Liability for aircraft components – including case studies - how not to get fatigued!

Evening Seminar – NSW Branch Aviation Law Association of Australia and New Zealand

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Dr William A J Higgs & Geoffrey Parker SC
Elizabeth Street Chambers
Warning

- There is more aeronautical knowledge than law in this presentation.
Take away messages

- Like in all litigious matters one has to have a case theory –
  - case theory will depend in large part on the correct identification of the cause of the aircraft crash
  - It the blueprint from which you will conduct your case
  - Here lies the problem! – the identification of actual cause is difficult (one or multiple causes)
- Identification needs to be specific rather than general
  - Pleading negligent design versus pleading a cause of action relating to what actually happened or what was the actual cause
- In large part, it is what the experts say backed by hard science?
Take away messages

- Identification of the relevant expert should depend on your preliminary thesis as the cause of the accident (the ‘loop’)
  - This process is ‘circular’ because you won’t know the actual cause until you engage the relevant expert
  - Metallurgist versus mechanical or aeronautical engineer versus LAME – don’t ask a aero eng to opine on fracture and fatigue, don’t ask a metallurgist to opine on aircraft design
  - Fracture / fatigue (metallurgist) or design (aeronautical/mechanical engineer), non manufactured part (LAME/engineer)

- Once cause of accident is identified then one can plead on the basis of the applicable law.
- One of the purposes of this presentation will give you some added knowledge about aircraft engineering concepts to enable you to close the ‘loop’ quicker to save costs searching for experts or more relevantly, the right one/s and conduct the litigation more efficiency (CPA)
The hypothesis is that a little bit of aircraft engineering knowledge would assist in identifying the cause of the crash - specifically by shaping your preliminary thesis and identification of experts – ultimately to guide you in ascertaining the cause of the crash.

Then it is a case of deciding on the applicable law..............whether it be all or some of the following:

- Australian Consumer Law - ‘safety defect’
- Trade Practices Act 1974 - ‘defect’
- Negligence
- Contract
Take away messages - knowledge

- What engineering/aeronautical knowledge do you need to close the ‘loop’
  - How aircraft stay in the air – the basic principles
  - How aerodynamic loads are transmitted from within the aircraft structure such as the critical conduits for load transmission such as lugs and fasteners
  - The nature of the load transmission mechanism ie shear forces, clamping forces etc

- Most common failure mechanisms
  - It’s extremely rare that aircraft parts fail due to faulty design
  - It’s extremely rare that aircraft fail due to overloading
  - Incorrect use of materials, problems introduced in manufacture process; perhaps
  - Fracture and then fatigue failure; almost always

- Design rationale or theory applicable to aircraft design
  - Basic principles of aircraft structures
  - Concepts of safe life, fail safe and damage tolerance
  - Fracture and fatigue principles - key
Part I

- How aircraft stay in the air
- Flight envelope
- Structure
- Fracture & Fatigue

Part II

- Case study – Crash of Robinson R-22 Mariner II helicopter (VH-MIB) on 30 May 2004
- Legal aspects
How aircraft stay in the air
Straight, horizontal, steady flight

Four forces:
- **Weight (W)** - aircraft empty weight, fuel and payload
- **Lift (L)** - wing but also fuselage
- **Drag (D)** - fuselage, wings and tail
- **Thrust (T)** - engines

For V & alt. = constant

Force Equilibrium:
- \( L = W \)
- \( D = T \)
Lift

The formula for the LIFT is:

\[ L = CL \times \left( \frac{1}{2} \rho V^2 \right) \times S \]

ie lift increases by square in V, so does D then more power > D

- \( CL \) = Lift coefficient
- \( \rho \) = Density of the air [kg/m³]
- \( V \) = Air speed [m/s]
- \( S \) = Wing area [m²]

Lift is calculated for each section of the wing and then aggregated to get the total lift for the wing, which looks parabolic.
Generation of Lift

- Sum of static and dynamic pressure remains constant:
  \[ p_1 + \frac{1}{2} \rho V_1^2 = p_2 + \frac{1}{2} \rho V_2^2 \]
  \[ p + \frac{1}{2} \rho V^2 = \text{constant} \quad \text{(along a streamline)} \]

- Consequences: greater V → lesser Ps

- Lift by pressure difference ie force from high pressure to low pressure

- Airfoil – curvature of upper surface is greater than for lower surface therefore higher V

- Angle of attack increases lift (next slide)
Generation of Lift

- Nice smooth laminar flow (straight line)
- Note: this is not a symmetric looking airfoil. A symmetric airfoil would have zero lift at zero alpha.

