PLASTIC OR METAL - THE JUDGEMENT FACTORS

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Abstract

The choice between composite and metal for an aircraft component is dependent upon three parameters: weight, cost and reliability. High strength composites will generally yield the lowest weight design, but relative cost and serviceability data are needed to facilitate a balanced judgement. Economic comparisons should take into account any indirect factors such as component development, tooling, structural testing and quality control.

Sufficient experience has been generated to establish the cost-effectiveness of composites for lightly loaded structures and flying control surfaces. However, the amount of certification testing and quality control checking required should perhaps be reviewed as further experience accumulates.

Composite primary structures are becoming conventional in military aircraft, but major civil applications such as large wings and fuselages remain to be substantiated. The economics appear to be finely balanced, due partly to the extensive development and proving required and the high cost of the pre-impregnate materials. However, with the aid of demonstrator programmes and automated manufacturing processes, it is anticipated that composites will eventually be established in such applications.

1. Introduction

The benefits of high strength composite materials are now well established and with judicious application significant weight savings can be achieved for almost any structure compared with the metal equivalent. Despite this, the materials have been slow in achieving the major breakthrough predicted, particularly in the civil field. This is due partly to early caution, but also to difficulties in identifying potentially cost-effective applications and generating the necessary confidence to proceed.

In the mid-70's British Aerospace (BAe) recognised the need for a dedicated development programme to establish the technology for introducing carbon fibre composite (CFC) components; otherwise the predominant use of metals would be perpetuated. For military applications the responsibility was placed at Warton, whilst the civil development work has been undertaken largely at Weybridge in conjunction with the Civil Division at Hatfield. The aim of the programme was to gradually extend the level of CFC technology from secondary structure applications to flying control surfaces and ultimately to primary structures. At each stage experience would be gained in both design and manufacture, thus developing confidence and establishing a basis for recognising where CFC could offer a useful advantage.

The criteria for applying CFC tend to be different for military and civil aircraft, since performance is generally the primary military consideration, whereas economic and airworthiness aspects are more important in the civil case which is the main subject of this paper.

In order to be able to make a balanced judgement it is necessary to have some basic understanding of all the factors involved, including comparative weights, non-recurring and recurring costs, engineering timescales, airworthiness considerations and operational reliability. Much remains to be learned on all these subjects, but useful data have already accumulated from the above programmes and form the basis of the following generalised discussion.

2. Engineering Development for CFC Lightly-Loaded Applications

2.1 Early BAe Work

British Aerospace involvement with high strength composites began about 1970 when a number of small CFC demonstrator items, such as airbrakes and rudder trim tabs, were manufactured for flight trials on military aircraft.

The military work was gradually extended into larger panels and doors and subsequently into primary structures including a demonstrator CFC taileron for the Tornado aircraft and a demonstrator wing for the Jaguar. More recently, BAe has been involved in the development of the CFC wing for the SAAB Scania JAS 39 'Gripen' combat aircraft, and the CFC wings and fuselage components for the Experimental Aircraft Programme (EAP) technology demonstrator.

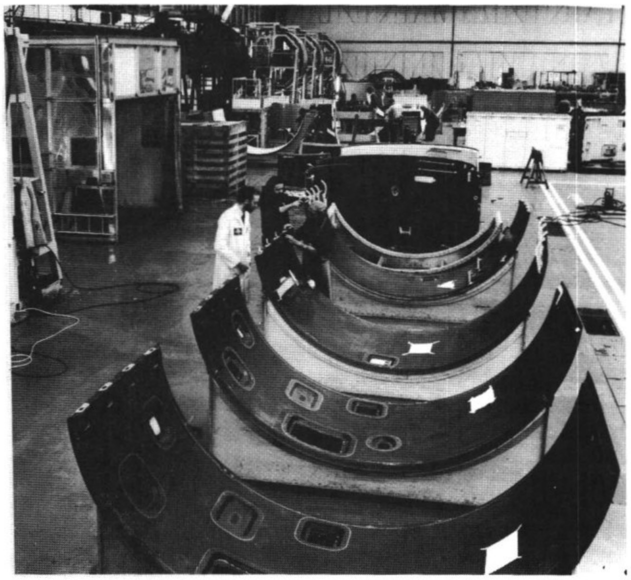

Figure 1. CFC fan cowl doors for RB211 engine

The civil programme was initiated in the mid-70's with the development of some relatively simple CFC components to demonstrate the basic design and manufacturing principles and obtain some in-service experience. These included panels on VC10 aircraft to measure moisture uptake, large honeycomb panels on the VC10 rudder and CFC woven fabric panels on the BAe One-Eleven engine attachment stubs. This work, which has been described elsewhere (1,2), enabled the basic design, manufacturing and quality control methods to be established for CFC and aramid lightly-loaded components, with particular attention being paid to economic processes such as co-curing.

Between 1978 and 1981 series production experience was gained by the manufacture for Rolls-Royce of the CFC fan cowl doors for the underwing-mounted RB211 engines on the Lockheed Tristar (Fig.1). At the time, these were the largest CFC components in production for the civil market. Although a weight saving of 27 per cent was achieved, the need for interchangeability with the existing metal doors and utilisation of the available jigs resulted in some design compromise, and the component was never fully engineered for manufacturing efficiency. Nevertheless, over 100 doors were produced and continue to provide satisfactory airline service worldwide.

