CARBON FIBERS AND COMPOSITES

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With the wide diversity of technical disciplines represented at this Risk Analysis conference, it seemed appropriate to present a paper discussing the basic nature of composite materials. Carbon fiber composites and their area of current and planned application in civil aircraft will be discussed, specifically to set the framework for the papers which follow dealing with various aspects of the risk analysis. In the area of composites, there are two elements, filaments and matrices, that have to be combined to make these kinds of materials (figure 1). Glass filaments have been available for a number of years and have been a part of composite materials, getting widespread usage on the current generation of commercial transport aircraft in such things as fairings and other lightly-loaded or non-load-carrying structures to a large extent. Glass is not generally considered to be a high performance fiber in the sense of the rest of the filaments listed here; boron, graphite, and PRD-49, or Kevlar, as it is known today. Of all these fibers or filaments that are currently in use in composite materials, only the graphite is electrically conductive. Therein lies the problem. Graphite filaments have very desirable mechanical and physical properties and they are potentially cheap

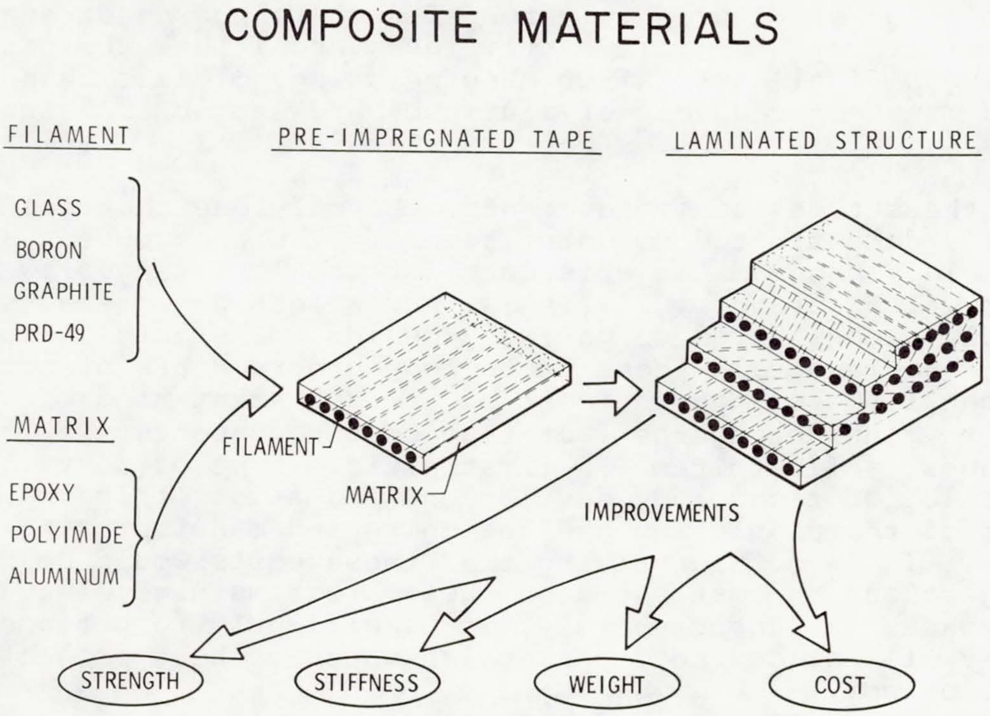


Figure 1

to produce, so they may be used in many applications where the other filaments may not.

