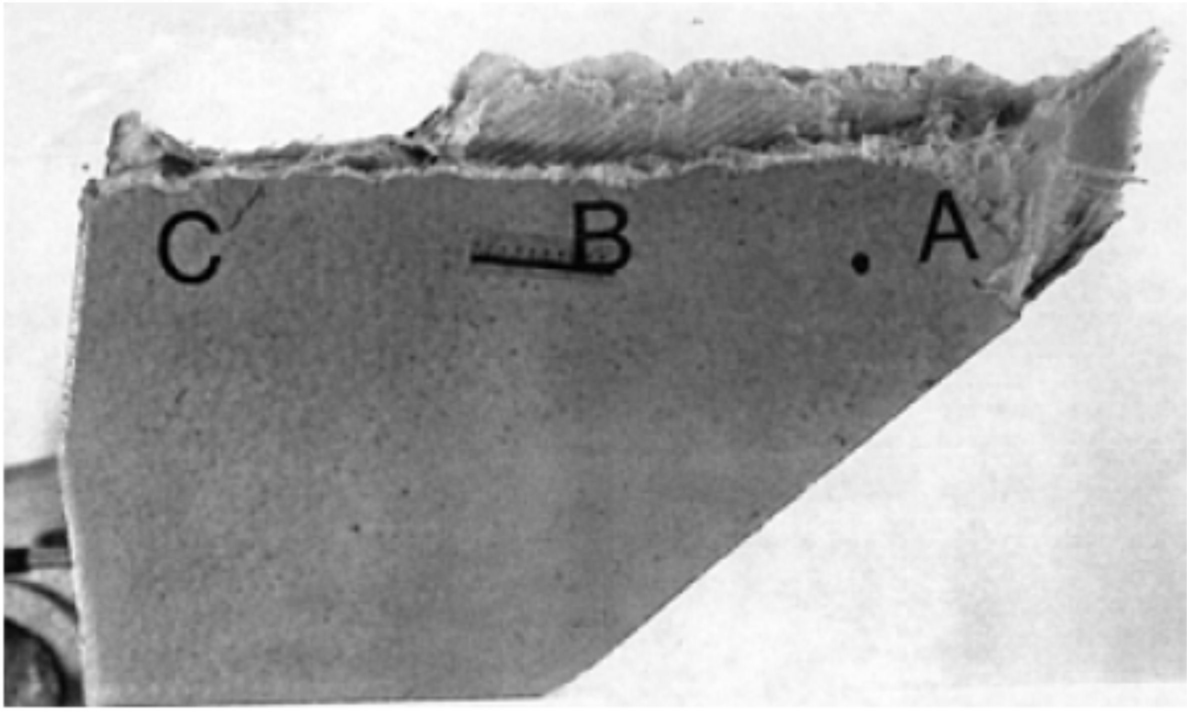


Figure 5-16 - Three different failure modes exhibited on the surface of a fractured, translaminar helicopter rotor blade. A, fatigue initiation; B, translaminar bending; C, fibre crushing during final fracture (ASM, 2001)

This phenomenon can also be identified in localised fractures. The ‘mirror, mist, and hackle’ morphology is one example which can identify crack origin, crack propagation and final fracture zones (Kumar, *et al* 2012). Another example is ‘zoning’ which was recognised during impact damage where visual examination identified that two types of fracture mechanism had occurred on the fracture surface. The first was associated with the impact damage and the second was due to peeling (Hull & Shi, 1993).

5.4 Failure modes

This section continues the survey by presenting the characteristics which are associated with failure mode identification and the effect from different materials and degradation mechanisms.

5.4.1 Tensile Failure

Tensile fracture surfaces of unidirectional materials which have failed in a translaminar plane are typically characterised by a fracture surface that is perpendicular to the direction of the applied load (Stumpff & Snide, 1986; Saliba, 1988; Greenhalgh, 2009). The fracture surface may also appear rough or irregular (Kumar, *et al*, 2012), or shiny with evidence of fibres protruding from the surface (Kar, 1992; Kar 1992a; Greenhalgh, 2009; ASM, 2003a; Ginty & Chamis, 1985; Shikhmanter et al, 1991) (figure 5-17). In the case of woven composite materials, fibre pullout may otherwise be referred to as tow pull-out (Cox, Dadkhah, Morris & Flintoff, 1994).

Glass-fibre has an inherently weak matrix / fibre interface and thus will have greater fibre pull-out. Thermoplastics and toughened matrices too will have a failure exhibiting increased fibre pull-out (Greenhalgh, 2009). Significant fibre pull-out leads to a characteristic fibrous or 'broom-like' fracture feature appearance of the fracture surface.

It has been suggested that a ductile or brittle failure can be distinguished from visual interpretation of the fracture surface. Stumpff and Snide (1986) suggests that a brittle failure is characterised by minimal fibre pullout with fibres at approximately the same length whilst a ductile failure is characterised by significant amounts of fibre pullout with fibre lengths varying widely.

When considering laminates, Greenhalgh (2009) suggests that if the plies have failed on the same plane then the failure is considered brittle with limited secondary damage such as ply splitting or delamination. Greenhalgh (2009) goes on further to state that if the failure has occurred on different planes, and hence undergone substantial secondary damage such as increased ply splitting and delamination, then this may imply a higher fracture toughness and strength. In some instances the tension failure of unidirectional materials has created a catastrophic failure whereby very little of the specimen is left intact (Ginty & Chamis, 1985).

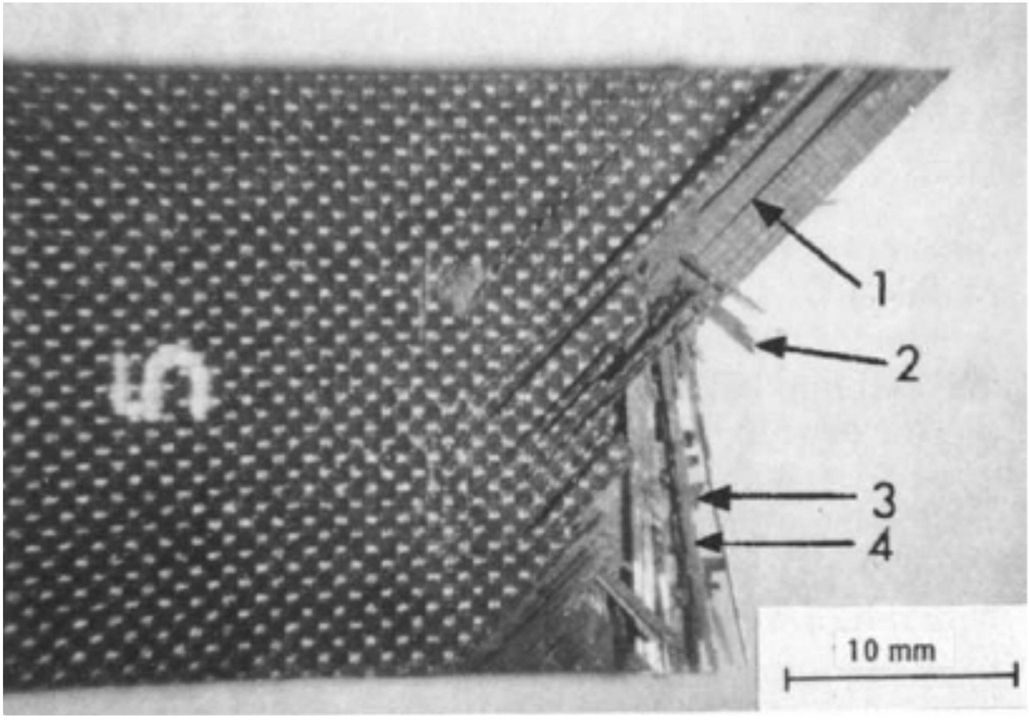


Figure 5-17 – Tensile Fracture of a multi-directional laminate. 1 and 2 – fractures in +/-45° plies, parallel to and through the fibres, respectively; 3 – fracture of fibres in 0° ply; 4 – fracture parallel to fibres in 90° ply. (Shikhmanter et al, 1991)

The degree of fibre pull-out is influenced by the fibre type and the matrix type (and hence is likely to differ between material types) and is strongly dependent on the strength of the fibre-matrix interface (Hull, 1999). A weakening in any one of these constituents, for example due to a degradation mechanism, will change the failure characteristics of that material. Thus, an increased or reduced degree of fibre pull-out relative to a pristine failure can be indicative of degradation within the composite material.

An increase in temperature can decrease the modulus of the matrix and increased moisture has a similar effect. Additionally, moisture ingress can also potentially degrade the interface between the fibres and the resin (Miller & Wingert 1979). Both excessive temperature and high moisture absorption have been shown to reduce the strength of the composite material and upon failure have been shown to increase the degree of fibre brooming (e.g. Miller & Wingert, 1979; Saliba, 1988).

If the fibres have been degraded, as can be the case in stress corrosion cracking of E-glass fibres, the relative strength of the fibre compared to the matrix / fibre interface would reduce (Figure 5-18). Thus a material which would normally have a tensile failure dominated by significant fibre brooming, would instead have the flat fracture surface (Roulin-Moloney, 1989).

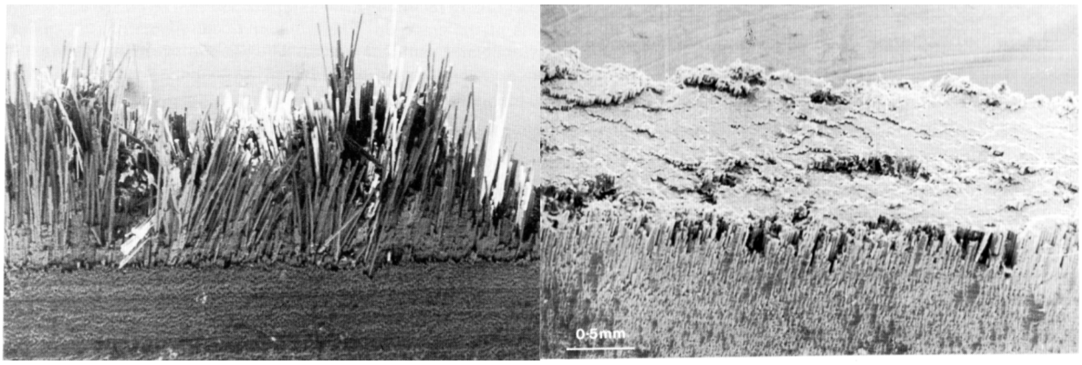


Figure 5-18 – Stress corrosion cracking of E-glass fibres. Image to the left shows a pristine failure and the image to the right shows fracture, of the same material, but under stress corrosion cracking (Roulin-Moloney, 1989).

There are numerous characteristics that can assist the investigator in identifying a tensile failure and the possible degradation mechanisms that have occurred. Whilst features such as geometry and surface appearance can provide information, a significant means to identify tensile failures is through identifying fibre pullout and fibre brooming. As the brooming characteristic is also associated with the bond strength between the fibre and matrix it can also be used to identify failures that may have suffered degradation of the fibre / matrix interface or through premature fibre failure. However, the ability to recognise a failure that has suffered degradation is likely to be subjective as the degree of fibre failure is dependent on the material type. A judgement however may be made through comparison either, to an expectation of the failure features of an identical material, or from a comparative failure of a pristine failure of the same material.

5.4.2 Compression failure

Failure in compression is dependent on the way that the loading is applied and, in particular, on the degree of lateral constraint. It is the matrix which controls the lateral constraint. Hence as the matrix can fail at a load lower than that of the fibres, the compressive strength of the composite in these circumstances can be considerably lower than that of a tensile failure (Purslow, 1981).

If the composite structure is relatively long compared to its lateral cross-section and insufficient lateral constraint is applied, then there will be a tendency for the structure to buckle. If the compression loading is sustained whilst buckling has initiated, then the failure is likely to be a combination of both compressive load and flexural load (Purslow, 1981; Greenhalgh, 2009). The following discussion is focused on the failure characteristics of compressive failures with limited buckling. However, the apparent gross buckling of a composite material can be a significant indication that a compression failure has occurred.

Compression failures in unidirectional composites are typically characterised by fracture surfaces at an angle to the normal plane due to the shear component from compression loading (Purslow, 1981; Purslow, 1988; Franz, 1991; ASM, 2003a). The resultant fracture surfaces undergo rubbing and smearing as the fracture surfaces move across each other (Purslow, 1981; Purslow, 1988) and hence the fracture surface generally has the appearance of a flat, dull/matt surface (Greenhalgh, 2009). Additionally, due to the nature of compression loading, the fracture surface is likely to have indications of secondary damage such as delamination and longitudinal splitting (Saliba, 1988; ASM, 2003a). Multiple failure modes and mechanisms have been described during compression failure, namely; longitudinal splitting (Saliba, 1988; Purslow, 1988; Nakanishi, Hana, Hamada, 1997), shear failure (Nakanishi *et al*, 1996), microbuckling (Vinod, Sunil, Nayaka, Shenoy, Murali, Nafidi, 2010; Saliba, 1988), and delamination (Greenhalgh, 2009) (Figure 5-19).

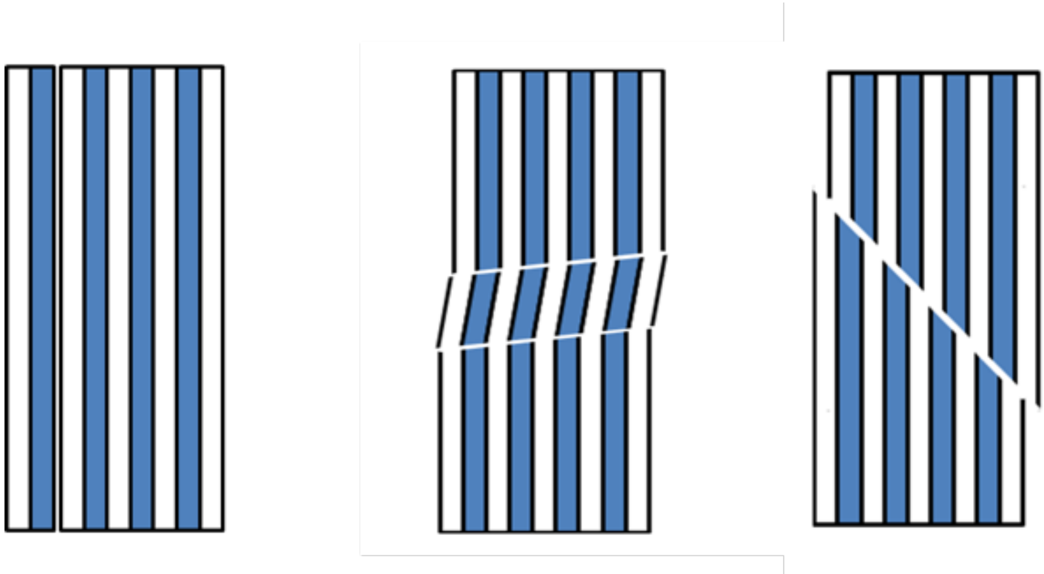


Figure 5-19 – Failure modes under compression loading, a) longitudinal splitting, b) microbuckling, and c) shear failure.

During compression loading, the matrix provides lateral support to the fibres to promote pure compression failure and hence inhibit fibre failure through fibre buckling (known hereafter as microbuckling). If the matrix is successful at inhibiting microbuckling then the expected failure mode will be through shear. In shear failure the fibres fracture due to the shear component of the compression load and hence a higher loading to failure is attained (Purslow 1981). Experimentation found the shear crack to be consistently 30° (Shikhmanter *et al*, 1991) and there is usually limited longitudinal splitting present. In earlier brittle matrix systems, the likely mode of failure would be in shear.

In tougher resins, there is a tendency for the material to fail through microbuckling. The formation of a band or plane of microbuckling is termed a kink band. The kink band failure plane is typically at an angle of 70°-50° to the fibre axis (Purslow, 1988). When a kink band forms with limited delamination, this may promote the formation of a second kink band region which intercepts the existing kink band to form a wedge (Greenhalgh, 2009). A stepped fracture surface may also be apparent (Purslow, 1981; Vinod *et al*, 2010), as are the formation of longitudinal splits.

In unidirectional materials, delamination and longitudinal splitting is typically created by the fracture faces being forced into one another (Greenhalgh, 2009). In multi-directional laminates the creation of delaminations is also promoted by the difference in load carrying capabilities between the load bearing and off-axis plies. Delamination formation separates the plies and hence reduces lateral support promoting local buckling in the load bearing plies (Purslow, 1988). In either case, as the delaminated fracture faces reduce lateral constraint, a characteristic bulge may appear at the region of fracture (Greenhalgh, 2009).

Splitting failure mode is formed when numerous cracks and delaminations form parallel to the loading direction and the material splays out into a coarse broom-like appearance. If the loading is sustained then further delaminating and splitting is likely to occur as the material is forced into itself.

Local buckling is a failure mode noted in sandwich composite skin panels during wreckage investigation research conducted by the NIAR (Tomblin & Ng, 2001). Here it was noted that upper skin panel compression buckling occurred which coincided with foam core failures, due to the positive bending of the wing. Where separation of the wing had occurred, and hence the laminate had suffered peel failures, the ability to identify the skin panel compression buckling had diminished.

It is likely that as a compressive load is applied to a polymer composite laminate, global buckling of the laminate may initiate. When this occurs, the flexural loading encourages delamination of the laminate. The laminate will thus fail under a mixture of compressive failure (such as shear) and local buckling (flexural failure) producing a ‘green stick fracture’ (Tsampas et al, 2012). In this instance the two regions are individually identifiable and suggest that a breakdown in the lateral constraint through delamination preceded the compression fracture.

The tendency for a material to fail under a particular mode is dependent on the constituent properties of the composite (i.e. the properties of the fibre, the matrix and the interface), and is influenced by degradation within the material. When compared to carbon fibres, glass fibres generally have a lower stiffness and a weaker interface (Greenhalgh, 2009). This tends to promote an increase in longitudinal splitting but both microbuckling and shear can occur. Aramid fibres are weak under compressive loading due to the fibrillar construction of the fibres and as such are likely to fail by kinking (Greenhalgh, 2009). Delamination will almost always precede in-plane compression failure.

Similar to tension failures, if a composite system exhibits a failure mode uncharacteristic of the expected mode of failure, then this may be indicative of a degradation mechanism within the matrix or interface.

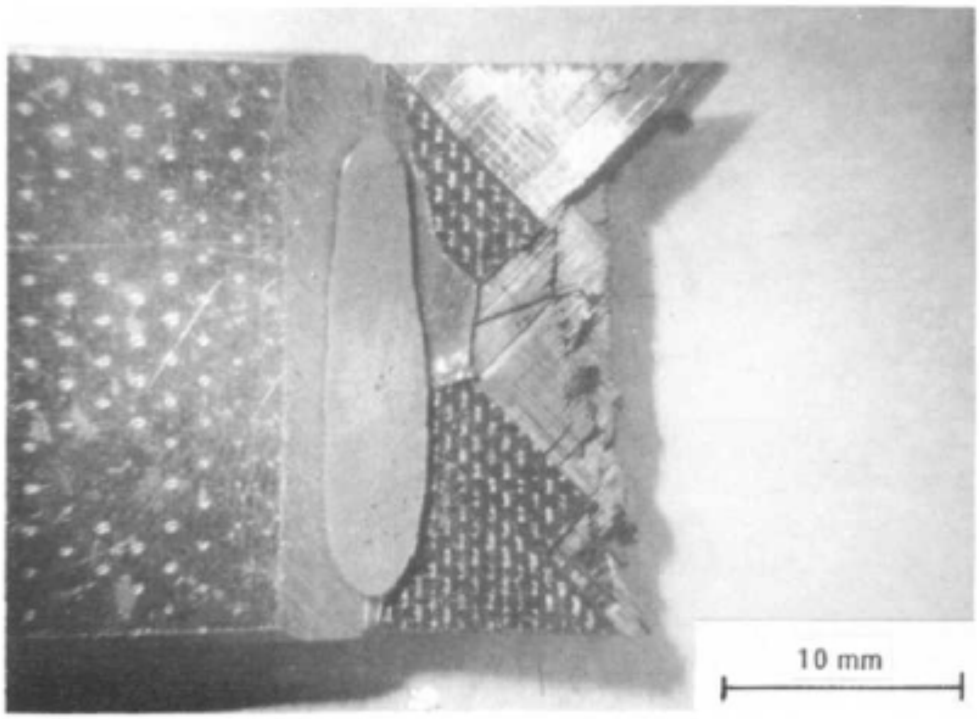


Figure 5-20 – Compressive fracture (Shikhmanter *et al*, 1991)

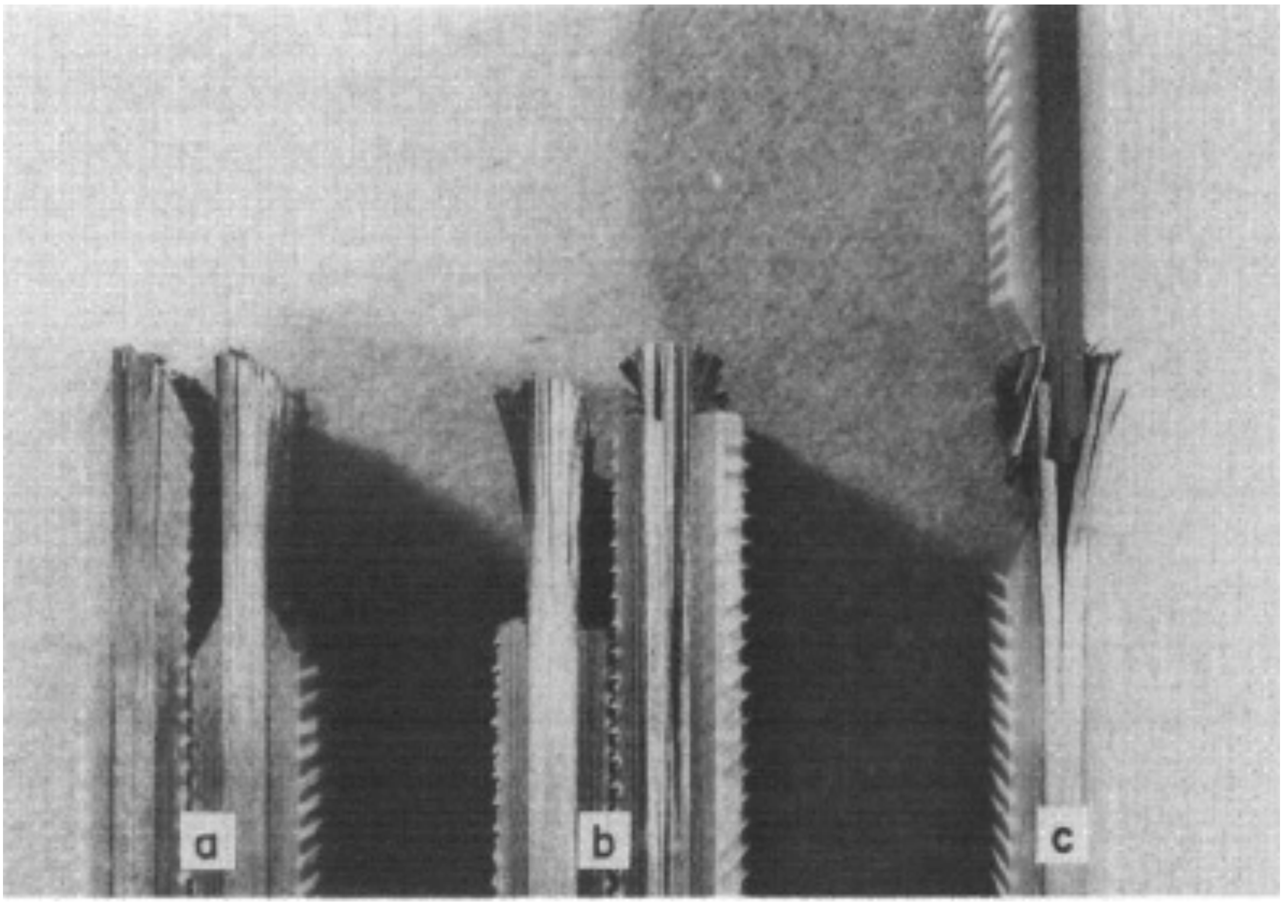


Figure 5-21 – Compressive fracture, a) shear failure, b) microbuckling failure, c) splitting failure (Shikhmanter *et al*, 1991)

5.4.3 Flexural Failures

As a bending load is applied to a structure, a tensile strain will be applied to the convex side of the bending structure and a compression strain is applied to the concave side of the bending structure. As a result, the failure characteristics are those that appear under compression and tension failures (Shikhmanter *et al*, 1991).

Translaminar unidirectional flexural failure of composite laminates generally exhibits both tensile and compressive failure regions on the fracture surface separated by a neutral axis (Dillon, Buggy, 1995). The differences between the two regions are generally visible which in turn allows identification of the neutral axis (ASM, 2003a).

Due to the lower strength of composite materials in compression, the failure usually initiates in compression (Purslow, 1981; Purslow, 1988). However, as the compression surface is usually still capable of carrying load after the initial fracture, the neutral axis has a tendency to remain relatively central across the failure (Purslow, 1981; Purslow, 1988). The relative sizes of the tensile and compression zones can provide an indication as to the type of loading during failure. In the case of a buckling failure, which is failing under a mixture of compression and flexural failure, there is likely to be a larger compression zone to tensile zone (Purslow, 1988; Greenhalgh, 2009). Furthermore, if a stress concentration occurs on the tensile face of the component which initiates tensile failure prior to compression failure, then the fracture face is likely to contain only tensile failure characteristics (Purslow, 1988).

In multi-directional laminates, the flexural loading may instigate delamination prior to translaminar fracture from the shear component. This creates a series of sub-laminates within the composite laminate which will each individually fail in flexure. The resultant visual appearance is a banding across the laminate of alternating compression and tension failure (figure 5-22) (Purslow, 1988; Greenhalgh, 2009).

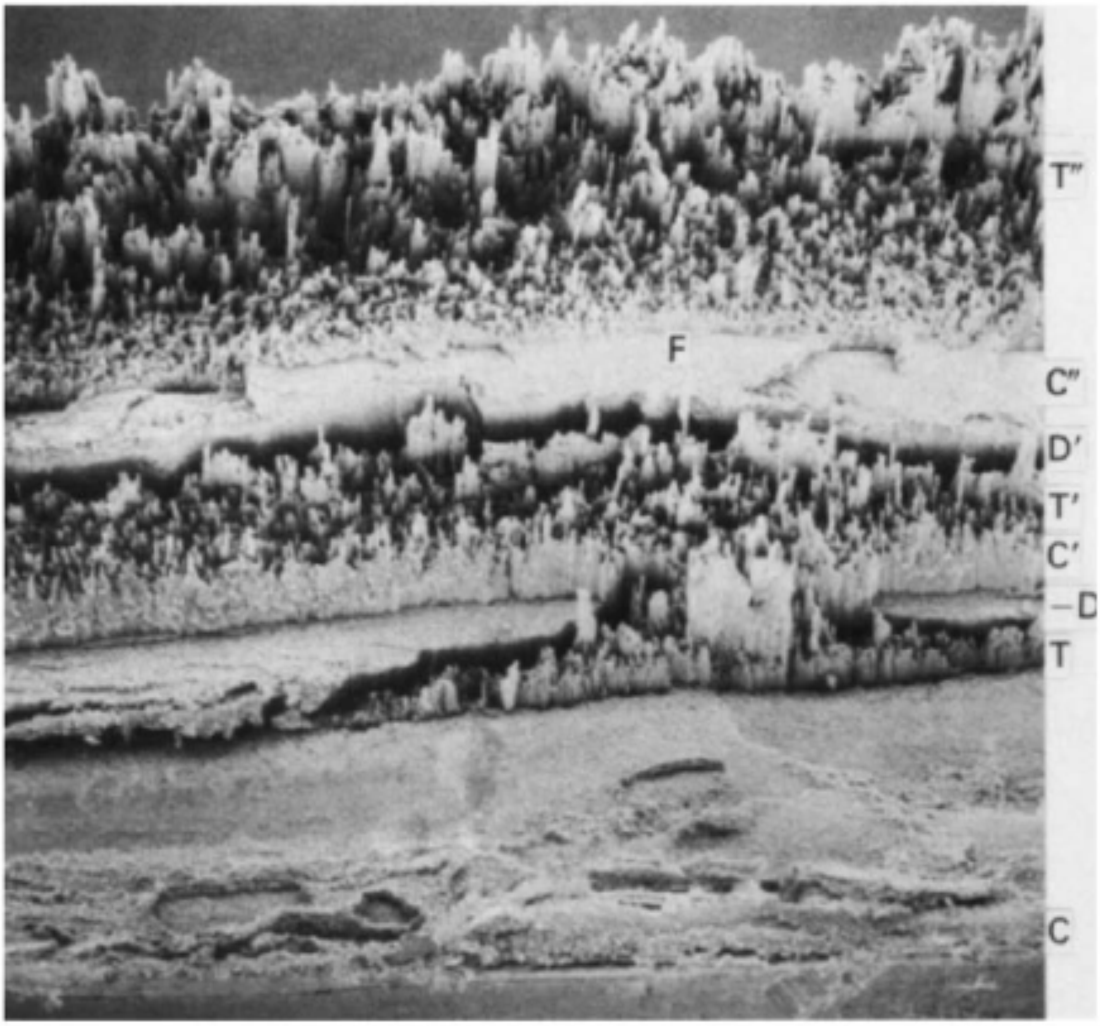


Figure 5-22 – Multiple flexural failures due to delamination ~(x25) (Purslow, 1988a)

5.4.4 Translaminar shear

Upon application of translaminar shear in unidirectional composite materials, the material tends to split longitudinally and thus form extensive splitting prior to translaminar separation (Greenhalgh, 2009). In multidirectional laminates failing under translaminar shear, the 0° ply exhibits a stepped fracture with the step size being approximately equal to the ply thickness (Greenhalgh, 2009).

5.4.5 Peel – Interlaminar Mode I failure

Visually, interlaminar peel fracture surfaces exhibit glossy reflective appearance (Greenhalgh, 2009; Purlsow, 1986; Purlsow, 1987; Purslow, 1984), with some banding and resin covering most of the fibres on the fracture surfaces (ASM, 2003a; Greenhalgh, 2009), and can be less planar than interlaminar shear failures (Purslow, 1986). It is also reported that peel failures of carbon fibre laminates consist of a dark fracture appearance (ASM, 2003; Purslow, 1986; Purslow, 1987) although the tone changes depend on the crack speed with paler regions representing slower crack growth and darker regions suggesting fast crack growth (Greenhalgh, 2009; Purslow 1987). This change in speed may produce visually apparent ribs or bands (Greenhalgh, 2009; ASM, 2003; Purslow, 1986) that can typically be used to determine the propagation direction and fracture origin. It has also been suggested by Greenhalgh (2009) that they may indicate the presence of cyclic loading.

In experimentation using thermoplastic matric composites, Purslow (1987) determined that the surface appearance is influenced by fracture rate, with a relatively slow fracture containing a rough fracture surface and fracture surface becoming smoother with increased fracture rate. The difference being that under slow crack growth, the matrix fractures in a ductile manner with ductile deformation of the matrix occurring, and under fast fracture conditions, the matrix behaves in a brittle manner with limited plasticity occurring.

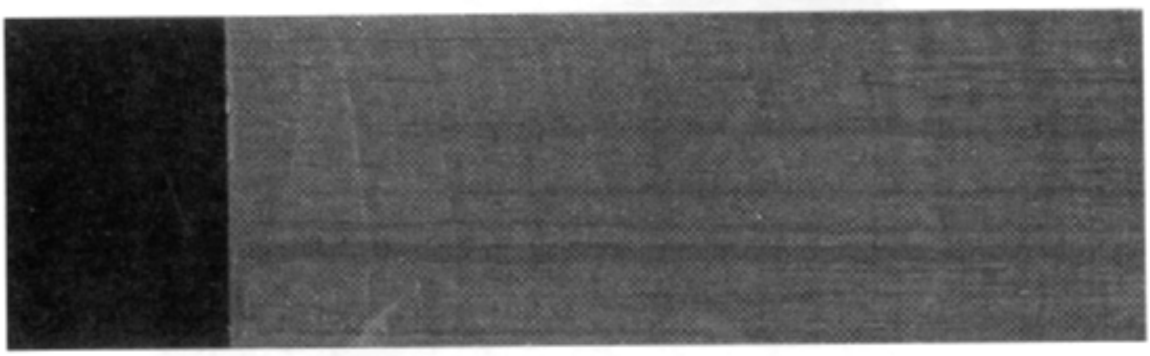


Figure 5-23 - Typical mode I fracture surface from a DCB specimen (x2) (Greenhalgh, 2009)

5.4.6 Shear – Interlaminar Mode II failure

Visually, interlaminar shear fracture surfaces exhibit milky white (ASM, 2003a), dull matt fracture surfaces (ASM, 2003a; Greenhalgh, 2009; Purslow, 1986) that are smooth and non-reflective (Greenhalgh, 2009). It has been suggested by Greenhalgh (2009) that crack propagation direction can be ascertained by identifying the degree of debris on the fracture surface. It is suggested that the initiation point will be the fracture surface that has undergone the most fracture abrasion and thus will have the greater degree of surface rubbing and hence debris. Greenhalgh (2009) goes on further to stress this may prove misleading if the failure has undergone changes in loading throughout the period of crack growth.

Interlaminar shear failure tends to occur and remain in between the laminae and thus has a tendency to remain planar (Purslow, 1986), with the direction of shear strain tending to be aligned with the fibre direction (Purslow, 1981).

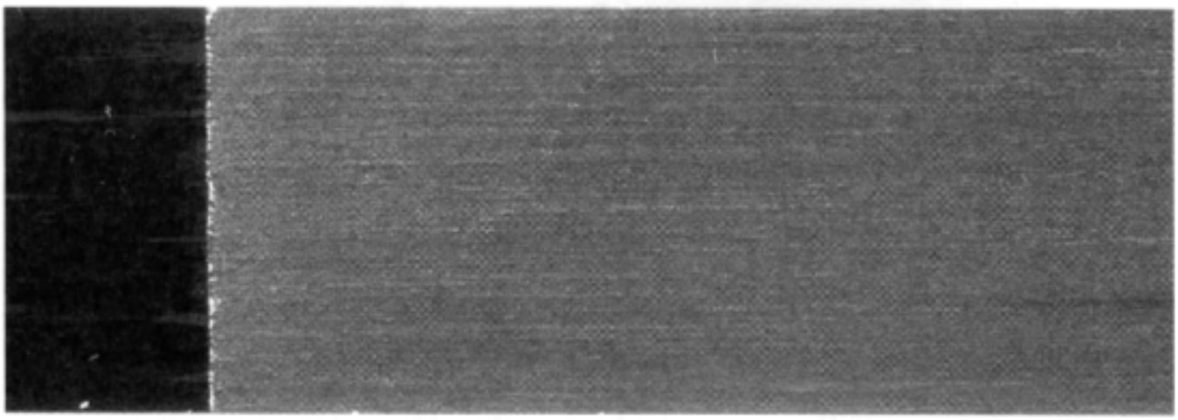


Figure 5-24 - Typical mode II fracture surface from an ENF specimen (x2). (Greenhalgh, 2009)

It has been suggested by ASM (2001) that the differences in appearance between mode I and mode II fractures can be used to identify pre-existing impact damage:

> *"The internal delamination (area surrounded by arrows in the figure [5-25]) resulting from the impact damage exhibits a whitish appearance, whereas the newly separated, Mode I tensile failure had a dark, reflective surface appearance. The differences in reflectivity are thought to be the result of the differences in failure modes, with the impact region in this specimen more representative of a combination of compression and*

Mode II shear failure, and the separated region more indicative of Mode I tensile failure."

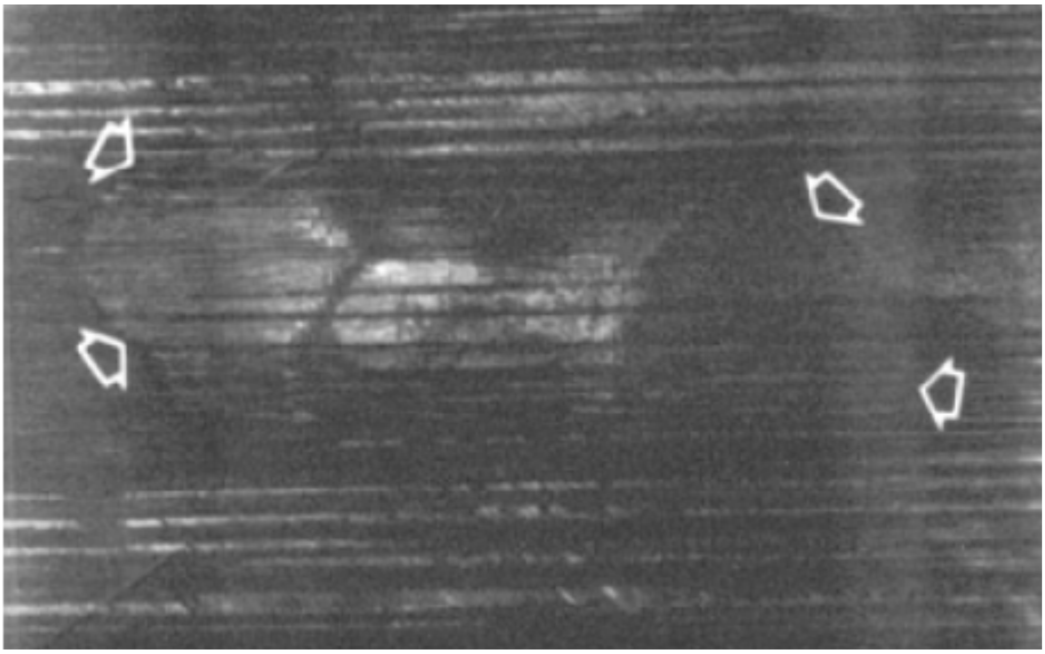


Figure 5-25 - Reflectivity differences on a delaminated fracture surface indicative of the impact damage. ~0.5X (ASM, 2001)

Whilst figure 5-25 demonstrates a pre-existing delamination which is exposed due to subsequent failure, there may be instances where the delaminated surfaces remain concealed. Greenhalgh (2009) suggests that in this instance "lightly pressing the surface to see if it deforms can verify this".

5.4.7 Fatigue

Fatigue is a mechanism which can usually be identified visually or macroscopically in metallic materials. However, fatigue failure in composite materials can appear from a visual and macroscopic perspective as a static failure (Franz, 1991; ASM, 2003a). This results in fatigue failures of composite materials being potentially more difficult to interpret. The mechanism of fatigue is also different between composites and metallic materials. In metallic materials a fatigue failure is usually associated with an initiation site (ASM, 2003a) from which a crack extends through dislocation migration (Greenhalgh, 2009). The crack tip forms a stress concentration. As the crack progresses under different loading conditions, the visually apparent beach marks are formed which represent changes in crack growth.

In the case of polymer composite materials, the above mechanism is not possible due to the amorphous nature of typical resins where, in pristine materials, significant fatigue crack growth is not expected to develop below 60% of static failure stress (Greenhalgh, 2009). Instead, fatigue in polymer composite materials is associated with a number of “sub-critical failure modes, all of which result in a highly diffuse damage zone” (Scheirs, 2000).

It is reasonable to suggest that fatigue in composite structures may occur in regions where environmental factors, damage or pre-existing defects are present, hence introducing higher local stresses.

It is accepted that the only practical means of identifying fatigue is through high magnification examination (Greenhalgh & Hiley, 2009). However table 5-2 illustrates potential changes in visual characteristics that may occur in fatigued components, compared to that of their static failed counterpart.

Category	Limitations	Features	Comments	Source
General features	Opaque materials such as Carbon Fibre	Surface splitting or delamination	Surface splitting or delamination are also likely to occur under static loading	Greenhalgh & Hiley, 2009
General features	Glass fibre with a transparent or semi-opaque resin	Evidence of internal fracture, both delamination and matrix cracking, normally observed as areas of whitening/frosting within the matrix resin and at fibre/matrix interfaces owing to light scattering effects.	The distribution of this damage will vary considerably depending on the lay-up and architecture of the fibre reinforcement.	Trappe & Harbich, 2006; Greenhalgh & Hiley, 2009; Fujii, Shiina, and Okubo, 1994
General features		Presence of defects, stress raisers or pre-existing damage		Greenhalgh & Hiley, 2009
General features		Flatter fracture surface appearance		Lang, Manson, Hertzberg, 1987
Interlaminar / intralaminar (Bulk polymer)	Thermoplastic polymers	Stress whitening		Lang, Manson, Hertzberg, 1987
Interlaminar / intralaminar (Bulk polymer)		Mirror/Mist/Hackle phenomenon		Hertzberg, Manson, 1980
Interlaminar		Beach marks	Can be present under mode I tension and mode II shear fatigue loading	ASM, 2003a
Interlaminar	Mode I failure	Smoother texture and exhibit enhanced reflectivity	With glass fibre reinforced composites, the macroscopic differences between static and fatigue fracture are often even more subtle	Hiley, 1999

Table 5-2 – Fatigue failure characteristics

Category	Limitations	Features	Comments	Source
Interlaminar		Identification of a static / fatigue boundary	Often, the boundary between fatigue (smooth) and static (rough) is quite clear macroscopically	Greenhalgh & Hiley, 2009
Intralaminar	Glass fibre with a transparent or semi-opaque resin	Opaque matrix cracking	Indications of significant increase in matrix cracking	Trappe & Harbich, 2006
Translaminar	Tension-Tension fatigue	Enhanced broom-like features		Kawai, Morishita, Fuzi, Sakurai, and Kemmochi, 1996
Translaminar	Tension-Compression fatigue	reduction in longitudinal splitting, significantly more delaminating	Compared to Tension-Tension failure. Will fail under compressive cycle	Greenhalgh, 2009
Translaminar	Flexural fatigue	Curved compressive fracture face		Dillon & Buggy, 1995
Translaminar	Flexural fatigue in multi-direction composites	Enhanced delamination and longitudinal splitting		Dillon & Buggy, 1995
Translaminar	Flexural fatigue in unidirectional composites	Enhanced fibre brooming on tensile face,		Greenhalgh, 2009
Lightweight aircraft wing structure	Flexural fatigue under spectrum loading and limit loading	Limited whitening/frosting within the semi-opaque GFRP structure. Primary failure mode noted as buckling of the wing shell due to fatigue failure of the foam core in the sandwich.	Wing sections manufactured by Alexander Schleicher GmbH & Co.	Grasse , Trappe, Hickmann, Meister, 2010

Table 5-2 – Fatigue failure characteristics (Continued)

Whilst not a fatigue mechanism, flutter is an aeroelastic cyclic loading which increases in amplitude until the structure fails through overload. There is a paucity of information on recognising flutter failure characteristics but patterns may be similar to those associated with fatigue. ASM (2003) provides an example where:

> *"… numerous small cracks found in the resin of a fractured, graphite-epoxy wing spar. These cracks were visually evident and progressed along the length of the delaminated spar interfaces. Further investigation into the cause of the spar failure revealed that it failed as a result of the wings going into a flutter-failure mode, which then resulted in the extensive, progressive cracking noted along the length of the spar. Further evidence of a dynamic failure such as flutter was found on the transverse fracture surfaces of the spar. The transverse fractures exhibited extensive smearing of the entire fracture surface, a feature not generally found in overload failures of a component."*

5.4.8 Lightning Strike

Damage to aircraft from lightning strikes can result from both 'direct' and 'indirect' (or induced) effects (Rakov & Uman, 2003; AAIB, 1999). Direct effects refer to the physical damage created by the attachment and passage of lightning on the aircraft structure and will be discussed here.