2.2 Airbus Wing Trailing Edge Structure

Launch of the Airbus A300-600 aircraft in 1981 provided the first proper opportunity to apply the cost-effective CFC processes developed. The low speed outboard ailerons were not required for this model and were to be replaced by fixed structure. It was decided that CFC would be used to save weight, provided the costs were competitive with metal. Every effort was made, therefore, to apply value engineering to the design and the solution adopted is illustrated in Fig.2. The component is basically wedge-shaped, with a span of approximately 4.5 metres and 1.5 metre chord. The skin panels are constant thickness co-cured Nomex sandwich, with two layers of five-harness satin weave carbon fibre fabric on each face. A 120 deg C self-adhesive resin system is used to obviate the need for an adhesive film between skins and core. A pre-laminated cotton reinforced phenolic strip (Tufnol) is used to build up the required panel edge thicknesses.

To complete the structure, the skin panels are adhesive bonded to pre-moulded carbon fibre ribs using a 120 deg C curing adhesive. Structural tests demonstrated that with the ribs bonded to the inner face of the sandwich skins the honeycomb core was capable of transmitting the local shear and transverse tension loads without reinforcement. However, a few anti-peel rivets are incorporated at the ends of the ribs, and these pass through thin stainless steel Acre sleeves which are potted into the honeycomb to prevent crushing during riveting. Skin porosity is controlled by the application of a pin-hole filling epoxy primer, which was demonstrated to prevent moisture transmission even under vacuum differential pressure. Series production of this CFC component began in 1982 and proved sufficiently successful to warrant the introduction of a similar CFC structure on the A310-300 aircraft in place of the existing metal version. This component, which has been in production for about two years, provides a weight saving greater than 30 per cent and a reduction in manufacturing manhours.

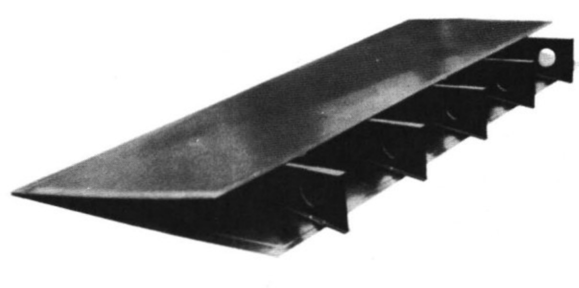

Figure 2. A300-600 wing CFC trailing edge structure

2.3 A320 Flap Track Fairings

Carbon fibre skinned Nomex honeycomb construction is also being used for a number of large fairings in production at Weybridge for the A320 aircraft. These include the canoe-shaped flap track fairings which were originally conceived as aramid structures. However, the better mechanical properties of CFC enabled the honeycomb core depth to be reduced, resulting in smaller fairings with lower aerodynamic drag. The same woven fabric and self-adhesive resin system are used as in the trailing edge structures discussed in 2.2.

2.4 Small Panels and Access Doors

The work undertaken on access doors may also be worthy of mention. Although individually these may not be of great significance, a large number of CFC access panels are used on both the A310 and A320 wings, and the accumulative weight saving is significant. On the A310-300 aircraft, many of the CFC panels were developed to replace existing metal or glass-reinforced plastic (GRP) versions, and direct comparison of weights and costs was possible. The GRP panels were generally of honeycomb sandwich construction, and replacement by CFC (Fig.3) enabled fewer layers of pre-impregnate to be used and the core depth to be reduced. Many of the panels incorporated aluminium foil on the inner face for electro-magnetic compatibility (EMC) protection, and the shallow core depth ameliorated difficulties with draping the foil at the chamfered panel edges. Very thin outer skins are sealed with a polyvinylfluoride (pvf) film to prevent moisture penetration.

Further weight reduction is achieved by the use of syntactic core to build up the required edge thickness to accommodate the panel fasteners. This material is less than half the density of CFC and is incorporated in the panel layup as uncured film 0.5 mm thick, containing a thin aramid reinforcing scrim.

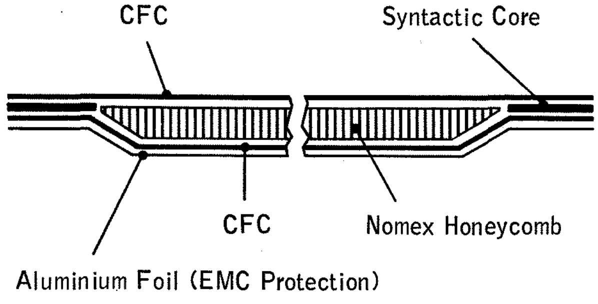

Figure 3. Typical CFC access panel construction

Environmental and impact tests confirmed the suitability of the product for lightly loaded 120 deg C curing panels with Camloc type fasteners. Panel weight savings up to 40 per cent were commonly achieved compared with the existing GRP standard, at comparable units costs.