- As alpha increases turbulence starts to occur near and then airflow completely separates and the wing stalls (loses lift completely) leading to high drag
Load transmission
Transmission of lift

All lift force is transmitted through lugs (shown in red)
Principal Structural Elements

- Complex wingbox
- Multiple rib designs
- All elements
Bolted Joints
Flight Envelope
Flight Envelope

- Diagram are used to determine combination of flight conditions and load factors to which the aircraft structure must be designed.
- ‘Pushing the envelope’ - this phrase is used to refer to an aircraft being taken to, and perhaps beyond, its designated altitude and speed limits.
- You will all remember in Top Gun Viper saying “We’re going to teach you to fly the F-14 right to the edge of the envelope, faster than you have flown before.”
- Nowadays the software doesn’t permit the pilot to fly the aircraft outside of the envelope.
China Airlines Flight 006 damaged by going outside its flight envelope to gain control after a drop of 3,000 m in 20 seconds - resulting from disconnection of autopilot and pilot error resulting in 5 g pull out - would have been fun!
Loads – use of a V-n diagram

- \( N = \frac{L}{W} \) or ‘g’
- Normal aircraft are designed for \( n \) of 2.5-3.8 and -1 to -1.5 neg g
- Acrobatic aircraft are designed for 4.4 and neg -3g
- Transport 5g and -2g
- Fighter aircraft 6.5-10 and -3 to -6
- Means that at higher speeds, the maximum g could be exceeds compared to lower speeds.
Loads

- Limit Load: Load experienced once in a lifetime
- Ultimate load: limit load x safety factor
- $V_{\text{min}} = \text{stall speed}$
- $V_a = \text{design manoeuvring speed}$
- $V_c = \text{design cruise speed}$
- $V_d = \text{design diving speed}$
- Parameters largely chosen by designed subject
Structure
Anatomy of a structure

- A structure is an assembly of multiple structural elements. Each element participates in (some of) the functions of the structure.
- Structural elements are joined together.
- Most structural elements are derivatives of a beam.
- Goal is to minimise weight:
  - So less lift required.
  - Means less drag.
  - Means less thrust.
  - Means less fuel.
From Truss to Beam

- In the beginning of flight, aircraft structures were truss structures. For aerodynamic reasons they were closed with fabric.
- The basic truss is very simple, elegant and light weight

If true hinges, any rotation will prevent rotation by welding hinges. Still some distortion. More elegant? No distortion, aircraft structures are built from these.
From Truss to Beam

- The diagonal element can also be a **cable**. A cable can not be loaded in compression. So two **cables** are necessary.

- One cable can be replaced by one **rod**. Rods can be loaded both in tension and compression.

- Effectively replacing two **cables** with one **rod**
From Truss to Beam

- What happens when two diagonal rods are used? What are the advantages and disadvantages?

- The structure becomes: - more difficult to assemble (no hinge at crossing), - heavier (2 bars)?

- There is one advantage however, the structure has some “reserve”. One rod may fail but there is redundancy- *fail safe structure*
From Truss to Beam

- Each element strong enough to stay intact for the entire life cycle (**Safe life**)
- One element may fail: other elements strong enough to stay intact for limited time; inspection interval required!! (**Fail safe**)
- Which option is lighter??
- Which option is ‘safer’?
From Truss to Beam

- The rod can be replaced by a thin sheet or skin.
From Truss to Beam - transformation

- Beam comprised of trusses
- ‘Wire braced’ structure
- Combination of rods and wires
- Increasing thickness of the rods to the left - WHY?
- This is not truss for the vertical rods and wires – WHY NOT?
From Truss to Beam - transformation

- External force $F$
- Induces Bending moment $M$
- Truss applies force to the supports (red arrows)
- Support reacts on Truss for equilibrium (blue arrows)
From Truss to Beam – transformation complete!