Rupke, (2002) has suggested that the 'direct' effects of lightning on aircraft structures can be split into the following mechanisms:

- Melting or burn-through.
- Resistive heating.
- Magnetic force effects.
- Acoustic shock effects.
- Arcing and sparking at bonds, hinges and joints.
- Ignition of vapours within fuel tanks.

Composite materials will suffer mostly from acoustic shock waves. Rupke (2002) goes on further to suggest:

> *"It should be emphasized, however, that, carbon composites are conductors, albeit resistive conductors. They are therefore subject to the same influences as metal structures, although in different degree. They are, for example, subject to magnetic forces, as well as arcing and sparking at bonds and resistive heating. Non-conductive composites, such as fiberglass and aramid fiber reinforced plastics will be subject to dielectric breakdown and puncture".*

Resistive heating (Fisher & Plumer, 1977; Rupke, 2002), or Joule heating (AAIB, 1999), concerns the increased temperature rise associated with a current flowing through a material of high resistance or of insufficient cross section to carry the current.

Acoustic shock waves and overpressure is associated with the expansion of air heated by the lightning current. The damage to the aircraft results from transfer of the kinetic energy from the expanding air into the aircraft structure (AAIB, 1999). This mode can be recognised by heavy sooting, internal spatter and explosive fragmentation. These modes are especially prominent when the shock wave forms inside an enclosed resistive composite structure (e.g. an aircraft wing) as a result of a lightning strike puncturing the skin and attaching to the internal metallic fittings (e.g. flight control rods) (Fisher & Plumer, 1977).

The following will concentrate on the visual characteristics of lightning attachment and burn-through, highlighting some of the potential visual characteristics that can be seen from both resistive conductors (i.e. carbon fibre and Boron) and non-conductors (i.e. Aramids and Glass Fibre).

Melting or burn-through is concerned with the effects of the lightning arc at locations on the aircraft structure at which the lightning attaches and departs. There are areas, or zones, on the aircraft where the probability and severity of lightning strike damage can be predicted (Robinson, Greenhalgh & Pinho, 2012).

As Carbon fibre and Boron filaments are resistive conductors (Rupke, 2002), upon lightning attachment there is some degree of dissipation of the electrical current and heat along the lengths of the fibres. As the resin is usually non-conductive, the degree of heat dissipation is reduced transverse to the fibres and at plies further from the surface of the laminate. This typically results in elliptical damage patterns with the major axis aligned in the direction of the fibres with the most significant damage occurring on the surface ply (Figure 5-26 & figure 5-27) (Greenhalgh, 2009). There is however electrical arcing between the carbon fibres which creates intralaminar and interlaminar damage to the polymer resin (ASM, 2010a).

At the direct point of lightning attachment, the heating is high enough to melt and vaporise the polymer resin (melting point of resin typically 315°C) scorch and vaporise the fibres (melting point of graphite typically 3735°C) (Fisher & Plumer, 1977; Greenhalgh, 2009). The immediate area around this ‘zone’ contains vaporised polymer resin (ASM, 2010a) and significant delaminations (Fisher & Plumer, 1977). Furthermore, the visual characteristics are highly dependent on particular factors such as the nature of constituents, the architecture, the existence of lightning strike protection, the characteristics of the paint layers and the strength of the lightning strike (ASM, 2010a).

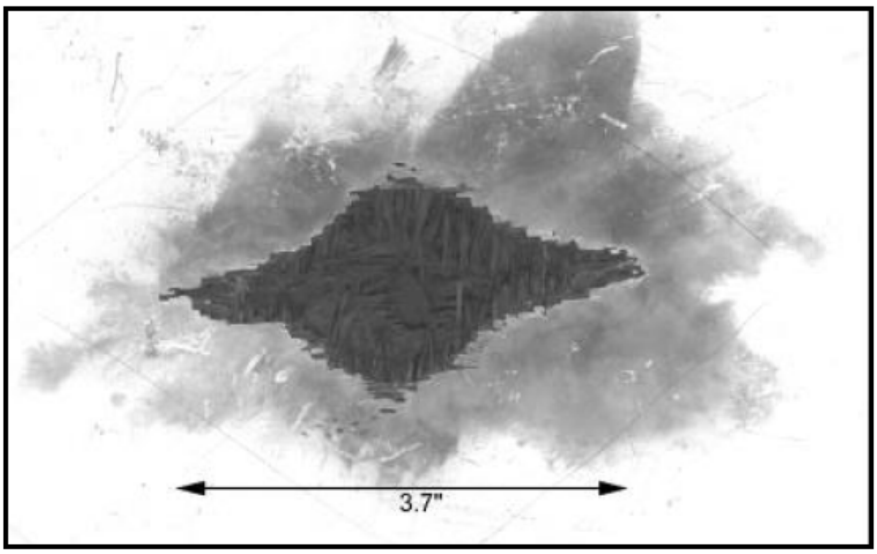


Figure 5-26 - Zone 2A strike to exterior surface of unprotected 4 ply 0.052 in. thick laminate of woven cloth plies (Rupke, 2002)

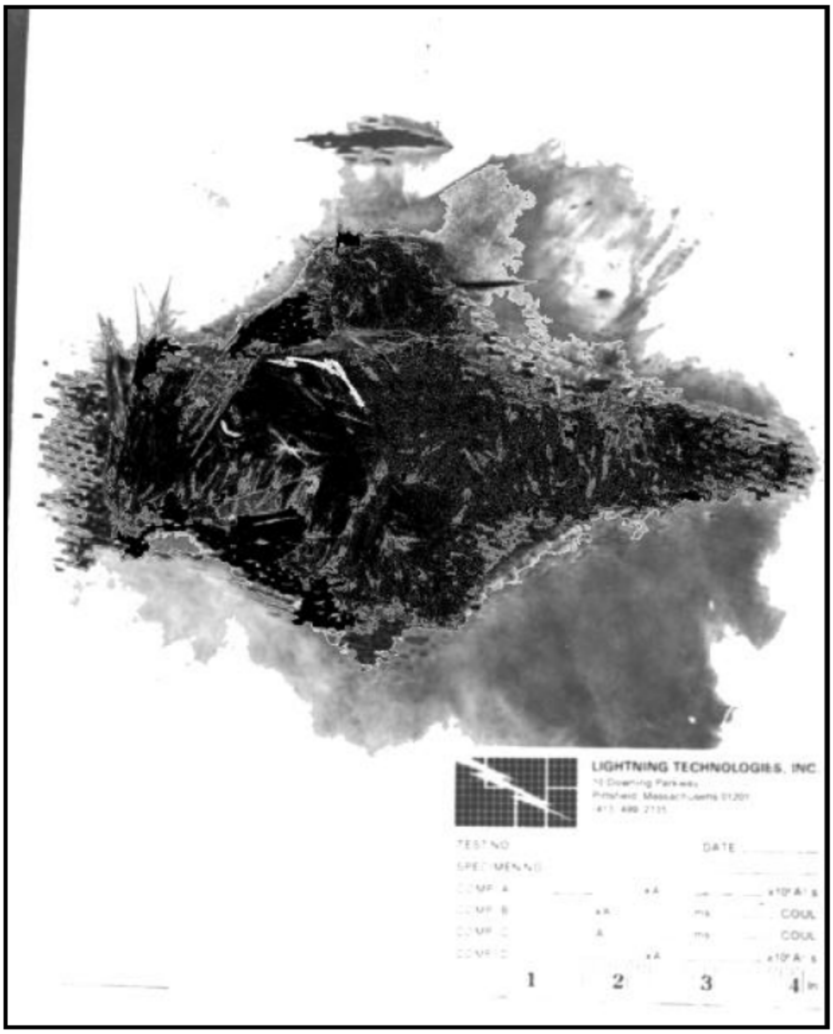


Figure 5-27 – Zone 1A strike to a painted exterior surface of unprotected 4 ply 0.052 in. CFC laminate of woven cloth (Rupke, 2002)

When considering bonded joints, it has been suggested by Fisher & Plumer (1977) that as most adhesives are highly resistive, arcing of current across bonded joints results in the release of sufficient gas pressure to separate the adhesive from the structure. This failure mode was experienced in an investigation of a polymer composite glider by the UK Air Accidents Investigation Branch (AAIB, 1999).

5.4.9 Manufacturing and material defects

One of the most critical aspects of polymer composite materials is their sensitivity to defects (Greenhalgh & Hiley, 2008). A polymer composite material, which is relatively resistant to fatigue, can easily be susceptible to fatigue if a manufacturing defect is present which significantly reduces the structure’s load carrying capability.

A manufacturing defect can be identified in a failure in a number of ways. Firstly, the failure may be apparent on the translaminar fracture surface (Greenhalgh & Hiley, 2008). Secondly, the defect may be obvious in the area surrounding the fracture (such as discoloration). Finally, it is possible that the manufacturing defect influences the failure mechanism (Greenhalgh & Hiley, 2003).

Whilst it is out of the scope of this survey to cover all types and degrees of manufacturing defect, the significant forms are identified in table 5-3. The defect is highlighted in the first column and an introduction to the defect and possible visual features are discussed in the second column.

Defect	Potential effects and visual and macroscopic characteristics
Interlaminar voids / inclusions	Large voids can cause gross deformation of the structure (bulging), which may be identified through pressing on the area. (Greenhalgh, 2009).
Fibre waviness	For 0° ply waviness in [0, 45, 90,–45]2S laminate, static strength reduction is 10% for slight waviness and 25% for extreme waviness. Fatigue life is reduced at least by a factor of 10 (ASM, 2001). Can be classified as in-plane and out-of-plane waviness (Joyce & Moon, 1999; Greenhalgh, 2009). Visually, the fibre waviness may influence the buckling resistance of the composite structure and hence premature global buckling may be induced (Hsaio & Daniels, 1996)
Porosity	Degrades matrix-dominated properties. 1% porosity reduces strength by 5% and fatigue life by 50% (ASM, 2003).
Surface notches	Static strength reduction of up to 50%. Strength reduction is small for notch sizes that are expected in service. Incorrect drilling speeds can introduce delaminations, splitting and scorching around the hole. (Greenhalgh, 2009)
Thermal overexposure	Embrittlement and reduction of toughness up to complete loss of structural integrity (ASM, 2003)
Thermal underexposure	Excessive ductility of the matrix (Astrom, 1997). Increased fibre bridging on intralaminar mode I surface. Delamination dominated failure on translaminar tension. Rapid cooling of thermoplastics post cure also results in over ductile matrices. (El Kadi & Denault, 2001)
Low fibre volume fraction	Typical fibre volume fraction is 65% (Purslow, 1983). In areas where there is low fibre volume fraction (resin rich areas), the local stiffness and strength will reduce thus creating potential failure initiation sites. Resin rich areas can behave like bulk polymers and thus can have visual failure characteristics. (Greenhalgh, 2009)
High fibre volume fraction	In areas where there is high fibre volume fraction (resin starved regions). Translaminar failures will tend to exhibit an increased degree of fibre/matrix debonding, such as brooming (Williams & Rhodes, 1982)
Contamination and inclusions	When they are large, they will act as stress concentrations, promoting failure under most loading conditions and lowering the toughness of the material (Greenhalgh, 2009)
Poor fibre / matrix bonding	From a macroscopic perspective, poor fibre/matrix bond strength is often associated with brush-like failures (Greenhalgh, 2009). Reduction in delamination resistance, particularly under mode II loading (Greenhalgh, 2009), increased longitudinal splitting under cyclic loading, reducing fatigue life (Greenhalgh, 2009) and fibre splinters in mode I peel (ASM, 2003a).

Table 5-3 – manufacturing defects and potential visual characteristics

5.4.10 Environmental effects

The effects of environmental degradation on aircraft structures are well known and have been a cause of many accidents (Findlay & Harrison, 2002). Historically, as aircraft structures have been predominantly constructed using metals, the experience and knowledge on understanding and identifying corrosion has advanced. Composites, whilst generally having a better tolerance to environmental degradation, are still susceptible to degradation and the types of degradation mechanisms can be significantly different to those of metals.

Environmental effects on composites have the ability to reduce the load carrying capacity of the structure and also to alter the fracture characteristics. The ability to identify the change in characteristics and link them to degradation mechanisms may give investigators clues as to the presence of material degradation in a failed composite structure.

Whilst composite materials have a reputation as having excellent resistance to environmental effects (Armstrong *et al*, 2005), conditions of environmental extremes have been shown to significantly reduce their overall strength (Kar, 1992c; Ginty & Chamis, 1985). In general, an increase in exposure time or increase in severity typically results in decreasing mechanical performance and increasing visual extent of the degrading mechanism (Greenhalgh, 2009). As a result of this, evidence of the degrading mechanism may only be visually or macroscopically evident under severe conditions.

Significant environmental conditions that have been discussed in literature include: exposure to corrosive environments, submersion in water, exposure to moisture, change in temperature, and long-term physical and chemical stability (Harris, 1999). The effect that each of these mechanisms has on composite materials has been researched extensively as have the effects of combined mechanisms, e.g. hygrothermal effects.

Historically, the understanding of the effects on composite materials following exposure to corrosive environments has not been of significant concern as epoxy composite materials have shown resistance to typical service-related fluids which are basic in nature (e.g. hydraulic fluids, fuels, etc) (DoD, 2002). Epoxy resins do however suffer from accelerated aging under the presence of highly acidic fluids and as such manufacturers may restrict the use of certain cleaning solvents on aircraft (e.g. Schempp-Hirth, 1982). Furthermore there are occasions where basic service fluids may react with water to form acidic fluids and thus pose a risk to the epoxy material. In conducting the investigation into the in-flight separation of the rudder on Air Transat flight 961 (TSB, 2005), phosphoric acid was identified to have formed when hydraulic fluid mixed with atmospheric water. It was identified that the phosphoric acid had attacked the epoxy resin of a similar aircraft creating irreversible damage to the core/face sheet interface through weakening of the bond.

Some thermoplastic resin systems, although they have excellent resistance to moisture and hydraulic oils, have poorer resistance to fuels. In the case of PEEK, fuel exposure can lower the material's glass transition temperature and hence reduce the capability to withstand high temperature (DoD, 2002).

Although in general, it is the matrix properties which are degraded by such contaminants, environmental factors may also cause degradation of the fibres. Carbon, boron, and other ceramic reinforcements are highly resistant to all but the most highly oxidising acids and only become affected by temperatures elevated in excess of that which the matrix can withstand. Others, particularly glass and aramid fibres, can be significantly affected even at low exposure levels of water or acidic environments (Harris, 1999). Environmental stress corrosion cracking is one example of a mechanism which creates premature failure through degradation of glass fibres (Roulin-Moloney, 1989).

Perhaps the most prominent visual cues of environmental degradation are gross changes in colour or physical appearance. Tests involving adhesive specimens immersed in jet fuel, anti-icing fluid and hydraulic fluid over a prolonged period in heightened temperatures have shown progressive changes in colour and visible swelling (Sugita, Winkelmann, & La Saponara, 2010). Swelling of the matrix was also noted during testing under immersion in various aqueous media (Kishore & Maiti, 2001). Furthermore, evidence of thermal degradation can also be manifested as paint discolouration, blistering at the surface and charring (Greenhalgh, 2009).

Ginty & Chamis, (1985) in reporting on the fracturing of over-aged carbon fibre specimens, reported on a black greasy residue being indicative of chemical degradation in the matrix system:

> *"One other point worth mentioning is that the physical handling of these fractured $[\pm\theta_2]_s$ overaged laminates resulted in a black greasy residue on the skin. The authors have never observed this before even though hundreds of graphite/epoxy specimens have been handled. This is apparently indicative of a chemical breakdown of the old resin and is an additional characteristic of an overaged prepreg."*

Physical change in the material may also be evident if exposure to high temperature is severe enough. In the case of thermoplastic resins systems, the matrix will become excessively soft leading to gross deformation of the structure and internal movement of the fibres within the matrix leading to increased voidage and inhomogeneous resin distribution (Greenhalgh, 2009). This in turn will lead to a reduction in the matrix dominated properties such as in compression.

As a general rule, when attempting to identify potential environmental degrading mechanisms, the best approach is to compare the suspect fracture surfaces with those from materials which have failed in a similar manner and which are known not to have been subject to environmental degradation (Kar, 1992; ASM, 2003a). Typically, the influence of gross environmental degradation may be identified through visual interpretation (Kar, 1992), but identifying discrete degradation, the type of environmental condition and the severity of the particular degrading factor can be difficult (Greenhalgh, 2009). Furthermore, environmental extremes at fracture tend to be more visually pronounced in the fracture features of translaminar fractures rather than interlaminar fractures (Kar, 1992).

Environmental degradation typically involves a reduction in the strength of the fibre / matrix bond (Greenhalgh, 2009; ASM, 2003a). This subsequently promotes longitudinal splitting failure under tension loading, and delamination failure under compression loading (Greenhalgh, 2009). Translaminar fracture surfaces generated under tension loading exhibit a greater degree of longitudinal splitting and hence may present a visually apparent increase in fibre brooming. This has been reported under conditions such as moisture (Greenhalgh, 2009), increased temperature (Stumpff and Snide, 1986) and under combined hot and wet conditions (Kar, 1992). The effect of temperature is usually only apparent when the temperature exceeds one half of the glass transition temperature (Kar, 1992, ASM, 2003a) or when there are high levels of moisture absorption (ASM, 2003a). Conversely, when tensile failure occurs at low temperatures, the fracture surface is typically brittle and flat in appearance (Greenhalgh, 2009).

Under compression loading the effect of environmental degradation is particularly damaging to the material's performance. As previously noted, under conditions of high temperature and high moisture absorption, the matrix suffers from reduced fibre / matrix strength, the matrix softens and becomes more ductile. This promotes failure through global instability, local instability (kinkband formation) or excessive degradation of the fibre/matrix interface leading to green stick fracture (Kar, 1992c). Which failure occurs preferentially depends on the relative degradation in matrix stiffness and that of the fibre / matrix interface (Greenhalgh, 2009).

Under flexural loading the failure mechanism tends to change under increased temperature. Whist the failure at low temperatures tends to be dominated by translaminar fracture, failure at increased temperature tends to change through increased delamination. This is due to the reduced mode II shear performance of the laminate at elevated temperatures (Stumpff & Snide, 1986).

In the case of glass fibre reinforced composites Environmental Stress Corrosion Cracking (ESCC) can manifest from exposure to a corrosive environment and an applied stress. The corrosive environment can be water, acidic or alkaline with the effect being increased in the presence of alkaline or acidic media (Harris, 1999). The failure occurs from the point of a stress raiser which is exposed to a degrading environment (Roulin-Moloney, 1989).

It has been highlighted by Roulin-Moloney, (1989) that the main features of this failure mode are:

1. *An acidic environment is present*

2. *Failure occurs at low applied loads*

3. *Fracture appears to propagate from a stress raiser*

4. *Fracture surfaces are planar in the region of the stress raiser*

The degree of degradation is dependent on the level of applied stress and the time of exposure to the corrosive environment, so too are the failure characteristics. With low stress the fracture surface can be very planar with limited fibre pullout occurring. As the stress is increased, the extent of fibre / matrix debonding increases leading to an increasing proportion of out of plane failure occurring (Hull, 1999). The fracture then tends to appear visually as a stepped surface. Increasing the stress further, increases the degree of fibre matrix failure and hence the degree of fibre pullout increases substantially (Greenhalgh, 2009).

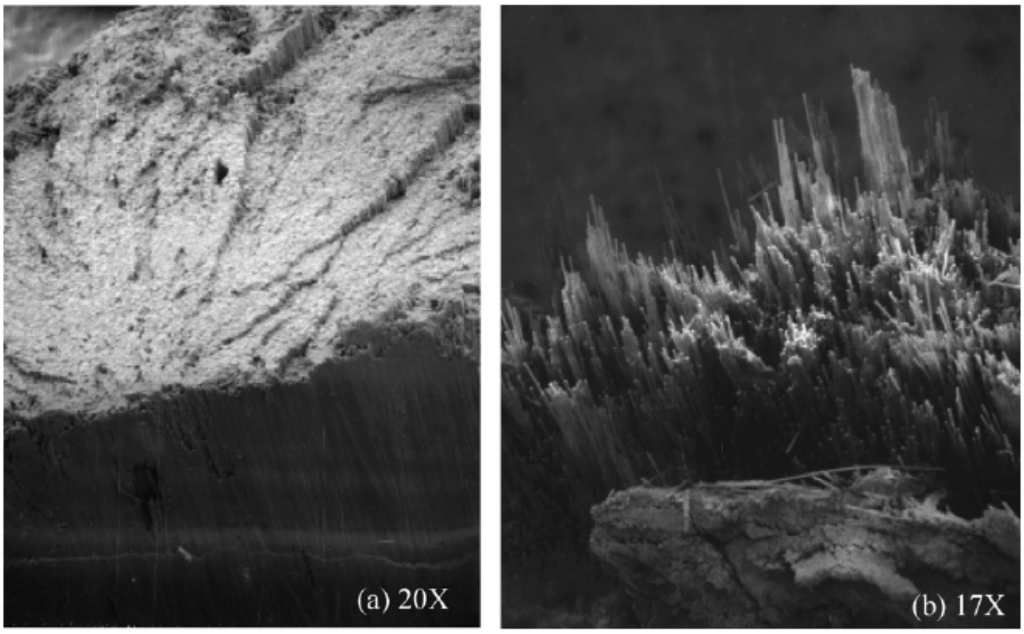


Figure 5-28 – The effect of ESCC on fracture surfaces *(a) ESCC fracture surface of a failed beam in an FRP grating. (b) pristine grating beam that was mechanically overloaded* (Myers, Kytömaa & Smith, 2007)

5.4.11 Impact

The post-impact plastic deformation of a metallic structure can be used by investigators to qualitatively understand the size, shape and energy of the impactor (Rakow & Pettinger, 2007). In contrast however, composite materials absorb energy either elastically or through damage accumulation with little energy absorbed through plastic deformation.

When considering impact damage to composite materials it is typically categorised as low velocity, high velocity or hyper velocity impact (Richardson & Wisheart, 1996). However, other categories do exist such as medium velocity impact (Greenhalgh, 2009). This segregation is traditionally based on the different structural responses and subsequent damage states. Bibo & Hogg, (1996) state that under low velocity loading the contact time is relatively long and the response is global thus the structure's geometry determines the energy absorbing failure mechanisms. Whereas, in high velocity impacts, the laminate is unable to respond globally but rather responds locally to the area of impact and thus the local damage is likely to be more severe. An alternative definition however has been suggested by Davies & Olsson (2004), which concerns the impactor mass / plate mass ratios. In this instance the structural response of the laminate is differentiated between a 'small mass impact' and a 'large mass impact'.

The definition of a low velocity impact typically encompasses events such as hail strike, ground handling related damage, maintenance related damage and runway debris damage (ASM, 2010). As mentioned above, these impact events will be characterised by similar structural responses and subsequent damage states. However, the impact damage mechanisms are also influenced by the interaction between the local indentation created by the impactor, and the global deflection of the laminate (Robinson, Greenhalgh, and Pinho, 2012). For example, when the laminate back face is supported or when the effect of global deflection is negligible, pure indentation damage will be observed (Robinson *et al*, 2012).

Low velocity impacts can be the most serious in nature for brittle composites as they have a limited means of energy absorption through permanent deformation or significant indentation, and hence the damage accrued may be hidden. Moreover, it is likely that the laminate will suffer significant internal damage in the form of fibre damage, matrix cracking and delamination as a result of the excessive laminate deflection, with the laminate returning to its original plane leaving limited evidence of impact (Greenhalgh, 2009). This event is known as BVID (Barely Visible Impact Damage) which although may visually appear benign, can reduce the laminate strength in compression by as much as 70% (Davies & Olsson, 2004).

Although low velocity impact damage can be created by a variety of circumstances, the macroscopic appearance is typically unique compared to other defects or failure modes (Greenhalgh, 2009).

Visually identifiable evidence of a low velocity having occurred includes 'back face splitting' occurring on the back face of the laminate, and indentation damage occurring at the site of impact. Back face splitting damage typically involves the intralaminar splitting of the rear facing laminate, due to high membrane stresses during bending (Richardson & Wisheart, 1996), with the laminate delaminating and protruding from the face of the laminate. The mechanism has been mentioned as a visual identifying feature by numerous researchers such as: Bucinell, (1999); David-West, Nash & Banks, (2008); Walker, Sohn & Hu, (2002); and Schoeppner & Abrate, (2000). Indentation, or front face damage, typically involves a depressed region indicating matrix crushing and local fibre breakage (Schoeppner & Abrate, 2000). It should be noted, especially in the case of the back face splitting, that should the laminate fracture transversely and subsequently separate, the visual identifying features may be lessened.

A mechanism which may assist in identifying the existence of impact damage, especially in the case of BVID, relates to the mechanism of compression cracking as discussed in section 5.4.4. In Figure 5-9, which demonstrates the compression failure of a laminate which has been impacted, the transverse fracture is seen to intercept the impact region at the lower extent of delamination and then circumvent the impact area to the upper most section of the impact area. Greenhalgh (1989), in discussing delamination growth in carbon fibre laminates under compression, suggests that the primary transverse failure occurred internal to the laminate at the maximum deflection of the surface plies. The visible surface translaminar cracking occurred at the boundary of the delamination growth and intercepted the primary fracture internal to the laminate. Thus following translaminar separation of the laminate, the impacted surface of the laminate is likely to show the fracture extending around the circumference of the impact site.

Internally, the laminate is likely to have suffered significant matrix cracking, delamination and fibre fracture (Robinson *et al*, 2012). Where the laminate has been free to flex globally, the dominant internal stress is associated with that created during flexure of the laminate (Bibo & Hogg, 1996). Consequently, the delaminated region created by the impact, is dominated by mode II shear failure and fibre fracture due to impactor contact and excessive membrane stresses (Davies & Olsson, 2004).

Unlike in opaque composites such as carbon fibre, in transparent and semi-opaque composites such as glass fibre and aramid fibre composites, the otherwise hidden interior damage is usually visibly evident as a whitening / frosting within the laminate (Greenhalgh, 2009). If the interior delaminated surfaces are visible then there are additional features which may suggest the area has been subject to an impact. Visually, the interlaminar fracture surfaces of the impact region will exhibit more evidence of mode II failure, whilst the subsequent delamination is likely to consist of primary mode I failure (ASM, 2003a). The shape of the mode II region may also be indicative of an impact event. The delaminations are usually 'peanut shaped', extending parallel to the fibres of the lower ply, are typically between plies of different orientation and of increasing size for increasing changes in ply angle (Davies & Olsson, 2004; Hull & Shi, 1993). The peanut-shaped impact region may also exhibit considerably more matrix debris compared to the surrounding area (ASM, 2003a).

Typically, as velocity is increased, the laminate has less ability to respond through global flexure and hence the impact damage becomes more localised (Greenhalgh, 2009). When the velocity is high enough, penetration of the laminate occurs with the impact area characterised by gross localised damage and fibre fracture, with reduced delamination and splitting occurring outside of the impact area (Greenhalgh, 2009).

The damage state also increases as impact energy is increased. Under low energy impacts, the failure mechanism is dominated by ply splitting. Delaminations then form from these ply splits. As energy is increased, the number of splits and delaminations increases until the energy has increased to a level which can initiate fibre fracture. As the energy is increased further, fibre fracture at the point of impact dominates leading to the penetration of the laminate (Greenhalgh, 2009).

The extent of damage generated on the structure can be influenced by numerous factors. These in turn will vary the damage characteristics and hence the visual interpretation and understanding of the impact event. The most significant of which are the material form, the fibre and matrix types, the architecture of the laminate, the architecture of the structure, and the loading conditions at time of impact.

So far the discussion has focussed on impact on monolithic structures, particularly on laminates. When considering impact to sandwich structures, the laminate face sheets will involve the same damage features as in plain monolithic laminates, although the impact damage will be more localised. Invariably however, core crushing is likely to be observed with the possibility of the face sheet being deformed into the area of core crushing, or the face sheet reflecting back leaving a void in the space of core crushing (Olsson, 2002).

Woven fabric laminates have a better damage tolerance to impact than angle-ply unidirectional tape laminates due to the higher toughness inherent with the woven architecture (Kim & Sham, 2000). Furthermore, the impact region of delamination is characterised by a star shape, rather than a peanut shape, with the points lying on the warp and weft strand directions (Kim & Sham, 2000). The increased damage tolerance to impact is also apparent in toughened matrix systems such as those found in thermoplastic resins.

5.4.12 Bonded Joints

Composite components can either be combined prior to cure to create a detailed monolithic structure, assembled using secondary bonding (Campbell, 2010), mechanical fastened, or both bonding and mechanical fastening (Sugita, Winkelmann & La Saponara, 2010). As there is a strong reliance on adhesive bonding use in general aviation aircraft manufacturing (Van Rijn, 2000), it will be included within the scope of the survey.

Visually apparent changes or variations from the original adhesive colour can be indicative of degradation. In particular it may indicate moisture absorption, undercure, overheating or, in the case of semi-opaque and transparent adhesives, extreme cases of porosity or indications as to the depth of adhesive (ASM, 2001).

The geometric failure of the adhesive bond may also provide an indication as to the relative strength of the bonded joint. Davis and Tomblin (2007) suggest three basic failure modes within adhesive bonds, namely:

- Failure within the adherend – This involves failure of the composite material which is being bonded to and thus from the perspective of the adhesive, the bond is stronger relative to the materials being bonded together.
- Cohesive failure – This involves failure within the adhesive and thus suggests that the strength capabilities of the adhesive have been exceeded. In this situation the adhesive is relatively weaker compared to the adherend.
- Adhesion failure – This involves failure of the interface between the adhesive and the adherend. This suggests an inadequate bond has been achieved between the adhesive and the bond. This typically corresponds with failure loads substantially below the design strength.

These three failure modes are typical to both bonded joints and bonded repairs. Further failure modes have been presented including oscillatory, alternating and mixed (figure 5-29) (da Silva, Öchsner, Adams, 2011; Chen and Dillard 2001).

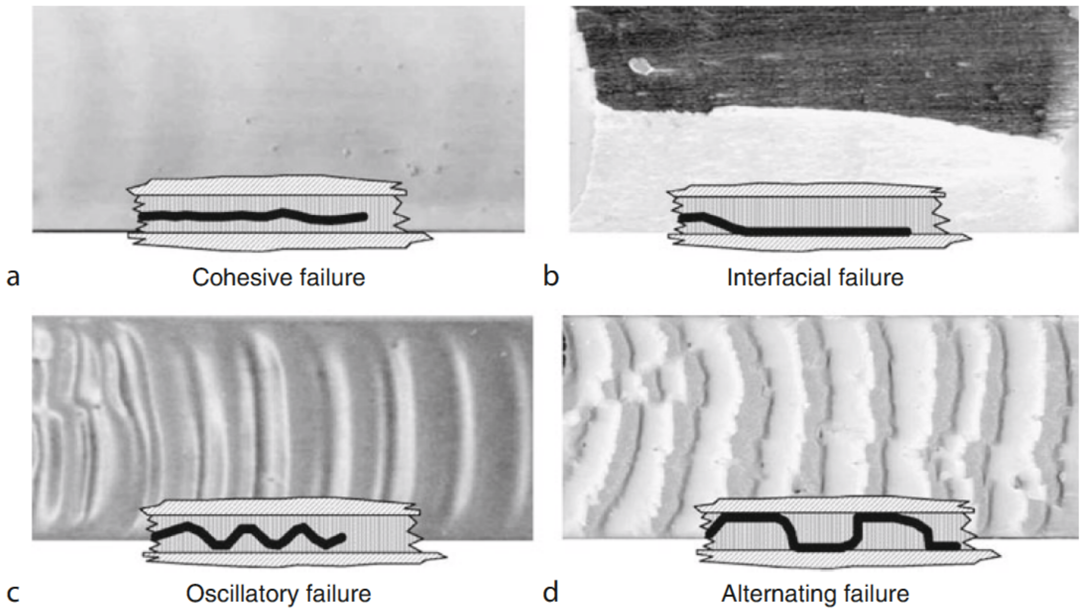


Figure 5-29 – Bonding failure mechanisms (Chen and Dillard, 2001)

Adhesion failures are characterised by the adhesive separating from the adherend at the interfacial bonding line. The failure occurs due to hydration of the chemical bonds which form the link between the adhesive and the adherend surface (Davis & Bond, 1999).

It is suggested by Davis & Tomblin (2007) that adhesion failures are generated in three ways.

- Contamination of the bonding surfaces which prevents the formation of a chemical bond
- Insufficient surface preparation that results in an insufficient chemically active surface which is resistant to hydration, or
- The adhesive had cured before the formation of the bond.

Visually, surfaces that have separated due to adhesion failure may be characterised by smooth glossy surfaces which at higher magnification may show little evidence of deformation. This visual cue may be indicative of poor surface preparation prior to application of the adhesive and hence poor bonding between the adherend and the adhesive (ASM, 2001). The adherend may also show an absence of residing adhesive, confirming that an adhesion failure occurred with poor chemical bonding. Areas of the adherend which provide sudden geometrical changes in the adhesive can also be used to identify premature adhesion failure. Davis & Bond, (1999) provide an example where serial numbers have been visible in the adhesive, again suggesting that adhesion failure had occurred with the adhesive separating from the adherend at the interface. da Silva, Öchsner, Adams, (2011) presents an example where the adherends were cured many months prior to bonding. During this period the laminate had absorbed moisture. When the adhesive was applied to the pre-cured laminates, the heat from the bonding process drove the moisture to the laminate surface and thus significantly degraded the bond strength. The bond failed (having passed quality control inspections) leaving a perfect replica of the original peel ply (figure 5-30).

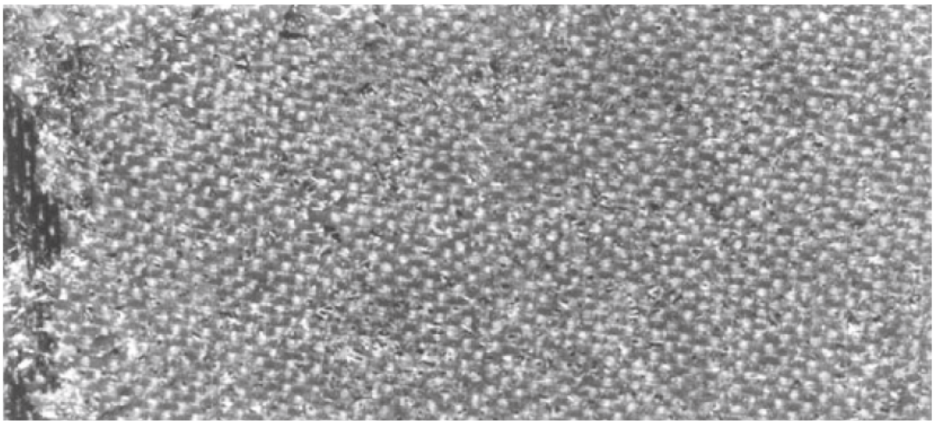


Figure 5-30 – Peel-ply imprint left by the failure of an adhesive to bond to a composite surface, ~10x magnification (da Silva, Öchsner, Adams, 2011)

Conversely, a lack of such detail on the adhesive surface can indicate that insufficient adhesive or pressure was applied during assembly and as such the adhesive and the adherend were not mated. This will leave a smooth surface with an apparent lack of a fingerprint on the adhesive of the adherend (Figure. 5-31) (BFU, 2006).

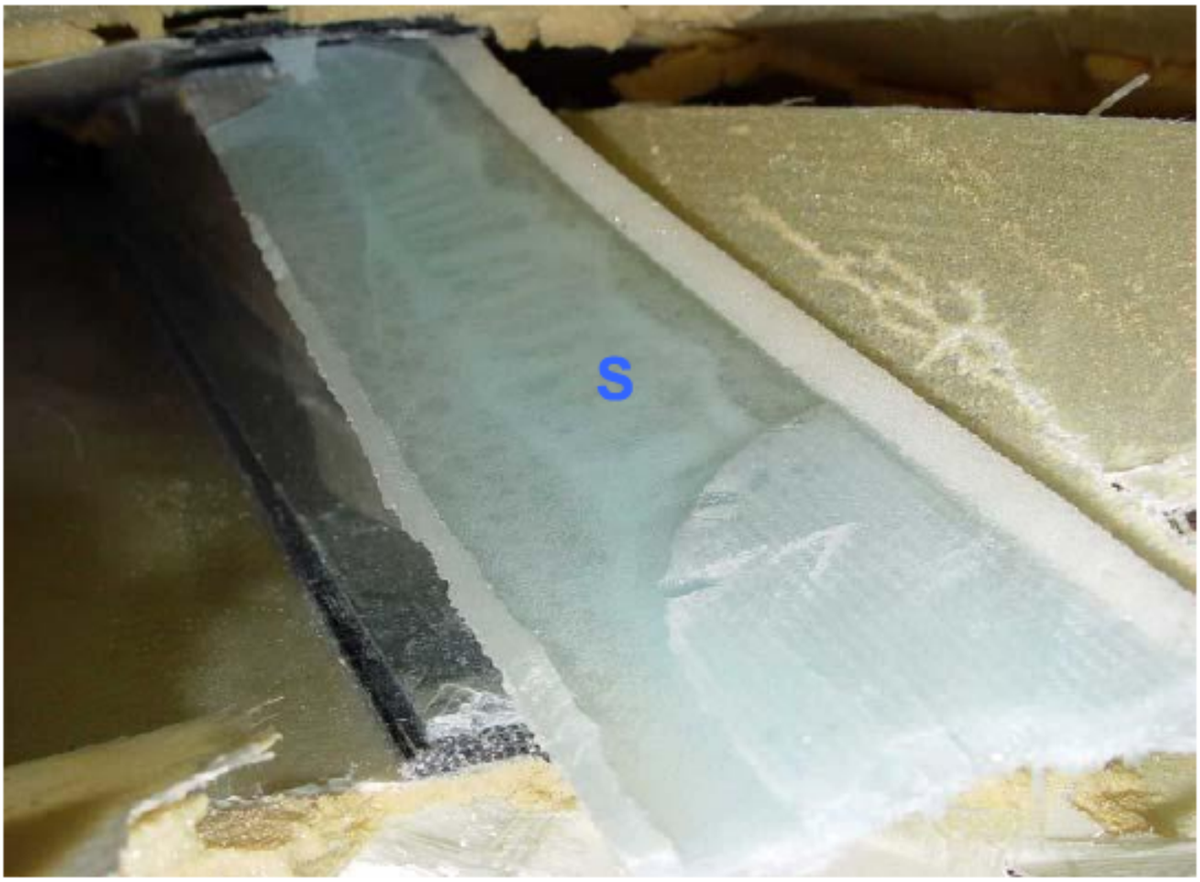


Figure 5-31 - Defective Bonding between the shear web(s) and the upper spar cap indicated by S (BFU, 2006).

Cohesion failures concern the fracture of the adhesive material. Typically cohesive failures are visually characterised by the presence of adhesive material on both faces of the adherends (Davis & Bond, 1999). The failure is typically of mode II shear but it may occur due to either mode I or mixed mode III failure. In cohesion failures, the adhesive surface typically appears rough and may have a lighter colour than the bulk adhesive material. Whilst generally cohesive failures suggest the adhesive has failed at a relatively high stress, this may suggest a premature failure if the bonding area is insufficient or the adhesive has visible signs of weakness such as high porosity.

If the adhesive system is formed around a carrier cloth, then the cloth would provide a preferential location for the cohesive failure to occur. If a cohesion failure has occurred outside of the carrier cloth, then this may be indicative of a degrading adhesive to adherend interface. Especially if the failure has a visible stepped fracture consisting of both an adhesion and cohesion failure, then this is likely to be indicative of adhesion failure degrading the bond strength with the final cohesion failure occurring, as the remaining bond is no longer capable of carrying the load (Davis & Bond, 1999).

Figure 5-32 illustrates the typical failure modes of a sandwich core failure which may be visually evident.

