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Cost Factors Contributing to the Choice of Aerospace Advanced Materials

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Context

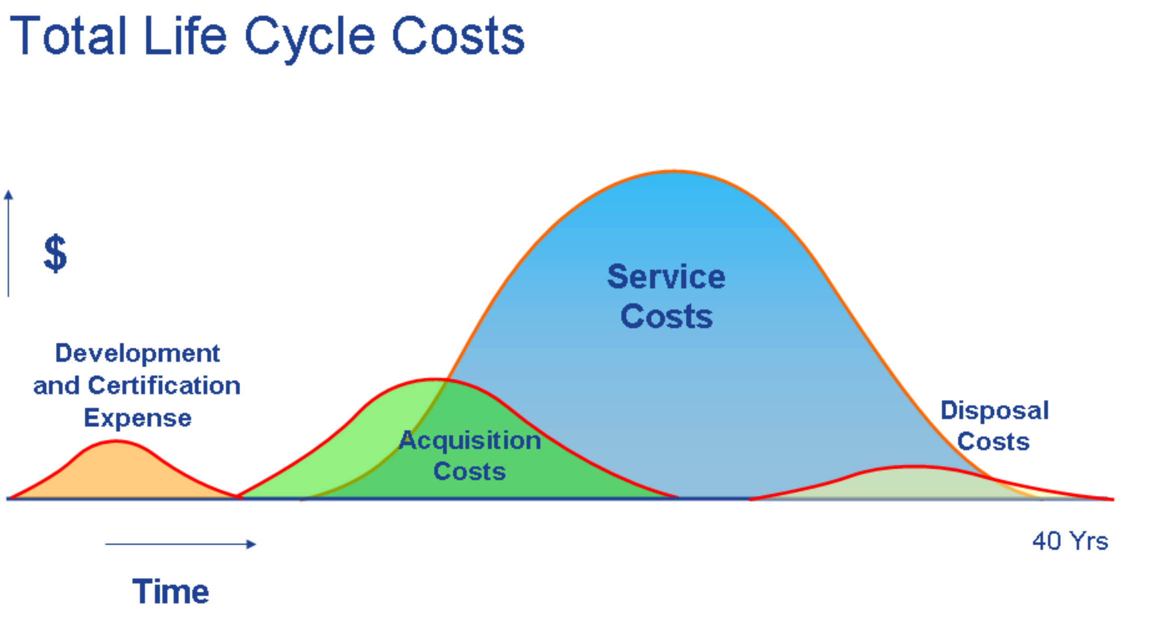
The materials selection process for the most recently proposed military and civil aircraft has centred substantially around the use of advanced carbon composites versus conventional high strength aluminum alloys. The former material type has been selected for use in increasing proportion.

Aircraft	Approximate Proportion of Carbon Composites
A400M	35%
JSF	40%
B787 Dreamliner	50%
A350 XWB	50%+
Bombardier C-Series	50%+

The decision-making process associated with materials selection is complex by nature and differs from one original equipment manufacturer to another. It is of necessity a multi-disciplinary process and focuses on classic trade-off compromises that involve cost, weight, structural strength, aerodynamic smoothness, durability, maintainability and ease of repair. The Cost Engineer, whether specializing in parametric estimating or in traditional bottom-up detailed estimating, is a key contributor to this process. The reality is however that the marketers have tended to have had more influence on materials choice than the engineers, on the basis that "the greater proportion of advanced materials featured within the aircraft structure, the more advanced the aircraft". This paper advocates the classic trade-study approach considering the relationships between the above mentioned functionalities and relevant aircraft service history, with a particular emphasis on cost. The author seeks firstly to identify those specific applications of advanced composites have either not seemed to have adequately followed this approach or to advocate decision making without having considered all of the pertinent information, and secondly identify the composite applications that are likely to be the most cost effective.

Total Life Cycle Costs (Whole Life Costs)

The chart below illustrates the typical life cycle of an aircraft or an item of aircraft equipment. Typically purchasers of aircraft components and equipment pay lip service to the whole life cost of the goods, but concentrate on the development and acquisition costs only. Whereas the greatest proportion of aircraft costs occur during the in-service period.