- Truss can be replaced by sheet metal
- Web plate instead of diagonal tubes
- Web plate – shear forces; flanges– tension and compression forces
From Truss to Beam

- When applying high forces on the structure, buckling starts. Compression forces cause local buckling of sheet.

- Elastic buckling is no Failure! Only reduced compression load carrying capabilities. Tensile forces are fully carried.

- So long as stresses are within limits of the material the buckling is not problematic.

- Although it can be quite scary to see the buckling happening!
From Truss to Beam

- No its not a full fuel tank!
- Skin buckling due to shear loads
- Perfectly safe Yes/No?
Typical wing or fuselage support structure

- This is an example of plastic buckling = Failure!!
- Note the local buckling of the flange on the top flange surface
Principal Structural Elements

- Principal Structural Element – primary structure – carry loads - failure is/can be catastrophic
- Non-principal structural elements – secondary structures failure is not catastrophic (e.g. fairings, some hatches)
- Most Structural Elements are “beamlike” elements
Principal Structural Elements

- What Beam elements do you discover?
- Spar
- Stringers
- Frame
Failure behavior materials

- Within the limits of load diagram,
  - Material should not fail
  - Metal should not yield
  - Composite should not damage
Aloha flight 243. The accident involved an explosive decompression in a 19 year old Boeing 737-200 aircraft on 28 April 1988. According to the United States National Transportation Safety Board (NTSB) accident report, the aircraft had 35,496 airframe flight hours and 89,680 flight cycles, which is an average flight time of 25 minutes.

Fracture & Fatigue
Fatigue

- Fatigue leads to failure of structures.
- Fatigue is critical in load transmission pathways.
- Dynamic loading – repetitive – leads to fatigue failure.
- Unavoidable in aircraft structures to flight cycles (landing and takeoff; rotation; variable loading on Aircraft due to aerobatics for instance).
- Example: Paperclip - try to break one! the paper clip will not break if only bent once, however, if it is repeatedly loaded, it will eventually break.
- Every time you bend the paper clip microscopic damage occurs.
- (Repetitive) forces are always smaller than breaking force destroys the part!!
Fracture and Fatigue

- SN-curve

  In some materials, notably ferrous alloys, the S – N curve flattens out eventually, so that below a certain endurance limit ‘σ’ failure does not occur no matter how long the loads are cycled (not in this case).

- The designer will size the structure to keep the stresses below endurance limit σ by a suitable safety factor if cyclic loads are to be withstood.

- In principle, components designed so that the applied stresses do not exceed the known endurance limit shouldn’t fail in service (not quite true; see stress concentration below)

- This process determines cycles to inspections.
The stress is concentrated around the crack tip or flaw developing the concept of stress concentration. Stress raisers are defined as the flaws having the ability to amplify an applied stress in the locale.
Fracture and Fatigue

- A damage tolerant design or ‘safety by inspection’ should allow cracks to be detected before they reach the critical length that will lead to failure.

- The damage tolerance approach is based on the principle that while cracks due to fatigue and corrosion will develop in the aircraft structure, the process can be understood and controlled.

- To ensure that this occurs there should be at least two opportunities to detect the crack prior to it reaching its critical length.

- Based on experiment and maths, the damage tolerance method may be used but is not mandatory; the safe-life or fail-safe methods may be used instead.

- The underlying philosophy of damage tolerance design is that damage can, and must, be detected before it becomes critical.

- Therefore, scheduled inspections are a central element of the continuing airworthiness processes for a damage tolerance aircraft type.
Fracture and Fatigue

Figure below shows the fracture surface of a fatigue structural failure of an aircraft main spar, the primary load bearing element of the wing.
Fracture and Fatigue

- Mating fracture surfaces of left lower main spar attachment lug, resulted in failure of wing structure. Pilot fatally injured.

Source: ATSB - In-flight breakup involving PZL Mielec M18A Dromader, VH-TZJ; Budawang National Park about 37 km west of Ulladulla.
Fracture and Fatigue

- Location of Boeing 767 Body Station 1809.5 bulkhead and wing front spar pitch load fittings
Helicopter VH-MIB
The crew of the Robinson R22 helicopter were undertaking a fence line inspection at about 30 to 40 ft above ground level.