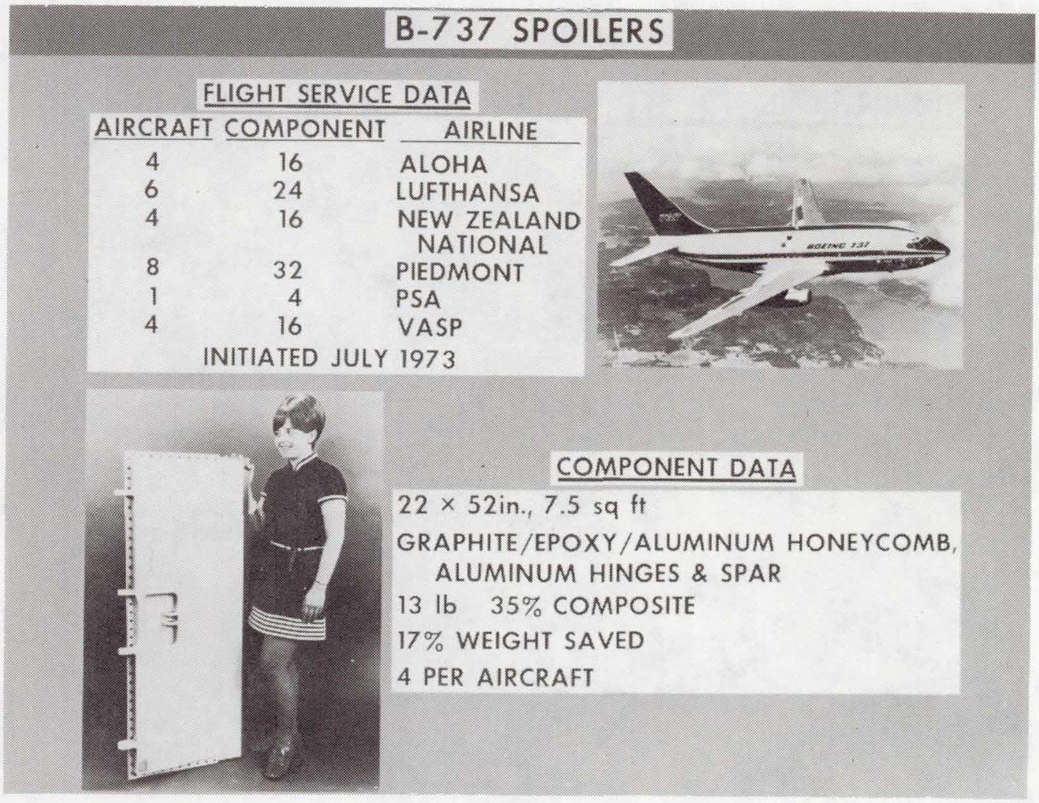
All of the filaments must be combined with matrix materials in order to make up a structural composite material. There are a variety of matrix materials around that are being used today in different applications; however, the one that we are primarily concerned with is epoxy. The epoxy matrix is the kind of material that is used in most of the commercial applications of composite materials. Polyimides and the aluminum-alloy matrices are generally used for special applications or for high temperature applications.

The first step is to combine a matrix and a filament into what we call a preimpregnated tape. The filaments are collimated into a parallel layup, and the matrix is worked in around them and partially cured so that it will stay in place with subsequent handling. For greatest ease in handling, the tape should have a reasonable amount of tackiness to hold it in place in the laminated structure. This tape material in which the fibers are all running parallel then can be worked into a laminate--cut up and stacked into multiple plies or layers so that the different layers or plies of the material have the fibers in various orientations. After a build up of a laminated structure of this type, it is processed through a high temperature and high pressure curing cycle in an autoclave. The final product then is a composite laminated structure which has significant improvements over the existing aluminum alloy structures in terms of such things as strength and stiffness; it weighs significantly less, and it has the potential for having a final cost, after manufacturing, of less than the finished manufactured cost of aluminum hardware in the aircraft business.

Of these types of improvements, the only one that has not been adequately demonstrated to date is cost. There have been a number of technology programs in existence for the last ten or twelve years in which strength, stiffness, and weight savings have been adequately demonstrated on parts by design, manufacture, and test. The cost bubble on all these technology programs has always been significantly more than the cost of an equivalent kind of item in metal, but considering the fact that cost represents, in most of these cases, a first item - a first article type of cost, it includes a lot of technology development and a lot of learning on the part of the people who are designing and manufacturing these articles. It is not surprising that these costs would be high. The projections on cost based on these programs have always been very attractive. Unfortunately, it is difficult to get good hard data that will allow one to establish whether these projections are real or not.

There is one other area that has been of some concern in terms of going to extended applications of composites in the aircraft business and that is the long term durability. It is well known that on a short term basis, the advantages of strength, stiffness, and weight saving exist; the question is how well these advantages will hold up in the 15 to 20 years that the composite part will have to be in service if it goes on a commercial airplane. So, the program that I am going to be talking about subsequently will be addressing those two issues, the long term durability and the cost item.