In the composites materials selection process typical trade studies seem to take cognisance of the whole life cost by considering the amortised development cost together with the manufacturing or acquisition cost of one material versus the other and then applying a cost premium/penalty to the unit weight differential, presently circa $500/lb recurring. This caters for in-service costs such as fuel usage and weight based landing fees, or equivalent payload advantage, however significant costs such as maintenance, repairs, overhauls and spare parts are largely ignored in the cost equation. Rather, qualitative statements are made, particularly in the case of a composites application. These statements are rarely based on reality, due simply to the fact that beyond the normal warranty period the true cost of operational ownership is not well documented due to the use of third-party repair operations and reversed engineered spare parts. An historic illustration is presented in the next section of this paper.

In the last 100 bid proposals relating to composite parts with which the author has been involved, the cost of disposal has not required to be addressed. It has been assumed that this cost is being addressed collectively at the top level by the aircraft OEMs, and has not therefore been passed down the supply chain. If the aerospace industry follows automotive practice, as has been the case historically, the whole supply chain will eventually bear its share of disposal costs. We as cost engineers need to know and understand better, the assumed processes and corresponding costs associated with composites disposal. This issue is thought by the author to be so important that a section is devoted to it towards the end of this paper.

Historic Example

When Boeing launched the then new B737-400 into service in 1990 it believed it had incorporated cost/weight effective fan cowl doors in its nacelle system[1]. These under wing pylon mounted doors were designed and produced using inner and outer door skins manufactured from advanced carbon composite with an epoxy resin system and sandwiching an aluminium honeycomb structure. Based on the dimensions of the doors, the unit acquisition cost to Boeing from its nacelle supplier equates to circa $150k at present (2010) economic conditions for an aircraft set of 4-doors. This compares to $130 - $140k for the equivalent doors using the previous aluminium honeycomb configuration, i.e. 7% – 15% more expensive, but being circa 15% lighter than the conventional aluminium honeycomb sandwich configuration previously used on Boeing aircraft this saving of 60lbs per aircraft is still deemed to be cost effective using $500/kg as the typical weight penalty.

The warranty period offered to operators was the greater of: 6,000 flying hours or 3-years from the entry into service (EIS) of the aircraft on to which they were fitted. In-service problems began to occur shortly after the warranty expired that reflected badly on the integrity of the original door design. It must be borne in mind that the proximity of an under-wing nacelle to the ground[2] during take-off and landing makes any nacelle component sensitive to runway conditions and susceptible to runway related foreign object damage (FOD). The fan cowls are generally situated on the largest diameter of the power-plant as they provide access to the largest diameter of the engine. This makes them closest to the ground of all the nacelle components. The nacelle is also prominent when the aircraft is on the stand, with high potential for accidental damage from baggage carts and catering trucks. The following problems causing the doors to have to be removed from the aircraft for repair were experienced and logged by airline operators:

(1) De-lamination – Where the adhesive bond has broken down between one layer of the carbon fiber composite construction material comprising the outer door skin and another.

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[1] Fan cowl doors are the large aerodynamic access panels which are located between the nose cowl and the thrust reverser providing accessibility to the engine fan case, including those accessories that may be fan case mounted..

[2] The Boeing 737 aircraft referred to is well known for the “flat” aerodynamic lines of the nacelle approximately +/- 45 degrees from the bottom dead centre line when viewed from head on. This is not, as many would think, to optimize drag, specific fuel consumption (SFC) or aerodynamic noise, but to provide additional ground clearance on landing with the undercarriage bottomed out.

(2) Damage to skin – Comprising punctures and gouges to the external surface of the door.

(3) Leading Edge erosion – Where the edge to the forefront of the door, which interfaces with, and lands on, the inlet cowl has been wasted away by the high speed airflow that is experienced during aircraft operation.