3. Economics of CFC Lightly-Loaded Structures

3.1 Engineering Approach

'Designed by Committee' has in the past been used as an expression of engineering disparagement, but the advent of composites has transformed the situation and it has been found invaluable to derive the initial design schemes in committee, even for relatively minor items. Early discussions involving design and stress offices, production engineering, materials specialists and cost estimators have generally resulted in a balanced and efficient solution. It is probably reasonable to assume that many CFC designs are better optimised than the equivalent metal structures, but this is difficult to allow for when making comparisons.

3.2 Non-Recurring Cost Factors

The use of advanced composites will almost invariably provide a significant weight saving for simple lightly-loaded structures, but it is important to analyse the comparative costs. For this purpose, account must be taken of both recurring and non-recurring contributions. The main non-recurring factors are design, development, tooling and structural testing.

Generally the design effort required will be similar for metal or composite construction and, once the basic techniques and processes have been established for the class of component, the amount of special development needed is relatively small. Furthermore, the need for structural testing of CFC lightly-loaded components has diminished with the accumulation of experience. The main element in non-recurring costs is therefore tooling.

For honeycomb sandwich components with only moderate curvature, such as the skin panels for the Airbus wing trailing edge structure and various fairings and access doors, simple mould tools made from aluminium alloy or GRP are satisfactory. These comprise a skin formed to the component curvature and supported by an egg-box substructure, with a thin loose CFC 'slipper plate' on the tool face to cater for differential thermal expansion during autoclave curing. Where component edges are to be moulded to finished dimensions to obviate subsequent routing, a CFC 'picture frame' is located on the tool

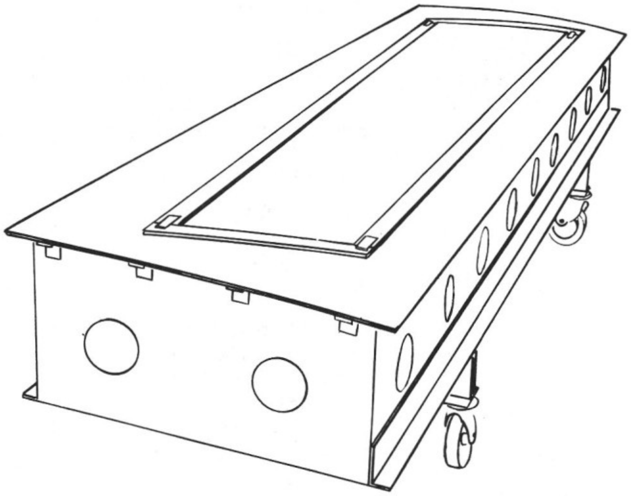

Figure 4. Typical mould tool for CFC sandwich panels

and the preimpregnate is trimmed to fit snuggly inside. Figure 4 shows a typical tool of this type. Experience has shown that the cost of this type of tooling is compatible with that for the equivalent metal components. For the Airbus trailing edge structure, the extra operation of bonding the skins to the ribs using a 120 deg C curing adhesive is effected by applying local mechanical pressure while supporting the rib webs with plates to prevent buckling.

The tooling procedure for the A320 flap track fairings was necessarily more difficult because of the more complex shapes. The first stage was to produce durable master models which could be used in the manufacture of numerous templates and interchangeability gauges as well as the component mould tools. Long-term retention of the master models without distortion was required to facilitate future tool duplication. To meet these requirements the masters were produced by accurately locating a series of vertical metal profile plates on a rigid metal base, then infilling with an epoxy material. GRP splashes were then taken off the masters, using a 'wet' epoxy, and subsequently 'paste' masters were prepared off the splashes. These were made from an epoxy two-part mix material reinforced with short-strand glass, with a gel-coat on the tool surface. Finally, the production 'female' moulds (Fig.5) were manufactured in CFC using a special tooling epoxy resin system which could be autoclave cured up to 95 deg C on the 'paste' masters and subsequently postcured up to 150 deg C while free standing in an oven. These moulds were reinforced with CFC external ribs and base to maintain the shape and provide robustness for continuous production use. Electroform nickel moulds were considered as an alternative, but CFC was favoured because it offered lower elapsed time for tool manufacture. The route for producing the CFC tools was deliberately conservative to avoid the risk of heating the master models and inducing distortion. Nonetheless, the cost of the tooling was estimated to be no higher than for the substantial stretch form blocks which would be required to manufacture the equivalent metal components.

3.3 Relative Material Costs

When evaluating recurring production costs it is necessary to include materials, manufacturing manhours, quality control and technical support. For lightly-loaded components, the use of advanced composites will usually incur extra material costs, even with careful nesting of shapes in the pre-impregnate to minimise wastage. The cost of carbon fibre preimpregnate is typically about twenty times that of conventional aluminium alloy for the same weight (Table 1- overleaf). However, less material is required for CFC and utilisation is generally more efficient than for metal. This applies particularly in the case of machined plate where utilisation may be as low as 10 per cent. Allowing for the consumable materials (vacuum film, bleed cloth, release ply, etc) needed for composites production, which add about five per cent, and other items such as honeycomb core, adhesive, mechanical fasteners and various fittings and parts which are common to both CFC and metal designs, the ratio of total material costs for CFC components compared with metal is usually of the order four to one.

