6. NOT SUITABLE

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When Boeing decided for the all-composite 787, engineers from Airbus - who had far more experience with composites including the warning signs discussed before - were quickly to announce publicly that Boeing was pushing the envelope too far 282). *The 'cons' listed before, illustrate that Airbus had a point when they argued, back in 2004, that 'Unless they (Boeing) have discovered some new law of physics or some new manufacturing process that nobody in the world has ever heard of - and we know they have not - then they either will be sub-optimal, in which case they will make an airplane and it will cost them a fortune to do it, or they will come back toward the best engineering and manufacturing standards and build a plane with less than 30 percent composites'* 110)*. They couldn't be more right, but somehow Airbus made an U-turn - as was explained before - although no breakthrough technologies have emerged with composites since Boeing and before that Airbus decided for all-composite aircraft - except for the introductions of aluminum reinforced composites that are successfully applied with the A380. Before long Airbus' contention will prove to be correct - indeed - 'composites are just not good enough' or at least not suitable to be exposed to the extremely harsh conditions that apply to civil aircraft.*

Several of the cons listed before pose a safety issue, which is usually solved by adding weight - when the materials don't provide the required safety is has to be built into the structure. Composites appear to be much more sensitive to damage than aluminum, certainly so when externally exposed. This starts already with the manufacturing, when residual stresses and micro cracks cannot be avoided and more serious flaws and defects can occur that might pass inspection unnoticed. It is from these insidious anomalies that damage develops when stresses exceed certain threshold and lead to debonding and delamination and ultimately to crack development. Moreover, composites are in amorphous state, which means that they creep and can absorb moisture that strongly affects physical behaviour, crack initiation and crack growth and accelerate degradation. Also temperature has a strong effect on physical behaviour of composites. As has been indicated, even minor insidious damage can have significant influence on the structural integrity of the composite. But such damage is often very difficult to detect, proper mapping requires non-destructive testing, repair is complicated and the original structural integrity cannot be retained - what is achieved with repair depends largely on the skill of the repairperson. Little is known on how all this affects performance during impact, lightning strike, crash and fire - not to mention combined actions. This poses a real problem with damage tolerance that has also been adapted for all-composite aircraft.

Damage tolerance philosophy

Damage tolerance philosophy has been developed in aviation to try to define the maximum level of damage at which the material or structure is still suitable and safe for the intended application 207) *- where different levels can be set for the various parts of the structure. This requires that development of damage is carefully monitored at numerous sites, through inspection or malfunction, such that appropriate measures can be taken before the critical damage level is exceeded* 178).

In aviation, over a long period of time involving many tragic accidents 222), damage tolerance philosophy has gradually transformed into damage tolerance methodology 179) and this has led to the present unprecedented safety record that has been achieved with aluminum aircraft. Ranked at the top of damage tolerance capability is the aluminum reinforced composite structure applied for the upper fuselage of the A380, which offers damage tolerance features on both material- and structural level 180) 181), as will be discussed later.

Unfortunately, the ‘old’ design methodology is of limited relevance for composites because they damage and fail in ways very different from aluminium, how different has yet to be learned and the safety record has to be awaited for. What is known, is that damage tolerance is far more complicated with all-composite aircraft than with traditional aluminium aircraft, not only because composites get damaged so easily but can damage and fail in many other and different ways than aluminium and these failure modes can possibly interact - that is affect each other. This means that with all-composite aircraft a new or at least strongly revised damage tolerance philosophy has to be worked out and developed into a new damage tolerance methodology over time 176) 177) 139) - largely based on practical experience that has to be gained over rather long period of time to come.

For the moment the approach has to be based on results of physical testing that enable only a partial picture because it is impossible to include the many parameters that influence composite behaviour – not to mention ‘unk-unk’. Lack of experience and incomplete physical test results also hinder development and verification of models, so important with the development of new aircraft. Most worrisome is that composites pose certain thresholds that may not be recognized yet, are trivialized or just ignored.

Emerging ways out

Many laboratories around the world are working on projects to improve on composite properties - driven by the vulnerability of composites because of possible ingress of water and other liquids, breakdown by UV radiation, poor impact resistance, hard to detect hidden damage, problems with inspection and repair as well as poor impact performance, limited lightning strike protection, low crashworthiness and toxic flammability - and to ease on inspection and repair Some will be highlighted in brief later.

As explained in some detail before, properties of composites are determined by the type of fibre and the kind of polymer, their volume distribution, configuration, architecture and the curing cycle. Through careful selection, adjustment, additives and other inclusions is it possible to further modify these properties and even to provide composites with improved and new properties. A most interesting development in this respect, where the advantages add up for all properties, is reinforcement of composites by inserting thin layers of aluminium between the layers of the composite - such structural sandwich composites are officially called fibre metal laminates (FML) and are here treated as aluminium reinforced composites that will be discussed in brief later.

The problem researchers are facing is that most of time the improvement of one property goes at the expense of another and it has to be checked to what extend the improvement that is achieved in one field affects other fields - and whether application is worthwhile the effort, that is, not counterproductive. This makes research so expensive and time consuming. At a more advanced level nanotechnology, natural fibres and biomaterials are researched - amongst others. With nano composites, one of the biggest problem researchers are facing is to get the extremely fine additives properly divided throughout the composite - that is the resin - and there are serious health concerns, so have certain nanoparticles been observed to penetrate through healthy human skin. Natural fibres and fibre reinforced bio-materials are another important source of inspiration - trying to imitate nature - the paradox is here that plastics - the prime material researched to copy bio-materials - is not a natural material but a synthetic material. Some of these developments will be discussed in some detail later.

Impact performance with all-composite aircraft

Impact performance of composites has drawn much attention in recent years but only limited progress has been made. Composites' susceptibility to impact damage is still a mayor concern with applications in aviation 182) 183) 184)*. As one recent review puts it, 'Scanning three decades of information on the impact performance of polymer matrix fibre composites is a sobering experience.'* 156)*. But some progress has been made – composites are now used very successfully in crash surviving cells in Formula 1 doing a job that metals could not. Also composite helmets have contributed in dramatic way to safety, for example with helmets, but again be careful. 'If the helmet is visibly damaged (cracked outer shell, crushed or cracked foam liner or any other damage)* *or involved in a serious crash, don't use it. Damage to a helmet is not always visible! Some or all of the helmet's protective capacity is used up when impacted'* 352).

Impact performance is a major problem with composites in that these materials show poor impact response, the more so at higher temperatures and when the impact face is stressed or in vibration. Impact can cause serious delamination, even at low impact velocity. The reason for the low impact performance is that composites lack plastic deformation that characterizes metals. Composites behave more brittle and this means that permanent damage occurs above a certain stress level. The low transverse and interlaminar shear strength and the typical laminar structure adds to this behaviour. Impact response can be strongly affected when the composite is already damaged.

Present state of the art

Impact performance is an extremely complex material property that is not well understood. Impact strength is arguably one of the most important but less comprehended material properties This is an important area of research - certainly so when plastic composites are involved - that is hindered because impact strength can't be properly measured and researched since a proper test method is not available. Being not familiar with a problem often leads to taking refugee in modeling. So far it has proved to be extremely difficult - if not impossible - to simulate and predict impact response. In recent years engineers have gained much better knowledge about damage mechanics - numerical stress analyses are now routine and allows for more detailed study of impact performance

- but the many parameters that affect impact performance pose still an insurmountable problem with both physical testing and mathematical modelling. The number of variables that have to be taken into account to simulate possible impact conditions are far too great to include in any physical test program or mathematical simulation model - these models serve only for qualitative estimation.

Improvement - with composites, impact performance can be improved through newly developed toughened polymers, longer fibres, high strain fibres, controlled fibre matrix interface, addition of short fibres (whiskers), impact absorbing fillers and three-dimensional fibre architecture (stitching). The problem is that such measures normally go at the expense of other physical properties and can therefore be applied to limited extend only 184).

So is impact performance improved by strong bonding and tough matrices but such composites exhibit in general inferior fatigue properties to those with brittle matrices. High strain fibres are known to lower the modules. Too strong bonds can increase brittleness - hence decrease impact performance. Quantities of energy absorbing fillers that can be added to the composite are limited because they negatively affect other physical properties. Liquid rubber toughening is successfully applied with epoxy resins, but the amount of elastomers that can be added is limited because it affects glass transition temperature. Conflicting results have been reported regarding the improvement that can be obtained through stitching. Moreover, for a given impact, both toughened and brittle composites suffer about the same degradation in residual strength. Thicker laminate is in aviation only option with special parts of the structure - because of the weight penalty – but most often the only way out. With critical parts thermoplastic composites can be used as well as glass and aramid composites. Such materials provide much better impact resistance that thermoset composites, but also here at the expense of other physical properties. For example, aramid composites have a much higher impact absorbing capacity than aluminium but are low on compressive strength and absorb much water. Glass fibre epoxy composites provide good impact performance but have poor fatigue strength.

The present state of the art is that - when special measures are taken - with advanced theromoset epoxy fibre composites an impact absorbing capacity can be attained about equal to thermoplastic glass fibre composites, still far under that of aluminium, and this puts - should put - a limit to applications in aviation.

> *Impact improving additives*
>
> Thermoplastic composites are less strong but show significant better impact performance than thermoset composites and it is possible to improve impact performance of thermosets through thermoplastic toughening. It has been reported that blending of some 5% thermoplast with the thermoset increases fracture energy more then tenfold. Plasticizers are added to improve on brittleness with thermoplastics, but these cannot be used with thermosets because the modifier would exude out of the matrix during curing and accumulate at the surface. It is, however, possible to add a modifier to the epoxy that forms a separate toughening phase such that the intrinsic properties of the resin are retained. Liquid rubber toughening is achieved through chemistry in that extremely fine rubber particles form during mixing that disperse and are bonded to the epoxy matrix and hinder crack propagation - at micro level - at the crack tip. Optimum concentration of rubber is 10% to 15% when the impact strength is about doubled. To be effective the particles should not be too big, that is <5 micron and many other parameters have to be considered including formulation, processing and curing. But also here increase of toughness is accompanied by decrease of the modulus and thermal stability and increases the tendency for water absorption. Research is focussing in particular on improving the particle to matrix adhesion. Another approach is to add preformed rubber particles to the resin. This way particle size distribution is controlled but the composition of the rubber has to be modified to enhance chemical bonding with the matrix.

Fillers that are considered to improve on impact performance like alumina, silica and glass are extremely difficult to disperse in the polymer matrices and it has been found that these particles become easily debonded from the matrix during service - leading to failure of the composite - achieving the opposite of what is aimed for. Another most promising approach is nano reinforcement or nano modification of epoxies with nanoclay and carbon nanotubes.

Smectic clays - also called swelling clays - have a specific three-layered structure of extremely thin (~100 nm) sheets that are composed of aluminium and magnesium hydroxides. The problem again is the dispersal of these tiny clay nanoparticles. This is difficult because the inorganic particles are often hydrophilic (water absorbing) and the polymer matrices hydrophobic (water repellent). Special solvents are being developed to eliminate this thermodynamic barrier. Smectic clays exhibit extremely strong ion exchange and this makes it possible to modify the clay through simple ion exchange that enables the penetration of polymer molecules between the layers. Such modified clay can be easily dispersed in thermoset resins like epoxy that are than cured to become epoxy-clay nano composites. Research in this field has already shown that stiffness can be improved without affecting toughness. Furthermore, nanocomposites do reduce water and solvent permeability - hence the absorption of water and other liquids.

Nanofillers are also expected to improve on impact performance, but this is still emerging technology. Nano particles like silicon whiskers, nanoclay particles, silicon tubes and carbon nanotubes can be dispersed in the polymer matrix. Research focuses in particular on carbon nanotubes. These are light, exhibit extraordinary high tensile strength and elastic modules that make ultra-strong composites possible. Although dispersible, uniform distribution is also here still a critical issue and as always, problems will emerge that have to be solved when research becomes more real world. It can for example be imagined that the some tenfold difference in strength between these nano tubes and the fibre makes it very difficult to strengthen the polymers effectively.