About six years ago, NASA started a program with the Boeing Company in which the spoilers of the 737 transport aircraft were selected for redesign with graphite-epoxy composite. The aluminum skins on those spoilers were replaced with graphite-epoxy skins; the rest of the spoiler structure was retained exactly the same as it was in the aluminum production spoilers. A flight article was obtained which was qualified by test and certificated by the FAA for its airworthiness. These spoilers, shown in figure 2, were roughly 0.6 x 1.3 m (22 x 52 inches) in planform, had graphite-epoxy skin, aluminum honeycomb core. aluminum hinges and an aluminum leading-edge spar. The total spoiler weight was approximately 6 kg (13 pounds), of which 35 percent is composite material.



B-737 SPOILERS

FLIGHT SERVICE DATA

AIRCRAFT	COMPONENT	AIRLINE
4	16	ALOHA
6	24	LUFTHANSA
4	16	NEW ZEALAND NATIONAL
8	32	PIEDMONT
1	4	PSA
4	16	VASP

INITIATED JULY 1973

COMPONENT DATA

22 × 52in., 7.5 sq ft

GRAPHITE/EPOXY/ALUMINUM HONEYCOMB, ALUMINUM HINGES & SPAR

13 lb 35% COMPOSITE

17% WEIGHT SAVED

4 PER AIRCRAFT

Figure 2

A 17 percent weight saving on these spoilers was obtained by just replacing the skins. Boeing manufactured 108 of these to be installed, four per aircraft, on 27 commercial airplanes. The initial installations were in the airlines that are listed in figure 2 on some of their fleet of 737 transport aircraft. Shortly after the program started, PSA sold four of their 737's to a Brazilian airline, VASP, with the graphite spoilers that were attached. Subsequently, PSA sold their one remaining 737 with graphite-epoxy spoilers to Frontier Airlines.

Spoiler flight service was initiated in 1973, and over 5 years of flight service have been achieved on most of these components. Boeing composite engineers have periodically inspected all of them on the aircraft. In addition, through a scheduled removal system, selected spoilers are removed from service annually, shipped back to the factory at Boeing, and thoroughly inspected by ultrasonics. These spoilers are then tested to destruction to determine if any changes have occurred in residual strength after service, compared with the initial strengths that were established in the original test program. After 5 years of this type of inspection, the graphite-epoxy spoiler is still looking good, the durability is still good, and a long service life is projected. Again, this was not a cost-type program, it was strictly a program to generate confidence in the long term durability of these material

Figure 3 shows another component of a similar nature, the

Figure 3

graphite-epoxy upper aft rudder, which is flying on eight DC-10 transport aircraft on selected airlines, also to establish some information about the long-term durability. A close-up of this rudder is shown in figure 4. The rudder is over 3.6 m (12 feet) tall. The black portion of this rudder is all graphite-epoxy; there are aluminum hinge fittings on it, the white portions on the leading edge, the trailing edge, and at the top are fiber-glass fairings, but all the rest of it is graphite-epoxy. It represents a rather significant piece of hardware; it is manufactured in a rather innovative type process that molds the complete graphite structure in a single one-piece operation. This is the kind of manufacturing that brings down the number of man-hours required in assembly of pieces of sheet metal by riveting, and therefore projects a cost-effective method of manufacturing for a finished piece of hardware like this rudder. Of the eight rudders that are in service, some have been flying as long as 2 1/2 years and the service experience with these has been entirely satisfactory. They are also inspected on a periodic basis by both airline maintenance and Douglas composite engineers.