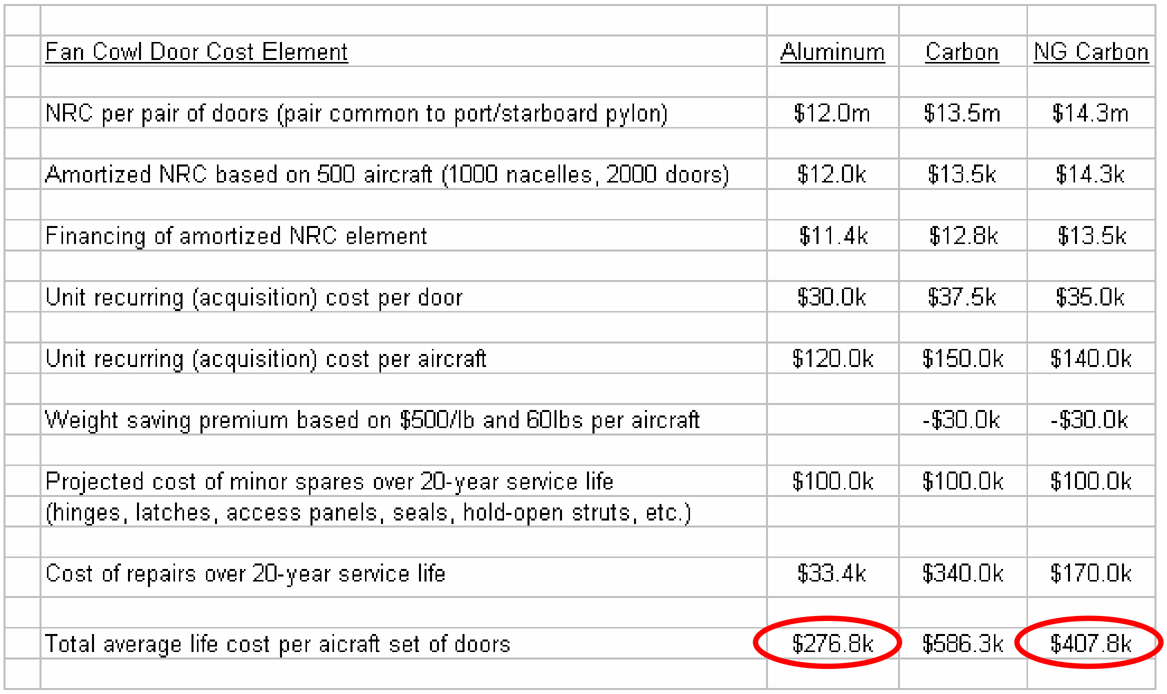
(4) Loose/damaged door latches – This problem is mainly due to neglect by service engineers/mechanics.

(5) Damage to interior of cowl – This can occur through leakage of hot air from the engine pneumatic bleed systems which provide high pressure hot air for anti-icing and air-starter and to propel the aircraft air-conditioning system. Typically leakage occurs at a loose or badly seated v-joint, but a burst duct is possible. Hydraulic and lubrication systems are also housed by the fan cowl doors and can cause chemical damage.

(6) Baggage cart and catering truck mishaps.

It will be observed that de-lamination and potentially leading edge erosion are the only problems noted above that are associated with carbon fiber composite being the construction material choice for the doors and that all the other problems could equally well occur with the predecessor aluminum alloy honeycomb door construction, however metal components often deform on impact rather than break or delaminate, such that they continue to be serviceable even when damaged. Metallic components are also more convenient for local repair by fitting a patch, panel beating or realignment, in which cases door removal is not required.
The composite doors begin to demonstrate severe de-lamination problems after only three years in service, and require repairs at twelve to twenty-four months after the first repair. The repairs are expensive and are difficult to perform for most airlines, so the airlines are held captive to the limited and specialized repair market for composites. An OEM replacement is available for $200K+ per door but has only been considered by airlines if a door has been damaged beyond repair. Repair is achieved by way of a hot bonding process that partly replicates the thermo-setting process by which the bonded door panel has been originally manufactured. This involves removal of the door from the aircraft to an external facility to perform an autoclave-assisted cure of the epoxy repair resin. Even a minor repair can cost as much as $35,000, and may be as high as $65,000 for a more comprehensive repair. A third party MRO supplier offers a door exchange facility on a remove and return basis. Exchanges are $45,000, and a further exchange will be required again in just a short time [12-24 months].
were appropriate for the replacement door configuration:

The above demonstrates how the failure to recognise, evaluate and address whole life cycle cost elements such as susceptibility to damage, ease of repair and ease of maintenance at the concept stage, leads to an unaffordable product entering into service. Moreover the next generation Fan Cowls are also of composite design of monolithic configuration. This reduces manufacturing cost by reducing the number of cure cycles and makes the product more reliable in service. It is nevertheless still prone to de-lamination and necessitates specialist repair in the event of runway or apron damage, illustrating that lessons have not been learned from history. See the table below for comparative costs.