To try to compensate for or to eliminate side effects altogether, research is also performed with hybrid blends of rubber, nanoparticles and nanoclay reinforced resin where first tests show encouraging results. But also this research is at its infancy and will take many years before such materials can be applied for practical purposes, if ever.

Lightning strike performance with all-composite aircraft

When an aircraft is struck by lighting, the aluminium airframe acts as a Faraday's Cage that shields the passengers and the crew from the large electric field outside the cabin and the electronic equipment from magnetic radiation - the aluminium structure provides a continuous conducting shell. Still, special measures have to be taken to ensure that the lighting current remains on the aircraft's external surface by providing effective conductive paths and shielding of the cables and other sensitive equipment and software through grounding. Any discontinuities in the conductive shell that hinder the free passage of the lightning current compromises the efficiency and can lead to fatal accidents - lighting that stops in an aircraft is deadly

> *Incidents involving aircraft struck by lightning happen frequently* 363) *but only some led to fatal accidents. Pan Am 707 crashed in the US when a fuel tank exploded after being struck by lightning in 1963 with 81 people dead* 187)*. In a similar way an Iranian air force 747 crashed in Spain in 1976 when 17 died* 188)*. Not lighting but a wiring short cut near the fuel tank is the probable cause of the explosion on a TWA 747 over New York in 1996 with 230 victims* 189)*.*

With all composite aircraft the composite shell is neither conductive nor continuous and provides no protection against strike and there is only limited volume of metal left in the aircraft for grounding and shielding of the electronic equipment. Special measures have to be taken to make the structure behave as a Faraday cage. Again, these measures add to the weight in significant way but it cannot be avoided that all composite aircraft remain vulnerable to lighting strike - whatever measures are taken, all-composite aircraft will never provide the lighting strike protection *obtained with aluminium aircraft, not even near. Regulations had already to be compromised to be able to certify composite aircraft - traditional aluminum aircraft are longer regarded bench mark.*

Lightning

At any given moment there can be as many as 2,000 thunderstorms active across the globe, which means more than 14,500,000 storms a year - or on average some 40 lightings strikes per second worldwide 185). Pilots always try to keep away from thunderstorms but an aircraft has not to fly in an electrically charged cloud to be struck by lighting. An aircraft can trigger lightning strikes - so-called 'bolts from the bleu' - up fifty miles from where the radar indicates precipitation 185). The U.S. Department of transportation has published extensive analyses of some 95 lighting strike reports 186) which indicates that on average a civil aircraft triggers a lighting bolt one to two times a year or about once very 1,500 hours in the air. Susceptibility to lightning strike varies with different aircraft depending on size, shape and speed and the airframe design and it appears that some pilots are better in avoiding lightning strikes than others.

Most dangerous is positive lightning that forms at the top of the clouds and make up 5% of all strikes - flash duration is longer and peak charge and potential can reach as much as 300.000 amperes and 1 million volts, ten times stronger than negative strikes that are charged from the ground. Most frequent struck are extremities such as the nose radome, wing tips and empennage.

When lightning strikes

When lighting strikes the composite structure is hit with great force when the lighting bolt attaches at the arc point - followed by the discharge of the lightning current that has normally a peak amplitude of 100 to 200 kA. The structure has to be able to carry this current unhindered from the initial attachment point to another extremity where it exits the aircraft, normally the tail. Not only extremities are subject to attachment. When the aircraft is struck by lighting in flight, it moves through the flash that has a dwell time that lasts typically for some 25 to 50 ms. During this time lapse the aircraft can move some 10 to 20 meters through the flash when the arc point can be swept back up to 15 m and reattach to the aircraft. This means that the flash then spreads over more arc roots that now describes an arc channel and no single point receives the full energy - and explains why not only extremities are struck by lighting – other parts are also vulnerable but normally at lower current. With aircraft a distinction can be made between *zone 1* - that has a high probability of a initial attachment, *zone 2* - that has a high probability of reattachment and a *zone 3* - that does normally not experience attachment but must be able to carry substantial lighting current.

Another phenomenon involves static charge that may develop during flight - again more so at composite faces because it does not conduct electricity. Static charge may result in electrical noise that can interfere with the aircrafts' electronic systems - and even hurt people when they make contact with the aircraft after landing before the aircraft is electrically grounded.

Measures to protect the fuel tanks from lighting strike

Most important is that electrical continuity is obtained and maintained throughout the structure of the aircraft - that is assurance of uninterrupted electrical connection between separate parts in a way that free passage of the lightning current is not hindered. This is extremely difficult to achieve, since each fastener, joint, fiber interface, panel edge and numerous other locations present potential electrical discontinuities that can create hot spots, edge-glow and sparks that can ignite the fuel and interfere with the electronic systems. Providing electrical continuity is undoubtedly a main drive for Airbus to choose for panel design with the A350 - that might give some if not total advantage in this respect over the 787 barrel concept, as will be discussed later.

To protect an all-composite aircraft from lighting strike requires a multi-layered approach as has been discussed before. Measures to protect the fuel tanks include sufficient thick skin to avoid hot spots, current return networks that enable the lighting strike to disperse immediately along the skin of the aircraft and special fasteners that transmit the current safely to the substructure without sparking and - most important - an electrical structural framework that involves as many metal parts as possible that are connected in continuous way to provide the for ground network. As a last line of defence the fuel tanks are provided with an inerting system.

Thickness of composite skin

Experience has learned that aluminium skin with a thickness of 2 mm provides acceptable protection for arc roots. This contrary to composites that can become heavily damaged at and in the direct vicinity of the attachment point, involving delamination and even breakage as has been discussed before. Also hotter hot spots can develop at the inside of the skin. Significant thicker skin might therefore be required at suspected zones with composites – at least 5 mm has been suggested 323) and it is also required that damaged arc points are repaired immediately.

Jointing

Next potential hazard area's are the joints and its interfaces that have to carry the current on its passage through the composite structure. Joints involve both composite interfaces and composite metal interfaces and can be mechanically fastened and adhesively bonded.

With adhesively bonded joints the glue line is usually dielectric. That hinders the transfer of the lightning current and causes voltage stresses across these joints. When the stresses exceed the joint's dielectric strength, the insulation will break down and arcing and sparking are then difficult to avoid. These adhesives can contain voids where the current tends to concentrate and this can lead to localized heating and even explosive expansion - and there is the possibility that magnetically generated high parting forces develop in the adhesive. Adhesively bonded joints can therefore not be used with primary structures - and this can pose also a problem with patched repair of composites as will be discussed later.

That leaves only mechanical joints for primary structures and these do also pose problems with lightning. The surface layers have usually a surplus of resin that does not provide good electrical contact that can hinder also here quick dissipation of the lightening strike current. High local current densities can develop at the joints between the skin panels and the aircraft substructure that tend to concentrate at the fastener points. With metallic fasteners highly conductive arcing is likely to occur when the current is unable to dissipate sufficiently quickly and when there is any gap between the hole and the fastener where currents can jump and trigger a spark.

Sparking

With sparking a distinction can be made between voltage sparking that is the result of dielectric breakdown and thermal sparking that consists of burning fragments or melted material thrown out of hot spots. The temperatures of both types of sparks are high and are potential sources of fire or explosion when near to a fuel tank. This means that any gap that can cause sparking in the vicinity of the tanks must be avoided, in particular gaps between skin fasteners and its hole. Special fasteners have been designed that are supposed to transmit lightning current safely to the substructure. Only real world experience will learn whether such claims hold. To be effective, these fasteners have to be spark-free fitted in the composite - and remain spark free fitted during the lifetime of the aircraft - in particular fasteners that penetrate the composite tank. Any gap between the fastener - head, shaft and bolt - and the fastener hole has to be avoided. That is not an easy – if not impossible - task, as is now also admitted by Boeing, as has been discussed before.

Any electrical component of the fuel system has to be insulated from the structure - in particular those present in composite fuel tanks. Inside the fuel tank, the fasteners have to be encapsulated with electrically insulating layers. Also any gap inside the fuel tanks that can possibly cause edge glow through spraying of electrons has to be sealed with a non-conducting material. Sealing is a meticulous job and the quality depends largely on the skill of the sealer - reliable inspection of all seals inside the fuel tank is virtually impossible - also discussed before. It is therefore preferred to protect the fasteners also along the skin, preferably with a conductive layer that is isolated from the fastener heads such that the current is dispensed over the surface of the aircraft. The conductive layer can also be connected with the fasteners in a way that a conductive path is provided that diverts much of the current away from the fasteners and that the current is shared between more than one fastener. Effectiveness is questionable. It is also possible to install the fasteners in a way that they transmit current safely to the inner grounding of the aircraft - but difficult to achieve with so many fasteners involved.

Conductive surface layer

With aluminium aircraft the metal skin provides normally sufficient means to safely disperse and divert the currents. With all-composite aircraft this is much more difficult to achieve. The composite skin can be provided with a conductive surface layer that extends about the entire outer surface of the aircraft. The conductive layer can be buried inside the structure as an internally bonded layer, or applied to the outside of the composite as an externally bonded layer on top of the composite skin - both layers can be connected to the ground plane that includes essentially all metal components in the aircraft. Ideally such layers should be attached with the composite in a way that they contribute to the strength of the structure – probably only possible through aluminium reinforcement.

Internally bonded conductive layers - are incorporated between outside plies of the composite prior to curing and involve expanded metal foil, metal grid or an interwoven wire fabric - electrically conductive stitching has been proposed 351). With such layers high electrical currents are driven into the skin when lighting strikes and these currents must be diverted. This requires a connected electrical path that transfers the current, but each joint and fastener presents a discontinuity as has been discussed before. Actually, several interconnected conductive paths can be created throughout the structure, which give currents way to leave the aircraft. The conductive layer can be isolated from the fasteners but also connected with selected fasteners - either to divert electrical current away form the fasteners or to permit current distribution between fasteners. However, such return network may not always dissipate sufficient energy away quickly enough - with the danger of arcing and sparking, in particular at the fastener points. Another concern is that with these networks it cannot be reliable predicted where current will go once the aircraft is struck by lighting. Dealing with such uncertainties, engineers tend to over design many areas of the structure and duplicate protections to try to provide acceptable lighting strike safety such at the expanse of much weight - but the net effect remains unclear, in particular to what extend the sparking threshold is or can be improved.

Interwoven wire fabric, copper grid and aluminium foil are widely applied with all-composite aircraft. Copper has an even greater resistivity than aluminum and is preferred with extremities and other critical areas. Specific parts or zones of the aircraft can be provided with either single or double layers of grid or foil integrated on the upper sides - possibly also on the lower sides - depending on the probability of lightning attachment. Application of such layers in the composite is complicated and time consuming, yet rather expensive. Efficiency has yet to be experienced but serious problems are already expected with these structures in service - as Boeing admits 357) 359).

So are the coefficients of thermal expansion of these materials incompatible with the resin and the fibres and yet sources of composite cracking due to differential expansion. The foil or grid has to be very accurately positioned on the outside of the composite lay-up prior to curing. Wrinkling can pose a serious problem with both lay-up and curing. Drilling of fastener holes may contaminate the fuel tank with copper - the drill can easily grad the wire and cause serious damage to the composite. Composites have low impact tolerance and the interior structure of the composite can get easily damaged in service including the foil, grid and interwoven fabric. It is very difficult to detect such damage - difficult to assess and even more difficult to repair - and may present a long-term ageing issue. Last but not least, these integrated layers add significantly to the weight but do not add to the strength - to the contrary they may weaken the structure to considerable degree due to the effects listed before.

