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Composites are well researched and basic properties and behaviour are fairly well known. However, less is known on how all composite aircraft will behave in the long run when applied at the scale here involved, with exposure of very large and very thin composite skin to the extremely harsh conditions that apply to aircraft. How will structural integrity be affected by the combined influence of extreme mechanical and environmental cyclic loading when the composites degrade because of ageing and fatigue as well as possible damage and repair. Mechanical loading is probably nowhere so severe as with aircraft that experience continuous pressurization and depressurization, extreme vibrations and impact *sequences. Environmental conditions involve hefty temperature gradients combined with large variations in humidity, exposure to ice and snow as well as intense UV radiation and possible attack by solutes - an ideal environment for degradation of polymers. With physical testing, conditions can only be simulated to limited extend and only certain combinations can be studied in some detail only. Reliable modelling will only be possible when practical experience is gained with aircraft in service over longer period of time.*

Composites differ from metal alloys in that they contain two distinct phases - fibres in a polymer matrix - hence have a heterogeneous laminated structure that behaves highly anisotropic. The typical structure does, however, provide the composite with some unique features, the pros. The cons are not always recognized and are frequently ignored or underestimated or whatever, labelled as *'red herrings'* during a recent *Aviation Today* webinar 153).

With composites the pros are well known by now and include lightweight, stiffness, high fatigue strength, non corrosiveness, easy mouldable in slim complex perfectly smooth aerodynamically shapes and reduced part count because composites allow for manufacturing of large size one piece sections. These properties make composites eminently suitable for civil aircraft - although composite structures tend to have higher manufacturing costs than metallic structures, but assembly was thought to be much cheaper. The pros were expected to enable lighter and stronger aircraft that are lower on fuel and need far less maintenance – and allow improving on flying experience.

Typically, the cons are not so well highlighted and shed a different light on composites. Not all cons listed below are necessarily disadvantages and include differences that require a new if not distinct approach when compared to aluminum. Several cons pose safety risks - some unknown with aluminium aircraft - and this puts limits on damage tolerance. The most important 'cons' will here be discussed in brief and refer in particular to *thermoset carbon fibre reinforced epoxy resin composites* that are predominantly used in all-composite aircraft.

Heterogeneous structure

Aluminium is a straightforward homogeneous alloy, contrary to composites that have extremely complex heterogeneous composition and structure at both nano, micro and macro level. Composites comprise a resin matrix that surrounds and supports the carbon fibres. The mechanical properties of resin systems are not very high. They are there to transfer the forces and to protect the fibres from environmental damage. The fibres deliver the composite its strength and the interaction between the fibres and the matrix delivers the composite its unique properties, in particular high specific strength and modulus - that is relative to density - and fatigue resistance. Control of the fibre matrix interface makes it possible to adjust certain properties. More specific, composite properties are determined by the fibre (type, quality, diameter, length) and the fibre volume fraction, the matrix (type, quality) and the fibre-matrix bond strength as well as the fibre arrangement (fibre orientation and weave of the fibre, number and thickness of the individual layers, their stacking sequence, stitching), manufacturing and moulding (lay up, prepeg) and the curing conditions. The huge range of fibres, resins, manufacturing processes and possible manipulation of the interfacial bond strength give composites their real advantage over other materials; in that it is possible to tailor the composite optimally for particular load bearing constructions and even to vary properties (thickness and fibre architecture) along its surface. However, the heterogeneous structure, specific interfacial bond strength and complex architecture pose also serious problems with design, manufacturing, inspection, testing and repair.

Amorphous state

Thermoset composites differ also from metal in that the resin polymer matrix has an amorphous structure, hence is in glassy (non-equilibrium) state. More precise, polymers describe extremely long chains of molecules - epoxy resins that are used in aviation composites have a three-dimensional network structure were the polymers are highly crosslinked through chemical bonding. That composites have an amorphous structure means that they are brittle and creep and that small foreign molecules can diffuse into the polymer network, which can affect the molecular structure - this means that composites can absorb moisture. The network is also vulnerable to radiation. Over time this can lead to ageing that describes degradation of the composite. Ageing has a strong effect on physical properties, as will be discussed later. Amorphous also means that properties of composites can change over time due to possible rearrangement of the structure of the polymer.

Glass transition temperature

Amorphous and glassy materials differ from crystalline materials in that they don't transfer from solid phase into fluid or melted phase with abrupt change of structure and density at a certain temperature. When the temperature of amorphous material increases there is a gradual transformation from ordered to disordered molecular state. This means that amorphous materials - like polymers - don't have a sharp melting temperature but that melting takes place over certain temperature range.

Upon heating the polymer goes first through the glass transition temperature - also a range - when the amorphous solid transforms from a rigid to a rubbery state to transform into the fluid state when the melting temperature is reached. Temperatures vary with the type of polymer and are with aviation composites in the 100^0C to 150^0C range - far below the temperatures that affect aluminum. The melting temperature decides the curing temperature but the glass transition temperature is decisive for the physical properties of the polymer. The physical properties show profound change in the range of the glass transition temperature and pose a boundary to composite applications. Elastic modules may for example decrease by a factor 1000 when the temperature is raised through the glass transition range. Other properties that change rapidly include next to elastic properties, strength, stress redistribution, vibration and damping behaviour, coefficient of thermal expansion, heat capacity and electrical properties - actually every property is affected in dramatic way and in turn affect fracture behaviour, failure modes, stress redistribution, vibration and damping properties, impact performance, lightning strike resistance, crashworthiness, flammability and so on. Note that the glass transition temperature is reduced significantly when water absorption takes place - and can also be affected by fatigue and ageing and repair.

