Australian Government

Australian Transport Safety Bureau

ATSB TRANSPORT SAFETY INVESTIGATION REPORT

Aviation Research and Analysis Report – AR-2007-021

Final

# Fibre composite aircraft – capability and safety

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**ATSB TRANSPORT SAFETY RESEARCH REPORT**

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# Fibre composite aircraft – capability and safety

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Cover photo courtesy of Lee Thomas.

**Abstract**

For many decades, fibre composites have been replacing traditional aluminium structures in a wide variety of aircraft types. From the first all-composite kit plane released in 1957, composites are widespread today in commercial aircraft and many other aircraft types. This is due to the cost and weight savings that materials such as glass/phenolic and carbon/epoxy offer aircraft manufacturers over aluminium, while maintaining or surpassing its strength and durability.

This study provides an overview of fibre composite use in aircraft and the issues associated with its use, with a focus on aircraft operating in Australia that contain these materials. There are almost 2,000 aircraft on the Australian civil register made of, or containing, fibre composite materials. This includes most of the mainline jet fleet, effectively all sailplanes and gliders, many popular general aviation (GA) aircraft, and a third of the growing amateur-built aircraft category.

There is a lot of conflicting or incorrect information in the aviation community about the safety and capability of fibre composite materials. Composite structures behave very differently under normal loads than equivalent metal structures. Fatigue and corrosion have been proven through trials of composite repair patches to be much less prevalent in composites compared with metals. Subsurface damage such as delamination however can go undetected for long periods and result in sudden catastrophic failure. It is important that operators of fibre composite aircraft are aware of the correct detection and repair procedures for composite structures.

First responders involved in post-crash cleanup operations have expressed concerns about the long-term effects from exposure to products released from burning composites. Current research suggests some types of fibre dust may pose an inhalation risk similar to asbestos. Released fibres can be needle-sharp, and can cause skin and eye irritation. In the event of a post-crash fire, smoke and toxic gases are released from decomposing composites, presenting further health risks.

# THE AUSTRALIAN TRANSPORT SAFETY BUREAU

The Australian Transport Safety Bureau (ATSB) is an operationally independent multi-modal bureau within the Australian Government Department of Infrastructure, Transport, Regional Development and Local Government. ATSB investigations are independent of regulatory, operator or other external organisations.

The ATSB is responsible for investigating accidents and other transport safety matters involving civil aviation, marine and rail operations in Australia that fall within Commonwealth jurisdiction, as well as participating in overseas investigations involving Australian registered aircraft and ships. A primary concern is the safety of commercial transport, with particular regard to fare-paying passenger operations.

The ATSB performs its functions in accordance with the provisions of the *Transport Safety Investigation Act 2003* and Regulations and, where applicable, relevant international agreements.

**Purpose of safety investigations**

The object of a safety investigation is to enhance safety. To reduce safety-related risk, ATSB investigations determine and communicate the safety factors related to the transport safety matter being investigated.

It is not the object of an investigation to determine blame or liability. However, an investigation report must include factual material of sufficient weight to support the analysis and findings. At all times the ATSB endeavours to balance the use of material that could imply adverse comment with the need to properly explain what happened, and why, in a fair and unbiased manner.

**Developing safety action**

Central to the ATSB's investigation of transport safety matters is the early identification of safety issues in the transport environment. The ATSB prefers to encourage the relevant organisation(s) to proactively initiate safety action rather than release formal recommendations. However, depending on the level of risk associated with a safety issue and the extent of corrective action undertaken by the relevant organisation, a recommendation may be issued either during or at the end of an investigation.

The ATSB has decided that when safety recommendations are issued, they will focus on clearly describing the safety issue of concern, rather than providing instructions or opinions on the method of corrective action. As with equivalent overseas organisations, the ATSB has no power to implement its recommendations. It is a matter for the body to which an ATSB recommendation is directed (for example the relevant regulator in consultation with industry) to assess the costs and benefits of any particular means of addressing a safety issue.

**About ATSB investigation reports:** How investigation reports are organised and definitions of terms used in ATSB reports, such as safety factor, contributing safety factor and safety issue, are provided on the ATSB web site www.atsb.gov.au.

# ABBREVIATIONS

| | |
|---|---|
| **AAIB** | Air Accident Investigation Branch, Department for Transport (UK) |
| **AC** | Advisory circular |
| **AGATE** | Advanced General Aviation Transport Experiments |
| **ARH** | Armed reconnaissance helicopter |
| **ATSB** | Australian Transport Safety Bureau |
| **BAe** | British Aerospace plc (now BAE Systems plc) |
| **BVID** | Barely visible impact damage |
| **CFRP** | Carbon fibre reinforced plastic |
| **CO** | Carbon monoxide |
| **$CO_2$** | Carbon dioxide |
| **DoD** | Department of Defence |
| **DSTO** | Defence Science and Technology Organisation |
| **FAA** | Federal Aviation Administration (US) |
| **FAR** | Federal aviation regulation (US) |
| **GA** | General aviation |
| **GFRP** | Glass fibre reinforced plastic |
| **µm** | Micron |
| **MSDS** | Material safety data sheet |
| **NASA** | National Aeronautics and Space Administration (US) |
| **NDT** | Non-destructive testing |
| **NTSB** | National Transportation Safety Board (US) |
| **OH&S** | Occupational health and safety |
| **PPE** | Personal protective equipment |
| **RPT** | Regular public transport |
| **SOP** | Standard operating procedure |
| **TSI** | Transport Safety Investigator |
| **UK** | United Kingdom |
| **US** | United States of America |
| **VLJ** | Very light jet |

# EXECUTIVE SUMMARY

For many decades, fibre composites have been replacing traditional aluminium structures in a wide variety of aircraft types. From the first all-composite kit plane released in 1957, composites are widespread today in areas from cabin furnishings through to key structural members such as fuselages, wing boxes, control surfaces and empennages. This is due to the cost and weight savings that these materials offer aircraft manufacturers over aluminium, while maintaining or surpassing its strength and durability.

The purpose of this report was to provide an overview of fibre composite use in aircraft and the issues associated with its use, with a focus on aircraft operating in Australia that contain these materials. There are almost 2,000 aircraft on the Australian civil register made of, or containing, fibre composite materials. This includes most of the mainline jet fleet, effectively all sailplanes and gliders, many popular general aviation (GA) aircraft, and a third of the growing amateur-built aircraft category. Aircraft such as the Cirrus, Robinson R22/R44, Lancair and Jabiru ranges all contain significant composite structures.

Composites are formed from two materials – a reinforcing fibre which is woven into a ply, and a matrix material which bonds the plies together and provides the stiffness to shape the fibres into structures. Fibre composites used in aircraft generally are one of two types: carbon/epoxy which is used in major load-bearing structures, and glass/phenolic which is used in cabin furnishings and amateur-built aircraft structures. Plies of these materials are bonded together to form laminates, with the thickness of the laminate depending on the strength required for a particular structure.

Traditionally, aircraft structures have been made of metal, and hence there is a wealth of knowledge amongst regulators, investigators, maintainers and operators about the load capabilities, damage tolerance and reparability of these structures. In composite aircraft accidents, much less is known about how fibre composites behave under impact loads, how to identify failure modes, and what safety precautions must be taken by accident investigators when handling composites. The behaviour of these materials compared to equivalent metal structures was discussed when placed under tension, compression, bending and shear loads.

Impact behaviour of composite airframes was discussed, with a focus on delamination as it is the primary cause of failure. Common non-destructive techniques to identify delamination include tap testing, pulse echo and a range of ultrasonic methods. There have been several research efforts to test the survivability of composite airframes in a crash, and to measure the severity of subsurface damage that occurs. This includes the NASA AGATE program which simulated a hard surface impact of a Lancair Columbia 300 aircraft, and showed that while structures remained relatively intact after a crash, barely visible subsurface delamination and cracking can occur. Standard repair schemes for impact damage were highlighted, particularly non-patch repairs, bonded external repairs and scarf repairs. Programs to apply composite repair patches to fatigued metallic structures were trialled successfully in the 1980s and 1990s, with repairs requiring little maintenance or inspection over long periods of service time.

With the increase in the number of fibre composite flying in our skies likely to continue with the boom in amateur-built and very light jet (VLJ) aircraft, it is reasonable to assume that investigators will encounter these materials more often at accident sites. Composite structures pose new challenges for clean up crews and first responders, due to their flammability characteristics. While glass/phenolic composites have low flammability, carbon/epoxy and vinyl ester-based structures burn easily and produce thick, toxic smoke. Large amounts of carbon monoxide and dioxide can be produced in post-crash fires, and appropriate breathing apparatus must be worn. The safety risks of handling composite materials were explored, as fibrous debris is needle-sharp and can cause skin and eye irritation. More importantly, dust from some advanced fibre composites (such as E-glass) may have the potential to pose an inhalation threat similar to asbestos if handled improperly. In the event of a crash and post-impact fire, it is critically important for emergency services to evacuate passengers to a location upwind of the accident and away from fibre composite debris. Timely action will minimise passengers' exposure to these risks.

Typical first responders such as the police and fire services were contacted to find out what information or training, if any, they gave to make staff aware of the hazards of handling composite debris. This survey found that knowledge of composite hazards, and appropriate response methods are very disjointed between different emergency services in different states. The Australian Transport Safety Bureau (ATSB) provides materials such as the such as the *Civil and Military Aircraft Accident Procedures for Police and Emergency Services Personnel* to make this information more easily accessible to first responders, and to ensure their safety at aircraft accident sites.

It would be prudent for emergency services to review their aircraft accident response procedures, or develop specific procedures if they do not currently exist. Measures that could be implemented to do this include training workshops, incorporating ATSB accident response methods into Standard Operating Procedures, and development of 'first response' equipment and information kits for first responders.

# 1 INTRODUCTION

The use of fibre composite materials has been common in general aviation (GA), kit and amateur-built aircraft for many years. The use of these materials for primary structural components in aircraft is becoming more prevalent as the amateur-built sector continues to grow strongly. Composites are finding increasing use in the next generation of airliners, in particular the Boeing 787 Dreamliner which contains approximately 50% composites by weight, including major structural elements such as the fuselage, wing, spars and stringers. Composites are also finding applications in other aviation components, such as turbofan engine blades and cowlings.

With a growth in the number of aircraft operating in Australia which contain or are constructed from fibre composites, there is likely to be a greater proportion of accidents in the future where composite materials may be present. While there is a wealth of knowledge amongst industry, government and aviators about the behaviour of traditional metal aircraft structures in aircraft accidents, less is known about how fibre composites behave under impact loads, how to identify failure modes, and what safety precautions must be taken by accident investigators when handling composites. This lack of knowledge across both the industry and the public about fibre composite materials has led to many myths and misunderstandings about their inherent safety, and the correct maintenance and inspection procedures for composite structures.

The Australian Transport Safety Bureau (ATSB) has identified this lack of knowledge as a possible safety issue, both for those operating and maintaining fibre composite aircraft, as well as for accident investigators and first-response emergency personnel attending the site of an aircraft accident.

The purpose of this report is to:

- Identify what fibre composite aircraft are prevalent on the Australian civil register;
- Identify current and projected trends in fibre composite use in commercial, general aviation and amateur-built aircraft;
- Identify common aircraft structures and components in which composites are used;
- Discuss the load behaviour and reparability of composite structures;
- Identify the hazards of fibre composite debris at aircraft accident sites, and the risks it can pose to emergency personnel, public and investigators if not managed correctly;
- Appropriate response methods and protective equipment to be used by first responders to an accident site where fibre composite materials may be present;
- Capture the current procedures and equipment that is used by emergency personnel when responding to aircraft accidents, particularly if the presence of fibre composite materials is suspected.

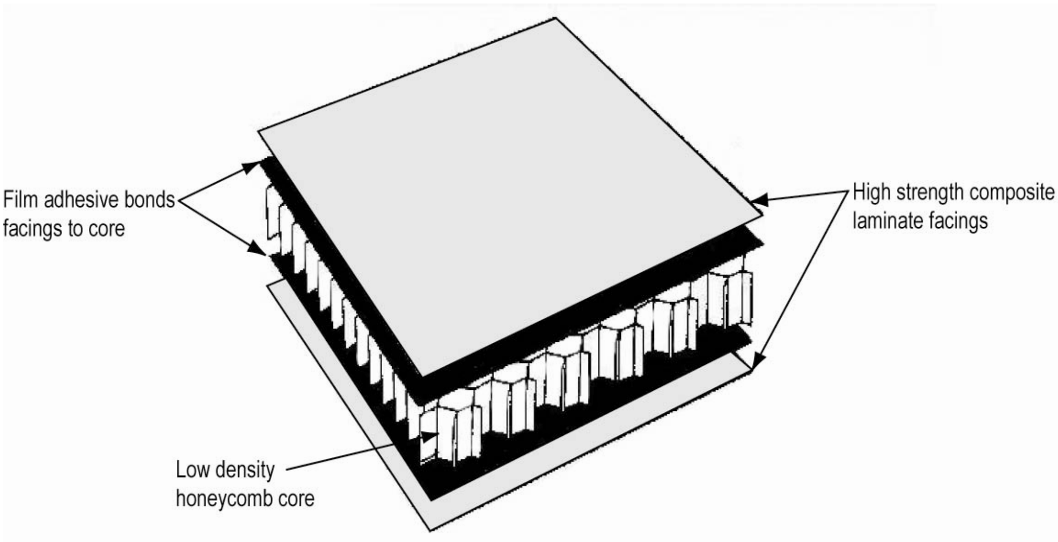
# 2 TYPICAL AIRCRAFT FIBRE COMPOSITES

## 2.1 What are fibre composites?

Fibre composite materials are a physical combination of two or more compatible materials, generally consisting of a primary fibre and a binder material. Generally, the binder material forms a matrix to hold the fibres together and fill voids between them. This reinforced matrix structure allows stress transfer between the fibres. Plies of matrix are layered together to form composite laminates, increasing their strength and allowing the composite to be used as a structural material. To provide extra strength and shape, a core material is often sandwiched between two sheets of composite laminate (such as foam, aluminium or Nomex honeycomb) (Figure 1). The name of the composite usually identifies what the fibre and matrix materials are (e.g. glass/phenolic, carbon/epoxy composites).

