3. FRONT RUNNER

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Of course aircraft can be build all-composite - why not - but one has to deem whether it is worth the effort and to discard seventy-five years of experience with aluminium aircraft and to start again essentially from scratch - certainly so when it is doubtful whether substantial savings can be made on weight and maintenance and appropriate safety standards can most probably not be met, certainly not the unprecedented standards achieved with aluminum aircraft. As engineers at Airbus and Boeing now know, demonstrating that composites are lighter and stronger is not the same as demonstrating that lighter civil aircraft can be build all-composite.

History learns that when a revolutionary designed aircraft enters service, engineers get confronted with problems that have not and could not have been imagined, were ignored or overlooked due to what is known in aviation as *unknown unknown* or *'unk unk'*. Dealing with *unk-unk* - that is solving the problems - often requires a largely empirical approach, in some cases dominated by rules of the thumb learned from often painful if not tragic experiences. It is extremely difficult to translate such empirical know-how and attitude, gained over very long periods, to new materials and structural concepts - virtually impossible with composites.

Uncharted territory

With all-composite aircraft civil aviation is entering uncharted territory littered with *unk unk* - composites' properties and behaviour are well known, but are largely *unk unk* at the scale and extreme loading that apply to civil aircraft. Long time experience with aluminium offers little support because composites show completely different physical behaviour - how different has yet to be found out - what is known is that composites are famously low on damage tolerance. Service history with aviation composites is limited and mainly restricted to small-scale sandwiched panel constructions. Large-scale application of laminate composites with aircraft is new - large barrel sections and complete wing sections have never been tried with composites before and have to meet the extreme criteria set for civil aircraft. Scaling poses serious problems - both with design and with manufacturing - and requires extreme engineering. The enormous joint constructions that connect the barrel sections and the wings and other parts of the structure pose huge problems with design and manufacturing. Completely new design standards and construction methods had to be developed as well as sophisticated tooling and processing techniques to meet the very strict specifications and tolerances. *Unk unk* puts boundaries to reliable modelling that is so essential with the development of new aircraft but of limited value here since appropriate validation is not possible yet. At the same time measures have to be devised that compensate for composites' poor damage tolerance but limit increase in weight, which has proven to be extremely difficult - if not impossible.

Sudden switch to all-composite aircraft

Starting development in 2003, the first test flight with the 787 was set for August 2007 and first delivery for May 2008 with peak production rate of 7 per month by 2010. With the order book swelling Boeing shifted to more aggressive ramp up. Ambitious to the extreme and putting enormous pressure on engineering, 40 aircraft were scheduled for assembly in 2008, with testing for certification to proceed along the production line - based on large scale one-piece sections to be manufactured at partners around the world and completely prefabricated flown into Everett for final assembly - assembly rate was to be steadily cut short to just 3 days - 14 days with the 777 - to be able to roll out 112 aircraft in 2009 with production rate to be increased to 14 to 16 a month by 2010/11. That was on paper and paper is patient.

The sudden switch to all-composite civil aircraft as initiated by Boeing had immense implications. In composite terms the 787 is an exceptional structure - nothing on this scale had ever been attempted with composites before - not even near. Effectively the engineers had to set overboard virtually all experience gained over some seventy-five years with aluminium aircraft and to start almost from scratch. Boeing nor Airbus nor any other party or organization in this world had any experience or recollection whatsoever with regard to all-composite civil aircraft at this scale - that is size and magnitude of physical loading - nor with comparable applications even near to this scale. Experience at Boeing was limited to small scale applications with the 777 that entered the market in 1996, just 12 years ago, with an airframe some 9% composite structure by weight, including large parts of the tail section - and applications with military aircraft, in particular the B-2 stealth bomber and with the F22 fighter jet where application of composites had to be scaled back from initially 50% to some 25%.

Probably guided by the unknown, problems connected with the enormous scaling were initially largely underestimated. In similar way the possible advantages that can be obtained with composites were overestimated, if not exaggerated. Indeed, before long, engineers learned that the design and the manufacturing of all-composite aircraft of this size proved to be immensely more difficult and complicated than was initially anticipated and that there was no experience in this field in this world. Outsourcing some 70% of the activities worldwide was thought to bring expertise and experience but contributed to the problems up to level that Boeing completely lost oversight by 2007.

Boeing is now facing ever longer delays, huge costs overruns, still enormous difficulties with design and manufacturing, serious problems with inspection and repair and large overweight as well as loss of credibility with customers and serious friction with partners. A large number of 787's has been sold at low prices but the cost for R&D, quality assurance, manufacturing and materials have been rising at alarming rate. The price of carbon fibre follows essentially that of oil and has increased from $5 a pound in 2006 to well over $20 by 2008 44) - the present drop in oil price won't last. Manufacturing and assembly appears far more complicated than originally anticipated and will take much more time as Boeing and its partners are still struggling to meet extreme strict specifications. It will take quite some time to reach an acceptable production rate - whatever that rate is going to be - nobody can tell how the present economic crisis will affect the project, but this will have severe consequences as has been discussed before.

The 787 will not deliver on the guaranteed low weight-low fuel performance and will need much more inspection and repair as promised. Airlines have to be compensated for late delivery and underperformance, eating away the margins and long-term program profitability. The certification timeline is still uncertain, as the first test aircraft has yet to fly.

E for 8

Over a period of more than fifty years - from 707 to triple 7 - seven's have been a lucky number for Boeing indeed and when Boeing announced the world's first new all-composite aircraft it was originally dubbed 7E7 with 'E' for efficient – so we are told – other suggest E was for excellent and employees at Boeing thought of E for Everett. A *'name your plane'* contest organized by Boeing attracted some 500.000 votes worldwide and decided for *'Dreamliner'* past the initial frontrunner 'Global Cruiser' by a margin of only 2.500 votes. Then Boeing decided to change *'E for 8'* to show how much it values China where the number '8' is considered *'good luck'* - in Manderin and Cantonese 'eight' sounds as *'to make money'* - and how much it values orders from China for the 787 Dreamliner that would be ready in time to fly passengers to the 2008 Beijing Olympics. Very much appreciated, no doubt, by President Hu Jintao, when he visited - guest of honour - the assembly plant at Everett, May 2006, telling the cheering crowd that *'Boeing is a household name in China'*. The 787 didn't make it before the Olympic Games but by then six Chinese airlines had already ordered 60 787s. Probably a bit frustrated by developments Chinese Airlines announced - by March 2009 - that the Dreamliner doesn't *'fully meet the quality Boeing touted earlier'* and may cancel or postpone delivery [291)]. Whatever the reason, the Chinese started development of their own jetliner in 2009 - the C-919 - where 9 means *'forever'* in Chinese culture [292)].

Decision making at Boeing

The impression is that at Boeing the decision to go all-composite was regarded to be the first key decision without realizing - at least insufficiently - that the first crucial decision had by then already been taken by accepting composites for what they were thought to be worth: *taking light plastic for light aircraft*. Explaining to the press in 2005 what composites are all about *'Making carbon-fibre parts might be described as a massive wallpapering operation - with the paper really being wide tape, loosely woven from super strong carbon fibres, then soaked in a honey-thick mixture of polymers. The gooey tapes are plastered on the inside of moulds or wrapped around shells called mandrels, and then baked. The heat triggers a chemical reaction that turns the polymers into a hard, incredibly sturdy structure'* [45)] explains a lot. It was, however, realized at the time that *'even cracks too small to seen could then spread under the stresses of high-speed flight and the dramatic changes in outside air pressure and temperature as a jet climbs to around 30,000 feet'* - no problem - '*the Japanese supplier of Boeing's carbon-fibre tape, impregnates the fibbers with a proprietary mixture: The epoxy that provides strength and hardness is surrounded by a polymer with a different density. This combination makes the surface less prone to impact damage - and if damage does occur, it prevents cracks from spreading*' 9). With a professor on hand to reassure - '*Because of this breakthrough, I will be sleeping soundly whenever I take off on a composite airplane*' 9) - quite reassuring indeed.

Fully confident Boeing decided to go for all-composite, apparently not questioning whether composites would deliver as promised - probably convinced that know-how and expertise could be bought or developed in time given enough money. That sets in motion the chain of decisions that have come in the open - amongst others - to decide to global outsource more 70% of the workload to partners who would provide the know-how and shoulder a substantial part of the costs, to decide for as large as possible one-piece parts including a complete barrel approach without realizing the complicated tooling and difficult manufacturing technology that had to be newly developed, to decide for a target weight that was far below what could be attained, to decide for a schedule that was far to tight, to decide to let extern inexperienced engineers work out the details and at the same time to decide to set the marketing in full swung and to decide to guarantee on fuel economy, performance, less maintenance and more payload without physical evidence that supports such claims and to decide to go for an 'unlimited or at least unprecedented' number of orders and further ramp up production once interest in the aircraft catapulted - and to decide not to inform customers when serious problems surfaced and apparently also not to inform the test pilots and the regulator as will be discussed later. And it was apparently decided to ignore composites' low damage tolerance.

> With all these airline executives apparently so interested in the 787, it is difficult to understand why Boeing did take so many orders - or was it also here bonus driven. When the aircraft performs only near to what has been claimed, it would have become a runner anyway. With proven performance the aircraft could have sold at much better price and at much better conditions and avoid the risks of claims because of late delivery and underperformance. Now, facing long delays and underperformance, Boeing has to work itself out of this mess and brace itself for the renegotiating of the contracts with the partners and some fifty airlines involving some nine hundred aircraft. Moreover, facing the economic downturn airlines will exploit late delivery and possible underperformance as a good excuse to defer and cancel orders without penalty payments.