Externally bonded conductive overlay - research is also ongoing on the development of composites with low - at least substantial lower resistivity that provide more conductive behaviour, shielding against magnetic induction and better electroctrostatic discharge. Overlays involve self-adhesive appliqué, films and strips that are applied to the composites' surface after curing and after jointing. The technology of externally applied bonded overlays was originally developed to replace painting with fighter aircraft. Paintless aircraft coatings can withstand forces up to 5g's and speeds up to at least Mach 1.8 and last up to 5 years compared to 3 years with painted coatings. Paintless technology applies self-adhesive films - essentially quite similar to Teflon. Appliqué shapes can be cut to follow complex curved contours. They are applied under pressure and can be peeled of just using hot high-pressure water. Joints and fasteners are covered and a surface is produced without wrinkles, tears, tenting and creases.

This technology has been proposed to provide composite surfaces of aircraft with an overlay of conductive material after curing - but is still in development and involves partly emerging technology. A first proposal involved a metal layer that is disposed directly on the composite surface and is then covered by a polymeric sheet such that layers are adhesively bonded to the composite substrate - providing a structure essentially similar to the composite with internally bonded conductive layer that is now produced in two steps 356). Not well thought through - may be - because the metal layer may place the composite substrate still in direct contact with large amounts of energy from lightning strike. This can however be simply avoided when the metal is spaced apart from the underlying composite substrate by a dielectric interlayer - that is with an appliqué where the metal foil is sandwiched between two polymeric layers and than attached to the aircraft surface 359).

Other possible improvements of appliqué that have been proposed include fibres that are dispersed in the top polymeric coating and provides the appliqué with anti static properties to avoid the problems with static charge 355). The appliqué can also be provided with extra dielectric strips along the substrate that allow for better insulation of the composite structure at critical locations - that is above fasteners fuel tanks and extremities where direct lighting strike is to be expected. A patterned metal foil has been suggested that supports the development of localized coronas during lightning strike - by providing a two dimensional lighting converter that transports the energy of a lightning strike above

> the substrates surface over a wide area, the current is this way supposed to be diverted along the surface via specific pathways such that critical areas are avoided [355]. Also the application of two appliqués has been proposed to be positioned on top of each other on the composite substrate [357]. The conductive layers of each appliqué can then be connected with the aid of surface conductors and it is claimed that this allows for deterministic control of both the current and the current path.

It is claimed that such externally bonded conductive appliqués provides much better lightning strike safety than internally bonded conductive layers - but that has to be awaited if ever applied. Serious question marks can however be raised with regard to claims that suggest strongly reduced manufacturing costs, reduced overall weight of the lightning protection scheme, weight savings obtained when the appliqué is also used as paint and improved repairability and 'supportability'. For the moment it appears that adaptation of appliqué technology to improve on fire strike performance of all-composite aircraft is a desperate attempt to solve a problem that can't be solved – that is for the moment.

'Conducting the composite'

The ultimate goal is the development of conductive matrix material that provides more conductive behaviour, shielding against magnetic induction and better electroctrostatic discharge. An obvious choice are fillers of conducting material. The problem is that these fillers have to provide continuity within the matrix . As indicated before, lightning produces an extremely strong charge that concentrates initially at one spot. Conductive particles that are insulated might get very hot and even explode - essentially in a way similar to voids. Continuity requires close packing with contact points between the particles and this can only be achieved when the packing contains sufficient particles that are uniformly dispersed throughout the matrix - particle size distribution is important. This requires relative high volumes that will affect other properties - this effect might be beneficial but can also cause problems.

> Various fillers are researched. The problem is to obtain electrical continuity throughout the matrix. That might need rather high quantities. Fine metal powders would do - silver, copper, nickel, iron and carbon, or fibres made of or coated with such metals - but most probably at the expense of too much weight to be considered for aviation composites. Carbon nanotubes poses extremely high conductivity and have in theory the potential to provide the composite with electrical conductivity - and many other interesting features are claimed with carbon nanotubes as will be discussed later. Also metallic nanostrands have been proposed 412). These are out of nickel or iron and have an average diameter under about four microns. The nanostrands cross each other to provide many current pathways in random orientation with electrical conductivity in all directions. It is claimed that such nanostrands may also provide additional mechanical strength and/or thermal conductivity. With nanomaterials it is however not yet clear what the implications are for production, manufacturing, weight and other physical properties - and of course costs. But it will be very difficult to beat monolithic aluminium and aluminium reinforced composites t where low resistivity comes for free along with other superior aviation properties - and have to be regarded benchmark in this field of development.

Inerting of fuel tanks.

As a last line of defence - and probably the only reliable one - an inerting system can be installed that keeps the spaces in the tanks above the fuel, the ullage, filled with inert nitrogen during the flight 195). For that, fuel tanks can be provided with on board inert gas generation systems - OBIGGS - a measure that has recently been ruled compulsory for the heated centre wing fuel tanks of all civil aircraft 194) as has been discussed before. Bleed air from the engines is filtered for nitrogen and pumped into the centre wing tank as the fuel tank empties, rendering any vapour fuels inert because the level of oxygen is too low to support a fire or explosion. FAA specifies that oxygen content in the ullage must be kept below 12% [248)]- 9% is to be preferred [324)] and systems are already available that attain lower values, for example GOBIGGS that do not use bleed air and allows for the system to run without engines operating [269)]. With the 787 the engines do not bleed air - and air for the inerting system is now drawn from inside the aircraft. Inerting is undoubtedly a major step forwards but ruling is not strict and this leaves possibility for problems - if not catastrophic failure. As has been explained before, FAA rules that inerting is limited to the heated tanks, no back up system is required and in case of malfunction the plane is allowed to fly for up to ten days with their lone inerting system inoperative, awaiting repair [272)]. Note that the metal wire mesh and foil are essentially also without back-up system and can get easily - hidden - damaged.

Electromagnetic shielding.

With all-composite aircraft lightning strike protection focus strongly on fuel tank protection. However, modern aircraft are stuffed with electronics and so on and one can wonder whether an aircraft - even aluminium aircraft - can still provide sufficient shielding to avoid short circuits or other malfunction when hit by lighting. Every lightning bolt generates a very strong electromagnetic pulse. Cables and wiring receive these disturbances like an antenna and conduct them directly to the equipment - it only requires a few volts higher than the regulator voltage to put the highly sensitive aircraft electronics out of action. In the worst case, this could cause flight control to fail. Aircraft need over voltage protection to prevent that the avionics' software can be affected. The paths of least resistance should therefore not include any vulnerable systems and control cables - and electronic flight instruments must be properly shielded from disruption by the intense electromagnetic field generated by lighting strike *363)*.

Even with the best Faraday Case certain boundaries should not be exceeded - some kind of 'Faraday threshold' that defines the maximal 'amount' of electrical and electronic circuits that is allowed for within a particular shielding structure. This is certainly an issue with all composite aircraft, but should also be considered with aluminium aircraft that are becoming ever more 'electrical and electronic dependent'. Composites offer no electromagnetic shielding, which means that with all-composite aircraft potential shielding capacity is reduced with at least 70% when compared with aluminum aircraft - at the same time is the more electric 787 stuffed with electrical and electronic equipment, probably twice as much than conventional less electrical aircraft. Problem is that it is not possible to quantify the amount of shielding material that is required to provide the necessary shielding capacity - this can't be tested nor modelled in any reliable way.

Physical testing

The discussion illustrates that providing all-composite aircraft with a reliable lightning strike protection system is a very complicated issue - as is realized by Airbus *'we have to develop new test procedures for lightning protection through which we can verify the suitability of both the hardware and software. This calls for using simulation at all levels of development - at the component supplier, at the system supplier and at the aircraft manufacturer responsible for specifying the avionic systems'* 191) However, with lighting strike physical testing is very difficult and it is even more difficult to model such events even with aluminium aircraft - and can't be relied upon yet with all-composite aircraft other than for qualitative orientation.

A complicated issue

On the one hand there isn't enough metal to divert lighting current away - on the other hand there is only limited metal available to shield the aircraft from magnetic induction and electrostatic discharge. The measures that can be taken to provide all-composite aircraft certain lighting strike tolerance are numerous, complex, extremely expensive, add significant mass without contributing to the strength, are most vulnerable to both mechanical and environmental loading, inspection is very complicated and the systems are difficult to maintain and to repair and when all applied do not provide the level of lightning strike safety set with aluminium aircraft - not even near.

With all-composite aircraft both the fuel tanks and the aircraft electronics remain vulnerable when lighting strikes whatever measures are taken and it seems that not much can be done to further improve on lighting strike performance - except adapting much more strict rules with inerting and even that will leave the aircraft still vulnerable.

With traditional aircraft lighting protection of is obtained through a continuous structure constructed out of some 50 tons or more of aluminium and other metals that provide a perfect Faraday cage. With all-composite aircraft a couple of hundred pounds of copper and aluminium that are inserted between the outer plies of the composite as mesh or foil are supposed to provide the aircraft with a Faraday cage structure – moreover the conductive network is typical highly discontinuous. It is not possible to test to test the continuity of the network, that can have been easily damaged during manufacturing, is damaged during drilling of the fasteners holes and with cut-outs and can't be properly restored when the composite structure has to be repaired.

It is therefore difficult to understand that regulators are now prepared to ease specifications for lighting strike protection - as has been discussed before - traditional aluminum aircraft are longer regarded benchmark. This is questionable behaviour as the above discussion illustrates - and now read this

> Suck
>
> Airbus draws attention that scientists *'are now working on ways to prevent lightning strikes from even occurring. Their intention is to actually "suck" an approaching storm out of the sky. Using a three billion watt laser beam, they are changing the air's properties so that it becomes as conductive as a wire. At the approach of a storm, the scientists intend to use the laser beam to establish a link to the cloud through which the lightning is to be discharged'* but *Airbus admits that 'as yet - this procedure appears to be both complicated and impractical. But, given time and further technology development, this may change'* 192) - that is, may be by 2050.

Crash performance with all-composite aircraft

Crash behaviour of all-composite aircraft is very different from aluminium aircraft. In a crash, composites have a strong tendency to fragment, to defibrillate and to scatter - producing sharp edged cracks and fragments. With a crash from great height the structure - or what's left of it - will probably not be recognizable as an aircraft. Tests have to show whether the composite fuselage poses a safety-issue in case of a crash landing. But from the material perspective it appears that with identical crash, survivability rate will be significant *lower than with traditional aluminium aircraft when no special measures are taken - energy absorbing systems are being studied that can be integrated in the structure, for example the keel beam* 202) *- but again, this will add to the weight.*

Miraculously, three planes crashed recently without fatalities - only minor injuries - a fourth crash caused unfortunately nine fatalities.

> January 17th 2008 a Boeing 777 crashed-landed at Heathrow when the engine failed seconds before landing. The pilots managed to make a 'controlled' crash-landing, unfortunately just meters short of the runway. Although heavily damaged all 152 passengers and crew survived the crash with only minor injuries. December 23rd 2008 a Boeing 737 carrying 122 passengers and crew veered off the runway at Denver during take off and hit a small building next to the runway to catch fire. Very heavily damaged 38 passengers were injured. January 16th 2009 an Airbus 320 crash landed in the Hudson short after take off - the airplane remained intact and afloat long enough for all 155 passengers and crew to leave the floating aircraft in orderly way. February 25th 2009, a Boeing 737 carrying 134 passengers and crew stalled just before landing at Schiphol at a height of about 150 m (1950 ft) to drop nearly vertically to crash 1 km short of the runway at soft ground, causing nine fatal casualties. The fuselage remained largely intact but movement of the interior in front of the cabin after impact caused 9 fatalities, among them the three pilots. Crashworthiness was astounding - the plane did not catch fire - with most people walking form the plane before first responders arrived at the scene.

Thanks to the very good crashworthiness of these aircraft - involving two 737s, a 777 and an A320 - 554 passengers and crew survived these crashes. It has yet to be awaited how all-composite aircraft are going to perform in such situations.