Carbon/epoxy and glass/epoxy fibre composites are generally used in primary structures. Glass/phenolic is not used in primary structures due to its brittleness and the evolution of volatiles, and finds use in secondary structures and cabin furnishings (Green 1990).

**Figure 1: Typical composite laminate/honeycomb sandwich structure**




Source: Department of Materials Science & Metallurgy, University of Cambridge

(www.msm.cam.ac.uk/phase-trans/2001/stef/img8.htm)

## 2.2 What fibre composites are used in aircraft?

Composite materials are very common in a variety of applications, for example plywood is a good example of a composite material in everyday use. In aviation, composite aircraft usually contain one or a combination of the following materials.

- Carbon/epoxy (CFRP) – used as a primary structural and skin material.
- Kevlar/epoxy – mostly used in military applications, in primary structures and amour plating.
- Glass fibre - used as a structural and skin material (on amateur-built and GA aircraft).
- Glass/phenolic (GFRP) – used in interior fittings, furnishings and structures.
- Boron/epoxy – used in composite repair patches, older composite structures.

# 3 FIBRE COMPOSITE USE IN AIRCRAFT – PAST, PRESENT AND FUTURE

## 3.1 Fibre composite use in aircraft since WWII

Composites are not new in aircraft. Since the first glass fibre-reinforced aircraft entered production in 1957, composites have been used heavily in military, experimental, general aviation (GA) and amateur-built planes, and slowly but surely have found major applications in commercial aircraft. They have also been used for many years in the manufacture of helicopter rotor blades, gliders and sailplanes. This is due to the weight savings, greater strength and stiffness, aerodynamic smoothness, and resistance to fatigue and corrosion that fibre composite materials offer over traditional metal structures.

Technology maturation and acceptance however takes a long time in the aerospace industry, in the case of composites it has taken 50 years or more (Sater, Lesieutre & Martin 2006). This has led to misunderstandings and public confusion surrounding the safety of fibre composite aeroplanes. Media comments preceding the rollout of the first Boeing 787 Dreamliner (which is over half composite by weight, including the fuselage, wings, empennage and engine components) such as “the plastic airplane” and “Is the world ready for a plane baked in an oven?” exemplify this (Thomas 2007).

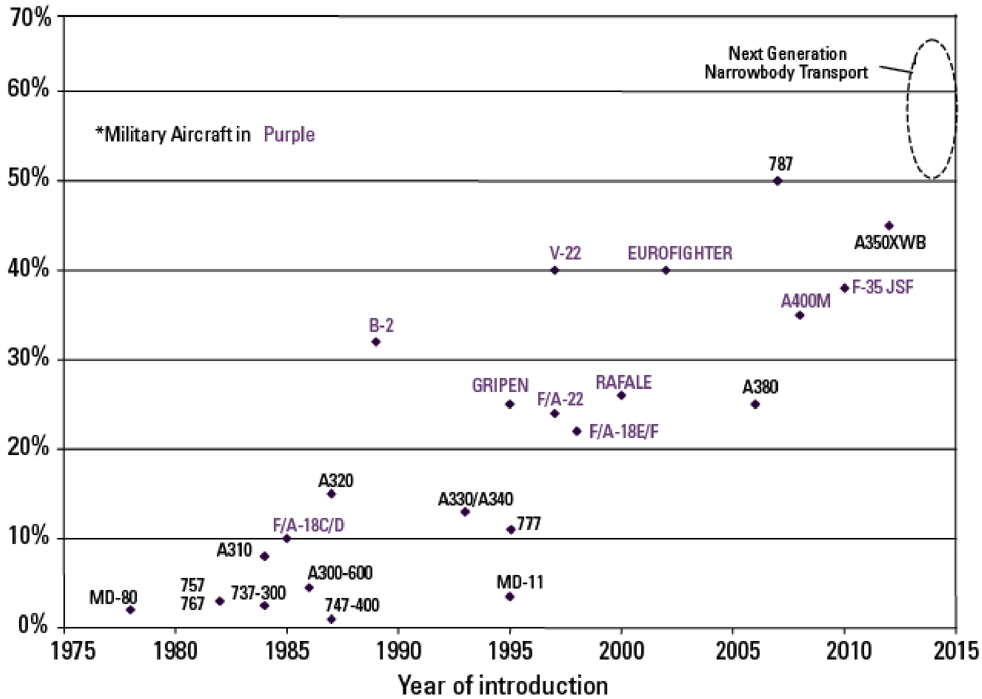
The primary reason that has driven the increased use of composites in aircraft, particularly in airliners, is their reduced weight compared to equivalent metal structures. A Federal Aviation Administration (FAA) Advanced Materials Research Program report found that for every pound of weight saved on a commercial aircraft, there is a US$100-300 cost saving over the service life of that aircraft (Werfelman 2007). In service, the replacement of the original steel brakes used on the BAe/Aerospatiale Concorde with carbon fibre brakes in 1974 resulted in a 600 kg weight saving. With every kilogram of weight saved on the Concorde reported to have been worth £500 (in 1990 pounds) to British Airways each year in savings when the aircraft was in service (Fisher 1990), the clear and significant financial savings have led to carbon fibre brakes becoming standard equipment on all new airliners. The Boeing 787 Dreamliner, with its widespread composite use in primary structures, will result in an aircraft that is 10,000 lb lighter and burns 20% less fuel than a comparably-sized all-aluminium aircraft (Massengill 2005). In today’s global economic environment where oil is at a premium and fuel prices are at an all-time high, the use of new fuel-efficient technologies in aircraft continues to have significant commercial appeal to airlines. These case studies show that fibre composite use in aircraft results in significant weight savings, increased payload capacity and reduced fuel burn, allowing airlines using these aircraft to remain profitable in the face of rising fuel costs.

## 3.2 Fibre composite applications in airliners

Fibre composites have been used in an ever-increasing percentage of jet airliner structures for several decades (Figure 2). Boeing began using composites over 30 years ago in 737 spoilers; composites have now replaced light alloys to create significantly lighter and lower-maintenance control surfaces and empennages in the

737 Classic (-300, -400 and -500) and Next Generation (-600, -700, -800 and -900) models, 757, 767 and 777 product lines. The 787 Dreamliner is a defining aircraft in the use of fibre composites – it will be the first airliner that is primarily composite, with a fully composite skin, fuselage, wing box and empennage (Werfelman 2007). This is a quantum leap when compared to the current generation of airliners containing composite components (the Boeing 777, which is 9% composite by weight) (Sater, Lesieutre & Martin 2006). Such a large increase in composite use brings numerous production and safety challenges to aircraft manufacturers.

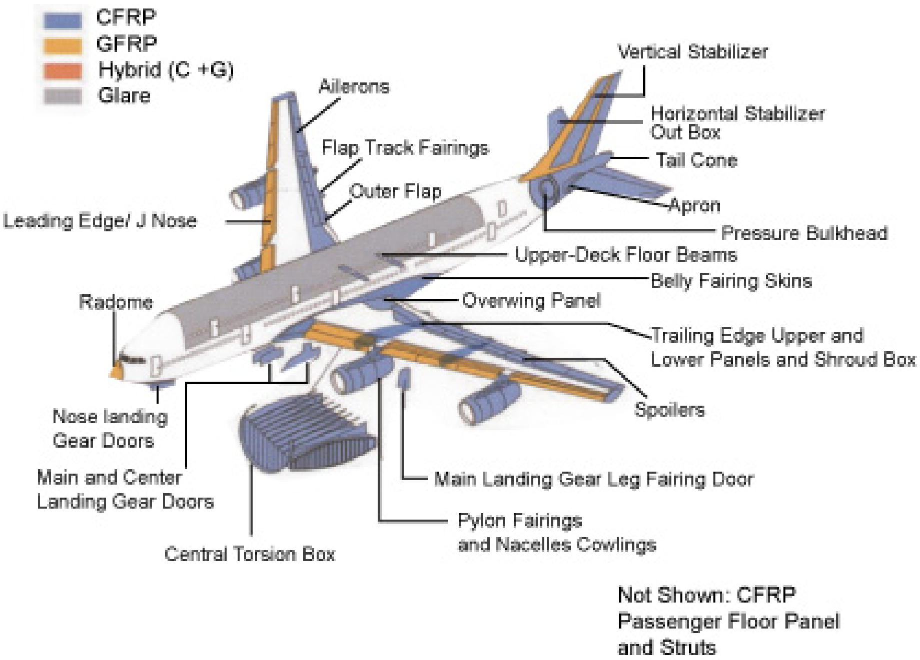
**Figure 2: The growth of composite structure on major aircraft programs (1975-2010) as a percentage of weight**




Source: Teal Group, Boeing, Airbus, Composite Market Reports

The Airbus A310 and A300-600 in 1985 were the first airliners to utilise fibre composites for a major structural component. The vertical fins of these aircraft are constructed of carbon-fibre reinforced plastic (CFRP), with other components such as the wing leading edge, control surfaces and fairings made from composites. The use of composite empennages was carried across into the highly successful A320, A330 and A340 families, allowing optimisation of the vertical fin to improve aerodynamics and hence reduce fuel consumption and improve the flying characteristics of the aircraft (Middleton 1990). In 2006, commentators wrote that "the Airbus A380 is scheduled to enter service with an airframe that is 25% composite by weight, including an all-composite centre wing box" (Rakow & Pettinger 2006). Figure 3 highlights the key fibre composite components used in the A380.

**Figure 3: Airbus A380 major composite components**




Source: FAA

Lockheed and McDonnell Douglas were also leaders in the use of composite structures in airliners, with composite rudder and aileron segments having proven reliable in-service on the L-1011 TriStar and DC10 fleets for over 30 years without issue. Composite doubler repairs also have found a niche market for repairs to traditional metallic structures on both airliners and military aircraft. Examples include the boron/epoxy composite straps developed by the US Sandia National Laboratories to repair fatigued cabin and cargo door corners on the L-1011 and DC10. These composite doublers were installed in high-cycle aircraft (such as those being used as freighters) in 1997, and since that time have been in continuous service and have not developed any flaws (Roach 2000).

Fibre composites have also found applications in aircraft subsystems, most notably in turbofan and turboprop engines. Largely composite compressors were used in the Rolls-Royce RB162 turbojet as far back as the 1960s, which was used as a booster engine for the Hawker Siddeley Trident 3B. The RB211 turbofan trialled the use of composite fan blades during its development, and in production had composite engine cowl doors on the Lockheed L-1011 TriStar in the 1970s (Middleton 1990). The use of composite structures in such high-load components as compressor and main fan blades has proven successful, and the General Electric GENx turbofan (an engine option for the Boeing 747-8 and 787 Dreamliner) will enter service with composite fan blades, containment casing and cowling.

Engine cowlings on most airliners are manufactured from fibre composites, including cowlings on helicopters such as the Eurocopter EH101, and the lower nacelle for the Pratt & Whitney Canada PW100 on the Bombardier DHC-8 (Middleton 1990). Many propellers used on amateur-built, GA, and regional turboprop aircraft are also made from fibre composite, with major manufacturers such as Dowty Rotol and MT using glass/carbon fibre blades. Applications include the six-bladed propellers fitted to the Bombardier Q400 and Lockheed C-130J Hercules.

## 3.3 Fibre composite aircraft on the Australian register

As of mid-2007, a significant number of aircraft on the Australian civil aircraft register (VH-) contained major structures manufactured from fibre composites. Most of these aircraft were amateur-built and GA aircraft, gliders/sailplanes and light helicopters. The majority of the Australian jet airliner fleet also contains composite components.

A full list of all composite and partially composite aircraft on the Australian register with two examples or more is provided in Appendix A as an attachment to this report. These aircraft are listed in order of how many are listed on the register as of mid-2007. The major parts of each aircraft that are made from fibre composites are also identified. There were almost 2,000 aircraft on the Australian register that contain fibre composites, including over 300 amateur-built composite aircraft. This represents approximately one-third of all amateur-built aircraft in Australia that were flying or under construction in mid-2007.