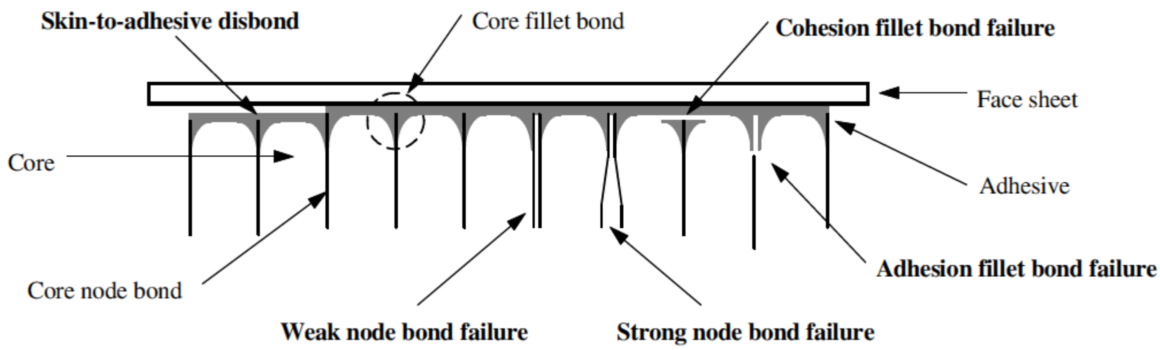


Figure 5-32 - Adhesive bond failure modes for honeycomb sandwich panels (Davis & Bond, 1999).

It is suggested by Davis & Bond (2007) that when encountering cohesion failures in sandwich panels, the most likely cause will be internal pressure within the core due to heating cycles, especially when moisture is contained within the core. They go further to suggest that impact damage is likely only to cause cohesion failure of the adhesive if the impact energy is high enough to cause visible evidence of an impact occurring. This however will involve visible crushing of the core and fracture of the fillet bonds. Fatigue, they suggest, is not likely to occur as the adhesive shear strength of the adhesive is substantially higher than the shear strength of core.

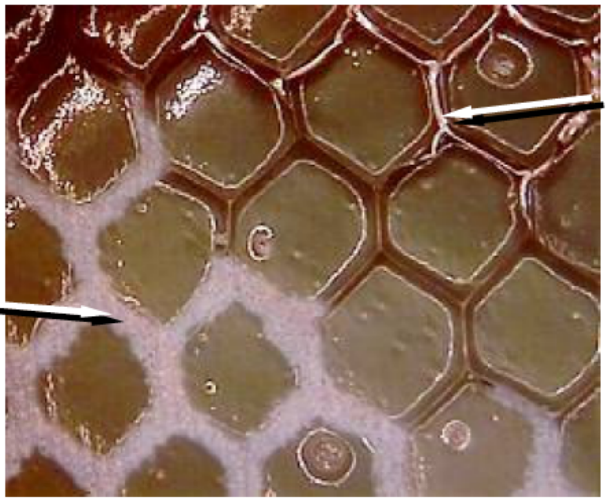
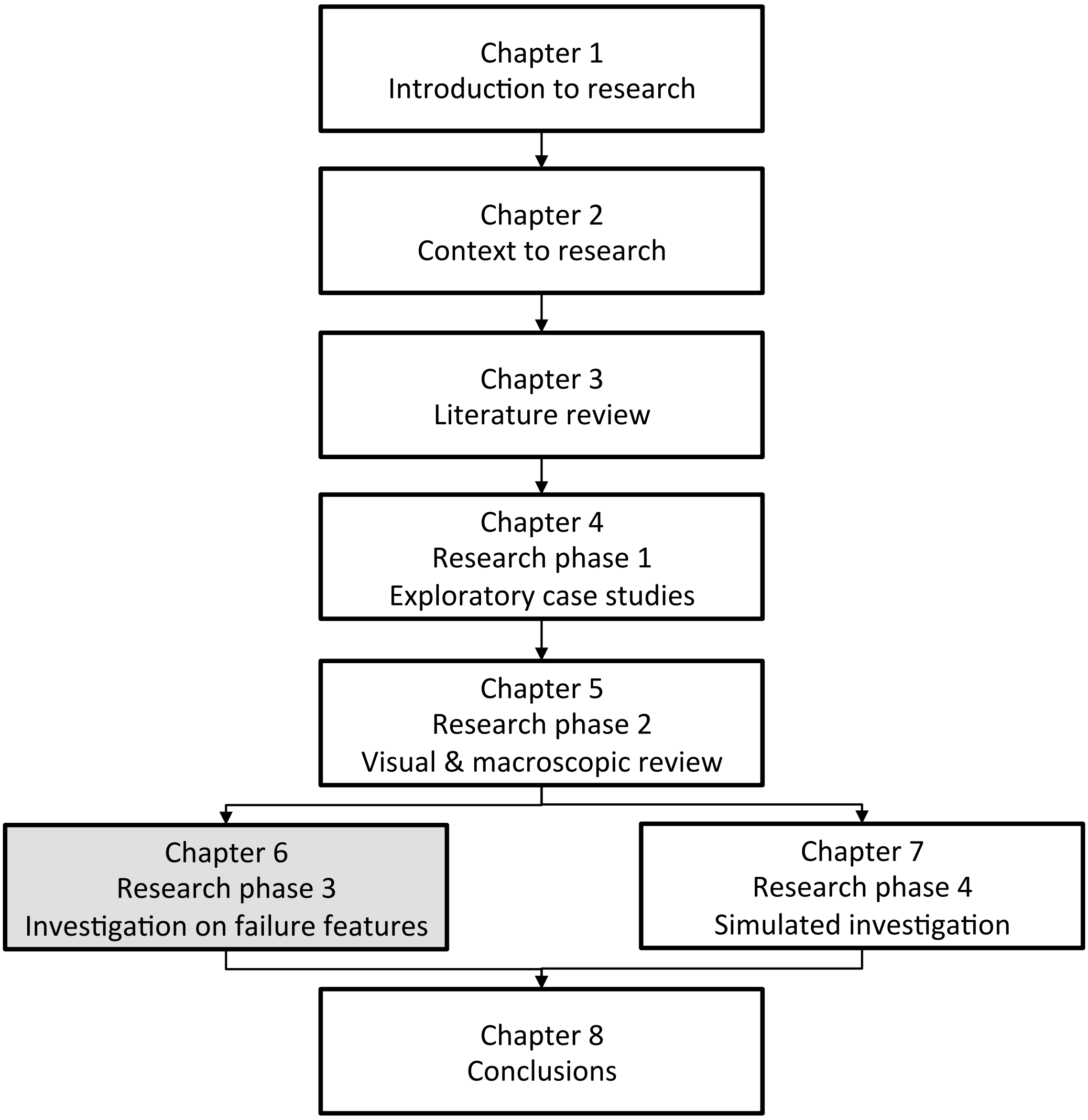


Figure 5-33 - Flatwise tension failure of a sandwich panel. Internal pressure developed during a repair heating cycle causes cohesion failure of the fillet bonds and core cell wall fracture. (Davis & Bond, 1999)

5.5 Chapter summary

This chapter has conducted a survey of literature to identify failure characteristics of polymer composite materials. Empirical findings from the first phase of the research programme were utilised to ensure that the characteristics identified are appropriate to the aircraft accident investigation practitioner. This chapter outlined the characteristics identified, detailing the information they can provide and how they can support the accident investigation process. This leads to the next phase of the research programme which is to apply the identified characteristics to aircraft wreckage.

6 THE VISUAL AND MACROSCOPIC INTERPRETATION OF A FRACTURED POLYMER COMPOSITE STRUCTURE



The previous chapter identified and presented failure characteristics appropriate to the interpretation of polymer composite failures from a visual and macroscopic perspective. This chapter presents the third phase of the research programme which is to apply the identified characteristics to polymer composite aircraft wreckage in a structured and controlled manner.

Firstly, this chapter presents an overview and the research objectives for this phase (section 6.1). Then it discusses the programme through which the polymer composite wreckage was created (Section 6.3 through 6.6). Finally it discusses the application of the characteristics identified in chapter 5 to the polymer composite wreckage (Section 6.7).

6.1 Overview and objectives

As identified in chapter 3, there is no predefined methodology which can be used as a basis for conducting this phase of the research programme. As a result, the objectives for this phase were adapted to separate the process into five key tasks. Each of the tasks is highlighted below and is subsequently discussed in further detail throughout the chapter:

1. Specimen selection
2. Programme design for specimen generation
3. Specimen preparation
4. Specimen generation
5. Visual and macroscopic evaluation

It is the purpose of this phase to design, conduct and evaluate a study whereby the failure features (as identified in chapter 5) can be tested practically for use within the accident investigation process. To achieve this aim it is necessary to identify a suitable specimen in which the characteristics can be tested. The sample for failure characteristic generation itself has a multitude of possibilities including the use of existing wreckage or the generation of artificial wreckage.

It is necessary to understand the basis from which a failure analysis is conducted such that an appropriate method for specimen generation can be identified.

A diagram of one such failure analysis procedure is illustrated in Figure 6-1. The diagram is of the Failure Analysis Logic Network as presented by ASM (2001). This was created from the work conducted by Boeing (i.e. Kar, 1992, Kar, 1992b) and is representative of similar models presented by other authors (Greenhalgh, 2009).

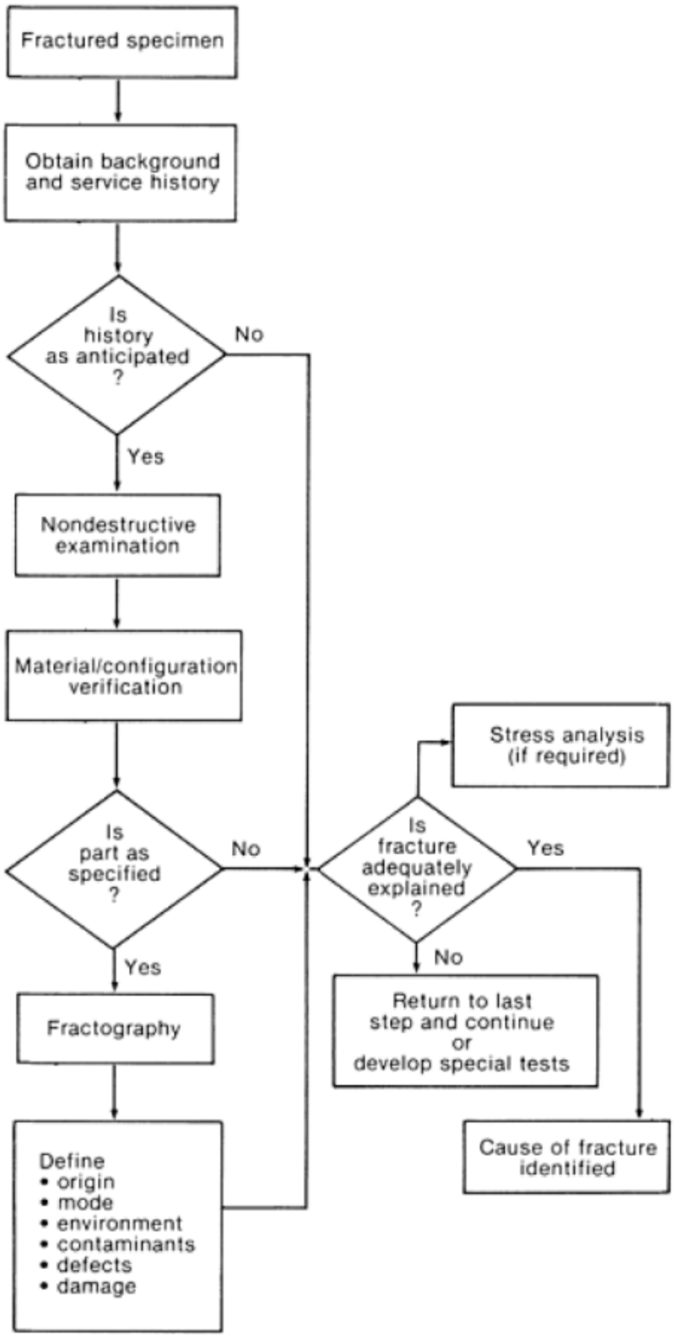


Figure 6-1 – Failure Analysis Logic Network (FALN) (ASM, 2001)

Excluding the occasional exception, the primary purpose of a failure analysis is to identify the root cause of a failure (Dennies, 2002). As such the input to the process is the specimen to undergo the analysis. The intended outcome is a determination of the root cause to failure. Typically this would involve understanding the sequence and source of failure (Greenhalgh, 2009).

Importantly the FALN (figure 6-1) uses the identification of visual characteristics, among other forms, as a source of evidence to assist in understanding the sequence and source of failure and hence identifying the root cause. Furthermore, as the root cause is not known, multiple sources of evidence are triangulated to point to a common root cause providing greater reassurance as to the validity of the conclusion. With respect to visual features, conclusions drawn from these can typically be verified by conducting further testing (ASM, 2001).

This suggests that in conducting a failure analysis, conclusions drawn from interpreting visual features should be verified by other means. Thus if a 'blind' (i.e. a situation when the failure root cause is not known by the investigator) fractured specimen is examined to determine what visual features are available and how they can assist in identifying the root cause, then confirmation by some other means must be sought.

A study of this type would involve obtaining fractured specimens, conducting a visual examination, hypothesise the failure sequence and root cause, and finally confirm those findings utilising higher magnification analysis.

As the specimen is selected 'blind', then the sampling is random. In the study being conducted however, it is critical that the specimens are of significance to the characteristics as identified in chapter 5.

It is impractical to choose specimens that have already undergone failure analysis to determine the root cause, as those specimens are likely to have undergone some form of destructive examination and / or be part of a sensitive investigation where access would be unlikely.

An alternative option to this method is to choose specimens which are blind to the researcher but have been fractured by others in a controlled and consistent manner. Unfortunately it is impractical to locate specimens in a 'blind' manner which is able to meet the requirement of providing representative examples of the failure of complex structures in a manner consistent with those of an aircraft accident. This is due to restrictions of access, limited nature of such specimens being produced and the extreme difficulty in the researcher remaining blind to the failure scenario.

The final option is for the researcher to create the specimens and thus have control in the failure modes, the root cause to failure and, to a certain degree, the macroscopic failure sequence. Thus, confidence can be suggested in interpreting the failure characteristics. In this scenario however, caution must be taken to minimise the biases created by the researcher having a preconceived notion of what characteristics should be seen and where. Triangulation of evidence through the fracturing of multiple specimens, or member checking through the use of independent observers must be used to minimise this threat.

Moreover, this offers the advantages that the researcher has the ability to undertake an investigation in reverse. For example, a typical accident investigation is tasked with using evidence to identify the sequence of events leading up to the accident and to identify the primary root cause(s). In the above mentioned situation, the researcher is using the known root cause(s) of the failure and the known sequence of failure to assist in identifying the evidence (the visual characteristics). Following this the fractographic surfaces can be examined to identify the corresponding features. To achieve this however it is critical that formal test methods are utilised such that the fracture process can be understood with confidence.

When considering the desired objectives of this phase it is thus preferable to utilise the latter method where specimens are created by the researcher, in a manner that is consistent with loading methods that have a scientific foundation. The identification of the visual failure characteristics are then supported by the planned, and observed, failure of the specimen.

6.2 Task 1 - Specimen selection

The objective of this task is to select specimens which are suitable for controlled fracture. The task was thus split into 5 sections as described in Figure 6-2.

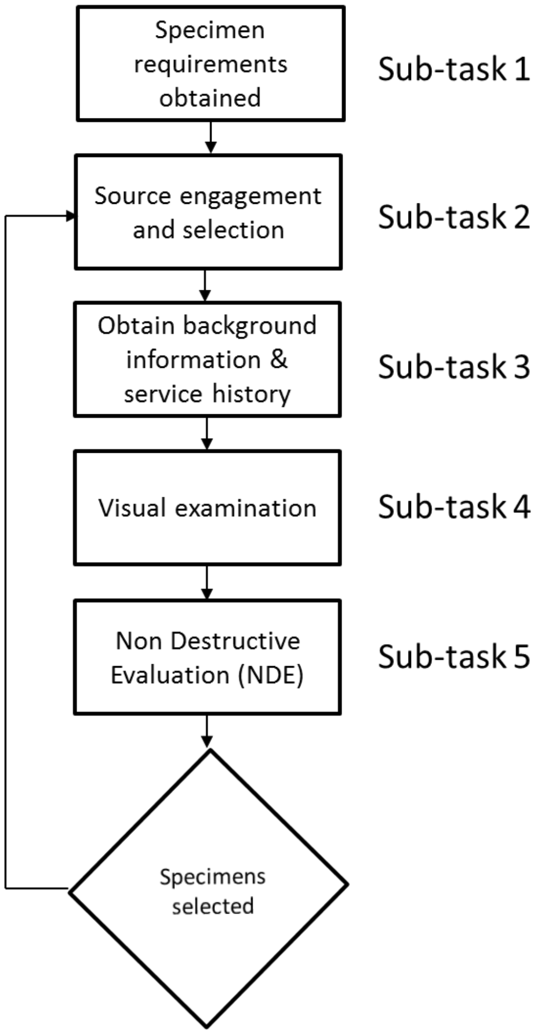


Figure 6-2 – Sub tasks for specimen selection (Source: Author)

6.2.1 Choosing the correct specimen to meet the requirements of the research objectives

It has been presented in chapter 3 that the basis for understanding failure characteristics has been largely derived from the testing and examination of coupon-sized specimens. Whilst these provide controlled failure of individual composite structures, they are unable to offer the complexity otherwise found on larger structure. The use of coupons a) limits the examination of multiple failure modes which would otherwise interact during failure, b) restricts the scope for identifying new characteristics which would be associated with a larger structure, and c) removes the realism from the aircraft accident investigation scenario whereby, without a high degree of complexity to the fractured specimen, it would be difficult to link the coupon-sized fracture to the wider investigation. The latter factor is a critical aspect of the investigation as highlighted in findings from the first phase of this research (chapter 4).

It would have been ideal to have a full-scale, complete, airframe but this option had to be excluded and the scale of the testing would have been impractical within the boundaries of this research. Instead a suitable specimen would be that of a component or structure representative of an all composite GA aircraft. Moreover, the fracturing of a component or structure from a batch built aircraft which had accumulated a significant number of flight hours would be beneficial. This would offer the benefit of an example which had undergone a real world manufacturing process, was 'scarred' with the normalities of an aircraft in use and would represent failure characteristics of a non-pristine material. In this case Non Destructive Evaluation (NDE) would be utilised to identify any significant anomalies in the structure prior to fracture.

6.2.2 Engagement for obtaining aircraft structure

Cranfield University's Safety and Accident Investigation Centre's (CSAIC) operates with close ties to the investigation community and has experience in obtaining aircraft wreckage and components. When specimens had been identified which potentially suited the requirement of the study, informal requests to obtain the wreckage for research purposes were made. Initial attempts were unsuccessful, however a potential candidate was offered to CSAIC. Steps were subsequently taken to transfer ownership of the aircraft to CSAIC. As a matter of ethical consideration and professional courtesy, permission to use the aircraft for research purposes was requested from the previous owner, the accident pilot and from those persons that had assisted in obtaining the aircraft for use by CSAIC. All persons offered their support.

The following describes the key features of the aircraft obtained.

Description of the Schempp-Hirth Nimbus 3

The following was extracted from the English edition of the Schempp-Hirth Nimbus 3/24.5 flight manual, July 1982 issue with amendments to March 1994.

The text has been amended to include only data relevant to the accident aircraft.

The Nimbus-3 is a single seat high performance Open Class sailplane in CFP/FRP construction, flap equipped, with a T-tail (fin & rudder, stabilizer and elevator). It can be flown in 22.9m, 24.5m or 25.5m configuration. [At the time of the accident the glider was flown in the 25.5m configuration].

The six-piece [… 25.5m …] wing has a multi-trapezoid planform and Schempp-Hirth type airbrakes on the upper surface. Flaps and ailerons have internal drives. Water ballast tanks are integral compartments in the wing nose with a total capacity of [338] litres. [The aircraft complies with modification Bulletin No. 286-20 to increase water ballast quantity].

Wing shells are of Carbon fibre/foam-sandwich with spar flanges of carbon fibre rovings and shear webs of FRP/foam-sandwich.

The sailplane Nimbus-3[25.5] is not certified for aerobatics.

Technical Data

Wing span	25.5m (83.66ft)
Wing area	16.9m2 (181.91 sqft)
Aspect ratio	38.4
Fuselage length	7.63m (25.03ft)
Fuselage width	0.62m (2.03ft)
Fuselage height	0.81m (2.66ft)
Empty weight	408kg (899lb)
Max A.U.W	750kg (1653lb)
Wing loading	28-44 kg/m2 (5.7-9.0 lb/sqft)
Max permitted speed Vne	146 knots (168mph, 270km/h)
Manoeuvring speed Va	102 knots (118mph, 190kph)

The first flight of the Nimbus 3 occurred in January 1981 (Schempp-Hirth, 2010) and production continued until succeeded by the Schempp-Hirth Nimbus 4. First flight of the Nimbus 4 occurred in 1990 (Schempp-Hirth, 2010).

6.2.3 Obtain background history and service information

According to the general procedure for failure analysis, the collation of background information regarding the failure should include details such as; background information on material, fabrication, design, loads, environment, and service or test history (Kar, 1992b). The following sources of information were investigated to obtain the required background information; maintenance manual, flight manual, maintenance log book, accident report, incident/accident report (electronic), information from the previous owner and accident pilot. A summary of the information obtained is provided below.

At the time of the accident the aircraft was conducting a cross-country flight. Whilst returning to the departure airfield it became apparent to the pilot that there was insufficient height to be able to glide to return to the airfield and thus the pilot elected to carry out a landing into an agricultural field. Whilst on approach, and having shortly passed the downwind boundary of the intended landing field, the glider struck a power line in a 'wings level' attitude (or possibly very slightly left wing low) which was running at right angles to the approach path and at a height of 25ft. Contact with the wire rapidly decelerated the glider to virtually zero airspeed, after which the glider pitched nose down and struck the ground in a vertical attitude, coming to rest inverted and pointing back along the initial approach path.

Initial examination of the wreckage was conducted by the investigators following the departure of the emergency services. It was reported that the cockpit area of the glider was destroyed as far as the seat back of the pilot's seat. Additionally, there was some visible damage to both wings and control surfaces, and the horizontal stabiliser and top of the fin had suffered severe impact damage due to contact with the ground.

There was no reported indication of a structural failure which contributed to the accident. Nor was there any suggestion of structural damage or structural failure prior to the impact with the power lines.

The aircraft logbooks were examined to understand the history of the aircraft structure. At the time of the accident the aircraft had accumulated in excess of 3,500 flight hours. According to the owner, the aircraft had previously suffered a ground handling accident which resulted in the repair of the rear fuselage section. Additionally the aircraft had undergone gel coat refinishing of the outer wing sections following 1143 hours flight time.

6.2.4 Visual examination

A visual examination was conducted to identify the type and location of visible damage, with a view to making an initial assessment on locating specimens for subsequent experimentation. The visual examination was conducted outside in daylight conditions and was recorded using photography (Canon 1100D with a Canon EF-S 18-55mm 1:3.5-5.6III zoom lens and a Canon EF 50mm 1:2.5 Macro lens) and a photo log. The individual features were identifiable through a unique numbering system with a scale being used on close up photos. Tactile methods such as pushing on soft and rippled areas, prying and scraping were also used. A summary of the visual examination is given below.

The glider was received to the facility de-rigged and stowed within the glider trailer. The forward section of the fuselage structure was severely disrupted with the first third of the nose being fragmented and detached from the main fuselage. The horizontal stabiliser had suffered significant arcing as a result of collision with the power lines with the upper and lower surfaces containing a large quantity of arcing spots, each surrounded by what appeared to be sooty deposits. The vertical stabiliser had fractured at the tip near to where the horizontal stabiliser connects to the vertical stabiliser resulting in the vertical stabiliser separating from the main structure. The empennage and the fuselage were thus considered as not suitable for testing due to the extent of pre-existing damage.

The wing sections were assembled together and onto the glider fuselage to check for indications of gross damage. The wings are attached to each other within the fuselage recess through the insertion of the main bolt between the fork spar stub on the left wing and the tongue spar stub on the right wing. The wings also contain a single pin located towards the leading edge and a single pin towards the trailing edge. These engage into bearings located in the fuselage. During assembly of the glider it was not possible to fully engage the main bolt through both the fork spar and tongue spar. It appeared that the pin was restricted from entering the trailing section of the fork stub spar on the left wing which was likely to have been as a result of deformation of the aircraft structure (further deformation was located on the control rod linkages located in the vicinity of the spar stubs). The cause as to why the pin would not fully insert was not determined and thus it could not be ascertained to what extent this damage was related to deformation of the wing structure.

The left inner wing section had suffered significant leading edge damage which coincided with a probable location of impact with the power line. The area was severely fractured with evidence of sooty deposits around the fracture area. The inner wing sections were thus deemed as not suitable for testing due to the extent of pre-existing damage.

The remaining outer wing sections connected together without noticeable difficulty and whilst damage was evident, the damage was limited and localised. The outer and wing tip sections were then removed from the aircraft in preparation for in-depth visual examination (Figure 6-3).

Figure 6-3 – outer wing sections removed from the aircraft (Source: Author)

The wing sections were intact with no major pieces missing and thus were examined for potential use during the testing phase. The examination identified four predominant groups of features.

The first being marks and deposits consistent primarily with minor damage occurring during handling and storage.

The first group presented the majority of features identified and as there was no evidence of these presenting significant structural weaknesses, they were deemed as acceptable.

The next group involved visible damage to the structure in the form of chips, dents, gouges and surface shape irregularities. Although visually these did not appear to present structural damage to the wing, they were deemed as requiring NDE to ascertain any significant underlying issues. These could not be directly associated with the accident.

The third group consisted of visible damage that was likely to have been associated with the accident. The most significant damage was localised span-wise cracking of the skin along the spar foot, and points of visible arcing. Both of these damage mechanisms contained visible sooting deposits and were further assessed using NDE.

The final category involved sections of the wing which were deemed as unacceptable for use in the testing. This included an area on the leading edge of the right and the root of the outer wing section. This area had suffered significant damage consistent with crushing damage of the leading edge root section following forward momentum movement of the outer wing section, pivoting about the main spar.

Figure 6-4 – Span-wise crack showing evidence of arcing damage (Source: Author)

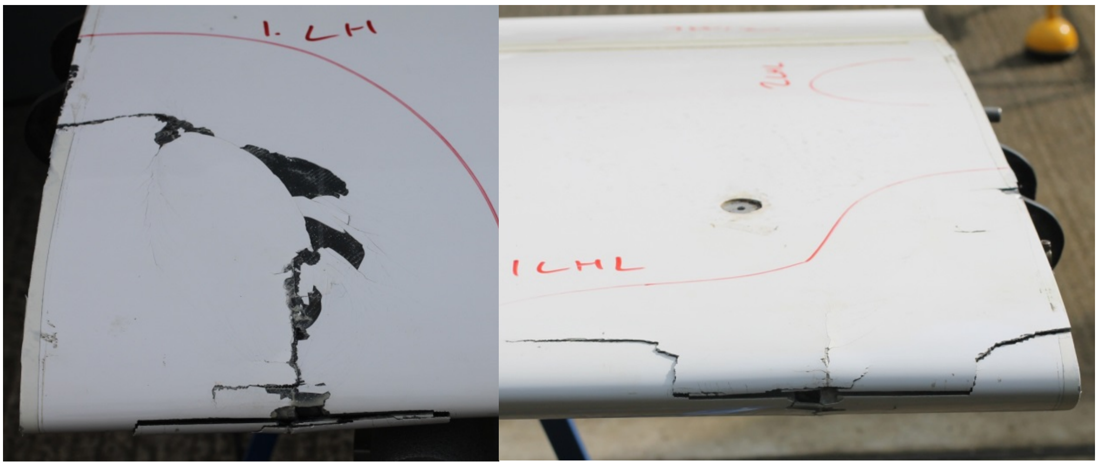


Figure 6-5 – Leading edge damage of the right and the root of the outer wing section. Left picture = Upper surface, right picture = lower surface (Source: Author)

6.2.5 Non Destructive Evaluation of outer wing sections

An important aspect of an analysis involving a composite component, especially where there is evidence of prior event such as an impact, is to identify the extent of subsurface damage (Armstrong *et al*, 2005). This is especially significant as composite materials are notorious for sub-surface damage which is visibly benign (Davies & Olsson, 2004).

The use of non-destructive evaluations to assess internal damage, is used within a variety of fields, each with their own objectives and hence their own requirements. As such, understanding this requirement, as well as the capabilities of the NDE techniques, is critical to identifying the appropriate method (FAA, 1998). Examples include: failure analysis, where NDE is used for identifying the conditions of subsurface damage: documenting and planning subsequent destructive examination (Smith & Grove, 1987); incremental testing of a structure either during testing or in service (Stumpff, 2001); and in-service damage assessment and repair (Armstrong *et al*, 2005).

The aim of the NDE test is to identify conditions of significant subsurface damage that may create fracture initiation sites or potentially influence the intended failure mode.

Although the most frequently used NDE methods in composite fractography are Ultrasound and Radiography (Greenhalgh, 2009), a review was conducted to determine the most suitable methods. The results are shown in table 6-1. Dye Penetrant was excluded as this method is for surface analysis and contains penetrating dyes which may interfere with the visual features. Moisture meters were also excluded as they are unable to be used with carbon fibre composites.

	Delamination (<10 mm)	Delamination (>10 mm)	Crack	Disbond	Void	Impact (BVI)	Porosity	Inclusion	Erosion	Core splice	Core disbond	Core crushing	Matrix Cracking	Fibre breakage	Kissing Bond	Environment ingress	Fibre Wrinkling/Waviness	Fibre and ply misalignment	Incorrect cure	Excess resin	Excess fibre
Acoustic Emission (AE)	◉	◉	◉	○		◉					○	⊙	●	●							
Acoustic Impact (AI)	○	⊙		⊙	○	⊙		○		⊙	●	●		⊙	○						
Coin Testing (CO)	○	⊙		⊙	○	⊙		○		⊙	●	●		⊙	○						
Laser Shearography (LS)	◉	●	◉	●	⊙	●	◉	◉	⊙	◉	●	⊙		⊙	⊙	⊙	⊙	○		⊙	⊙
Mechanical Impedance (MI)	⊙	⊙		⊙	○	⊙		⊙		⊙	●	●		⊙	○						
Membrane Resonance (MR)	⊙	⊙		⊙	○	⊙		⊙		⊙	●	●		⊙	○						
Thermography (TT)	◉	●	⊙	●	⊙	◉	⊙	◉	◉	⊙	●	⊙			○	●	○	○		⊙	⊙
Ultrasonic Amplitude C-Scan (UC)	◉	●		●	●	●	◉	◉	◉	⊙	●	◉			○	◉	◉	◉	○	⊙	⊙
Ultrasonic Thickness A-Scan (UA)	⊙	◉		◉	⊙	●	⊙	◉	◉	○	◉	⊙				⊙	○				
Ultrasonic 0 deg PE B-Scan (UB)	◉	●		●	⊙	●	⊙	◉	●	○	◉	⊙				⊙	◉	○	⊙	⊙	⊙
Ultrasonic Depth Scan (UD)	◉	●		●	⊙	●	⊙	⊙	●		◉								⊙	◉	◉
Visual (V)			⊙			⊙			○	○		○	○	○		○	○	○		○	○
X-Radiography (XR)	◉	◉	◉	⊙	●	⊙	●	⊙	⊙	◉	⊙	⊙	⊙	⊙		⊙	○	⊙		○	○

●	High applicability	◉	Good applicability	⊙	Some applicability	○	Limited applicability		No applicability

Table 6-1 – NDE detectability matrix (redrawn from Netcomposites, 2012)

Due to their generally high and good applicability and suitability to detect a wide array of flaws / defects, it was decided that ultrasonic phased array technique should be used. The NDE testing was conducted by a member of Cranfield University's School of Applied Science using an Olympus Omniscan Mx. Initial trials however proved inadequate due to the complex shape of the wing and the limited information available to assist calibration. The time and resources required to produce adequate results was determined as too extensive to meet the aims of this phase. The method was thus changed to audiosonic which, although discussed as subjective in its interpretation and hence reliability, is also recognised in particular circumstances as being a competent form of NDE (Armstrong, *et al*, 2005; Cawley & Adams, 1988; Campbell, 2003). However, due to the limited penetration into thick laminates, a secondary NDE method was required.

The author, using a stainless steel plain edge circular disc, conducted the audiosonic examination. The disc had an outer diameter of 25mm (see Armstrong et al, 2005) and a weight of approximately seven grams. The process was entirely manual whereby the inspector would tap the structure using the circular disc and interpret the audio resonance response from the structure through the human ear. Indications of delamination or disbonds were noted through changes in the frequency of the sound emitted. The accuracy of the tap test can be increased if a reference area, with a known defect, is used to identify the change in acoustic response (Phelps, 1979). To familiarise the inspector with the change in acoustic response, numerous reference specimens with defects were examined. Despite this, it was acknowledged that the inspector had not undergone formal training in the application of audio sonic measurement, and hence the results were interpreted with associated regard. This did not detract however from the use of audiosonic as a preliminary inspection technique for assessing the structure prior to further NDE examination.

The results of the audiosonic NDE suggested that there were no significant defects detectable other than those that were already visually evident. In addition, the areas which were visually damaged either did not have any apparent subsurface damage or the upper subsurface damage was fairly localised to the visually apparent damaged area.

Although the NDE was not evidence of the structure being free from subsurface damage, it was sufficient to determine that the outer wing sections were suitable for use within the testing program. To counter the limitations in the audiosonic technique, Computed Tomography was undertaken to examine the areas of intended fracture. As this was conducted after sectioning of the wings, it is discussed further in 6.4.2.

The fracture test programme was designed to create wreckage suitable to the objectives of the research by using the outer wing sections from a Schempp-Hirth Nimbus 3.

6.3 Task 2 – Programme design for specimen generation

It was the purpose of this task to design a method which will create realistic aircraft wreckage from using the outer wing sections off of a Schempp-Hirth Nimbus 3 glider. To achieve this, methods of loading full size components and sub-components was investigated. Identified methods were considered against the requirements for the testing and a suitable method was established. The testing method, fixture design, instrumentation, and data reporting are described with each of the sub-tasks being discussed independently.

6.3.1 Failure method design

The first consideration in designing the method by which a large-scale component is to be mechanically loaded is to consider the purpose of the loading (ASM, 2001). It is only through understanding the purpose of the test, that decisions can be made as to how the loading should be applied and thus how the test fixture should be designed.

The purpose of the loading is to apply a simple mechanism which can, within reason, create a failure similar to that which would be experienced in the failure of an aircraft structure. It is accepted that to recreate the dynamics in which an aircraft will fail structurally in-flight would require a complexity which is beyond the scope of this research. Therefore, the loading regime will be restricted to static simple loading. This is accepted as a limitation of this research.

Another consideration is the manner of loading, including the loading profiles at particular locations of the wing structure and the spectrum of loading which should be applied. Both of these factors assist in ensuring that the loading applied to the structure is representative of loads applied during flight conditions. To understand these loads however requires substantial effort through conducting computational models or through load monitoring through flight testing, (See Mileshkin, Scott, & Wood, 1987; Persson, 2011). It is accepted that to recreate a flight spectrum or through mimicking local loading would require a complexity which is beyond the scope of this research. Therefore simple loading regimes and methods will only be considered in this research. This is accepted as a limitation of this research.

Researchers have applied loading to aerofoil sections using numerous different methods. Cantilever loading was applied to fracture a wingbox by Greenhalgh, Millson, Thompson, Sayers (1999). A modified cantilever loading, with the aim of producing multiple failures in a single aerofoil structure, was applied to a wind turbine by Jørgensen, Borum, McGugan, Thomsen, Jensen, Debel and Sørensen (2004). Three point (e.g. Purslow, 1984) and four point (e.g. Musial, Bourne, Hughes & Zuteck, 2001) bend test methods have been used. Four point bending offers an advantage over three point bending as the loading points are positioned such that they minimise interference with the fracture process (Purslow, 1981). Bespoke test fixtures have also been created, designed to produce multiple loading modes to a wing section such as torsional moments as well as flap-wise loading (Grasse, Trappe, Hickmann & Meister, 2010).

Multiple methods exist for applying the load from the test fixture to the specimen. These include applying the load through the internal structure such as through the shear web or through both spar caps. Alternatively, the loads can be applied to the external structure, one example being through the use of rollers such as those used when loading coupon sized elements under four point bending such as described in ASTM D6272 (ASTM, 2010). Methods of attachment can also vary to include fastening, bonding or free attachment where the fixture is not directly fixed to the specimen.

When applying the load, considerations must be made for the effect the loading will have on the structure local to the loading points, otherwise local failure at the loading points may dominate the fracturing process. When applying the load through internal structures, any reduction in strength or integrity that the attachment may create (Gilchrist, Kinloch, Matthews & Osiyemi, 1996) must be countered by increasing the strength local to the loading point. Moreover, care must be taken to avoid out of plane loads and the inducement of stress concentrations to the structure which would otherwise promote premature failure of the composite structure (ASM, 2001).

When applying the load to the external structure, consideration must be taken such that the contact area is large enough to avoid the inducement of severe local stresses (Gilchrist *et al*, 1995). Furthermore, the loading point must maintain consistent contact with the specimen through the testing procedure to avoid point loads occurring on the corners of the loading points. This is typically achieved either through the contact surface having a curved surface, as in the case of rollers, or the contact surface being fixed to the specimen but being free to rotate where the loading point connects to the test fixture. The use of rollers however will require modification if a reciprocal loading is to be applied to the specimen.

Whilst all possibilities were considered as a means to create the fractured specimens, the four point bending method was selected. This was due to the distinct advantages that four point bending offered over alternative methods. Moreover, the ability to conduct the loading of a specimen in a manner which is controlled and precise, whilst adhering to standardised test methods (e.g. ASTM D6272) is critical to producing fracture mechanisms of the intended mode.

Firstly, the design philosophy of the four point bend arrangement presents limited shear force on the specimen and a constant bending moment between the inner supports. This would therefore offer the ability to provide flexural loading onto the wing section whilst minimising the influence of the loading points on the fracture.

Furthermore, the four point loading could be conducted such that reasonably small lengths of wing structure can be fractured at any one time. This would increase the opportunity for conducting multiple fractures by cutting the wing into multiple samples.

Due to the wing section and the load bearing spar caps being tapered, there may be a preference for the wing section to fracture in the region of the central loading support located closest to the outer wing section. To overcome this, the failure location can be positioned towards the mid-point of the specimen by introducing a preferential site for failure initiation. This can be achieved by incorporating degradation at the point of preferential failure. This increases the reliability of a fracture occurring in the midpoint of the wing section and assists the research by introducing degradation mechanisms as failure modes.

Additionally the four point test fixture can also be designed such that loading can be applied in tension and compression, thus allowing the potential for cyclic tension-compression flexural loading. This can be achieved through the use of formers, or yokes, which attach to the upper and lower surface of the wing structure. The use of formers has the disadvantage of not providing as realistic distribution of air loads as other methods can provide, and also they provide concentrating of loads at the location of the formers. The method does however require a less complex setup and is less costly (ASM, 2001).

6.3.2 Testing machine and fixture design

Typically, the application of load onto large structures is conducted by the use of bespoke loading equipment (e.g. Greenhalgh *et al*, 1999), modified commercial equipment (e.g. Musial, Bourne, Hughes & Zuteck, 2001), or through the use of large laboratory test equipment (e.g. Gilchrist *et al*, 1995).

For reasons of simplicity whilst maintaining rigour in loading and subsequent fracturing, a single actuator 1MN servo-hydraulic biaxial fatigue machine manufactured by Mayes was utilised.

The four point test fixture (figure 6-6) was designed to accommodate a maximum static load of 160kN. A safety margin was incorporated in addition to the maximum static load. Fatigue calculations were not conducted. The joints for tension and compression were designed to incorporate flexibility such that as the specimen undergoes flexural deformation, the former attachment points are free to rotate to reduce accumulation of point loading.

The formers were constructed from softwood with each softwood former being shaped to fit the profile of the wing. In addition, Ethylene Vinyl Acetate (EVA) foam was incorporated between the wooden mouldings and the wing surface to assist in restricting movement of the aerofoil between the mouldings and to reduce point loading.

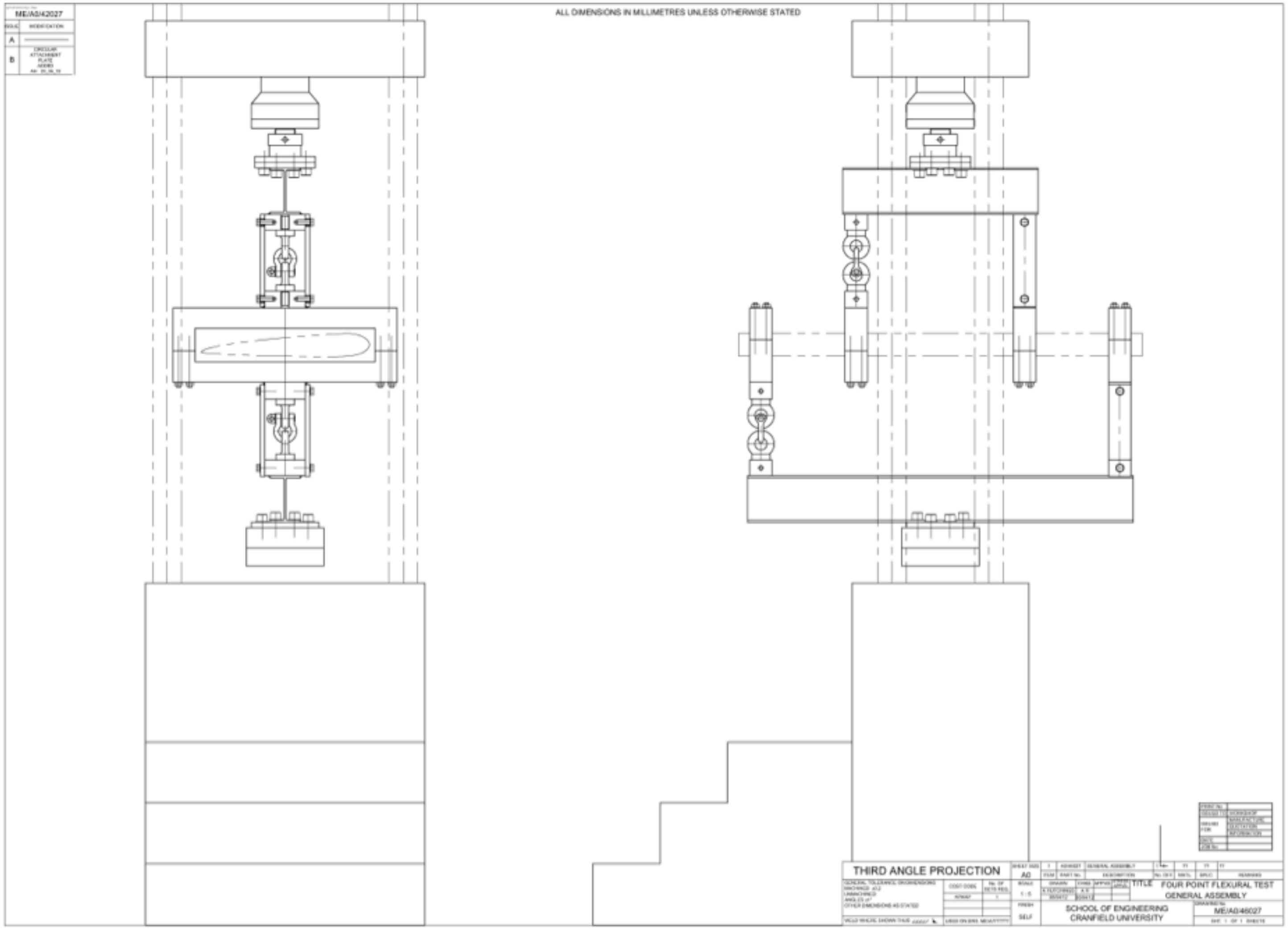


Figure 6-6 – Test fixture fitted to 1MN Mayers servo-hydraulic machine (Hutchins, 2012)

6.3.3 Instrumentation and data acquisition

The appropriate selection of strain gauges is essential to ensure accurate and reliable data, suitability to the environmental conditions of the test, ease of installation and reducing the total cost of data collection (Micro-Measurements, Vishay, 2011).