> As indicated before, Boeing is rather confident that crashworthiness will not pose a problem with all-composite aircraft 165). Three fuselage drop test onto a test platform have been performed by Boeing in 2007 involving composite

cut away sections of the fuselage, without its top *'to account for the missing top structure (called the crown), additional braces, supports and ballast were added to simulate the mass of the airplane and match internal loads,'* and *'the half barrel and the platform were instrumented so we could measure the results'* 348). No details have been made public by either Boeing or FAA - except that *'Boeing was not able to comment on how the composites held up compared to aluminum, nor.....to comment on the results of the test or how they tested ......we're still analyzing our results, but initial indications show the test was successful and achieved many of the goals intended'* 348). Later, somewhat more specific, the test *'was a success matching computer predictions'* 228). Indeed it takes Boeing quite some time to perform the analyses - these test were performed two years ago, August 2007 404).

It appears that with the certification of the crashworthiness of the 787, Boeing and FAA almost fully rely on computer modelling *'to cover every possible crash scenario'* 328). May be that this scenario also covers that whistleblower who went public in 2007 and claimed, among others, that the all-composite structure of the 787 is not near as crashworthy as that of a comparable aluminium structure 328) - vigorously denied by Boeing *'we wouldn't create a product that isn't safe for the flying public.......we fly on those airplanes. Our children fly on those airplanes'* 328). Then why the secrecy - and think of all those proud Boeing employees who took their children to the roll out ceremony back in 2007 were they were told by their fathers that 'this baby is going to fly in two months'.

Airbus expressed a more cautious view in 2006 *'to date, all the development work undertaken on either side of the Atlantic up to now has been on metallic structures. With aluminium, engineers know exactly how it behaves in a crash scenario, and we certify the fuselages in similar way from the outset. However, from* *testing performed with all-composite aircraft so far, it appears that engineers do know that it does not react in the same way. In fact, we do know that due to the lack of absorption of energy it will introduce into the passenger much more Gs and loads, compared with when a metal cabin structure deforms on impact. I am not saying we cannot solve the problem, but presently it is uncharted territory'* 111).

With crash behaviour of all-composite aircraft also toxic flammability and heat transfer characteristics have to be taken into account. As was pointed out before, composite scatter in a crash landing and when the scattered composites catch fire significant quantities of dense toxic smoke and respirable carbon fibres may be released, which pose a safety issue not only to passengers and crew who are severely hindered when they try to escape, but also to first responders and can even affect the airport and surroundings - not to mention when a crash happens in a densely populated area - as will be discussed later.

Fire performance with all-composite aircraft

FAA safety regulations that apply to aluminium aircraft dictate 'that passengers must be able to escape a large, wide-body aircraft within five minutes of a crash landing without being incapacitated, injured or hindered by heat, toxic fumes or smoke released from combustion of the cabin materials' 168)*. The intention is that these regulations should also apply to all-composite aircraft, but this will be very difficult to achieve.*

The FAA recognizes that composites behave different with fire than aluminium - *'Conventional aluminum fuselage material does not contribute to in flight fire propagation'* [243] contrary to composites where *'the fuselage cannot be assumed to have the fire resistance previously afforded by aluminum during the in flight fire'* [243]. The FAA also draws attention that with in flight fires with aluminium aircraft, the thermal-acoustic insulation provides a path for flame propagation and fire growth - *'incidents revealed unexpected flame spread along the insulation film covering material of the thermal/acoustic insulation. In all cases, the ignition source was relatively modest and, in most cases, was electrical in origin'* [243]. Ample reason for the FAA to impose special conditions that require that - *'the 787 provides the same level of in flight survivability as with a conventional aluminium fuselage aircraft'* [243] - with the remark that *'Factors in fuel tank survivability are the structural integrity of the wing and tank, flammability of the tank, burn-through resistance of the wing skin and the presence of auto-ignition threats during exposure to a fire'* [244]. To gain better insight FAA has asked the *International Aircraft Systems Fire Protection Working Group* to compare flammability of aluminium and composite fuel tanks. First results that will be discussed in some detail later, show that behaviour is very different indeed, as was to be expected. Although research is still ongoing and much is still far from clear, it appears that the *'FAA has just begun studying the effects of composite materials on fuselage and fuel tank safety, but the airplane was certified by the FAA months ago'* [258].

The FAA recognizes also that composites burn and that burning composites can emit dangerous matter [248] and specifies that - *'resistance to flame propagation must be shown, and all products of combustion that may result must be evaluated for toxicity and found acceptable'* [243] - it has to be awaited how acceptability will be interpreted.

Fuel tank

Civil aircraft have normally several fuel tanks. The main fuel tanks are in the wings. Additional fuel tanks can be placed in the centre wing box and in the tail part. The fuel in the wing tanks and in the tail is in direct contact with the outside skin and is more affected by the surrounding temperature. In flight temperature in the wing tanks can drop to -50 C. Fuel in the inboard tanks has a much higher temperature due to heat transfer by the environmental condition system. The fuel-air ratio in the ullage increases with temperature - is actually 20 times greater then when the fuel is allowed to cool naturally to ambient temperatures at 30,000 ft. This means that the heated tanks are at greater risk to contain a flammable mixture 353).

Special conditions target the safety of the fuel tanks in particular and take into account flammability of fuel vapour in the ullage 243), burn through of the composite tank 244) and possible damage of the tank by tire burst debris 247). These special conditions cover also lightning strike protection. In addition all heated tanks have now to be provided with a fuel inerting system 255), as was discussed before.

> Several accidents happened in the past involving explosion of the fuel tank 254). A 727 of Avianca departed from Bogotá in 1989, while climbing a bomb detonated on board, igniting fuel vapours in an empty fuel tank causing 107 fatalities 256). The centre wing tank of a 737, operated by Philippine Air Lines, exploded while taxiing on the ground in Manila in 1990, with 8 fatalities 250). The explosion mid air of the centre wing tank of a 747 operated by TWA, 12 minutes after take off from JFK in 1996, with 230 fatalities, was referred to before 252). The centre wing tank of a Boeing 737 of Thai Airways exploded in Bangkok, 2001, half an hour before scheduled take off, with one fatality 251). In 2006 the left wing fuel tank of a Boeing 727 of Transmile Air Service exploded in

Bangalore while being towed on ground, with no casualties [253)].

These accidents all involve Boeing aircraft, Airbus has so far not suffered a fuel tank explosion, but the FAA *'concluded that Airbus jets remain [also] vulnerable'* [257)], a view supported by research of Sandia [254)].

Also fuel leaks following penetration or rupture of the lower wing by fragments of tires have caused accidents in the past [372)]. In one incident, in Honolulu, Hawaii, a tire on a Boeing Model 747 burst and tire debris penetrated a fuel tank access cover, causing a substantial fuel leak. Takeoff was aborted and passengers were evacuated down the emergency chutes into pools of fuel, which fortunately had not ignited. After a subsequent Boeing Model 737 accident - in Manchester, England, 2000, in which a fuel tank access panel was penetrated by engine debris - the FAA ruled that fuel tank access panels must be resistant to both tire and engine debris. An extensive test program was executed XXX). In another event in 2000, on the Concorde airplane, an unanticipated failure mode occurred when tire debris impacted the fuel tank. The initial impact of the tire debris did not penetrate the fuel tank, but a pressure wave caused by the tire impact caused the fuel tank to rupture. Regulatory authorities subsequently required modifications to Concorde airplanes, as has been discussed before. Concorde experienced tire debris damage earlier, as was discussed before.

Aluminum fuel tank

Aluminium wings and fuel tanks have the ability to withstand post crash fire conditions. According FAA, aluminium fuel tanks greatly reduce the threat of fuel explosion for the following reasons [244)]. Aluminum readily transmits the heat of a fuel-fed external fire to fuel in the tank, which means that the upper flammability limit in the ullage is driven rapidly above the auto-ignition temperature prior to burn through. Aluminum also dissipates heat adequately across fuel wetted tank surfaces so that localized heat hot spots do not occur. And the heat absorbing capacity of aluminium and fuel prevents burn through and wing collapse - and this provides a time interval for evacuation. Based on these findings, the *Aircraft Systems Fire Working Group* compared composite and aluminum fuel tanks 258).

Fuel tank fire resistance

As to be expected, it was found that aluminium panels are effective in transmitting heat in transverse direction and are very effective in convective heat transfer to air, in particular in moving air stream. When exposed to heat, in flight airflow provides sufficient cooling - 500 to 600 F at 200 mph - to prevent burn through of the aluminium panel but substantially less cooling is obtained at ground conditions when the panel heats up gradually and burn through can occur when the temperature of the aluminium is sufficiently increased - during the test after some 15 minutes at 1220 F. Composites do not effectively transfer heat in transversal - in the plane - direction but do transmit heat in normal - through the thickness – direction, although at significant lower capacity than aluminium panels. When exposed to heat, topside temperatures of the composite panel peaked 600 F at ground conditions. Compared with these results, in flight topside temperature was 200 F lower at 200 mph and 350 F lower at 350 mph. The composite panels did not burn through - the resin is flammable and is consumed on the panel surface but it was found that the exposed fibres act as a fire blocking layer and prevent further damage to the interior of the panel 259). Prior damage to the composite panel did not alter fire behaviour.

Fuel tank flammability

Composite fuel tanks appear to be more flammable than aluminium tanks because of different thermal behaviour, in particular heat transfer and heat absorption capacity. As explained before, aluminium is highly thermally conductive and composites behave more as an insulator. This affects conditions in the tank, in particular the temperature and fuel concentration in the ullage above the bulk fuel, which decides flammability 246).

On the ground, flammability drivers are the surrounding temperature and heating of the top skin by sunlight in particular. Bulk temperature remains low when the temperature in the ullage increases, except for the top layer of the fuel that heats up causing evaporation of the fuel. This means that in a composite tank the ullage reaches higher temperature than in an aluminium tank due to the higher heat absorbing capacity of the composite. No surprise therefore when the FAA reports that *'testing shows large increase in flammability with composite wing tank skin not seen with aluminium skin when heated from top at ground conditions'* 245).

In flight, flammability drivers are decreasing pressure and lower temperature and a spike occurs when the when the plane gains attitude - first the pressure decreases causing evaporation rate to increase followed by rapid cooling caused by cold air flow that triggers rapid condensation. According FAA tests, temperature drops faster in aluminium tank and *'significant increase in both ullage temperature and flammability are observed with composite as compared with aluminium skin'* 245).

This explains the driving force behind the decision by Boeing to install fuel inerting systems in all the fuel tanks of the 787. With composites the wing tanks are probably more vulnerable than the centre tanks, as also Boeing admits *'If the*

787 wings were aluminum, rather than composite, Boeing probably would have elected to have a fuel-inerting system for only the centre fuel tank' 195). But inerting is only effective when seen as an essential element of layered safety inerting and not, or to a much lesser extent, when it is seen as an enhancement to safety as is presently the case.

First conclusions

It was concluded that composite fuel tanks are significantly more flammable, both at the ground and in flight 245). Aluminum cools much better in flight and composite panels are more burn through resistant at ground conditions 259) - but aluminum does hold long enough. However, while retaining stiffness, a composite panel gets hotter and gives of gas when exposed to live fire, which gas is flammable and contains hazardous and toxic matter 259), as explained before. This poses a serious safety risk - both in flight and at the ground - how serious illustrate the following accidents.

> October 17th 1990, a RAF Harrier GR5 crashed in a field on the island of Moers in Denmark - the pilot escaped with minor injuries. There was an intense fire that was dealt with by the local fire service. The structure was about 0.6 tonnes out of carbon fibre composites and the wreckage was spread over a distance of 250 m with strands of composite material spread over a cone shaped area of 70 m. The RSU crew wore goggles, ori-nasal masks and filters to give respiratory protection and they sprayed the site to damp down the dust - but soon suffered respiratory problems, sore throats, eye and skin irritation and apparently ran away from the site – and later had rapidly increasing discomfort with breathing - caused by the vast amount of airborne dust that was released from the burnt

composite material within the crater [268]. The site was temporarily evacuated and the crew that recovered the wreckage had to wear full-length chemical protection suits and upgraded respirators.