Operating temperatures

Civil aircraft can experience rather high - and very low - temperatures in service. This poses no problem with aluminium, contrary to composites where maximum operating temperatures have to be set - well below the glass transition temperature to leave a safety margin that has to include the effects of possible water absorption. Aviation composites that are typically cured at 180 C show a glass transition temperature of 150 C that can drop 25 C when it absorbs some 1% water. Aircraft are exposed to heat sources that include the power plants, de-icing equipment and air conditioning units that can heat up nearby parts and panels. This has to be taken into account when composites are present in these areas. Aerodynamic heating that is produced through contact with airflow at very high velocity is a serious concern with supersonic aircraft, not at subsonic velocities. The skin of civil aircraft cruising at typically 850 km/h cools down to the surrounding environment - that can reach minus 70 ^{0}C at 35.000 ft (to plus 70 ^{0}C at airports).

> Aerodynamic heating is most intense on re-entry of the space shuttle when the heat shield is exposed to temperatures of 2300 F/1260 C. The famous SR-71 would expand several inches flying at Mach 3 when the leading edge reached some 600 ^{0}C. With the Concorde skin temperatures were reached up to150 C when flying at its cruise Mach 2.4 speed 362).

Operating temperature range that has been set for all composite aircraft should be set between about minus - 70 C and + 70 C. Little is known how composites are affected by such large cyclic temperatures differentials taken other conditions into account that apply and were listed before.

Anisotropic behaviour

Aluminium behaves isotropic, but composites show strong anisotropic behaviour due to its heterogeneous structure and possible insidious damage. This makes it extremely difficult to model physical behaviour. Composites have excellent properties in the plane of the shell, with strength in the fibre direction significant higher than metal - that is in tension and to a lesser extend in compression. Strength in the plane transversally to the fibre orientation is about equal to metal. However, performance out of the plane is poor - through the thickness strength of composites is about an order of magnitude lower than that of metals and translates in poor performance in shear, impact and stress redistribution. This limits the application of composites essentially to two-dimensional loading conditions and it has to be taken into account that two-dimensional loading can result in through the thickness stresses - mind that large areas of the fuselage have thickness of just 2 mm. Different fibre orientations may increase impact resistance and transversal properties but this goes at the expense of longitudinal performance. Three dimensional fibre architecture through stitching may increase transversal strength to certain extend.

Also other physical properties are affected - so are electrical and thermal conductivity and coefficient of expansion also influenced by the fibre architecture and are different in the plane and normal to the plane.

Residual stress

The thermal coefficient of expansion of the matrix is much higher than that of the fibres. It can therefore not be avoided that tension is introduced in the matrix when the composite is cooled after curing at 150 to 200 ^{0}C. Thermally induced residual stresses in the matrix can partly translate into flaws and structural irregularities at nano level that develop into interfacial micro cracks along the interfaces, which are inherent part of the composite structure. Such insidious damage can lead to poor fibre matrix bond strength and influences fatigue, ageing and damage performance of all-composite aircraft, which are loaded to extreme. To limit residual stress, temperature gradients have to be kept within 1 to 2 degrees Celsius at every point of the structure during curing in the autoclave and in particular during subsequent cooling, which is very difficult to achieve with the large one-piece sections here involved. More serious flaws can be expected when the gradients are even slightly exceeded.

Manufacturing defects

Other typical insidious defects and irregularities can occur during manufacturing, assembly, maintenance and repair. These include, amongst others, resin rich and resin dry areas, fibre misalignment, porosity, delaminations, inclusions of foreign materials, damaged cut outs and misdrilled holes, all of which seriously affect composite behaviour. *'...the lack of experience, or even the possibility of manufacturing composite structures with imperfections, makes the forecast of future failures and strength very difficult'* 4). Most important is that impact is avoided. Intensive non-destructive testing during the various stages of production is therefore critical. Attaining the very strict dimensional tolerances poses another problem with the very large one-piece sections, as has been discussed before.

Deformation behaviour

Contrary to metals, composites behave rather brittle than ductile and are therefore low on toughness. Stress-strain behaviour develops between of that of the brittle fibre and the elastic polymer matrix, depending strongly on the fibre volume fraction. Deformation behaviour of composites is very sensitive to strain rate (rate of deformation), environmental conditions, in particular sudden temperature change and the presence of moisture, and to what extend the composite contains flaws and defects - and is damaged or affected by degradation. Creep that is time dependent deformation also influences deformation. Moreover, deformation behaviour differs greatly depending on direction, and composites perform different under tension and compression. Deformation behaviour has to be studied for static loading, cyclic loading and dynamic loading, taking into account the effects of possible damage and degradation due to cyclic environmental loading – and is far more complicated than with homogenous isotropic aluminium.