Fibre composites have been used extensively in amateur-built aircraft kits since the 1970s, when the Rand KR-1 kit was introduced. Since this time, many kit aircraft continue to heavily utilise composites, as many parts could be pre-moulded at the factory by the manufacturer, reducing build time and part count, and simplifying the required tooling and assembly procedures for the amateur builder. As fibre composites are a woven textile which is hardened by a thermoset resin (such as epoxy), they can be easily moulded into complex shapes. Loads are carried by the network of fibres in the composite, allowing these complex shapes to be used without the need for additional structural support. These factors make composite a more flexible building material than metal, allowing stronger, more aerodynamic aircraft, while reducing part count, weight and fuel consumption.

**Figure 4: Rand KR-2 (derivative of the KR-1)**

Source: http://www.fly-kr.com

Common amateur-built and kit aircraft made of, or containing, fibre composite components flying in Australia include:

- Jabiru aircraft series (J200, J400/430, SK/SP);
- Glasair/GlaStar;
- RotorWay helicopter series (Exec 90, 162/162F);
- Lancair aircraft series (320, 360, IV);
- Europa XS/Classic; and
- Rutan aircraft series (e.g. Long-EZ and VariEze).

Common GA aircraft made of or containing fibre composites flying in Australia include:

- Robinson R22 and R44 helicopters;
- Most Eurocopter helicopters (including the Squirrel, EC120 and EC135)
- Cirrus SR20 and SR22;
- Grob G-115;
- Diamond Star DA40;
- Jabiru aircraft series (e.g. J160, J230, J430); and
- most models of glider and sailplane (including Schempp-Hirth, Schleicher, Glasflugel, Schnider, Schweizer, EIRI and Glaser-Dirks).

A number of turbofan and turboprop aircraft operating Regular Public Transport (RPT) services in Australia contain significant fibre composite components:

- Boeing 737;
- Bombardier/De Havilland Canada DHC-8;
- Embraer E-Jet family;
- Boeing 767;
- Airbus A320 family; and
- Airbus A330.

There are also a number of other modern airliners that contain significant fibre composite structures that are operated by overseas carriers to and from Australia. These include:

- Airbus A300-600 (composite vertical fin);
- Airbus A320 family (composite empennage, control surfaces and engine cowls);
- Airbus A330/A340 (composite empennage, control surfaces, keel beam and engine cowls);
- Boeing 777 (composite empennage, control surfaces and engine cowls);
- Lockheed L-1011 TriStar (composite vertical fin box and ailerons); and
- McDonnell Douglas DC-10/MD-11 (composite upper rudder).

Fibre composites are extensively used in aircraft cabins and furnishings. The composite most used in pressurised aircraft cabins is glass/phenolic, for numerous moulded components such as overhead lockers, cabin ceiling and panelling, galley structures, and cabin partitions and doors. In all, phenolic composites account for 80-90% of the interior furnishings of modern passenger aircraft. (Mouritz 2006). Carbon fibre/Nomex honeycomb composite sandwiches are often fabricated into cabin and cargo hold floor panels, in aircraft such as Boeing 767 and newer models of the Boeing 747 (Middleton 1990). Glass fibre and carbon/epoxy composites also find small applications on largely aluminium aircraft such as the Cessna 152 and Pilatus PC-12, in fairings and wingtips.

## 3.4 Fibre composite aircraft in Australian military service

The military has historically been at the forefront of fibre composite use in combat aircraft and helicopters, as shown in Figure 2. Materials such as CFRP and Kevlar are widely used in modern military aircraft skin and structures as they provide superior battle damage resilience to metal, reduce structural weight (allowing for greater weapon loads) and in-turn reduce fuel consumption. Fibre composite use is prevalent in many military aircraft currently or soon to be in service with the Royal Australian Air Force, Australian Army and Royal Australian Navy. They include:

- Lockheed C-130 Hercules (composite flaps, control surfaces, propellers, strap repairs/doublers for repairing original aluminium structures);
- McDonnell Douglas F/A-18A Hornet (composites make up 10% of structure, 50% of aircraft skin by weight) (Middleton 1990);
- British Aerospace Hawk 127 (Kevlar/epoxy nose reinforcement);
- Eurocopter Tiger ARH (CFRP composite structure and skin, composite rotor blades);
- Eurocopter MRH90;
- most helicopters, which are fitted with CFRP composite main and tail rotors;
- Lockheed Martin F-35 Joint Strike Fighter (JSF);
- Boeing F/A-18F Super Hornet (over 20% composite structure by weight); and
- future Unmanned Air Vehicles (UAVs) such as the Global Hawk, which incorporate major composite structures and composite battle armour.

The Defence and Science Technology Organisation (DSTO) Air Vehicles Division in Melbourne focuses on supporting these and other Australian military aircraft though the research and development of composite repairs to metallic aircraft structures. The role of DSTO is now expanding into new support areas, such as controlling environmental degradation and repairing composite airframes.

## 3.5 Future fibre composite aircraft projects

Fibre composite structures are finding increasing use in the upcoming generation of aircraft. In terms of airliners, the Boeing 787 Dreamliner, Airbus A380 and A350XWB programs contain a large percentage (by weight) of composites, including many key structural components. Existing aircraft families, especially those that make up the mainstay of the worldwide airline fleet (such as the Boeing 737, Boeing 777, Airbus A320 family and Airbus A330/A340) will continue to make significant use of composites in control surfaces, stabilisers and engine components.

Composite aircraft have been commercially available to home builders for decades, and following the severe curtailing of GA aircraft manufacturing in 1980s, many new manufacturers entered the expanding amateur-built and GA sectors. These manufacturers are minimising production costs by developing new aircraft that utilise carbon fibre reinforced plastic (CFRP) and glass fibre reinforced plastic (GFRP) fibre composites in their primary structures. In addition, CFRP/GFRP is popular for its high-strength, low-maintenance and lightweight properties. Developments in low-cost, small turbofan technology are driving the new Very Light Jet (VLJ) market, where composites are also finding wide applications for the same reasons. Table 1 highlights some of the major fibre composite aircraft projects as of mid-2007, which can be expected to be seen on the Australian register in the next few years.

**Table 1: Upcoming fibre composite aircraft programs (early-2008)**

| Amateur-built kit aircraft | GA aircraft | Very light jets (VLJs) |
|---|---|---|
| Aerocat Amphibian (4-place amphibian) | Diamond DA20 | Cirrus Jet |
| Compair 9/12 | Diamond DA42 Twin Star | Diamond D-Jet |
| Conroy Sparrow XC | Cessna NGP | Eclipse 500 |
| Epic Dynasty | Cirrus SR22 Turbo | Epic Elite |
| Epic Escape | Columbia 400 | Epic Victory |
| Epic LT | Ion 120 | Grob SPn |
| Foxcon Terrier 200 | Socata Fuscomp project | HA-420 HondaJet |
| Ion 100/105/110 | Vulcanair P.68 | Liberty XL-2 |
| Ravin 500 | | Spectrum S-33 Independence |
| Tango Foxtrot/Tango | | Spectrum S-40 Freedom |
| Velocity XL/SE | | |

# 4 COMPOSITE BEHAVIOUR UNDER LOAD

## 4.1 Overview

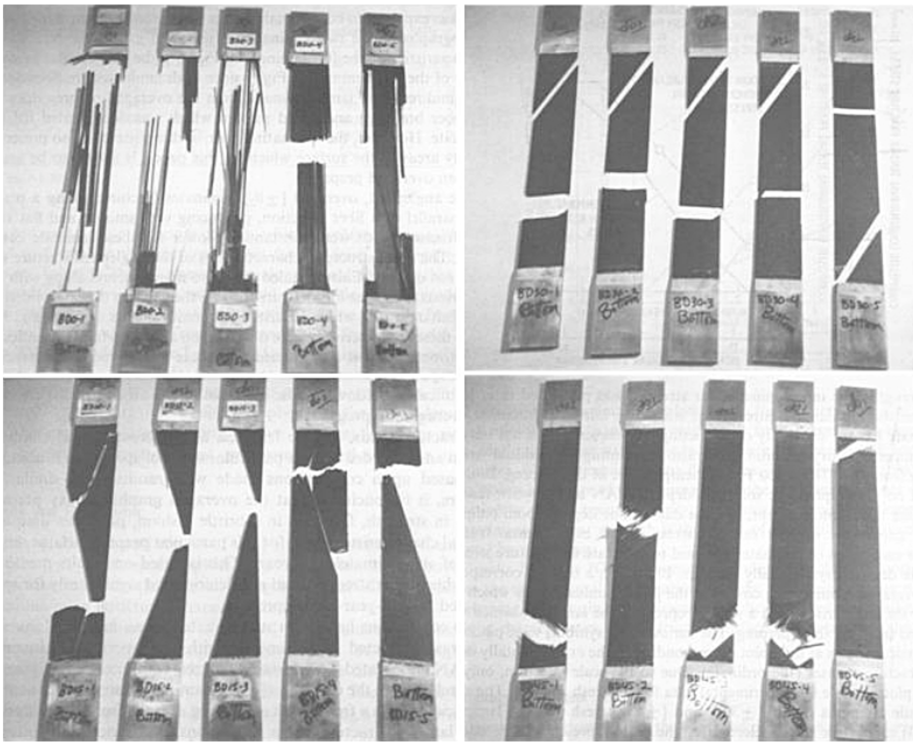
There are significant differences in the behaviour of fibre composites compared to traditional metallic (aluminium, steel and titanium) structures when placed under load, or when failure occurs. Often this causes composite structures to fail in ways which metals cannot. For example, a metal structure in tension would fail in tension, whereas an equivalent composite structure in tension might fail in bending (Rakow & Pettinger 2006). This is because the composite is a fibrous matrix with multiple load paths: plies in a laminate may be oriented differently, be of varying thickness, or imperfections may exist between the plies such as air bubbles which cause it to behave differently. Composites are generally brittle, so undergo little deformation as a warning that failure is about to occur (unlike metals which are generally ductile and will deform before failure). All of these variables are unique to composites, and directly affect how they fail and behave under load. As a result, it is inherently more difficult for Transport Safety Investigators (TSIs) to analyse failed composite structures and clearly determine what types of loads were involved.

## 4.2 Tension and shear stress

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.

Figure 5 shows a series of carbon fibre reinforced plastic (CFRP) samples that failed under exactly the same tension force, yet show a huge variety in failure patterns. The samples were split into four groups, each group having the ply fibres oriented in a different direction. Some of the samples splintered upon failure (upper left), others have snapped or sheared at an angle (upper right and lower left), while in some samples the fracture surface is ripped (lower right). This variety of failures is due to the variation that is inherent in composite structures: different fibre orientations, and imperfections between plies in the laminate. This highlights the challenge of analysing composite structures that have failed in tension.

**Figure 5: Range of CFRP composite sample failures, all under the same tension force**

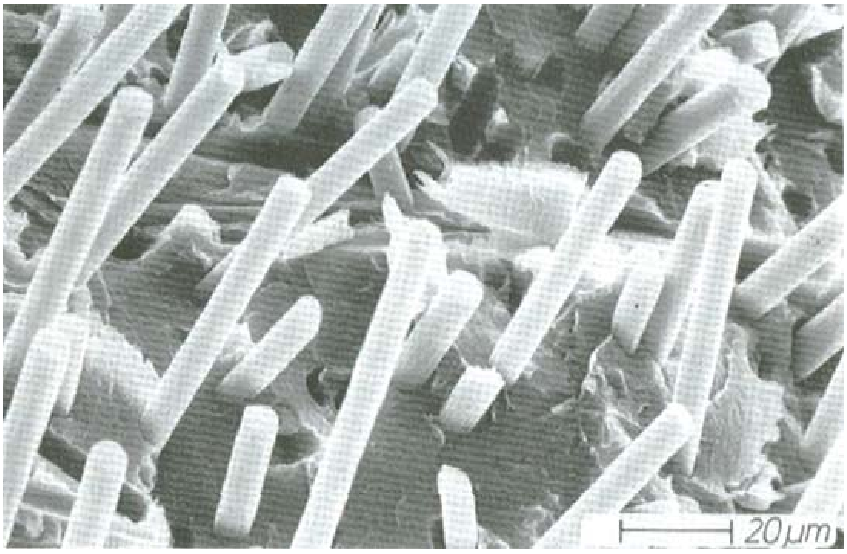


Source: Rakow & Pettinger 2006

On a microscopic level, each of these samples share common signs that indicate tension failure. In all failures of composite structures under tension, the fracture surface generally has a rough appearance.

When the fibres are aligned in the direction of the tensile load, fractured fibres are often found sticking out at the fracture surface. This is called fibre pullout, and is a typical indicator of tension failure in composite structures (Figure 6). Fibre pullout is caused by the individual fibres breaking and being pulled out of the matrix. This results in holes in the matrix, which is another indication of tension failure. In some tensile failures where the matrix itself fails, the fibres do not break. This is called fibre bridging.