January 9th 1997 another Harrier encountered a problem on take-off for a proposed low-level training flight and crashed back onto the runway at RAF Laarbruch, Germany. The aircraft crashed inverted and was destroyed by an intense fire, even though fire crews were on the scene immediately and extinguished the blaze within two minutes. This is what eye witnesses later reported when the recovery team arrived *'The Fibres that float up with the smoke just clog your lungs for life....all groundcrew ran away from the crash site and site guards had to have medical tests afterwards.... the runway was closed for two weeks while several dinky little hangar sweepers were written-off gathering all the Carbon Fibres from the floor'. 'The fibres do not just clog your lungs, they are not degradable they are hard, sharp and unremovable, they literally shred your lungs from the inside out with their movement.... the SGT in charge lost something like 40% lung capacity over 6 months and the rest of the poor beggars faired no better...after that it was full suits and masks to prevent it happening again.....'* [265].

August 2nd 2005 an Airbus A340 - some 28 tonnes out of composite - crash landed at Toronto airport [261]. All on board were evacuated with minor injuries. During the escape, a major fire had started under the plane. Unburned fuel collected under the aircraft and reignited several times before finally being extinguished. Because the aircraft had stopped moving before the fire commenced respirable fibres spread only 100 to 200m also helped by a shower of rain. Clean up involved the removal of over 200 tons of contaminated earth, ash and debris and required the use of respirators for all those working at the crash site – during which activities the landing strip had to remain closed.

The above discussion fully supports the view expressed by the Aviation Safety & Security Digest *'So there is an interesting, mortal choice here: the aluminum panel can burn through, admitting more oxygen to feed the fire, but the composite panel, while retaining stiffness, gets hotter, smokes and gives off a flammable gas, both of which can kill occupants. The results are preliminary, but they do suggest that more must be done for occupant survivability in a composite fuselage than an aluminum one. An airplane with a composite structure that's on fire will maintain integrity, but the inside of the cabin, absent smoke hoods and fire suppression, could well become a lethal inferno before the aircraft can land and airport fire and rescue squads could come to the rescue'* 258).

Carbon fibre dust

As explained before, carbon fibre dust poses a major safety issue. Fibres with diameters < 3 micron and length < 80 micron are respirable and penetrate deep in the long - where fibres with length < 15 micron are cleared from the lungs by cellular activity but fibres between 15 micron and 80 micron remain in the lung 248).

The health risks associated with carbon fibres exposure are not clearly understood - but research in this field that focuses on such materials as asbestos and glass fibre suggests that also respirable carbon fibres may lead to pathological effects such as pulmonary fibrosis that can cause mesothelioma and asbestosis and increase the risk of long cancer 263). The FAA published a comprehensive study that deals with the health hazards of combustion products from aircraft composite materials that concludes that *'the incineration of external structural aircraft components results in hazardous conditions... for aircraft cabin* *occupants...[and] for fire, rescue personnel and investigation and recovery teams in the immediate postcrash situation'* [248]. It is therefore difficult to understand why FAA nor Boeing and Airbus - spending tens of billions on development of all-composite aircraft - did not involve themselves with this most important safety aspect.

Virgin carbon fibres that have not been exposed to fire have diameters typically between 5 and 10 micron and studies do not provide adequate evidence of fibrosis or carcinogenic effects [267]. Finer fibres can be produced when composites are cut and drilled and prepared for repair. Significant finer fibres are released when a carbon fibre is exposed to fire. When the resin burns of, the carbon fibres are exposed to turbulent oxidizing environment that causes them to break up into much smaller needle like and fibrillated fibre particles with diameter typically 2 to 3 micron and length < 80 micron, that are respirable [271] - and are not cleared from the lungs at later stage. The fibrils are often partly broken and split - essentially in a way wood brakes up - pose extremely large specific surface and are of irregular configuration and texture. They are highly electrical conductive and have a very strong affinity for the highly toxic and hazardous dirt that is released from the burning epoxy matrix - smoke that contains combustion gases and soot from incomplete combustion that contaminate the fibrils. The hot fibres carry the highly toxic soot particles into the skin, eyes, and wounds and very deep in the lungs and hinder escape from a burning aircraft.

To date, no toxicological studies have been conducted to assess health effects of inhalation of contaminated carbon micro fibres released in fire and of possible synergistic interaction between the various combustion products - PAHs, nitrogenous aromatics and phenolics that are known mutagens and carcinogens in animals [248)]. Research in this field by the *Defence Evaluation and Research Agency* (UK) had to be stopped when the *Civil Aviation Authority* did not make additional budget available [261)]. But based on research with other fibres, health hazards with respirable contaminated carbon fibrils most probably include damage to tissues, lungs and other organs, possibly leading to cancer [264)].

Also first responders face such exposure, but they have at least the possibility of protecting clothing [266)] - not so the passengers and not so the public when the plane crashes in or near residential area. Site cleaning requires also special measures - as was indicated before - but can pose a problem when released micro fibres are carried by the fire plume and disperse downwind in the atmosphere contaminating vast areas [271)]. Possible interference with power grid and electronic equipment because of the electrical conductive nature of the fibre dust was pointed out before [270)].

Fire fighting with all-composite aircraft

Boeing has informed the airport authorities at Everett, WA's, Paine Field, where the 787 will perform its flight testing, that there isn't any effective difference between a composite airplane and a traditional one. According Boeing 'the 787 will be as safe, or safer than, today's airplanes' [325)] *or more specific 'Each new generation of aircraft tends to be safer than the generation that preceded it'* [340)]. *Let's have a closer look.*

According Boeing tests performed with composite materials used for the 787 show that these do not propagate an in-flight fire, that the fuselage skin is an excellent fire barrier and resists flame penetration far longer than an aluminum fuselage, that the toxic gas levels produced in a post-crash fire scenario are similar for both a composite fuselage and an aluminum fuselage and that there was no prolonged burning or re-ignition of the composite skin after tests were completed [349)]. It is not known how these tests were performed – no details have been made public. But what is known, is that Boeings' findings are in sharp contrast to extensive research performed by the Australian Government - cited before [166)] [166)] - which results are completely in line with what happened when a B-2 bomber crashed February 2008, which accident will be discussed later.

FAA has published some test results on flammability of the composites that are applied with the 787. Actually basic properties were tested that should have been available and supplied by Toray already a long time ago. The effect of oxygen, although regarded *'an important factor'* and the influence of fuel were not examined. Regarding flammability test concentrated on the resin - *'the properties pertain to the characteristics of the resin material as the carbon fibres do not generally burn'*. It was noted that *'the carbon fibre can also oxidize under high temperature conditions, and this was observed even at low heat fluxes'* but this was not further researched. The test showed that resin material vaporizes which produces internal pressure in the composite causing swelling *'to over twice its volume and the porosity after burning is about 65%'* and it is recognized that this affects physical properties. However, the strength of degraded material was not addressed - yet the report maintains that *'the use of a carbon composite for aircraft construction can have advantages over aluminum. For example, aluminum will melt at 660°C in large fires. Typically, for a composite material, the degradation temperature to cause burning is 300°-500°C, but it will maintain structural integrity during burning'. 'The fibers create an insulating, char-like structure that causes a reduction in the internal heating and consequently the burning rate drops in time. As the burning* *rate drops, extinction can naturally occur due to insufficient heating. As is common of charring materials, external heat flux is required to sustain burning and flame spread'*. These 'findings' are however not substantiated by the tests here performed and are not in line with real world conditions.

Real world conditions

Indeed, both these results and the finding of Boeing are in sharp contrast with what happened when a US Air Force Northrop Grumman B-2A bomber - some 80% out of mainly carbon fibre composite - crashed on the runway in Guam February 23rd 2008, shortly after take off, fortunately with no casualties. Boeing was subcontractor on the B-2 program that provided a source of know-how applied with the 787 – which was not particularly appreciated by the US Government at that time 405).

On the runway, just after take off the pilots lost control and were able to safely eject before the plane crushed at the runway. The plane contained more than 20,000 gallons of fuel that burst in flames. With an aluminium civil aircraft it takes with such crash only minutes to knock down the exterior fire and some 10 to 15 minutes to extinguish the interior fire. With the B-2 the fire department had water on the fire within 3 minutes after it started and they kept pouring water. The aircraft burned for 4 to 6 hours and smouldering and intermittent flaming at random locations across the aircraft and deep-seated smouldering combustion continued for approximately 24-48 hours. Some 83,000 gallons were needed - when available they had poured more - where an aluminium aircraft would require typically some 10,000 gallons 350).

It appears that the fire went through four distinct combustion stages. Combustion of the fuel took about 20 to 30 minutes when fireballs can create flame temperatures in excess of 2000 F, followed by flaming combustion of the composite structure that transitioned to intermittent flare up at random locations across the aircraft for some 4 to 6 hours. The inboard and outboard wing assembly, wing tips, leading and trailing edge showed signs of thermal exposure of at least 1700 F - the centre body at least 1200 F. Smouldering and intermittent flaming at random locations continued until 48 hours into initial response. After 24 hours cool down was taking place through the composite thickness still with indications of internal deep smouldering and it took in total 48 hours to reach the final cool down stage, still with a hint of light smoke being released. The lengthy response required trucks to leave the scene to re-supply, interrupting the suppression or cool down process, allowing the heat to continue to penetrate and burn through thickness, layer by layer 350).

Valuable lessons

Valuable lessons have been learnt. Most important, that - contrary to the test result obtained by Boeing who maintains that *'The 787 composites don't act the same as the composites in the B-2'* 349) but provides no details - the composite structure adds fuel that propagates the fire, that the composite structure is not an excellent fire barrier and that flame and heat do continue to penetrate through the thickness for up to 24 hours, that with composites vast amounts of toxic gas levels carbon fibres are produced in a post-crash fire scenario where an aluminum structure produces none and - that there is hugely prolonged burning and re-ignition and smouldering of the composites that can continue for up to another 24 hours - which means that a fire that is knocked down with an aluminum aircraft in some 15 minutes can take up to 48 hours to extinguish with an all-composite aircraft.

The accident with the B2 confirmed the conjecture that composite aircraft fires differ completely from aluminium aircraft fires. In particular the length and intensity of the fire and the amount of water needed were probably unexpected to the fire department involved, but not to people familiar with composites. Heat continued to penetrate and burn through the thickness - layer by layer - and cooling and flame suppression occurred in similar way. This requires a totally different approach. Vast amounts of water and many more trucks must be readily available at all airports. Fire fighters have to consider composite thickness and locations with large volumes of composites like the wing box and the keel beam. New fire fighting equipment is needed, including tools to cut, move and pry the composites as well as instruments to detect deep seating smouldering. Fire fighters have to be informed that it more difficult to cut and drill through aluminium reinforced composites applied with the A380 than through traditional aluminium. Plain composites require again a different tackling. New techniques have to be developed to deal with the extremely toxic smoke and airborne fibres. All this requires that fire fighters have to be specifically trained for composite aircraft fire - moreover, the length of time of the fire requires that many more fire fighters may have to be deployed – doubling of the crews at airport might be appropriate. Last but not least, all-composite aircraft can also crash in residential areas.

All this is set in motion by the decision of aircraft manufacturers to go all-composite but just ignored the problem. It is really appalling to read that FAA maintains that environmental and fire fighting issues are beyond its scope of certification *'the concern raised regarding fire fighting and potential environmental* *ramficatitions of composite airframes are not airworthiness issues'* 349). Nevertheless, these issues will have far reaching consequences, as one respected specialist puts it - *'the dangers are so great that the entire 787 program should be cancelled'* 349). Or can composites be made more fire resistant - in a way that they comply in practice with the results obtained by Boeing at their test facilities.