Brittleness

Metals are ductile and elastic deformation warns that fracture is about to happen and this leaves normally sufficient time for measures to prevent sudden failure. This is applied in aviation, where design of aluminium civil aircraft is largely based on damage tolerance. This means that damage is allowed for, but inspection procedures have to be in place that guarantee that the maximum level of damage at which the material or structure is still suitable and safe for the intended application is not exceeded. However, composites are brittle and this means that fracture occurs more suddenly, if not sudden, leaving a limited window of opportunity for timely warning before catastrophic failure - in a way essentially similar to behaviour of high strength steel. Damage tolerance is therefore more difficult to apply with composites than with aluminium, as will be discussed later. The capability of metal structures to re-distribute load between its members is *one* reason which provides additional margin of safety to the metallic analysis methods, which is not the case for composite structures as discussed above.

Water absorption

Contrary to metals, composites do not corrode but can absorb water, through diffusion - polymer resins up to more than 1%, depending on atmospheric humidity. Moisture plasticizes the matrix resin reducing those properties that depend on the resin, such as shear, compression stiffness and strength, the more so with (sudden) change in temperature. This can lead to increased residual stress, formation of new micro cracks as well as extension of existing ones and in turn initiate or extend delamination and debonding sites that allow for further absorption. Moisture absorption or desorption can even trigger passage from stable crack growth to very rapid crack growth 23). Water can carry other strange substances and of course also other fluids and gasses can be absorbed.

Failure

Unlike metals where failure occurs essentially by single crack propagation, failure of composites occurs through damage accumulation involving different *damage modes* that include fibre breakage and matrix cracking, debonding, transverse ply cracking and delamination - sometimes independently, sometimes interactively - depending on the stress that is applied, leading to a variety of *failure modes* completely different from aluminium and completely different for the fibres and the matrix, and involve such behaviour as fibre failure, fibre pull out, fibre bridging, resin cracking and hackles 154). A fundamental feature of composite structures is that, in most cases, failure is not a unique event, but a gradual sequence of micro cracking and delamination, leading eventually to structural collapse. This means that prediction of failure is extremely complex. Engineers have proposed a great number of failure theories, nineteen of which have been critically reviewed recently 155). Results are encouraging, but there is still a long way to go and a universal approach seems not achievable. So far it is not possible to include all relevant parameters, most noticeably the effects of thermally induced residual stress, moisture absorption and temperature - that play such important role with aviation composites. Failure theories are based on either stress distribution or fracture mechanics. In particular the prediction of through the thickness failure, that requires a fracture mechanics approach, has proved to be extremely difficult - impact behaviour merges into the general area of damage mechanics 156). Tension fibre failures are generally well predicted but compression matrix failures are often more important with composite aircraft structures and more difficult to predict.

Compressive strength

Compression loading can lead to micro buckling of the fibres, which is a predominant failure mode with composites. Compressive strengths are often quoted at just 50 to 60% of the corresponding tensile value. But it is very difficult to measure uniaxial compressive strength, with different methods producing differing values. There is still intense debate whether true axial compression strength of composites can be measured with available methods. Moreover, compressive strength in the plane is strongly affected when even minor delamination has occurred, in particular through low velocity impact. The *Compression after Impact Test* has been developed to measure residual compressive strength of damaged composite panels and has become an industrial standard 157). Compressive strength after impact is regarded a critical design measure in the aerospace industry 158). The measured value has, however, no discrete structural meaning but provides a measure to determine sensitivity to impact and other damage which is useful for qualitative comparison 401). Note that the way a composite part is damaged before testing for residual strength is not standardized, but strongly affects the measured value.

Stress redistribution

Manufacturing of large composite parts is complicated hence costly, but assembly requires much less fasteners and other joint constructions, which are often the weakest part of the structure. According Boeing *'10,000 holes have to be drilled to assemble the 787 fuselage, compared with a million holes on the 747 jumbo jet'* 159). However, ten thousand holes that have to be drilled in the composite barrel to attach the frames means still a substantial weakening of the hull and all these holes complicate modelling and calculation of stress distribution throughout the fuselage which is also affected by differing thicknesses of the hull and cut outs for the window, doors, landing gear and so on.

To avoid problems with galvanic corrosion, high tech titanium fasteners have to be used with composites. These are very strong and allow for extreme stress concentration, but composites have very limited ability to redistribute loads at structural features such as fasteners. The lack of plasticity of composites limits stress re-distribution (160) and sets boundaries with design. This phenomenon is not well understood but the result is that fastener holes are quite notch and brass sensitive. Moreover, when drilling holes it cannot be avoided that fibres are cut, destroying part of the load path. This causes considerable loss in strength, locally typical half of the original strength (401) and can make it necessary to increase the thickness of the laminate in the vicinity of stress raisers or strengthen the fastening point otherwise.