**Figure 6: An example of fibre pullout**

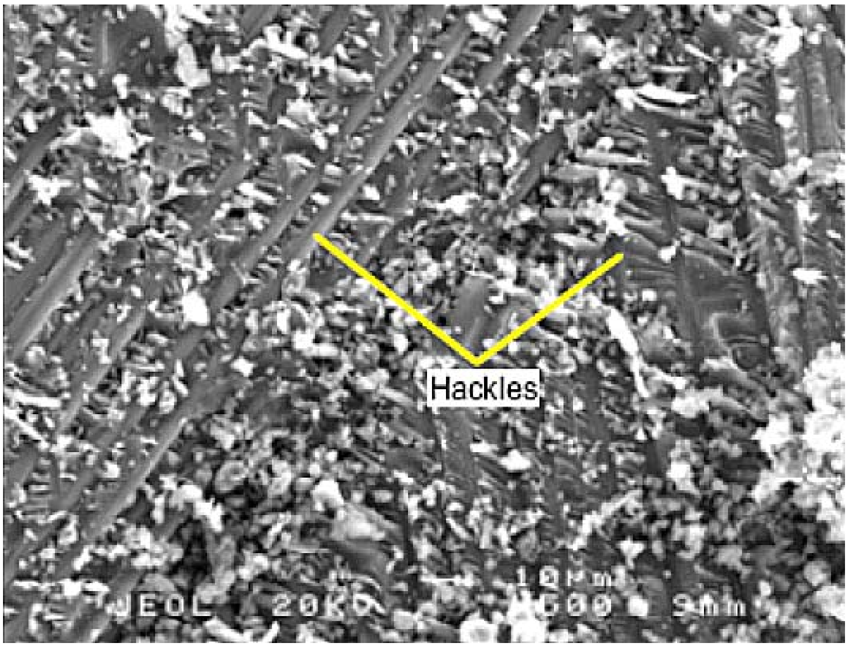



Source: Rakow & Pettinger 2006

The length of pulled-out fibres can indicate the environmental and loading conditions that the composite was exposed to at the time of failure, such as exposure to moisture, temperature and rate of loading.

When the fibres are not aligned in the direction of the tensile load (i.e. are under shear stress), common with multiple-ply laminates, failure often occurs in the matrix rather than the fibres. Tension matrix failures generally occur between fibres at the fibre-matrix interface, or as shear failures between plies. These types of matrix failures usually cause hackles, which are rough features on the fracture surface (Figure 7) (Rakow & Pettinger 2006).

**Figure 7: An example of the formation of hackles when composite laminates are under shear stress (marked)**




Source: Rakow & Pettinger 2006

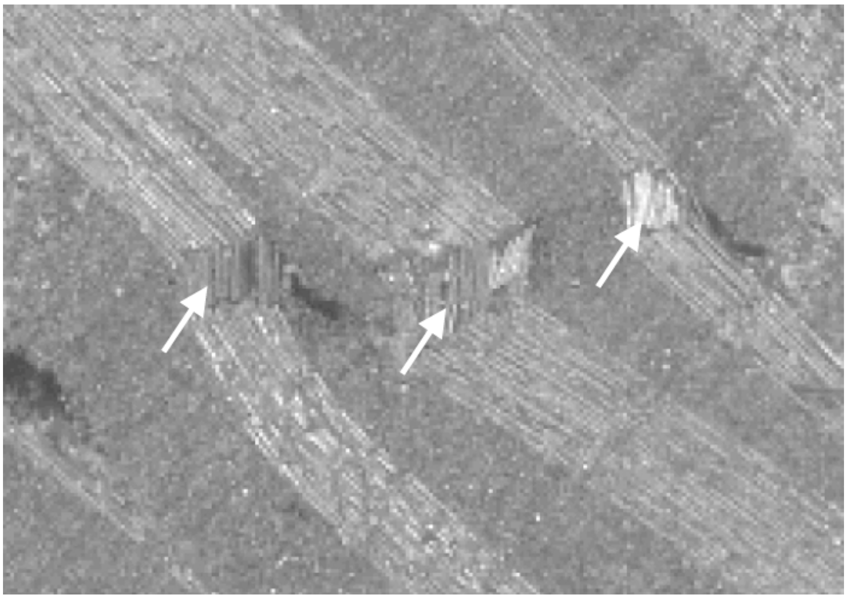
In summary, key signs showing that a fibre composite structure has failed in tension are:

- a rough fracture surface;
- fibre pullout (tension load in the direction of fibres);
- holes in matrix (associated with fibre pullout);
- fibre bridging (indicates matrix failure); or
- hackles (indicates shear failure of matrix).

## 4.3 Compression

On a microscopic level, a major indication of compression failure in fibre composites is the formation of kink bands in the fibres (Figure 8). Because fibres are poor in compression, kink bands occur due to plastic bucking as the compressive load approaches a critical level. Matrix splitting is often associated with these kink bands, which can be seen as gaps in the matrix at the failure surface. It occurs at points of high-stress concentration in the matrix, such as the fibre-matrix interface and between plies (i.e. in areas of delamination).

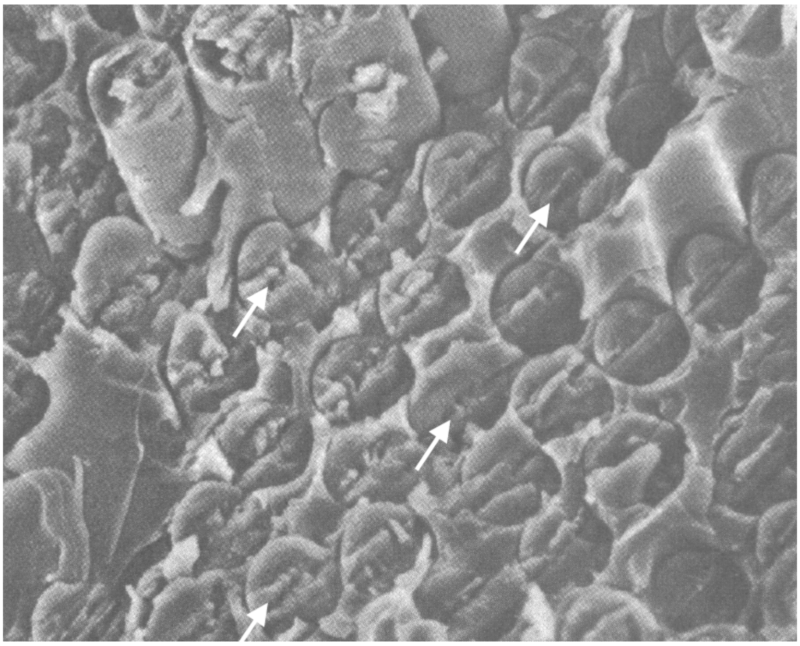
**Figure 8: Formation of kink bands when composite laminates are under compression (marked with arrows)**



Source: Rakow & Pettinger 2006

Buckling can also be seen at the fibre ends, in the form of chop marks (Figure 9). The chop marks occur along the neutral axis of the bending fibre, separating the half in compression from the half in tension (Rakow & Pettinger 2006).

**Figure 9: Formation of chop marks along the neutral bending axis (marked with arrows)**

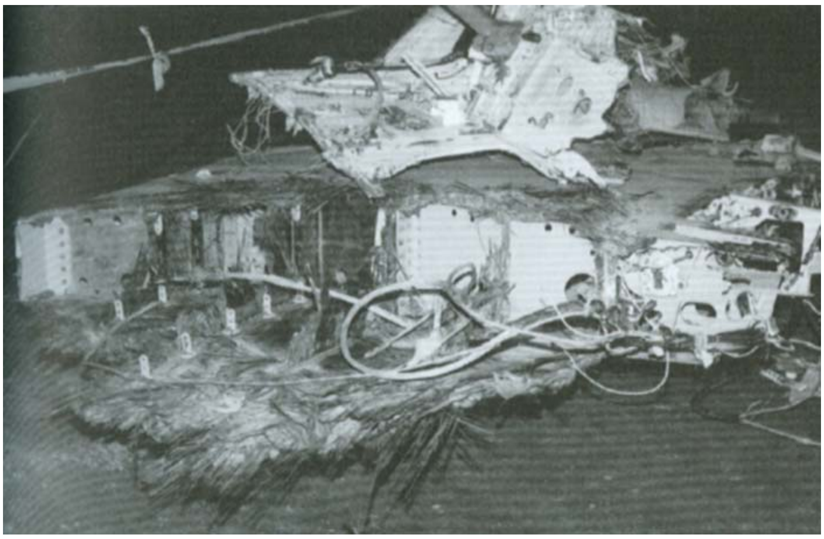


Source: Rakow & Pettinger 2006

## 4.4 Bending

Fibre composite structures that have failed in bending show obvious signs of tension and compression around the neutral bending axis. One side of the structure will contain pulled-out fibres (the side in tension), while the other will be relatively flat (the side in compression) (Rakow & Pettinger 2006). The wing in Figure 10, which failed in bending, shows drastically the difference between the tension and compression sides.

**Figure 10: Wing that failed in bending, showing the difference between the tension (lower) and compression (upper) sides**



Source: Rakow & Pettinger 2006

## 4.5 Fatigue

While fibre composite structures are significantly less susceptible to fatigue failure than traditional aircraft metals like aluminium, fatigue can still occur. While fatigue can be identified easily in metals (e.g. beach marks), signs of fatigue fracture in composites are microscopic and occur irregularly.

Striations at the fibre-matrix interface are a sign of fatigue in composite structures, with one striation representing one load cycle. However, striations may only occur in certain areas of the structure, and their small size and poor visibility (often apparent only under high magnifications and oblique lighting) makes them difficult to spot.

With repeated loading of the fibre composite structure, fatigue may become more easily visible. Fatigue fracture surfaces rub against each other, leaving abrasion marks on the ends of broken fibres and in the matrix (Rakow & Pettinger 2006). Broken fibres will be randomly dispersed throughout the area of the structure under load. As more fibres break, localised stress concentrations form which lead to fibre-matrix disbonding between plies. If the fatigue damage is not identified and is left unchecked, matrix cracking will begin to occur from the weakest plies (transverse ply) to the strongest (longitudinal ply) under repeated cyclic loading. The fatigue life of the structure will reduce as the density of these matrix cracks increases, until catastrophic failure occurs (Krishnamurthy 2006).

In recent years, the ATSB identified serious fatigue cracking of metallic Robinson R22 main rotor blades worldwide following a fatal accident in 2003. While rotor blades on Robinson helicopters are not made of fibre composites (they are adhesively bonded composite metallic structures), degradation of the adhesive that held the rotor blade structure and skin together caused the adhesive matrix to crack and disbond. It was the fatigue failure of the adhesive matrix that led to a change in the load distribution, and increased stress concentration on the bolts attaching the blade root to the rotor hub. Ingress of moisture through the cracks in the adhesive matrix led to corrosion of the aluminium bolt holes, which accelerated fatigue cracking in the blade root.

The case study below shows how fatigue of matrix materials (such as adhesives) can be a safety issue in metallic aircraft assemblies that are composite bonded structures. The issue of adhesive degradation due to fatigue is also an issue for fibre composite structures, as adhesives act in these structures as the matrix/binding material to hold the load-bearing fibres together.

## Case study: Robinson R22 in-flight blade root failures

On 20 June 2003, a Robinson R22 Mariner helicopter, registration VH-OHA, was involved in a fatal accident 13 km northwest of Camden Airport while being used for flying instruction.

An examination of the wreckage revealed that one of the two main rotor blades had separated from the helicopter during flight.

Further examination determined that the blade root fitting had fractured at the inboard bolthole of the blade root to blade spar joint. The blade root fitting is an aluminium alloy forging that accommodates the blade spindle and bearings. This fracture was the result of fatigue crack growth in the blade root fitting. The fracture occurred under normal flight loads, and within the specified operation life limit of the rotor blade. At the time of the accident, this was 2,200 hours.

The rotor blades and components in the Robinson R22 are not made of fibre composites (they are composite-bonded metal structures). However, an adhesive was used to attach the rotor blade skin to the blade root fitting.

Degradation of the adhesive between the blade root fitting and the rotor blade skin caused disbonding. This disbonding changed the load transfer paths and local stress distribution in the joint, resulting in an increase in the magnitude of alternating stresses in the inboard bolt region. An increase in the magnitude of these stresses precipitated the failure of the rotor blade.

Observation of the disbonded surfaces indicated that initial disbonding had occurred through progressive crack growth in the adhesive matrix. Adhesive cracking is a result of fatigue, and is affected by moisture, high temperatures, as well as the magnitude and number of alternating stress cycles. In the rotor failure of VH-OHA, adhesive cracking allowed moisture and salts to enter the inboard bolthole, causing localised pitting corrosion. This further reduced the operational time to fatigue cracking by increasing stress concentrations on the bolthole, and reducing the resistance of the material to fatigue crack initiation.

When adhesive disbonding occurs beneath the skin, skin cracking does not occur to indicate subsurface damage. In the case of VH-OHA, disbonding of the adhesive matrix meant that there would have been no visual indication of fatigue cracking in the blade root fitting prior to the accident.

A survey of blades from a variety of Australian and worldwide R22 helicopter operations showed that disbonding in the spar/fitting adhesive joint was widespread across many types of operations, flight profiles and environments.

The investigation of this accident led to a number of safety actions, both in Australia and overseas. The manufacturer issued a safety letter and a service bulletin relating to revised retirement lives for main rotor blades, and introduced a redesigned main rotor blade into service. CASA required the retirement of main rotor blades similar to those on VH-OHA by 1 March 2006 on Australian registered Robinson R22 helicopters.