The crew had initiated a turn, a loud bang was heard and the helicopter began to yaw quickly before striking the ground.

Passenger sustained serious injuries. The pilot subsequently died of his injuries.

The flex plate in the forward flexible coupling of the main rotor drive was found fractured at one of the two attachment points to the main rotor gearbox yoke.

The flex plate fractured due to the propagation of a fatigue crack at one of the bolted connections between the plate and main rotor gearbox yoke.

Do we understand the language? Yes/No?
Legal

- Do we understand this language? Yes/No?

- Claims based on general law of negligence and a s 74 TPA claim solely against the manufacturer where basically the issue was whether the helicopter and/or the Maintenance Manual had a “defect”, for the purposes of s 75AD and s 75AE of the Trade Practices Act.

- In my view a most bizarre outcome (manufacturer lost on appeal), when clearly the engineering was clear on the cause of the crash, as we will see.

- The bolted joint was disassembled by a LAME at some time after the manufacture of the helicopter (although that was an inference)

- My view of the outcome of the case is that for all flight critical components a maintenance manual must be able to detect a loose bolt irrespective of whether the component had been correctly serviced in accordance with the maintenance manual in the first place.
Main rotor gearbox drive components in the wreckage of VH-MIB

- Power to drive the main and tail rotors is transmitted from the engine to the rotor drive train via a multiple Vee belt drive and clutch system.
- A shaft transmitted power forward from the clutch to the main rotor gearbox and aft to the tail rotor gearbox.
- Flexible couplings are located at the input to the main rotor gearbox (also known as the “forward” flexible coupling) and at both ends of the tail rotor drive shaft.
- The flexible couplings accommodate differences in drive shaft axial alignment.
- Bolting a single, four-armed, thin stainless plate between the main rotor gearbox yoke and the drive shaft yoke.
Components of failed forward coupling

(Source: ATSB TRANSPORT SAFETY INVESTIGATION REPORT - Aviation Occurrence Report – 200401917)
Main rotor gearbox drive components in the wreckage of VH-MIB
Components of the forward flexible coupling

This figure is an assemblage of photographs of the individual components of a forward flexible coupling.
Flexplate
Flexplate fracture surfaces

Flexplate (not actual)
2 fracture surfaces (above & below)
Top crack first to go
Crack directions
Final fracture
Final fracture and disconnection from the main rotor gearbox yoke occurred by net section yielding as crack growth from the inner surface of the bolt hole neared the edge of the flexplate arm.

The rate of fatigue crack growth could not be determined with certainty, however, the general features of the fatigue fracture surfaces indicate that crack growth was slow and occurred over the period of more than a few flights.
What do we know so far?

- Conclusion: The examination of the main rotor and tail rotor drive components recovered from the helicopter wreckage established that the flexplate in the forward flexible coupling fractured as a result of the propagation of a fatigue crack at one of the bolted connections between the plate and main rotor gearbox yoke.

- That’s the analysis so far, but it tells us nothing about who or what actually caused the crash.

- Why not?
What caused the initial fracture which started the propagation.

- Was it due to overloading? (pilot excessive ‘g’)
- Was it a manufacturing defect? (manufacturer)
- Was it due to fretting (rubbing) caused by failure to tighten nut, which led to a crack (LAME service)
- Was it due to incorrect selection of material? (LAME servicer; manufacturer)
- Was it due to incorrect use of fasteners (LAME servicer, manufacturer)

All of which are **likely to cause a starter crack** which could propagate to failure.

All of which dictate separate cause of actions.

**A plug for my thesis** - you need to know the cause of the crash - your case theory). (Neg/ACL/TPA/contract)
The assembly instructions for the flexplate bolted joints require that each of the four bolted assemblies be tightened 240 in-lb of torque to the nut. The nut is secured by a secondary locking mechanism in the form of a stamped sheet steel nut (Palnut) tightened against the installed nut.

Defined it as a critical fastener

The instructions for assembling critical fasteners included a warning that at least two threads up to a maximum of four threads must be exposed beyond the end of the nut to allow the proper installation of the locking Palnut.