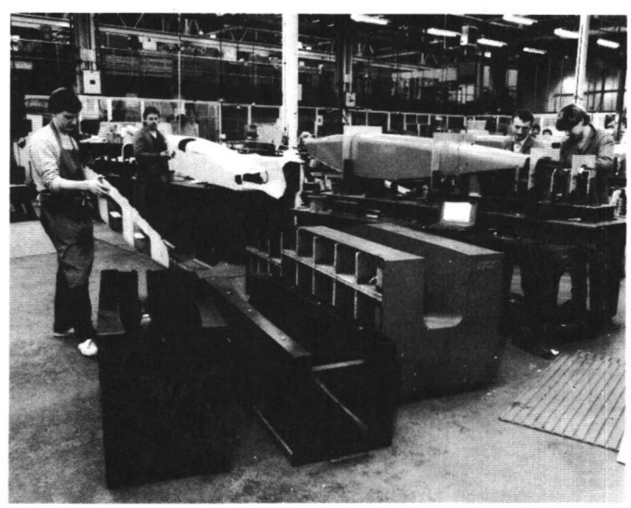

Figure 5. Carbon fibre mould tool

Material	Cost
CFC woven fabric preimpregnate	100
Standard CFC tape preimpregnate	100
Intermediate modulus CFC tape preimpregnate (projected cost)	150
Glass fabric preimpregnate	35
Aramid fabric preimpregnate	67
Conventional aluminium alloy	5
Aluminium-lithium alloy	14

Table 1. Comparative cost of materials (Indicative values - US Dollars per kg)

3.4 Recurring Manhours

It is difficult to derive meaningful parametric data on manufacturing manhours for CFC components, since the complexity of individual items cannot readily be allowed for. A typical value is about nine manhours per kilogramme including assembly of details, but this is subject to considerable deviation. Generally, the manufacturing costs for this class of CFC component have tended to be about three times the material costs and, on the basis that for a metal component the material costs are 75 per cent lower, the manufacturing manhours for CFC need to be about 20 per cent lower than for metal to break even. Such a reduction has been found feasible in a wide range of lightly-loaded components, and it is now generally expected that composites will provide the most cost- effective solution for such applications.

3.5 Quality Control

There is sometimes a tendency to treat CFC components as special items simply because of the materials employed, and it is essential therefore to ensure that the quality control requirements are based primarily on the function of the item; otherwise quality assurance costs may be unnecessarily high.

For lightly-loaded components, the BAe procedure has been to undertake full non-destructive testing (NDT) of the initial sets (ultrasonic and radiographic as relevant) until consistent quality has been confirmed, and then to reduce the frequency of full inspection to a level commensurate with the significance of the part. However, visual inspection is undertaken for all components, as well as NDT of any critical areas. For process control, honeycomb peel specimens and test laminates accompany each autoclave batch of components, although the laminates are not tested unless a problem arises. Completeness of cure is checked by thermal analysis of offcuts from the components.

3.6 Choice of Materials

With careful design, the use of composites in lightly-loaded structures will generally yield a significant weight saving and a reduction in manufacturing manhours which will compensate for the higher material costs. Fabricated aluminium-lithium alloy construction will tend to be less efficient as an alternative, since the weight saving will be lower and the high price of the alloy will not be offset by reduced labour costs. The choice of fibre type for this class of composite component is often marginal, since GRP will usually offer slightly lower unit costs but less weight saving than aramid or CFC. In a range of component studies it has been found that the difference in cost is generally small, since the better mechanical properties of CFC result in less material quantity being required for the skins or honeycomb core. This largely offsets the higher material costs compared with GRP or aramid (Table 1). Weight has usually proved to be the deciding factor, since the extra weight saving relative to GRP has been sufficient to compensate for the small cost premium. There is often little to choose between CFC and aramid in unit weight and cost, but the advantages of standardising on one type of material, together with the easier drilling and routing of CFC and its better electrical bonding characteristics, have generally led BAe to a preference for CFC.

4. Flying Control Surfaces

4.1 Comparative Studies

In most cases the level of aerodynamic loading on flying control surfaces is sufficiently low for the structural solution to follow the lines discussed above, but airworthiness requirements demand more attention to design testing and quality control.

Honeycomb sandwich construction generally provides the simplest CFC solution, examples of which are the A320 ailerons (Fig.6) and spoilers which are in series production. The former comprise CFC/Nomex honeycomb skin panels which are adhesive bonded to CFC ribs and spar, while the latter are of a CFC skinned full-depth honeycomb design. Before deciding on the form of construction, project studies were undertaken with different structural concepts including metal solutions, and comparative weights and manufacturing costs were estimated.