When the fastener hole is slightly damaged or incorrect drilled and when fasteners not precisely fit stresses can locally concentrate in the hole, which can lead to development of complicated failure modes, typically through transverse micro cracking, delamination and finally fibre pull out - and even breakage of the fastener. Any interference with the fit affects also lighting strike resistance, as will be discussed later. Tolerances have therefore to be very strict; sometimes a few thousandths of an inch and hole strengthening procedures have possibly to be applied to obtain good fastener support. The holes must be straight, concentric and have the exact diameter; any burr to the fastener holes has to be avoided. This can pose a serious problem with assembly and an even greater problem with repair. It is very difficult to avoid damage to the hole when fasteners are frequently removed and replaced, which has to be taken into account with maintenance. Most important is that fieldable methods become available for non-destructive testing of these fastening points and other joint constructions.

Vibration and damping

Composites have very different vibration and damping properties, which are strongly affected when the composite is damaged and by changes in temperature, moisture and numerous other parameters – much more so than with metals. But this is still poorly understood. Modelling is not possible yet and engineers often have to adapt trial and error, trying to get vibration and damping under control. With the A400M military airlifter it has already proven to be very difficult to control vibration with the large all-composite wings during the development phase. September 2008 it was reported that delivery of the plane *'has been delayed indefinitely'* (21) officially *'due to the* *"unavailability of the propulsion system'* 197), as has been discussed before. Uncontrolled vibration is here at the root of the problems and the composite wings are most probably involved. For the moment engineers don't know how to solve the problems 6).

Noise control

Composites have lower mass that limits noise insulation. Also composites' specific damping characteristics require adaptation of sophisticated noise control technology to cope with turbulent boundary layer and engine shock cell. With aircraft the aim is to limit the noise control weight – that is the weight of the materials applied for noise insulation - to 1% of the maximum takeoff load, which is substantial. With aluminium aircraft noise control is largely obtained through insulation blankets that provide also thermal insulation, as well as fuselage and payload damping. With all composite aircraft attention focuses on integrally damped composites, for example sandwich with add-on and co-cured damping layers out of visco-elastic materials and epoxy materials 199). How this affects the weight issue is not known yet. Also much attention is paid to nano technology to improve on acoustic properties of composites.

Impact performance

Contrary to aluminium, composites are famously low on impact strength and get (too) easily damaged, which means that composites '*are often not the best choice of material for structures that are suspect to repeated impact* 161). The FAA has therefore issued special conditions with regard to tire debris penetration of the fuel tank of the 787 247) - with aluminium fuel tank as benchmark. But the whole plane is vulnerable to impact, which poses a serious safety issue.

As was pointed out before, composites are very strong in the plane, but far less so normal to the plane, with very low impact performance through the thickness. High strength carbon epoxy composites that are used in aircraft have actually the lowest energy absorbing capability of all composites and it appears that this behaviour can be improved to limited extend only 156) as will be discussed in more detail later. Even single low velocity impact can cause extensive sub-surface damage that strongly affects the structural integrity of the composite, in particular delamination that is not or barely visible for the eye. Such so-called hidden damage poses a serious safety risk with aviation composites since aircraft are prone to impact through accidental collision with ground handling equipment, tool damage, de-icer impact, moisture and rain, sand storm, runway debris, engine thrown debris, blade loss and rotor burst, hail stone, lightning strike shock wave, bird strike, meteorites, hard landing, busted tire debris and wheel threats – and even when walked on by mechanics and inspectors. Remind that the accidents with the Concorde and the Space Shuttle Columbia were both caused by impact. As indicated before, with civil aircraft, the fuselage belt is prone to damage by impact - more than the wings - through luggage loaders, catering trucks and passenger jetways. Testing and simulation of impact response of composites is a complex problem 402) and it will still take quite some time to design reliable models. Development is hindered in that no suitable test method is available to test composites - or construction materials in general - for impact response 35).

Hidden damage

A typical difference with metals is that composites can hide damage that spreads under the surface. The structure may appear sound until the moment that it shatters. This so-called hidden or insidious damage can involve debonding between the fibre and the matrix and delamination. Unknown with aluminum, insidious damage is a failure mode typical with composites. Composites have a laminated structure and relative light impact, cyclic stress and ingress of fluid can cause separation or delamination along the interfaces between the matrix and the fibres. It is often very difficult to detect early development. Even widespread delamination can remain invisible or hardly visible to the eye and can be very difficult to detect with available test methods. It develops normally gradually over time out of flaws and other structural anomalies and local delaminations that always exist between composite layers and are caused by build up of stresses during curing, cutting openings, drilling of fastener holes, handling of the parts, relative light impact and repair as has been indicated before. As indicated before, with aircraft it is impossible to avoid impact in service. One has to be constantly aware of accidental impact - according Airbus *'You get a surprising amount of times when people dent or tear the fuselage skin by driving vehicles into it......it's more difficult to detect the extent of the damage with carbon fibre. You don't know whether it has spread six, twelve or even twenty inches to the left or right'* 14). Thickness of vulnerable parts has to be increased to more than 5 to 10 mm or otherwise strengthened, for example around doors and hatches and special measures have to be taken to protect the cargo space and the fuel tanks in particular. Although applied on limited scale, serious problems have already occurred with composite rudders - that involve sandwiched composites - as has been discussed before. The *'Delaminated Aircraft Problem Report at Listing Problem reports.Aircraftdata.Net'* lists already many hundreds composite parts of aircraft that have been delaminated in service.