At the time these decisions were made nobody realised that they were in for some very unpleasant surprises that would gradually unfold over the years when composites did not live up to expectations. Some will be highlighted here in brief.

Avoiding micromanagement

With hardly any experience on composites at this scale - either on behaviour, manufacturing, inspection nor repair - Boeing had to rely almost completely on the partners and other extern expertise for know-how. This was new to them. Used to the traditional model to provide designs to suppliers to be followed-up - a system called *'build-to-print'* - it must have been extremely difficult for Boeing engineers to find their place in this new environment. It was no longer Boeing's legendary *'it is our way or no way'.* Instead management conceived a new philosophy. Engineers were told to take some distance and not to *'micromanage the partners'*, but to give them more responsibility and to encourage them *'to show their expertise'* such that *'innovation can flourish'* and to make sure that *'there is no duplication of work'* 46). Boeing would only provide the overall design drawings and specifications and it was agreed that '*these outside companies would* *coordinate with one another to produce whole sections of the plane, stuffed with assembled components, systems, ducting, insulation, and wiring - Boeing workers in Everett would merely have to connect the major parts of the aircraft'.* 311)

Before long it became clear, first to the partners and at a much later stage to Boeing, that little fundamental knowledge was available in this world about applications with composites at this scale - that is aviation composites - and this hindered the development of proper models so important with design of aircraft. Specialist in this field did apparently not have all that anticipated unique expertise to perform such complicated design after all. Partners in the global network were soon fully occupied with design and construction of the extreme tooling and kept asking for more detailed drawings. It was rather late indeed, if not too late, when Boeing realized that the new management philosophy did not work - but by then they had completely lost oversight. Much more permanent physical presence at all sites and facilities is a must with a project of such complexity and magnitude and should have been arranged from day one - or from day two but not later. Boeing now admits that outsourcing appears to have been be less successful than anticipated or was hoped for - *'we may have gone a little too far, too fast'* 311) - and has signalled that in hindsight the super-site concept is to be preferred 47).

Battle for the pounds

The weight of an aircraft can be expressed in different ways. MTOW or Maximum Takeoff Weight is the maximum weight at which the pilot of the aircraft is allowed to attempt to take off. MZFW or Maximum Zero Fuel Weight is the total weight of the aircraft and all its contents, minus the total weight of the fuel on board. MWE or Manufacturers Weight Empty is the weight of an aircraft, without taking into account any baggage, passenges,or usable fuel - and is mostly used to compare the evolution of weight development during design. With firm configuration of the design - September 2005 - the target weights of the 787-8 were set at MTOW of 216 tons, MZFW of 154 tons and a MWE of 95.5 tons.

The weight of an aircraft determines fuel economy, performance and the payload that can be carried - performance is usually expressed as the range or the maximum distance an aircraft can fly 336) and can also be defined as the operation costs per seat. An overweight of for example 2500 lbs means that an airline flying the maximum range will have to take ten passengers of the plane - or can fly a shorter range when the number of passengers is maintained.

Overweight is a familiar problem with new aircraft and what is also familiar is that it is extremely difficult to get the weight down once the design has been worked out. What you save at great costs on one element you lose again with another. It is already quite an achievement to avoid the weight from going upwards. With more exact figures coming in when the design evaluated, managers started to get worried about of the overall deadweight of the aircraft by 2005 9) when it became clear that overweight had increased to 5,800 lbs / 2630 kg over its target weight 319) - which had to be brought down. However, with the composites already counting for some 80 percent of the construction material's volume, this leaves little room for rather radical modifications that are here obviously needed. Engineers, already stressed to the limit, were told to evaluate all parts of the structure for extra pounds again and were instructed to *'design to zero tolerance'* 319) - meaning that it was no longer allowed to build in extra margins for strength or thickness - that is safety. Such is easier said than done because the engineers did not have any reliable models to their disposal to meat such zero tolerance and could only try to make calculated guesses. Another problem was to coordinate all the changes and modifications, which can affect so many other parts of the overall structure and the manufacturing process at different sites overseas. But somehow the engineers managed to shed a dramatic 2,500 lbs - difficult to believe, but according Boeing this was achieved within two weeks 319).

Engineers shaved off pounds and many parts were newly designed, among them the window construction. A simple success was booked when it was decided to abandon the wireless system, saving some 200 pounds, also because of concerns about the amount of bandwidth available 146). But it soon became clear that shaving weight was a painstaking process with mostly 1- and 2- pound and sometimes 10-pound savings. Engineers looked for ways to load the extremely strong titanium fasteners more to their ultimate limit possible through strengthening of the holes, using less overlap and optimization of the configuration of the fasteners. These unique fasteners are not only very expensive, but also not readily available on the market. It takes not only much time to design such fasteners but also to develop the necessary tools for mass production and this led to long production lead times and consequent long delays. Supply became a real problem when other engineers decided - had to decide - that the titanium fasteners had to be completely redesigned to meet stringent specifications set for lighting strike protection. This required modification of virtually all drawings and even worse, these new fasteners had a production lead time of some 60 weeks. Before long, steady modification and shortage of fasteners led to total disarray at the global work floor when partners started to ship sections to Everett clipped with temporary fasteners. Then the FAA issued a number of *'special conditions'*, involving amongst others the fuel tank 50) and the lighting protection system 51). These conditions were still not met by 2009, but added soon dramatically to the weight.

Some weight was saved but the overall pressure remained upward rather than downward - rather steeply actually - and the *'battle for the pounds'* started to become an extremely costly exercise - next to long delays, cost overruns of *'several hundreds of millions of dollars'* were already reported by the end of 2006 52). As indicated, in 2005 the plane could still *'be put on diet'* 319) shaving 2,500 lbs but that left still 2,500 lbs overweight. By 2006 Boeing had to admit that the 787 was *'a bit on the pouchy side .... or about 5,000 1bs overweight...but the baby was healthy'* 54) - by 2007 overweight had again dramatically increased to some 14,000 lbs, according a key customer 55). Again, numerous parts were redesigned, other exchanged for lighter ones. But by the end of 2008, Dreamliner One was rumoured to *'have gained 21,050 lbs since firm configuration in September 2005'* 7) - this weight growth originated 4,300 lbs from the fuselage and 2,900 lbs from the wing detail sizing and design. Wiring and installation contributed with 3,250 lbs.

This involves the six test aircraft, but exact figures have not been released.

This means the six test aircraft will be have extremely large overweight and Boeing has recognized that also the first planes that will be delivered will be significant overweight. Again exact figures were not released - March 2009 Boeing declared that *'The first airplane that will provide us with meaningful weight is airplane No.7 and we won't weigh that for some time'* 291) - but overweight on the first 19 planes is expected to be well in excess of 4,500 lbs, far too much to meet its performance objectives in terms of range, economy and payload 337) - *'I pity the airlines that get the first ones'* 336). This means that the 20% fuel efficiency won't be met and to make things worse, the engines aren't meeting their projected fuel savings either. Reports suggest that the General Electric GEnx missed specific fuel consumption targets by 2-3% and the Rolls-Royce Trent by 3-4% 7) that effect range accordingly. 303). From ZA 120 the 787 will be modified to rectify for empty weight - that is from 2011 - amongst others with completely revised wing design. On the other hand issues will surface during certification that need modification and will add to the weight - and overweight of 5,000 lbs - may be up to 10,000 lbs - has to be accepted in the end, and this will limit the range in significant way. But for the moment Boeing remains upbeat in that the 787 will *"meet mission payload commitments to all customers'* 337).

An analysis error

Among many other problems, Boeing engineers, discovered *'an analysis error'* when the massive composite centre wing box (17.4ft/5.3m long - 19ft/5.8m wide - 4ft/1.2m thick) buckled during testing56) performed during the first half of 2007 - that is before roll out.

> The wing box is a cantilevered beam that carries the wing to the fuselage and supports leading-edge and trailing-edge devices, control surfaces, engines and landing gear. The upper and lower faces and the wing spars are made from the same composite material as the fuselage while the wing ribs are machined from single pieces of aluminium. The centre wing box is the foundation of the aircraft from where the design of the total structure is worked out. Engineers are very reluctant to change the design of this most critical part at a later stage because it is extremely difficult to see what implications this has to both the centre wing box and the structure as a whole - certainly

so with a structure largely composed out of a material never tried before at this scale and with no proper models at hand.

Working under enormous pressure - *'Teams were previously trying to brute-force through some of these problems'* 16) - engineers tried to save on weight on the wing box by thinning out the density of the spars. Too much apparently and the spars had now to be *'beefed up'* 58). This means that at that time, the models that were in place to calculate stress distribution didn't work - are '*not exactly perfect*' 58) as Boeing puts it - and this poses a major safety issue.

Strengthening required *'aluminium stiffeners'* to be affixed alongside the spars 59) as well as *'about 200 clips and brackets and about 500 fasteners'* 58) - this indicates that the wingbox must have been really shaved off and makes one wonder whether or would it have buckled also without shaving. It took until November 2008 when the strengthened wing box was destructively tested again and withstood now the loads up to 1.5 times - or 150 percent for three seconds - of the highest aerodynamic load that the aircraft could ever be expected to see 60). The full-scale test involved a 50-foot part that represents only a portion of the wing section, beginning at about the centre of the 787 and stopping at about two-thirds of the span of the wing. After achieving the 150% threshold for three seconds, the loading was further increased until the wing broke. According Boeing *'with sufficient margin'* 274) but declined to make public what load was achieved because *'on its own, the number is meaningless and people would try to make inferences that would not be founded with the proper context'* 274) - why such cryptic statement. Probably because the sufficient margin was wide above the limit, which indicates that the models are still far from accurate.