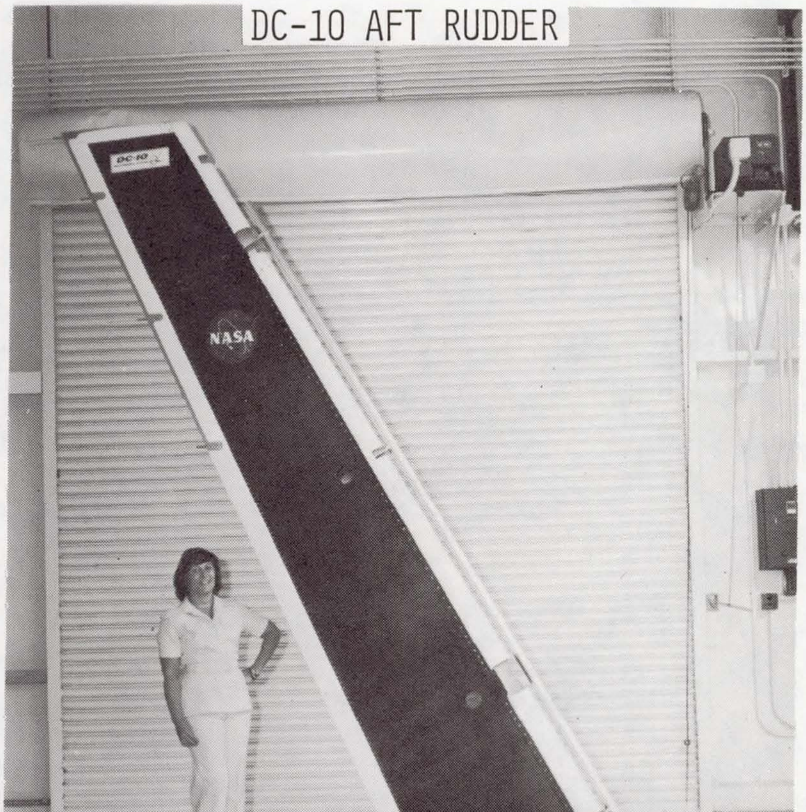


Figure 4

The first civil production commitment to composites that has occurred right from the very beginning of the design of a new aircraft happens to be with the Sikorsky S-76 helicopter, shown in figure 5. In this figure the three prototype helicopters that are being used in the flight certification program are shown. The main spar of the tail rotor is graphite-epoxy. There is a graphite-epoxy reinforcement of the spar of the horizontal stabilizer. Ther is also graphite-epoxy in a reinforcing mode in several of the doors and fairings in the forward portion of the helicopter, and there is a graphite-epoxy linkage in the root end of the main rotor blade system. All in all, there is somewhere between 20 and 23 kg (45 and 50 pounds) of graphite-epoxy composite in this production commitment by Sikorsky to this new helicopter. It is expected to have widespread usage, initially in the oil field support role, and later branching out into a much larger area of civil applicatio

Several years ago, NASA decided to try and accelerate the technology development of key areas for fuel savings through the ACEE (Aircraft Energy Efficiency) program. One part of this program is the ACEE composite structures which is trying to establish a firm base for manufacturing cost projections on selected components. The ACEE composites program deals with two sets of civil aircraft structures - secondary structures and medium primary structures.

FIRST PRODUCTION COMMITMENT OF GRAPHITE-EPOXY
TO CIVIL AIRCRAFT - SIKORSKY S-76 HELICOPTER

Figure 5

Components in the secondary structures area are shown in figure 6. The elevator on the 727 was selected by Boeing as a demonstration article for the manufacturing development program. Douglas selected the upper aft rudder on the DC-10, because based on the experience of the first 10 rudders that had been manufactured in the R&D program, they believed that there were some significant changes which could be made in their manufacturing technique, and which would do an even better job of driving the manufacturing costs down on an article of that type. Lockheed chose the aileron on the L-1011, and that also is a graphite-epoxy component and is being worked very hard at the present time in both design and manufacturing.

These three secondary structural components have some rather interesting characteristics, as shown in figure 7. The design weight of the composite part is the total weight of that part as it would be installed on the aircraft. In the case of the elevator, the weights are for only one-half of the elevator, which was all that was in the early part of the development program. For a flight article a complete ship set is needed, so those weights would be doubled. There are some rather significant poundages involved here as compared with the original flight service component weights of the spoilers. The aileron weight is also a single, left-hand unit weight. For a ship set for flight, a minimum of two ailerons would be needed. The interesting thing here is the expected weight savings of 25 to 33 percent, which has now been verified in several of these articles. That is significant from the standpoint that weight saving translates directly in a retrofit program into fuel savings, or into increased payloads. For a new design with these kinds of materials and these kinds of weight savings in hand right from the beginning, a synergistic effect will produce even greater benefits than just the direct weight savings on that particular component.