Hidden damage can strongly affect the structural integrity of the composite - *'at the point were damage is non-visible, the structural composite no longer meets its original design objectives'* 158) - in particular when insidious damage occurs in the vicinity of fasteners and joints and allows for ingress of moisture and gasses that can lead to further degradation. With delamination caused by impact, *reduction in strength has been reported of 50% at the point were damage is not or barely visible up to 75% at the point were visible damage is observed* 162). This means that hidden damage is a serious problem with aviation composites - it poses a major safety concern 401) 402) - because it is so difficult to avoid and so difficult to detect.

Fatigue

Composite aircraft are significantly less susceptible to fatigue failure then aluminium aircraft but fatigue can still occur and affect structural integrity in time 170) 381). The fibres provide composites with high fatigue strength, but only when supported by a strong brittle matrix. The fibre matrix interface plays here a very important role. Composites with well-bonded tough matrices often exhibit inferior fatigue properties to those with brittle matrices. This means that lower fatigue strength can be obtained when impact strength is increased. Fatigue life is controlled, at the microscopic level, by the progressive accumulation of broken fibres on the tensile side of the specimens. This process is affected by temperature and strongly affected by possible ingress of moisture. Inherent residual stress and micro cracks may not cause immediate degradation but makes the composite vulnerable for prolonged cyclic loading, certainly so when the composite becomes damaged, and when delamination proceeds progressively undetected for longer period and starts interacting with other insidious damage - a process that is further accelerated when the composite is hit by impact at that location. Delaminated sites can grow and do so, and it is therefore difficult to understand when both Boeing and Airbus declare that with composites in aircraft *'No Fatigue Damage inspection is required'* 176) 177).

Ageing

Boeing and Airbus also declare that with all composite aircraft *'No specific inspection for Environmental Deterioration is required'* 176) 177). Indeed, composites do not corrode like metals due to electrochemical reactions but severe degradation can occur due to ageing - with ageing affecting fatigue and visa versa. Knowledge about long term performance of composites is limited 171) and there are still many uncertainties, certainly so with environmental degradation of composites at the extreme conditions that apply to aircraft and no lifetime prediction recipe is available for composites yet 172).

Ageing results from damage caused by physical and chemical attack due to environmental loading. As pointed out before, with aircraft environmental loading of externally exposed composites is much more extreme than any other known application and this loading is continuous, repetitive and cyclic - and it is the combination with intense cyclic mechanical loading that has to be considered. Know how is largely based on testing in rather sterile environment that differs totally from the operating environment that includes very large temperature gradients, intense UV radiation and exposure to moisture, ice and possibly aggressive fluids and gasses. Surrounding temperatures vary with each flight from over +60 ^{0}C at the ground to below -60 ^{0}C at 35,000 ft (10.670 m) when even adsorbed monolayers of water molecules freeze. At the same time the polymers are heavily stressed due to the cyclic loading and continuous vibrations that are known to simulate the deterioration processes - in time, the composite becomes increasingly vulnerable to both environmental and mechanical loading. Likewise fatigue, insidious damage increases sensitivity to ageing in significant way.

Composites can absorb gasses, vapours and water and other fluids through diffusion and capillary action - possible through degradation of protective coatings and impact or other kind of surface damage. With aircraft surfaces can become contaminated with water, salt spray, de-icing solutions, cleaning substances, oil, grease and hydraulic fluid. Ingress of strange substances can cause swelling and possible dissolution when solute molecules are able to fit between the macromolecular chains of the polymers and push these apart. Such polymeric degradation causes the polymer to plasticize - which affects modulus, strength and brittleness, induce creep, glass transition temperature and thermal expansion coefficients and electric properties. Moreover, swelling can cause stresses in the fibres. Serious debounding caused by ingress of hydraulic fluid 48) has already occurred with composite rudders in service, as been discussed before. A list of materials that can cause damage to composites is being developed for the 787 and includes for example insecticide spray commonly used to disinfect aircraft.

Degradation can also be caused by so-called scission when molecular chain bonds are broken because of radiation, chemical reaction and heat. This actually means that the molecular chains become shorter and this affects mechanical properties, resistance to chemical attack and can cause shifts in the glass transition temperature. Chemical reaction involves typically oxygen and ozone that can cause or accelerate chain scission. Radiation involves, among others, UV (ultraviolet) rays. These have short wavelength and possess sufficient energy to penetrate the polymer. UV radiation and ozone can cause degradation of the polymer that can cause surface embrittlement and hence less impact resistance. Carbon fibres are not affected by UV but have of course to be fully protected form oxygen - but oxidation cannot be avoided when delamination spreads unnoticed for longer period of time.

Several test programs are under way with composite parts of aircraft that have been in service for longer period of time. First results that have been reported are encouraging. The initial teardown of a 737 horizontal stabilizer has shown little effects of long time service experience. Mechanical and physical property tests have shown little difference in values after 18 years and 52,000 flight hours 173). At the same time very serious problems have occurred in recent years with composite rudders involving Airbus aircraft that were not so long in service, as has been discussed before.