Boeing must now decide to break the wing on one of the 787 test planes - a most dramatic moment as the A380 demonstrated when the wing broke 3% short of the intended 150% threshold. With the A380 the wing is out of aluminium and the wingbox out of composite and for this configuration the models at Airbus were apparently very accurate indeed. But does this mean that the construction is safe when applied to all-composite. The 150% threshold is based on long experience with aluminium aircraft and is now adapted for configurations partly (A380) or completely (787) out of composites. Only time will tell whether such threshold is sufficient with such designs – in particular out of all-composite.

Travelled work

Continuous redesigns, problems with extreme tolerances, special tooling and specifications for drilling and placing and shortage of fasteners in particular led to complete chaos - first at the partners and than at Everett were units arrived provided with temporary fasteners, wrong fasteners, wrongly placed fasteners, wrongly positioned fasteners, wrongly drilled fastener holes, fasteners installed with stacks of washers as work around for improper length and fastening points that were overlooked, not to mention the general quality of the fastening points including possible strengthening - in what came to be known as travelled work. It is not so difficult to imagine how this worked out on the global work floor:

> *An engineer at Boeing inspired by the whatever it cost's policy to save on weight has set another milestone, saving 1.05 pounds on an element near the wing box. Brilliant at first sight, it requires revision of some fifty drawings involving parts at three different overseas partners - some of these drawings had already been revised more than fifteen times. The partners have by now passed the stage of frustration and just except what comes in from Boeing. One Japanese partner who could no longer deal with the endless stream of redesigns had to call in an extern engineering office to supervise and coordinate only the revisions involving fourteen engineers. They now receive revision number eighteen from that particular 1.05 pound saving element and try to figure out what the consequences are. This time the change is not so dramatic. Actually less holes have to be cut but with stricter tolerances. The workshop had just set new standards in achieving 0.05 tolerance - now it must be 0.03. This can be done but requires a new robotic laser guided tool costing 350K - not Yens but Dollars. The accountant still gets upset and asks Boeing who is going to pay for this. Boeing agrees to take 50% but than it appears that delivery time is 13 weeks. The workshop decides to go on with production and do the corrections afterwards. After 16 weeks the new tool arrives and after some mistakes that destroy two elements they get control of the tool and finish the parts - a new tolerance record is set but now two parts are missing. Production is asked to deliver two extra parts - takes ten weeks - such problems always seem to take ten weeks. At the assembly they find out that new fasteners are required. These have been*

> *ordered immediately but purchase forgot to inform that delivery time is again ten weeks. When Boeing is informed they know already about the problem with the fasteners, 'the Chief is personally dealing with it and delivery will be advanced'. After three weeks still no fasteners and everything is ready for shipment – the Dreamlifter is to arrive within two weeks or so. Also the replaced elements are not yet ready. A young Japanese assistant suggests that Boeing can send down a F22 to pick up the unfinished parts later - he is fired. By now Boeing is receiving complaints about the fasteners from all partners. Unknown to management, a Boeing engineer at the work floor works out a new strategy. 'Send down the parts but mark where fasteners are missing than we will fix it over here. Signed Fred'. What Fred does not know is that the Japanese get paid the moment the parts are aboard the Dreamlifter. 'Dear Mr Fred, Sent Dreamlifter five times, kind regards, Signed Hiroshi'. In Japan a small army of engineers begins marking. The Chief is just leaving for the 2007 Paris Air Show when he gets the good news. 'The Japanese seem finally to have things under control - all of them'. The next day the first Dreamlifter rolls in at Everett. Everybody is exited. The Chief decides to make a stop in London and arranges an informal gathering with his Japanese friends at a Park Lane roof bar. Later, back in his suite he tells his secretary 'perfect guys these Japanese but who the hell is Fred'. Five days later all production halls in Japan are empty. The problem is now back where it started but it was getting a pretty mess at Everett - with what is now called travelled work - most of the markings were in Japanese. Fred took the last Dreamlifter outbound and decided to stay in Japan.*

It soon became a mess in Everett - indeed - as the Chief later reflected when he was replaced - *'That whole production system is built for 1,200 pieces.....everything about it was designed for 1,200 parts......we threw 30,000 at it'* 61).

Problems no problems

Instead of informing their customers and shareholders and the FAA - and put things in order with the buckled wing box, the shortage of fasteners, problems with overseas partners, problems to comply with special conditions for certification and the alarming overweight, to mention a few - Boeing decided turning a blind eye and to roll out the first Dreamliner before a jubilant crowd of 15,000 - backed up by another 25,000 in a nearby stadium - at 4:25 p.m. on the 8th of July 2007, blindly driven by their successful marketing. To Tom Brokaw the honour to emcee the probably biggest marketing hoax ever - calling the 787 *'a rock star of the future'*[275). The press loved it *'the backdrop parted and sunshine glinted off the blue and white aircraft fresh from the paint shop as it was tugged closer to the building. As is Boeing's tradition, everyone rushed the plane for a closer look; Vivaldi's Four Season's played from the speakers'*[275) - undoubtedly inspired by the roll out of the 'Skyfleet airliner' at Miami Airport featured in the latest James Bond.

Indeed, there's no business like show business - all that was presented was a Hollywood version of what looked like a 787 - a patch up with temporary clipped outer skin painted in Boeing's signature. Difficult to believe, but this was really all that had been achieved and nobody noticed. Everybody seemed too exited. Boeing - *'history making'*[315) - the launch customer *'epoch making'*[320) - another customer *'this is precisely the kind of milestone in the industry we need'*[275) - the analyst *'it will be revolutionary'* - the consultant *'the 787 represents an entirely new way of producing planes'*[85). The test pilot who was introduced to the press and was supposed to fly the first 787 by September apparently did not have a clue -*'It's just cool to see all hours of hard work and ideas come together'*[63). One customers felt left in the dark - *'You'd think that if you buy 74 airplanes, they'd let you take a peek'*[63). But nobody, absolute nobody, questioned the status of the other five test aircraft - there were none.

Boeing maintained that 'this hollow thing' would make its first test flight within a couple of months - *'the first test flights won't happen until a month later than originally scheduled - But Boeing executives insist that the first plane will be delivered to ANA on time'*[320) – confirmed by The Chief *'We have no intentions to be late into service'*[64). But time goes by and one day in September Boeing had to admit production problems - that first flight would be delayed three months until December - but this *'would not affect first delivery'*[276). When a reporter informed about the certification timeline - no problem there either *'doing around-the-clock flight-testing. We're essentially going to be running an airline, 24 hours a day, seven days a week'*[65). The market got a bit concerned but gave Boeing still the benefit of the doubt - a senior strategist - *'this is a large public company.*

They can't afford to be arrogant and mislead in any way' [276]. Already October 2007 first official delays had to be announced concerning first delivery and The Chief was to be replaced [66] - he had completely lost oversight, not to say touch with reality. How to call it - mislead, deceive, betray, beguile, delude, dupe, hoodwink, bamboozle, double-cross - difficult to say. Analysts were quick to point out that the delay - then six months only - *'could wind up costing Boeing $1 billion'* [67]. Much longer delays were to follow.

'Neither pleasing or displeasing'

Everybody saw it coming but the move comes apparently as a surprise for the outgoing Chief. Somehow he lost control and in the end he was probably under too enormous stress to perform and pressed this stress upon his organization to a level apparently far beyond the human limit [343]. That can work on an incidental base but is bound to backfire when applied for too long. Here it apparently did, but who is to blame. Probably all management involved.

They should have send him right away, for a couple of months or so on leave to Hawaii - pay and perks - to come to terms and to improve on his handicap with his carbon fibre shaft titanium headed golf clubs. They didn't and now it was not particular helpful when the former Chief publicly blamed his former partners - it is understood a bit out of frustration - and used rather blunt phrasing [68]. A bit of an embarrassment for the new Chief - *'neither pleasing or displeasing'* [69] - who now had something to explain in boardrooms in Japan:

> *The boardroom in Japan, tea just served, smiling as always 'yes we understand now unks-unks'. The Japanese do want to know what Boeing means with a 'super-site concept' - because that is what they have in mind already for quite some time on a new island to be raised next to Osaka's Kansai Airport. Also 'build-to-print' appeals to them - 'you Americans have so good ideas but always little late'. But then things get serious in the Japanese boardroom when the CEO hands over a photocopy to the trusted Boeing vice president, who already noted that there were quite some papers from Airbus*

> *floating around on the table. The copy heads 'Boeing may junk worldwide assembly for next year* (68) *' and the CEO asks in his best English 'What does jonking means ?' Another executive sifting through his Airbus letters hands over another photocopy that's heading 'Some of these guys we won't use again* (68) *' and asks 'Hho is Gay?' The Boeing's vice president's secretary – lovely lady had already caught the eyes - starts now sifting through her papers, some from the White House, and with an irresistible smile hands over a personal letter from the new Chief that reads 'We are going to do what we need to support out partners at this crucial time...'* (70).