During the tests the wing sections were instrumented with strain gauges orientated to measure strain in the span-wise direction. It has been previously suggested that gauges with large surface areas should be chosen when instrumenting large composite structures as the large surface area averages out the local inconsistencies (Combs, 1995) and compensates for the nonhomogeneous architecture of composite materials (Micro-Measurements, Vishay, 2011). The strain gauges selected were the general purpose single element Tokyo Sokki Kenkyujo type FLA-10-11, which has a backing width of 5mm and a length of 16.7mm. The gauges have a resistance of 120 +/-0.3 ohms and a gauge factor of 2.11 +/-1%. Whilst it is beneficial in composite materials to have a strain gauge of higher resistance to reduce thermal effects due to heat generation (Combs, 1995), any increased degradation in the installation resistance, such as by moisture, will have a greater effect in higher resistance gauges (Gittins, 2005). Despite having a potential for greater error due to thermal effects, gauges of 120Ω were chosen. Gauges of such resistance have previously been used in conducting experiments on composite structures (McKelvie & Perry, 1998; Lomov, Van Den Broucke, Tümer, Verpoest, Dufort, de Luca, 2004). Cyanoacrylate adhesive approved for strain gauge use was used exclusively for bonding the strain gauges to the composite structure. A National Instruments SC-2345 SCC with a strain gauge module was attached to the strain gauges for strain monitoring throughout the testing. Data was recorded using a laptop.

Strain gages were located on both the tension and compression surfaces. Two strain gauges were located on the surface of the spar cap in compression, positioned at 1/3rd in from the leading edge of the spar cap and 2/3rd in from the leading edge. A third strain gauge was located on the lower tensile spar cap at a half distance in from the leading edge of the spar cap. A fourth strain gauge was located on the wing skin mid-way between the spar cap and the leading edge. The fifth strain gauge was located on the upper trailing edge surface, in a central location to the rear spar (figure 6-7). All strain gauges were located at the span-wise mid-section of the wing structure (e.g. 0.85m from the specimen root). The exception to this positioning was when the strain gauge would have been in direct placement of a visible impact location. In this instance the strain gauges were moved span-wise towards the wing tip. Whilst it was desirable to place strain gauges on the inner parts of the wing section (e.g. on the lower spar caps to detect buckling and on the shear web), the restricted access within the specimens prevented this.

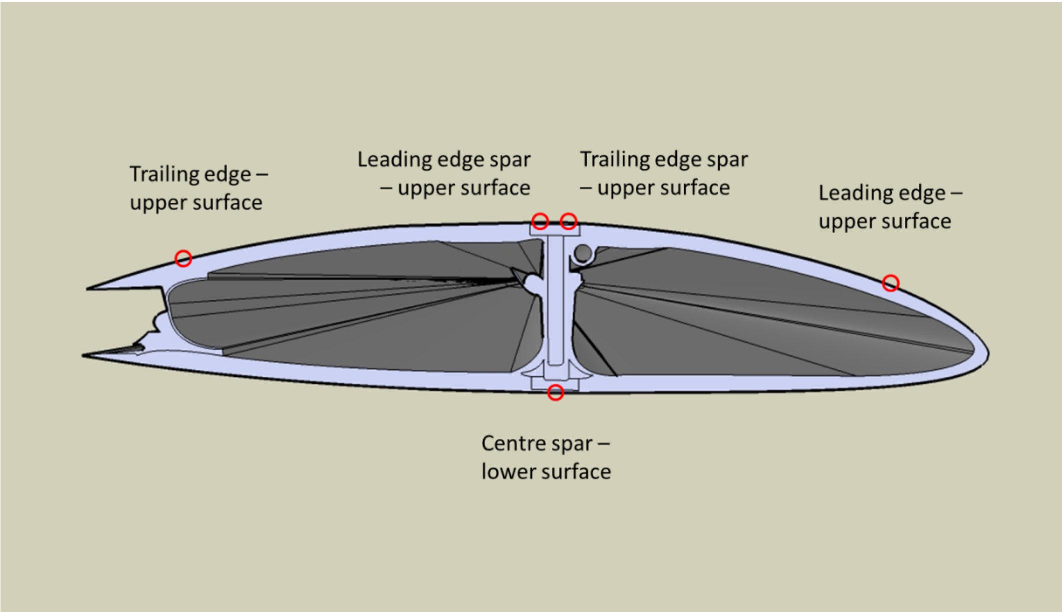


Figure 6-7 – Positioning of the strain gauges on the wing section (Source: Author)

The wing deflection was obtained from recording the displacement of the servo-hydraulic actuator. Whilst this would not directly replicate the displacement of the wing centre, classical beam theory can be used to relate the movement of the centre formers to the aerofoil centre (Gilchrist *et al* 1996).

To ensure confidentiality all strain values in this report are normalized with one value, i.e. all strain values in this report are divided by the same number.

6.3.4 Test procedure

A total of four pairs of specimens measuring 1750mm long were scheduled to be fractured with differing load patterns (static and cyclic) and incorporating different degradation mechanisms. A pair consisted of two specimens cut from identical locations from the left hand and right hand wing sections. The pairs were planned to be fractured in the same loading method and have similar degradation mechanisms. The fracturing in pairs was intended to provide multiple failures of similar structures such that triangulation can be made between the fractured pairs. For example, the examination of the lower spar may reveal the characteristic of tensile failure. By creating an additional specimen which, a) failed under the same loading, b) was from a near identical section of wing, and c) was degraded under a similar damage mechanism, the comparison of the lower spar from each specimen can be made. If the lower spars from each specimen are similar in characteristic, and represent the observed failure mode during the fracturing process, then through triangulation of evidence the failure characteristic is likely to be representative. Each pair would hence form the basis of literal replication.

During the testing it became apparent that the specimen fixture had a number of design inadequacies which resulted in the fixture not being able to perform adequately. Firstly, the height of the fixture once assembled was insufficient for the servo-hydraulic machine to be operated in tension mode. This therefore removed the opportunity to conduct the planned cyclic loading and resulted in all static loading being conducted in compression mode.

The fixture had insufficient lateral constraint in compression mode. When the compression mode was applied, the resistance created by the fixture was insufficient to prevent lateral movement of the specimen. Hence, the specimen tended to move out of the machine, pivoting about the former to beam attachment points. This was overcome through the use of a harness to prevent outward motion of the outer formers. Whilst this was adequate in preventing the lateral motion, it also added restriction to the pivoting of the outer formers.

The weight of the fixture presented significant challenges to the assembly, disassembly and operation of the test fixture. The safety issues were resolved through the use of harnesses which restricted movement in the event of catastrophic failure. From the perspective of the testing, the excess weight created point loads on the structure from the edges of the formers. This resulted in the premature failure in two of the specimens, in which the fracture initiated at the loading point.

In total, one pair of the specimens was successfully fractured, with the fractures occurring in the centre of the specimen. One other pair failed prematurely at the loading points with the remaining two pairs being abandoned due to the inadequacies of the test fixture. Therefore the investigation of thermal and multiple site impact degradation mechanisms were not completed. Furthermore, the cyclic loading was not completed. The following discussion will be limited to the specimens which were fractured successfully.

6.4 Task 3 - Specimen preparation

Each of the outer wing sections from the Schempp-Hirth nimbus 3 glider were divided into a total of four sections, three at 1750mm long and one section at 2000mm long (Figure 6-8). An angle grinder with a diamond coated cutting wheel and a reciprocating saw with an 8” carbide cutting blade were used to section the wing as per recommendations by Campbell (2010) and Armstrong *et al* (2005). In addition, advice was sought from professionals who had experience in sectioning composite structures (most notably from the health and safety manager of the AAIB, and from Recovair, a specialised aircraft rescue and recovery service), and from relevant literature (Greenhalgh, 2009; Roulin-Moloney, 1988; Moore, 2009). The inner metallic control rods and the ailerons were removed following sectioning so that they would not influence the failure.

Prior to the sectioning a risk assessment was conducted in accordance with Cranfield University’s General Risk Assessment Policy CU-HAS-3.01.

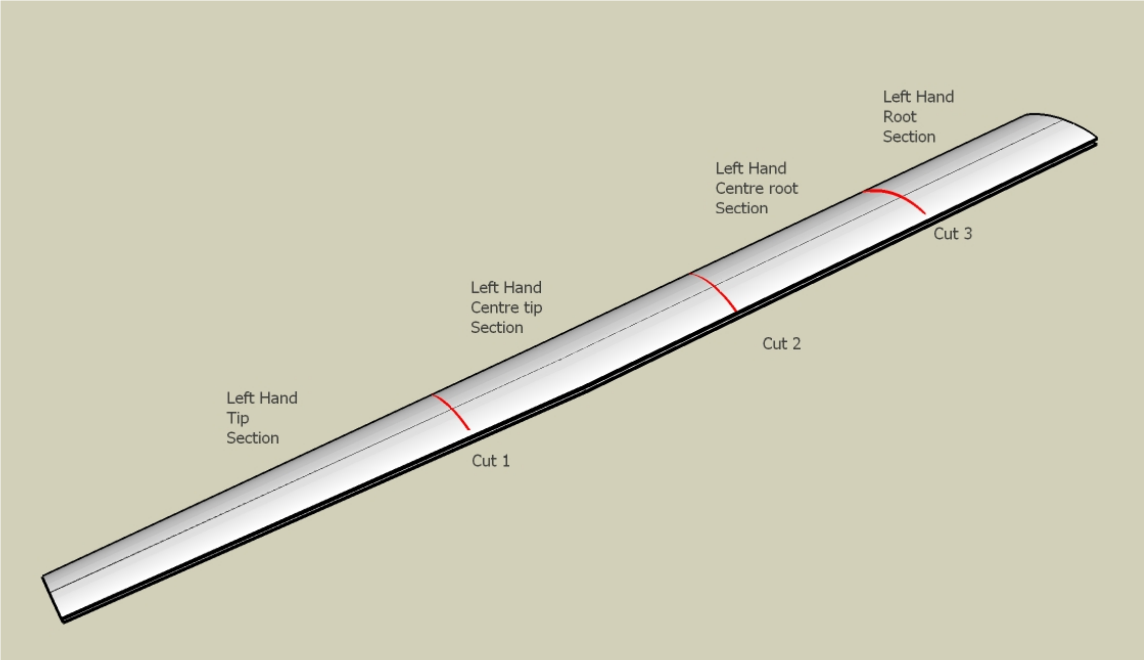


Figure 6-8 – Illustration of sectioning of the left hand outer wing section (Source: Author)

6.4.1 Pre Impact condition assessment

Subsequent to sectioning, the areas immediate to the cut surfaces were visually examined for significant damage created during the cutting process. Whilst cracking in the gel coat was identified immediate to the cut surface, there was no evidence of significant damage introduced to the specimen.

In continuation to section 6.2.5, the NDE was continued using internal visual inspection and 3D Computed Tomography (CT) examination. The internal inspection involved the use of a Dewalt DCT410S1 Inspection camera with photo and video capture capability, and a 6ft probe.

6.4.1.1 3D computer tomography NDE

3D Computed Tomography of the sections was conducted using a bespoke X-Tek Systems Ltd real-time X-ray and CT system. The wing sections were placed vertically into a 2.3m x 2.3m x 2.5m high X-ray room. The wing sections were rotated on a five axis manipulator during the X-ray imaging process. Four sections of the wing were examined, namely the two most outer sections from each wing due to the wider chord sections not being able to fit into the X-ray room. To maximise the area of the wing section being imaged, each wing section was scanned twice with each of the imaged areas overlapping in the central region of the wing (Figure 6-9).

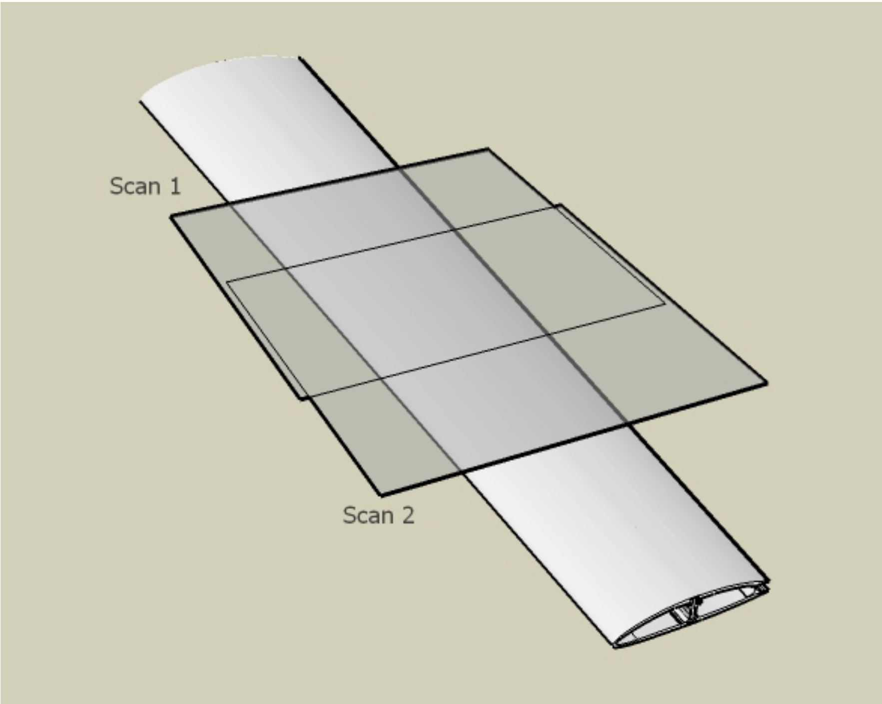


Figure 6-9 – Illustration of X-ray imagery overlap (Source: Author)

The settings for conducting the X-ray imaging is illustrated in table 6-2 and an example of the 3D CT image is given in figure 6-10.

Section	Scan Number	Scan lower limit (measured from specimen wing tip)	Scan upper limit (measured from specimen wing tip)	X-ray voltage	Volume elements (voxels)	Resolution	Number of projections	Angular step
		cm	cm	kV	mm	µm/voxel		°
LH wing tip	1	84	109	380	1043 x 1018 x 897	192 x 192 x 192	3142	0.115
	2	60	90	380	1492 x 1498 x 778	192 x 192 x 192	3142	0.115
RH wing Tip	1	84	108	380	1492 x 1498 x 654	192 x 192 x 192	3142	0.115
	2	68	95	380	1492 x 1498 x 654	192 x 192 x 192	3142	0.115
LH centre wing tip	1	61	92	380	1493 x 1486 x 796	162 x 162 x 162	3142	0.115
	2	82	110	380	1494 x 1489 x 687	162 x 162 x 162	3142	0.115
RH centre wing tip	1	67	90	380	-	-	300	1.2
	2	83	105	380	-	-	252	1.4

Table 6-2 – X-ray settings (Source: Author)

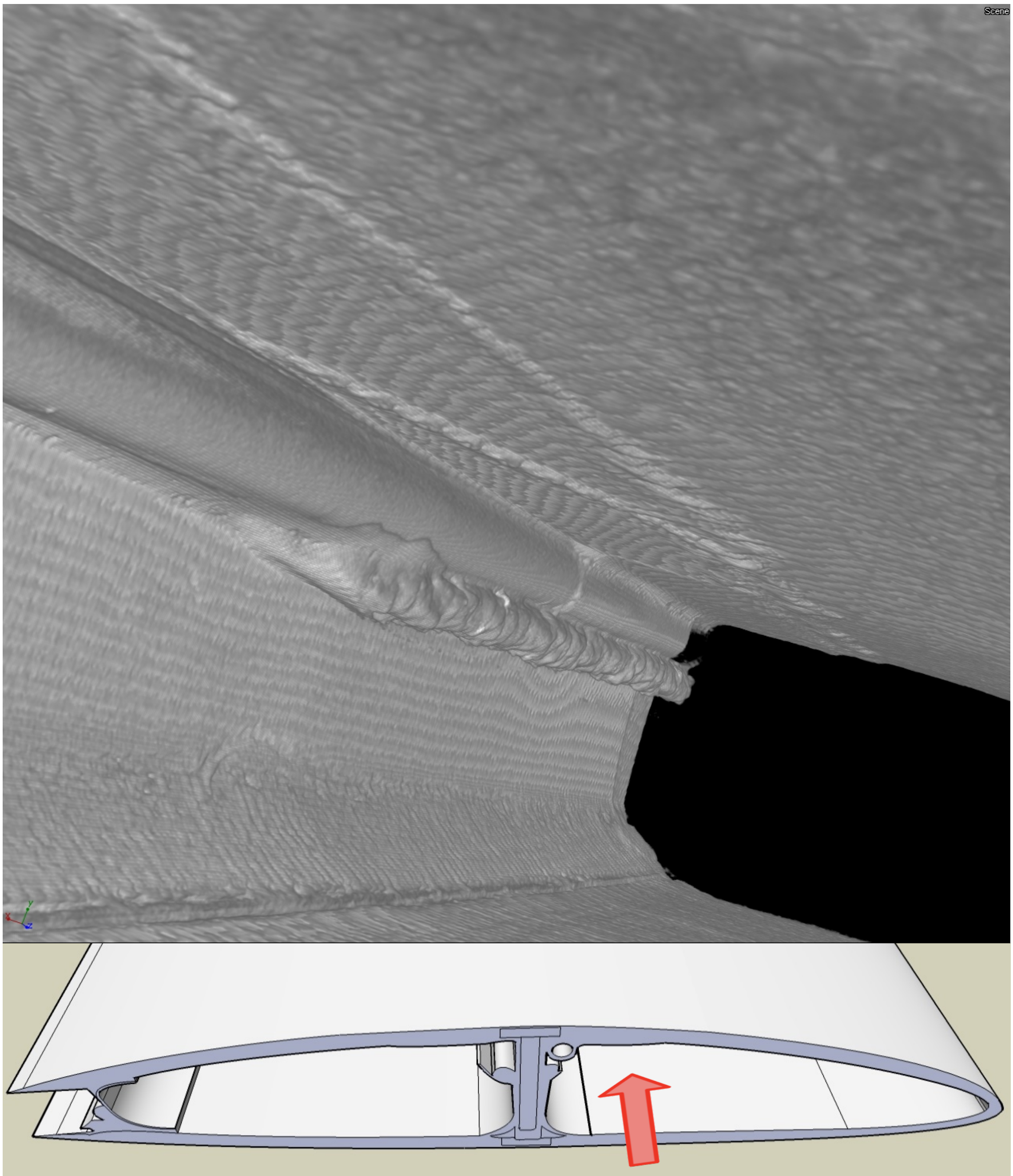


Figure 6-10 – 3D CT image of the internal, leading edge wing structure (the structure on the left of the CT image is the shear web) (Source: Author)

The CT images were stored as 2D slices of the wing section, with the slices being taken span-wise through the chord, from the upper surface moving to the lower surface, and from the leading edge moving through the wing to the trailing edge. The images were subsequently analysed for evidence of anomalies or damage which may be significant enough to either promote or influence the fracturing process.

The examination of the CT images identified indications that suggest inclusions, voids, and intralaminar cracking may be present. The areas of polymer composite which were identified as potentially containing voids and intralaminar cracking were found in relatively low quantities and sizes which would not be significant to the fracturing programme.

There were however indications of a non-symmetric placement of the lower spar cap between the left and right wing sections, which can be identified by comparing figures 6-11 & 6-12. This was confirmed by examining the visible spar in the cut sections and was present primarily in the outer sections of the left wing, with the specimens near the root having a lesser degree of non-symmetry. It was felt that the anomaly would not present an issue for conducting the fracturing programme. Moreover, the anomaly may be of value during the visual and macroscopic examination where the fractured surface will be examined to confirm if the non-symmetrical placement can be identified.

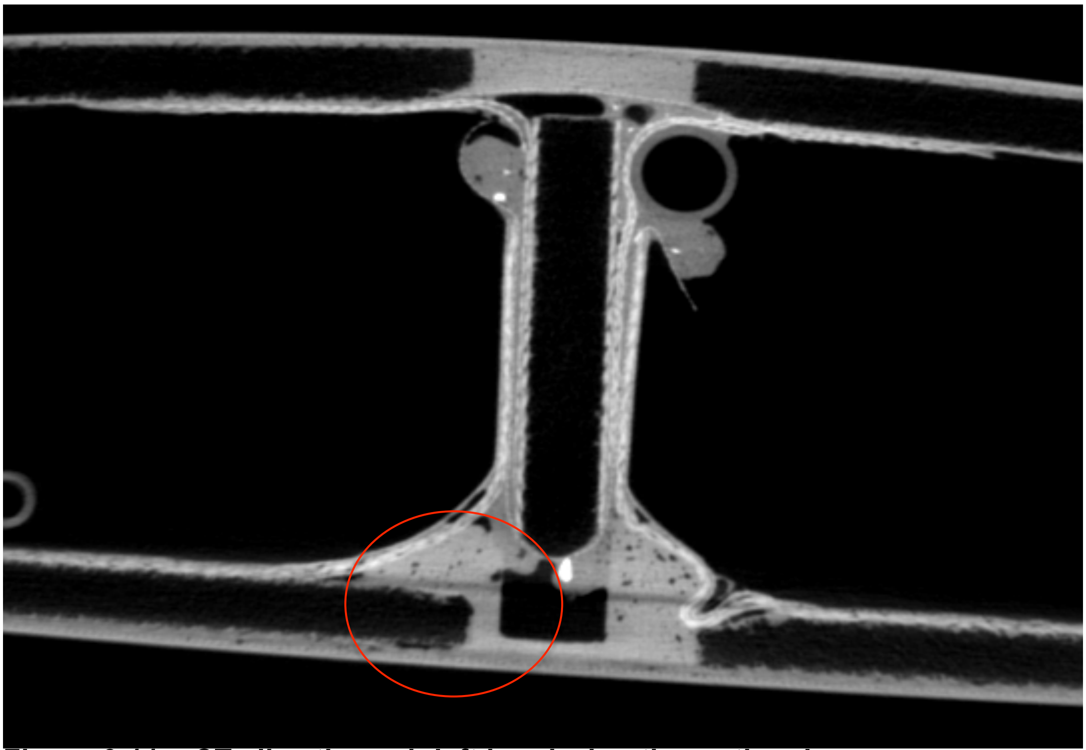


Figure 6-11 – CT slice through left hand wing tip section, lower spar cap anomaly highlighted (Source: Author)

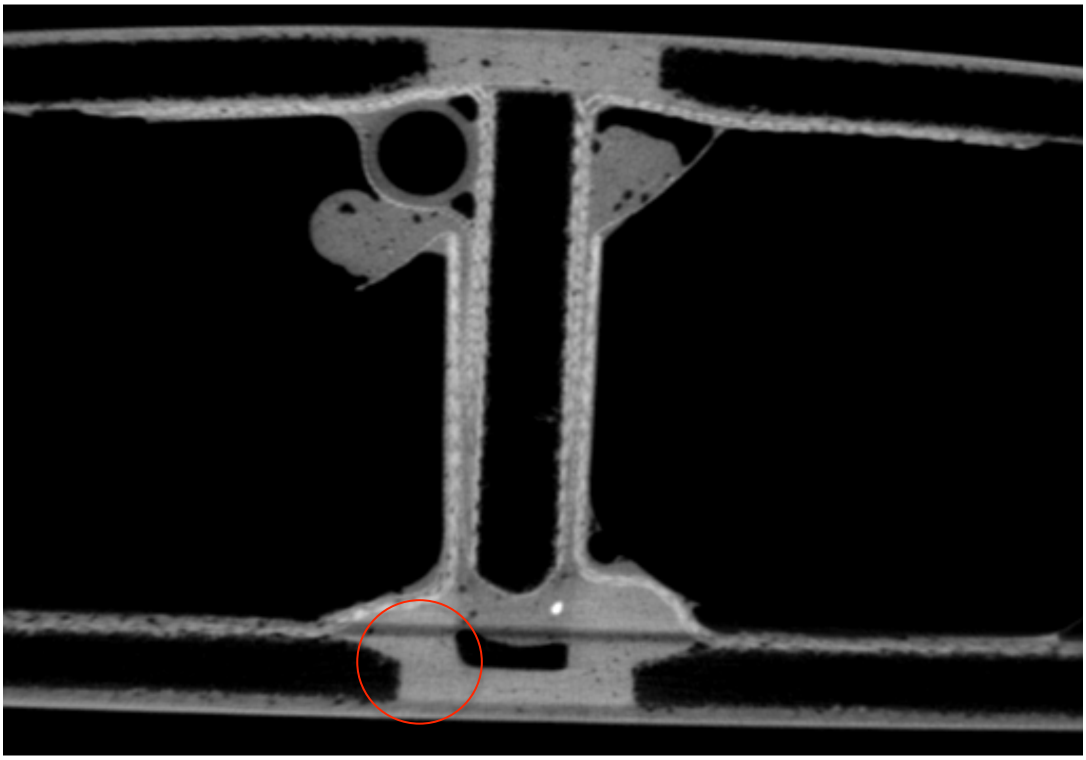


Figure 6-12 – CT slice through right hand wing tip section, lower spar cap highlighted for comparison to figure 6-11 (Source: Author)

6.4.2 Applying the degradation mechanism

The degradation mechanisms chosen for the specimens that performed satisfactorily during the fracture process was impact damage, with the impact location undergoing compression after impact. The impacts were targeted at the centre of the wing section, midway between the inner yokes. This ensured the failure could be encouraged to initiate at a location away from the structure of the test fixture, hence minimising the interference with the developing fracture.

The right hand outer root section was to undergo a blunt impact to reduce the visible appearance of the impact location. The left hand outer root section was to undergo a more localised impact in the centre of the spar cap and a blunt impact of the spar foot, adjacent to the sharp impact. The impact energies were selected to be appropriate with the expected energy limit of 50J for dropped tools or runway debris (Davies & Olsson, 2004), and the FAA airworthiness requirement of 136J (100ft.lb) (Greenhalgh *et al* 1999).

A Rosand Type 5 Falling Weight Impact (FWI) tower was used to create the impact damage to the specimens. The right hand centre root wing section received a 75J impact using an 87mm diameter hemispherical impactor (Figure 6-13). The impact location was central to the upper spar cap. The left hand centre root wing section received a 75J impact to the upper spar cap using a 20mm diameter hemispherical impactor (Figure 6-14). Additionally, the spar foot adjacent to the initial impact received a subsequent impact of 50J using an 87mm hemispherical impactor (figure 6-13 & 6-14).

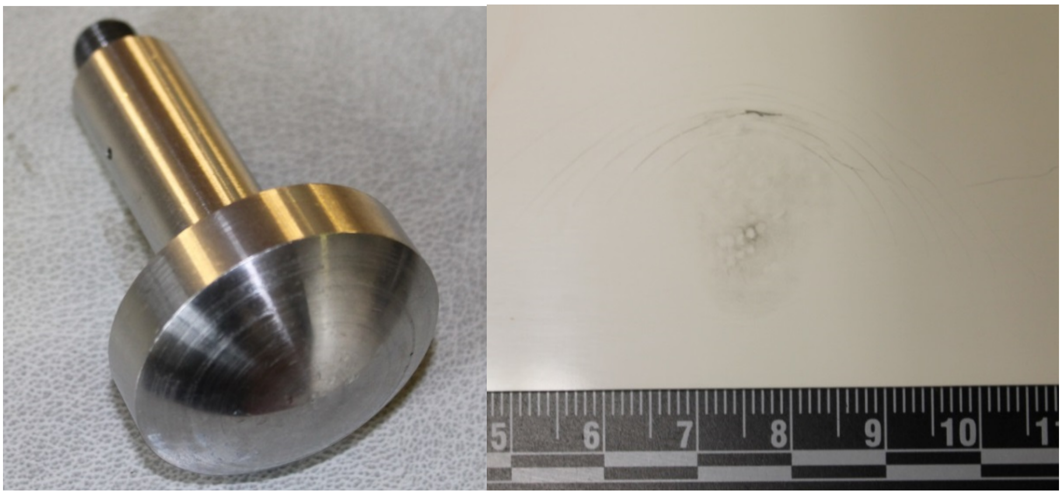


Figure 6-13 – 87mm hemispherical impactor with corresponding specimen impact damage (Source: Author)

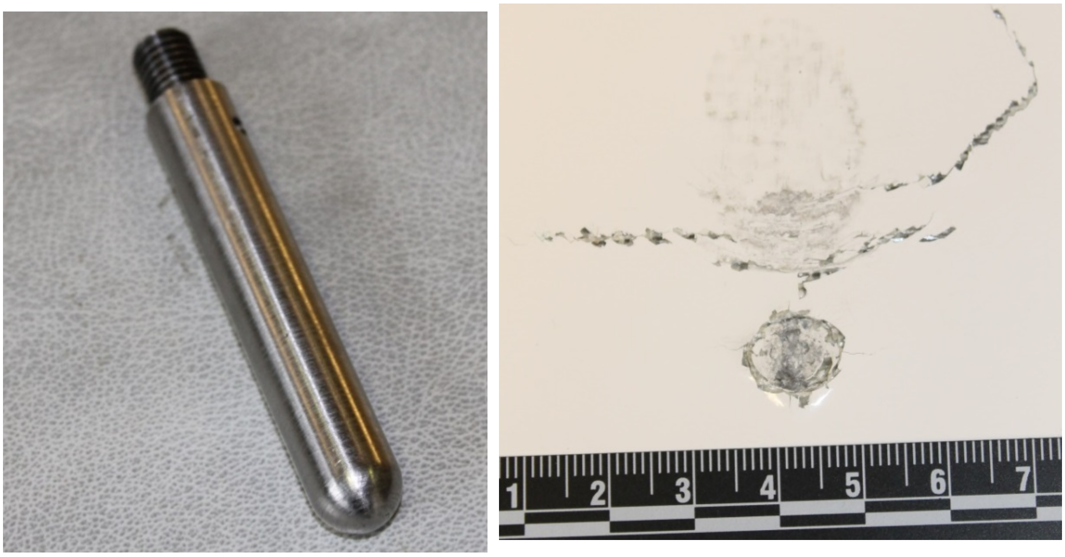


Figure 6-14 – 20mm hemispherical impactor with corresponding specimen impact damage (lower impact point) (Source: Author)

For impact testing, the specimens were supported at the wing section root and tip using trestles of steel construction. The supporting locations were 1500mm apart, being an equal distance of 750mm from the impact location. This arrangement allowed the structure a degree of global flexural response to the impact which was deemed as more appropriate to the objectives of the research. If the structure had been supported in an open aperture located on the lower spar cap then the shear web is likely to have sustained greater damage due to higher compression loading.

As a means to record the change in physical shape of the wing surface as a result of the impact, the area of impact was imaged using a 3D scanner. To enable a comparison, the scanning was conducted prior to impact and following the impact event. Adhesive markers were placed within the outer regions of the impact area such that the pre impact and post impact scans could be aligned.

During the scanning process the need to monitor the room temperature became apparent as the initial scanning process experienced misalignment between object scans when the room temperature fluctuated heavily. This became apparent when the scanning was paused and restarted in significant different ambient conditions to the previous scan. This issue was exacerbated due to the scanning equipment being located in a room susceptible to variations in temperature due to the heating effect of direct sunlight, and due to the scanning being conducted in the summer months.

Whilst the link between the temperature and the misalignment in scanning was conjecture, all successive scans were conducted in the early evening and completed in a single attempt. The issue of misalignment was subsequently not encountered.

6.5 Task 4 – Specimen generation

Prior to conducting the assembly of the test fixture and subsequent testing, a risk assessment of the testing was conducted in accordance with Cranfield University's generic risk assessment procedure (See appendix A). As a result of the risk assessment, assembly instructions for the test fixture were created (See Appendix B & C).

The schematic for the test rig is shown in Figure 6-16. The image illustrates the test fixture configured in compression mode. In addition to the fixture shown in the illustration, there were numerous safety harness added, with the primary aim of supporting the fixture in the event of catastrophic and sudden failure of the specimen. In addition, harnesses were added to the outer yokes to provide additional lateral constraint for testing.

Once the fixture had been assembled, the servo-hydraulic machine was adjusted such that the fixture was in its neutral state. The wing section was subsequently fed into the test fixture such that it could rest in its mounted position without any moment applied to the specimen (Figure 6-15). The strain gauges were attached, calibrated to zero and then functionally tested. The displacement transducers and load cell were zeroed and a video camera, which was pointing towards the upper surface of the wing section, was started. The specimen in the fixture was checked for security prior to the test commencing. For the two test specimens which were successfully fractured the loading was applied under displacement control. After each specimen, the fixture and apparatus hardware was inspected for damage.

Figure 6-15 – Assembled test fixture (Source: Author)

6.5.1 Results from data acquisition

The results from the data acquisition can be found in Appendix C and Appendix D. Appendix C details the left hand centre root specimen, with graphs showing load vs. actuator displacement, measured strains vs. load, and actuator displacement history. During the loading the specimen is partially unloaded before being reloaded to fracture. This moment is displayed as loops in the strain vs. load chart. Appendix D details the same information but for the right hand centre root specimen.

To ensure confidentiality, all load and strain values are normalized, i.e. all strain values for both specimens are divided by a number, and all load values for both specimens are divided by a different number.

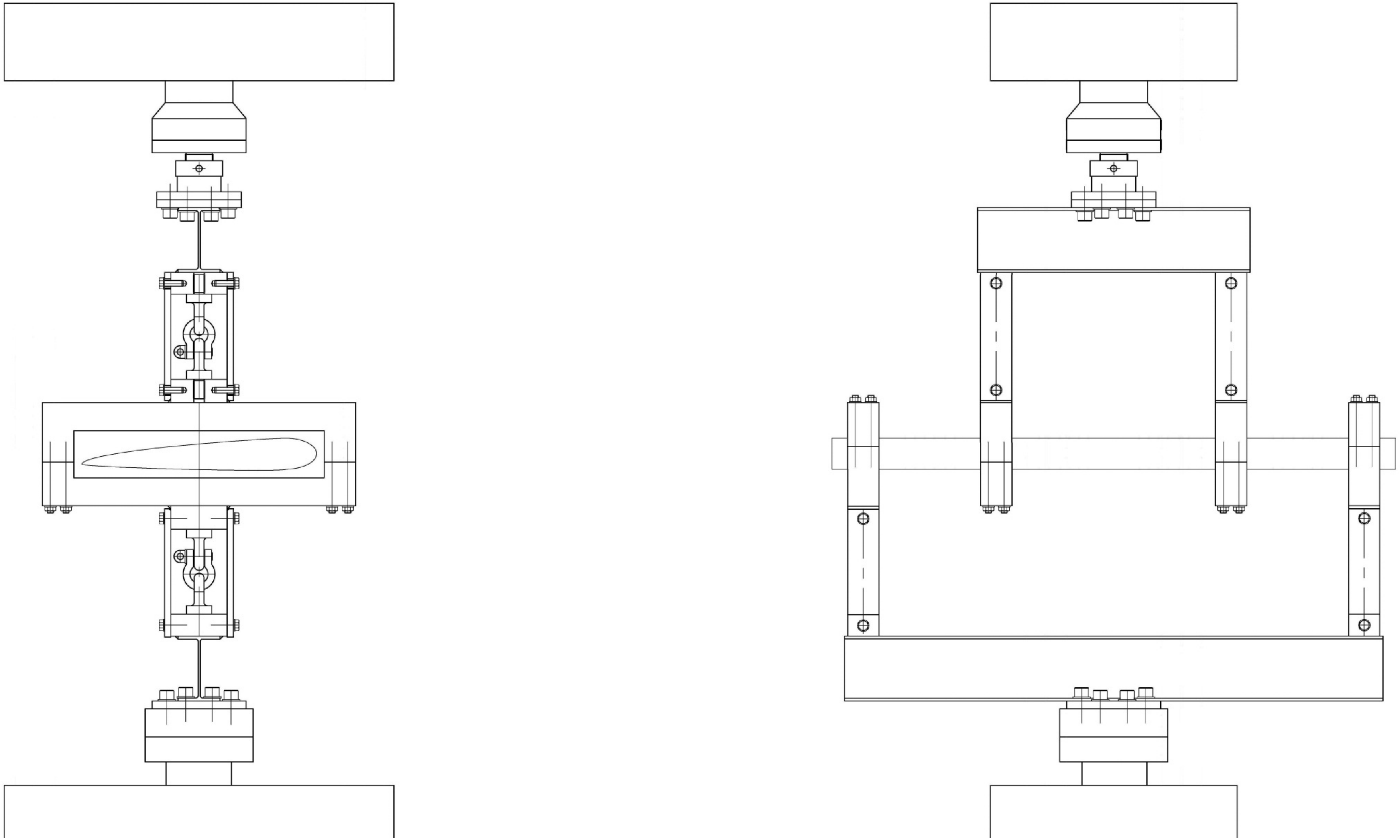


Figure 6-16 – Fixture design in four point flexural via compression configuration (redrawn from Hutchins, 2012)

6.5.2 Specimen separation

Following the initial loading to failure on the servohydraulic test machine, the specimen was further loaded to complete translaminar fracture and hence fracture separation. As the servohydraulic machine was unable to offer the range of displacement necessary for complete separation, the test fixture was partly reassembled in an open facility with a load being applied in a manner consistent with the four point bend configuration, using an electric cable drum winch.

As the wing section had already been fractured, this phase of specimen generation did not include displacement, load or strain measurements. The specimen separation was recorded however, using still and video photography to monitor the fracture progression as visible from the upper and lower sufaces. A schematic for the specimen fixture used for this phase of the specimen failure is shown in Figure 6-17. The area in the schematic identified by Z was attached to a solid surface. The point identified by a Y was attached to a 5,443kg rated max load electric drum winch. The winch was single speed with a no load line speed of 5.4m/min and a full load line speed of 1m/min. The loading was applied discontinuously such that the separation could be controlled for purposes of safety.

Upon separation the specimens were sectioned to reduce the span-wise length. The sectioning was conducted such that only the non damaged root and tip ends were removed to avoid damaging the fractured regions.

A cut sample from the left wing tip was subsequently subjected to 450°C in a furnace to burn off the resin. The decomposition temperature of the glass fibres and carbon fibres were significantly higher and hence the process removed the resin and kept the fibres in their original architectural configuration. Each layer was subsequently removed using tweezers and recorded to identify the layup of the section.