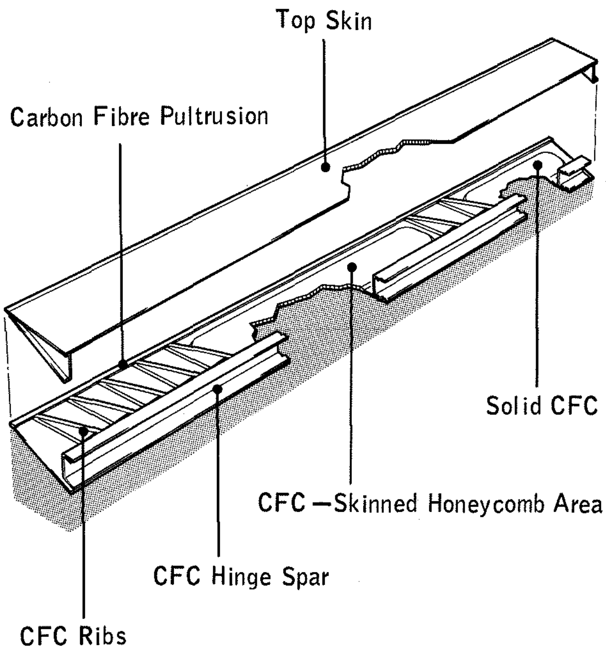

Figure 6. A320 CFC aileron construction

It was found that CFC provided a weight saving of about 25 per cent and that the recurring costs were similar for both the CFC and metal versions. Tooling costs were also comparable, but extra costs are incurred with CFC because of the additional structural test requirements.

4.2 Choice of Resin System

The normal practice for flying control surfaces is to employ a 175 deg C curing resin system rather than 120 deg C because of the better retention of mechanical properties at the aircraft maximum operating temperature under moisture soak conditions. This choice was made, for example, on the A320 ailerons although the construction and operating conditions are similar to those for the more lightly-loaded A300/A310 trailing edge structure which utilises a 120 deg C system. The selection of the more conservative 175 deg C system has some adverse effect on aileron costs, because a film adhesive is needed between the skins and honeycomb core, and certain features of the tooling are rendered more difficult.

Frequently the technical case against using a 120 deg C system is marginal and is based on tests under fairly extreme simulated environmental conditions. It is usually stipulated that specimens should be soaked to an equilibrium condition at elevated temperature (typically 70 deg C) and high humidity prior to testing, and this has a more critical effect on 120 deg C systems than 175 deg C. Continuing effort is needed to confirm whether such testing is properly representative (2) and whether the requirement to combine fully factored ultimate loading with the worst moisture and temperature conditions might be relaxed in particular cases, once greater in-service experience has accumulated.

4.3 Structural Testing

Until more extensive experience and confidence has been established with CFC flying control surfaces, comprehensive structural testing is required for design confirmation and certification purposes. In the case of the A320 aileron, for example, twenty torsion boxes were called for, representing the critical regions of the structure, as well as a range of other detail tests.

Finally, a complete aileron was required for testing. Static, fatigue, damage tolerance and lightning strike tests were undertaken on the specimens after moisture conditioning. The damaged components were then used to demonstrate repair techniques.

A considerably smaller test programme would suffice for a metal component, and the cost of the extra testing for CFC is quite significant. If it were recovered by amortising over 200 production sets, the unit cost would be increased by about 10 per cent. It is essential, therefore, to continue to accumulate all the relevant test evidence as it becomes available, in order to minimise the test programme required for future similar applications.

4.4 Quality Assurance

Quality control test requirements also have a bearing on the economics of CFC. As an example, full ultrasonic inspection of every A320 aileron part would add about seven per cent to the recurring manhours. Consequently, it is always important to ensure that the amount of NDT specified is not superfluous for the function of the particular component. In the case of the aileron, failure would not prejudice flight safety, and therefore gradual reduction of the level of NDT is planned, although critical areas will continue to be fully examined. Process control checks using thermal analysis, peel specimens and test laminates will also be continued. For more critical control surfaces, such as flaps and elevators, relaxation of NDT is more difficult to justify, and the total cost of quality control, including materials checking, stage inspection, process control tests and NDT could well exceed 10 per cent of the basic production costs.

4.5 Capital Investment

The efficient manufacture of composite components requires a considerable investment in capital equipment, as indicated by the examples in Table 2. While curing facilities and NDT equipment are essential, other items can only be justified on the basis of improved production efficiency and a significant throughput of work is necessary to recover the outlay. Before committing the spend, a balanced judgement needs to be made based on the existing workload and the potential extra work likely to be attracted due to the improvement in efficiency. Once such equipment has been procured there is a need to ensure that it is adequately utilised, and this may influence the selection of composites for components where the choice of materials is marginal.

Equipment	Cost
Medium size autoclave	0.8
Tape laying machine (moderate complexity)	1.5
N.C. preimpregnate cutter and marker	0.4
Water jet cutter and robot	0.3
Multi-axis N.C. honeycomb carver	0.3
Ultrasonic inspection equipment	0.4

Table 2. Typical costs for capital equipment (US Dollars - millions)

4.6 Operational Reliability

Customer acceptability is a major consideration when choosing materials, and it is essential to ensure that any composite components will meet the aircraft serviceability requirements and can be readily repaired if any minor damage is sustained. From the feedback to date, CFC components are generally performing satisfactorily in airline service and, where damage has occurred, simple in-situ repairs have usually proved adequate (3). There is a concern by the airlines that the parts integration desirable for economic CFC component production results in large units which may be expensive to replace and costly to hold as spares. Simple methods of repair, both temporary and permanent, are therefore necessary to satisfy operating economics, and need to be catered for at the design stage.