Trying to regain oversight

Confident to fix the problems - *'the schedule is the schedule'* (16) - the new Chief started of *'stamping a voice of authority across the entire program'* (69) reorganizing the 787 division with *'one of the first things to 'retire' the development teams because the 787-8 model is now 100-percent designed'* (71) - clearly not informed yet about all problems. At a conference call December 11th 2008, the new Chief is still fully confident that *'the plan we announced in October for the 787 is unchanged: to fly the first aeroplane around the end of the first quarter of 2008 and begin deliveries in late November or December time frame, and to deliver 109 aeroplanes in 2009'* (277) and then detailed some fifty issues indicating that was fully in control.

But soon enough the new Chief soon found out that trying to regain oversight proved to be much more difficult than expected *'Boeing has solved the big problems but remains frustrated by small details in the process'* (72). He had to deal with the partners who bear a substantial part of the $10 billion development costs and were now not only facing logistical problems because of endless tweaks in the design and production, but also problems with cash flow and more delays were to follow - but no more conference calls.

Already April 10th 2008, the new Chief had to issue a third revision to the delivery schedule and a fourth delay to the 787's inaugural test flight, bringing the project some seventeen months behind the original schedule - or about 150 aircraft representing $ 22,5 billion in late revenues at 2007 list price. According to the revised schedule, the first test flight wasn't expected to take place until the fourth quarter of 2008, first delivery was pushed back to the third quarter of 2009 and the production rate for the aircraft was expected to reach 10 a month not before 2012. And it would get worse, much worse.

Closely involved

Most worrisome is that the Federal Aviation Agency (FAA), who claims to be closely involved with the project since 2002 73) did not notice developments at that time and declared - September 2007, just days before the first delay was announced - that they agreed with Boeing *'to squeeze flight testing of an entirely new breed of jetliner into just five months using six aircraft, starting January 2008 '*73) - also ambitious to the extreme. Certification of the 777 took 11 months of flight-testing and involved nine aircraft, back in 1995. Again the FAA *'The 777 program was, however, inherently slowed by three engines needing approval compared with the 787's two, and less computer modelling than is available today'*73). But the 777 is a rather conservative design when compared to the first time ever all-composite 787 with large section design never tried before. The fuselage is out of five large sections and the wings each out of one part. Computer modelling may have advanced during recent years but cannot be relied upon with the certification of complicate composite structures because the programs haven't been properly validated yet. Moreover, the 787 is designed as a first *'more electrical plane'*73) that generates 1,450 MW of electrical power - five times that of the 767 and enough to supply 400 homes - to power *'a host of new technologies'*74), all of which requires careful testing for certification 75). It is therefore realistic to assume that certification will be far more complex than with any aircraft before and will take much longer than presently anticipated, that is, when not too big problems surface - which cannot be ruled out given the troubled history of the project. Some eighteen months is probably a more realistic time frame. But at that time - 2007- the 787 could not have been certified anyway, because Boeing was still working hard to meet some 16 special conditions issued by the FAA.

Special conditions

The FAA issues 'special conditions' when an airplane will have novel or unusual design features when compared to state of the art technology that aren't addressed by existing regulations and standards. Special conditions contain normally additional safety standards and it's up to the manufacturer to demonstrate to the FAA that the airplane meets these standards. With the 787 these involve, amongst others, crashworthiness and lighting strike protection, the latter closely related with special conditions that deal with fuel tank safety.

Some special conditions were resolved by May 2009, with others progress is not clear. Worse, it now appears that Boeing can't meet the special conditions for lighting strike protection but that does not pose a problem since FAA now agreed – officially it is still a proposal - to relax fuel tank safety regulations 322). Furthermore, there is still an important topic that is not covered by special conditions - yet.

When lightning strikes

Aluminum is one of the best conductors around and provides the aircraft excellent protection when lighting strikes. With composites the probability to trigger a lightning bolt is about the same than with an aluminum structure, but composites behave more as insulators and do not readily conduct lighting away as aluminium does. This means that all-composite aircraft are most vulnerable to the extreme electrical currents that are generated when the aircraft is hit by a lighting strike. Joints are susceptible, fasteners in particular. Fasteners that will be discussed in more detail later are used to secure the skin of the aircraft to an underlying support structure. For example the wing skin is secured by fasteners to the framework of ribs, spars and cross members. When the aircraft is struck by lighting any fastener in the skin concentrate current and are sources of arcing and sparking - that can cause the composite to heat up and might even catch fire. Any gap between the fastener and the composite and in other parts of the structure that can cause spark has to be avoided. The danger of sparking is particularly serious near fuel tanks where even a tiny spark can be disastrous and has to be avoided at any cost.

§ 25.981

Ample reason for FAA to issued 'special conditions' - in addition to earlier recommendations (330) - that demand Boeing to provide clarification of the lighting strike requirements, in particular that the 787 complies with requirement § 25.981(a)(3) from Amendment 25-102, that explicitly rules that any anticipated latent failure condition does not leave the airplane one failure away from a catastrophic fuel tank ignition:

> 25.981(a): *"No ignition source may be present at each point in the fuel tank or fuel tank system where catastrophic failure could occur due to ignition of fuel or vapors. This must be shown by:*
>
> *"(3) Demonstrating that an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and from all combinations of failures not shown to be extremely improbable. The effects of manufacturing variability, aging, wear, corrosion, and likely damage must be considered."*

With lighting strike protection FAA pursues a dual approach that focuses on the probability of ignition sources in and in the direct vicinity of the fuel tanks and on reducing the flammability of the fuel tanks.

A multilayered approach

Boeing recognized already at the early stages of the development that the composite structure of the 787 is much more vulnerable to lighting strike than an aluminium structure. Boeing has cooperated on this issue with FAA since 2004 with a team '*to assist FAA in wording and interpretation*' 299). Boeing and FAA decided for a multilayered approach to comply with rule § 25.981(a)(3) - that was believed to guarantee the 787 a lightning strike protection similar to that of aluminium aircraft. Electrical continuity in the composite frame is obtained through a wire mesh that is embedded in the composite skin. Extremities of the aircraft where lightning is expected to attach - wing tips, engine nacelles, horizontal stabilizer and tail - are provided with copper foils that has an even lower electrical resistivity than aluminium mesh that is used at the other faces. Possibly sparking at the fastener points is avoided through close spark free fitting of the fasteners and as an extra precautionary measure the heads of the fasteners are sealed on the inside of the fuel tank. Also any gap inside the wings that could cause edge glow - that is spraying of electrons in a lightning strike - is sealed. As a last line of defence it was decided to install an inerting system that keeps the spaces in the tanks above the fuel filled with inert nitrogen during the flight, a rule issued by FAA - July 22, 2008 - that applies since to civil aircraft in general 321). These all sounds reassuring but at closer look these measures do not provide the safety that is achieved with aluminium aircraft where lighting strike protection comes with the material - that is essentially for free. Certainly not in the way FAA is interpreting the rules.

Catch 22

By 2008 it became clear that the structural layers did not provide the lightning strike protection that was hoped for. According a high level Boeing lighting expert '*Boeing spent years trying to develop triple layers of structural lightning protection for every 787 fuel tank fastener and joint, but we were unable to identify the technical means at many locations in the wings*' 299). It proved to be extremely difficult - they could have known - to obtain the intended electrical continuity because of joints and other discontinuities. Also spark free and arc free fitting of all fasteners and the application of cap sealing proved to be more complicated than anticipated - the quality depends largely on skill of the mechanics and adequate inspection procedures were not in place. But even when the work could be correctly executed, it is virtually impossible to maintain structural integrity during the long service of the composite structure, up to forty years, because of damage, wear and repair - and again difficult for inspection. FAA now admits that inspection of features inside fuel tanks involves a Catch 22 - *'this requires access to the fuel tanks, which is usually only scheduled a few times during the life of the airplane. Increasing the frequency of internal fuel tank inspections could have the undesirable effect of increasing the possibility of damaging the lightning protection features or other design features during the inspection process'* 322).

Quite embarrassing

Deemed necessary five years ago - Boeing now argue that the multilayer approach is impractical and recognizes also that *'reliable inspections and monitoring for various structural design features may not be feasible'* 322). Quite embarrassing for Boeing and even more embarrassing for FAA who now accepts Boeing's 'impracticality' argument and proposes an amendment that loosens fuel tank safety rules in rather dramatic way. Difficult to understand that all of the sudden - *'instead of requiring three independent protection measures for any feature that could cause sparking or arcing, the revised policy would allow to have just one safeguard'* 299) - breaking radically away from the traditional concept of redundancy for safety. Even worse, that one safeguard can't be relied upon either.

Not an essential element

It appears that inerting is not the last line of defence but the only one left that can be relied upon. Apparently not so according FAA. Although compulsory, inerting is seen by FAA as an enhancement to safety and not as an essential element of layered safety. This means that only one inerting system has to be installed - no back up system is required. Moreover, FAA allows for that lone system to be inoperative in case of malfunction for 10 days awaiting repair, allows that only the heated wing tanks have to be inerted and allows for maximum 12% oxygen in the tank (247) instead of 9% that is generally deemed necessary to guarantee effective inerting (342). It is also allows for internal ignition sources like fuel pumps, conduits, wire and so on to be routed through fuel tanks. This means that the inerting system will contribute in only limited way to lighting strike protection.