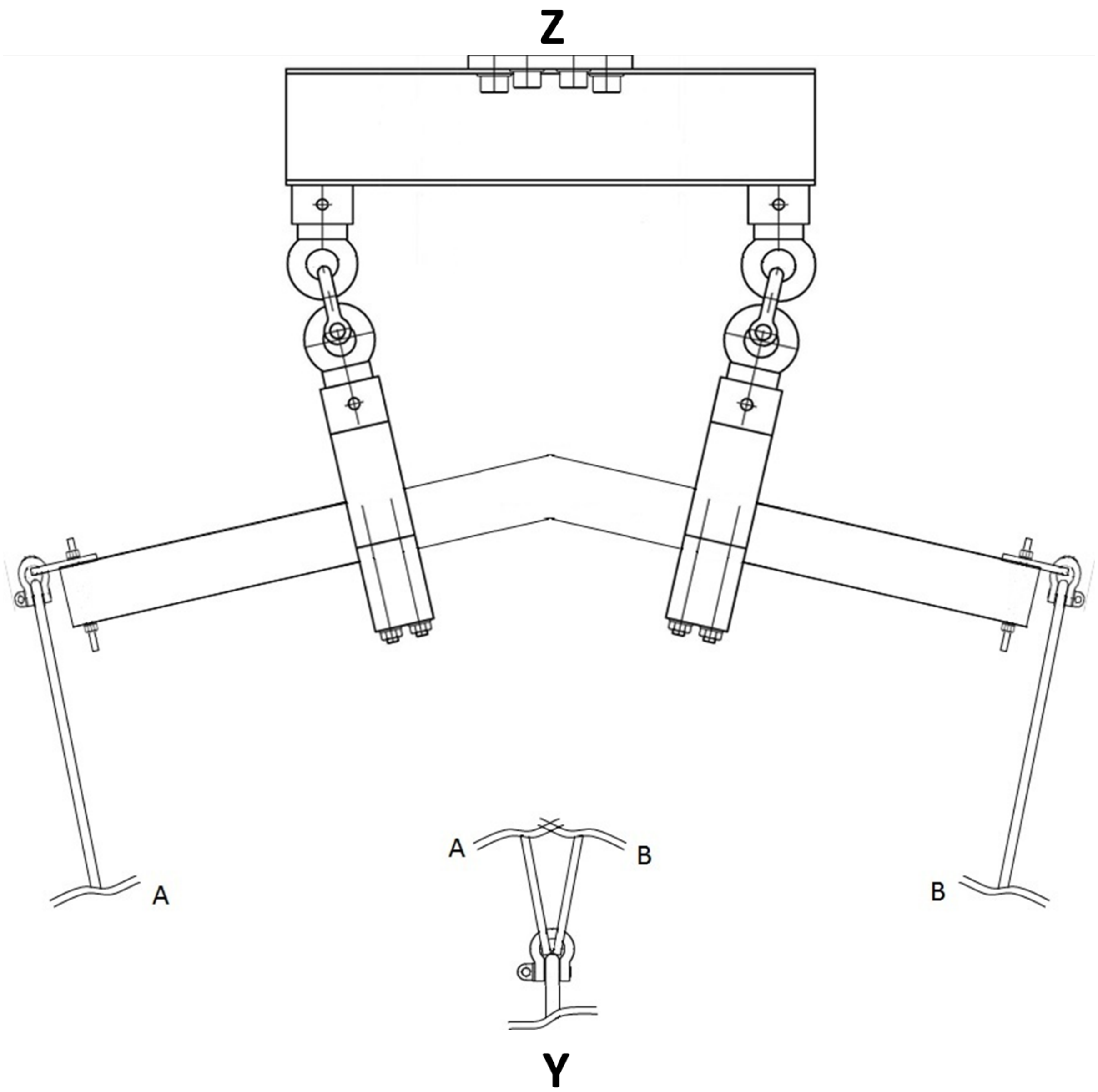


Figure 6-17 – Loading fixture utilised for the separation of the wing structure (modified from Hutchins, 2012)

6.6 Task 5 - Visual and Macroscopic Evaluation

In the investigation which follows, each mode of failure which occurred within the failed wing sections will be compared against the failure characteristics identified in chapter 5. The features identified in the failed wing sections will then be described and illustrated using macrophotographs from typical examples from the specimens. Where multiple accounts of the same failure have occurred, a typical illustrative example will be given with descriptions highlighting all of the areas on the wing from which the feature was identified. Macrophotographs will be presented for all failure modes identified to promote transparency during the examination.

This evidence will then be amalgamated with the intention of understanding available evidence which may be used to interpret the sequence of failure and highlight the failure initiation site and ultimate cause of failure. It is intended that this process should be a non-destructive examination and thus there will be no dissection of the structure to gain access to internal failures such as delaminations.

In addition to comparing the fractures with that of the characteristics identified in chapter 5, any additional characteristics identified during the examination which are not included in the literature survey from chapter 5 will be recorded and described.

The examination was conducted using standard visual examination, 12.5X macroscopic examination using an Eschenbach 12.5x / 50D /40 illuminated hand-held magnifier, and magnifications up to 25X were conducted using an Olympus SZX10 Stereo Microscope. Illumination was provided via fluorescent lamps of 6500K Correlated Colour Temperature and portable super bright LEDs. Photographs were taken using a Canon 1100D with a Canon EF-S 18-55mm 1:3.5-5.6III zoom lens and a Canon EF 50mm 1:2.5 Macro lens.

6.6.1 General description of failure

The broken specimen of the left wing section is shown in figure 6-18 (upper surface) and figure 6-19 (lower surface). The fracture is dominated by a chord-wise translaminar fracture with the presence of span-wise secondary damage. The fractured sections remained relatively intact with materials separated from the main fracture being limited to sections of the upper spar cap, the shear web and adhesive. The upper surface consists of a translaminar chord-wise fracture which is influenced by the impact location and the aileron fittings. The lower translaminar fracture is chord-wise with the exception the regions between trailing edge spar, spar cap and leading edge, where the fracture deflects to a span-wise direction. The leading edge suffered from a span-wise fracture. The right wing section failed in a similar manner albeit the deflection on the upper surface is not present and the span-wise deflection on the lower surface is more pronounced.

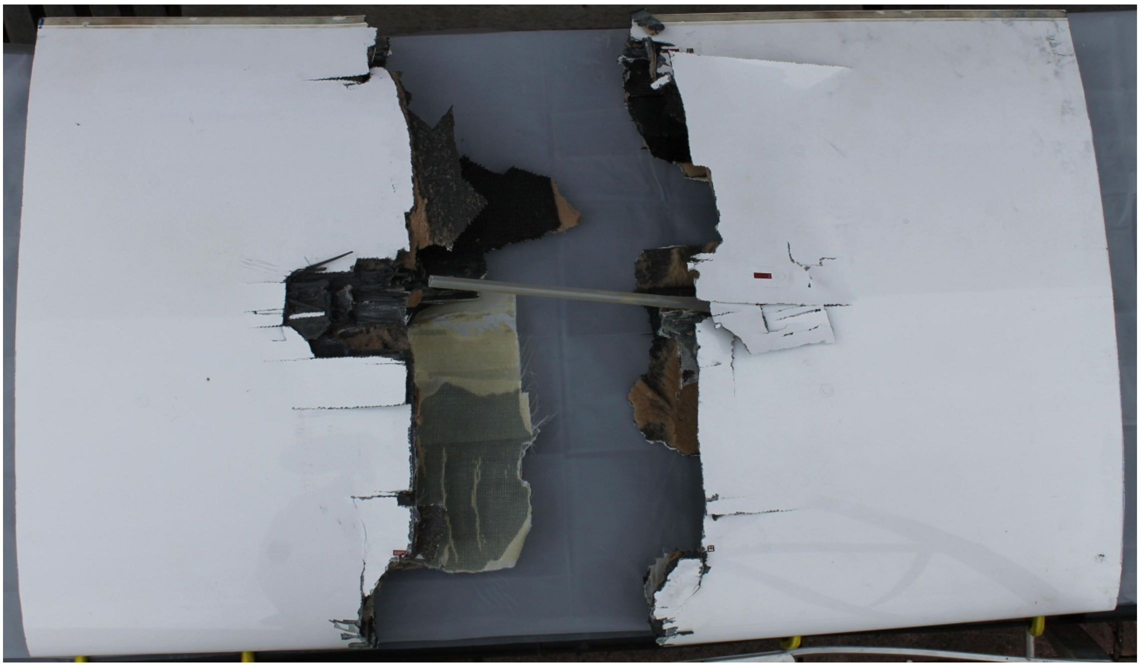


Figure 6-18 - Upper surface view of the left hand wing section (Source: Author)

Figure 6-19 - Lower surface view of the left hand wing section (Source: Author)

6.6.2 Evaluation of characteristics against those identified in the literature survey

6.6.2.1 Flexural failure of unidirectional material (section 5.5.3)

Figure 6-20 illustrates the lower spar cap from the left wing section. There are two distinct regions within the spar cap with the region closest to the lower skin showing a bright, fibrous fracture surface. The fracture surface is relatively flat with visible indications of fibre brooming across the width. The neutral axis is clearly visible and distinctly parallel to the lower spar surface.

The visual features on the lower spar cap are indicative of a tensile failure. The degree of fibre brooming between the two specimens is similar suggesting that neither fracture was significantly degraded compared to the other. The volume of fibre brooming varied across the fracture surface with the trailing edge side of the left wing lower spar cap and the leading edge side of the right wing lower spar cap have significantly shorter fibres protruding. The degree of protruding fibres increases across the surface until the opposite side of the spar cap is reached which has a considerably greater degree of protruding fibre length and longitudinal splitting. This may be indicative of the direction of crack propagation across the fracture surface, although this cannot be confirmed.

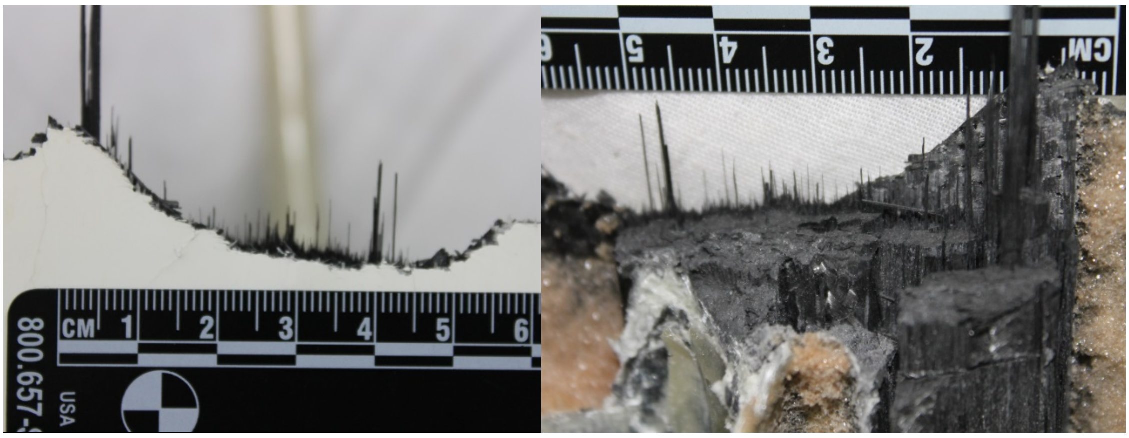


Figure 6-20 – Lower spar cap from the left wing showing characteristics of flexural failure. Note the tensile fracture surface (Source: Author)

The remaining region which represents the upper section of the spar cap shows a flat dull and stepped fracture face with a distinct absence of protruding fibres (Figure 6-21). There was evidence of longitudinal splitting occurring and the fracture surface being angled at between 20° and 45°. The dull fracture surface also appears to show evidence of debris and smearing, consistent with compression failure. The compression region of the fracture surface is also apparently larger in surface area than that of the tensile failure. This suggests that an element of global compression load may have been applied to the lower spar cap at the time of failure, although this cannot be confirmed.

Figure 6-21 – Lower spar cap from the left wing showing characteristics of flexural failure. Note the compressive fracture surface (Source: Author)

Figure 6-22 – lower spar cap from the right wing (Source: Author)

The features present on the lower spar cap are very distinct and suggest that the lower spar cap had failed in flexural failure during the failure sequence. The lower most section of the spar cap had distinct characteristics of tensile failure. The uppermost section of the spar cap had distinct characteristics associated with compression failure. The characteristics suggest the flexural loading of the lower spar cap was in the positive flap-wise orientation.

6.6.2.2 Tensile failure (section 5.5.1)

Evidence of tensile failure was apparent on the woven laminate located on the inner and outer laminates of the lower sandwich structure. There was evidence of fibres protruding, albeit to a lesser degree than noticed on the unidirectional material. The protruding fibres were predominantly located on the +/-45° plane and the 0° plane.

Figure 6-23 – Lower sandwich structure from the right wing illustrating fibre pullout. The orientation of the protruding fibres are +/-45° (Source: Author)

Figure 6-24 – Lower sandwich structure showing evidence of tensile failure. The orientation of the protruding fibres are 0° (Source: Author)

6.6.2.3 Compression failure (section 5.5.2)

The upper spar caps from both wing sections showed visible characteristics representing compression failure. The spar caps were manufactured from unidirectional carbon fibre.

Figure 6-25 illustrates the upper wing spar from the right wing section, located on the fractured section nearest to the wing root. The spar has suffered from significant longitudinal splitting and translaminar fracturing. This has resulted in significant material loss. The unidirectional fibres are also splayed out, having resulted from the fractured ends of the spar having been forced into one another. The translaminar fractures which are visible also display visible characteristics of compression failure with flat dull fracture surfaces with a distinct absence of protruding fibres (Figure 6-26). There is also evidence of material from the shear web having been forced into the fractured upper spar.

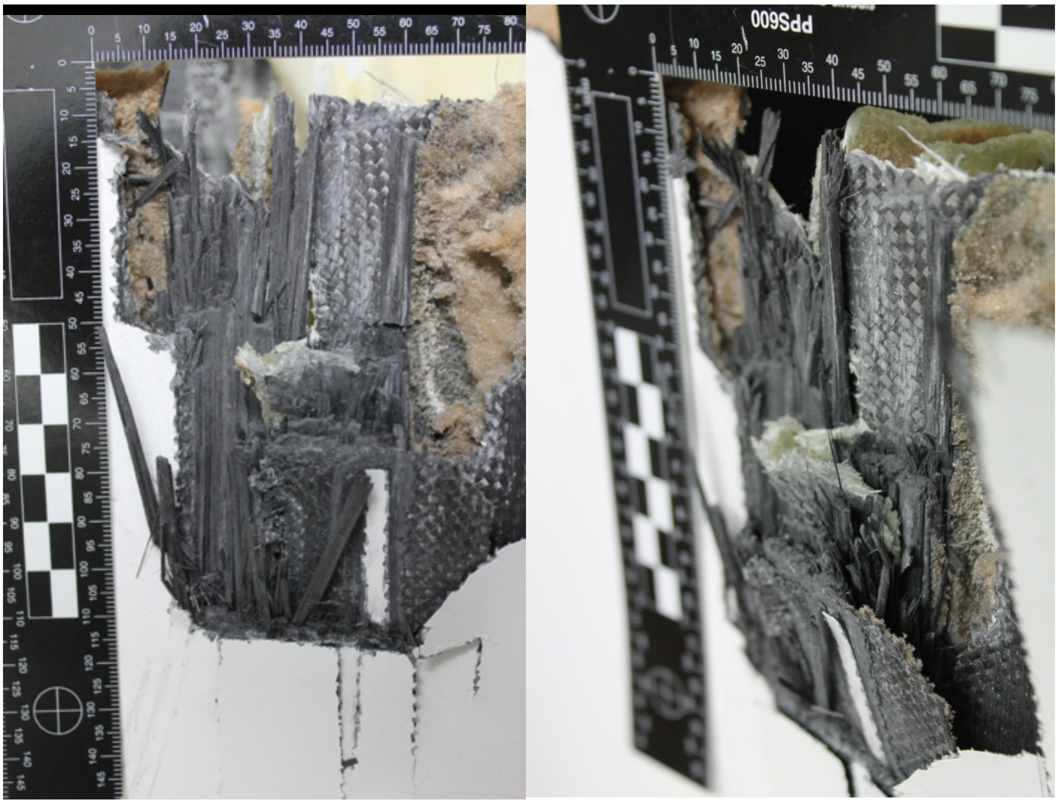


Figure 6-25 - Upper wing spar from the right wing section, illustrating significant longitudinal splitting, translaminar fracturing, brooming and material loss (Source: Author)

Figure 6-26 – Section of the lower spar cap illustrating significant longitudinal splitting and evidence of compressive translaminar fracture (Source: Author)

The features present on the upper spar cap are very distinct and suggest that the upper spar cap had failed predominantly in compression with evidence of significant post fracture splitting as the spar had continued under compression post fracture.

The upper aerofoil section fractured and separated chord-wise extending the whole width of the wing section, extending through the impact site and into the upper spar cap. The fracture was predominantly perpendicular to the span of the wing section. In the left wing specimen the leading and trailing edge sections where the fracture was displaced towards the root. The deflection of the fracture at these locations was approximately 50mm in the span direction and for the trailing edge deflection occurred as though deflecting around the structural reinforcement of the aileron hinge attachment. The surfaces were flat with limited evidence of protruding fibres. Of the fibres which were protruding, most were predominantly deformed out of their original plane.

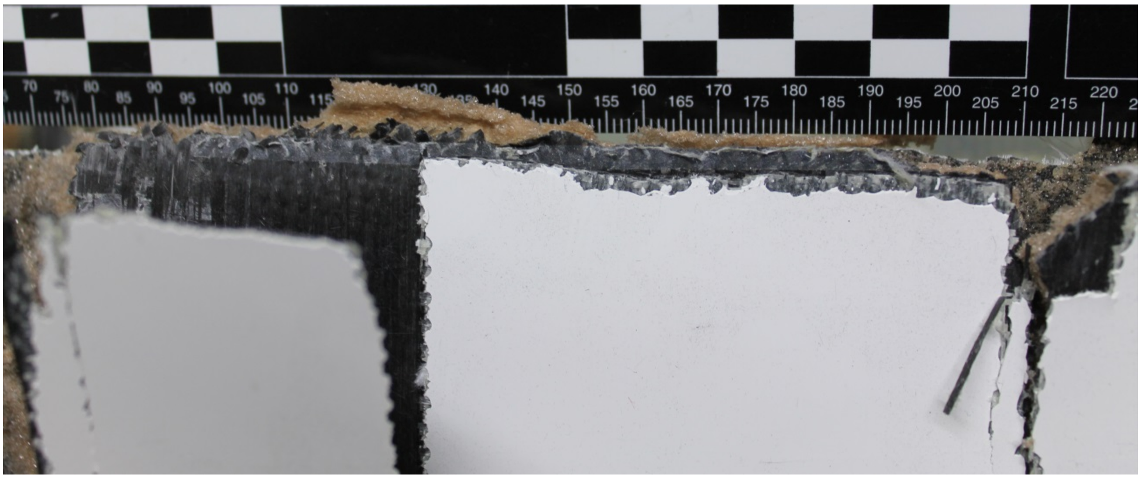


Figure 6-27 - Upper sandwich structure fracture surface from the upper wing surface (Source: Author)

6.6.2.4 Translaminar shear (Section 5.5.4)

The unidirectional spar caps and the sandwich laminates were examined for evidence of translaminar shear. A visual examination was conducted throughout the specimen. Although the upper spar caps suffered from significant longitudinal splitting, the deformation and brooming of the fibres was inconsistent with shear being applied.

A macroscopic examination up to x25 was conducted on the +/-45° plies which had undergone tensile failure. No evidence of in-plane shear was identified.

6.6.2.5 Interlaminar Shear & peel region (sections 5.5.5 & 5.5.6)

The areas local to the impact site were examined for evidence of a peel and shear boundary which may suggest the presence of an impact. On both specimens there was evidence of smearing, material loss and sharp variations in the fracture plane. As a result of these it was not possible to identify indications of the impact from the existence of a peel and shear boundary.

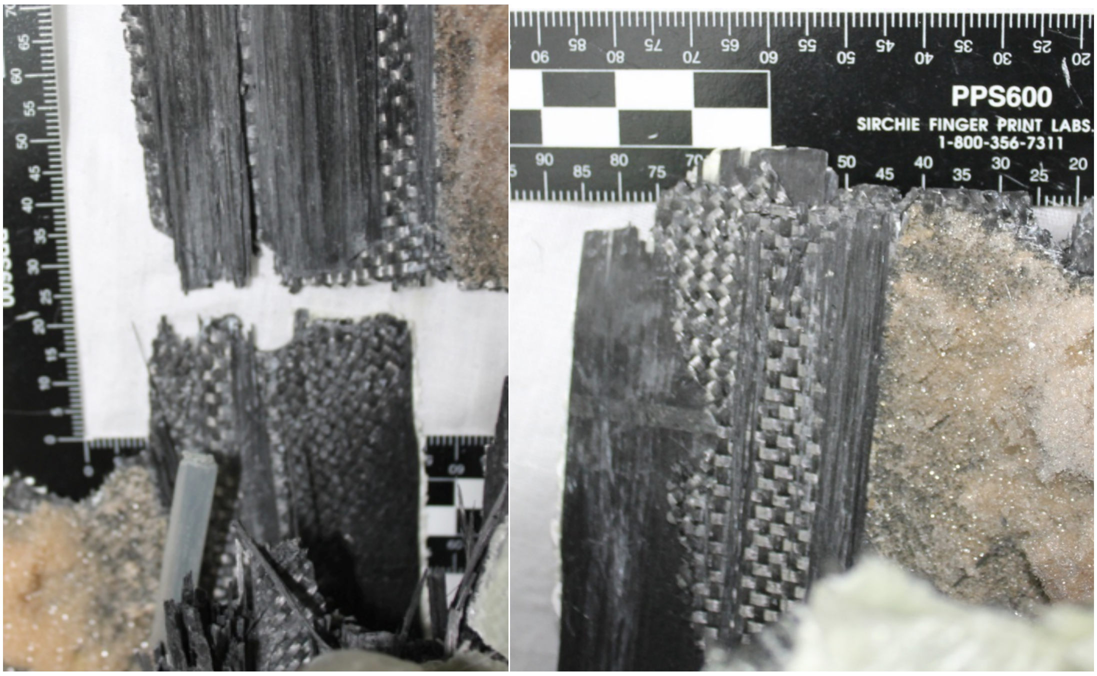


Figure 6-28 – Regions of impact damage. The penetrating damage on the left wing (left image) and the blunt impact damage to the right wing (right image) (Source: Author)

The remaining structures were examined for the presence of interlaminar peel failure, shear failure and a peel / shear boundary. The majority of the intralaminar fractures appeared as glossy and dark reflective surfaces. This suggests that the majority of the intralaminar surfaces were peel failures. There was however evidence of regions within close proximity to the lower and upper spar caps immediate to the chord-wise fracture, as having a lighter less reflective appearance. This may suggest that these regions failed in shear failure although a change in appearance due to abrasion cannot be ruled out.

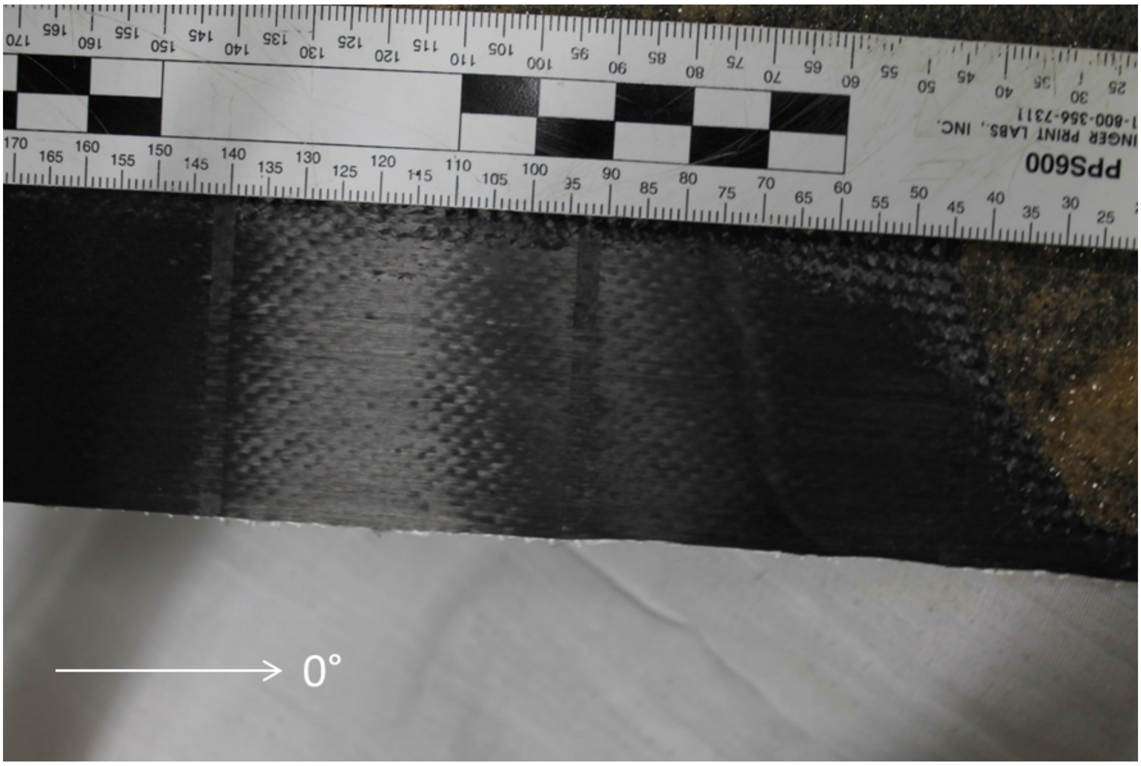


Figure 6-29 – Glossy reflective appearance of an interlaminar failure. The failure plane is along the 0° orientation (Source: Author)

6.6.2.6 Fatigue (Section 5.5.7)

The specimens were examined for evidence of fatigue failure. Whilst glass fibre was a constituent of the specimen, its use was predominantly restricted to internal plies within the laminate. Moreover, the visible interlaminar fractures occurred within the carbon fibre laminates leaving few translucent fracture surfaces visible.

The exception was the shear web which was constructed of glass fibre woven laminates. The laminate also joined the lower sandwich skin and hence presented a translucent layer above the opaque carbon fibre skin. Upon examination there was evidence of the whitening or frosting appearance where the material had fractured (figure 6-30), including where a polymer tube had pulled through laminate. The area around this which had not fractured had a distinct difference in visual appearance as there was an absence of the whitening. This absence of whitening from the internal structure suggests that the glass fibre structures within the laminate have not undergone widespread micro-cracking.

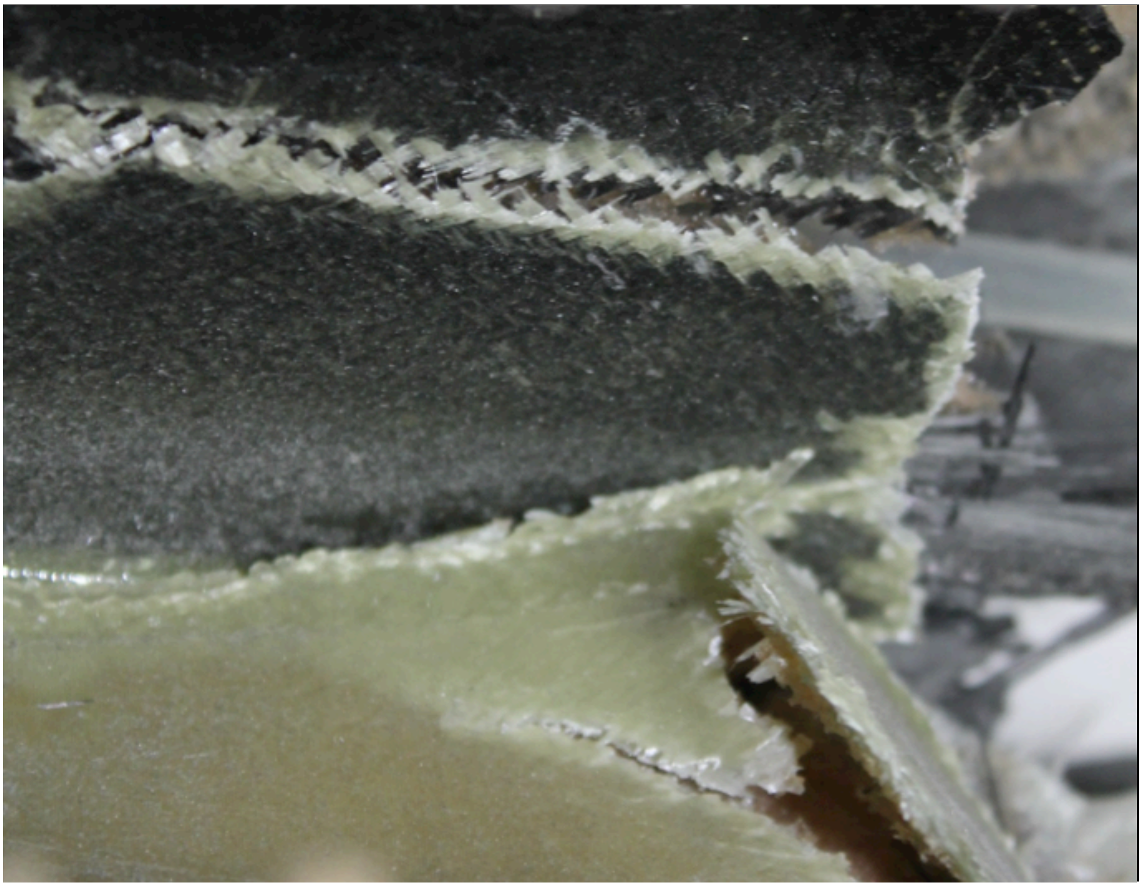


Figure 6-30 – Internal fracture of the shear web (bottom of picture) and the upper laminate skin (Source: Author)

6.6.2.7 Lightning strike (Section 5.5.8)

The visible characteristics associated with arcing and heat effects could not be identified on the fracture surfaces. Visible signs of arcing (sooting and penetration) could be identified on the surface of the left hand specimen although this was located at some 18cm from the primary chord-wise fracture and 5cm from the nearest span-wise fracture (Fig 6.31).

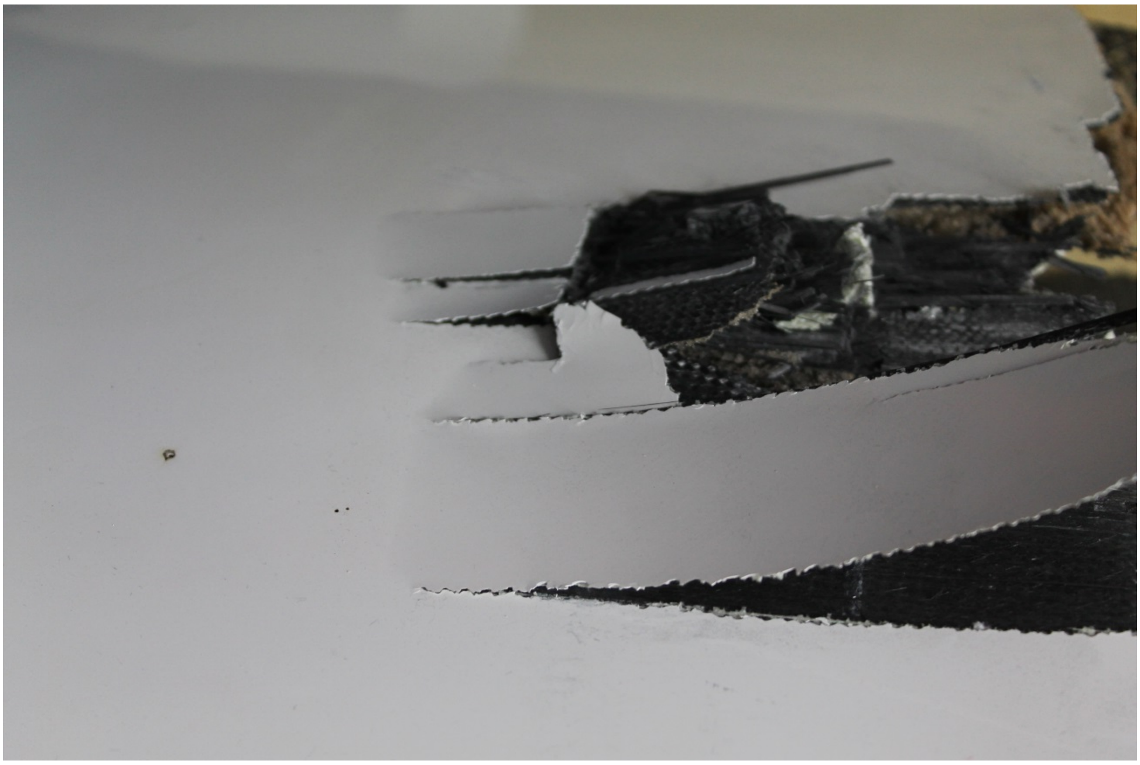


Figure 6-31 – Left wing upper surface. The point of arcing is visible on the left hand side of the image (Source: Author)

6.6.2.8 Manufacturing defects (Section 5.5.9)

During the 3D CT examination of the specimen, the lower spar cap of the left wing was identified as having a non-symmetric placement. This was confirmed by examining the cut section of the spar cap. Upon examination of the lower spar it was apparent that although the spar had failed catastrophically, the non-symmetric placement could still be identified (Figure 6-32)

The visual examination of the translaminar fracture surfaces could not identify voids, areas of porosity or indications that the fracture profile had been altered by the existence of an anomaly. This cannot confirm that voids were not present as the compression fracture is plausible to obliterate their presence.

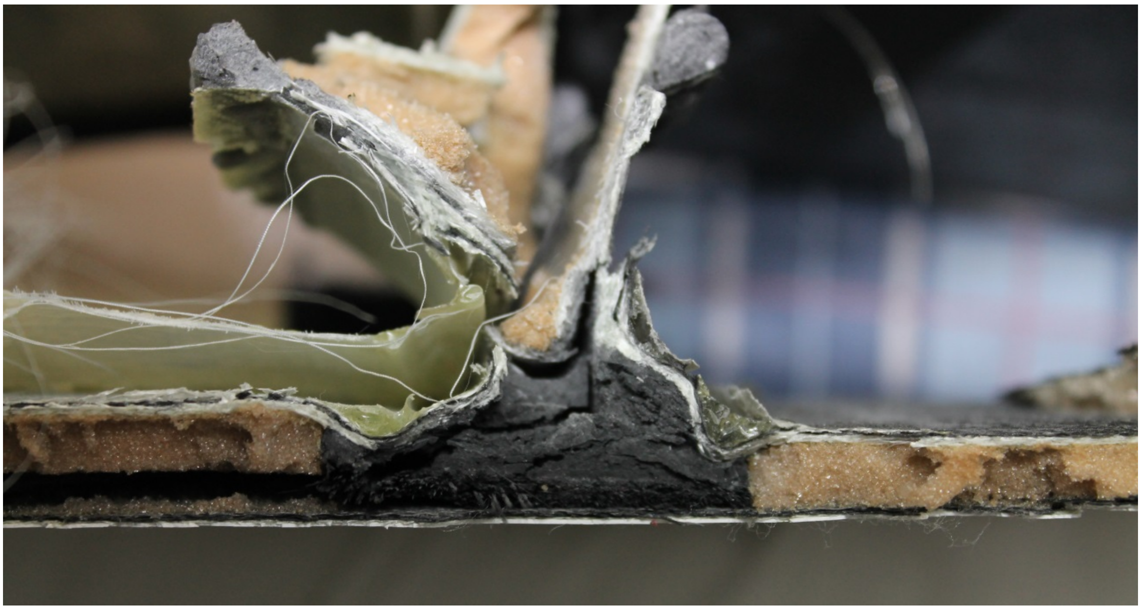


Figure 6-32 – Left hand wing lower spar cap (Source: Author)

6.6.2.9 Environmental Effects (Section 5.5.10)

The structure was examined for evidence of environmental degradation. There were no apparent localised changes in hue, evidence of swelling or evidence of thermal effects.

6.6.2.10 Impact (Section 5.5.11)

Both wing sections were subjected to impacts on the upper spar cap prior to loading. The right wing was subjected to an impact associated with a blunt impact and the left wing was subjected to a partially penetrating impact. In both instances the wing sections fractured at the location of the impacts.

During the failure process the unidirectional upper spar caps were severely disrupted resulting in substantial loss of material. It is likely that a significant volume of the unidirectional material which had been directly in the impact zone had been forced into the corresponding fracture surfaces. Thus, a portion of the impact zone is unlikely to be identified without permanently disrupting the fracture. Moreover, this could not be guaranteed as the fibres which had been in the impact zone may have been shed during the failure process. Figure 6-33 illustrates sections of unidirectional upper spar cap which are known to have resided in the original impact zone.

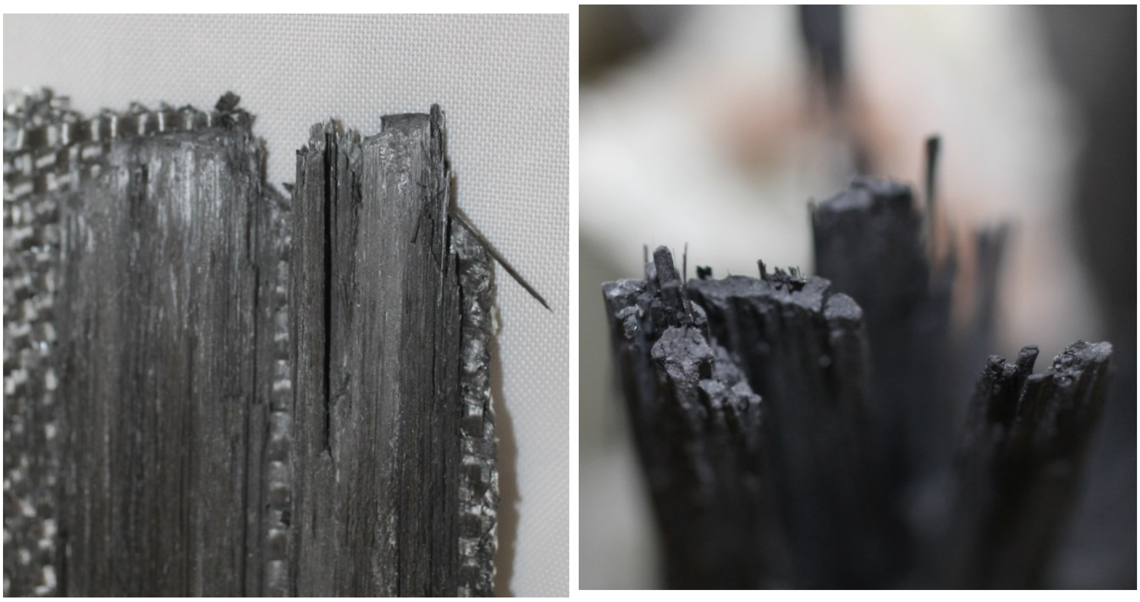


Figure 6-33 – Translaminar fractures of unidirectional fibres identified as occurring on the primary fracture within the impact zone (Source: Author)

From the few sections of unidirectional material located within the original impact zone as illustrated, there was little evidence to suggest an impact had occurred. This supports the known visual and macroscopic mechanisms of recognising impact damage which are predominantly based on the pre-translaminar fracture inspection of impacted composite materials.

The upper skin, which is a multidirectional laminate, is located above the unidirectional spar cap and thus is the first point of impact. During the failure process the laminate survived relatively intact and in addition the impact influenced the translaminar fracture crossing the impact region of the upper skin.

Figure 6-34 illustrates the post fracture impact region from the semi-penetrating impact occurring on the right wing. The translaminar fracture intercepting the impact location is the primary chord-wise fracture. The chord-wise fracture was the point of primary translaminar separation within the specimen and thus the impact site was separated between the specimen root section and specimen tip section. The left image illustrates the separated pieces placed in close proximity with the leftmost piece being from the tip section and the rightmost piece being from the root. The right image illustrates the two pieces placed together, although separated slightly in the through thickness direction.

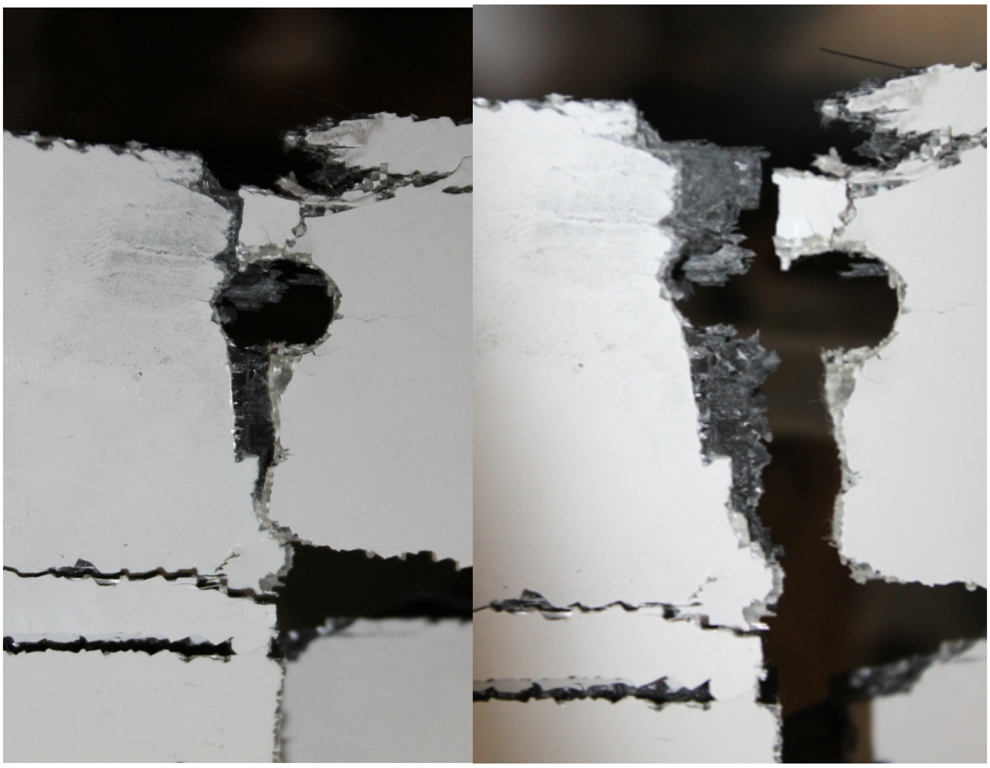


Figure 6-34 – Left wing upper laminate from the impact location (Source: Author)

When comparing the pre-fracture and post-fracture conditions, it is noticeable that the post-fracture state has remained relatively well preserved compared to the pre-fractured characteristics (figure 6-35).

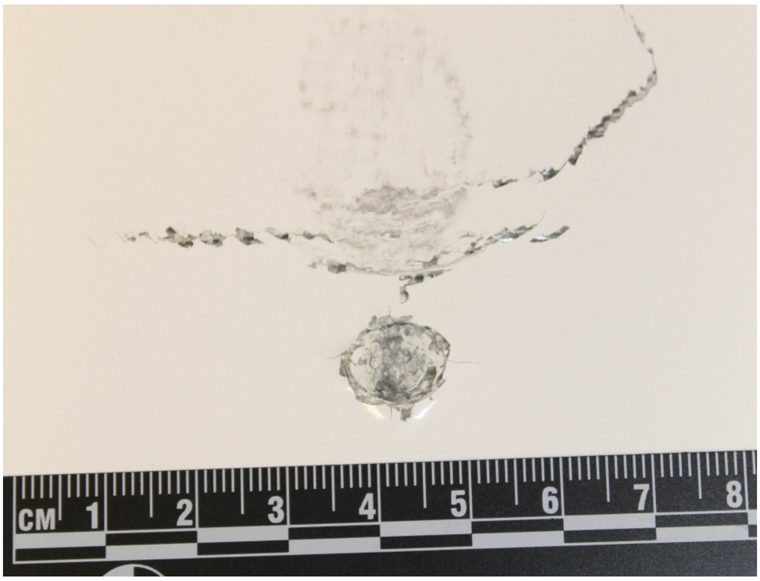


Figure 6-35 – Left wing upper surface impact location (Source: Author)

The impact location is relatively easily distinguishable compared to the chord-wise translaminar fracture. Figure 6-36 illustrates the location of impact on the tip section of the specimen. This illustrates the visible semi-circular pattern of the impact location against a relatively straight chord-wise fracture.