Fire retardant additives

Fire resistance can be improved with additives 184). Conventional flame-retardants include inorganic fillers. Non-toxic metal hydroxides are for example used to obtain smoke reduction. To be effective rather large quantities have to be added which affect mechanical properties. Halogenated flame retardants are used that act as gas barrier and promote char formation which both retard flame. These chemicals do however release toxic gases and pose a health hazard. New developments in this field focus on phosphorous substances. The presence of phosphorous helps to form layers of char on the burning polymer, killing the fire. Research has shown that certain phosphorous agents are very effective flame-retardants and release less toxic gases and smoke. Phosphorous agents may, however, affect curing behaviour of the resin and hence the mechanical properties of the composite. New phosphorous chemicals have been proposed that exhibit further improved flame retardancy and enhanced toughness. Nanoclays have also been investigated and found to both stabilize and reduce flammability also through the formation of char. They do not release toxic gases and improve on the mechanical properties - on toughness in particular as has been discussed before. Unfortunately they are inadequate on their own but in combination with a conventional flame retardant very good results have been obtained and it has been shown that the amount of conventional retardants can be significantly reduced when relative small amounts of nanoclay are added. But how do such combined additions affect physical properties is not known yet. For the moment it appears that coatings that provide a fire screen that retard fire spread offer the best available solution – although with limited effect and again with significant increase of the weight.

Damage tolerance with all-composite aircraft

With aluminium aircraft damage tolerance comes largely 'for free' when compared with all-composite aircraft - even 'more for free' damage tolerance can be obtained with composed aircraft, in particular through the application of aluminium reinforced composites that will be discussed in brief later. Lightning strike and impact do not pose real problems with aluminium but appear unsolvable safety issues with composites. Contrary to aluminium that is not flammable, composites add effectively fuel to the fire, cause long fires when large quantities of hazardous substances are released. Crashworthiness is not known with all-composite aircraft but will probably never provide the safety achieved with aluminium aircraft. Last but not least, with composites the affect of numerous material properties is not understood when exposed long time to the extreme conditions that apply to aircraft - modelling, so important with design of aircraft is with all-composite aircraft still emerging technology. Most worrisome with all-composite aircraft is that damage tolerance combinations of different types of damage have to be considered - here called damage tolerance arrangements that have not been studied in any detail yet.

As has been discussed before, ignorance caused the accidents with the Comet, Concorde and Columbia. Learning from history there is serious reason to worry when Boeing claims that '*The composite fuselage will be so strong that if there is no visible damage, no repair will be required*' 14) and Airbus claims that '*if damage cannot be seen the aircraft can be safely flown with that damage for the remainder of its time in service*' 205). As the word says, hidden damage can't be seen, but can involve rather widespread delamination or other insidious defects, several delamination sites near to each other, damaged lighting strike grid or foil, broken fasteners and so on. These won't do much harm with aluminium aircraft but can be fatal with all-composite aircraft. Before making such statements let's wait for experience - the first all-composite aircraft has yet to fly.

Wide spread damage

With all-composite aircraft damage may not be visible but can involve many different parts. These may not pose a problem on its own but can cause a serious safety issue through possible interaction or collective action involving more damage sites. With multiple site damage even nearby located similar hidden damage sites might cause problems and more so when different types of damage are involved. With all-composite aircraft multiple site damage can involve delaminations at nearby locations. Also involved might be manufacturing flaws, broken fasteners and damage to parts of the lighting protection system to mention a few - which typically do not pose serious problems with aluminium aircraft. But also with aluminium aircraft problems occurred unexpectedly. The accident with Aloha flight 234 in 1988 cited before was caused by multiple site damage when several fatigue cracks joined in the aluminium structure and broke through the crack arresters that were in place to prevent this, a phenomena until then not recognized in fracture mechanics, now called *wide spread damage* 206). Interesting enough, the Aloha incident has pushed the industry to speed up the development of aluminum reinforced composite structures, designed for high damage tolerance performance and low weight at the same time. This topic is discussed further in a following section.

Damage tolerance arrangements

Much more so than with aluminium aircraft, all-composite aircraft are prone to combinations of possible damage modes, and such *damage tolerance arrangements* have to be seriously considered. All-composite civil aircraft are, for example, most vulnerable to combination of impact and lighting strike – again not a problem with aluminium aircraft. Even with the most advanced lighting protection systems in place - including fuel tank inerting - such arrangement can lead to catastrophic failure, essentially in a way similar to the accident that destroyed the Space Shuttle Columbia. Here it could not be avoided that an impact of a piece of foam that broke loose from the external fuel tank during take off damaged one of the reinforced carbon-carbon panels that protect the wing edge - unfortunately at a critical site as was explained before. There was ample time for inspection in space but this was somehow refused and this ignorance led to the accident when the structure became overheated during re-entry. But most important was that repeated damage to the heat protection shield was ignored for many years. It appears that 'widespread ignorance' already starts to creep in with all-composite aircraft.

> *Impact - lightning strike arrangement*
>
> *An all-composite aircraft counters heavy turbulence during a storm when struck by large 50 mm hailstones. Several high tech titanium skin fasteners get damaged at a critical location near to a fuel tank together with it the copper foil surrounding these fasteners, creating exactly the non-conductive path and gap that were tried so desperately to avoid. Adding Murphy's Law, the inerting system malfunctioned already for some days and was to be fixed in three days - no nitrogen in ullage. Then lighting strikes. No window of opportunity to avoid disaster, whatever damage tolerance methodology in place. That's the way real accidents do happen.*

Another obvious damage tolerance arrangement involves a survivable crash when the composite structure catches fire.

> *Crash-fire arrangement*
>
> *With traditional aluminium aircraft epoxy composites have been abandoned from the cabin interior - with all-composite aircraft the cabin is now completely surrounded with just*

> *such composites, that are also used for the wings, fuel tanks and much more. Crashworthiness has to be awaited but might be much less than with aluminum aircraft. Don't count on the ullage inerting system with a crash - when it cannot hinder the plane to catch fire or a fuel tank to explode. How to escape from a partly crumbled environment with sharp edged broken composite panels, some hot softened plastic sticking to skin, hands and clothes, surrounded by thick combustion gases, soot particles and high concentrations of carbon dust - that cause clogging of the lungs, choking and extreme eye irritation. The ones who manage to escape 'unhurt' might face long-term health problems - even cancer - because of inhalation of contaminated micro fibrils. Worth considering to provide passengers and crew next to oxygen mask and life vest also with a protective respirator gas mask and suitable gloves - or at least inform the passengers of the dangers of the composites surrounding them during the safety instruction before take off.*

Testing for certification with all-composite aircraft

Certification - although recognized to be of utmost importance - is in this respect a relative idea since every commercial aircraft that crashed in the past was certified and flaws in design and unknowns including wrong choice of construction materials or different then expected material behaviour were often found afterwards to be the cause of accidents including a number of fatal accidents – some described in detail in appendices of this report.

Testing and accompanying modelling for certification concentrate in first instance on static strength 411), fatigue strength, damage tolerance and ageing, essentially in ways similar to aluminum aircraft and involve with the 787 two aircraft. Testing is based on the building block approach when first materials are tested and certified 406), then components, then structural parts, then complete sections and finally complete structures and aircraft. Four aircraft are tested in flight under most rigorous conditions that '*involve extreme turns with high G forces, rejected take offs and challenging stalls'* 73) and so on - mind that with the 787 test aircraft the wing box is temporarily strengthened and numerous fasteners are installed incorrectly.

Limit load testing

With the 787 testing of the static aircraft involves worse case predicted loads an aircraft would encounter in service, which so-called *limit load* is then pushed to *ultimate load* 50% beyond that limit load. This safety margin is based on long experience with all aluminium aircraft and it can be questioned whether a similar margin can be safely applied with composite structures - based on no physical experience whatsoever. With the Comet engineers deemed double safety margins sufficient. Certification involves, among others, a high blow test when the internal pressure in the fuselage is raised to 150% for two hours, a 150% deflection of the wings, 150% aerodynamic loading of the wing box, ground vibration testing for wing flutter and a fatigue test involving long time pressurization and depressurization of the fuselage.

With the 787 the wing box was successfully tested - but had to be 'beefed-up' to meet the specifications. The high blow is also claimed to be a success but Boeing later discovered that thousands of fasteners had to be replaced due to the loading, as has been discussed before. The wings will be bended to 26 ft / 8m deflection. That is where it went 'wrong' with the A380 when the wing buckled at 1.45 times limit load, 3.3% short of the target of 150% 208) - with the A380 the wings are not composite but the 11 tonnes wing box is. The FEM models in place at Airbus proved to accurate indeed and engineers deemed a strengthening 30 kg aluminium strip sufficient to compensate for the failure. But a new test should have been performed. At Boeing, modelling has proved to be far from reliable yet, as has been discussed before. Boeing now chooses not to reveal how much the design threshold is exceeded when structures are loaded to destruction just that 1500% is achieved – apparently afraid to reveal how far models still are out of touch. Ultimate wing deflection has yet to be performed with the 787, but Boeing has not yet decided whether to push for destruction beyond 150%, which would be stupid not to do - not knowing for sure whether the 150% threshold is sufficient with an all-composite wing and it would provide valuable information on the models. Engineers apparently overruled by marketing forces - Comet all over again. The fuselage will undergo 165,000 pressurized and depressurized cycles, a three-year test program planned to start the first quarter of 2009. Again, the 4 Comets crashed although the test aircraft had withstood 18,000 applications of repeated pressurizations - when the test was repeated after the crashes at more realistic conditions, the fuselage failed after 1830 pressurizations.

More complex

Then the situation becomes much more complex with composites, entering new territory. Different parts of the complete structure have to be tested where type, composition, structure, interface, architecture and thickness - and hence behaviour - of the composite can vary in significant way to aluminium. Stress distribution has to be studied, which can be quite extreme around the fasteners and the same applies for the often very complicated other joint constructions that contain metal parts and involve specific adhesive bonds. This is not well understood at this scale as is also the case with the affects of vibration and damping.

Next, environmental conditions have to be taken into account. Physical properties, including stress strain behaviour, crack growth rate or delamination spread. Stress redistribution and vibration are strongly affected by temperature and even more so by diffusion of moisture, as has been indicated before. Also other degradation, due to possible exposure to chemicals, ozone and UV radiation, have to be studied – amongst others. Again, far more complicated than with aluminium aircraft. Also here full-scale tests are required to learn how performance is affected - note that the behaviour of the structure can be very different from that of the individual parts.

Dynamic loading

Dynamic loading to test impact performance poses a problem because methods to simulate and measure impact performance are for testing of small coupons [209)] and scaling of the results to actual dimensions and real conditions has proved to be extremely difficult and not very reliable. Higher impact velocities - important for studying the effects of for example impact of rotor burst fragments - can be obtained with the pressure gun [402)] but this is rather complicated and poses severe restrictions with testing.

Aluminum aircraft testing that involves 4.5 lbs / 2 kg artificial bird impact against the windows at 350 knots / 400 mph / 650 km/h and impact of 2 inch / 50 mm hailstone impact at 621 mph / 1000 kmh won't do. With all-composite aircraft the - larger - glass windows offer far better impact resistance than the composite skin. Note that cockpit windows at the flight deck have been smashed by hail numerous times in the past. Important parameters like impact velocity, angle of impact and repetitive loading cannot be examined properly, not to mention the influence of the configuration of the impactor and whether the impact face is stressed [182)].

What is essentially required is the inclusion of numerous insidious anomalies at critical locations in the test program, together with cyclic environmental conditions. The wing could for example be tested again for maximum deflection at such conditions. Other damage related issues include lighting strike resistance, crash behaviour and toxic flammability that have been discussed before Also the affect repair has on the structural integrity has to be included in a full-scale test program. Most difficult but virtually impossible with state of the art testing procedures is simulation of damage tolerance arrangements, discussed before. Again, all this does not pose much of a problem with aluminium.

Difficult to understand that FAA apparently supports the view of Boeing that with the 787 testing for certification can be round up in some seven months - around the clock with no time for reflection. Whatever the outcome, the picture will be unsatisfactory - actually is already - and this is a most worrisome development.