*Source: ATSB Aviation Safety Investigation Report 200302820*

# 5 BEHAVIOUR OF COMPOSITES IN HIGH-LOAD AND IMPACT SITUATIONS

The use of fibre composites in aircraft eliminates many of the reasons for scheduled inspections, such as fatigue and corrosion that lead to failure under high loads. (Mulcair & Villiers 2006). This is highlighted by Tony Carolan, general manager of business development for Hawker de Havilland: “We have replaced the wing flaps on the C-130 Hercules Transport for the Royal Australian Air Force. These metal flaps normally start cracking after 3,000 hours. We stopped testing the composite flaps at 60,000 hours.” (Thomas 2007).

Nevertheless aircraft owners and operators should not be complacent about the durability of composite structures, and assume that they will never fail. Composite components can fail with catastrophic results, such as the in the crash of American Airlines Airbus A300-600 Flight 587 in November 2001. In this accident, the carbon/epoxy vertical stabiliser broke off in-flight. This was caused by the first officer applying excessively large yaw control inputs, causing bending failure of the composite attachment lugs at the base of the fin to occur. This resulted in the loss of the aircraft and 265 fatalities (National Transportation Safety Board 2004).

Identifying sources of possible failure in composite aircraft structures before they become serious can prevent catastrophic accidents and save lives.

## 5.1 Failure characteristics of fibre composite matrices

Fibre composite structures fail in different ways to metal structures traditionally used in aircraft.

### 5.1.1 Delamination

Delamination, the growth of cracks between different plies in a laminate, is the most common failure mode for fibre composite structures. It occurs when shear loads are applied between plies in the laminate. Since the fibres are significantly stronger in tension than the matrix, the matrix cracks and delamination occurs (Brimhall 2007).

Delamination can propagate throughout the composite structure upon repeated loading, causing catastrophic failure if left undetected (Rakow & Pettinger 2006).

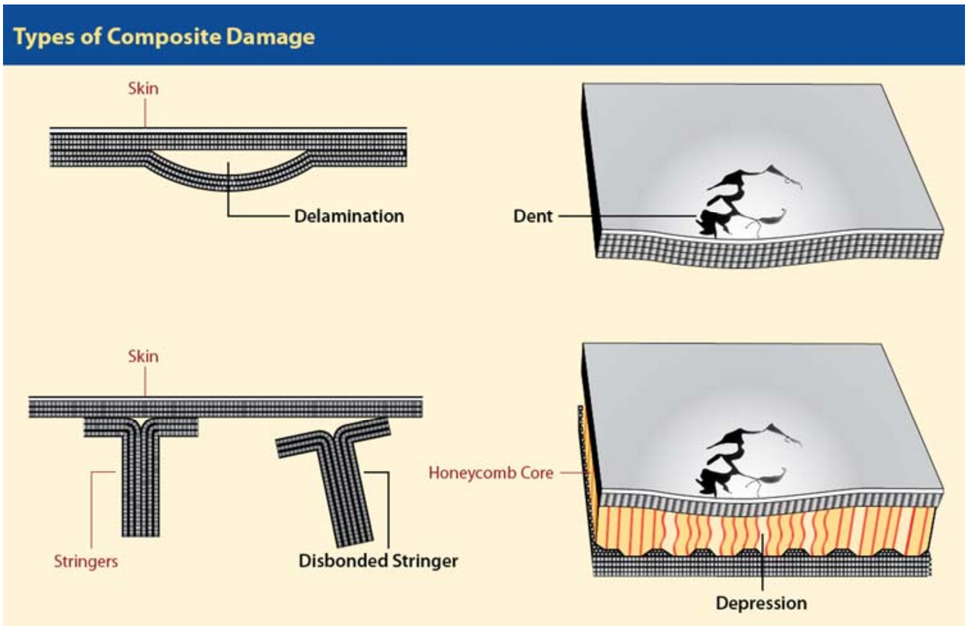
Delamination failures are characterised as one or a combination of three modes:

- opening (Mode I);
- sliding-shear (Mode II); or
- tearing-shear (Mode III).

Previously, only Modes I and II were considered when analysing the tolerance of composite structures to damage, however a new edge crack torsion test has allowed better analysis of toughness against Mode III failures (Glaessgen & Schoeppner 2006).

Figure 11 shows how delamination and disbonding occur in a composite laminate.

**Figure 11: Delamination (Mode I) and disbonding in composite laminates**




Source: Werfelman 2007

### 5.1.2 Other failure mechanisms

Manufacturing defects are a major cause of premature failure in fibre composite structures. This is due to the difficulty of fibre composite manufacturing processes compared to metal structures, and the fact that most composite structures continue to be laid up by hand. Automated production using large autoclaves is still a relatively new process, and as a result quality problems do occur. This production method may introduce flaws into composite structures, until lay-up and quality control techniques are refined. For example, one of the ten test fuselage barrels manufactured by Boeing as part of the Federal Aviation Administration (FAA) certification process for the 787 Dreamliner was deemed unacceptable due to excessive porosity caused by trapped air between plies of carbon fibre. Flaws between plies cause poor bonding between plies in the laminate, which can lead to delamination or stringer disbonding (Mulcair & Villiers 2006).

Reactions between fibre composites and water are another potential contributing factor to failure. If moisture penetrated into the matrix of a sheet of laminate, it is possible that it could be drawn inwards along exposed fibres and into other plies in the laminate. During a normal cycle, this moisture would expand and contract as it froze/thawed, causing subsurface damage to fibres and leading to delamination (Mulcair & Villiers 2006). A high-profile example of bonding matrix failure due to the presence of moisture was the rudder separation of Concorde G-BOAF in 1989 between Christchurch, New Zealand and Sydney:

### Case study: Rudder failure due to corrosion and debonding

On 12 April 1989, Concorde G-BOAF sustained a rudder separation while travelling from Christchurch, New Zealand to Sydney. At the time of the accident, the aircraft had been in service for 10 years.

The then Australian Civil Aviation Authority (CAA) found that the rudder failed due to delamination between the aluminium honeycomb and the skin surface. Extensive corrosion on the inner skin surface was also present. According to the British Air Accident Investigation Branch (AAIB), the de-bond had slowly grown to a critical size before rapidly increasing to failure.

The rudder was manufactured with an aluminium alloy skin and aluminium honeycomb inner structure that was bonded together using a phenolic resin. Post manufacture, the rudder assembly had been modified when a trailing edge fairing was riveted to the rudder assembly.

When the rudder was originally constructed, the rivets and fasteners that penetrated through to the honeycomb core were kept to a minimum. This was to prevent moisture breeching the core, leading to corrosion. However, the trailing edge fairing modification relied on a large number of rivet holes.

The CAA investigation found that no sealant paint was present on many of the rivet heads on the undamaged section of the rudder. The unsealed rivet heads may have allowed moister to enter the structure, causing corrosion. The rate of corrosion was increased through a galvanic reaction between the steel in the rivets and the aluminium in the honeycomb and skin.

The CAA investigation found that the de-bond of the skin from the honeycomb core was due to corrosion products wedging between the skin and the adhesive.

The Concorde rudder failure is an example of the effects of ageing on an aircraft structure. Over time, corrosion led to the de-bonding and ultimately the failure of the rudder structure. Prior to the G-BOAF accident, the rudder was not considered to be an area susceptible to corrosion and debonding.

As a result of the accident, the British Civil Aviation Authority and the French Direction Générale de l'Aviation Civile issued airworthiness directives, mandating repeated non destructive inspections (NDI) and 'tap' testing to ensure that there was no de-bonding of the rudder structure.

*Source: ATSB 2007a*

Finally, heat damage can cause degradation of fibre composite structures through surface oxidation. Common sources of heat damage in normal aircraft operations include lightning strikes and hot jet exhaust blast. Lightning strikes can damage composite aircraft in several ways, including puncture of the aircraft skin, delamination of the skin and other composite structural members, adhesive disbonding, and crimping due to magnetic force effects (Pryzby & Plumer 1984).

## 5.2 Typical impact behaviour of fibre composite matrices

### 5.2.1 Barely visible impact damage (BVID)

Impact behaviour is a very important consideration when designing aircraft structures. The airframe must be able to withstand the low and medium energy "wear and tear" impacts of everyday use, such as dropped tools, hard landings, hail, handling during maintenance and loading, birdstrikes, and stone impacts on takeoff, landing and taxi. Subsurface damage caused by this sort of wear and tear is known as barely visible impact damage (BVID).

Fibre composite structures are brittle rather than ductile. Unlike ductile metallic aircraft materials (such as aluminium) which undergo permanent deformation on impact, composites show little or no impact damage on the surface until failure occurs. In the meantime, subsurface BVID has the opportunity to spread and weaken the structure. As a result, impact damage on composite aircraft can go undetected for long periods until catastrophic failure (such as separation of major structures) happens.

This sudden failure was shown in a US military test where a 6 kg ball was repeatedly dropped from varying heights onto a section of composite laminate reinforced with composite stiffeners. In the first few impacts, there was no visual indication of damage, and the sound of the impact remained constant. As the test continued however, the sound changed as sub-surface impact damage developed, until the composite section delaminated and the stiffeners shattered (Mulcair & Villiers 2006).

Carbon/epoxy composite structures are particularly susceptible to low-impact damage, as multiple delaminations can occur in a small area of the structure. This causes stress concentrations, increasing the onset of premature failure. In glass/phenolic structures, delaminations often occur over large areas, reducing stress concentrations but making damaged areas more difficult to locate and repair (Dorey 1990).

To ensure BVID does not cause delamination resulting in structural failure, composite aircraft components are often designed with a factor of safety of 3 or more (i.e. design stresses are less that a third of the failure stresses) (Dorey 1990). Factors of safety such as these have been employed in the sizing of the major composite structures (such as the fuselage) in the Boeing 787 Dreamliner (Mulcair & Villiers 2006). In traditional metal structures, factors of safety of 1.5 or less are usually employed. Even with increased safety factors, composite structures still offer significant weight savings over light alloy structures.

### 5.2.2 Impact behaviour research programs

The lack of knowledge and data on the impact and energy-absorbing behaviour of fibre composite aircraft in crashes has been identified by industry in recent years. In 2001, NASA formed the AGATE Advanced Crashworthiness Group to research and test the impact resistance and survivability of composite airframes in general aviation (GA) aircraft. This program, run as a partnership with the FAA, GA aircraft manufacturers and Wichita State University, fixed a stock Lancair Columbia 300 all-composite aircraft to a moving rig designed to simulate a hard-surface impact. Upon impact with the ground, the glass fibre/Nomex fuselage remained intact and suffered little damage above the cabin floor level. Accelerometers placed throughout the cabin also indicated that all occupants would have survived the crash. The composite empennage separated from the fuselage due to impact bending moments, and occurred at a location where there were discontinuities in the composite structure (e.g. laminate thickness change, fuselage frame located at that point). The damage and separation of the tailplane did not produce any glass fibre dust that might have posed a hazard to the test personnel (Henderson, Hooper & Lyle 2002).

A further test was conducted by NASA and Bell Helicopter in 2002 to simulate water and soft-ground composite aircraft impacts. A five foot-diameter glass fibre/foam composite fuselage section was suspended above and then dropped into a pool of water. Upon impact the outer skin underwent some delamination; however the foam core and water absorbed much of the 20G impact energy. This resulted in little visible damage to the fuselage section. However, it was later discovered that cracking had occurred in a number of the composite structural support beams between the fuselage base and the cabin floor (Fasanella et al. 2003).

# 6 REPAIRABILITY OF COMPOSITE STRUCTURES

## 6.1 Identifying damage to composite structures

There are numerous non-destructive testing (NDT) techniques to help identify BVID and other subsurface damage. Some of the major ones approved for use by the FAA under AC 43.13-1B 'Acceptable Methods, Techniques and Practices – Aircraft Inspection and Repair' are (Federal Aviation Administration 1998):

### *Low-tech*

- **"Tap test"**

  A widely used low-cost and portable NDT technique, involves tapping composite with a coin or small hammer to listen for "dead" or "flat" spots which may indicate sub-surface damage.

- **Surface bulging**

  Localised bulges are a visible indication of trapped gas bubbles or delamination in a composite structure (Werfelman 2006).

### *High-tech*

- **Ultrasonics/Pulse Echo**

  Sound pulses are transmitted through the composite structure on one side, reflect off the opposite side and are received back at the transmitter. Sub-surface damage causes a decrease in the amplitude of the received pulse, proportional to the size of the defect.

- **X-ray tomography (CT scan)**

  X-ray conducted of composite structure, useful for detecting variations in composition of the composite. Poor at detecting cracks and delaminations.

- **Infrared imaging/thermography**

  Uses radiant electromagnetic thermal energy to detect flaws. The presence of sub-surface damage is identified by localised temperature differences in the composite structure.

- **Laser shearography**

  Portable, tripod-mounted unit that uses vacuum, thermal flux or vibration to place stress on the composite to detect sub-surface damage.

Destructive tests can also be employed to visually identify sub-surface damage as a colour change in the composite laminate. In carbon/epoxy composites, delaminations appear as dull, whitish areas, and stand out from the surrounding undamaged areas which are black and shiny (Rakow & Pettinger 2006). Failure analysis and investigation organisations such as the Defence Science and Technology Organisation (DSTO) and the Australian Transport Safety Bureau (ATSB) use a suite of scanning electron microscopes and other materialographic techniques to understand the general nature of why failures occurred, and the major forces and load paths involved. For more detailed evaluation, analysis is contracted out to specialist consultant organisations.