Figure 6-36 – Left wing upper surface. The impact location can be identified as a semi-circular cut-out in the top centre of the image (Source: Author)

Figure 6-37 illustrates the post fracture impact region from the blunt impact. The translaminar fracture intercepting the impact location is the chord-wise fracture. This chord-wise fracture is the point of primary translaminar separation within the specimen and thus the impact site was separated between the specimen root section and specimen tip section. The post fracture separation has resulted in the translaminar fracture appearing to circumvent the blunt impact location. This has created a visible change in the characteristics of the otherwise primarily straight translaminar fracture (Figure 6-37 & 6-38).

Figure 6-37 – Deflection of the translaminar fracture induced by the impact (Source: Author)

Figure 6-38 – Right wing upper surface. The impact location can be identified as a semi-circular fracture deviation on the top centre of the image (Source: Author)

6.6.2.11 Bonded joints (Section 5.5.12)

Both specimens were examined for failures within the bonded areas. Areas thought not to contain structural bonding were not included in the examination.

Internal fracture of the sandwich areas occurred predominantly through core failure. The trailing edge from the right hand root section exhibited adherend and a mixed cohesive / adhesive failure. There was no gross evidence within the structure associated with the smooth glossy features associated with inadequate bonding.

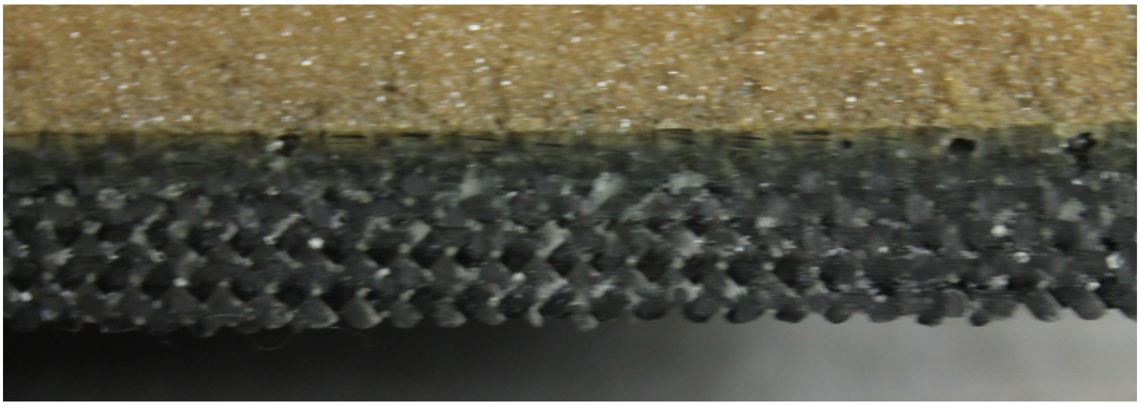


Figure 6-39 – Bonding failure of the trailing edge (Source: Author)

6.6.2.12 Radials (Section 5.4.1)

The translaminar unidirectional fracture surfaces that had failed in tension were rough and fibrous, thus radials were not visible.

6.6.2.13 Chevron Features (Section 5.4.2)

The multi-directional laminates located in the lower translaminar fracture surface were examined for evidence of chevron patterns. Upon examination it was evident that the woven laminates had fractured on multiple laminate layers and thus a clear fracture plane was not visible. The chevron patterns hence could not be identified.

6.6.2.14 Continuity of fractures (Section 5.4.3)

The fracture of the upper aerofoil section was predominantly perpendicular to the span of the wing section.

In the left wing specimen, the leading and trailing edge sections where the fracture was displaced towards the root.

The deflection of the fracture at these locations was approximately 50mm in the span direction. The trailing edge deflection occurred as the crack propagation was influenced by the structural reinforcement of the aileron hinge attachment.

6.6.2.15 Compression cracking (Section 5.4.4)

The upper surfaces of the wing were examined for evidence of compression cracking. It was identified that the upper most layer of fibres were of woven fabric orientated 0° / 90°. Greenhalgh & Cox (1992) suggests this configuration is unlikely to produce meaningful information. The examination was unable to identify evidence supporting the appearance of compression cracking. The examination was conducted visually and macroscopically.

6.6.2.16 Tide Marks (Section 5.4.5)

The intralaminar fracture surfaces were examined for evidence of tide marks. The feature was not visually evident which is to be expected as the banding typically occurs in toughened thermosets and thermoplastics.

6.6.2.17 Crack bifurcation (Section 5.4.6)

The upper surfaces and shear web were examined for evidence of crack bifurcation. Whilst span-wise fracturing was evident around the chord-wise fracture, the occurrence of crack bifurcation was not identified within the structure.

6.6.2.18 A tendency to follow the 0° interface (Section 5.4.7)

The interlaminar surfaces were examined for evidence of crack propagation along the 0° interface and for a transition to a 0° interface. In all cases of interlaminar fracture, the fracture either originated within the 0° plane or transitioned towards the 0° plane. Moreover, the transition tended to occur from the +/-45° laminate into the 0° laminate with the transition occurring in line with the 45° fibre orientation (figure 6-40).

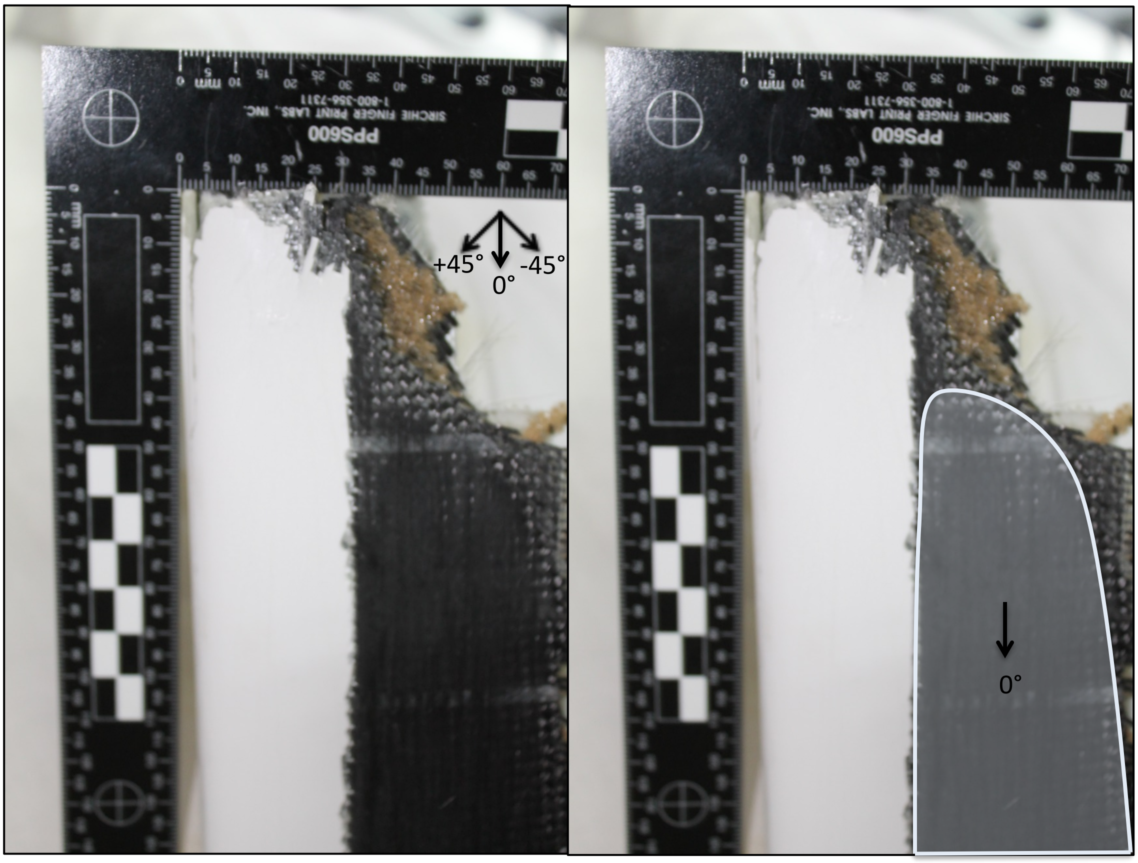


Figure 6-40 – A fracture showing the tendency to move to a 0° laminate (Source: Author)

The exception to this was where the interlaminar fracture growth was influenced by a structural feature or pre-existing damage mechanism. For example where the interlaminar fracture had intercepted a loading point, it was apparent that the loading point had created a chord-wise fracture. Where an interlaminar fracture intercepted this location the fracture jumped from a 0° plane into a +/-45° plane. The jump had occurred due to the translaminar fracture in the 0° plane in effect representing a 90° orientation which would promote the transfer of the crack growth plane.

Where two interlaminar cracks which were transitioning parallel but through separate layers intercepted, there was a tendency for the region between the two crack fronts to contain an intralaminar fracture within the intermediate plies between the two cracks. Thus this represented a narrow band of interlaminar fracture contained within a ply of +/-45°.

6.6.2.19 Serrations (Section 5.4.8)

The structure was examined for serrations either created on the surface finish, or within interlaminar peel and shear boundaries.

There was evidence of serrations created due to the fracturing of the gel coat. The serrations were predominantly evident on the span-wise fractures of the upper surface, with the configuration of the serrations suggesting fracture moving outwards from the primary chord-wise fracture to the root and tip sections. The serrations were indistinct along the entire fracture and thus it was necessary to consider the majority as representing the probable propagation direction. It should be noted however that the features were not supported with an academic foundation and thus were unable to suggest a failure mode or crack propagation direction with any degree of certainty.

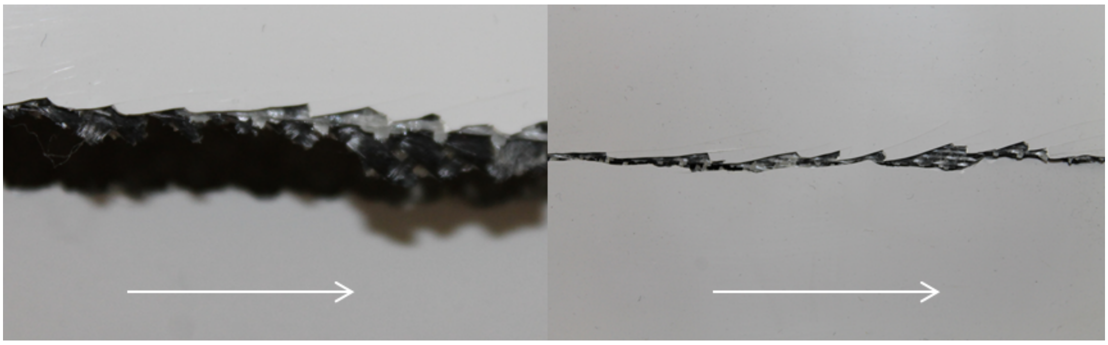


Figure 6-41 – Evidence of serrations on the upper gel coat (Source: Author)

The features were also evident on the chord-wise primary fracture although the features were significantly fewer and hence unable to provide evidence of tearing or crack propagation direction.

6.6.2.20 Effects of stress raisers (Section 5.4.9)

The most prominent and important stress raiser which occurred on the structure was the impact location. It was evident in both specimens that the translaminar fracture had directly intercepted the locations of the impacts. It can therefore be postulated that the impact locations were aligned with the primary path of fracture, and hence likely to have initiated the fracture, rather than influenced an already occurring fracture. This case is strengthened when considering the design of the test rig and the location of impact within the test specimen.

In the case of a four-point bend fixture, the theoretical bending moment is constant between the middle yokes (Hodgkinson, 2000) (figure 6-42). However, whilst the test fixture was designed such that the point stresses induced by the yoke were minimised, it was not possible to remove this in its entirety. Thus, the most likely failure scenario was at the centre or outer yokes located on the outer wing tip, where the spar was of smaller cross-section than the root. This is supported by the fact that all experiments that did not fail in the centre of the wing section did so instead at the location of the yoke.

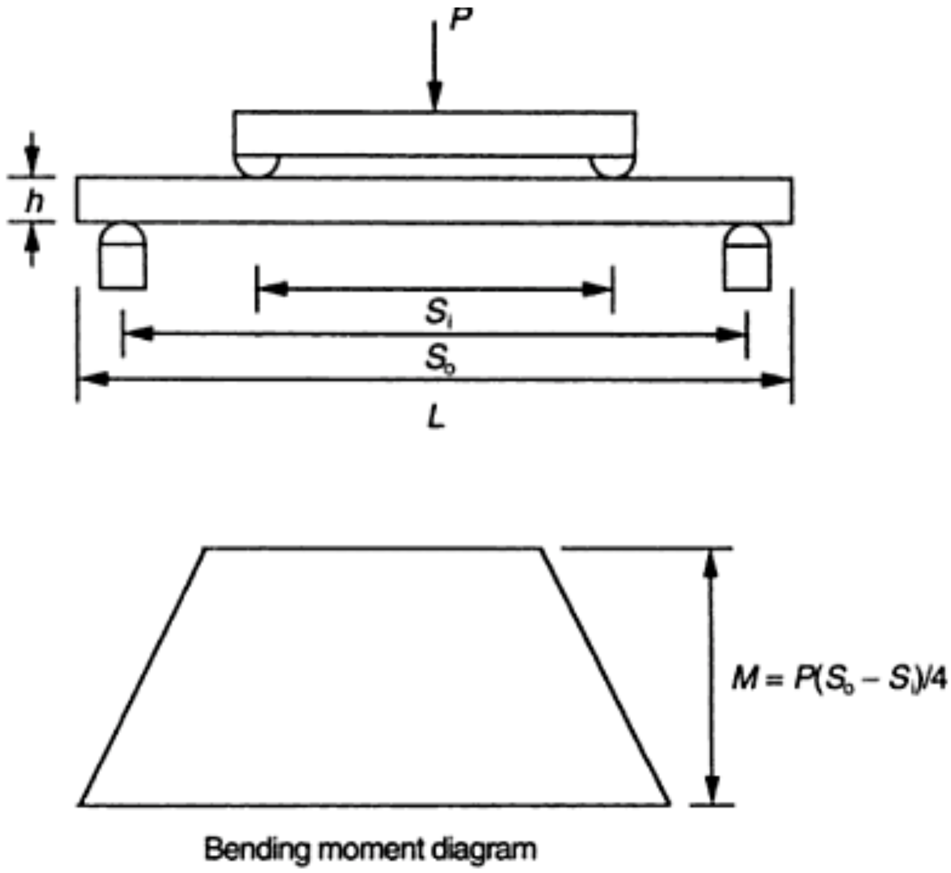


Figure 6-42 – Four point test fixture with bending moment diagram (Hodgkinson, 2000) (Source: Author)

Furthermore, the fracture path did not visibly intercept any prominent features on the wing sections that may have acted as a stress raiser. Hence, when considering the nature and extent of the degradation mechanisms applied, it is probable that this directly influenced the failure of the wing section.

6.6.2.21 Differentiating between different failure zones (Section 5.4.10)

The specimens were examined initially from a gross scale (visually) and then examined macroscopically for evidence of local failure zones. Visually, there was clear evidence of different modes occurring.

The lower aerofoil section fractured and separated chord-wise extending the whole width of the wing section. The leading edge, trailing edge and lower spar cap areas had similarly failed perpendicular to the span. The sections in-between, which represent unreinforced sandwich skin areas, have suffered fractures extending span-wise releasing a ‘U shaped tab’ of material. The width and depth of the trailing edge tab are approximately 60mm and 200mm respectively and the width and depth of the leading edge tab are approximately 90mm and 150mm respectively. Within the span length sides of these tabs, the composite has failed at an angle with the inner face of the composite representing the widest part of the angle.

Figure 6-43 – Lower surface of the left wing (Source: Author)

The review of images and video footage take during the fracture and subsequent separation process confirmed that these features were created late in the failure sequence, and thus they can be used to deduce the failure sequence. During flexural loading the primary load was taken by the spars located in the leading edge, trailing edge and central spar caps. During failure, the translaminar fracture propagated chord-wise from these regions. As the upper and lower load bearing spars lost their load carrying capability, the flexure of the wing became more extreme. The longitudinal tensile loading on the skin regions between the spars thus changed to have an increasing degree of through thickness tearing component. The tearing component then dominated the subsequent failure and thus the crack propagated with a significant span-wise direction.

It can be deduced from this feature that the spars failed prior to the wing skin which failed later in the sequence. This feature may be of benefit if the wing skin, or perhaps the leading edge or trailing edge spar, had failed prematurely. In this case the wing skin is likely to have a chord-wise fracture in the region of premature failure.

6.6.3 Identification of additional features - Permanent deformation

Composite materials are classed as brittle materials and hence during failure tend to undergo limited plastic deformation. To this end literature on macroscopic and visual interpretation of composite material failures has not discussed the aspects of permanent deformation or a retained change in shape which may occur due to fracturing or physical restriction from returning to the original position. It is apparent that permanent deformation occurred in the fractured specimens with implications which offer significant assistance in understanding the failure of the structure.

The multi-directional upper skin laminate underwent significant permanent deformation in places without significant visible translaminar cracking occurring in the deformed regions. Subsequent to lightly pressing the surfaces the deformed sections returned to their deformed shape. The deformation was present on the upper surfaces of all specimens. However it was more prominent on the specimens which had ‘tab’ sections of the wing skin removed. Therefore the deformation suggests that the upper wing skins had undergone a bending motion in the positive flap-wise orientation in respect to the wing layout.

Figure 6-44 – Leading edge of the right wing specimen (Source: Author)

In addition, the upper spar cap on all sections had evidence of being deformed in the same direction as the upper skin (Figure, 6-45). The deformation of the spar was different however, with indications of both curvature of the unidirectional material and fibres having pivoted about translaminar fractures located further into the spar cap. The movement of unbroken fibres back to the original position is apparently restricted by the fibres which had been fractured and forced into the new position. This indicated that the upper spar cap had been defected in the positive flap-wise orientation.

Figure 6-45 – Deformation of the upper spar cap from the right wing (Source: Author)

Further evidence of fractured movement within the material creating a record of permanent deformation is visible in a polymer pipe which had been forced through the upper wing sandwich lower skin. The polymer tube had fractured and remained within the sandwich structure (Figure 6-46). This was consistent with the tube being pulled through the lower skin section of the upper sandwich.

Figure 6-46 – Pull through of a polymer tube inducing fracture of the upper skin lower laminate (Source: Author)

6.6.4 Identification of the failure sequence

The objective of this phase of the research is to examine a complex failure to identify what information may be available to assist the investigation practitioner in understanding composite wreckage. The identification of failure characteristics has been based on knowledge from a literature survey (chapter 5). The following is a description of the failure mechanism and failure mode from the information identified during the examination.

- The primary fracture occurred distinctly chord-wise suggesting limited torsional failure.
- The global deformation and visual fracture features suggest the wing failed due to positive flexural loading.
- The lower spar failed in positive flexure, suggesting that the upper surface failed first and in compression. Moreover, following the compression failure of the upper wing, the wing continued in positive flexural loading with the wing pivoting about the lower spar.

- The lower skin failed subsequent to the load bearing structures and failed late in the fracture sequence when the wing had undergone significant bending.
- There were no indications of premature failure from environmental, bonding or fatigue mechanisms.
- Although the upper spar cap was heavily disrupted, the upper skin recorded evidence of impacts occurring on the upper spar cap. The impact sites intersected the fracture cleanly and thus are likely to have been involved in the fracture, rather than influencing an already occurring fracture.
- The evidence was seen on both specimens in the same context suggesting the specimens had both failed in the same manner.

6.6.5 Examination summary

It can be concluded that the examination of the structure has identified the presence of visual and macroscopic characteristics. From the identification of these individual characteristics it was possible to develop a scenario, based on facts, as to the failure sequence of the structure. There are however some significant issues which, when considered against the understanding of polymer composite failure characteristics as developed during the literature survey, are likely to present some significant challenges and issues to the accident investigator. These are discussed below.

The fragmentation of the polymer composite structure is likely to present significant issues to the identification of the characteristics. By the nature of the four point bend test design the fragmentation of the composite structure was conservative. For example, the specimen was not subjected to airflow, nor was it subjected to ground impact damage. Both of these processes are likely to either remove material from the fracture surface or add further damage to the existing surface, especially as the fractured regions are already significantly degraded. This is likely to provide less of an issue to some of the features such as the gross permanent deformation, as the bulk of the characteristic may still be available.

An area which provides concern is the impacted region. The impacted regions were significant both by nature of the energy and of the visual characteristics prior to fracture. Moreover, they provided initiation sites from which the failure occurred. Within this region both loss of material occurred as well as substantial secondary damage. This reduced the volume of visual and macroscopic information available from which an interpretation can be made. Furthermore, if further loss of material had occurred due to airflow then the few pieces of material remaining from which to provide an indication of the impact may have been removed. In this instance, if a piece of the wing skin had been removed which identified the impact, it would be very improbable that the identification of an impact could be made. Moreover, if a ground impact had occurred on the fracture surface, further secondary damage may be introduced into the impact area which could further reduced the ability to identify the impact region.

It is therefore apparent that whilst the fracture sequence can be obtained using evidence from multiple areas of the structure, the ability to identify a region of local degradation is likely to be of significant issue to the investigation. This is because the local degraded region is likely to be the only evidence available of the occurrence and it will likely be subject to significant secondary damage. If this area is subsequently heavily disrupted during ground impact or removed in-flight during the breakup sequence, then the only evidence of the degradation may appear as a small piece within the wreckage trail, or appear inconspicuously within the wreckage.

This suggests that it is imperative that understandings of the failure mechanisms and structure design, including those that include degradation, are provided to the investigator. From this, the investigator will be in a position to make better founded decisions earlier on in the investigation to aid in evidence gathering and preservation. From this perspective the investigator may be asking the questions as to “how much material loss has occurred in this section and hence do I need to locate the remainder?”. This is a time dependent question which the investigator needs to ask in the field, rather than after the wreckage has been recovered, otherwise the opportunity may have been lost.

6.7 Summary

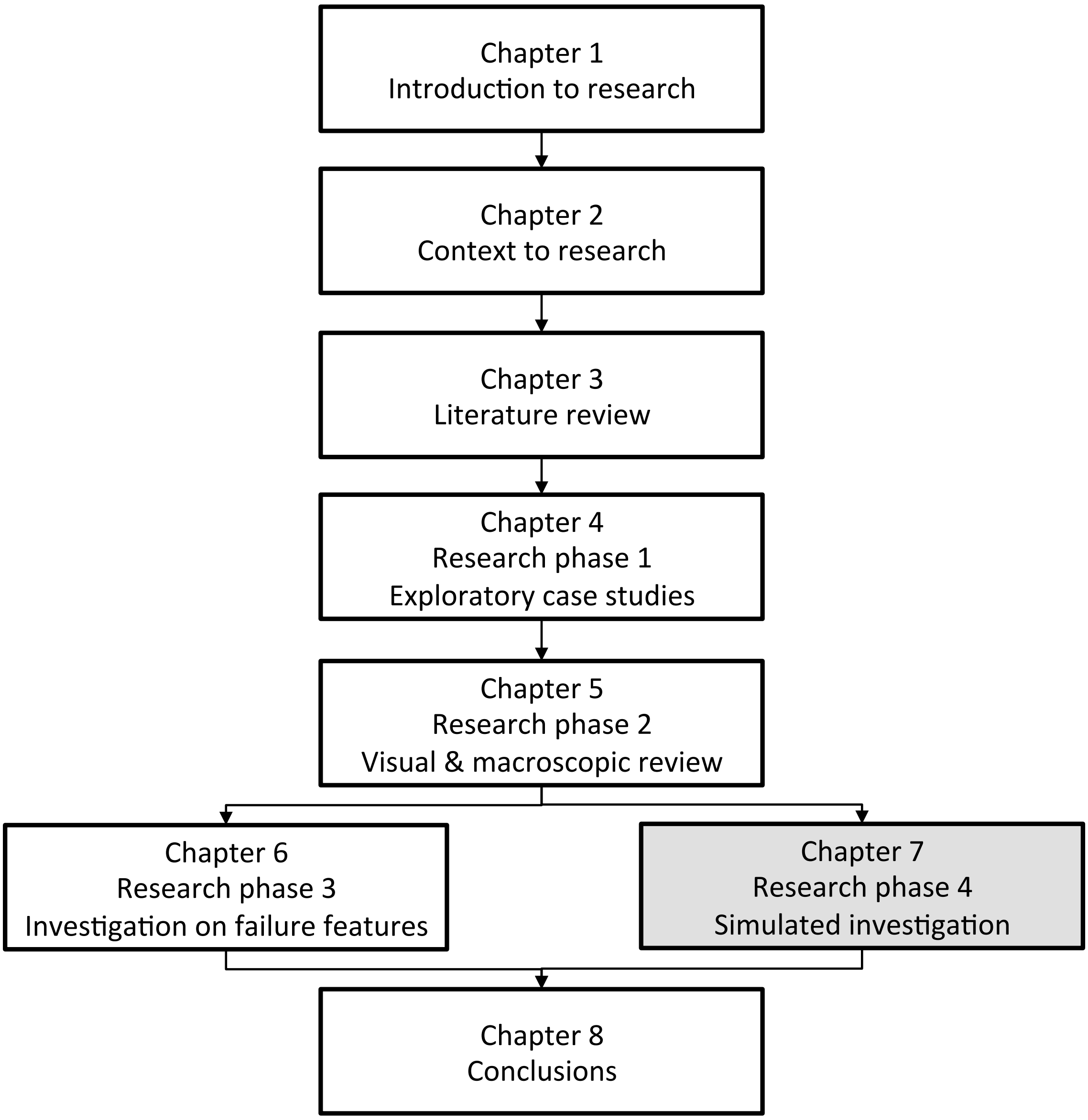
The examination has illustrated the application of visual and macroscopic interpretation to successfully illustrate the failure sequence of a complex composite structure. Whilst the fracture mode was known by the researcher the examination relied on the identification of specific characteristics, as detailed in chapter 5, to confirm the failure sequence and probable location of failure initiation. The interpretation of the failure was within the context of the investigation practitioner rather than the subject matter expert and was restricted to magnifications of 25X.

The examination suggested that the specimens had failed in positive flexural loading with limited torsion. The fracture initiated at the upper surface with the flexural loading continuing but pivoting about the lower spar cap. The upper spar cap subsequently suffered significant disruption as the surfaces were forced into one another. The upper surface fracture had coincided with evidence of impact damage on the upper spar cap which is likely to have been the initiation point for the fracture.

The examination identified limitations. Firstly the interpretation of the crack growth direction through the use of visual and macroscopic examination was limited. Secondly the failure scenario did not include all failure mechanisms (e.g. hygrothermal effects), and thus while the examination presented information suggesting that the mechanisms were absent, it was unable to be tested in a scenario where all of the mechanism was present. It should be stressed therefore that whilst the investigation in this phase illustrates the successful use of the characteristics within a single case of two specimens, it was not tested in all fracture scenarios, all materials and all architectures. To do this would be impractical. Moreover, the examination highlights potential issues that may be presented to the investigator, especially due to local degradation mechanisms. The results also illustrate that whilst a successful determination can be made, the method of visual and macroscopic examination is not able to provide the detail which would otherwise be determined during an in-depth fractographic examination by a material expert.

This phase of the research programme has identified failure characteristics apparent on simulated aircraft wreckage and has used them to determine the failure mode and failure sequence. It is fitting that the next phase of the research programme focus on the examination of the composite wreckage by investigation practitioners. This will assist in establishing the level of interpretation of a composite failure by investigation practitioners, and will examine the investigation of a composite structure within the context of the overall investigation process.

7 THE INVESTIGATION OF A SIMULATED ACCIDENT BY INVESTIGATION PRACTITIONERS



The previous chapter presented an interpretation of visual and macroscopic failure characteristics, of the failure of a polymer composite wing section. This chapter presents the fourth and final phase of the research programme and explores the examination of a polymer composite failure undertaken by investigation practitioners. This phase utilises an investigation methodology to evaluate the process undertaken by accident investigators.

Firstly, this chapter gives an overview of this research phase (section 7.1). Then it discusses the programme through which the simulated method was created (Section 7.3 through 7.6) and finally, it discusses the application of the simulated method and the results achieved (Section 7.10).

7.1 Overview and objective

The case study research phase (chapter 4) has produced an understanding of, and a framework for, the structural investigation, including the examination of aircraft wreckage. Next, the polymer composite fracturing phase has demonstrated some of the visual and macroscopic failure characteristics which may be present within aircraft wreckage (chapter 6). It is therefore fitting that the next phase is focussed on establishing:

- What information accident investigators currently elicit from composite wreckage
- What conclusions are being made from the information elicited
- How the examination is influenced by the wider investigation,
- How the examination influences the wider investigation, and, if applicable
- How visual characteristics can assist investigation practitioners.

The objective of this phase is to design, conduct and evaluate a study to determine how accident investigation practitioners currently use failure characteristics to assist the accident investigation process. This will involve an understanding of the investigation process within the context of the characteristics identified by the participant.

To meet the objectives it is necessary to conduct a longitudinal study of the accident investigation process. It has been suggested in chapter 4 that to conduct these using actual investigations will be impractical. Therefore the method chosen for this phase is a simulated accident investigation.

7.2 Research design and methodology

A key feature of this phase is to expand on the findings from the previous phases of the research programme. The case study phase of the research programme has suggested a framework of the investigation process. The process is illustrated in figure 7-1 and is explained briefly. For more detailed information please visit chapter 4.12.1.

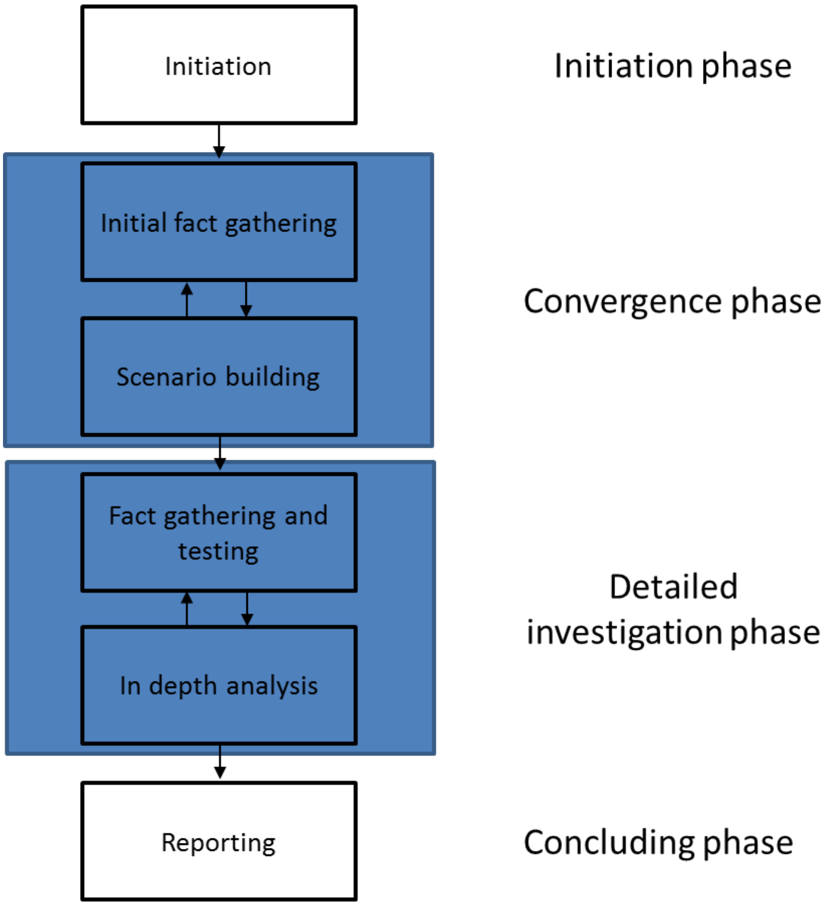


Figure 7-1 – A framework for the examination of aircraft structures within the context of an accident investigation (Source: Author)

The initiation phase involves the period between first notification and the time at which the majority of the investigators effort is focussed on fact gathering. Predominantly this phase involves predominantly procedural activities with discretionary judgement being made. This phase includes:

- Receipt of initial notification,
- The initial response, and

- Site attendance, assessment and stabilisation.

The initiation phase is followed by the convergence stage. The convergence phase involves the period when the investigator is focussed primarily on initial fact gathering. This phase follows the initiation phase and culminates when the investigation enters the detailed investigation. This phase contains two segments, namely: Onsite fact preservation; gathering and orientation stage; and the Exploration of facts stage.

The detailed investigation phase followed the completion of the convergence phase and finalised when the relevant areas of examination, testing or research, had reached a valid conclusion or the evidence collection had become saturated. This phase differed from the convergence stage as the predominant focus was in detailed examination of specific structural areas. To accomplish this task the examination typically involves formal confirmation (fractographic, design, construction, stress analysis, judgement based on location of failure etc.) testing (mechanical, construction, etc.), comparison to existing structures, and further research.

Finally, the investigation proceeded to the conclusion phase. This phase primarily focused on the creation of recommendations, communication of findings, formal reporting and release of the investigation report.

The framework suggests that as well as being a dynamic activity, the investigation is heavily dependent on the discretion of the investigator, introducing influential factors such as experience or bias. Moreover, whilst existing research has provided frameworks and models to assist in understanding accident development and causality, it is the data collection abilities of the investigator that determine whether the appropriate facts are collected and hence whether the analysis is sufficient.

Therefore, it is not sufficient to simply use the numbers and types of facts requested as a means to establish how thoroughly the scenario was investigated. This was identified in the first phase of the research programme where the level of in-field composite examination was reduced when:

- External facts eliminated the structures investigation as a line of enquiry, and
- External facts identified that a structural failure was highly probably. The investigator's reaction to this was to place priority on preserving the evidence for recovery and further detailed investigation. Hence the elicitation of facts from the composite wreckage in the field was not of priority.

It is accepted therefore that the study of what facts (characteristics) are identified by the investigator maybe insufficient to draw meaningful conclusions. Rather, the methodology should focus on the lines of enquiry undertaken during the investigation and the characteristics elicited from the composite specimens. These should be recorded with the practitioners reasoning, the influencing factors and within the context of the investigation; thereby understanding what was discovered, why it was discovered and how it influences the investigation.

Due to the impracticalities of conducting this on a real-life investigation, the practitioners were immersed into a rich simulation that allowed them to reflect professional practice.

To ensure that the research was conducted in an effective and rigorous manner, the following criteria must be addressed:

- The use of simulations in accident investigation studies
- Design of the data collection protocol, including:
- Development of the hypothetical simulation
- Participant selection and engagement
- Execution of the simulation
- Analysis and discussion

7.3 Simulations in accident investigation studies

The use of simulated investigations for accident research has been conducted by many authors and in many different forms (e.g. Rubinsky & Smith, 1973; Torell & Bremberg, 1995; Drury, Woodcock, Richards, Sarac & Shylla, 2002;

Balbahadur & Woodcock, 2012; Drury, Wenner & Kritkausky, 1999; Drury, Ma & Woodcock, 2002). A publication outlining a methodology for conducting simulated investigations for accident investigation research was published by Woodcock, Drury, Smiley & Ma (2005). This paper was a latter publication based on a methodology created by Woodcock, K. and Smiley in 1999 (Woodcock, 2012). The method has been adapted by the primary authors for use in a variety of situations.

The simulated investigation method is designed such that the researcher can control the investigation scenario, thus ensuring that the key components for investigation are included. It also allows multiple participants to conduct the same investigation, albeit separately. This provides an opportunity of increasing external validity, or in the case of qualitative research, increasing transferability.

According to Woodcock *et al* (2005), the key aspects of the simulated investigation method are the creation of a hypothetical but complete scenario. To aid in realism the scenario can be developed from a factual example (Drury *et al*, 2002; Woodcock *et al*, 2005).

The simulated investigation method as described by Woodcock *et al* (2005) specifically restricts the interview to verbal dialogue:

> "To make information acquisition explicit rather than tacit, all ''observed'' information must be obtained by requesting a description of what could be seen in a certain place at the time of the investigation. Gestures may be used to make the descriptions more three dimensional, but pictures and diagrams are not used."

This perspective biases evidence availability within the hypothetical scenario heavily towards that of testimonial evidence elicited from witnesses. Whilst this has been selected as a basis for ease of data collection for the researcher, it is questionable as to whether this provides a valid simulation of an investigation. For example, Stott (2009) suggests that there are three sources of evidence, People, Environment and Equipment. Furthermore, ICAO (2001) suggest that sources of information can be split into primary and secondary sources with primary sources consisting of physical examination, documentation, recordings, Interviews, direct observation and simulation, with secondary sources consisting of subject matter experts, databases and technical literature. In fact, it was reported by Woodcock *et al* (2005) that the experienced practitioners noted during the post interview debriefing that the lack of visual cues was felt dissimilar to the real world practices:

> "The main area where the experienced investigators described the simulations as dissimilar is the lack of site visits. The realism of site visits could be simulated using pictures, diagrams, and other graphic devices, however this makes measurement problematic."

In an attempt to increase realism, the participants of a subsequent study (i.e. Drury *et al*., 2002; Ma *et al*., 2003) were informed that the simulation was a telephone investigation being conducted away from the accident site. It was reported by Woodcock *et al* (2005) that this was accepted amongst those participants;

> *"They appeared to find this a realistic and familiar explanation of the lack of documents and photographs".*

It should be noted that this study was conducted using participants with a wide range of investigation experience (including participants who had no investigation experience). Moreover, it cannot be assumed that a telephone interview would be accepted by experienced practitioners, for an event which otherwise would be a deployable investigation (AAIB, 2008).

It is therefore necessary for the data collection protocol to include methods appropriate to the elicitation of information from the use of graphics, images or artefacts.

7.4 Limitations of the simulated investigation method

In examining the method it is apparent that there are certain limitations which present dissimilar contexts to a real world investigation. The first regards the time to which the simulation is conducted. Ensuring a realistic time frame for the participants is essential for participant agreement. Initial estimates placed this at one hour for the simulation plus allowance for introduction and debrief. It is impractical to suggest a real world investigation can be conducted during this time, especially when past real world investigations have taken in excess of 5 years to complete (NTSB, 2012). It is thus suggested that the study will reduce the participants' ability to cogitate over the information during a longer period and thus it may not reflect the true extent of the investigators role. Furthermore, real world investigation is a task where it is seldom a process whereby the investigator is not influenced, for the better, by external resource. For example is was discovered in the first phase of this research programme that the investigator utilises informal methods of brainstorming by discussing the investigation with others. This may be to get a different viewpoint, to see if external experience can assist or even to provoke ones lines of thinking. In discussing the method Woodcock, *et al* (2005) suggest if the above scenario occurs where the investigator seeks to discuss the views of the role playing researcher, the response should be generated towards a general opinion or inconclusive remark. Whilst this places emphasis on the investigator to create the answers without external assistance, it does also remove potential fruitful lines of enquiry that the investigator may not have realised on their own. On the other side however, if the researcher plays the role of the experienced colleague and thus suggests to the participant potential fruitful lines of enquiry, then the researcher, having created the simulation, is creating unacceptable bias into the simulation.

A table was created as part of the data collection protocol to assist the researcher in recording the progression of the simulated investigation. This was abandoned during the first interview as it became apparent that the completing of the form by the researcher was potentially distracting the participant during the exercise. This was due to the close proximity between the participant and researcher during the conducting of the interview. Instead, the tabular form was verified against the audio recording during data analysis and thus errors in recording were corrected. This did not affect the summary sheet which was completed after the interview.

7.5 Data collection protocol

This section presents the process taken to design the data collection protocol. It starts by discussing the protocol applied for the inclusion of graphics, images and artefacts.

7.5.1 Use of visual references in research

Visual sociology is a collection of approaches in which researchers use visual materials to portray, describe, or analyse social phenomena (Harper, 2002). Whilst the application of visual methods in social research is diverse, including ethnographic description, the study of social processes in the laboratory, in studies of social change, and as a means through which phenomenological sociology may be constructed and communicated, an area of interest is the use of visual images in interviewing. Photo-elicitation research is based on the principal of inserting visual media into a research semi-structured interview as a means to increase the quality of empirical data obtained during the interview. Moreover, the addition of images to an otherwise verbal exchange introduces greater use of the participants visual conscious and hence more information and a different type of information may be elicited (Harper, 2002).

Collier (1957) conducted an experiment aimed at determining whether the insertion of photographs during interviews, which had relevance to the participant and research subject, elicited a greater depth of information from the participant. The experiment was conducted using a control group (images were excluded) and the test group (images were included). In concluding on the research, Collier stated:

> *"The material obtained with photographs was precise and at times even encyclopaedic; the control interviews were less structured, rambling, and freer in association. Statements in the photo-interviews were in direct response to the graphic probes and differed in character as the content of the pictures differed, whereas the character of the control interviews seemed rather to be governed by the mood of the informants."*

Subsequent coding of the data also confirmed that imagery focussed the content of the interview more so than the verbal dialogue alone. It is also interesting to note that it was felt by Collier (1957), that the use of imagery had a positive role in the rapport between the researcher and the participant:

> *"Another point borne out by the analysis was that, while both of the second non-picture interviews had been less full than the first and showed a decline in the informants' responsiveness, the "check" interviews reversed the trend and produced more material. This can be interpreted as an indication that photographs can be stimulating and can help to overcome the fatigue and repetition often encountered in verbal interviews. It is also safe to assume that the photographs were an aid to rapport in opening the field of discussion, whereas in the control interviews we sometimes had to press against resistance and apathy."*

This is especially significant in situations where the interviewee feels they are participating in a test where photographs can provide a neutral ground between the researcher and participant (Banks, 2001).