Practicality approach

The practicality approach now proposed by FAA is rather confusing. So is the installation of arc/spark free fasteners provided with cap seals inside the tank regarded as practical - but the installation of double cap seals to retain of a bolt that fails under tension is considered unpractical. Labelled as unpractical to provide fault tolerance - that is the property that enables a system to continue operating properly in the event of the failure of some of its component - are fatigue cracks within structural elements, failure that leads to separation from the hole including complete fracture of the bolts and failure of sealants. The approach - however vague but deemed practical by Boeing and FAA - appears to concentrate on more structural design review that indicates critical areas, on engineering reviews that identify failure modes of design, on manufacturing process and on service history records and instructions to identify critical design configurations that might affect airworthiness. Indeed, rather confusing and difficult to understand the underlying reasoning.

One in a billion

FAA regulations demand a cold statistical outcome (322) in that the design of the 787 has to insure that the chance of lighting sparking a fuel tank explosion in flight is less than one in a billion - based on safety analyses that have to be worked out and show that the risk of catastrophic vapour ignition in the fuel tank system due to lighting is extremely improbable and is on the order of one in a billion during operation at worst case scenario. The analysis has to demonstrate acceptable safety and not the equivalent - at least - that is obtained with aluminium aircraft that are apparently no longer benchmark. For such analyses one needs a sophisticated computer program and a very large and powerful computer - 'that is the first to fail when lighting strikes'.

Safety assessment involves Monte Carlo analysis 326) that considers such parameters as the probability of fuel tank vapour flammability, the probability of lighting, the probability of lighting attachment including the location, a distribution of lighting wave fronts and with it a distribution of lighting strike energy. And many other data have to be included such as volatility of the fuel or how the flammability envelope is effected by the so-called flammability drivers - temperature and pressure - and the expected effectiveness of the structural protection layers and the way the inerting system can be considered to contribute. The tank is considered non-flammable if *'either the tank is outside the flammability envelope for the fuel on board, or the oxygen level is below 12%'*. Analysis should focus not on individual aircraft but on the fleet - the estimate is to be *'a new fleet average flammability exposure limit of 3 percent of all fuel tanks'* 324). Based on the results of such analysis FAA will consider granting exemptions from requirement 25.981(a)(3) - that apparently can't be met by Boeing with the all-composite 787 - but the foregoing discussion illustrates that neither way reliable protection is obtained, whatever the outcome of the analyses.

Fierce opposition

May be existing regulation is too strict and may have to be revised in some way but it appears that to obtain reasonable lightning strike protection the thickness of the composite skin has to be significantly increased and hence becomes a serious weight issue. Standards issued recently by the UK Ministry of Defence dictate that with skins enclosing fuel *'many years practical aviation experience has shown that 2 mm thick aluminium alloy provides acceptable lightning strike protection'* but with composites the skin *'should in any case be not less than 5 mm thick'* [323]. FAA seems to have a different view and argues that because *'to this day...not one manufacturer has been able to demonstrate compliance with that rule [§ 25.981(a)(3)].... it's time to re-evaluate our approach'* [322] and now proposes to permit only one system for lighting protection - leaving the airplane in a lighting storm *'only one failure way from catastrophe'* as the engineers involved put it [299].

No wonder that the proposal stirred fierce opposition, most noticeably from inside the local FAA office where technical specialists responsible for certifying new airplanes do not agree with their management - *'the national union representing about 190 Seattle-based FAA engineers submitted a formal critique to the agency, calling the new policy "an unjustified step backward in safety"'* [299] - other experts agree [324] [325].

As indicated before, the 787 is a first more electrical plane and it has yet to be seen whether an all-composite structure can safely protect all this electric circuits and electronics and so on from damage and be shielded form lightning strike currents and electromagnetic fields - which might pose an even greater risk than the fuel tanks.

Other special conditions

With regard to special conditions issued for crashworthiness [203] tests have been performed [329] but the results are disputed [328]. Boeing comments that *'We have to demonstrate [to the FAA] comparable crashworthiness to today's airplanes........we are doing that'* [328]. Further results have not been made public by June 2009. Special conditions have also been issued with regard tire debris penetration of fuel tank structure [247] - by June 2009 the status was still unknown. Also rotor fragment burst impact has to be considered and the possibly necessity of fragment barrier systems when a rotor disk of a main propulsion engine fails and broken engine fragments can damage the fuselage section of the aircraft [396)]. Closely related with lightning strike protection are special conditions that deal with composite fuselage in-flight fire/flammability [243)] and composite wing and fuel tank structure fire protection [244)]. Recent research by the FAA shows that aluminium fuel tanks behave indeed very differently from aluminium fuel tanks [245)]. According the researchers involved, much research has still to be performed in this field to be able to properly evaluate all safety aspects - and certification might be a bit premature [258)]. Flammability of composites appears to be much worse than Boeing's test results suggest, as will be discussed in more detail later. An important topic that is not yet covered by special condition - but has been studied by FAA [248)] - involves health hazards related to contaminated respirable fibrils that are released in great quantity when carbon fibre composites catch fire, and will also be dealt with later.

What's left is improved flying experience

When substantial lower weight is not attained and when savings on fuel and maintenance are not attained as promised, all what's left is improved flying experience - *'the 787 might be the first plane that passengers actually choose to fly because of new interior amenities, such as more pressurization, more humidity, bigger windows, more room as well as a lower carbon footprint per seat'* [77)].

The superior strength of the composite fuselage allows for higher pressurization in the passenger cabin, which means that it is easier to control temperature, humidity and ventilation. Cabin pressure will be set for a lower, more comfortable altitude - 6,000 ft down from 8,000 ft. Cabin air is provided by electrically driven compressors using no engine bleed air, reducing the smell of fuel. Ozone is removed from the outside air and an advanced cabin air-conditioning system provides better air quality - air purification filters will filter out microscopic particles - bacteria, viruses and fungi.

Relative humidity will be up to about 15% from the industry average of about 5% and the aircraft's insulation is designed to resist build up of moisture Not mentioned is that composite's lower mass provides less sound isolation - but Boeing is isolating certain loud functions with the 787, such as pumps and motors, and using sound absorption technology to further reduce the noise to the cabin. Boeing promises also a smoother ride with less turbulence because new technology is applied - horizontal gust horizontal gust suppression is already applied with the 777 and the 787 is also equipped with vertical gust suppression. These systems dampen the magnitude of horizontal and vertical motion that passengers experience when the aircraft is hit by turbulence, but one has to await vibration. According Boeing, a composite fuselage allows for much larger windows. As indicated before, larger windows were also promised with the Comet. With the 787, windows will be 10.7 in by 18.4 in - 60% bigger than the 777 and 80% bigger than the Airbus 330 and A340 - but then they found that some windows had to be eliminated because they interfered with a joint.......7). The 787 has ditched window covers for electronic dimming control - *'A circular control button under each window has five settings that allow passengers to change the amount of light that comes through the window. The electrochromic window, from PPG, uses an electrical current to darken a conductive medium between two layers of glass'* 78).

> Aviation is one of the fastest growing contributors to CO2 emissions, producing about 3 per cent of all EU CO2 emissions - more than oil refineries or steel works. Experts forecast that airlines will account for 5 per cent of global warming in 2050 394). As for the promised lower carbon footprint with the 787, composites do only contribute when significant saving on weight is attained and that has yet to seen. It appears that most reduction comes from the new powerhouses - also because of large-scale application of composites - but these engines can also be fit with aluminium aircraft. With similar trust, these powerhouses are claimed to consume some 20% less fuel, emit about 20% less CO2 and cut NOx emissions about by half and provide a noise footprint

50% lower than the 767 79) - but rumour has it, as was indicated before, that with testing specific fuel targets have been missed with some 2% to 4% 7). Another promising approach is biofuel - where very good results have been obtained on a two hour test flight with a 747-400 - that indicates that a 50/50 blend of jatropha based fuel and standard jet fuel could cut fuel burn by 1.2% and CO2 redution of 10-75% 395). Savings obtained with more efficient engines and bio fuel apply of course also to aluminium aircraft.

All this will undoubtedly please many - CO2 reduction in particular - but with all-composite civil aircraft public's perspective will focus above all on the most important of flying experiences - *safety* - which has not been properly addressed by either Boeing nor Airbus nor FAA so far, as will be discussed in more detail later.

A monolithic approach

The 787 has a length of 182 ft (56m) with a cross section of 19 ft (5.8.m). Wingspan is 197 ft (60m). The fuselage will be the largest composite pressure vessel ever built - much larger than anything attempted before and has to hold at extreme conditions. The same applies essentially for the wings. With the fuselage the engineers opted for a barrel approach. A one-piece fuselage has been considered but now consists out of five large monolithic sections - forward, aft and three centre barrel sections up to 42 ft (13m) long - supported by titanium and composite frames that are fastened to the composite hull. The wings are each out of one piece and the tail section contains the horizontal stabilizer and vertical fin section. Also the large wing box, the keel beam and most of the frames and many other primary structures are out of composites - probably more so than originally planned to try to save on weight.