In large aircraft containing fibre composite structures (such as the Boeing 777 and 787), manufacturers generally size structures so that barely visible impact damage (BVID) does not grow over time to cause delamination. Approved maintenance procedures on these aircraft allow operators to safely leave BVID undetected and unrepaired for the life of the aircraft (Mulcair & Villiers 2006).

## 6.2 Common techniques for repairing damaged/fatigued composite structures

There are currently three types of repairs to composite structures:

- non-patch repairs - suitable for minor damage where NDT has showed that no serious delamination or disbonding has occurred;
- bonded external patch repairs – the most common type of repair, suitable for repairing laminates and composite skin less than 2 mm (sixteen plies) in thickness; and
- bonded scarf repairs – suitable where repairs to thick sections of composite are required.

Each manufacturer will generally provide a suite of approved patch repairs for common skin and airframe damage. If a different repair is required, a CAR 35-approved technician or aeronautical engineer is authorised by CASA to develop repair schemes (composite, wood, metal or any other material). For Australian Defence Force aircraft, DSTO Air Vehicles Division in Melbourne has facilities to design repairs, and manufacture and test them for a variety of in-service conditions. This includes environmental testing, as well as standard mechanical tests in bending, tension, compression, and impact.

### 6.2.1 Non-patch repairs

Non-patch repair techniques include injection, which is used for minor sub-surface flaws and delaminations such as those caused by moisture. Injection repairs involve injecting thermosetting resin under pressure into the affected area to fill the void. For minor surface damage, filler/potting repairs can be applied by filling the affected area with fibre flock, smoothing back and then curing.

### 6.2.2 Bonded external patch repairs

Bonded external patches usually consist of a tapered single lap-joint bonded over the affected area. This sort of patch is widely employed as they are simple to apply in the field, and restore between 70 and 100 percent of the original material strength. External patches should always be longer than required so that there will be minimal shear stress in the affected region (preventing creep of cracks or delamination), and to give a factor of safety against in-service damage to the repair (possible disbonding, environmental degradation etc.

### 6.2.3 Bonded scarf repairs

Bonded scarf repairs are advantageous for repairing large damaged areas as the damage is cut away and replaced with the scarf patch. Scarf patches are tapered to minimise shear stress on the adhesive join, and hence required large amounts of undamaged material to be removed from the affected structure to form the required taper angle. Scarf patches are significantly more difficult and time-consuming to apply than bonded external patches, and have long cure times due to their thickness (Baker 1990).

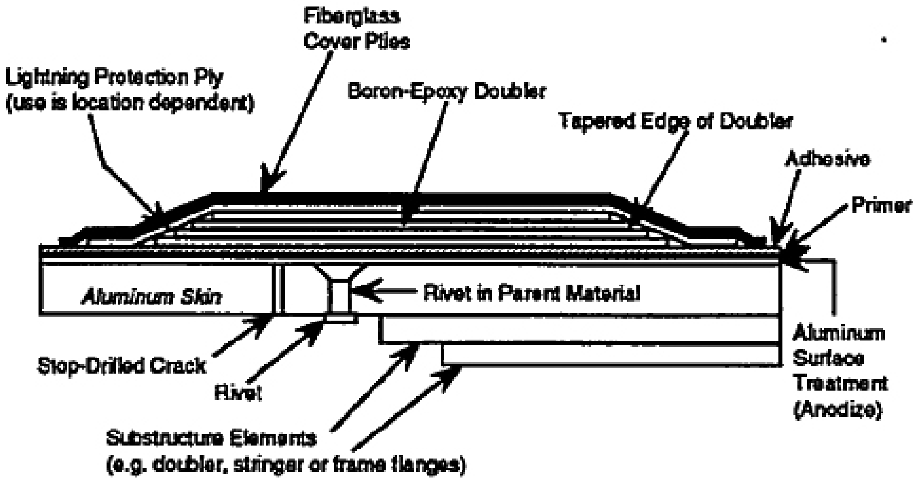
## 6.3 Common techniques for repairing damaged/fatigued metallic structures using composite patches

The use of carbon fibre reinforced plastic (CFRP) or boron fibre composite repair patches to repair fatigued, cracked or damaged metal structures in aircraft became commonplace in the 1980s and 1990s. In the past, aluminium or titanium doubler plates were riveted over the damaged areas, however over time these plates cause further flaws in the surrounding skin, leading to additional aircraft maintenance tasks. Composite doublers are advantageous over metal doublers in a number of ways:

- significantly less weight that equivalent metal doublers;
- more uniform stress distribution – composite patches carry shear load across the whole adhesive surface, compared to metal patches which concentrate stress on the edges;
- corrosion-resistant;
- can be readily formed into complex shapes to provide better coverage of the damaged area – metal patches may require machining in irregular areas such as door and window corners; and
- quick turnaround time for common repairs – often less than twelve hours (German 1997).

Composite repair patches have successfully been applied to many metallic structures across a range of aircraft types where cracking or accidental damage has occurred, or where replacement metal parts are no longer available. Examples include pylon ribs on the Panavia Tornado GR.1, BAe Harrier T.4 engine doors, constant speed drive unit intakes on the Handley Page Victor, and Boeing 757 rudder and ailerons (Armstrong 1990) (Elkins 1990) (Figure 12).

**Figure 12: Cross-section of a typical composite repair patch to an aluminium structure**




Source: Roach 2000

The long-term integrity of composite repair patches to wear and environmental degradation is excellent. An example of this is a Qantas Boeing 747-300, which was fitted in 1990 with a series of nine demonstrator bonding repairs as part of a Boeing/DSTO program to assess the long-term durability of bonded composite repairs to metal aircraft. At the end of the program in 1999, it was found that all of the repair patches were in excellent structural condition, with no signs of cracking or disbonding. This was despite the severe environmental conditions that the patches were exposed to over nine years of service, such as weather and temperature changes, Foreign Object Damage and signs of damage from normal wear-and-tear. In addition, the patches had not caused any damage to surrounding aluminium skin (Geddes 1999). Similarly successful composite patches were installed by Sandia National Laboratories in the United States to a Delta Airlines Lockheed L-1011 TriStar in 1997 to reinforce fatigued door corners. These patches were last inspected in 2000 and showed no flaws, despite several years of regular airline service (Roach 2000).

## 6.4 Industry awareness of correct composite repair procedures

In the civilian environment, there are a small number of organisations that run training courses on fibre composite capability and safety. Ontario-based Renaissance Aeronautics operates a 2 week practical course covering composite material fabrication, damage evaluation and repair, with a significant focus on BVID and failures caused by poor manufacturing and repairs. This course is certified by the Canadian Aviation Maintenance Council and has received positive reviews from the Canadian Transport Safety Bureau (TSB).

Boeing also runs a similar on-demand course covering the capabilities and correct repair procedures for composite aircraft materials.

# 7 POST-CRASH SAFETY AND HANDLING OF COMPOSITE MATERIALS

## 7.1 Response methods to accident sites where composites are present

There is great diversity in fibre composite applications in aircraft: varying types of fibre and bonding/matrix chemicals, processing methods, and the location of composite structures in aircraft. As a result, information about appropriate response methods and safety procedures when attending to an accident site where fibre composite debris is present is often conflicting or inconsistent (Olson 1994).

This report aims to summarise the key information that first responders need to know before responding to a composite aircraft crash – what they might find, the risks to their safety, how to protect themselves, and what to do once they reach the crash site.

### 7.1.1 What is the threat?

Composite aircraft usually contain one or a combination of the following materials.

- Carbon/epoxy (CFRP) – used as a primary structural and skin material.
- Kevlar/epoxy – mostly used in military applications, in primary structures and amour plating.
- Glass fibre - used as a structural and skin material (on amateur-built and GA aircraft).
- Glass/phenolic (GFRP) – used in interior fittings, furnishings and structures.
- Boron/epoxy – used in composite repair patches, older composite structures.

Glass/phenolic structures have excellent fire resistance properties, superior to most next-generation advanced composite materials. However, carbon/epoxy (frequently used in major aircraft structures) has poor fire resistance, easily igniting and burning when exposed to fire (Mouritz 2006).

In the event of a composite aircraft crash and/or fire, first responders should be aware of the dangers of both fibre fragments released from damaged composite structures, and the smoke/noxious gases from the bonding epoxy matrix which may have burned away (Figure 13).

In an impact, these fibres can be released if any composite structures shatter or are subjected to fire or explosion. These fibres are very small and lightweight, and are likely to be in the atmosphere. They are also easily carried by wind currents, and may travel substantial distances from the crash site. Released composite fibres are a respiratory hazard much like asbestos, and similar safety precautions should be taken in regards to breathing apparatus, clothing and decontamination.

**Figure 13: Burnt composite fibres in the rudder section of a Boeing 737-400 following a post-impact fire**

Source: ATSB

### 7.1.2 What equipment is required?

Personnel involved with handling fibre composites, or working in areas where fibre composite dust may be present should wear full Personal Protective Equipment (PPE). The ATSB *Safety Investigation Guidelines Manual – OH&S Guidelines* specifies the equipment that transport safety investigators (TSIs) must wear when attending composite aircraft accident sites:

- rubber gloves beneath heavy leather gloves (as fibres may penetrate the skin causing irritation);
- safety goggles;
- a solid pair of boots;
- full-face dust and mist respirator incorporating capable of filtering particles below 3µm in size (plus a supply of spare filters);
- chemical/biohazard protective suit; and
- Protective overalls (ATSB 2007b), (Gandhi & Lyon 1998).

The Appendix to the ATSB *OH&S Guidelines* reproduces text from a United States Army Safety Centre publication, adapted from USAF (1996), which also states that self-contained breathing apparatus should be worn.

The aircraft type involved should be identified, as should the location and types of fibre composites used in that aircraft (see Appendix A for common fibre composite aircraft on the Australian civil aircraft register).

In preparation for attending a composite aircraft crash site, a package should be put together for first responders and investigators that contains concise and pertinent information and key equipment. Olson suggests that this kit might include:

- OH&S guidelines for handling composite materials;
- mishap checklist;
- Material Safety Data Sheets (MSDS) for common fibre composites;
- medical/first aid information;
- fixant/stripper solution;
- fixant/stripper solution information;
- equipment for applying fixant/stripper;
- personal protective equipment (PPE); and
- aircraft-specific composite data (what types of fibre composites are used, and where they are located) (Olson 1994).

Only equipment that can be easily decontaminated should be taken to the accident site, such as easily washable cameras and tape recorders. Equipment that cannot easily be decontaminated (such as writing pads and tool kits) should not be taken on site (ATSB 2007b).

### 7.1.3 What first responders should do

All personnel not directly involved in initial response operations should keep well clear, and moved upwind at a safe distance from the accident site. The ATSB *Safety Investigation Guidelines Manual – OH&S Guidelines* recommend contacting the Office of Airspace Regulation (Civil Aviation Safety Authority) to establish a temporary restricted airspace area around the accident site. This area should be a minimum of 1 nautical mile in diameter and at least 500 feet high. This will prevent media and other helicopters/aircraft traffic from flying over the crash site and further dispersing any fibre composite dust before a fixant has been applied (Australian Transport Safety Bureau 2007). There should not be any rush for accident investigators to enter the site until personnel have been briefed on the hazards present, and the risks posed by fibre composites.

After entering the crash site, the investigators' first priority should be to protect all electrical equipment. Released composite fibres are highly conductive and their small size means that they can easily interfere with and damage electrical components. At all times, disturbing or handling fibre composite structures that appear to have shattered or have been exposed to fire should be avoided. This will minimise the amount of fibre dust that is released into the atmosphere, which can pose a health risk.

A fixant should be applied to all damaged/destroyed composite structures and areas of fibre composite dust as soon as possible. A fixant is a substance used to contain or 'hold down' dust from damaged fibre composites after impact, a fire or explosion to reduce the dispersion hazard (Olson 1994). Suitable fixants for stabilising fibre composites are polyacrylic acid and floor wax, the latter of which is more commonly available in Australia. If floor wax is used as a fixant, it should be mixed in a 10:1 ratio with water, and applied generously to the entire wreckage area to ensure all surfaces are thoroughly wetted. If the accident site is on a hard land surface (such as a concrete or asphalt runway), floor wax is not suitable and aircraft firefighting foam or protein foam should be used instead. Fixant can be applied using a backpack sprayer, such as those used to fight fires. Suitable sprayers are widely available from gardening and hardware stores (ATSB 2007b).

If protective gloves are removed at any time, hands should be washed thoroughly. All activities involving contact with the eyes or mouth should be avoided, including eating, drinking, applying sunscreen, using mobile phones, or changing contact lenses. After leaving the site, shower before removing protective overalls, and then shower again to remove any fibres that may have come into contact with the skin (ATSB 2007b).

Upon leaving the crash site, all used disposable equipment should be placed into plastic bags and marked 'CONTAMINATED' for burial. If clothing or equipment is not disposable, it should be laundered at approved laundries only after consultation with appropriately qualified OH&S representatives.

These procedures are standard practice for handling fibre composite debris, and are used by the US Department of Defense Composite Material Fire Safety Training Program, the Federal Aviation Administration (FAA), US National Transportation Safety Board (NTSB), and the Royal Air Force (Gandhi & Lyon 1998).