Although the use of images during interviews is deemed as a "simple idea of inserting a photograph into a research interview" (Harper, 2002), there are particular considerations which should be used on selecting images and understanding how the images may influence the interview. Aside from ensuring that the images are relevant to the nature of the research and, in most cases, relevant to the participant, Banks (2001) suggests that the researcher should distinguish between the form (external narratives) and content (internal narratives) of the visual image. Furthermore, Harper (2002) suggests that the images should not reflect the normal views of the participant as this leads to limitations on the participant being able to express thought on the subject, rather visual images should "break the frame" and offer differing views such as aerial images or close-up images.

The above considerations were applied to the selecting of suitable cases and suitable imagery.

7.5.2 Think Aloud method

A method suggested by Woodcock *et al* (2005) as a potential means to transfer otherwise tacit information into explicit information is through the use of Think Aloud protocol.

The think aloud method consists of requesting participants to 'Think Aloud' whilst solving a problem with the researcher analysing the verbal responses (Van Someren, Barnard, Sandberg, 1994). Whilst this method is used in psychology as a means to understand cognitive processes, it is also used as a means to extract knowledge from expert practitioners. Van Someren *et al* (1994) suggest that in the case of expert practitioners, it is difficult for them to explain what they do, thus the think aloud method focusses on the practitioner verbalising what they do whilst doing it.

This however conflicts with a finding by Woodcock *et al* (2005) which suggests the simulation should be conducted with the interviewer 'acting' the roles of the interviewees:

> "… can be made more realistic by projecting character into the ''people'' answering the interviewees' questions, using vocal inflection and vernacular speech, adopting natural style. Trials using neutral delivery of information from the story reference page often evoked questions in the third person and shorter searches overall."

However, it would be inappropriate and confusing to suggest that the participants should step in and out of the hypothetical scenario when images are presented. It is therefore suggested that for the purposes of this research the interviewer should maintain the interviewee and interviewer relationship. Additionally this reduces the workload on the interviewer and hence increases concentration on the data elicited and conducting of the interview.

7.5.3 Data collection framework

The case study phase has suggested that the process by which the investigation is conducted includes:

- Initiation phase
    - Receipt of initial notification
    - Initial response
    - Site attendance assessment and stabilisation
- Convergence phase
    - Onsite fact preservation, gathering and orientation
    - Exploration of facts
- Detailed investigation phase
- Conclusion

Thus the scenario should start at the beginning of the investigation with the receipt of initial notification. It is necessary to record the lines of enquiry taken by the participant, the facts retrieved and subsequent investigative direction taken by the participant. It is anticipated from findings in phase one of the research programme that actions taken by the participant during the initiation phase is predominantly procedural. Thus the researcher should utilise this phase as a period to ensure the simulation is producing the intended data and importantly that the participant is comfortable rendering and sharing their thoughts.

Whilst it would be possible to continue the simulation through to where the participant presented a conclusion to the investigation, this presented two problems. Firstly, by presenting irrelevant and relevant data with a causal chain complex enough to avoid the researcher inadvertently suggesting a particular path, continuing the simulation to a conclusion would require a considerable commitment of time from the participant.

Secondly, as highlighted in the case study phase of the research, during the detailed investigation phase it is anticipated that the practitioner would follow particular lines of enquiry in comprehensive detail. It is perhaps unrealistic to expect that a simulated investigation would cover convincingly such detail, due to, a) the level of resource requirement would be impractical, b) the length of time for interview may jeopardise the willingness of participants, and c) the collection of data concerning the detailed investigation process may not provide sufficient data concerning the investigation process from a generic perspective. One such example is where the practitioners may request significant input from material experts (e.g. the participant may request laboratory analysis on composite structures that are deemed to be of significance to the simulated investigation).

Whilst this initial approach and dialogue with the material experts is of significant interest to the research objectives, it would be impractical for the simulation realistically to cover the detailed investigation that may ensue. For example, it is reasonable in the initial stages of the investigation to simulate that a material expert is temporarily unavailable and only non-specific information from the material expert is available at that moment in time. This would be difficult to maintain with realism during the detailed investigation phase where it may be likely that detailed dialogue between the practitioner and material expert would be necessary.

It is appropriate that the simulation be bought to a close when either a) the participant, through their own investigative process, has reached a position where detailed consultation with a forensic laboratory for failure analysis of the wing sections is requested, or b) a conclusion to the investigation is provided by the participant to the researcher. Furthermore, when the advised time limit is reached, the participant will be given the option to continue or stop the simulation. If the simulation has been closed due to the participant requesting forensic examination on the composite structure, a summary of how the participant would conduct the detailed examination will be requested.

7.6 Participant selection and engagement

The participants of the study must align with the scope of the overall research study and thus eligible participants were limited to professional investigators who were not specialised to a particular type or manufacture of aircraft. Government investigators were approached. Due to scope limitations in the research, potential candidates were targeted to those located solely within the UK. The UK Air Accidents Investigation Branch (AAIB) and the UK Military Air Accident Investigation Branch (MilAAIB) were formally approached. Both organisations agreed to participate with three participants from the AAIB and five from the MilAAIB. During the data collection phase a participant from the AAIB had to withdraw due to work related commitments. There was a wide variation of investigation, structural investigation and composite wreckage investigation experience amongst the participants.

Although the professional investigators who volunteered were likely to conduct investigations in groups, it was elected to conduct the simulation on the basis of a single practitioner. Although this may diminish the realism of the simulation, it was considered that to include group dynamics into the research would be detrimental to the data collection. Therefore this is accepted as a limitation in the research.

7.6.1 Ethical considerations

Agreement to partake in the research was solely at the discretion of the participant. Prior to conducting the simulation each participant was advised that involvement in this case study was entirely voluntary and they may decide to withdraw from the study at any time without prejudice. The participants were also informed that they may decline to answer any questions that they would prefer not to answer.

7.6.2 Confidentiality, anonymity and data security

The collection of personal data as defined in the Data Protection Act 1998 (HMSO, 1998) will not provide additional benefit to the research. Therefore, the collection of personal data was excluded from data collection to maximise the anonymity of the data.

Although the decision had been made to collect anonymous data and thus details relating to an individual were not requested, it was also decided that with permission from the participant, the interviews would be audio recorded. This was undertaken to ensure the accuracy of the data. It was stressed to the participant that the audio recording will be solely for use in this research project and will be immediately deleted following transcription. It was also highlighted that the transcription will also be restricted for use within the research project, will be stored anonymously and will not be published or distributed.

The decision to audio record the interview presented two issues. Firstly, personal data may be mentioned inadvertently during the course of the interview. If this occurred then software was utilised post interview to cut the personal data from the recording. Secondly, the audio was recorded directly without voice altering software being used to change the tone of the participants' voice. Although this was not deemed as making the data identifiable, it was accepted that all of the data should be treated with security measures compliant to the data protection act as a precautionary measure.

Information security was hence designed to confirm to principle seven of the data protection act. The audio and transcript files were encrypted using 256bit AES algorithm and were stored on a password protected computer and backup drive. The researcher had sole access to the decryption key, the computer and the backup drive. The computer was protected from malicious software by a firewall and anti-virus software. Once completed, the data was permanently deleted using professional data removal software.

7.6.3 Conducting the interview

The simulation was conducted at the participants' place of work and in an isolated meeting room that offered a comfortable environment with limited opportunity for noise or distraction. The researcher provided a background to the overall research project, discussed freedom of participation, assured the participant of anonymity and detailed measures taken for data protection. If the participant was willing to continue then the simulated method was described to the participant and a request to audio record the interview was made.

The data collection was in the format of an interview. Following on from the researcher providing the initial notification, the participant continued by leading the questioning and 'thinking aloud' their thoughts and actions. This process was explained to the participant during the pre-interview briefing. The participant progressed through the simulation by requesting further information from the researcher as they followed their individual lines of enquiry. The researcher had information available which could either be given to the participant, such as images, or verbally provided to the investigator, such as during an interview between an investigator and a witness. If the request had not been anticipated then the researcher would respond by stating that the information was not available. This was deemed as representative of a real-world investigation where particular information may not be available to the investigator (Woodcock *et al*, 2005). A pen and paper were available to the participant for them to record information.

The interview was continued until either the objectives of the research had been met, or the allotted interview time had elapsed, whichever occurred first. If the allotted time for the interviewed had had elapsed without the objectives being met then the participant was informed that the time had expired but if the participant was in agreement then the researcher would like to continue. All simulations continued until the research objectives had been met with some of the participants agreeing to continue past the allotted time.

Arrangements were made for the participants to be interviewed at each organisation on a back-to-back basis. There was a period of five weeks from the end of the interviewing at the first organisation to the start of interviewing at the second and final organisation.

When the simulation had finished, the participant was asked verbally for demographics data and was debriefed on the interview. The debriefing involved thanking the participant for their time, offering reassurances of confidentiality, asking the participant not to discuss the scenario with colleagues who may be latter participants, and offering answers to any questions they had. Typically the participant asked how they performed and whether their summary was correct. In response positive feedback was given.

7.7 Hypothetical scenario development

The core feature of the simulated investigation method is the preparation of a complete accident investigation story (Woodcock *et al*, 2005). As suggested by

Woodcock *et al* (2005), a real accident investigation can be used as the basis of the scenario and as a source for material. A literature search was conducted to identify a suitable case. In line with the objectives of this phase of the research, the literature search was limited to:

- Only cases that included, or had the potential to include, a field investigation
- Involved a high performance single seat glider, such that the fractured wing sections from phase three of the research programme could be written into the scenario.
- A scenario that would provide a rich source of material from which a scenario could be created

Additionally, consideration was given to ensure that the case material once adapted into a hypothetical scenario should:

- Not have an obvious single cause
- Not be overly complex such that it cannot be reasonably investigated in a short period of time
- Be located within a remote location where the use of subject matter experts was likely to be reduced, and means of recovery would be difficult

The literature search identified a number of potential cases. NTSB investigation WPR09FA089 (NTSB, 2009) was selected. It met the requirements above and offered an interesting, rich storyline which could be realistically adapted to involve a composite failure scenario to match the failure of the specimens created in phase three.

The information retrieved from the NTSB public docket (NTSB, 2009a) provided a basis from which the scenario was created. Scenario developed would thus involve the modification of the current scenario to fit the fracture specimens as created in phase three. Irrelevant data was also added to reflect real world investigations and, the scenario was expanded to include information that the participant was likely to investigate. Where available, additional information added to the scenario was obtained from credible sources rather than created solely by the researcher. For example the following were used in the expansion of the adaptation of the original scenario:

- Standard Operating Procedures (SOP's) from current investigation agencies
- Additional material sourced from other accident investigations
- Material from academic institutions researching in support of structural and wreckage investigations
- Material from simulated investigations created for the purpose of accident investigation training

The information contained within the developed scenario is summarised in table 7-1.

Information type		Data type	Source of original material
Initial Notification		Text	Data presented based on AAIB Initial Notification form F16 (AAIB, 2008)
Background information	Accident history of type	Text	Contains relevant and irrelevant accident history. Five cases were adapted: • LAX99MA251 (NTSB, 2002a) • A-028/2000 (CIAIAC, 2003) • CA18/2/3/8395 (SACAA, 2011) • LAX99LA215 (NTSB, 1999) • LAX06LA024 (NTSB, 2007)
	Location information	Text	Accident location of WPR09FA089 adapted and summarised based on information from Stalker, (2010)
	Air Map	Graphic	Air Map adapted from FAA (2012)
	Pre-accident aircraft image	Graphic	Generic image of a Nimbus 3
	Basic Aircraft data	Text	Created from Nimbus flight manual (Schempp-hirth, 1982a)
	Nimbus plan view	Graphic	Created from Nimbus flight manual (Schempp-hirth, 1982a)
	Area forecast	Text	Modified from (NTSB, 2009a)
Meteorology	Gliding club forecast	Text	Modified from (NTSB, 2009a)
	Nearest airport	Text	Modified from (NTSB, 2009a)
	(Local Analysis and Prediction system) LAPS	Text & Graphic	Modified from (NTSB, 2009a)
	AIRMET	Text	Modified from (NTSB, 2009a)
	Regional Atmospheric Prediction Model (RASP)	Text & Graphic	Modified from (NTSB, 2009a)
	Satellite	Text & Graphic	Modified from (NTSB, 2009a)
	Science station	Text	Modified from (NTSB, 2009a)
	SIGMET	Text	Modified from (NTSB, 2009a)
	Surface chart	Text & Graphic	Modified from (NTSB, 2009a)
	Terminal Aerodrome Forecast (TAF)	Text	Modified from (NTSB, 2009a)
	Upper air chart	Text & Graphic	Modified from (NTSB, 2009a)
	Upper air data	Text & Graphic	Modified from (NTSB, 2009a)
	Winds and temp aloft	Text & Graphic	Modified from (NTSB, 2009a)
	Pilot reports	Text	Modified from (NTSB, 2009a)

Table 7-1 – Evidence and sources used in the hypothetical accident scenario

Information type		Data type	Source of original material
Aircraft documents	Flight Manual	Text & Graphic	From original aircraft document (Schempp-hirth, 1982a)
	Maintenance Manual	Text & Graphic	From original aircraft document (Schempp-hirth, 1982)
	Maintenance record	Text	Modified from accident aircraft manual
Wreckage photography		Graphic	Image from investigation WPR09FA089 (NTSB, 2009a)
Wreckage examination	Photograph of retrieved recorder	Graphic	Modified from (NTSB, 2009a)
	Oxygen system recovered from wreckage	Graphic	Modified from (NTSB, 2009a)
	Wreckage Plot	Graphic	Modified from (NTSB, 2009a)
	Failed wing sections	Artefact	As created during chapter 6
GPS	3D flight path plot	Graphic	Modified from (NTSB, 2009a)
	Data information	Text	Modified from (NTSB, 2009a)
	Visual representation of data	Text & Graphic	Modified from (NTSB, 2009a)
Planned route		Text	Modified from (NTSB, 2009a) and FAA (2012)
Notice to Airmen (NOTAM)		Text	Modified from (U.S. Department of the Navy, 2007) and (FAA, 2010)
Pathology	Post mortem examination	Text	Created from (Timmermans, 2007)
	Medical records	Text	Created from (NTSB, 2009a) & (Timmermans, 2007)
	Toxicology	Text	Modified from (NTSB, 2009a)
Aircraft modifications	Oxygen system – AV	Text & Graphic	Modified from (NTSB, 2009a) & (NTSB, 2009a)
	Oxygen system – EDS	Text & Graphic	Modified from (NTSB, 2009a)
	Oxygen system - photo aircraft interior	Graphic	Modified from (NTSB, 2009a)
Pilot records		Text	Hypothetical based on scenario.
Witnesses	Duty Pilot	Text	Hypothetical based on scenario.
	Glider Pilot	Text	Hypothetical based on scenario.
	Tug Pilot	Text	Hypothetical based on scenario.
	Winch operator	Text	Hypothetical based on scenario.
	Boss	Text	Hypothetical based on scenario.
	Local police	Text	Created with data from (NTSB, 2012a)

Table 7-1 – Evidence and sources used in the hypothetical accident scenario (continued)

Upon completion, the scenario was analysed to identify the salient relevant and irrelevant lines of enquiry. The sources of information were arranged into a table of information and subsequently into a scenario time-line. The relevant and irrelevant lines of enquiry were then scrutinised in each of the forms for a) inconsistencies between facts and in sequencing, b) identification of facts and leads that were missing, and c) realism of the overall scenario. Where information was not easily identifiable, hooks were placed throughout the scenario as a realistic indicator to the investigator of a potential line of enquiry.

Additionally, a date and time was attached to each source of information highlighting when it occurred in the timeline of the hypothetical story, and when the information will be available for the participant. This established a means to add realism to the scenario as particular sources of information can only be retrieved by the participant once certain conditions have been met, e.g. information from the data recorder can only be retrieved following collection from the accident site and despatched for analysis.

The simulation commenced with the participant receiving a verbal notification of an accident having occurred. This notification replicated the initial information which would reasonably be passed onto the participant as the investigator in a real life scenario. The participant subsequently responded to the researcher by thinking aloud their immediate thoughts, next actions, and requests for further information. The narrative used as the initial notification was as follows where the words replaced by XXXX were fictitious names:

> *On Jan 6th at 18:34 local (04:34 UTC), XXXX Airport reported to XXXX Police a missing aircraft. The aircraft was reportedly conducting a local wave soaring flight on an island called XXXX, located in the mid Pacific (-10 hours UTC). The XXXX Police immediately organised a search using aircraft. The search resumed the next day and located what appeared to be wreckage of an aircraft on the side of Mount XXXX. There appeared to be no signs of life. The aircraft being reported missing was G-XXXX, a UK mainland registered aircraft. The XXXX Police are organising a party to ascend the mountain to determine the status of the pilot. In the*

meantime, the UK based XXXX Consulate contacted your organisation to inform of the situation. It was expressed by the island nation that they had no means to investigate the accident. It was thus decided that your organisation will conduct the investigation. It is known that the pilot of the accident aircraft is a UK citizen who was conducting a glider altitude attempt.

Predetermined responses were arranged according to the area of investigation, (e.g. data relating to meteorology were grouped together). The grouping of facts reflected the logical and sequential relationships among the areas of investigation. Although it is the participant who decides on the sequence of the investigation, the grouping was established to improve the process by which the interviewer could locate the relevant information and respond efficiently to the participant's request.

A table was created to assist in the recording of the progression of the simulated investigation.

7.8 Pilot testing and external simulation validation

It was deliberated by the researcher as to whether the scenario should undergo scrutiny from external persons prior to the data collection phase or to undergo pilot testing.

Conducting a pilot study was ruled out for two reasons. It has already been identified that the target audience of the research was relatively small with only two sites within the UK. To undertake a pilot study would involve either departing the UK or selecting participants who are outside of the intended scope of data collection. The use of participants located within the sites of main study was rejected due to the potential reduction in participants for the primary study and the potential for site contamination due to the pilot stage.

Additionally, the simulation was designed as a rich source of information conducted based on the preferences of the participant. Hence, it was impractical that every potential route or line of enquiry within the investigation could be tested via a pilot study.

The alternative was for the simulation to be scrutinised by external volunteers who had experience with both simulation development and accident investigation. This may have benefited the scenario as conflicting or false information may have been identified by the external reviewer.

As the scenario was constructed from credible, realistic information and followed the basis of a contemporary investigation, it was considered that the scenario were unlikely to include significantly conflicting information. Therefore, the potential gains from recruiting an external reviewer to examine the complex scenario are unlikely to be significant. As an alternative, the participants during the primary study were debriefed on their perception of the realism of the scenario. Any issues that were highlighted would be recorded and modified for the next participant. In fact, only one minor issue was highlighted which did not affect the data collection.

7.9 Data analysis method

Data was collected in the form of audio-recording, notes made by the participant during the interview and summary sheets created by the researcher.

The data collection was split into two phases of the simulation, with a natural separation occurring between the overall investigation and the wreckage examination. The first phase involved the investigator moving through the initiation and convergence stages. The second phase involved the examination of the wreckage whereby the investigator will have an opportunity to elicit characteristics from the composite components. Whilst these two processes were interlinked, for clarity they will be discussed separately. The first phase was labelled ‘process phase’ and the second phase as the ‘composite examination phase’.

7.9.1 Process analysis phase

The analytic process for this stage was driven by the framework created during the case study phase of this research programme (section 4.12.1 or figure 7-1). The framework was a means to focus data collection, provide an opportunity for verification and provide a theory from which further understanding could be provoked.

Data collected for this phase included the audio recording, notes made by the participant, and summary sheets produced by the researcher. The audio recording was reviewed and the order in which the lines of enquiry (hereafter referred to as enquiry or enquiries) were undertaken by the participant was documented. The order of the enquiries was recorded in numerical order, with a narrative supporting the line of enquiry undertaken. The enquiries were coded such that cross participant comparison could be undertaken. Event State Networks (Miles & Huberman, 1994) were then formulated from the coded actions of the participant to form visual representations of the process undertaken by the participant. From these displays multiple tactics (e.g. clustering, noting patterns and themes) were used to draw understanding and conclusions.

In addition to the coding and Event State Networks, the audio recorders were reduced through the formation of memos. The memos were focussed on extracting key data relevant to the data collection framework (tables 4.2, 4.3, 4.4 & 4.5), and to highlight the patterns and themes as recognised by the researcher.

7.9.2 Composite examination analysis phase

The audio recording was cut to include only the period when the participant was investigating the wreckage. The recording was then coded into themes representing the characteristics identified by the participant. The framework for coding was based on the themes as established during the wreckage examination phase of this research programme, chapter 6. These are summarised in figures 7.2 & 7.3. Any new characteristics identified by the participant were recorded.

In addition to the audio recording, summary sheets were created by the researcher following the interviews.

Failure sequence referenced in chapter 6
The primary fracture occurred distinctly chord-wise with symmetrical failure pattern suggesting limited torsional failure.
The global deformation and visual fracture features suggest the wing failed due to positive flexural loading.
The lower spar failed in positive flexural, suggesting that the upper surface failed first and in compression. Moreover, following the compression failure of the upper wing, the wing continued in positive flexural loading with the wing pivoting about the lower spar.
The lower skin failed subsequent to the load bearing structure and failed late in the fracture sequence when the wing had undergone significant bending.
There were no indications of premature failure from environmental, bonding or fatigue mechanisms.
Although the upper spar cap was heavily disrupted, the upper skin recorded evidence of impacts occurring on the upper spar cap. The impact sites intersected the fracture cleanly and thus are likely to have been involved in the fracture, rather than influencing an already occurring fracture.
The evidence was seen on both specimens in the same context suggesting the specimens had both failed in the same manner.

Table 7-2 – Themes for identifying the failure sequence

Characteristic	Location	Evidence
Adherend failure	Bonded surfaces	Preferred bonding failure
Bright fracture surface	Lower spar cap	Tensile failure
Change fracture orientation	Lower wing skin	Change in mode from tensile to flexural
Cohesive failure	Bonded surfaces	Preferred bonding failure
Compression brooming	Upper spar cap	Compression failure
Crack coalescence	Upper wing skin	Failure sequence
Dark and Bright fracture surface	Interlaminar failures	Peel failure
Deflection of fracture	Upper wing skin	Impact damage
Dual failure zones	Lower spar cap	Local flexural failure
Dull and white fracture surface	Interlaminar failures	Shear failure
Dull fracture surface	Upper spar cap	Compression failure
	Lower spar cap	Compression failure
		Fatigue (Or absence)
Fibrous surface	Lower spar cap	Tensile failure
	Lower wing skin	Tensile failure
Foreign material forced into fracture	Upper spar cap	Compression failure
Fracture geometry	Sandwich	
Fracture geometry	Lower spar cap	Compression failure
	Lower spar cap	Tensile failure
Flat fracture surface	Upper wing skin	Compression failure
Local sooting and penetration	Upper wing skin	Arcing damage
Misplacement	Lower spar cap	Anomaly
Permanent deformation	Upper wing skin	Positive flexural
	Upper spar cap	Positive flexural
Preferential interface crack propagation	Interlaminar failures	Crack propagation direction
Pull through of polymer tube	Upper wing surface	Flexural failure
Serrations	Translaminar fracture	Crack propagation direction
Smooth fracture surface	Upper spar cap	Compression failure
	Upper wing skin	Compression failure
		Translaminar shear
Visible bruising	Upper wing skin	Impact damage
Visible penetration damage	Upper wing skin	Impact damage

Table 7-3 – Themes for characteristic identification

7.10 Analysis

In total seven participants partook in the research with all being professional accident investigators working for government organisations within the UK. Five participants were from the MilAAIB, a joint service military air accident investigation body operating as part of the UK Ministry of Defence (MoD). The remaining two participants were from the AAIB, the UK investigation body responsible for the investigation of civil aircraft accidents and serious incidents. All participants were male. Of the seven participants, six were engineering investigators with one being an operations investigator. The operations investigator was a member of the MilAAIB.

The following presents the findings from the analysis, starting with the composite phase.

7.10.1 Finding 1 – A clear understanding of failure mechanisms and characteristics is necessary to support the investigator

During the wider investigation process the investigators utilised reasoning to guide their decision making and for weighing lines of enquiry.

There was evidence of deductive reasoning, for example, whilst examining the wreckage plot the participant conducted the following:

> *Participant's 1st premise:* an aircraft which was intact at impact cannot have a wreckage spread over 6 miles without bouncing along the ground.
>
> *Participant's 2nd premise*: There is no evidence (i.e. ground scars) of the aircraft bouncing along the ground
>
> *Conclusion:* Therefore, the aircraft had broken up before it impacted the ground

The premises passed the deductive reasoning and thus the participant's response to the conclusion was firm, the line of enquiry for the aircraft impacting the ground complete was closed and the in-flight breakup scenario was pursued. Therefore deductive reasoning was used to eliminate lines of enquiry.

There was evidence of inductive reasoning, for example, whilst considering a plausible scenario for the breakup of the aircraft different participant conducted the following:

> *Participant's 1st premise:* symmetrical failures on both wings are unlikely to be related to manufacturing faults
>
> *Participant's 2nd premise*: the wings failed symmetrically
>
> *Conclusion:* Therefore, the wings are unlikely to have fractured due to manufacturing defects

A conclusion was drawn based on inductive reasoning. The investigator was not certain that the outcome was true but this allowed the investigator to weigh the lines of enquiry. Thus in using this logic the investigation temporarily closed the lines of enquiry, albeit keeping an open mind, until further evidence appeared to contradict the original logic. This occurred when the same participant examined the wreckage and identified what he suspected to be a manufacturing irregularity. The line of enquiry was hence reopened.

Finally, there was evidence of abductive reasoning, for example, whilst considering a plausible scenario for the breakup of the aircraft different participant conducted the following:

> *Participant's thoughts:* The aircraft suffered in-flight breakup
>
> *Participant's conclusion*: the aircraft may have failed due to a degradation mechanism

A possible explanation was drawn based on knowledge and prior experience. In this instance the participant did not know how to recognise degradation mechanisms in composite materials and thus a plausible explanation was put forward, albeit with an 'open mind'. This mechanism opened the line of enquiry albeit to the request of an external source. For example, upon concluding that it may have failed due to a degradation mechanism, and the practitioner had no means to confirm this, the assistance of the external expert was requested to examine the wreckage. When the forensic experts were requested following abductive reasoning, the summary of requests was akin to a shot gun approach. The experts would be requested to tell the investigator everything they could about the fracture.

The review of visual and macroscopic failure characteristics suggested that the evaluation of a failure can be potentially ambiguous in its identification. For example, in recognising environmental degradation mechanisms, the evidence may only be apparent under severe conditions (5.4.1). As another example, the identification of degradation in tensile failures may only be determined through comparison to pristine materials (see 5.4.10).

It is likely that the use of failure characteristics within the accident investigation scenario will be dominated by inductive reasoning. Whilst this may have the benefit of increasing the speed at which decisions can be made, (e.g. the investigator may be in a better position to focus the in-depth analysis to a particular region of the structure) there may be the opportunity for delay should the line of enquiry be closed until other contrary evidence is identified.

Firstly, this suggests that the current understanding of visual and macroscopic characteristics should be developed such that features and associated degradation mechanisms can be identified with greater confidence. This will encourage the lines of enquiry to be closed or opened with certainty, as the investigator will have a greater opportunity to use deductive reasoning.

Furthermore, the transfer of knowledge should focus on delivering clarity on the interpretation of characteristics, such that confidence in the interpretation can be achieved by the investigator. It is relevant therefore for the knowledge transfer to deliver information on failure mechanisms and their influence on the characteristics. This will enable the investigator to make a judgement based on understanding, and thus cater for the wide range of possibilities in failure characteristics.

7.10.2 Finding 2 – There is scope for increasing the number of failure characteristics extracted from the wreckage

During the wreckage examination, only a relatively small proportion of the available facts were reported by the participant. Table 7-4 illustrates the total number of facts reported by all of the participants. Firstly, it was discovered that this is not illustrative of the investigators ability to identify failure characteristics. Rather, it was the identification of failure characteristics within the context of the investigation scenario.

Consider the characteristics associated with impact damage. None of the participants reported that they had identified characteristics associated with this failure mechanism. It was apparent that this was related to the wreckage examination being influenced by the picture determined from the wider investigation. One of the participants had theorized prior to the wreckage examination that the symmetrical failure may have been created by the long distance transportation of the aircraft (the long distance transportation was a component of the scenario). Therefore, the investigator approached the wreckage examination searching for characteristics that may confirm such failure. Furthermore, the investigator had suggested further sources of information that may confirm this occurrence. A request to see the transportation and storage equipment was hence requested.

On this occasion the investigator had approached the examination with an induced line of enquiry. The wreckage was examined to identify characteristics which may confirm the occurrence of pre-existing damage. The investigator suggested an alternative means to confirm the plausibility of the hypothesis by examining the transportation rig. On this occasion, despite looking for external damage the investigator was unable to identify the impact characteristics. However, alternative sources were proposed which may either confirm the occurrence, or increase the weight of the original line of enquiry.

It is therefore plausible that had the investigator identified the characteristics of the impact damage, then the line of enquiry being developed would have been reinforced earlier in the investigation. This is likely to have led to prioritisation on the examination of the transportation rig and perhaps the earlier involvement of the composite material SME (Subject Matter Expert) by electronically transferring images of the suspect area for a specialist opinion.

Furthermore, when the examination was commenced, the initial approach was similar across all participants. Having previously identified that an in-flight breakup had occurred, all of the participants approached the wreckage wanting to understand the very last moments of the aircraft prior to the separation. This line of enquiry was intended to draw information from the wreckage not necessarily to understand how the structure failed but to understand what was the aircraft doing that made the wings to fail? This understanding was subsequently drawn into the context of the wider scenario such that lines of enquiry, which may not be concerning structural failure, could be followed. For example:

> *Participant's 1st evidence:* the wings failed symmetrically (location)
>
> *Participant's 2nd evidence:* there was little torsional failure suggesting little forward speed (flat break rather than angled)
>
> *Participant's 3rd evidence:* the wings failed upwards suggesting a high vertical velocity (deformation of the structure)
>
> *Conclusion:* The aircraft may have broken up with low forward speed, and high vertical descent and the wings failing in overload.
>
> *Conflicting evidence:* location of wing failure not consistent with the conclusion
>
> *Developing lines of enquiry:* What situations may have occurred to put the aircraft into this situation? Did the aircraft enter into a flat spin? Did an airbrake deploy mid-flight?
>
> *Sources of further information:* Aircraft accident history, flight controls

The initial stages of understanding the dynamics of breakup were correctly identified by all participants. It was evident also that the purpose of gaining this understanding was to identify the aircraft dynamics at breakup in order to promote further lines of enquiry. The characteristics identified during this event were dominated by generic features, i.e. global fracture angle, deformation, locations of the fracture with respect to the aircraft design. There references to specific fracture features, but these were not dominating the participants' interpretation.

Whilst the investigators were able to elicit information from the wreckage, the elicitation was predominantly conducted through generic techniques which were not unique to composite materials. There was subsequently less information extracted where characteristics were unique to composite materials, even though there was evidence of participants searching for such information.

This suggests that there is a potential that the investigation can be assisted by promoting knowledge transfer about the recognition of failure characteristics. This transfer is likely to aid the investigation by strengthening lines of enquiry earlier in the investigation, rather than by introducing new lines of enquiry which otherwise would not be identified.

Characteristic	Location	Evidence	No.
Adherend failure	Bonded surfaces	Preferred bonding failure	1
Bright fracture surface	Lower spar cap	Tensile failure	0
Change fracture orientation	Lower wing skin	Change in mode from tensile to flexural	1
Cohesive failure	Bonded surfaces	Preferred bonding failure	0
Compression brooming	Upper spar cap	Compression failure	4
Crack coalescence	Upper wing skin	Failure sequence	0
Dark and Bright fracture surface	Interlaminar failures	Peel failure	0
Deflection of fracture	upper wing skin	Impact damage	0
Dual failure zones	Lower spar cap	Local flexural failure	0
Dull and white fracture surface	interlaminar failures	Shear failure	0
Dull fracture surface	Upper spar cap	Compression failure	1
	Lower spar cap	Compression failure	0
		Flutter (Or absence)	2
		Fatigue (Or absence)	1
Fibrous surface	Lower spar cap	Tensile failure	5
	Lower wing skin	Tensile failure	1
Shear web material forced into fracture	Upper spar cap	Compression failure	0
Fracture geometry	Sandwich		1
Fracture geometry	Lower spar cap	Compression failure	2
	Lower spar cap	Tensile failure	2
Flat fracture surface	Upper wing skin	Compression failure	2
Local sooting and penetration	Upper wing skin	Arcing damage	0
Misplacement	Lower spar cap	Anomaly	0
Permanent deformation	Upper wing skin	Positive flexural	7
	Upper spar cap	Positive flexural	2
Preferential interface crack propagation	Interlaminar failures	Crack propagation direction	0
pull through of polymer tube	Upper wing surface	Flexural failure	3
Serrations	Translaminar fracture	crack propagation direction	0
Smooth fracture surface	Upper spar cap	Compression failure	1
	Upper wing skin	Compression failure	0
		Translaminar shear	0
Visible bruising	Upper wing skin	Impact damage	0
Visible penetration damage	Upper wing skin	Impact damage	0

Table 7-4 – Total number of characteristics elicited from the wreckage by the practitioners

7.10.3 Finding 3 – The elicitation of specific characteristics from the composite wreckage, resulted in the output of focused lines of enquiry

It was apparent that the investigation process is a dynamic system which utilises triangulation of facts rather than single pieces of evidence. This fact was identified within many facets of evidence collection, including the examination of the composite wreckage. For example, flutter was considered as a plausible line of enquiry as to why the structure failed. The generation of this line of enquiry came from sources of evidence such as:

- The wreckage distribution suggested in-flight breakup
- The aircraft's [hypothetical] accident history suggested a history of accidents involving flutter
- The locations of the fractures on the wing

Potential sources of evidence to test this hypothesis came from many areas of investigation, for example:

- Failure characteristics identified in the wreckage by the investigator
- In-depth failure examination using SME's.
- Load characteristics during flutter – to confirm if a correlation is evident between the point of failure and the expected flutter failure
- Flutter analysis using SME's.
- Meteorological data on weather conditions
- The pilots history of flying the glider and, specifically, in the meteorological conditions
- GPS data to confirm speed at time of breakup compared to flutter speeds
- History of the pilots approach to flying

Whilst some of the evidence is weighted higher than others in pointing to the occurrence of flutter, multiple sources of evidence were deemed as accessible, which could assist in understanding the line of enquiry. Therefore, had the "Failure characteristics identified in the wreckage by the investigator" not been possible, then the investigator could potentially rely on the other sources of evidence to follow the lines of enquiry. This would suggest that the inability to identify failure characteristics is not of detriment to the investigation.

However, what became apparent was that the investigator followed the most appropriate lines of enquiry for the given circumstance. Typically this would involve selecting appropriate sources of evidence based on the weight of the line of enquiry and the efficiency with which the conclusion could be drawn. For example, during the early hypothesising of the accident all of the investigators suggested that loss of consciousness (LOC) through failure of the oxygen system was a significant possibility. The circumstances of the accident certainly suggested this hypothesis was plausible.

At this stage of the investigation there were no pieces of evidence suggesting the accident had occurred due to LOC, thus the hypothesis was suggested by abductive reasoning; the aircraft was flying at altitudes where an oxygen system was necessary, therefore the accident may have occurred due to LOC. Hence, the line of enquiry had no substantial means by which it could be weighted. Initial sources approached were those which were within the immediate reach of the investigator, for example asking if there were reports of a distress call made. Following this, and when on the accident site, the participant was presented with the remains of the oxygen system. The system was checked by the practitioner for oxygen left in the tank, positioning of valves and any obvious signs of leakage not caused by the ground impact. Whilst some of these may have been ruled out temporarily, others would have increased the weight of the line of enquiry. Subsequently, if evidence was found to have identified a possibility that the oxygen system had failed, a dominant line of enquiry would involve the oxygen system. Emphasis could thus have been placed on gaining evidence from pathologists and from a detailed examination of the system.

This pattern of using evidence to weigh lines of enquiry and temporarily closed them, was identified to occur within those practitioners who conducted examination of the characteristics specific to polymer composite materials. For example, a number of different characteristics were used to rule out potential causes of failure and hence these lines of enquiry were temporarily closed.

Equally, the weighting of lines of enquiry and the clarity with which the subsequent actions were taken, were based on the recognition and confidence in recognising characteristics. Specifically, the recognition of failure characteristics associated with degradation mechanisms or defects heightened the weighting of the line of enquiry.

Therefore, the practitioners who elicited more specific characteristics from the composite wreckage followed with more specific lines of enquiry.

7.10.4 Review of the investigation process for field investigations

Due to the results obtained from practitioners, the process model as described in the first phase of the research programme was revised. The following is offered as an improved framework with supporting evidence as identified during this part of the research programme.

1. **The initiation phase**

The first stage of the field investigation model is the initiation phase. The initiation phases commences when the investigator is informed of the accident and is appointed to respond. The initiation phase continues until the investigator is focused on the collection of primary evidence. The suceeding phase is identified as the convergence phase. Whilst this may suggest the phases are independent, in reality the two phases overlap with the initiation phase diminishing as investigator effort is focused onto the convergence stage.

Facts are gathered during this phase, with three primary reasons for facts being gathered at this time:

- To acquaint the investigator with the accident scenario
- To prepare for the field investigation
- For efficiency

Detailed information on each of the steps contained within the initiation phase is given below.

a. ***Receipt of initial notification***

This is a procedural step based on the agencies initial reporting procedure.

b. Initial response

This was both procedural and discretionary, based on investigation agency requirements and investigator judgment. It included the following stages.

Organizational tasks (Primarily procedural)

- Clarification on the event
- Clarification on the potential for criminality
- Establishing communications with key stakeholders, including
  - Notifying accredited representatives
- Team organisation
- Logistic arrangements and information
- Consideration for support from SME’s
- Seek clarification on the fatality

Initial facts gathered (procedural and discretionary)

- Location details
- Aircraft details, including
  - Aircraft registration details
  - Batch information
  - Airworthiness review information
- Meteorological after-cast
- Flight / maintenance manuals
- Accident history

In addition to the initial facts as stated above the investigator may decide to choose to commence additional fact gathering prior to the arrival on site. For example if the logistical arrangements or time limitations prevent immediate access on site, the investigator may utilise this time to gain additional facts from, for example, witnesses. This assists the field examination through the expansion of background information and the early development of potential lines of enquiry.

In addition, organisations may, as a matter of procedure, immediately start the gathering of a predetermined list of factual information once the notification is received. This may be conducted by an administrative staff member and subsequently presented to the investigator.

Due to the restricted nature of facts gathered at this stage, hypothesis generation is performed by abductive reasoning based on the preliminary information available. For example, initial reports may suggest that two aircraft crashed whilst conducting a display routine at an air display. Through abductive reasoning the investigator may hypothesis a mid-air collision whilst conducting a display routine. As the investigator has applied abductive reasoning, the weight of the hypothesis is equally treated by the investigator with an open mind.

c. *Site attendance, assessment and stabilisation*

This was a procedural step which started when the investigator arrived at the accident site. It included factors such as site management, liaison, communication, site security, contamination awareness, and prioritisation.

2. The convergence phase

The convergence phase involves the period when the investigator is primarily focussed on the gathering of facts, establishing lines of enquiry, and the initial development of lines of enquiry. This phase follows the initiation phase and culminates when the investigation enters the detailed investigation. The transition from the convergence stage to the detailed investigation phase is a phased process and no clear boundary exists.

a. Onsite fact preservation, gathering and orientation

The initial focus on the convergence stage of the investigation is in orientating the investigator with the accident site and the preservation of perishable evidence. The preservation of evidence was predominantly a procedural step whereby perishable evidence is determined and preserved. The conducting of the evidence preservation may be assisted by protocols created by the investigation agency or through prior training. The scope of what is perishable is dependent on the circumstances and hence may be at the discretion of the investigator.

During this phase a site appraisal was conducted to orientate the investigator with the accident site and to generate high level hypothesis surrounding the accident. This is likely to mark the stage where inductive reasoning begins to replace abductive reasoning.

b. Exploration of facts

This stage marks the point where the hypothesis generation by the investigator tends to move from being predominantly procedurally instigated to increasingly discretionary.

The evidence at the accident site will be recorded, preserved and gathered, with further evidence being gathered outside of the immediate accident site (e.g. witness evidence). This is an analytic and fact gathering stage, albeit the initial focus will be on recording, preserving and gathering of facts.

It is at this stage that high level lines of enquiry begin to appear or start to develop further, due to the substantial increase in factual information absorbed by the investigator. Moreover, more hypotheses are generated through inductive reasoning which tends to add weight to particular lines of enquiry. Through prioritising particular lines of enquiry, more effort can be focused on the relevant areas for investigation. Deductive reasoning is also used during this phase to close general hypotheses which may have appeared earlier in the phase.

The analysis being conducted at this stage is predominantly undertaken using discretionary means or informal analysis techniques, such as informal brainstorming with colleagues.

At the culmination of this phase the investigator will have an understanding of the scope of evidence and would have identified areas which are of key interest to the investigation.

Typically this stage would involve the examining of the wreckage at a visual level to identify abnormal or unusual failures and differentiating between cause and effect within the failures.

The ‘exploration of facts’ stage occurs throughout the period during which the investigator is conducting the on-site wreckage examination. Depending on the extent of the wreckage examination on-site, it may occur or continue in a secure environment away from the accident site and may include material expertise albeit the expertise will be to assist in the large scale surveying of the wreckage rather than conducting in-depth examinations. It culminates when the wreckage has been surveyed and the key areas of interest in the structure have been identified.