Mathematical modelling with all-composite aircraft

Mathematical modelling is nowadays a principal tool with the design of aluminum aircraft where simulations are based on the well-known homogeneous and isotropic behaviour of metals. But such modelling is much more complicated - not to sat immensely complex - with composite structures where the number of parameters soon far exceeds what can be tested and modelled. A next problem with composites is to decide how to deal with the many unknowns. On the one hand there is the structure of the composite that has to be modelled from nano via micro to macro level - at least these levels have to be considered with composite modelling - on the other hand there are the conditions of the mechanical loading and finally aspects of environmental loading - that affect each others behaviour as has been discussed before. Specific simplified structures might be tested at careful monitored conditions that suit the assumptions of the model, but then engineers are facing the problem how to translate results from such idealized and simplified behaviour to practical conditions and models. But one has to start somewhere, somehow.

Proper composite modelling requires extremely long solution times because of the typical inhomogeneous structure and anisotropic behaviour of the composite - even with strongly simplified models up to ten times longer than with metals - and than still assumed values have to be adapted for many unknowns, not to mention all ‘unk-unk’ that will surface once results become available from physical tests and practical experience. Boeing is still far from reliable modelling as has been pointed out before - it is illustrative that the 787-9 design is *'on hold pending availability of 787-8 ground and flight loads data essential to calibrate the computer models'* 7).

Verification of models is hindered by lack of suitable physical test results, which means that many models - probably most - that have been developed for all-composite aircraft are in essence qualitative in nature. But the danger looms that these models are exploited quantitatively and applied for certification - as presently seems to be the case. Be always aware that with certification the physical result is always the most important - and that the model is only a tool to calculate or simulate a possible outcome at very specific and often idealized conditions - so strikingly illustrated with the development of the Eurofighter

Eurofighter

Computer simulation has proved not to be a reliable tool with the design of the Eurofighter, some 40% out of composite. Here, the structures have been designed using state of the art modelling technology 210), but when physical test results became available from the *Development Major Aircraft Fatigue Tests* a total of 128 different damage locations were found including 62 fatigue cracks - all unexpected, that is, unnoticed by the models. Damages to composite elements were reported as minor and none needed repair, but tests were performed with fresh undamaged structures at room temperature and without moisture conditioning. It was concluded that *'the fatigue damages which occurred clearly show that a large portion of the fatigue critical sections were not recognized in the design process. The reason is that the stress analysis was not sufficient, whether it was not detailed enough or the Finite Element Model inaccurate, or for whatever reason. Another considerable portion has to be categorized as "bad detail design" or "assembly induced".'* 210)

This illustrates in a rather dramatic way the limitations of modelling as well as the necessity of thorough physical testing. With regard to composites it has to be stressed again that testing here only involved fatigue. Possible damage through delamination, ageing and so on were not taken into account

Inspection with all-composite aircraft

'Not being susceptible to fatigue and corrosion, Boeing 'guaranteed' the 787 to save 30% in direct cash operating expenses over 767- era airplanes with maintenance schedule intervals for most of the aircraft to be twice as long. For instance, the first external structural inspection for a 787 is set at six years of normal service rather than just three years for the 767. Similarly, the first internal structural inspection - heavy check - is planned at 12 years, rather than six on the 767' 211). *But all-composite aircraft have low damage tolerance and have to be inspected for accidental damage on continuous base – with such damage affecting both fatigue behaviour and ageing.*

Aircraft maintenance and repairs now represent about a quarter of a commercial fleet's operating costs and these costs are expected to soar when all-composite aircraft come into service because complex non-destructive inspection has to be in place on continuous base to detect accidental damage, in particular possible hidden damage. Not only involved are the very large skin surfaces but also other more massive composite parts including the fuel tanks as well as complicated joint constructions, fasteners and lightning protection systems.

Procedures must be in place for inspection of the aircraft. As has been pointed out before, comprehensive non-destructive testing has to be performed to verify the structural integrity of the composite parts - check for voids, porosity, delamination and so on - during the various stages of manufacturing. Such inspection is rather complicated and becomes even more complicated once the aircraft enters service because the engineer cannot rely on visual inspection as with aluminium aircraft. Detection of insidious damage requires non-destructive testing, but such sophisticated inspection methods cannot be used at the tarmac. Visual inspection remains, however, most important and inspectors have to learn to recognize composite damage modes that are completely different from aluminium and for repair it is important to identify the cause of the damage. A main challenge to airports is to train employees to take extreme care with all composite aircraft and to report any accidental impact however minor.

Tap testing

A simple method is the so-called tap test. Here the mechanic uses a weight (coin or hammer) to tap on the structure, listening for locations where the tapping produces a subtlety different response that indicate variations in the structure or damage - in a way similar mountaineers tap a rock surface to find a suitable not weathered joint or crack to mount a clamp to attach their ropes. Contrary to mountaineering where the inspection involves only a small area and is aided by visual observation, tap testing is not a reliable tool with all-composite aircraft because of the extremely large surfaces that have to be tapped and the method suffers from subjective interpretation and surrounding noise and other conditions like wind, rain and possible snow and ice – often only major delamination might be detected. Minor damage will go unnoticed and tap testing provides no information on damaged fasteners and light protection system. One can even wonder whether frequent tap hammering of composite faces is not going to pose a potential source of impact damage on its own. Difficult to believe, but at the time that Boeing decided for the all-composite 787, tap hammering was generally understood to provide sufficient means for inspection of all-composite aircraft.

> Boeing has developed a digital calibrated hammer for computer-aided tap testing of the 787 [212)] - Airbus developed also one but the Boeing seems to provide better results [367)]. The idea was to eliminate the interference of surrounding influences – in particular noise. The hammer captures the contact time between the strike and the surface rebound. Typical contact times vary from 200 to 1000 microseconds, with the longer times indicating damage. When the digital readout varies more than 10% along an area, sub surface damage might have occurred and more sophisticated non-destructive testing has to be performed. But also here mixed results are reported since many of the objections for manual tap testing listed before apply also here. Much more sophisticated methods have to be in place.

More sophisticated inspection required

More sophisticated inspection is required. First fieldable non-destructive testing devices are becoming available that allow for inspection at the tarmac [213)] - but need dry weather and clean surfaces that are not covered by snow and ice. When, somehow, insidious damage is detected or suspected at the tarmac, the aircraft has to be placed in a covered area for closer inspection and this might take quite some time.

> Non-destructive testing involves a recorder that must be in contact with or adjacent to the face of the suspected site to determine geometry, damage or composition in a way that structural integrity is not affected. Various technologies are available for specific inspection, based on optical microscopy, X-rays, ultrasonic resonance, acoustic emissions, laser optics, interferometry and shearography, infrared thermography, Fourier transform infrared spectroscopy and so on [174)].

Many of these methods are also already used for the inspection of aluminium aircraft but here one can rely heavily on visual observation. The problem with testing of all-composite aircraft is - next to the extremely large panel surfaces that have to examined - the shear number of different parts that include the joints, fasteners and the lightning protection system amongst others - which each require a completely different approach and specific test equipment that has yet to be developed.

3D definition

A reliable assessment of the residual integrity of the composite can only be made when an accurate description is available of the damaged part or site. For example, delamination is often spread over more layers and the patterns at each interface can be different in size, shape and orientation and the position and spatial geometry of all delaminations must be accurately identified and mapped including possible transverse matrix cracks. This requires a 3D definition. The situation becomes vastly more complicated when also joints, fasteners and lighting protection are involved, as will most often be the case. Another approach is to forget about testing and just to decide for repair.

Accessibility

More massive parts like the centre wing box and the keel beam are not externally exposed, but are subject to most intense cyclic loading and have to be inspected meticulously at intervals and when the structure has been stressed above or near to its certification levels. Large volumes require a totally different approach. It is, however, not always easy to determine when the aircraft has been overloaded and much depends on the pilots report, information from airport employees and mechanics as well as the expertise of the inspectors. Also accessibility with such complicated equipment can pose a problem. As indicated before inspection inside the fuel tanks - although of great importance - might do more harm than good because of possible damage caused during inspection. Here looms the danger of development of ignorance - getting used to the problem - that led to disaster with the Concorde and the Columbia, discussed before.

Health monitoring

Damage growth and structural failure can best be monitored on board with automated health monitoring systems that continuously, rather than periodically, make an assessment of the structural integrity of essential parts of the aircraft. Engineers are therefore working on the development of so-called structural health monitoring systems where the aircraft is provided with non-destructive test devices, which are coupled with sensors that are incorporated into the structure. Data are automatically processed, assess structural condition and signal the need for human intervention. These systems provide also greater access to difficult-to-inspect areas of complex structures and can eliminate the need for disassembly.

> *'The A380 incorporates a sophisticated pattern of electromagnets within the design. These apply a slowly increasing electromagnetic field to the structural metal beams, while a coil picks up distinct audio frequencies created by the material's magnetic domains as they align with the field. Prior to a plane going into service, the initial pattern is recorded and stored for use as reference for future superstructure checks. This allows ground staff to continually monitor the A380's airframe for defects by listening to the behaviour of the plane's structure in varying magnetic field - thereby providing an accurate picture of the state of the plane's structure. This system can indicate when the plane's structural integrity is threatened and when maintenance is required'*[214)]. With the A380 the skin does not have to be involved because this is out of aluminium and aluminium reinforced composite.

Health monitoring on continuous base of a composite skin is extremely complex - where to start - and must include the joints fasteners and lightning protection system. The idea is of embedding sensors in the composite that provide a signal when insidious damage occurs - indicative for example of delamination. And many other types of sensors have to be developed to monitor other parts listed before.

> Next to mature micro-electro mechanical systems devices, such as acoustic emission sensors, accelerometers, strain gauges and pressure sensors, recent advances in micro-sensors make it possible to develop miniature eddy current, ultrasonic, piezoelectric, and other devices that lend themselves to damage detection.

A very large number of sensors are required which add to the weight and will further complicate repair. Development will still take quite some time and the systems will be very costly and undoubtedly much more complicated and sensitive as now anticipated - and how is damage to and malfunction of the sensors controlled. But an alternative is emerging - may be - health monitoring additives that could become available in a distant future.

> *Health monitoring additives*
>
> Optical fibres are being investigated that have added to or are embedded in the composites to detect the location and the severity of the damage. An optical fibre is intended to fracture at the load that is supposed to cause damage to the composite - signalling a warning. Such broken optical fibres prevents light from being transmitted through the fibre and this effect can be measured. The problem is of course to provide the optical fibres with the required ductility. This can be achieved through etching of the optical fibres or provide them with a coating.
>
> And of course - also here - carbon nanotubes are researched that can be added

to the composite to form a network that is claimed to have the potential to monitor the 'health' of a composite structure like aircraft in that they can detect and identify damage within the composite. According the researchers, carbon nanotubes have an incredible ability to conduct heat and electricity - essentially in a way as human nerves. This means that they can act as sensors that provide a signal when for example a delamination has occurred or is about to develop.

Supposed that such health monitoring systems becomes reality - different systems are required for different parts - these systems are going to be extremely expensive - add to the weight - are part of the damaged part and have to be replaced during repair - and one can already wonder how such health monitoring devices are going to behave when exposed to the extreme conditions that apply to aircraft - in particular when lighting strikes.

Repair with all-composite aircraft

By 2009 the market for aircraft composite repair materials was still moderate, estimated at some $25 million annually. A dramatic increase to some $20 billion by 2011 has been suggested 358) *- probably based on the original sales and delivery estimates for the 787 - but even larger figures will become reality when all-composite aircraft enter service in greater number. This in shrill contrast to the savings on maintenance that were promised - if not guaranteed - by Boeing. Repair of all-composite aircraft will turn out to be far more complicated, time consuming and costly than presently anticipated. Contrary to aluminium aircraft, damage to composite aircraft structure involves normally several different types of damage affecting both mechanical and other physical properties. Methods focus mainly on repair of the composite material - that is, restoring its mechanical properties - in particular its strength. Experience with repair of laminate composite structures is limited and methods have still to be developed for the repair of the non-mechanical damage. Most important is that soon reliable composite repair stations become operational at each* *airport, which can deal with all kinds of repair. Success is crucial for the future of all-composite aircraft.*

Boeing is very well aware that repair of all-composite aircraft is far more complicated and critical than with aluminium aircraft and recognized - already back in 2005 - that special attention has to be paid to the repairability of the 787 *'Because composites are driven by ultimate strength performance rather than fatigue, which is the case with metals, "you have to design the repairability into the structure, you can't do it later" referring to analytical provisions considered in the design stage that will ensure restoration of ultimate strength capability as reflected in composite component design and composite repair protocols'* 225). And with all-composite aircraft here is more than ultimate strength that has to be considered.