## 7.2 Release of fibre composite particulates in post-crash fires

The flammability of fibre composites used in aircraft is regulated by Federal Aviation Administration (FAA) Part 25.853, and particularly Advisory Circular (AC) 20-107A 'Composite Aircraft Structures'. This Advisory Circular requires that burn tests be performed on exterior and engine compartment structures made of composites to ensure that they have the same or better fire resistance than equivalent aluminium structures. It also requires that composite materials used in aircraft cabins can withstand fire and heat to the same standard as all other transport aircraft, which are certified under FAA Federal Aviation Regulation (FAR) Part 25 (Federal Aviation Administration 1984). AC 20-107A is becoming more important as airliners use fibre composite structures more intensively. In the case of the all-composite fuselage of the Boeing 787 Dreamliner, the FAA has stated that the fuselage "cannot be assumed to have the fire resistance previously afforded by aluminium". This is partly precautionary, due to regulatory inexperience with large-scale applications of fibre composite in aircraft (Croft 2007). However, it is important to note that fibre composite materials do have different flammability characteristics than traditional aircraft materials such as aluminium, and should be treated as such.

The key area of difference between the flammability of metal versus composite structures is the chemicals used to bond fibres together. When composites are exposed to high temperatures (300-400 $^{o}$C and above), the bonding matrix decomposes, releasing heat, soot, smoke and toxic gases. The reinforcing fibres (such as aramid or carbon) may also decompose, creating fibrous dust and adding to the heat and toxic smoke (Mouritz 2006).

The ATSB report 'Fire Safety of Advanced Composites for Aircraft' published in 2006 is a good source of flammability test information for existing and upcoming fibre composite materials used in aircraft. This report compares the fire resistance of composite materials against key criteria: time-to-ignition, limiting oxygen index, heat release rate, flame spread rate, smoke and toxic gas release.

## 7.3 Health effects and toxicity of fibre composite materials used in aircraft

After an aircraft accident, there are a number of health hazards that first responders, Transport Safety Investigators (TSIs) and bystanders must be aware of if fibre composites are involved. Composite structures that have shattered upon impact are likely to have produced respirable fibres. Released fibres or splinters are needle-sharp, and can cause skin and eye irritation. In the event of a post-crash fire, smoke and toxic gases are also released from decomposing composites, presenting further health risks. Because of the serious health hazards that fibre composite debris poses in an accident, it is even more important that emergency personnel minimise survivor exposure. This can be done by evacuating passengers quickly to a location upwind of the accident which is away from composite dust and other debris.

Firefighters and first responders involved in post-crash cleanup and restoration operations have expressed concerns about the long-term effects from exposure to carbon fibres released from burning composites, and the special needs for extinguishing and handling incinerated fibre composite dust (Gandhi & Lyon 1998).

### 7.3.1 Smoke

Short-term exposure of people to smoke released from burning fibre composites is usually not considered a serious health hazard. Phenolic-based composites produce low levels of smoke, in comparison to epoxy and vinyl esters which produce the most smoke of all the common fibre composites used in aircraft. Epoxy and vinyl ester also produce much more dense smoke than phenolics (Mouritz 2006). The smoke from epoxies and vinyl esters can be extremely dense, making it difficult and disorienting for first responders to fight the fire.

### 7.3.2 Toxic gases

Toxic gases produced by decomposing bonding matrix materials are one of the most serious hazards for first responders and people in the vicinity of the accident site. It is estimated that 40% of all post-crash fire fatalities are caused by toxic combustion products and smoke from burning cabin furnishings. The greatest hazard is the carbon monoxide (CO) released in the fire. The amount of CO released depends on the type of matrix material, the temperature of the fire, and oxygen availability. Compared to other common fibre composites used in aircraft, phenolic-based composites release the lowest amount of CO and a moderate amount of carbon dioxide ($CO_2$). Epoxy-based composites release the highest amount of CO and a moderate amount of $CO_2$ (Mouritz 2006).

Decomposing matrix compounds can also release a number of other toxic gases into the immediate atmosphere. Phenolic composites (used in cabin furnishings and some structures) produce CO, $CO_2$, toluene, methane, acetone, propanol, propane, benzene, benzaldehyde and other aromatic compounds. Carbon/epoxy composites can produce over 100 toxic gases, including hydrogen chloride, hydrogen cyanide, hydrogen bromide and nitrogen dioxide. Several of these compounds are known mutagens and carcinogens in animals and humans. Failure to wear adequate PPE is likely to cause severe bouts of coughing and choking, extreme eye irritation, and long-term health problems caused by tissue and organ damage from exposure to these gases (Mouritz & Gibson 2006).

### 7.3.3 Fibre dust

In addition to bonding matrix compounds, the reinforcing fibres in composite structures can also pose OH&S hazards in an accident. Fibrous dust is released from composite structures if they shatter upon impact, or if they decompose in a post-crash fire. The dimensions of the fibres determine the inhalation hazard. Fibres with diameters smaller than 3 µm and shorter than 80 µm can be inhaled deep into the alveolar region of the lungs. Fibres shorter than 15 µm are cleared naturally from the lungs by cellular activity. However, fibres between 15-80 µm remain in the lungs. While further research is required into the long-term health effects of respirable fibre composite dust, current research in the medical community suggests that some types of advanced composite dust (such as E-glass) may lead to pathological effects such as pulmonary fibrosis, which causes diseases such as mesothelioma and asbestosis (IARC 2002). Respirable fibres may in addition adsorb toxic chemicals from the decomposing matrix material, which then enter the lungs and possibly cause acute or chronic effects. Temporary skin and eye irritation can be caused by exposure to sharp, fragmented fibres longer than 4-5 µm (microns).

Flammability tests on fibre composites have shown that only a small fraction of the released fibres are of respirable size. However, research suggests that inhalation of some advanced fibre composite dusts may have long-term health effects. Less is known about the health effects of inhaled carbon fibre dust; however current research suggests that carbon fibres are larger and pose less inhalation risk than silica, E-glass and other advanced fibres (ICAO 2008[1]). Laboratory tests show that unlike these advanced composite fibres, carbon fibres do not cause pulmonary fibrosis in animals (Gandhi & Lyon 1998).

## 7.4 Existing composite material safety programs

The ATSB has published OH&S information and guidelines in-place for TSIs and other first responders to an accident scene where fibre composite materials are present. This information, as well as other safety information needed when attending aircraft accident sites, forms part of the *Civil and Military Aircraft Accident Procedures for Police and Emergency Services Personnel*. This publication is currently in its fourth edition (June 2006), and is accompanied by an Aviation Accident Checklist for use by first responders at the accident site[2] (Figure 14).

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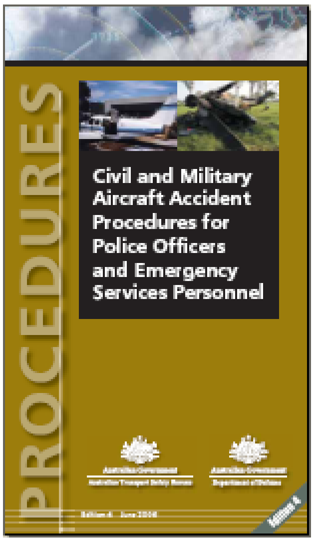
1 At the time of writing, ICAO Circular 315-AN/179 Hazards at Aircraft Accident Sites was in draft format. ICAO expected this circular to be publicly available in late-2008.

2 Electronic copies of the *Civil and Military Aircraft Accident Procedures for Police and Emergency Services Personnel* published by the ATSB and DDAAFS are available at http://www.atsb.gov.au/publications/2006/cil_mil.aspx

**Figure 14: ATSB/DDAAFS publication - Civil and Military Aircraft Accident Procedures for Police and Emergency Services Personnel**




The Air Accident Investigation Branch (AAIB), which is the counterpart to the ATSB in the United Kingdom, produces similar procedures for the British police, fire and ambulance services which are available on their website (http://www.aaib.gov.uk).

In the military, where there is significant experience using fibre composites in aircraft and armour, procedures and training courses exist for personnel who are responding to a crash where these materials are present. The US Department of Defense (DoD) has trained over 10,000 DoD firefighters, first responders and civilian firefighters through their *Composite Material Fire Safety Training Program*. This program focuses on cautious handling of composite material incidents, proper use of PPE, and proper decontamination procedures. It also gives course participants a better understanding of composite material construction and use, burn characteristics of common fibre composites, and the dangers faced by firefighters in an actual emergency situation (Anderl 2005).

The Australian Defence Force (ADF) provides specific guidance to Australian military personnel in fibre composite safety though the Directorate Defence Aviation & Air Force Safety (DDAAFS) *Safety Manual (Safetyman), Chapter 5*. This manual identifies the handling risks, hazards to equipment, required PPE, and response procedures to fibre composites at aircraft accident sites. Whilst broad, these guidelines recommend that fibre composite debris be treated in the same way as asbestos or any other particulate that can be inhaled or ingested. This is in-line with the DDAAFS policy that "any dust is bad dust". DDAAFS also co-produces the *Civil and Military Aircraft Accident Procedures for Police and Emergency Personnel* booklet with the ATSB. Both the procedures and checklist are available on the ATSB website (http://www.atsb.gov.au/publications/2006/cil_mil.aspx).

Hard copies can be requested by contacting the ATSB Publications Unit, PO Box 967, Civic Square, ACT 2608.

Both the *Safetyman* guidelines and first responders' booklet are coupled with ADF training programs to develop Hazardous Substance Safety Officers for the specific needs of groups working with composite and other hazardous materials. This training is developed and run by the Defence Safety Management Agency, and is non-aviation specific.

## 7.5 Australian emergency services first response procedures to aircraft accident sites

When an aircraft accident occurs, it is often not 'conveniently' in the bounds of an airport. In Australia, typical first responders to accident sites are the emergency services, such as State Police, Ambulance, Metropolitan and Country Fire Services.

When accidents do occur within airport lands, or in nearby areas, Airservices Australia Airport Rescue & Fire Fighting (ARFF) services will respond. These units are located at all of the major capital city and regional regular public transport (RPT) airports in Australia. Fibre composite hazard training is mandatory for all Australian ARFF firefighters, with competency-based training courses run internally by Airservices Australia. Airport fire stations also contain a full complement of PPE for attending fibre composite fires, including full-face respirators, splash suits, fixants and sprayers.

Airservices Australia works directly with metropolitan fire brigades by conducting joint training exercises, and with police and ambulance services via Airport Emergency Plans.

Typical first responders in Australia were contacted via an informal telephone survey to determine what guidance, training, and/or response procedures they had in place for attending aircraft accidents, and specifically for safe handling of fibre composite debris. The ultimate aim of collecting this information is to allow the ATSB to provide better information to first responders on the safety risks at aircraft crashes, by identifying where information is lacking.

The survey also sought to find out if the ATSB (or a third-party organisation) provided adequate access to safe composite material handling procedures for first responders.

### 7.5.1 Survey findings

As the emergency services are managed and operated by individual state governments, a lot of variation was found from state to state in the organisational knowledge of fibre composite hazards.

The emergency services that were contacted were:

- Western Australia Police;
- Queensland Police;
- South Australia Police;
- South Australian Ambulance Service;
- Victorian Country Fire Authority (CFA);
- New South Wales Fire Brigades;

- Melbourne Metropolitan Fire Board (MFB);
- Queensland Fire & Rescue Service; and
- South Australian Metropolitan Fire Service (MFS).

Police services have a range of response methods to aircraft accidents and identifying fibre composite hazards. These range from assessing each site on a case-by-case basis (often by using ATSB expertise), to having Standard Operating Procedures (SOPs) in some states. One such example is the South Australia Police, who have developed an Air Transport Accident Emergency Response Plan. This SOP is based on both airport plans, and the *Civil and Military Aircraft Accident Procedures for Police and Emergency Services Personnel* publication produced by the ATSB. A copy of this SOP is carried in all patrol cars along with basic PPE such as welder's gloves, hard hats and safety glasses, and officers are trained in the typical hazards they might encounter at an aircraft accident site.

State fire brigades, who are generally exposed to the greatest risk, also have SOPs or Chief Officers Standing Instructions in place for attending aircraft accidents and emergencies. These SOPs are often based on military or ATSB advice, such as the DoD *Military Aircraft Accident Sites* (1996) guidelines, and discuss risks such as fuel, bodily fluids, ordinates, ejection seats, and ballistic recovery systems. Few specifically identify fibre composite debris as a risk to be aware of at an aircraft accident site. The Queensland Fire & Rescue Service includes detailed composite safety information for firefighters-in-training as part of their *Diploma of Fire and Rescue Operations – Response to Aviation Incidents* syllabus.

There is significant regional variation in procedures. Most fire brigades have detailed handling procedures, equipment and training courses for responding to asbestos fires; these are also applicable to fibre composite fires where there are no specific procedures for composite material safety. Some fire services also release Safety Bulletins to highlight special risks and current issues such as fibre composite debris.

Ambulance services work with police and fire authorities at the accident site to recover any injured crew, passengers or bystanders, and are generally exposed to less risk from fibre composite debris and fires. Ambulance services generally have a hazardous materials (HAZMAT) (Chemical, Biological, Radiological) response procedure in place, which involves close cooperation with the fire service to operate decontamination and other facilities.