Thermal fatigue

Contrary to aluminium that has a homogenous composition, composites contain two distinct phases - the carbon fibres and the matrix resin – with show rather large differences in thermal expansion, as cited before. This means that significant tensile stresses can develop in the matrix when the composite is cooled far below its curing temperature, which add to possible residual stresses that have already build up. This can lead to interfacial debonding and microcracking of the matrix, even when no external load is applied. As has been indicated before, aircraft experience cyclic temperature drops far below the curing temperature - in concert with the heavy mechanical cyclic loading and are as such susceptible to thermal fatigue.

Sonic fatigue

Fighter jets experience extreme acoustic loading during manoeuvres that cause frequent damage due to sonic fatigue, in particular when flying fast and low 360). Such damage - mainly cracks in thin panels - requires specific repair to maintain sufficient damping. With civil aircraft acoustic loading is not so extreme and do not cause problem with aluminium aircraft but can cause problems with composites - delamination in particular 361) - due its specific damping behaviour. Aerodynamic noise level near engines can be sufficient to cause sonic fatigue with nearby composite parts when no special measures are taken. Composites are in particular susceptible to high frequent noise that can be produced by propulsion systems. More so, it is the contribution of sonic fatigue to other dynamic loading that may cause damage to composite parts in aircraft.

Thermal conductivity

Aluminium is highly thermally conductive, this contrary to composites that behave more as thermal insulators. Thermal conductivity determines heat transfer characteristics - heat absorbing capacity, heat rejection capacity and cooling capacity - and is of major importance to fire safety, together with toxic flammability. Composites heat at much lower rate, absorbs significant more heat and cool at much slower rate than aluminium that rejects heat readily when placed in a cooling environment - the same applies for lateral heat transfer. This means that composite fuel tanks behave completely different form aluminium tanks. Of particular concern is how aluminum and composite tanks affect flammability of the ullage - that is the empty space in the fuel tank above the fuel - at ground conditions and at higher altitude, as will be discussed later. The specific thermal conductivity of composites affects also behaviour during lightning strike.

Electrical resistance

Electrical resistance is expressed as resistivity or by its reverse that is called conductivity. Depending on their electrical resistance materials behave as conductors or insulators. With composites the carbon fibre is conductive but conductivity is limited to the direction of the fibres. The adhesive polymer matrix - a dielectric - insulates the fibres and greatly inhibits current flow in directions nonparallel to the fibres, even when the fibres are provided with a conductive - metal - coating. Composites have therefore very high resistivity, more than thousand times greater than that aluminium that is one of the best conductors around - copper has an even higher conductivity. The poor electrical conductivity limits the application as electromagnetic shielding, circuits, antennas, and affects lighting strike performance.

Lightning strike performance

Aluminium is a conductor, which means that with aluminium aircraft lightning strike protection ‘comes for free’ with the construction material. A lightning strike to an aircraft causes a high electric current, which may typically be of the order of a hundred thousand amps. The aluminium structure acts as a Faraday cage and carries the lightning current from the attachment point to the point of exit.

The lightning current pulse generates heat that concentrates at the attachment point - or arc root. This heat cannot escape to the surroundings during the short duration of the pulse and causes a high temperature at a relative small area that can produce a transient hot spot at the underside of the skin. With aluminium there will normally be a melting at the arc root - damage is normally limited to a pitted surface but the skin can melt through depending on the magnitude and the duration of the current and the thickness of the aluminium.

With composites - that behave as insulators - there are important differences in lighting strike performance. A composite aircraft structure is not able to readily conduct away the extreme electrical currents and electromagnetic fields that are generated when lighting attaches to the composite skin. Carbon fibre may be conductive but carbon fibre plies perform as very high resistance conductors, because the resin presents a highly capacitive dielectric - the large differences in resistivity of the carbon fibre and the resin matrix results in an increasing potential difference through the ply structure that provides no readily available electrically conductive path for discharge of the current.

Duration of lightning attachment can with composites be significant longer than with aluminium because of this high resistivity. This means that with composites much higher voltage gradients are generated at the arc root and consequently higher temperatures - and hotter transient hotspots are likely to develop. It has also to be taken into account that the resin has a relative low softening point. Although the arc root does normally not penetrate more than five plies, the temperatures caused by lighting strike may cause damage to the resin - such as charring, bond-breaking and loss of distortional capability and of course delamination. Differing coefficients of expansion in the plane and through the thickness cause differential expansion when lighting strikes that provides another cause of possible delamination. When the carbon fibres heat up above the pyrolization temperature of the surrounding matrix, resin can vaporize in the immediate strike area producing pockets with pressurized gas that may lead to delamination. When lighting strikes, the current pulse and the consequent increase in magnetic field generates an acoustic shock of a magnitude that can be sufficient to cause fracture of the composite skin and possibly delamination. All this can lead to significant loss of residual strength that makes the composite more vulnerable to subsequent mechanical and environmental loading. To avoid such consequences - or to limit the effect - the thickness of the composite layer may have to be increased in significant way, but that has a weight penalty.

The greatest danger with lighting strike is that it can cause sparking that can lead to explosion of the fuel tank and that it can cause disturbance of on board electronics and avionics software, as will be discussed in more detail later. Special measures have to be taken to protect the composite structure against ignition sources, shockwaves, electrical shorts and electrostatic discharge. Again at the expense of much weight - but with available technology it cannot be avoided that all composite aircraft will remain significant more vulnerable to lighting strike than aluminium aircraft. In this respect it is important to note that composites have the same probability of an attachment as an aluminium structure - in spite of its very high resistivity 323).