4.7 Cost-effectiveness

It has been found that, provided production aspects are considered at every stage of the design, CFC flying control surfaces will provide a weight saving of typically 25 per cent with unit costs similar to those for metal. However, in some cases the additional non-recurring factors, such as development and structural testing, will render the CFC application more costly overall, and only justifiable in terms of the weight advantage and associated improvement in aircraft performance. The value of the weight reduction will depend upon the particular project and the stage of introduction. Maximum advantage will be derived if the CFC applications are introduced at the outset, allowing the benefits to be escalated throughout the aircraft. Even so, direct operating costs (D.O.C.) are particularly sensitive to aircraft selling price, and a maximum cost/weight exchange rate usually applies. This limit will depend upon the value of weight saving in terms of airfield performance, payload capability and fuel efficiency. A more detailed discussion of this subject is provided in reference (4). The introduction of CFC components at a later stage will tend to be less cost-effective, because the aircraft geometry cannot be revised and also component re-tooling may be necessary. However, apart from improving fuel efficiency, such later introductions may be important to offset any increase in weight caused by essential aircraft modifications. The value of weight reduction will thus depend upon the circumstances prevailing, but a limit of about 500 US Dollars per kilogramme is fairly typical. Clearly it is important to minimise costs, and therefore for flying control surfaces the amount of testing required for certification needs to be continually reviewed, with full account taken of accumulating experience. With attention to this aspect, CFC will generally be the natural choice of material for this type of component.

Aluminium-lithium alloys offer a weight saving of approximately 10 per cent relative to conventional alloys, but at a material cost two to three times greater. Consequently, the unit recurring cost would normally be higher than for CFC. The new alloys may provide short-term advantages because of the smaller structural test programme, the conventional manufacturing methods and saving in capital investment. However, once the technology for CFC has been established, CFC will generally prevail over metals for this class of component.

5. CFC Primary Structures

5.1 General Background

The application of high performance composites in secondary structures is now well established and the main thrust is towards primary structure applications which offer the biggest potential weight savings. In the military field the extensive utilisation of CFC is becoming standard (5), with approximately 26 per cent of the AV8B (Harrier II) structural weight being CFC and about 40 per cent being assumed for new BAe projects. Weight is critical to the performance of such aircraft and dictates the choice of materials. However, for civil aircraft the selection of materials is dependent to a greater degree on economics and airworthiness considerations, and the larger size of components compared with those of military combat aircraft results in greater manufacturing difficulties. For these reasons civil applications have tended to lag behind the military, although it has been predicted that the wide-scale use of composites will provide the biggest performance benefits of any new technology apart from improved propulsion. However, as discussed in 4.7, aircraft selling price is equally critical, and the performance benefits would need to be balanced against any increase in costs. A further advantage of composite structures is the improved fatigue characteristics compared with metals, and this could eventually lead to a reduction in inspection frequency and the associated support costs.

5.2 CFC Military Wings

British Aerospace has developed several CFC military wings (6), the most recent (in partnership with Aeritalia) being for the EAP. Optimisation studies showed that the most efficient structural configuration for this low aspect ratio delta wing is multi-spar. This form of construction also has advantages in manufacturing, since the absence of stiffeners facilitates the use of an automated preimpregnate tape laying machine for the skin panels. After curing the skins, the pre-formed uncured spars were located into the tooling assembly with their flanges against the skin surfaces. The spars were then cured and adhesive bonded to the lower skin in a single operation. The upper skin panel was removed after moulding the spars, to facilitate installation of the ribs and systems. This process not only eliminated the need for mechanical fasteners in the lower skin but also dispensed with the need for shimming on final assembly of the upper skin. Fig.7 illustrates the form of construction of the wing.

5.3 Civil CFC Wing Demonstrator

While the above solution is efficient in both structural and manufacturing terms for low aspect ratio military wings, studies have shown that for the higher aspect ratio civil torque boxes a different form of construction is needed. The minimum weight solution for such applications is generally a multi-rib concept with spanwise stiffened skin panels. In addition, the fatigue and life requirements and certification route are different for civil and military aircraft, making it difficult for data to be read across. Consequently, BAe decided to commence a phased demonstrator programme for a CFC civil wing based on the BAe 125 executive aircraft. Completion of the programme will lead to full certification and flight trials by 1989, but regular reviews are planned to confirm that the technology objectives are being accomplished. The construction of this wing has already been described elsewhere (1).