Continuity of design

Design of all-composite aircraft is extremely complicated indeed - far more than aluminium aircraft - and this has serious consequences for inspection and repair. More than with other transport vehicles, the design of an aircraft must present a continuity - 'a physical continuum' - that provides the aircraft its structural integrity required for airworthiness. That is, amongst others, mechanical, aerodynamical, thermal, electrical and electromagnetical continuity - and involves all materials and where materials connect and interact. Any damage can break this continuity - this has to be detected in time through effective inspection and any structural discontinuity that affects structural integrity has to be restored through repair at short notice. Continuity is not such a problem with aluminium aircraft where for example electrical continuity comes for free - as an intrinsic continuity and this reflects in rather simple damage. This contrary to all-composite aircraft, where continuity has to be built in the aircraft - as artificial continuity. Damage is much more complex - damage at a single site normally breaks several discontinuities, listed before, that each may present a safety risk. Even with the best repair it is not possible to restore the original continuities - some more others less - and a repaired site introduces new discontinuity on its own. This can pose a serious problem because all-composite aircraft will develop repaired sites in rather large number over time with concentrations at zones that are most at risk.

Another dimension

Repair adds another dimension to the complexity of all-composite aircraft in that it introduces new discontinuities, in particular inclusions of moisture, voids and other possible irregularities. This affects performance. So attracts a repaired locality more load when the stiffness is increased and becomes overloaded - visa versa diverts load when the stiffness is too low, which may cause overloading of the surrounding structures. This has to be considered when a damaged site of an ageing structure is made ‘new again’ - not the original but present level of continuity might have to be restored to avoid overloading. Joints should be restored, including fasteners - in ways that paths for load transfer and stress redistribution are preserved. The substructure might be involved as well as restoration of structural continuity along cut outs - doors, hatches and windows – many of which are most vulnerable. Repair should not alter creep behaviour affecting stress relaxation, nor affect vibration and damping behaviour and aerodynamic performance should be maintained. Change in thermal expansion behaviour that can cause dilation has to be avoided. Electrical discontinuities can interrupt the ground system of the aircraft and affect lighting strike protection - broken electromagnetic continuity can cause disturbance with on board electronics. Shielding for galvanic corrosion has to be maintained. Glass transition temperature, flammability and durability should not be affected - at least not in too negative way - and this applies also to the composites surrounding the repaired site.

Methods for structural repair

Efforts are being made to standardize composite repair [368] *- repair methods and in particular repair materials - but this appears to be very difficult. So can Airbus materials not be used for the repair of a Boeing aircraft and also fasteners, joint constructions, lightning protection systems, protective coatings and so on are different. Also different non-destructive methods and procedures might have to be applied for inspection of certain parts of the 787 and the A350.*

Standard methods for structural repair of primary composites structures focus mainly on restoring mechanical continuity of the composite - in particular strength in the plane. These methods are further developed and much research is performed to improve on repair materials and methods of repair. Most experience has been gained with composite sandwich constructions [365] - much less so with composite laminates [366], but this is about to chance with the introduction of all-composite aircraft. Hardly any attention has so far been paid to repair of non-mechanical discontinuities and that is also to change.

Restoring mechanical continuity

With the standard methods for structural repair a damaged site is provided with a patch either as overlay or as inlay - and combinations of both. The patch can be out of the same material as the composite - but also out of another type of composite and materials including aluminium or titanium reinforced composites. For attachment the patches can be bolded and adhesively bonded to the composite. Bonded repairs are often stronger but are very complicated with composites - contrary to application with aluminium aircraft - and require great skill, special tooling, accurate inspection and is time consuming and costly.

Overlay patches can be attached to one or both sides of the composite. The latter is very popular with composite sandwich structures with a core plug as inlay in between the patches 365). With laminated composites inlay patches are placed in a cut out through the thickness and are then adhesively bonded to the composite with the aid of a film adhesive. To obtain sufficient bonding surface and to limit peel stresses, the outer edge of the cut out is flatly angled - as a scarf joint - at about 3^0. This has the disadvantage that much sound material has to be removed and this limits application with thicker laminates. Bolded repair is normally preferred with thicker laminates - more than 3 mm - also because available adhesives are not strong enough, but new stronger adhesive films are being developed. So far experience is limited - there is hardly any experience with repair of thicker laminates, not to mention repair of more massive composite parts like the wing boxes and the keel beams.

The patch can be a pre-cured such that it matches the properties of the original laminate. Achieving such properties is more difficult with prepeg inlays that have to be co-cured - but co-curing has the advantage that more complex shapes can be created, which can pose a problem with pre-cured patches. Both pre cured and co cured patches require that special measures have to be taken to remove any moisture from the repair before curing. Heat treatment is applied for complete drying - vacuum drying appears to contribute to drying to limited extend only. Next autoclaving is applied for curing of the repair. It is extremely important that the curing cycle is not interrupted in any way. Any loss of vacuum, pressure or temperature can lead to porosity and it has to be avoided that the surrounding composite is not negatively affected by the heat treatment. The quality of the patched site depends largely on the bond that is achieved through the adhesive film.

The outer and inner edges of the repair has to be at a distance at least 30 mm form any fastener - newly placed or existing - and there is a size threshold for the repair depending on the thickness of the laminate. Larger repair areas might require a bolded patch that includes additional fastener points that weaken the structure. Working through complex curvatures and around holes and cut outs can be very difficult, in particular with pre-cured patches. Doors and hatches might be regularly damaged - at about the same location – and it very difficult to repair a previously repaired site – especially in case this represents an overlap.

Patched repair may present good strength in the plane but possibly less so through the thickness in which case impact performance is affected. Joints pose another problem in that any change in stiffness over the joint can cause serious bending problems. As indicated before, fasteners have to be precisely - spark free - repositioned, this is very difficult to achieve and causes still headache at Boeing and its partners. When damaged, the copper and aluminium wire mesh and foil that are inserted between outer plies for lightning strike protection have to be carefully fixed. It will be extremely difficult to maintain electrical continuity throughout the adhesive film, necessary when fastener holes are involved - a problem not tackled yet - and the same applies for maintaining electromagnetic continuity. Any coating applied to reduce flammability and UV radiation and possible sensors for health monitoring require special attention. Substructure can be involved, either though contact, connection or damage. Any damage to the ground system and insulation for galvanic corrosion protection has to be carefully restored. Present methods for removing paint through chemical stripping can cause damage to the composite. Until paints are available that allow for chemical stripping or application of appliqués, paint has to be removed from the composite through abrasive stripping - water jet, dry ice, laser - which require special equipment and is time consuming. It appears that it is essential indeed '*to design the repairability into the structure, you can't do it later*'225).

Strength recovery with repair

The strength that can be recovered through bonded repair has been examined bu FAA in cooperation with a Russian Institute 413). Composite panels were tested that were provided with a hole that was repaired in different ways. The strength of the plain panel (150x360) was set for 100%, which strength dropped with about two-third when a so mm circular hole was cut in the middle of the panel. A one side patch repair doubled the strength of the damaged panel to 63% of the original strength. Then the hole was scarved such that along the scarf the conical cutout increased from 50 mm at the bottom to 90 mm at the top which hole decreased the strength to about 20% of the original panel. An inserted 8-layer patch with a one layer overlay on both side sides increased the strength almost threefold related to the scarved panel or 56% of the original strength. Roughening the surface around the scarf increased the strength to 71% and when the thickness of the overlays on both sides was increased to three layers a strength was obtained of 90% of original strength. As to be expected strength recovery was less when no cone was used and no scarfing was performed - with one side patching to some 60% of original strength. Affixing patches with fasteners only recovered 50% of the original strength. The engineers pointed out that '*one should bear in mind that the data are conditional since the efficiency of a particular repair strongly depends on production process used*' - but the results clearly indicate that even at ideal circumstances that here obviously apply the original strength cannot be retained. Much more research is needed in this field.

Flying repair stations

It will take a long - very long - time before airports can provide complete and reliable inspection and repair services for all-composite aircraft. As was indicated before, it took Boeing and its partner many years to get acquainted with composites – and they are still struggling. Repair in the field might in many instances be more complex then manufacturing and it will take engineers also many years to be trained, gain experience and expertise and become familiar with the special tools and materials – and to recognise the many different types of damage, to diagnose which discontinuities need restoration and to decide on the right methods of repair. Inspection of the repaired site has to include all discontinuities - with only methods available for detecting and repair of discontinuities within the composite structure.

Temporary repair that allows the plane to fly to better equipped repair stations and even to the manufacturer will become a big issue with the plane out of service for some considerable time. It has yet to be seen to what extend temporary repair is possible and who is qualified to OK temporary airworthiness. Originally Boeing had plans for a built-in maintenance platform in the tail section of the 787 *'It was done to make the airplane more operable, because certain things have to be done on the ground. That 'operability' criterion justified the extra weight of the platform'* 227) - wonder if it's still there, it involves weight, but it is a good idea to have certain tools and specific materials readily available. So, a better idea might be flying service stations - repair aircraft that have all necessary tools, materials and expert engineers for detailed inspection and repair on board.

Automation

Experts claim that repair can and should be automated. This sounds good but a closer look read reveals

> *'Accordion fringe interferometry provided automated high-resolution metrology without the traditional requirement of superimposed photogrammetry, thus accelerating throughput and improving accuracy. Laser shearography was seen to be a fast and accurate method for non-destructive testing, mapping defects onto the 3-D shape of the part. Ultrasonic cutting tools with high-accuracy 3-D control and precise cutters use these data to remove damaged material and accurately cut the stock textile and honeycomb materials needed for the repair. Laser assembly guidance systems integrated into the ultrasonic cutter ensure that the composite textiles are kitted properly, and also map the location of the kitted composite textiles onto the repair's surface, assuring a defect-free repair. Proprietary technologies tack the uncured composites into place prior to cure. These technologies, packaged as integrated end-effectors, swapped positions as they were needed in an intricate mechanical ballet'* 215),

and illustrates that there is still a long way to go - to say at least. But may be - in some distant future - self-healing composites will bring relief.

Self-healing additives

An even longer way to go, scientist are working on self healing composites - imitating nature - that is described as *'a novel alternative to damage tolerant design in that it removes the need to perform temporary repairs to damaged structures'*. This has to be awaited, but it is a fascinating development for researchers. Again one can wonder whether both resin and fibres can be made self-healing - otherwise it might be of limited or no advantage. But one has to start also here somewhere - somehow researchers are focussing only on the matrix - for the moment.

The idea is to embed micro or nano containers in the composite structure. These containers are filled with a healing agent, which is released into a damage site upon fracture. The micro containers can be tiny glass tubes or microcapsules with a hollowness of some 50%. The healing agent is a resin that heals the damage through polymerization. Research in this field is encouraging with healed samples that achieved more than 80% of their undamaged strength. The problem is of course also here the regular distribution of the microcontainers in the composite and whether these micro containers affect other properties. Research indicates minimal degradation in flexural strength and ply disruption.

So-called reflective composites are being developed that can detect and heal damage in load bearing airframe structures. Embedded piezoceramic 'pills' are able to sense changes in the composite structure when high frequency electrical signals are applied.
A shape memory polymer resin is than activated by heat that recovers the matrix from deformation damage and physically closes any delamination. Linear polymer chains within the matrix become mobile with heat and bridge the cracks. Repair takes place in less than seven minutes, that's fast, but might be too late anyway.

But imitating nature does not mean creating living materials, additives do work only once – then they are *'dead'* - but may be one day it is possible to create *'self healing self healers'*.