The warning provides an alert that if more than four threads are exposed the nut may seat against the bolt shank and result in inadequate joint clamping.
Schematic showing the relationship between various joint thicknesses and bolt grip length.

The coloured blocks represent the thickness of joint components.
Forward flexible coupling factory assembly
Initiation and growth of a fatigue crack

Growth to fracture represents a failure of the flexplate fracture control plan

Evidence of fretting wear. This type and degree of wear damage is indicative of operation with no clamping force in the bolted joint.

Looseness at the bolted joint at the flexplate failure location is due to a mismatch between joint thickness

Examination of contact marks on the bolt thread created during nut tightening indicated that the nut, installed on the bolt at the flexplate failure location, had not been advanced any further along the nut thread than its recovered position (i.e., so it wasn’t torqued and was in the no more than 4 and no less than 2 thread position.

It was only then a matter of time before the crash happened
McDermott & Ors v Robinson Helicopter Company [2014] QSC 34

That the manufacturer had a duty of care to exercise reasonable care to ensure the Maintenance Manual provided adequate inspection procedures during inspections and servicing:

- to detect cracks initiating at the bolt holes,
- the presence of fatigue cracking in that location,
- lack of torque in the bolted joints in the flexplate,
- fretting wear of the bolt shaft of the joint connections, and
- separation of the bonded washers

In essence what the plaintiff was suggesting was that the defendant had failed to require that the flexplate be verified by removal of the nuts, re-torquing of the bolted joints, and failed to provide adequate instructions to detect a lack of torque in the bolted joint.

The defendant denied these breaches and pleaded that the Maintenance Manual required provision of torque stripe which would indicate that the bolt had become loose.

The defendant allege that it was unnecessary, undesirable and uneconomical to remove parts including the flexplate at each 100 hour inspection. The plaintiffs denied this.
Plaintiffs - passenger and his wife - brought a claim for loss under TPA 75AD and s 75AE

Claiming that the goods (helicopter and Maintenance Manual) were defective (i.e. defective maintenance manual = defective helicopter)

Specifically that the inadequacies of the maintenance manual relating to inspection procedures (in particular the instructions relating to inspection did not convey what is required in sufficiently clear or comprehensive terms), both the helicopter and the maintenance manual were defective, and the defects caused the plaintiffs to suffer loss and damage.
Held no defect in Maintenance Manual and thus no defect in the helicopter

It was logical that the Maintenance Manual was defective the helicopter would also have been defective:

“the adequacy of [the Maintenance Manuals] provisions is a relevant circumstance in determining whether the safety of the helicopter is or is not such as persons are generally entitled to expect”

Wilson J on Appeal agreed with that conclusion and that was not amenable to argument.

75AD Liability for defective goods causing injuries—loss by injured individual

If:

(a) a corporation, in trade or commerce, supplies goods manufactured by it, and
(b) they have a defect; and
(c) because of the defect, an individual suffers injuries;
then:

(d) the corporation is liable to compensate the individual for the amount of the individual’s loss suffered as a result of the injuries; and
(e) the individual may recover that amount by action against the corporation, and

(f) if the individual dies because of the injuries—a law of a State or Territory about liability in respect of the death of individuals applies as if:

(i) the action were an action under the law of the State or Territory for damages in respect of the injuries; and
(ii) the defect were the corporation’s wrongful act, neglect or default.
Goods have a defect if their safety is not such as persons generally are entitled to expect.
The test stated in that section is whether or not the safety of the goods is such as persons generally are entitled to expect. The test has been described as providing an objective standard i.e. persons generally "are entitled to expect".

It is apparent from s 75AC(2) that the enquiry is broad-ranging, giving regard to "all relevant circumstances". In context, a relevant circumstance is one which has some bearing on what persons generally are entitled to expect with respect to the safety of the goods. Of the specific examples given in s 75AC(2), those found in paragraph (d) and, to a lesser extent, paragraph (e), are of most relevance.