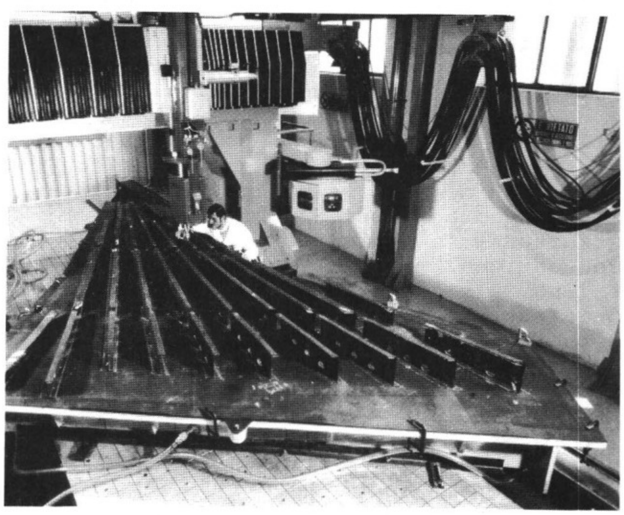

Figure 7. CFC multi-spar wing construction

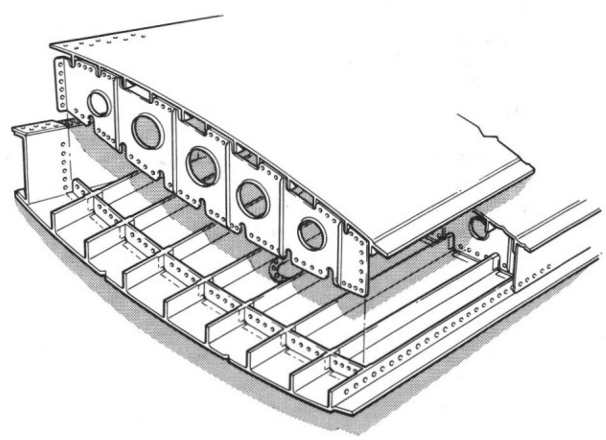

Figure 8. CFC multi-rib wing construction with stiffened skin panels

In the first phase of the programme detailed investigation was undertaken on a number of candidate configurations before adopting the solution depicted in Fig.8. The studies covered both multi-spar and multi-rib designs and several types of stiffener including hat, I-section and blades. Tooling methods and manufacturing costs were derived for each scheme. The final choice of a multi-rib solution with blade stiffened skin panels and blade intercostals for attaching the ribs was a compromise based on weight, cost, airworthiness considerations and applicability to other potential projects. A weight saving of approximately 22 per cent was estimated compared with the existing metal torque box. The cheapest solution would be a multi-spar structure based on the EAP, although the weight saving would be only 16 per cent for the BAe 125 wing. However, this approach was considered unacceptable for a civil aircraft because the operators and authorities require the ability to inspect all parts of the internal structure, which necessitates access through the spars. This would considerably complicate the in-situ moulding of the spars and increase the manufacturing costs. Also, the solution with intercostal stiffeners enables the ribs to be bolted internally, minimising the number of fasteners exposed through the skins and hence reducing any risk associated with lightning strike in a fuel environment. The crashworthiness of alternative wing configurations has also been addressed, but it is difficult to derive a procedure for predicting the relative performance of different materials and constructions. However, it is considered that the proposed CFC wing is satisfactory in this respect.

5.4 Relative Manufacturing Costs

During the detail study stage production cost estimates were derived for the CFC wing to compare with the existing metal wing values. It was assumed that automated shaping and laying of the preimpregnate would be adopted wherever feasible, since this reduces the laminating times by about two thirds. Because of the large number of layers involved, a CFC wing would not be commercially viable without recourse to such mechanical aids. It was predicted that the manufacturing hours for the CFC torque box, including allowance for NDT, would be slightly higher than for the existing metal box. There is also a penalty arising from the higher material costs, with the total materials bill for the CFC structure being approximately three times that for the metal version. Nonetheless, the cost of the weight saving was estimated to be less than 300 US Dollars per kg, which is probably within the 'ceiling' for acceptability, particularly for a new project which can be resized to take full advantage of the reduced weight.

Comparable studies were undertaken for aluminimum-lithium alloy construction and a possible weight saving of 8 per cent was calculated compared with the current metal standard. However, the relatively high price of the alloy would reduce the cost advantage of metallic materials over CFC, and it was estimated for this wing that the cost per unit of weight saved would be higher than for CFC. The main attraction of the aluminium-lithium alloys would be that some weight could be saved using conventional techniques and tooling, and with less development, structural testing and capital investment. All these factors affect the total cost of a CFC wing, but will reduce as experience is established.

5.5 Improved Materials

It was decided that intermediate modulus fibre and an improved toughness resin system should be used for the demonstrator wing. The increased modulus and higher allowable strains provide approximately five per cent extra weight saving compared with the established CFC materials. This is less than would normally be expected, because stability considerations predominate in much of the structural design and large areas involve major joints which are governed by bearing properties. Despite the general performance improvement, the new materials do not provide a comparable increase in static bearing strength which remains a significant weakness in composites. In addition to the extra weight saving, these materials offer valuable improvements in impact resistance and interlaminar toughness, important in regions of thickness variation and notches.

Currently, the price of preimpregnate with intermediate modulus fibre is almost double that of the conventional preimpregnate materials and is likely to remain relatively high because of the more complex fibre production process. Long-term predictions are difficult, but a price premium of 50 per cent for the improved performance preimpregnates would seem a reasonable assumption (Table 1), pending the outcome of market trends. This is compensated to some extent by the reduction in the amount of material required and the associated reduction in laminating time. With these assumptions, the cost of the extra weight saved using the new materials would generally be in the region of 300-400 US Dollars per kg, which has to be traded against the general benefits to the aircraft. Continued improvements in performance and price are desirable to substantiate the overall advantage of the new materials, but the effort involved in acquiring the necessary design data base needs to be allowed for when considering further derivatives.