The last column of figure 7 gives the carbon-epoxy composite weight in each of these components. In every case, the amount of composite that is used is a relatively small part of the total component weight. That is because of items like metal hinges and fittings that just cannot be replaced in the present state of technology, and in these kinds of secondary structures they account for a significant part of the total component weight. But even for this situation, significant weight savings are obtained on the total component. The carbon fiber weight in these components is about 70 percent of the carbon-epoxy composite weight in the last column. The epoxy matrix is the other 30 percent. One gram of carbon fiber, if broken or cut into one centimeter lengths, will produce about one million individual fibers, or one pound will yield about one billion fibers. Even at small fractions of fiber released in a fire accident, there may be large numbers of single carbon fibers released from the kind of poundages of structures that are shown.

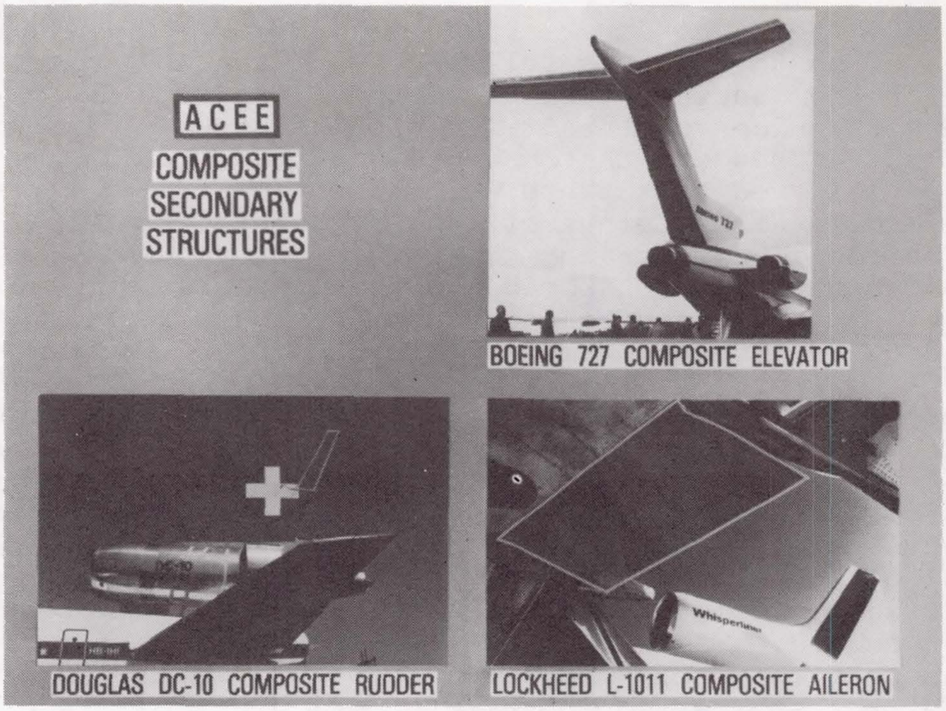


Figure 6

ACEE COMPOSITE SECONDARY STRUCTURES

COMPONENT	COMPOSITE DESIGN ESTIMATED WT. LB	EXPECTED WT. SAVINGS %	CARBON-EPOXY COMPOSITE ESTIMATED WEIGHT, LB
727 ELEVATOR	211	26	49
DC-10 RUDDER	61	33	27
L-1011 AILERON	105	25	55

Figure 7

Turning next to the composite primary structural components, figure 8 shows pictures of the selected components. For these ACEE programs, the aircraft companies selected a horizontal stabilizer on the 737, the vertical stabilizer on the DC-10, and the vertical fin on the L-1011. These begin to get to be sizeable pieces of structure, up to 7.6 m (25 feet) long. The estimated weights on these components, given in figure 9, are significantly greater than those for the secondary components. The weight savings are not as great because it is primary structure and more attention has to be paid to load-carrying capabilities, as opposed to just stiffness. The weight savings are still very significant in the 20 to 27 percent range, as opposed to the 25 to 33 percent for the secondary structures. But a more significant factor is the much larger percentage of the total component weight that is carbon composite. As the components get larger, the metal fittings become less in terms of the percentage of weight that is involved.