3. **Detailed investigation phase**

The detailed investigation phase commenced following the completion of the convergence phase and was finalised when the relevant areas of examination, testing or research, had reached a valid conclusion or the evidence collection had become saturated. This phase differed from the convergence stage as the predominant focus was in detailed examination of specific structural areas.

The detailed investigation phase may contain multiple detailed investigations covering different areas of the investigation. For example an oxygen delivery system may be subject to detailed examination to confirm if the system was operating correctly at the time of the occurrence. Additionally, a detailed examination may be conducted on the aircraft structure to determine how the structure had failed.

Within each of these in-depth examinations may occur sub-investigations which are supportive of the overall in-depth examination. For example, the detailed examination of the aircraft structure may entail failure analysis from a SME, an investigation of the flutter characteristics, and a stress / load investigation.

During this stage the wider scenario from the external evidence is largely known and thus there may be fewer external sources of evidence outside of the areas of in-depth investigation.

To accomplish this task the examination typically involves confirmation (fractographic, design, construction, stress analysis, judgement based on location of failure etc.) testing (mechanical, construction, etc.), comparison to existing structures, and further research.

4. **The concluding phase**

The concluding phase occurred following the completion of the detailed investigation phase and following the finalisation of analysis. This phase primarily focused on the creation of recommendations, communication of findings, formal reporting and release of the investigation report.

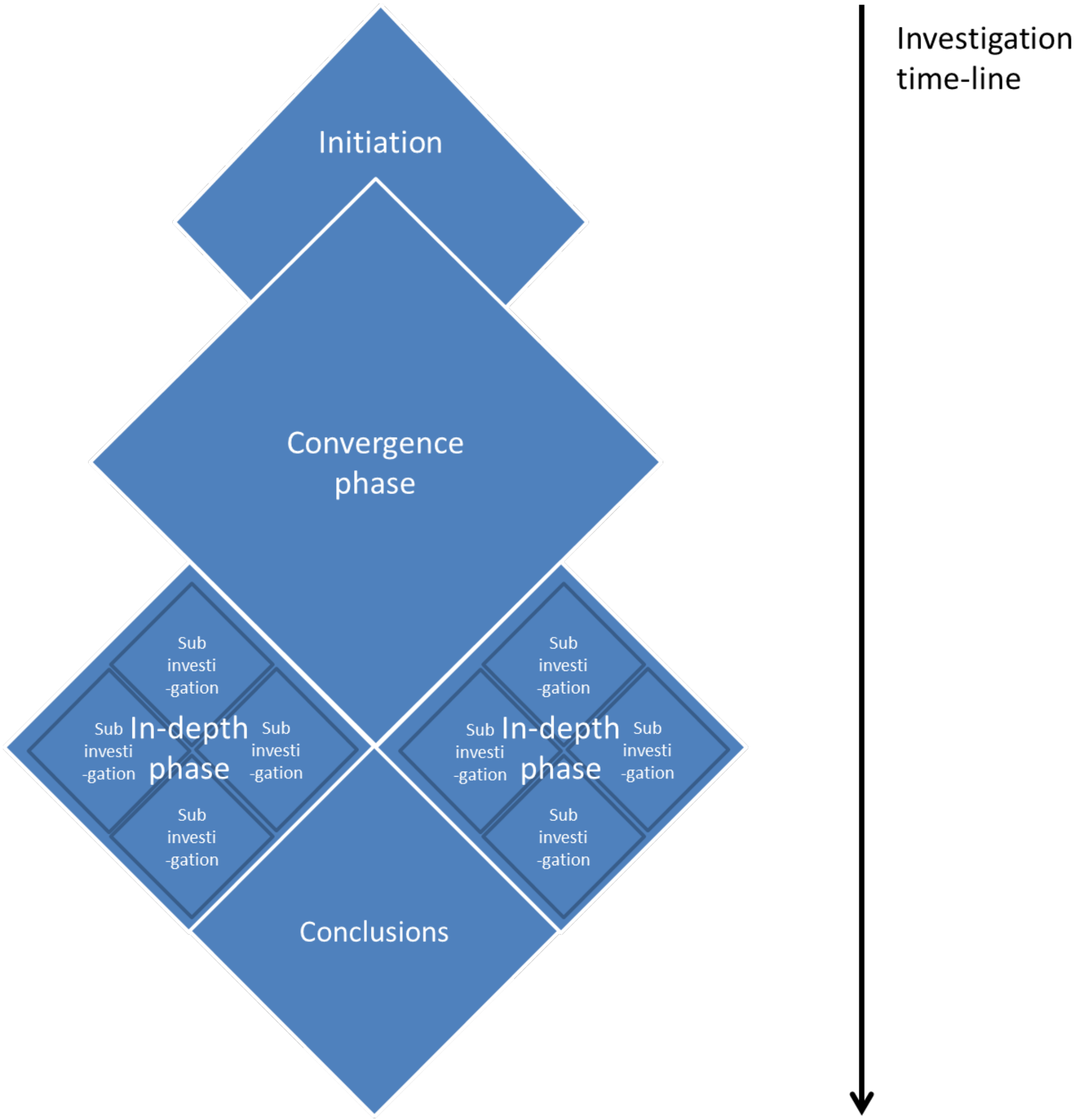


Figure 7-2 – Revised investigation model of the wreckage examination process (Source: Author)

7.11 Participant debriefing

During participant debriefing, one participant identified one inconsistency in the story. The inconsistency was minor however and the participant confirmed that it did not affect the participant's investigation effort. The inconsistent fact was not elicited by any other participant and thus the inconsistency did not influence the other participants.

Generally the participants felt that the simulation allowed them to provide a realistic representation of how they would conduct an investigation. Moreover, all of the participants stated that they enjoyed the simulation. However, areas of dissimilarity to the real-world were mentioned and they are summarised below:

1. The participants confirmed that they would typically conduct an investigation in a pair.
2. The enclosed environment prevented them from interacting with the others.
3. The investigators were undergoing a heightened state of assimilation due to the fast pace of simulated, when compared to a real-world investigation.

It would have been desirable to increase the richness of the data however this would require more time and the generation of a higher fidelity investigation scenario. The cost of arranging this is prohibitive and the ability to gain participants for an extended period of time is questionable. The current simulation was considered to be sufficient to meet the needs of the research objectives in this first research project into composite failure.

7.12 Chapter summary

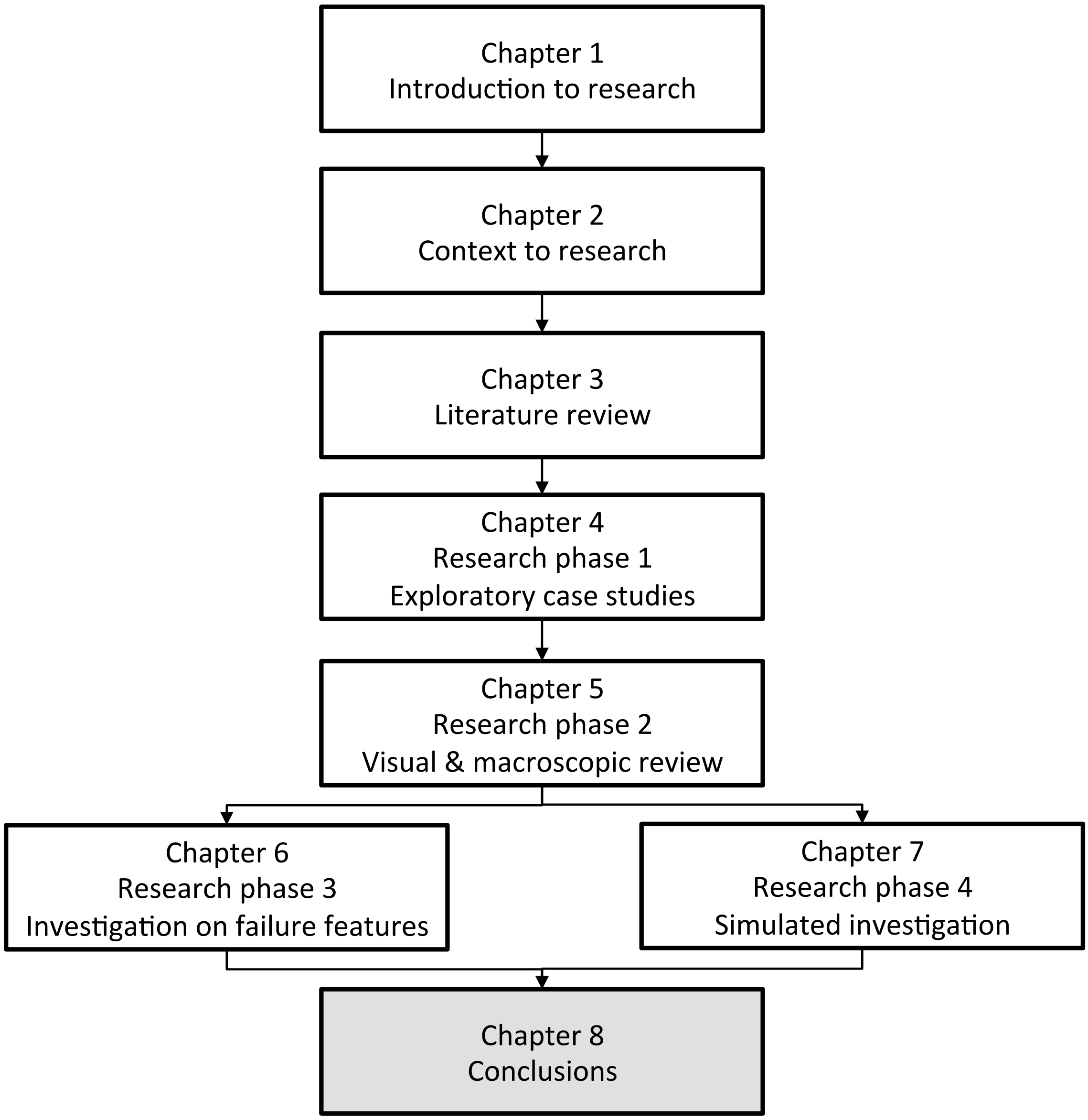
This chapter has presented the fourth and final objective of the research project, which was to study the examination of composite structures by aircraft accident investigation practitioners. The purpose of this stage was to establish how investigators approached the examination of wreckage, what information they elicited during the examination and the influence this had on the wider investigation. This study is therefore aimed at determining if an increase in the identification of failure characteristics during the field investigation phase would result in an increase in the specificity of subsequent lines of enquiry.

Seven participants took part in the study which involved the investigation, by the participant, of a hypothetical accident. The wreckage as created during the third phase of the research programme was utilised as key components of wreckage at the hypothetical accident site.

The study has suggested that an increase in the identification of failure characteristics will increase the efficiency of the investigation. However, for this to occur, the characteristics need to be identified with a level of clarity. In addition, the benefit to the investigation is likely to involve increased efficiency in which the lines of enquiry can be developed, rather identifying lines of enquiry which would otherwise not be found.

In addition, the simulated investigations were used to revisit the model created during the case study phase of the research programme. A revised model is hence presented (figure 7-2).

8 CONCLUSIONS



8.1 Overview of research problem

Anecdotal evidence suggests there is increasing concern within the accident investigation community regarding the continuing shift in airframe construction from metallic to polymer composite materials. Consequently, this project was created as a means to research the effect polymer composite materials has on the accident investigation community. Specifically, it was aimed at creating knowledge which could assist the accident investigator, from a practical perspective, in the examination of aircraft wreckage of polymer composite construction.

Laboratory research in characterising polymer composite failure features and practical experience from accident investigations, have generating two separate areas of understanding. To date, there has been no attempt to bring these two areas together, specifically in a way which can assist the field accident investigator. This research project is a first step towards filling this gap in knowledge.

This thesis describes a research project which aims to respond to particular aspects of this problem with the intent of providing a better understanding to assist practitioners, to increase the boundaries of knowledge within this field, and to offer a base from which further research can be conducted. The overall aim of the research was:

> *To determine if known visual and macroscopic failure features of polymer composites can assist the accident investigation practitioner in conducting the wreckage investigation and structural investigation.*

It became apparent early in the research that it would be necessary to concentrate research effort into two areas. Firstly, to understand how the examination of aircraft wreckage relates to the overall aircraft accident investigation (the area of implementation). Secondly, to identify visual and macroscopic failure features of polymer composite materials (the area from which knowledge will be transferred).

To achieve the overall research goal, four objectives were created with each providing a contribution to knowledge. The following discussion presents the overall research contribution made by this thesis and individually the research contributions made from each research objective.

8.2 Overall research contribution

The research has established that the current understanding of visual and macroscopic interpretation of composite material failures is well documented

(Chapter 5). The level of current knowledge is sufficient to provide visual and macroscopic indications as to the failure mode, fracture sequence and degradation mechanisms. However, it is recognised that the ability to identify failure characteristics is complicated by the diversity of physical appearance created by failure mechanisms in composite materials that do not occur in metallic materials. The research also confirms that the characteristics identified in literature are suitable to the needs of the investigative environment, contained within the process of investigation, and suitable to the practitioner (Chapter 4). Furthermore, the research programme recreates composite aircraft wreckage and successfully applies the identified characteristics onto the wreckage, determining the fracture sequence and identifying the failure initiation site (Chapter 6). This understanding is compared to that of the accident investigator who conclude the research by confirming that the identification of visual and macroscopic failure characteristics by the practitioner will benefit the investigation (Chapter 7).

Therefore, this research programme has methodically identified visual and macroscopic failure characteristics, and has proven that they can improve the accident investigation process, when being applied by the aircraft accident investigator.

The failure characteristics as identified in this research were seen principally through the research area of fractography. Within this area, the characterisation of visual failures was predominantly through the use of standard test coupons fractured under laboratory conditions. The research identified that these characteristics would need validating within a field investigation environment. This was achieved through the fracturing of large wing sections in a manner which replicated aircraft wreckage as near as practically possible (Chapter 6).

The fractured specimens were examined and the results confirmed that the visual failure characteristics seen in test coupons were present within the simulated wreckage. Moreover, these characteristics provided significant supporting evidence of the failure mode, failure sequence and the degradation mechanism type within the failure initiation site. Whilst this suggested that the use of visual and macroscopic examination can provide significant evidence within the wreckage environment, it could only suggest that the characteristics can assist an investigation within its limitations. It was thus necessary to understand the current knowledge of wreckage examination by accident investigation practitioners, and to further understand the real-time application of visual interpretation within the investigation context. This was undertaken using a hypothetical accident investigation.

The simulated investigation as undertaken identified that the current level of understanding was sufficient to make an assessment of the failure characteristics within the aircraft wreckage. There were however clear indications that the investigation process was adjusted based on the level of assessment undertaken. Moreover, it also identified that the failure characteristics existed within the specimen to answer questions that the investigators posed but could not answer. Therefore the transfer of knowledge of visual and macroscopic characteristics may assist the practitioners ability to make informed decisions on the opening or closing of lines of enquiry earlier in the investigation process. It is therefore apparent that the use of visual interpretation and macroscopic techniques has a scope for assisting the accident investigator in the wreckage examination. Additionally however, the research identified that the investigation is heavily interrelated, whereby the investigation 'process' and 'context' has a significant influence on the visual examination. Additionally, the scope of application is extremely diverse with no two accidents likely to be the same. It was therefore apparent that to implement and understand the use of the visual and macroscopic characteristics would require significant time, effort and scope.

This drew a natural close to this research and provided significant suggestions for further research. It is suggested that initially the failure characteristics should be communicated to the accident investigation community with a feedback mechanism established to monitor feasibility, usability, usefulness and success. Secondly, research should be conducted in longitudinal case studies to implement the characteristics into real-world investigations. Finally, it was identified that the visual characteristics were developed during the birth of fractography in polymer composites. Research should be re-established to identify visual characteristics in new materials and should look to cover areas of poor knowledge on degradation mechanisms.

In addition to the overall research contribution, each phase of the research has presented important contributions. These will be discussed individually below.

8.2.1 Exploratory multiple case study of the wreckage and structures examination (Chapter 4)

This phase involved the use of multiple case studies to conduct an exploratory study into the investigation of accidents involving polymer composite aircraft. Both primary and secondary data was collected with an aim to understand the process by which the investigation was conducted and the significant aspects discovered from the examination of composite wreckage. As a result of this phase a framework was created which described the investigation process with specific emphasis on the investigation involving the airframe. It may be postulated that whilst this framework was focused on case studies where the examination of the airframe was a principle factor, it may have transferability with modification to investigations where the focus may be on a non-structural aspect. This phase generated a detailed understanding of the stages within an investigation and provided a formalised process from which researchers and practitioners can understand the rationale of, and steps undertaken in, the examination process.

8.2.2 The evaluation of visual and macroscopic examination characteristics (Chapter 5)

This section provides a survey of the current status of the visual and macroscopic interpretation of polymer composite failures. This review provides a practical foundation to the current status of knowledge in this field. In addition the survey also provides a review on the recognition and understanding of visual and macroscopic characteristics of polymer composite materials. With further development this may assist the investigation practitioner in interpreting composite material failures.

8.2.3 The visual and macroscopic examination of a polymer composite structural failure - test case (Chapter 6)

This section involved the test design, conducting and subsequent failure examination of a polymer composite component. It does this as a means to examine the visual and macroscopic failure characteristics within a simulated accident investigation. The method employed involved the up-scaling of a four-point-bend-test to conduct a controlled failure of a polymer composite aircraft wing section. This task encountered significant problems and thus for researchers who would consider this method as a means to load a large structure to failure, there have been important 'lessons learned' which are described in detail in the chapter. However, the testing was successful, and a method is presented by which the controlled failure of a full scale aerofoil section can be conducted. Furthermore, the subsequent macroscopic and visual analysis of the aerofoil section provided a novel means by which a failure investigation can be conducted, in a controlled manner, to determine the availability of evidence in a simply failed structure where the failure process was controlled and documented.

It is shown that through experimentation using structures, an understanding of failure features can be ascertained. Further development in this area is necessary to increase the understanding of composite failures in differing scenarios.

8.2.4 A study into the examination of a polymer composite structural failure by accident investigation practitioner using the simulation method (Chapter 7)

This section used the simulation method, as developed by Woodcock et al (1995), to study the investigation, by practitioners, of a simulated accident scenario involving the simulated accident of a polymer composite aircraft. A study of the process by which the investigators conducted the simulation provided further evidence to support the investigation process framework as developed during the first phase of the research programme. Additionally, although the use of simulations as a means to conduct empirical research is well founded, the simulated method as proposed by Woodcock et al (1995) to be used in the study of accident investigations is reasonably less established. It was thus advantageous that this method be used not only to meet the aims of the research but also as a means of expanding the foundation of this method.

The information within this chapter provides important learning in the use of the method within the complex environment of an aircraft accident investigation. Moreover, to cope with the complexities of information that an aircraft accident investigator is likely to discover, the method was adapted to include the use of artefacts and graphics within the method. This included the use of the 'think-aloud' method as a means to verbalise practitioner interpretation.

8.3 Limitations in research

It is inevitable that any study is likely to be constrained by the scope, the scale and resources allowed to the researcher. Although the research has achieved the aim of exploring the investigation of polymer composite materials in aircraft accident investigations, a number of limitations have been encountered.

It became apparent during the research programme that the preferred methodology would be to conduct longitudinal studies of real time accident investigations using participant intervention or action research. This would allow the researcher to become absorbed into a current investigation and to react to a real-world event. This was not feasible however due to restrictions in access, the infrequencies of suitable accidents occurring and the lack of control the researcher would have over the event. A multi-phase programme was therefore conducted whereby past events were studied (phase 1) and a hypothetical accident scenario was created (phase 4).

In the case of the first phase of the research programme this had the limitation of studying cases following the event. In some cases this may have occurred years after the field examination may have occurred. Consequently, this will limit the depth of information elicited from the interviews as it required the participants to recollect the investigation. Although this was apparent, the first phase required an in-depth study where understanding could be drawn whilst maintaining flexibility. Consequently the case study was the appropriate method to utilise. The limitations posed by this phase were reduced by the use of a rigours data collection protocol and thus the implications of this limitation were minimised.

During the fourth phase of the research programme a hypothetical simulation was conducted. This introduced artificial constraints onto the investigators such as time, access and depth of information. This enclosed the investigator into an artificial setting which is likely to influence their behaviour such that differences may occur compared to their actual activities. Whilst the simulation was designed with rigour and the depth to replicate the information from a real investigation, it is accepted that it cannot be reality. A debriefing was used to identify the disparities between the hypothetical scenario and reality. The participants responded positively with few minor issues raised about the simulation. Importantly, the issues raised were those identified during the design of the hypothetical scenario and thus adjustments were made prior to the running of the simulations to minimise the effects.

A further limitation encountered was by the nature of accident investigation. Whilst the investigation is open and transparent, there are laws governing the release of data relating to investigations, and there are sensitive issues which require restraint. Consequently this prevented the selection of some cases for study in the first phase of the research programme and limited the availability of data in others. This has the potential for restricting case selection and for reducing the opportunity for data triangulation. Whilst this occurred, the case selection criteria ensured that suitable alternative cases were selected. Furthermore, sufficient support and access was granted by the investigators such that an array of sources of information was obtained. These are illustrated in each case description and thus the implications of data loss were minimised.

A further limitation is that all stages of the research programme were conducted with limited quantities of cases, hypothetical simulations or fractured specimens. Whilst it may seem reasonable to consider each of these as an equivalent to a sample size, the foundation of each of the research phases was on replication logic, where each case studied is the equivalent to an experiment in itself rather than the number of participants undertaking that one experiment.

This thus suggests that as four case studies were conducted for phase 1, then the generalization of this stage is high, but still obviously bound within the scope of the case studies selected. This is supportive evidence however that the results of this phase are extendable beyond the immediate scope of the case studies. Firstly, the case studies selected involved three agencies across two continents and thus had a geographical spread. Secondly, the case studies covered a variation of structural failures with the variation being conceptually devised rather than random selection. Thirdly, the theoretical grounding to the case studies was based on concepts that are generalised to all types of investigations. Thus, whilst the case studies were specifically selected to involve particular investigations, the means by which these were studied were based on generalised models and thus it may be found that the results can be generalised to differing types, scales and severities of accidents.

Perhaps the most significant limitation in generalizability occurred during the third phase of the research programme, namely the creation of specimens to explore the prevalence of failure characteristics in failed aircraft structures. Whilst the evaluation of material failure characteristics (chapter 5) revealed a wide array of characteristics that indicated potential, it was impractical, and outside of the resources available for this research, to further test the applicability and occurrence of all of these characteristics within the context to which they would be used. The creation of fractured specimens, with the intention of representing realistic aircraft wreckage (Chapter 6), was thus conducted but with the understanding that the testing of a limited number of the failure characteristics could be investigated. It should be noted however that the purpose of this phase was not merely to repeat the creation of known failure characteristics, which are in all practical sense fundamentally well founded in literature. Rather, it was focused on understanding the influence of failure characteristic recognition within the context of aircraft accident investigation (chapters 6 & 7), an aspect which is more fitting to the aims of this research and in providing its novel approach. On this basis, and within the already noted resource induced restrictions, the limited replication conducted in chapters 6 and 7 are not failings of generalizability within the individual chapters but perhaps more evidence to support the wider findings as discovered in chapters 4 & 5.

Lastly, there is likely to be bias during interpretation by the researcher. This is likely to be evident in all phases of the programme as the researcher became encapsulated in the research. This was minimised during phases 1 and 4 however through the use of analysis techniques designed to identify rival explanations. This bias is perhaps most evident in the third phase during the examination of the created wreckage by the researcher. It was impossible for the researcher to disremember the method by which the specimens were fractured, and therefore a bias was introduced to the examination of the specimens. It is therefore accepted that this phase was a study to triangulate the known failure mode with the expected characteristic. This therefore added confidence that the characteristics identified were those that actually occurred.

8.4 Suggestions for future research

Firstly, and perhaps the most significant direction for further research, concerns the replication of the study with an alternative focus for the research programme. Whilst this study has been oriented to explore past investigations (chapter 4) and simulate investigations (chapters 6 & 7), the research was not conducted in current investigations. The use of research methods which allow the researcher real-time access to current investigations such as longitudinal studies or action research may offer significant advantages in the quality of data and directly increase the practitioner focussed contribution to knowledge.

If adopted during the exploratory phase of the research project, it would refine the concept put forward by this study and may provide additional areas of interest. The expansion of the first phase is important as the knowledge forms a basis of understanding for the subsequent implementation. An increased understanding of this area will allow a better focus for research orientated towards assisting the practitioner as well as the creation of a refined framework.

During the subsequent research into the application of the characteristics, the ability to work closely with the practitioners will promote a greater feedback from the practitioner to the researcher and the close proximity to real-time investigations (including the wreckage) should promote findings with fewer limitations.

Another area which promotes further research relates to chapter 5, the review and evaluation of macroscopic and visual failure characteristics. As highlighted in this chapter, the majority of characterisation appeared from the pioneering years of fractography in polymer composite materials. Although the field is fairly well documented, there is perhaps further scope for research concentrated in the recognition of degradation mechanisms and in quantitative characterisation.

There is further scope for research in the use of simulated scenarios in aircraft accident investigation studies, similar to those conducted in chapter 7. The method, as developed by Woodcock et al (1995), has already been conducted in the investigation context and presents potential for further development in the methodology. Although the complexity of the method increased when applying into the aircraft accident investigation scenario, the methodology can be adapted for use within wider 'table top' investigation scenarios, or for use in higher fidelity accident investigation simulations as discussed by Braithwaite (2010).

Finally, additional expansion is recommended on the work undertaken in chapter 6. Through the increased number of experimental testing in fracturing structural elements with the aim of understanding visual and macroscopic failure characteristics, not only can the proposed characteristics in chapter 6 be verified, but there is potential for adding to knowledge in the area of known failure characteristics and the interactions that may be present when failing a larger structure. In this case it is recommended that the development of the testing method for specimen creation which was used in this research be also consider per the limitations found in the test fixture as discussed in chapter 6.

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Appendix A – Risk Assessment of test fixture

GENERAL RISK ASSESSMENT

1.

Building / Room No / Area:	**B57 / G28 / test lab**	**Department:**	**Air Transport**			**Risk Assessment Ref No:**	**CSAIC/ld/001**
Work Activity:	**Four Point testing – composite wing sections**		**Date of this assessment:**	**03/07/2012**		**Date review due:**	**N/A**

2. **Hazards Overview** *(If hazard is present insert X)*

Asbestos* /Dust (general, silica, etc)	X	Electricity (including Static / Capacitive)		Shared Workplace (incompatibilities, crowding, etc)	
Chemicals*		Machinery: Moving Parts / Ejection / Entrapment	X	Hot / Cold surfaces (>60°C or<5°C)	
Fire / Explosion / Flammable Vapours* / Hot Work (e.g. welding)/Firearms		Stored Energy (Pressure, Vacuum, etc)	X	Work Environment: e.g. Hot (>35°C), Cold (<5°C), Humid, Wet, Windy, Lightning	
Ionising Radiation*		Lifting Operations (e.g. cranes, lifts etc)	X	Shift Working	
Lead Work*		Work at Height (fall of person, object or material)	X	Out of hours / Lone Working	
Manual Handling (heavy loads, repetitive/awkward operations)*	X	Confined Spaces		Biological (e.g. Legionnaires Disease* from hot water)	
Noise* (>80dB(A) / Vibration	X	Excavation Work		Fume (e.g. Welding, Soldering, Asphyxiating gases)	
Non-ionising Radiation (Lasers/RF/UV/IR)		Slipping / Tripping / Falling (same level)	X	Failure of Service (e.g. cooling water supply)	
Display Screen Equipment* (PCs, Monitors)		Contact with stationary object (e.g. strike head)	X	Drowning	
Off-site Working (UK and Overseas) *		Sharps / Cutting / Grinding / Polishing devices	X	Intruders / Violence	
Firearms		Traffic (People, Vehicles, Driving)		Other:	

* Additional specific risk assessments are required if the risks from these types of hazard are evaluated as being significant (e.g. COSHH, DSE, Manual Handling Assessments)

3. **Next step: Complete "Evaluation of Risk* matrix (see page 2)**

4. **Additional Control Measures*** *(Complete this section for any Risk which is rated as 4 or more, or for which the Likelihood is 3)*

Ref No:	Action	Responsible Person	Completion Date
2	Compilation of test fixture build procedure (working rules) – CSAIC/ld/002	Leigh Dunn	10/07/12

* Note: The choice of controls should be implemented according to the following hierarchy - 1. Eliminate the hazard, 2. Substitute, 3. Reduce, 4. Isolate (enclose the hazard), 5. Regulate (e.g. numbers at risk, engineering controls or Safe System of Work), 6. Protection (e.g. PPE), 7. Discipline.

5.

Signatures	**Name (Capitals):**	**Position:**	**Signature:**	**Date**
Assessment by:	LEIGH DUNN	RESEARCH STUDENT	[redacted]	12/07/12
Approved by:	Graham Braithwaite	Head of Department	[redacted]	12/7/12

6. **Copies:** **(a)** The original of this form is to be retained by the originating department ~~and a copy is to be supplied to the Safety Department~~ *(not required ref Claire Chalkley 10/07/12).*
(b) Relevant information on risks and preventive / protective measures are required by law to be provided to employees so that they can ensure their own health & safety and not put others at risk.

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4. Additional Control Measures* *(Complete this section after carrying out Evaluation of Risk, for Risks identified with Risk Number 4 or over)*

Ref No:	Action	Responsible Person	Completion Date

* Note: The choice of controls should be implemented according to the following hierarchy - 1. Eliminate the hazard, 2. Substitute, 3. Reduce, 4. Isolate (enclose the hazard), 5. Regulate (e.g. numbers at risk, engineering controls or Safe System of Work), 6. Protection (e.g. PPE), 7. Discipline.

Evaluation of Risk

3.

Hazard Details			Persons at risk	Frequency / (Duration)	Controls in place	Residual Risk Evaluation		Risk rating
Ref No.	Hazard	Nature of Hazard / Adverse Effects (How is the hazard likely to put people at risk?)	Insert Code & (number of people)	Insert Code Letter & (Duration)	Insert Code Numbers	Severity of Harm Score 1 to 3	Likelihood of Occurrence Score 1 to 3	Multiply Severity × Likelihood
1	Airborne composite particles	Possible respiratory problems	A,B,C,E,F,G,J,K (10)	H/(3)	5,6,8,31, 41	1	2	2
2	Manual handling of fixture and specimens	Possible lifting injuries	A,B,L (3)	H/(6)	5,20,30,31, 35,37	2	2	4
3	Noise during specimen fracture	Hearing problems / deafness	A,B,C,D,E,F,G,J, K ,L(5)	H/(1)	5,30,31	1	1	1
4	Machinery: Moving Parts - Ejection	Specimen could be ejected / Injury	A,B,C,F,L (1)	H/(10)	5,30,31	3	1	3
5	Stored Energy	Stored energy in material whilst under load	A,B,C,F,L(2)	H/(10)	5,30,31	1	1	1
6	Lifting operations	Specimens and fixture may have to be lifted into position and removed using lifting equipment, incorrect lifting could lead to injury	A,B,L (3)	H/(10)	5,20,30,31, 34,35,37	3	1	3
7	Work at height	Steps leading to machine could cause injury if a fall occurs	A,B,L (3)	H/(20)	5,20,30,31, 37	2	1	2

Persons at Risk (Letter = Code)

A. Operator (skilled)	B. Operator (inexperienced)	C. Visitors	D. Office Staff	E. Cleaners	F. Students
G. Maintenance	H. New & Expectant Mothers	I. Disabled	J. Lone Worker	K. Contractor	L. Other

Frequency	Duration
H = Hourly, D = Daily, W = Weekly	Insert Hours per week
M = Monthly, Y = Yearly	

Controls (Number = Code)

1. Flameproof Equipment	10. Labelling	19. Hand rails	28. Lock-offs (e.g. padlock for maint)	37. Mechanical Aids (for lifting, etc)
2. Flame Failure Protection Device	11. Segregation	20. Access Aids e,g, stepladder	29. Maintenance	38. Job Rotation
3. Sprinklers	12. Earthing	21. Enclosed / fenced	30. Information	39. Stress Management
4. Other Flame Protection Measures	13. Isolation	22. Audible warning	31. Instruction / Training	40. Seating / Anti-glare
5. Personal Protection Equipment	14. Reduced Voltage	23. Fixed Guards	32. Method Statement	41. Good Housekeeping
6. Natural Ventilation	15. Circuit Breakers	24. Protection Devices (Interlocks etc)	33. Supervision	42. Vaccination
7. Local Exhaust Ventilation	16. Disinfection	25. Protection Appliances (Jigs, Holders, etc)	34. Authorised Person list	43. Other
8. Work Place Monitoring	17. Marked Gangways	26. Anthropometrics (e.g. beyond reach)	35. Rules	44.
9. Medical / Health Surveillance	18. Prohibited Zones	27. Permit to Work or other Safe System of Work	36. Silencers	45.

Severity of Harm		Likelihood of Occurrence
1 Slight	e.g. Superficial injuries; minor cuts and bruises; eye irritation from dust; temporary discomfort e.g. headaches	1. Low (Harm will seldom occur)
2. Serious	e.g. Lacerations; burns; concussions; serious sprains; dermatitis; work related upper limb disorders; asthma; deafness; minor fractures etc	2. Medium (Harm will often occur)
3. Major	e.g. Amputations; major fractures; multiple injuries; fatal injuries; poisoning; occupational cancer & other severely life shortening diseases	3. High (Certain or near certain)

Evaluation of Risk (Continued)

3.

Significant Risks (Continued)			Persons at risk	Frequency / (Duration)	Controls in place	Residual Risk Evaluation		Risk rating
Ref No.	Hazard	Nature of Risk (How is the hazard likely to put people at risk?)	Insert Code & (number of people)	Insert Code Number & (Duration)	Insert Code Numbers	Severity of Harm Score 1 to 3	Likelihood of Occurrence Score 1 to 3	Multiply Severity x Likelihood
8	Slipping / Tripping	Injury From Falling Over	A,B,C,D,E,F,G,L (1)	D/(5)	41	2	1	2
9	Contact with stationary object	Overhang of test fixture creates a bump hazard	A,B,C,F,L(4)	H/(20)	5,31	1	1	1
10	Sharps	Fractured specimens could cause injury	A,B(1)	H/(5)	31,34	2	1	2
11	Lab Hazards	For all other hazards associated with working in the lab (B57 / G28 / MTL) please see General Risk Assessment: MTL/BH/0212/R01						
12	Test Machine Hazard	For all other hazards associated with working with the test machine. Please see General Risk Assessment: MTL/BH/0212/E06						

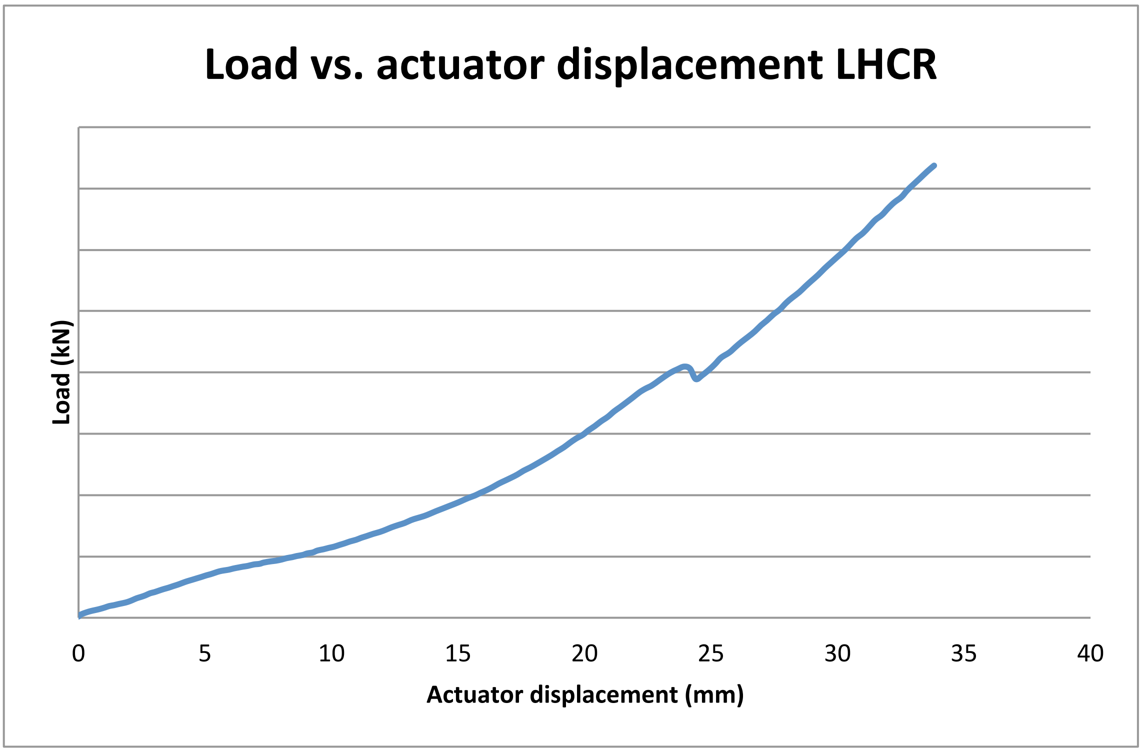
Additional Control Measures (Continued)

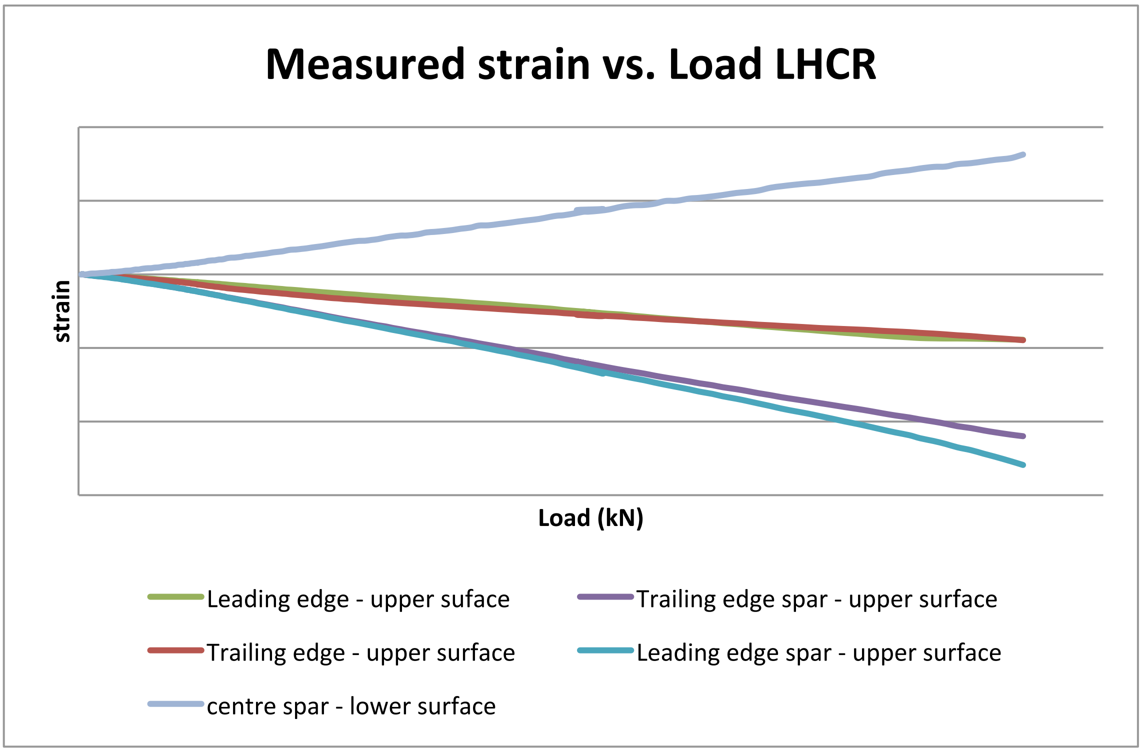
Appendix B – Test fixture assembly instructions

4 Point test fixture build procedure

Item	Lift to test	Persons	Tools required	Further information
Locking Nut	Manual	1	20mm bar	Screw locking nut onto spindle
Female upper fixture mount	Manual	1		Screw female upper fixture mount to spindle
Upper four point beam	Crane	2	Lifting sling - non duplex	Attach sling to centre of bar, around attachment plate. Crane and swing into lower actuator.
Connect upper beam	NA	2	32mm bolts and relevent socket	Lower test rig upper section whilst the beam is being held on the lower fixture. Rotate to fit and attach bolts. Raise upper section.
Lower beam	Crane	3	Lifting sling - non duplex	Attach sling to centre of bar, around attachment plate. Crane and swing into lower actuator.
Connect lower beam	NA	3	bolts and relevent socket / spanner	attach lower beam whilst 2 persons are supporting the ends
Connect upper beam upper wing clamps	crane	2	Small eyes and shackles, duplex lifting sling	Lift onto lower beam. Slide along with a person at each end, lower upper beam, attach shackle and raise upper beam.
Connect upper beam lower wing clamps	Crane	2	Small eyes and shackles, duplex lifting sling, bolts and socket	Lift onto lower beam. Slide along with a person at each end, lower upper beam, attach bolts and raise upper beam.
Attach compression brackets	Manual	1	socket	Raise upper beam to contact lower beam if required to allow the bolts to be inserted.
Lower beam wing clamps	Crane	2	Small eyes and shackles, duplex lifting sling, bolts and socket	Lift lower clamp onto lower beam. Attach to eyes using shackle. Lift upper clamp onto beam and connect to lower clamp.Connect compression brackets. Lower upper beam and attach a rope from the upper beam wing clamp to the lower beam wing clamp. Raise upper beam to raise lower clamp. Attach support clamp and tighten until the section is near vertical and secure.
Support lashings	manual	2	lashings	Connect lashings around upper fixture and to each end of upper wing clamp. This will act as a redundant safety feature.

Appendix C – LHCR data collection





Appendix D – LHCR data collection