The Explanatory Memorandum stated that in some cases, the role of "intermediaries" may be relevant.[217] The Explanatory Memorandum referred to the role of qualified medical practitioners and qualified pharmacists, when considering whether pharmaceutical products might be said to have a defect, because instructions provided to a consumer by the manufacturer were not complete. It seems to me that LAMEs are also intermediaries, and the instructions given to them in a document such as the Maintenance Manual may be relevant to determining whether the safety of the helicopter was, or was not, such as persons are generally entitled to expect.

The Explanatory Memorandum recognised as a class of defect which might mean that the safety of goods was not such as persons generally are entitled to expect, defects described as "instructional defects", said to be "caused by incorrect or inadequate warnings and instructions".[218] While it is the text of the statute to which regard is to be had in determining whether a party is entitled to compensation under these provisions, it seems to me that the Explanatory Memorandum is entirely consistent with that text.[219]

It might be regarded as self-evident that, without adequate maintenance, at some time a point will be reached where a helicopter cannot be flown safely; that LAMEs could not be expected to identify all that is necessary for the adequate maintenance of a helicopter without the benefit of maintenance instructions from the manufacturer; and that where the manufacturer provides a maintenance manual, the adequacy of its provisions is a relevant circumstance in determining whether the safety of the helicopter is or is not such as persons are generally entitled to expect.

I have earlier concluded that the effect of the instructions in the Maintenance Manual required a LAME, carrying out a 100 hourly inspection, to examine the condition of the torque stripe for Bolt 4; that if the condition of the torque stripe was not as specified in the Maintenance Manual, then the LAME was required to take further steps to ensure that the torque was in accordance with the Maintenance Manual; and that accordingly, compliance with the Maintenance Manual was sufficient to prevent the accident. It follows that my earlier conclusions mean that Mr and Mrs McDermott have failed to establish the existence of a defect in the goods supplied by Robinson.

If I were otherwise prepared to accept the submissions made on behalf of Mr and Mrs McDermott, it seems to me that the better basis on which they would then succeed would be that the helicopter had a defect[220]; although it seems to me that it would also be correct to say that the Maintenance Manual had a defect, and accordingly the claims could succeed on that basis. Indeed, according to the written submissions for Robinson, the latter analysis would be correct.[221]
Court of Appeal

- Finding that there was no defect in the Maintenance Manual was overturned on appeal in McDermott & Ors v Robinson Helicopter Company Incorporated [2014] QCA 357

- Approach adopted: “The case [at trial] focused not upon how the bolt became loose but, rather, why its looseness was not detected.”

- Also, consider this statement:
  
  “That approach to the question of negligence was plainly, with respect, right. This is a product liability case against the manufacturer of a helicopter, focusing on its service manual. There was ‘... a risk of catastrophic failure if one of the bolted joints for the flexplate became loose’. [36] The ‘... circumstance that the product is inherently extremely dangerous, or, that the gravity of the risk of injury which negligence creates is serious, only requires that a higher duty of care be exercised...’.

  [37] In light of the terms of the manual, with its clear wording directed towards checking the security of the bolts, and in light of the way the case was advanced for Robinson, the plaintiffs were not required to prove that the manual failed to address the risk of incompetence or negligence by LAMEs; only, rather, that it failed to adequately address an identified, and accepted, risk — that, for whatever reason, bolts might be loose. Insofar as Robinson appears to advance a different case on appeal, its arguments to that end must be rejected.” at [61] Wilson J
Implicitly, isn’t the Court of Appeal saying that the actions of the LAMEs in not assembling the bolted connection properly was *foreseeable*. Is this not setting a very high bar.

For example, what is the extent of the duty. For instance, imagine a situation where no nut was installed on the bolt by the LAME at the 100 hr service interval. The flexplate would propagate to destruction in a matter of hours (certainly under 100 hrs) or even the first flight. Obviously an inspection would be nugatory in that instance. (Note also that the 100 hr inspection interval would more likely be set to identify fatigue crack propagation and not bolt loosening.)

What may be practical outcome- reduced service intervals and di

Arguably at first instance Robinson should have made an attempt to establish negligence on the part of the LAMEs who did not assemble the bolded joint correctly and then establish that this broke the chain of causation.

However the finding of the Court of Appeal – that a Maintenance Manual must be able to identify a lose bolt installed on a flight critical notwithstanding an installation that did not follow the Maintenance Manual in the first place- would not have changed the outcome.