Fan Cowl Door Cost Element	Aluminum	Carbon	NG Carbon
NRC per pair of doors (pair common to port/starboard pylon)	$12.0m	$13.5m	$14.3m
Amortized NRC based on 500 aircraft (1000 nacelles, 2000 doors)	$12.0k	$13.5k	$14.3k
Financing of amortized NRC element	$11.4k	$12.8k	$13.5k
Unit recurring (acquisition) cost per door	$30.0k	$37.5k	$35.0k
Unit recurring (acquisition) cost per aircraft	$120.0k	$150.0k	$140.0k
Weight saving premium based on $500/lb and 60lbs per aircraft		-$30.0k	-$30.0k
Projected cost of minor spares over 20-year service life (hinges, latches, access panels, seals, hold-open struts, etc.)	$100.0k	$100.0k	$100.0k
Cost of repairs over 20-year service life	$33.4k	$340.0k	$170.0k
Total average life cost per aicraft set of doors	$276.8k	$586.3k	$407.8k

Recent Selection of Advanced Composites

The Boeing 787 “Dreamliner” is the first commercial aircraft to incorporate composite primary structures such as the main fuselage and wing-box into its baseline design. This bold step was taken based on Boeing’s 25-years of experience with advanced composites use on secondary structures, military applications of advanced composites use on primary structures and studies undertaken as part of the then recently shelved advanced civil aircraft program, the Sonic Cruiser.

Through use of advanced composites Boeing targeted to design an aircraft Despite having a density of just over 50% of that of a typical aluminum alloy, [3] and many superior mechanical properties, typical weight saving due to the introduction of advanced composites (carbon reinforced epoxies) rarely exceeds 15% relative to the equivalent aluminum alloy structure. This is due mainly to retaining other component attributes inherent in metals such as electrical conductivity essential in dissipating electrical charge associated with a lightning strike, providing fire/heat resistance, providing an interface with other metallic components. It was therefore ambitious for Boeing to seek a 30,000 – 40,000 lb

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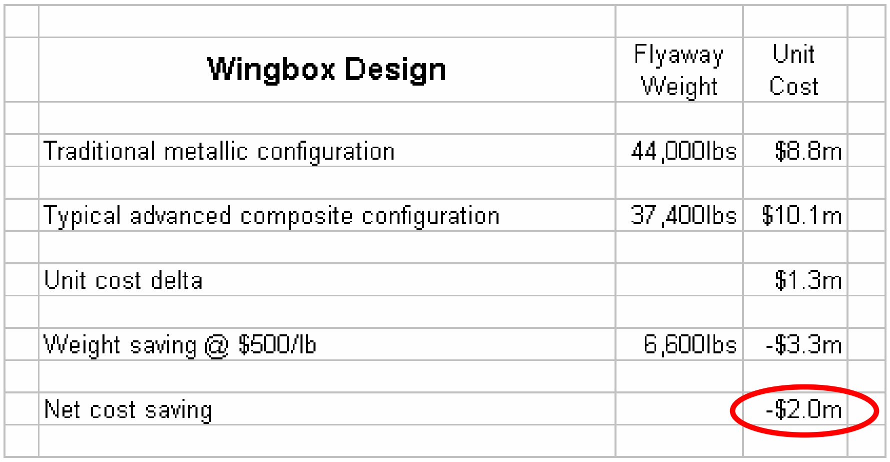
[3] 7075-T6

weight reduction on an aircraft with a structural weight of 290,000lbs[4] i.e. 11 – 14% lighter, using only 50% composites.