At the early stages of the design the thinking was that such large one piece sections are very strong - *'the structure of the 787 is essentially one giant macromolecule - everything is fastened through cross-linked chemical bonds reinforced with carbon fibre'* 80), that this enables maximum saving on weight - *'we ended up saving out three times what we were on the original design'*, that the one piece barrels are not too difficult to manufacture with state of the art technology - *'the innovation is not just in the materials, but how they build the tooling'* (80), need only a few major joints and require much less overlap - *'we don't have lap joint because we wrap them up'* (80), limit the number of fastening points beyond belief - *'one metal barrel requires some 1,500 sheets of aluminum held together by nearly 50,000 rivets...with plastics, the number of fasteners drops by 80%'* (80), that with composites *'the advantages go beyond weight saving'* (80) in that they need much less inspection - *'the composite 787, in contrast, may remain in service for 12 years before its first structural test. By staying out of the shed, the Dreamliner can make up to 113 additional flights'* (80), provide suburb aerodynamics - *'there is a giant coalescence of manufacturing technology, materials technology and forming that might actually allow us to make another jump in aerodynamic performance'* (80), allow for complete prefabrication for easy and quick assembly at Everett - *'the target for 787 final assembly in Everett is three days',* although *'this time frame does not include wing and tail integration that will be done in parallel feeder lines in Everett before final assembly. Nor does it include painting and testing that follow rollout'* (81) - and more features were envisaged - *'your structural system can also be a part of your acoustic damping system. It can also be a part of your thermal transfer system and your electrical system'* (80). Before long, design and production of these large one-piece units proved to be far more difficult and complex than ever anticipated - a happy dream turning nightmare - large overweight and long delays could not be avoided.

Large production units come with large capacity

The moulds, mandrels, automated tape layers and autoclaves for curing the large barrel sections, enormous wing box, complete wings and so on, represent very complicated often unique specially developed manufacturing technology. So are the autoclaves really huge robust high-pressure ovens - presently the largest in the world - with sizes up to 33 ft by 82 ft (10m by 25 m) and the design and construction demands extreme engineering 82). Large production units come with large capacity, which makes it very expensive to expand when only limited extra capacity is needed. Moreover, malfunction can occur, not to mention when such huge autoclave blows-up, it happened before - *'we had a little campfire last night'* 66) - when a piece of wood was left accidentally in the autoclave at one of the partners, or when a production unit breaks down otherwise beyond the possibility for repair. These units cannot be bought from shelve and the extreme engineering requires rather long delivery times not to mention the costs involved. Boeing's overambitious schedule does not leave much buffer neither for expansion nor any breakdown, with production slots already closed for years to come - but this might all change due to present economic problems, as has been discussed before.

Lay up rate

The fuselage sections are manufactured with newly developed robotic single head tape layers for computerized circumferential placement of composite tape on the cylindrical shaped mandrel that is rotated as the tape is applied 83). Openings for windows and doors and so on are cut out after curing when also the holes have to be drilled for mechanical fastening of the frames. It is not possible yet to include composite frames in a way that they are co-cured with the hull - avoiding mechanical fastening 'altogether' - but present mandrel technology allows for the thickness of the laminate to be varied. On the other hand such co-curing might introduce electrical discontinuities, as will be discussed later.

Automated lamination requires sophisticated software to assure that material lay-downs follow the desired path across the contour of the tool. Individual courses of material are programmed to meet component design criteria including gap and placement as well as ply orientation and thickness that are tailored to the requirements of specific location. Input to the programming software includes tool surface definitions, ply boundaries, ply orientations and machine processing parameters. Regardless all automation, a lay-up rate is attained of only 19 lbs/hr only 7), way down the intended rate of 80 lbs/hr. Even with two head machines, which are not available yet, lay up is expected to be limited to some 30 lbs/hr - a major set back to attain the scheduled production rate. After wrapping the mandrel is cured in the autoclave.

Exact curing regimes

With autoclaving many problems have still to be overcome. To meet the strict tolerances and to limit residual stresses and possibly excessive microcracking, curing temperatures have to remain constant during curing and cooling - that is within 1.0 to 1.5 ^{0}C - throughout the structure and this is a main challenge at this scale with each curing cycle. Exact curing regimes have to be worked out to be able to cope with the enormous differences in shape, size and thickness of the fuselage sections and the wings, not to mention the enormous wing box.

The shell structures of the fuselage sections of the 787 are for example up to 42 ft / 13 m long with cross diameters up to 19 ft / 5.8 m but thickness is typically some 2 to 3 mm along the underbelly and the upper fuselage, some 5 to 7 mm on the wings and between 6 to 8 mm in areas that surround doors and other cut outs that are prone to impact damage. On the other hand the all-composite centre wing box is massive - 17.4 ft /5.3 m long by 19 ft / 5.8 m wide and 4 ft / 1.2 m deep at its thickest point. Then there are the enormous wings and al kinds of frames and beams and so on. All of which require a totally different approach - mould design, prepeg lay-down, curing procedures and regimes, demoulding and preparation for assembly.

As indicated, the barrels are not yet tailored for final design and cut outs have to be made for the doors and windows and hatches. Cut edges need processing, stringers have to be placed and so on, which involves much extra work. Very precise water jet cutters are applied to avoid overheating of the laminates when cut for correct size. The fuselage frames - partly composite and partly titanium - are then attached to the fuselage skin with shear ties that are mechanically fastened to the frames and skins. This requires still a relative large amount - many thousands - of fastening holes to be precisely drilled. The cut outs and perforations weaken the structure of the hull in significant way, also because damage to the composite - fibres are cut - can't be avoided. Also with cutting and drilling there looms always the danger of delamination or other debonding and this has to be avoided - at any price - as will be discussed later but this is very difficult to achieve. Loss of structural integrity has to be compensated for by increasing the thickness of the laminate, at least in the direct vicinity of the holes and cut outs. This requires very strict inspection - involving complicated non-destructive testing on continuous base - not particular easy at the scale here involved. The sections are then prefabricated with all equipment and wiring to be transported on a modified 747-400 cargo jet - Dreamlifter - to Everett to be fixedly joined together within some three days - that is at least the aim.

Large scale joining

Even more complicated is the joining of these very big sections 84). The enormous joints that connect the barrel sections have never been tried at this scale and extreme loading and had to be complete newly developed for which fastening technology had to be stretched to its absolute limits. These joint constructions form potentially the weakest part within the airframe construction but experience extreme loading. Each joint presents a structural discontinuity where loads have to be transferred including vibrations. The joints should also provide electrical continuity to deal with lighting strikes. Peak stresses must be avoided because lack of plasticity of composites limits stress redistribution as will be discussed later - stress concentrations at and around the joints can become so extreme that they decide the design boundaries of the entire structure.

With aircraft, joints must be light, must form a continuous part of the lightning strike protection system and must allow for disassembly when a barrel section get damaged beyond repair in service - but it will remain extremely difficult if not impossible to replace a large barrel section at an airport, certainly so when also the joint has been damaged and might require two barrel sections to be replaced - or about half the aircraft.

Joining can be achieved through mechanical fastening, adhesive bonding and welding. Combinations are possible and the construction can involve dissimilar materials. Only mechanical fastening allows for disassembly. Where aluminum parts come in contact with composites an insulating layer has to be used to avoid galvanic corrosion and it has to be taken into account that metals and composites have very different stress and thermal behaviour. Mechanical fastening involves numerous holes and fasteners at which fasting points stresses concentrate that have to be redistributed. Adhesive bonding provides a stiff connection, makes it possible to distribute the stresses and hence limit peak stresses, is light and provides normally a more durable construction. However, application requires very special adhesives and thermal curing when such very strong aviation bonding is required. Note that these adhesives have very poor conductivity and cannot safely transfer lighting current - as will be discussed later - adhesive joints are therefore not used with primary structures. Welding is also possible but this technology is still in development for application at this scale. That leaves mechanical fastening as the only option for primary aircraft structures.

Mechanical fastening

With aluminium a very large amount of fasteners has to be placed - and there is much overlap - but fastening is essentially a simple task. Just drill a hole about the correct size, make sure that it is perfectly smooth and screw and bolt the sections together, if not punched. Repair is easy. Large composite sections require much less fasting points and much less overlap, but drilling of the holes and placing of the fasteners is far more complicated and critical than with aluminium. Repair is rather complicated. One can question what weighs more - structures held together by a large number of simple fasteners or a smaller number of extremely complicated ones. With composite fastening clear instructions and appropriate quality assurance procedures must be in place as well as qualified engineers. That's where Boeing completely failed.

With composites, titanium fasteners are used to avoid galvanic corrosion. Such fasteners are extremely strong and the configuration is tailored to provide optimum performance. This makes it possible to limit the number of fasteners but peak stresses should not be exceeded - stress concentrations that occur at the holes and cutouts in the composite put a boundary. Boeing has not released exact figures but claims that the 787 has 80% less fasteners than a comparable aircraft made out of aluminium 9). A rough estimate for the 787 is 350 to 400.000 most titanium fasteners - taken into account that the 767, slighter smaller than the 787, has about 1.8 million most aluminium fasteners and the 747 some 3 million.

It cannot be avoided that the composite gets damaged with drilling and significant strength is lost, as will be discussed later. Any discontinuity in the lightning protection system has to be restored. Certain holes have to be strengthened to obtain the necessary bearing load. This can be achieved by providing the overlap with an extra layer of laminate or otherwise adjustment of the composite configuration. Another approach is bonding of doublers or inserts, but these can cause great problems with replacement and repair.

The joints have to be very accurately aligned and the fasteners must be placed with extreme accuracy including any sleeves, washers and sleeves - and might require special encapsulation to avoid arcing and sparking when lighting strikes, as will be discussed later. Any damage has to be repaired, but it is very, very difficult to repair a damaged fastening point in a way that tolerances and structural integrity are met. These procedures require special tooling as well as very well trained and dedicated engineers.

Most important is effective inspection of each hole, of each damaged hole, of each repaired hole and of each placed fastener. This involves non-destructive testing that is time consuming, and sufficient qualified inspectors and testing equipment must be in place. Contrary to aluminium, with each fastening point the installation mechanic and the inspector must sign off that the hole has been correctly drilled and is not damaged, and that the right fastener is correctly placed and coated when specified. The lightning protection systems have to be dealt with in similar way.