All six of these ACEE programs are still very active. They are driving towards developing the manufacturing expertise on these types of components that will be building multiple components and are tracking the costs throughout all the operations in manufacturing so that a reasonable type of learning curve can be obtained. The preliminary indications are that in almost every case, at some reasonable number of units downstream, these composite components would become cost effective; that is, they would be cheaper to make

Figure 8

ACEE COMPOSITE PRIMARY STRUCTURES

COMPONENT	COMPOSITE DESIGN ESTIMATED WT. LB	EXPECTED WT. SAVINGS %	CARBON-EPOXY COMPOSITE ESTIMATED WEIGHT, LB
737 HOR. STAB.	183	27	163
DC-10 VERT. STAB.	743	20	489
L-1011 VERT. FIN.	645	25	503

Figure 9

as composite parts to put on the aircraft than the existing aluminum parts for that same aircraft. It is kind of a preliminary estimate in this stage of the game. The programs all have a year or more to go before they have the final cost figures and about all that can be said is that it looks optimistic at this stage that the manufacturing costs are going to be down on these types of elements.

The final figure, figure 10, outlines briefly some of the principal areas of projected usage in civil aviation for graphite composite. Dr. Harris' talk presented several curves that projected the total aerospace poundage that might be used in the years 1990 to 1993. The bulk of that usage is going to come in transport aircraft. Using things like the ACEE technology on empennage components, on control surface components, and wing trailing edge structure, and applying that technology on the next generation of aircraft will project usages of at least the order of 450 kg (1000 pounds) of graphite composite per aircraft. How rapidly that gets translated into the total fleet, of course, will depend on sales history. Based on some discussions with the manufacturers, it appears that by 1993, approximately 50% of the civil fleet will be carrying significant amounts of graphite composites in their structures. In the helicopter business, there probably will be at least as many of the civil helicopters carrying significant amounts of graphite composites, but the total impact

CIVIL AVIATION USAGE OF GRAPHITE COMPOSITES

- TRANSPORT AIRCRAFT
- HELICOPTERS
- GENERAL AVIATION AIRCRAFT

Figure 10

in terms of volume or pounds of composites will not be as great because the total weight of the helicopter structure is not as great as that of the civil transport aircraft. The percentage of composite will be large, but the total weight is small so the total amount of the composites will be relatively small. In the general aviation portion of the market there will be many more aircraft manufactured, but to date general aviation has taken a very small look at the possibilities of advanced composites, particularly graphite composites for application in their aircraft. The first area of application will probably be in the executive aircraft and probably in some of the flight control surfaces, borrowing from the technology of the civil transport manufacturers to update and upgrade the performance of the executive type jets that are being produced by general aviation. A big penetration of composites in this market is not anticipated through the 1990 time frame. However, it is an area that could grow rapidly. There are enough aircraft being manufactured that if only a few pounds were used on each one, it could still get to be significant total poundage compared to some of the other areas. Sooner or later they will get the manufacturing costs for their applications down to where it becomes competitive and then that part of the civil aviation program will grow rapidly, but at the moment the big user appears to be the civil transport aircraft in the 1990 time frame.

Question:

Is there any reason other than material properties that prevents the manufacturers from using the composites in other components of the aircraft, say more in the basic structural framework rather than empennage and wing trailing edge surfaces?

Answer:

I think it is again a question of level of confidence; when you begin to consider components like the main wing box structure, for example, you are committing extremely large capital resources to acquire the facilities to build that kind of structure with composite manufacturing techniques as opposed to building the smaller pieces which can be handled pretty much in existing or near term type facilities. I think it is largely that kind of thing, plus again some increased concern about the long term durability of major components which are not so readily repaired or replaced, if the situation should subsequently require it. The ACEE program has had three composite wing study contracts, the final reports are just in the process of being released, and they provided a preliminary look at this question of what is required and when could we go to a full wing type structure.

Question:

I understand that the 747 has carbon fiber floor panels. Is that correct?

Answer:

We have some Boeing representatives here who might care to comment on that specific question. To my knowledge they are not a production commitment at the present time. There are a number of them that are in-service as part of a company evaluation program of the performance of these panels, but I do not believe that Boeing has made a production commitment of these in the 747 line. Would anybody from Boeing care to comment on that?

Answer:
Cory McMillian, Boeing. That is correct, it is not a production commitment.