The B787 wingbox should have weighed circa 44,500lbs in metal and 37,500lbs in composite. Typical guidelines in trade studies is to offset the difference in unit cost associated with composites with the weight saving calculated at $500/lb. This takes into account the reduced operational cost based on fuel saved. It does not however take account of other cost of ownership categories such as maintenance and repair as illustrated by the historical example highlighted earlier in this paper. The simple cost justification of the composite with configuration is set out in the following table:



Wingbox Design	Flyaway Weight	Unit Cost
Traditional metallic configuration	44,000lbs	$8.8m
Typical advanced composite configuration	37,400lbs	$10.1m
Unit cost delta		$1.3m
Weight saving @ $500/lb	6,600lbs	-$3.3m
Net cost saving		-$2.0m

However during the course of the wing proof-of-concept, detail design, destructive testing and flight testing, the following occurrences have added both cost and weight:

- Retention of metallic ribs[5] between composite spars/top and bottom skins as composite ribs are thicker and reduce fuel tank capacity significantly. Also the rib to skin attachment requirements prevent free flow of fuel increasing the amount of unusable fuel which more than offsets any structural weight saving of composite over aluminum;
- Increased materials/processing due to the center wing box buckling issue revealed in March/April 2008;
- Additional lightning strike provisions;
- Addition of wing to fuselage fix (“side of body” modification)
- Possibility of need for structural integrity monitoring system (in lieu of periodic metal fatigue checks)

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As a result the comparison table could now look something like this:

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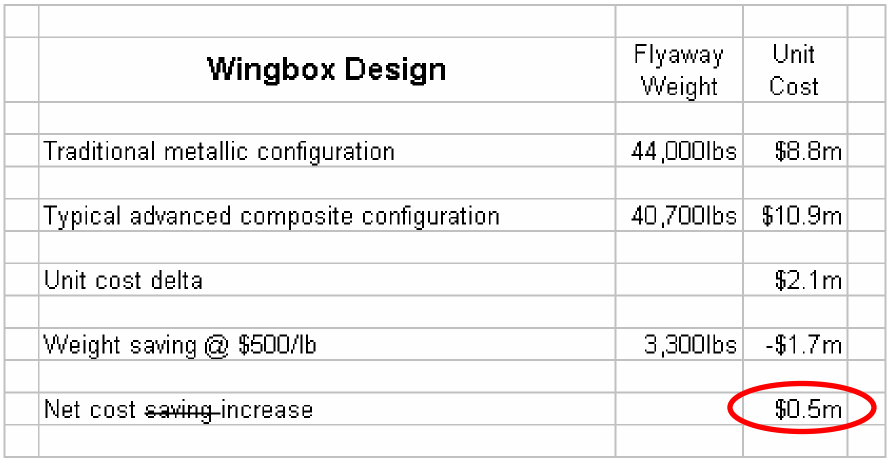
[4] The approximate weight of the equivalent configuration of the rival Airbus A330-300

[5] Is there a further risk associated with the differential coefficients of linear expansion between the two materials considering the temperature excursions experienced on a typical flight cycle?

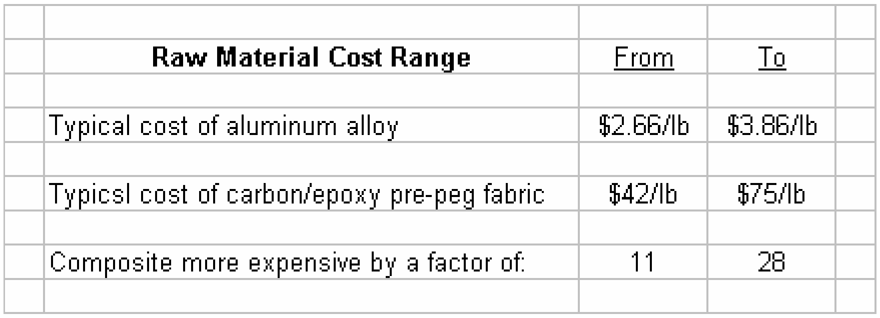


Wingbox Design	Flyaway Weight	Unit Cost
Traditional metallic configuration	44,000lbs	$8.8m
Typical advanced composite configuration	40,700lbs	$10.9m
Unit cost delta		$2.1m
Weight saving @ $500/lb	3,300lbs	-$1.7m
Net cost ~~saving~~ increase		$0.5m

Attention to these events has turned the savings around without even considering the potential disposal costs associated with carbon, which will be addressed at the conclusion of this paper.