Interaction with dissimilar materials

The global structure can be affected when adjacent parts are out of dissimilar materials that have different physical properties or interact otherwise and this has to be taken into account with the design - such variables make modelling extremely complicated in particular when composites are involved that are very difficult to model because of heterogenic and amorphous structure.

As indicated before, composites and metals show very different deformation behaviour under stress, which in turn can cause stresses and stress concentrations where composites are connected to aluminium and titanium parts. This affects joint constructions in particular that must be able to redistribute and spread these stresses to the surrounding materials.

Stresses are also generated due to the rather large differences in coefficients of thermal expansion of composite parts and adjacent aluminium and titanium parts. This also affects metal foil and mesh that are integrated between plies to provide the composite with electric continuity 350). Moreover, it has to be taken into account that operation temperatures in these parts can develop in different way because of differing specific thermal conductivity - which means that certain parts warm and cool at different rates. That affects for example the temperature of the fuel in the tanks and explains that flammability is different in composite and aluminium fuel tanks [353)].

Contact with other materials can also excite chemical reaction - composites are cathodic with respect to aluminum, which means that galvanic corrosion can occur where composites are in contact with aluminum. Aluminum fasteners can therefore not be applied with composites and isolation layers have to be applied where aluminium and composite parts join, connect or attach.

Crashworthiness

Composites behave brittle and cannot absorb energy like aluminum that behaves ductile and crumbles during a crash, but tend to delaminate very easily upon impact reducing mechanical performance [154)]. The FAA has therefore issued special conditions for crashworthiness of the 787 [203)] with aluminium fuselage as benchmark. Boeing maintains that drop tests performed with a 787 fuselage section demonstrate that '*energy is effectively absorbed*' [165)] - but no specifics have been made public so far. The aim is to develop reliable models that make it possible to simulate crash behaviour of the fuselage sections and make it possible to study the effectiveness of shock absorbing materials and structures, but that is extremely complicated with all composite aircraft [200)] - and has to be considered in connection with flammability. Results obtained with these models are suited for qualitative comparison only and cannot be applied for certification.

Composites break more like glass and show scattered crash behaviour - and this behaviour is influenced by temperature. Fragments are sharp, fibre dust even needle sharp and can cause skin and eye irritation and pose an inhalation risk in a way similar to asbestos [166)] - certainly so when fire is involved as will be explained later. Fragmentation of composites is expected to accelerate flammability in significant way due to increased exposed specific surface. Also here special measures have to be taken to guarantee safety of both passengers and crew and first responders and this applies also for engineers who have to be protected when working with composites during production, maintenance and repair [403)].

Fire behaviour

Aluminium has very low flammability - but does burn when exposed to very high temperature - contrary to composites that burn form the vaporization of the resin when exposed to fire. Fire is a major safety concern because it contributes to aircraft accidents and has causes many fatalities in the past - cabin interior materials and fuel tanks are of particular concern as will be discussed in more detail later. The FAA has therefore issued special conditions for the composite fuel tank of the 787, with aluminium fuel tank as benchmark. The special conditions focus in particular on keeping flammability in the ullage above the fuel as low as possible [243)] and that the fuel tank does not burn through when exposed to fire [244)] within the time frame necessary for safe evacuation - normally minimal five minutes.

Fire behaviour of composites involves thermal degradation, thermal softening, fire damage mechanics that includes deterioration of mechanical properties and health hazards due to toxic matter that is released [249)]. How a composite behaves with fire depends largely on the matrix material [168)]. The epoxy matrix ignites readily when exposed to higher temperatures (>350 ^{0}C) at rather low oxygen content - the more so when the composite is delaminated - and epoxy has, among resins, one of the highest heat release rate values, which means that these materials contribute strongly to the growth and spread of fire. Thermal softening of the polymer matrix causes delamination cracking and hence a sharp drop in compressive strength. Carbon fibres are heat resistant but soften already at 150 ^{0}C and this reduces the tensile strength. Distortion, buckling and failure can occur at higher temperature - which reduces the load bearing capacity - but the fibres hinder rapid burn through.

Epoxies are among the worst materials for the production of smoke and soot and produce rather high amounts of carbon monoxide and carbon dioxide. Also the fibres can release hazardous substances - large amounts of highly contaminated respirable fibres - as will be discussed later. Epoxy resins are therefore not allowed within the cabin where phenolic resins are applied that have excellent resistance to high temperature - but mechanical properties of phenolics are significantly lower due to high voids content. Special measures have to be taken to guarantee safety of both passengers and crew and first responders who are often not aware of the dangers - being used to aluminium aircraft.

Carbon dust

Aluminium does not release harmful material when a plane crashes and catches fire. Epoxy produces toxic smoke as has been indicated before. Carbon fibres don't burn but do also pose a serious health hazard when the epoxy catches fire 249). When the epoxy burns away, carbon fibres become exposed and subsequent oxidation leads to break up of the fibre and the release of hazardous fibrils. Glass fibre composites do not have this problem and are therefore applied within the cabin.