Some weight was saved - may be - much less than expected and came at a huge price - far higher than ever anticipated. Holes must be straight and concentric - many with countersinks and have to be drilled within extremely tight tolerances. Each of the thousands of fasteners has to be placed with great accuracy - as indicated before any gap must be avoided because of possible sparking when lightning strikes. When the structure attaches a lightning bolt currents are generated that can travel along the fibres. Any discontinuity in this path can cause a spark, most noticeably where the current reaches the end of a fibre where a hole has been drilled. When there is an even minuscule gap the current can jump to the end of another fibre causing a spark that releases energy - possibly enough to heat up the ends of the fibres that might even to catch fire. Near the fuel tanks an even a tiny spark can be disastrous. This poses a real problem with composites where each fastener is a potential source of sparking and arcing. Drilling of the holes and spark fit placing of the fasteners proved to be far more complicated and costly than was foreseen to a level that it would sink the project. At a rather late stage Boeing decided for another type of fastener – and drilling was automated wherever possible 238).

Those tiny fasteners

It appears that the problems with the fasteners were grossly underestimated for too long if not totally ignored. Fasteners have caused serious problems from the early start of the project when some pulled right through the composite. When first delays were announced back in 2007, Boeing blamed shortage of fasteners on the world market to be the cause of the problem 87) - not that late design change was at the root of problems.

Initially Boeing used a press fit and a sealant to overcome any gaps between the fastener and the hole, but engineers discovered that with this method *'unexpected amount of sparking inside the 787's wing tank caused by gaps between fastener heads and sleeves........thousands of fasteners had to be turned around, putting the heads on the outside instead of inside the fuel tank... for those fasteners that couldn't be turned around,* *a brush coat of sealant was added as an extra precaution'* [299].

To solve the problem the fasteners were completely redesigned to tapered sleeve bolt type - according Airbus [7] an infringement of one of their patents [331]. The sleeve expands to fill the hole but prevents damage to the hole and avoids sparking and edge glow within the fuel tanks. Unfortunately, these fasteners had a production lead time of some 60 weeks. To avoid further delays partners were instructed to install temporary fasteners that would be replaced at Everett, which led to travelled work discussed before. What Boeing didn't mention - and probably did not realize until recently - was that with composites removal and replacement of fasteners is a rather complex issue and requires very strict instructions and even more strict quality control procedures, much stricter than were in place.

> So can with travelled work a hole be found to be damaged because of incorrect drilling or because of temporary fastening. Damage can also occur during removal and during replacement and when the hole has to be adapted for correct diameter, countersinking or for tolerance or has to be strengthened otherwise. Wrongly positioned holes have to repaired and new holes to be drilled and possibly re-strengthened. It can be necessary to take large sections apart to provide sufficient access and room for removal of wrongly placed fasteners to be followed by inspection, possibly repair of the hole, replacement and final inspection. During these procedures other parts of the structure can get damaged as has been indicated before. Most important, electrical continuity and galvanic protection have to be maintained. Contrary to aluminium, composites can already be seriously damaged when a tool is dropped on the skin by accident and such damage is often not or hardly visible to the eye, hence difficult to discover and requires meticulous inspection for which reliable practical methods are not in place yet - as will be discussed in more detail later.

A striking discovery

September 6th 2008, Boeing machinists began a strike that would last for 58 days. Boeing was confident that the strike wouldn't affect delivery of the first 787, then still scheduled for August 2009 [88]. Actually, the strike was regarded a good opportunity for Boeing to put things in order on the work floor - *'When the mechanics come back I* *think they will find that is a fairly significant set of improvements that will make their jobs easier and allow them to spend more time doing what they do best, which is building high quality airplanes.'* 89). What the machinists found when they came back to work were not sets of improvements but lots of *'Quality-control inspectors crawling through the first two airplanes in the assembly bay "ripping all the systems out" everything that's in the way'* 90).

High Blow

During the strike Boeing performed the high blow - pressurization - test to ensure the integrity of the aircraft. During the test, that lasts about two hours, the internal pressure is gradually increased to 150 percent of the maximum levels expected ever to be seen in service. Whether such two-hour test is meaningful has to be awaited – here it led to a most unpleasant discovery.

The fuselage stood the test and with no end in sight for the strike Boeing took the opportunity to issue a positive press release *'The Boeing Co. (Everett, Wash.) successfully completed a high-pressure test - known as high blow - on the 787 Dreamliner static test airframe at its Everett factory on Sept. 27, but further work was postponed in the wake of a machinists strike'* 91). The Chief was very pleased with the results *'I am so proud of the team that has worked on this program and the progress we are making'* 332) - but soon it appeared that there really was not much to be so proud about.

Three defects

Inspectors had apparently some backlog and the long strike offered them plenty of opportunity to have closer look at the static airframe. To their surprise they found that *'some [of the fasteners] were left sticking up slightly from the titanium surface'* 92) and now they had had to inform the Chief that the *'pressurization test on one of the completed*

Dreamliners revealed a small gap under the heads of thousands of fasteners inside the fuselage....the bolts in question were used inside the fuselage to fasten titanium structure to carbon-fiber-reinforced plastic composite, and the problem emerged after a pressurization test in October' [90).

More specific analysis revealed three defects *'in some cases, drilling burs keep fastener heads from lying flush against the aircraft skin. In other cases, fastener pins are either too long or too short'.....'all three defects could impact the structural integrity of the joint. Long pins may not clamp parts with sufficient force. Short pins could provide insufficient shear or pullout strength. And proud fastener heads, those that stick out above the aircraft skin, concentrate loads in the burr area instead of spreading them over the skin'* 93).

About 8000

What started with *'a regular inspection of the static airframe'* set in motion further checks of the units in production, in particular a check of the tens of thousands of temporary fasteners that had been replaced in Everett due to travelled work. This revealed that '*about 3 percent of the fasteners installed on the five test airplanes under construction in Everett were installed incorrectly and must be removed and reinstalled to protect the airplane's structural integrity* 90)*'* - that *'the number of non-conformances vary in number by airplane but each of the airplanes is involved'* - and that *'that the location of these non-conforming fasteners is not isolated to any particular area of the airplanes'* 90). That's most worrisome because this means that the problems vary randomly in various areas of the airplanes on sections made by various suppliers - nothing less than a total mess. Further reports indicate that '*the total number of fasteners to be replaced per airplane is about 8,000'* 90) - with no clear pattern this can't be more than a rough estimate at such short notice. Replacement is a time consuming job - referring to early 2008 when fasteners were placed wrongly in the fuselage of a 787-test plane at one of Boeing's overseas production lines – involving only 11 fasteners stretching together just 11.8 inch (300 mm) repair caused *'a few days delay'* 94).

Root of problems

December 2008 an internal forty seven page Airbus document surfaced in the press - 'Boeing 787 Lessons Learned' 7) *- that reveals in quite frank detail a number of problems to which frequent reference has been made at these pages. Most valuable to Airbus undoubtedly, the contents are rather embarrassing to Boeing. Most was already known, but it was interesting to obtain some specifics about overweight, low production rates and so on. The report could backfire in that the market looses interest in all-composite aircraft, as first signs appear to indicate. Moreover, before long a similar report could surface about the A350 XWB.*

Again Boeing had to publicly concede that they are still not in control of things, but reassured that they had made progress - this time '*the issue was not with the fasteners but how they were installed'* 95). More in detail, a large number of holes were drilled at improper curved countersink depth to accommodate a bevel 96) - machine countersink depth was apparently set wrongly because of confusing specifications. The wrong countersink depth leaves a thin but important gap that limits load transfer and might play fatal havoc when lighting strikes.

Trying to restore confidence - the Boeing way

After the discovery of the inspectors *'Boeing couldn't not ignore the problem'* 95) and they could not blame the strike for another delay as they had probably in mind when they let the strike start and continue. First Boeing tried to play down the seriousness of the problem - arguing that during the high blow test *'the internal pressure is raised to 1.5 times the maximum the jet might see in service'* however *'the fasteners did not fail during this test, proving the strength of the structure is beyond what it needs to be'* 95). With criticism swelling into roar Boeing tried desperately to restore confidence arguing that the fasteners were definitely *'not in areas vulnerable to lightning strikes and not inside the fuel-filled wing, where a spark would be catastrophic'* 95) - difficult to understand since the particular 8000 or so non-conforming fasteners were not isolated to any particular area of the airplanes – and Boeing claimed that this was confirmed by lightning experts who *'are convinced the gaps involved in this case do not create any likelihood of a spark'* 95) - quite reassuring indeed and puts the previous discussion on lighting strike protection in quite different perspective.

Boeing had to admit that the specifications on how the fasteners are supposed to be installed were *'not as clear as they probably should have been'* 97). Other reports suggest - probably more to the point - *'limited engineering resources'* 24) and *'lack of oversight'* and *'low-wage, trained-on-the-job workers that had no precious aerospace engineering'* and *'lack of qualified non-destructive inspection/quality assurance personnel and equipment'* 7) to be at the root of problems.