Carbon versus Aluminum

A senior procurement executive with whom I was about to begin a meeting had been reviewing his company's latest long term purchasing commitments from strategic raw material suppliers. As he drew my attention to the typical cost of aluminum versus the typical cost of pre-impregnated carbon fabrics he asked "Why do we even consider composites?" The following table illustrates his concern.



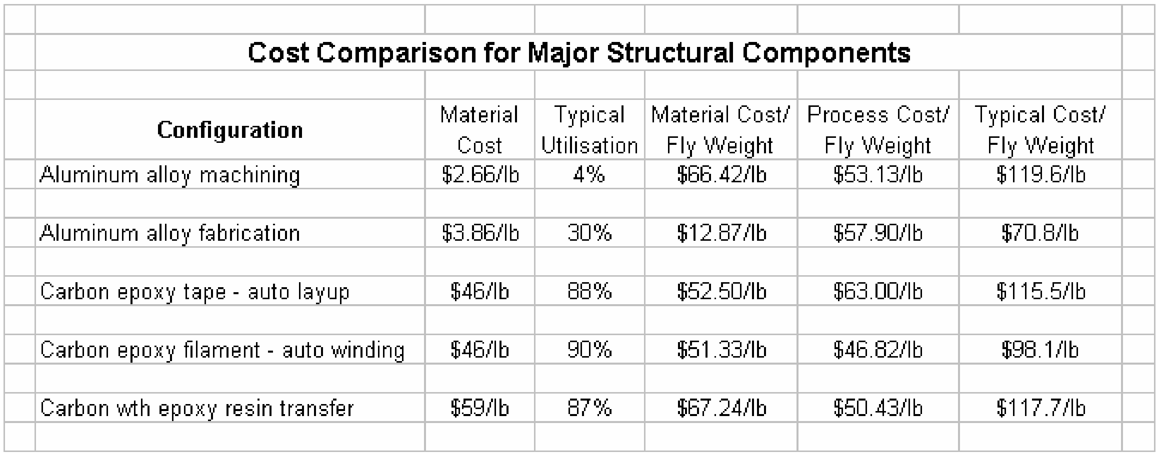
Raw Material Cost Range	From	To
Typical cost of aluminum alloy	$2.66/lb	$3.86/lb
Typicsl cost of carbon/epoxy pre-peg fabric	$42/lb	$75/lb
Composite more expensive by a factor of:	11	28

With the potential for the obvious advantages of using carbon composites to be eroded as illustrated by the prior content of this paper we may very well ask the question:

> "Based on the above raw material cost table how can carbon composites unit manufacturing costs ever be competitive against conventional high strength aluminum alloys at up to 28-times the raw material purchase costs?"

> Answer: “By addressing such subjects as material utilization and manufacturing processes.”

As cost engineers, we can help our organisation make the right choices early in the product concept phase by our providing the correct cost focus. The table below summarises typical unit manufacturing costs for several material types and configurations. Aluminum alloy certainly is inexpensive in its raw (sheet, bar, plate, billet) form, however present high speed metal removal techniques using new generation multi-axis CNC machines remove significant proportions of material. A study by the author of 200 machined structural components (spars, ribs, frames etc.) concluded that the average material yield was circa 4%, i.e. to produce a 40lb frame a 1000lb billet was used. Because of its high material cost carbon epoxy material has since its first use had a concentration on utilisation such that even in manufacturing first generation aerospace composite structures 70% utilisation is not untypical.