As indicated before, composites involved in crash without fire can cause a problem with escape from the wreckage, because of possibly sharp edges from broken parts and shattered fuselage parts. However, airborne dust particles can pose a far bigger problem with escape and hinder first responders - in particular fibrous dust that is liberated through oxidation of exposed carbon fibres. These fibrils are sharp and can penetrate the skin and eyes and can be inhaled. Health hazards depend on their diameter and length and to what extend the fibres are contaminated with matter that is released from burning and smouldering matrix material 264), as will be discussed later.

Another aspect of potential risk with carbon dust is short-circuiting of electrical and electronic systems because carbon fibres are electrically conductive, affecting nearby power distribution lines, transformers, radar and electronic equipment 262).

Inspection

As indicated before, insidious damage is with composites normally much more widespread than anticipated from visual inspection, if visible at all. With all-composite aircraft inspection for hidden damage has therefore to be performed on a continuous base - but this is easier said than done. Inspection for insidious damage is a very complex issue because of the very large surfaces that have to be examined. Neither visual inspection nor tap testing - that will be explained later - is reliable for this purpose. Next to the skin, also the joint constructions have to be checked including numerous fastening points. Also the light protection systems have to be monitored. A wide variety of non-destructive test methods are available and emerging 174), but suitable field methods and procedures to deal with all anomalies are not in place yet - it is still a big question mark how to inspect the joints, fastener points and lighting protection system. Continuous problems with composite rudders involving Airbus have already forced regulators to step in, as has been discussed before. The best solution is to provide the aircraft with a health monitoring system. Boeing and Airbus are working on such systems, but this is a very complex issue and development is still at its infancy, as will be discussed later.

Repair

Because of limited damage tolerance all composite aircraft get more easily - and much more frequently - damaged than aluminium aircraft. What is damaged has to be repaired but cannot made new again, except through complete replacement of the damaged part. Such direct part substitution is, however, not feasible with very large one-piece sections. It is extremely difficult - if not impossible - to exchange a complete barrel section at an airport, not to mention at a remote airport. Also with large panels, replacement is not exactly going to be an easy job. This will surely reflect in insurance costs.

Methods that enable perfect repair - and inspection - are therefore essential for economical and safe long-term management of all-composite aircraft 4) - and are decisive for the future of all composite aircraft. But even with best repair, it cannot be avoided that the structural integrity of the composite structure is affected - the more so when the number of repairs increases over time as is to be expected because of composites' limited damage tolerance and when damage occurs repeatedly at sites near to each other - which cannot be avoided because certain parts of the aircraft are more vulnerable.

Repair of all composite aircraft is far more complicated than with aluminium aircraft - but composites are successfully applied for repair of aluminium aircraft where adhesively bonded composites patches offer many advantages over bolded repairs where often new rivet holes are required that weaken the structure through additional stress concentrations 364). Moreover, composite patches offer good mechanical properties with very good fatigue and corrosion resistance, can be easily formed in complex shapes and might save time with repair - patch repair is normally simple and fast with aluminium, contrary to composite structures where bonded repair is much more complicated because of necessary cleaning, drying and thermal curing as will be discussed later.

Much attention has been paid to repair of aviation composites lately 358) 139) 175) 347), but technology is still far from mature. Repair is different for sandwiched structures panels 408) and composite laminates 366). It has taken Boeing and its partners a very long time and enormous resources to try get acquainted with composite manufacturing, inspection and repair technologies - and they are still struggling in the production halls where all kind of facilities and expert advice is readily available. Inspection and repair in service is often much more complicated - even at specialized base stations - and it will take considerable time for engineers to get familiar with repair of all composite aircraft structures. Inspection and repair of all composite aircraft will become a time consuming and very costly affair, regardless great technological advances and expertise that will emerge and develop.

With composites different types of damage can occur during manufacturing, assembly, operation and maintenance - and during inspection and repair of the aircraft. Damage can be visible but will in most cases involve insidious flaws and defects that are non or hardly visible and accurate description of the damaged site can be rather complicated, as has been indicated before. Next to the composite laminate, damage can involve complicated joint construction and fasteners, openings for doors windows and hatches, substructure and contact with the dissimilar materials, lightning protection system, electromagnetic shielding, aerodynamics and possibly protective coatings for flammability and UV radiation - that can involve very differing types of damage which restoration require specific methods of repair. It is therefore very important to know the exact cause of the damage.

The manufacturer's inspection and maintenance manual must precisely specify the repair and inspection techniques and repair materials that have to be applied for the different types of damage and various parts of the structure including when to decide that a section is beyond repair – the Structural Repair Manual is going to be quite a book that will be frequently updated. Structural repair will undoubtedly cause rather long downtime and be very costly in most of the cases.

Experience

Last but not least - *lack of experience* - with aviation composites. As indicated before no doubt the biggest problem with all composite aircraft is that Boeing nor Airbus nor any other party or organization in this world - including the regulators - have any experience or recollection whatsoever with regard to all-composite civil aircraft at this scale - that is size and magnitude - nor with comparable applications even near to this scale other than blades for wind turbines 223), and it cannot be denied that in civil aviation safety is largely based upon long time experience.