Facing another delay, Boeing promised *'We're going to strengthen our quality-management system'* 95) but could not resist to insist that in the end essentially the only worry is that *'It's a matter of whether the structure will hold together properly'* 95). According Boeing *'rework would not involve redrilling fasteners holes. But, depending on* *where fasteners are located, workers may need to move aside already-installed insulation or wiring to complete repairs'*[93]. But recountersinking is a meticulous job with composites that cannot be performed with the automated machines that are normally in place for drilling, but has to be performed by hand and requires great skill and very accurate inspection - to put it bluntly - this can't be repaired in proper way because of the vast numbers involved and insurmountable problems with accessibility - the plane should be dumped.

Deep, Deep Trouble

Inspection apparently completely failed - both at the partners and at Everett - and in all probability it has to be accepted that problems are much more widespread. Essentially all planes that are in various stages of production have to be re-inspected - confirmed by analysts who agreed that *'Boeing must inspect about 350,000 fasteners on each of the 20-plus 787s under production'*[98] - better to check each and every detail from nose to tail with non-destructive testing. With often limited or no access to most of the fasteners this essentially means that large sections of the planes have to be completely taken apart and this means that Boeing is in *Deep, Deep Trouble* - as the Simpsons would put it - but at Boeing there is a solution for every problem.

Somehow it became a habit

With the 787 somehow it became a habit to blame the fasteners - whenever something got wrong - and indeed a lot went wrong with the fasteners and will continue to do so. But next to the fasteners there are many other issues that have been adding to the troubles - and to the delays. So have the problems with the wing box, discussed before, taken about a year and a half to solve and the test aircraft have still temporary fixed wing boxes. Also production facilities did pose huge problems. May 5th 2008 it surfaced that at one of the partners involved with manufacture and integrate of the fuselage barrels *'The skills that staff brought to the 787 were not applicable to building aircraft'* 99) resulting in *'time-consuming fixes that had to be completed ...... delaying delivery or slowing final assembly'* 99) - FAA, found *'observations of foreign object debris and non-conformance with procedures'* 99) - loose objects left in the fuselage sections can knock out important systems, like hydraulics - and decided to shut down production for 24 hours for cleaning up 100). The partner soon pulled out of the project 101). A major setback was the much lower than expected lay up rates that requires significant expansion of these production facilities, as was indicated before. There are continuous rumours about delamination, so difficult to avoid with composites certainly at this scaling and complexity - fortunately these have not been confirmed so far 102) - but at Boeing this is no guarantee knowing now how often inspection failed already. July 15th 2008 it was reported that *'Test Flights for the Boeing's 787 Dreamliner are being delayed again due to problems with the verifying software in the brake control system'* 103). Another chief concern involved *'ongoing difficulty in working out bugs in the millions of lines of computer code that run the airplane's various systems, running form electric brakes to instruments in the cockpit'* 76). Some of these problems are 'normal' with development but remember that these problems surfaced long time after first delays were announced. Eventually problems with design, production and quality assurance will be solved - may be - given enough money and time, but the certification timeline remains uncertain and Boeing keeps shaken confidence beyond belief.

Problem solved

January 26th 2009 Boeing 'simply announced' that test flights will go ahead with part of the temporary or improperly held fasteners to be replaced after flight testing - problem solved - but the official statement is far short from setting the mind at rest. With no reliable simulation models in place and hardly any time for proper evaluation of the problems, Boeing apparently expects the world to believe that *'the small number of fasteners that won't be replaced are 1: not easy to reach and 2 don't represent a safety of flight issue. They have the ability to withstand the loads and number of cycles expected during the flight test program. They must be repaired before long-term operations begin so they will be replaced during the refurbishment program after flight test'* 229). Wonder who - apart from FAA - agrees with this policy. In a first reaction Boeing's engineer unions *'thinks all the fasteners should be replaced before test flight begins'* 229) - apparently not reason enough for FAA to put a question mark - indeed the role of FAA becomes ever more questionable indeed.

Something changed

It appears that not much changed at Boeing, regardless all problems and valuable lessons that could have been learned - Boeing still lacks oversight and it seems to be very difficult for them to realize the mess they keep creating - although something changed

Another Sunday

Boeing officially debuted the 787 Dreamliner on a Sunday - July 8th 2007 - when the aircraft rolled out forward out of the factory into blazing daylight. Attended by some 15,000 people, the premiere was broadcast live in nine different languages via satellite to more than 45 countries and to a nearby stadium where some 25,000 Boeing employees had gathered to follow the ceremony. Following the premiere, the aircraft was rolled in again to be prepared for first flight - according the Boeing press release 334) to be take place

> within months - late August or September 2007. The aircraft would stay more than 777 days on the production line before Dreamliner One - now dubbed ZA001 - would see the daylight again. Another Sunday - May 3rd 2009 - this time the plane rolled out backwards surrounded only by a handful of engineers and some dedicated spotters who had gathered at Everett's grassy knoll to watch the event form a distance - although a completely different plane one can only have one premiere. According the Boeing press release 335) first flight is now expected - or hoped for - to take place later this quarter. For the moment the aircraft is parked on the flight line beside the runway at Everett's Paine Field enjoying the sunshine - *'Out and closing in on wild bleu yonder'* 333).

Blame

May be some lessons have been learned - Boeing now seriously considers to do more work in-house *'We will probably do more of the design and even some of the major production for the next new airplanes ourselves as opposed to having it all out with the partners'* 150). This may be the right approach but blaming the partners again for the troubles - *'Our engineers and production workers are basically correcting the problems that should have never come to us in the first place - problems that are the result of the partners really not being done'* 138) – is far from the truth and will certainly backfire. For the moment Boeing is completely dependent on their partners - and will remain so for considerable time - and such remarks will not be appreciated. Again, only Boeing is to blame.

Towards first flight

When Dreamliner One finally lifts off the runway at PAE Paine Field in Everett this summer one can only wonder what is the purpose of testing an aircraft that is heavily overweight, has still serious flaws and of which the design has to be significantly modified to make it suitable for service.

> *The press has lost interest - except for Seattle newspapers - Boeing's public confidence has reached an all time low. But there are still some enthusiast 787 watchers around who report daily - sometimes twice daily including exclusive photographs and video clips - on developments surrounding ZA001 to ZA006 and beyond XXX). Apparently very much appreciated by many reading the many contributions that are received and published – and also appreciated for sure by many stockholders and analysts and this author who are offered an unique opportunity to follow things closely.*

As indicated before Boeing chooses to turn a blind eye whenever problems surface, as is also the case with the decision to start test flights with planes that still have serious flaws - something they may soon regret. The Dreamliner One rolled out July 8 2007 was a hollow shell held together by temporary clamps, clips and fasteners - the Dreamliner One rolled out May 3 2009 is still held together by numerous wrongly placed temporary fasteners and a provisionally strengthened wing box. Whatever the outcome, this is questionable behaviour and one can only hope for the best. Ignoring the problem - the fasteners will be dealt with after the test flights have been finished. But for sure, replacement during refurbishment is going to take a very long time - the structure might hold but wrongly placed fasteners will cause serious damage to the fastener holes when exposed to the severe and extreme loading conditions applied during flight testing - possibly beyond repair.

Exact overweight of the test aircraft is not known, but the aircraft empty dead weight is probably more than 20,000 lbs above its target of 191,000 lbs. Airbus claims that the first 787s that will be delivered will be some 4000 lbs overweight 7) - probably more. Further redesign is supposed to bring the weight down to its original weight specification 338) - most important through incorporation of a revised wing design - yet, as one analyst correctly noticed '*the contribution of technologies such as trailer edge variable chamber, raked blended winglets, drooping ailerons and spoilers, laminar flow* *optimized engine nacelles and additional engine performance improvements all leave open questions until real-world data can deliver a conclusive verdict on aircraft performance'* 337). Other parts that have been suggested for possible redesign include *'a revised aft-body join, new floor beams, seat tracks, composite wing ribs and structural fuel vent stringers, as well as "revised structural architecture" for the horizontal stabilizer'* 7).

No doubt, other necessary modifications will add to the weight - probably much more than presently anticipated. Given the history of the aircraft there is undoubtedly more unfinished business - there appear still to be problems with the software for the brake control system 339) and the landing gear is to modified again after the test flights to speed turnaround times following high-energy landings by improving the thermal part of the braking system 300).

> Take Care
>
> And for the test pilots - Take Care. No doubt the plain will fly all right, probably better than any plane before, but be careful. The aircraft is low on impact performance - as stated before with all-composite aircraft the windows provide better impact performance then the composite skin. Make sure tires don't burst and when they stick ice shapes on the plane 340) make certain that they don't break away during the flight. Crashworthiness is far from clear and be careful with the brakes. When you notice bad weather, move away at least 50 miles, don't rely on the lighting protection system. Watch these damned fasteners - they have already caused so many problems - you need them all. And for everybody on the ground, you are better not in the neighbourhood when an all-composite plane crashes and catches fire because the burning composites might release large amounts of hazardous smoke and contaminated respirable fibrils - stay inside if you can and keep doors and windows shut - note that *'Boeing will not fly over downtown Seattle for the first flight of the 787'* 340).

Difficult to say when the Dreamliner will enter service. Remind that with the A380 problems surfaced after the maiden flight and had nothing to do with the structure of the *aircraft - contrary to the 787 that faced continuous problems with the structure during development, which caused the delays. Moreover, the 787 is a fist 'more electrical plane' and that might play havoc - fortunately engineers had two years of extra time available for development. With regard to the certification timeline, Boeing's estimate of 8 to 9 months is probably too optimistic* 342). *Testing is around the clock 'Boeing has set up a 24h seven-day-week flight-test op operation'* 344) *- 'mission controlled* 345).