Cost Comparison for Major Structural Components

Configuration	Material Cost	Typical Utilisation	Material Cost/ Fly Weight	Process Cost/ Fly Weight	Typical Cost/ Fly Weight
Aluminum alloy machining	$2.66/lb	4%	$66.42/lb	$53.13/lb	$119.6/lb
Aluminum alloy fabrication	$3.86/lb	30%	$12.87/lb	$57.90/lb	$70.8/lb
Carbon epoxy tape - auto layup	$46/lb	88%	$52.50/lb	$63.00/lb	$115.5/lb
Carbon epoxy filament - auto winding	$46/lb	90%	$51.33/lb	$46.82/lb	$98.1/lb
Carbon wth epoxy resin transfer	$59/lb	87%	$67.24/lb	$50.43/lb	$117.7/lb

When the super efficient processes of auto lay-up, filament winding and resin transfer moulding (RTM) are employed composites stand a chance to compare favourably with structural aluminium components. Note however that aluminium fabrications are still extremely competitive. Composites are most effective when replacing metal fabrications with complex compound curvature where repeatability is often a problem, leading to hand finishing, the cost of which is not factored into the above table.

Composites Disposal

BS5760 describes whole life costs (WLC) as “The cumulative cost of a product over its life cycle”. A significant cost is the disposal of a physical part or component. Most industries recognise decommissioning or disposal as the final stage in this cycle, however the aerospace industry has, particularly in its civil sector, not fully addressed this final stage.

There is seemingly a lack of information on the cost of reconstituting/disposing of aircraft carbon composites. This is in part because the first generation of aircraft using carbon composites as structural materials are only now coming to the end of their useful life. It was only in 2006 that the first Boeing 777 was retired from service (approximately 12% carbon composite). Thereafter a period of time will follow whereby salvage and ‘cannibalism’ will take place on a commercial basis before the residual constituent materials are eventually disposed of. It is presently not the commercial practice of OEMs to place any residual value on the salvaging of aircraft parts, as this process has historically been taken care of by third party spares organisations. On this basis OEMs tend to regard the product life cycle as having ended at a premature point before the materials have been finally disposed of, e.g. aircraft retirement or some earlier stage based an assumed service life for the aircraft model based on its original design allowables. There is therefore poor consolidated history with regard to the total life cycle of aircraft parts in the true sense and consequently little basis for including a view of disposal cost at the bidding stage.

In 2010 it is forecast that almost 25 million kilograms of raw composite materials will be shipped to manufacturers globally, up from 15 million in 2005.[6] Allowing for processing, service life and salvage, this means that circa 2040 that 25 million kilograms of carbon composite material will have to be disposed of. However, taking into account growth in air transport globally, together with growth caused by the selection of carbon composite as a primary structural material as highlighted above, the amount of material to be disposed of a decade later in 2050 will be conservatively 100 million kilograms.

For aircraft containing large quantities of composite materials at least three issues prompt the necessity to address the final disposal problem:

1. The sheer annual future quantity of composite components requiring to be disposed of;
2. The toxic nature of the residual;
3. A lack of credible options whereby composite components can be safely disposed of or reconstituted.

There is a substantial source of uncertainty at the bidding stage as to the effect that the means of scrapping or reconstituting composite material parts has on the true cost of selecting carbon composite as a material in preference to the traditional aluminium alloys. Additionally it is still not evident:

- What the most effective process is;
- Whether that process is commercially viable to the aerospace industry, i.e. is carbon composite material an asset or a liability as a result of the disposal process?

It is the third party salvage, repair and spares organisations that hold the real knowledge on what the actual disposal process has been for the (very limited

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[6] Source: Opportunities for Composites in the Global Aerospace Market 20042010, EComposites, Inc

number of) carbon composite components that have finally been disposed of to date. and to place a rough order of magnitude value on these processes relative to the typical development, manufacture and in service cost of such components for recognition with a degree of certainty at the bidding stage. The environmental impact of the reconstitution and final disposal of carbon composite aircraft components relative to the environmental benefits that their inclusion generates must be considered versus that of conventional aircraft materials in terms of aircraft specific fuel consumption.

Summary and Conclusion

1. It appears that important decisions in the aerospace industry with regard to the selection of materials for structural components have been made on an inaccurate basis or with incomplete data;

2. The cost engineer is best positioned to influence the making of educated decisions relating to material selection on the basis of whole life cost information;

3. There is a wealth of historic cost data that needs to be mined, analysed, collated and made accessible in a meaningful form;

4. The means of disposal of aircraft that are substantially composite in their construction need to be identified with their corresponding costs.