5.6 Tooling Considerations

In the BAe 125 wing demonstrator the integrally-stiffened skin panels provide the most difficult tooling problem. The skin layers will be laid up on metal envelope tools formed to the outer skin profile and supported by metal egg-box structure. A CFC 'slipper' plate will be used on the tool face to accommodate differences in expansion during curing. The stiffeners will be laid up on male formers and pre-consolidated together before positioning on the skin laminates for autoclave curing. A number of alternative types of former have been evaluated to derive a reliable technique for moulding the stiffeners, including thermally expanding mandrels and inflatable rubber formers. The preferred solution is to use polyacrylic rubber formers reinforced with carbon fibre to prevent shrinkage. Gaps are left in the reinforcing to enable the rubber to be stretched by the curing pressure.

Tooling for the skin panels is inevitably expensive, since whatever method is adopted it is necessary to manufacture accurate master shapes as a first stage and this is equivalent to machining a complete replica. The cost of such tooling will usually be at least double that for metal skin panels, resulting in a cost penalty of the order 50 per cent for the complete torque box tooling.

The use of silicone rubber would substantially ease many tooling problems because of its good temperature performance and dimensional stability, its stretch capability and tear resistance, and its castability. However, within BAe this type of rubber has never been used for civil component tooling and is employed for military applications only under very strict control because of the danger of silicone migration affecting component adhesion.

Investigations have been underway for some time to derive an equivalent non-contaminating material, or a reliable method of preventing silicone release, but a fully satisfactory solution remains to be found.

5.7 Structural Testing

A full scale component test to demonstrate static and fatigue performance and damage tolerance behaviour will usually be necessary for a civil wing whether fabricated from metal or CFC. However, for a composite wing a wide range of sub-component tests will also be required. These will confirm the static and fatigue performance and variability of the critical structural

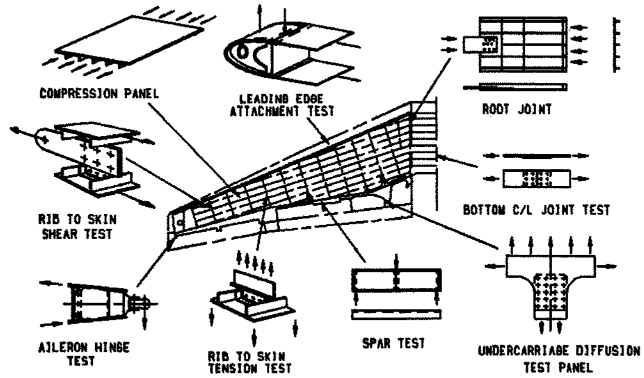

Figure 9. BAe 125 CFC demonstrator wing - subcomponent testing

features when subjected to simulated environmental exposure, as well as evaluating the effects of impact damage, manufacturing defects and lightning strike. Figure 9 depicts some of the specimen types defined for the BAe 125 wing demonstrator. Including both design substantiation and certification tests, over 100 specimens are required to cover all the features and conditions. The cost of this testing is substantial, as well as the elapsed time involved in manufacturing, pre-conditioning and fatigue cycling. This level of testing, together with the period required for production development, could affect the overall timescale for a new project and thus deter the utilisation of composites. One of the main purposes of a demonstrator programme, therefore, is to establish the relevant manufacturing technology and structural data to expedite future CFC applications, and it is important that the experience accumulated is admissible as part of the airworthiness substantiation for ensuing projects.

6. Conclusions

In addition to major military applications, BAe has now accumulated substantial experience in the cost-effective use of composites in civil aircraft. It has been established that, with simple design, often involving the use of honeycomb sandwich construction and syntactic core, weight savings up to 40 per cent can be achieved on lightly-loaded components. Manufacturing costs will generally be competitive with metal and therefore the use of CFC will prevail for these components despite the competition from aluminium-lithium alloys. However, the level of quality control testing specified needs to be commensurate with the airworthiness significance of the particular parts, rather than based on the materials chosen.

There is no doubt that advanced composites will also be widely used for flying control surfaces, where weight savings of typically 25 per cent can be achieved with recurring costs similar to those for metal. The extra cost of development and structural testing needs to be taken into account, but will reduce significantly as experience accumulates.

The more widespread use of composites in large civil primary structures such as wings is likely once sufficient confidence has been established in the technology and its economics and reliability. A structural weight saving of at least 20 per cent will be possible, with production manhours comparable to those for metal. However, the cost of materials will be higher and extra tooling and structural testing will be required. Furthermore, the timescale necessary to introduce a large CFC component is likely to be longer than for metal and could influence the choice of material at present, particularly since some weight saving could be achieved with current technology by the use of aluminium-lithium alloys. However, with the experience gained from CFC demonstrator programmes and smaller production components, costs and time-scales will reduce. It is predicted, therefore, that major civil CFC applications will gradually be substantiated, leading to widespread usage on all classes of aircraft.

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