### 7.5.2 Survey recommendations

It would be timely for first responders to review their aircraft emergency and hazardous material handling guidelines, and training in handling fibre composite debris for a number of reasons. Firstly, fibre composite materials are heavily used in general aviation (GA) and amateur-built aircraft, which are the most common aircraft accidents that state emergency services respond to. Fibre composite usage in airliners will continue to increase in the next decade, especially with the introduction of the Boeing 787 Dreamliner. Secondly, these materials can pose long-term and even fatal health hazards if not handled correctly.

The intent of the ATSB is to use this information to refine existing informational material (such as the *Civil and Military Aircraft Accident Procedures for Police and Emergency Services Personnel*), and promote accident safety awareness amongst the emergency services community by making this and other information easily available to typical first respondents, such as the emergency services. To support this, emergency services need to have the correct equipment available, be trained in correct response methods, and be aware of the OH&S risks unique to composite aircraft accidents. The aim of this guide is to make this information more easily accessible to first responders to assist them at crash sites and ensure their safety.

**Figure 15: Significant carbon fibre debris following an F/A-18 Hornet fire – a typical scene at future accident sites?**

Source: Directorate of Defence Aviation and Air Force Safety (DDAAFS), Department of Defence

# 8 CONCLUSION

This report provided an overview of the important material safety issues surrounding the significant increase in the use of fibre composite materials in aircraft structures. These materials present new and exciting possibilities for aircraft manufacturers to reduce manufacturing costs and weight while improving airframe strength, aerodynamics and durability. While fibre composites have been used successfully in a wide variety of aerospace applications in the last few decades, their more recent expansion into the growing amateur-built aircraft sector means that more people need to be better informed of the safe use of these materials. Currently, there is a lot of conflicting or incorrect information in the aviation community about the safety and capability of fibre composite materials. To ensure the continued safety of pilots and maintenance personnel who operate these aircraft, aviation regulators could consider making the provision of composite material education programs a higher priority. Such programs could focus on safe material handling, correct repair procedures for damaged composite structures, and techniques for conducting non-destructive inspection and detection of subsurface damage.

With the boom in the use of fibre composites in both amateur-built and general aviation (GA) aircraft and in major components of current and next-generation airliners, it is reasonable to expect that accident investigators and emergency services personnel will encounter these materials more frequently at crash sites in the future. Regulators are very experienced at identifying signs and causes of failure in traditional aircraft structures made from metal; however fibre composite structures fail in different and unusual ways that are still not fully understood. As a result, analysing failed composite structures will remain a significant challenge for regulators investigating the causes of aircraft accidents.

Fibre composite structures also present new safety challenges to investigators, first responders and bystanders at accident sites. Composite structures that have shattered upon impact are likely to have produced airborne fibres that are needle-sharp, causing skin and eye irritation. Fine fibre dust has the potential to remain in the lungs when inhaled. While further research is required, current research suggests that some types of advanced composite dust (such as E-glass) may increase the risk of pulmonary fibrosis and other asbestos-related diseases (IARC 2002). In the event of a post-crash fire, smoke and toxic gases are released from decomposing composites, presenting further health risks. All of these risks can be mitigated against if proper safety precautions are taken, in particular wearing appropriate protective equipment, protecting electrical equipment, moving bystanders away from the crash site, and applying fixant solution to all damaged composite structures to limit dust dispersal. After an accident, fibre composite materials can reduce passenger survivability of an accident due to the unique hazards they pose. It is important that emergency personnel evacuate passengers quickly to a location upwind of the crash site to minimise their exposure to these hazards.

A number of fibre composite safety courses exist overseas to train first responders about the OH&S hazards they may encounter at a fibre composite aircraft accident. Typical first responders to accident sites are the emergency services, such as State Police, Ambulance, Metropolitan and Country Fire Services. Typical first responders in Australia were contacted to determine what OH&S training they provided to their staff for safe handling of fibre composite materials. The survey also sought to find out if the ATSB (or another organisation) provided adequate and timely access to safe handling guidelines for fibre composite materials. This survey found that response methods and guidelines for attending composite aircraft accidents vary widely amongst states and emergency services.

The ATSB recognises that improving delivery of safety information to first responders attending accident sites, particularly for fibre composite aircraft, is an important issue to ensure public safety. Publications such as the *Civil and Military Aircraft Accident Procedures for Police and Emergency Services Personnel* provide a good background to these and other hazards at accident sites, and are targeted towards emergency services.

It would be prudent for emergency services to review their aircraft accident response procedures to incorporate composite-specific risks, or develop general aircraft accident response procedures if they do not currently exist. Measures that could be implemented to do this include training workshops, incorporating ATSB accident response methods into Standard Operating Procedures, and development of ‘first response’ equipment and information kits for first responders.

# 9 GLOSSARY

| | |
|---|---|
| **Autoclave** | A large chamber designed to cure large, laid-up composite structures more quickly by placing them under elevated heat and pressure. |
| **Bonding matrix** | The ‘glue’ that holds the reinforcing fibres in fibre composite structures together, giving them rigidity. Typical matrix materials include epoxy and phenolic resins. |
| **Composite doubler** | A fibre composite repair panel that is attached over the original structure where it is damaged, cracked or fatigued. The doubler is designed and attached in such a way that the load carried by the original structure is transferred to the doubler. |
| **Delamination** | A common type of damage to fibre composite structures. Plies of fibre composite in the laminate split apart, weakening the surrounding structure. Delamination can be caused by sub-surface damage, moisture and other sources. |
| **Empennage** | The tail surfaces of an aircraft, usually consisting of a vertical stabiliser (fin or tail) and horizontal stabilisers. |
| **Fibre flock** | A very fine fibrous material (often cotton), which is cut finely into a powder and mixed with a matrix material (such as epoxy) to form a paste. This paste can then be used to join composite structures, or to fill-in minor surface damage. |
| **Fibre pullout** | A phenomenon visible in fibre composite structures that have failed in tension. Individual fibres break under the tension force and are pulled out of the bonding matrix. Figure 6 shows an example of fibre pullout. |
| **Fixant** | A substance that is sprayed on damaged fibre composite structures to ‘hold down’ fibrous dust, which can become easily airborne and present health hazards. Floor wax is a commonly used fixant solution. |
| **Hackles** | A phenomenon visible as rough features on the failure surface of a fibre composite structure failed in shear. Shear loads in the laminate cause the bonding matrix to fail before the fibres. Figure 7 shows an example of hackles. |
| **Kink bands** | A phenomenon visible in fibre composite structures that have failed in compression. Kink bands are formed by fibres buckling before failure occurs and can be seen as cracks in the matrix. Figure 8 shows an example of kink bands. |
| **Laminate** | A sheet of composite material used in aircraft structures. It is made by bonding numerous plies of fibre together with a bonding material (e.g. epoxy). |
| **Load cycle** | Provides a measure of an aircraft or component’s operational life. One cycle is one takeoff plus one landing of an aircraft. |
| **Matrix splitting** | Separation of the matrix that holds together the fibres in a composite structure, often caused by damage or by excessive compression loads. |
| **Rib** | An aircraft structural member that runs transversely across the wing and is attached to the main spar. Ribs maintain the aerofoil shape of the wing and provide structural support for the skin. |
| **Scarf repair** | A repair patch used where structures are too damaged or too thick to apply a simple bonded doubler. The damaged area is cut away and replaced with the scarf, which is replacement section tapered to reduce shear stress where it is joined to the original undamaged structure. |
| **Spar** | The primary structural member in the wing of an aircraft, runs lengthways along the wing and attaches the wing to the fuselage. |
| **Stringer** | Thin structural member that runs down the length of an aircraft fuselage between frames, providing rigidity to the fuselage and as attachment points for the skin. |
| **Thermoset resin** | A polymer that can be cured to bond reinforcing fibres together into rigid composite plies and laminates. Typical thermosets used in aviation are epoxy and phenolic resin. |

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# 11 APPENDIX A: FIBRE COMPOSITE AIRCRAFT ON THE AUSTRALIAN CIVIL REGISTER

This list illustrates fibre composite structures on a number of common aircraft on the Australian VH register. This list is not intended to be exhaustive. For the most up-to-date information regarding composite use on particular aircraft models, contact the relevant manufacturer.

**Table A.1: Composite aircraft on the Australian register (amateur-built aircraft) (mid-2007)**

| Aircraft | Type | Number on register | Composite use | Composite type |
|---|---|---|---|---|
| Jabiru J200, 400/430, SK/SP | 2/4-place GA aircraft | 65 | All of aircraft | Glass fibre |
| Stoddard-Hamilton Glasair/GlaStar | 2-place GA aircraft | 57 | All of aircraft | Glass/vinyl ester, foam core |
| RotorWay Exec 90, 162/162F | 2-place helicopter | 48 | Rotor blades, skin | Glass fibre, foam core |
| Lancair 320/360/IV | 2/3-place GA aircraft | 45 | All of aircraft | Glass fibre, Nomex honeycomb core |
| Europa XS/Classic | 2-place GA aircraft/powered glider | 23 | All of aircraft | Glass fibre, foam core |
| Rutan Long-EZ | 2-place GA aircraft | 20 | All of aircraft | Glass fibre, foam core |
| SeaRey | 2-place amphibious ultralight | 18 | Hull, fuselage skin | Glass fibre, foam core |
| Rand KR-2 | 2-place GA aircraft | 17 | Skin and other components laid over wooden structure | Glass fibre, foam core |
| Rutan VariEze | 2-place GA aircraft | 10 | All of aircraft | Glass fibre, foam core |
| Monnett Sonerai | 2-place GA aircraft | 8 | Fuselage, empennage skin | Glass fibre |
| Rutan Quickie | 2-place GA aircraft | 8 | All of aircraft | Glass fibre, foam core |
| Viking Dragonfly | 2-place GA aircraft | 8 | All of aircraft | Glass fibre, foam core |
| Cozy Mk.IV | 4-place GA aircraft | 6 | All of aircraft | Glass fibre, foam core |
| Vans RV-10 | 4-place GA aircraft | 2 | Cabin top and doors, wingtips, propeller | Carbon/epoxy |

**Table A.2: Fibre composite aircraft on the Australian register (GA aircraft, helicopters and sailplanes) (mid-2007)**

| Aircraft | Type | Number on register | Composite use | Composite type |
|---|---|---|---|---|
| Robinson R22/R44 | 2/4-place helicopter | 624 | Chin, doors, roof | Glass fibre |
| Schempp-Hirth (all models) | Sailplane | 146 | All of aircraft | Glass fibre |
| Schleicher (all models) | Sailplane | 112 | All of aircraft | Glass fibre |
| Glasflugel Kestrel, Standard, Hornet, Mosquito | Sailplane | 112 | All of aircraft | Glass fibre |
| Eurocopter AS.350/355 Squirrel | 4-place helicopter | 95 | Main/tail rotor, some fuselage panels | Glass fibre |
| Cirrus SR20/SR22 | 4-place GA aircraft | 63 | All of aircraft, propeller | Glass fibre, foam core |
| Schnider (all models) | Sailplane | 61 | All of aircraft | Glass fibre |
| Grob G102, G103 Astir | Sailplane | 61 | All of aircraft | Glass fibre |
| Grob G-115 | 2-place GA aircraft | 55 | All of aircraft | Glass fibre, Carbon/epoxy |
| Schweizer (all models) | Sailplane | 44 | All of aircraft | Glass fibre |
| Glaser-Dirks DG200/400/500 | Sailplane | 26 | All of aircraft | Glass fibre |
| EIRI PIK-20 | Sailplane | 23 | All of aircraft | Glass fibre |
| Diamond Star DA40 | 4-place GA aircraft | 18 | All of aircraft | Glass fibre, Carbon/epoxy |
| Jabiru J160, J230, J430 | 2/4-place GA aircraft | 17 | All of aircraft | Glass fibre |
| Slingsby Firefly | 2-place GA aircraft | 17 | All of aircraft | Glass fibre |
| Eurocopter EC120/130 | 6/8-place helicopter | 16 | Main/tail rotor, fuselage/doors, stabiliser | Glass fibre, Carbon/epoxy |
| Eagle 150 | 2-place GA aircraft | 15 | All of aircraft | Glass fibre, foam core |
| DG Flugzeugbau (all models) | Sailplane | 7 | All of aircraft | Glass fibre |

**Table A.3: Fibre composite aircraft on the Australian register (airliners) (mid-2007)**

| Aircraft | Number on register | Composite use | Composite type |
|---|---|---|---|
| Boeing 737NG (-600, -700, -800, 900) | 82 | Control surfaces, engine cowling, winglets | CFRP |
| Bombardier DHC-8 | 56 | Lower engine nacelles | CFRP/Nomex honeycomb sandwich |
| Boeing 767 | 29 | Control surfaces, engine cowling and pylons | CFRP/Nomex honeycomb sandwich |
| Airbus A319/A320 | 24 | Empennage, control surfaces, engine cowling | CFRP/Nomex honeycomb sandwich |
| Boeing 737 Classic (-300, -400, -500) | 24 | Control surfaces, engine cowling | CFRP |
| Airbus A330 | 14 | Empennage, control surfaces, engine cowling | CFRP/Nomex honeycomb sandwich |