Composite Materials in Aerospace Applications

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Abstract- Fiber-reinforced polymer composite materials are fast gaining ground as preferred materials for construction of aircrafts and space crafts. In particular, their use as primary structural materials in recent years in several technology-demonstrator front-line aerospace projects world-wide has provided confidence leading to their acceptance as prime materials for aerospace vehicles. This paper gives a review of some of these developments with a discussion of the problems with the present generation composites and prospects for further developments. Although several applications in the aerospace vector are mentioned, the emphasis of the review is on applications of composites as structural materials where they have seen a significant growth in usage. A brief review of composites usage in aerospace sector is first given. The nature of composite materials behaviour and special problems in designing and working with them are then highlighted. The issues discussed relate to the impact damage and damage tolerance in general, environmental degradation and long-term durability.

Index Terms- Composite materials; aerospace applications.

I. INTRODUCTION

The range of materials can be classified into the categories: Metals, Polymers, Ceramics and inorganic glasses and composites. Metals lose their strength at elevated temperatures. High-Polymeric materials in general can withstand still lower temperatures. Ceramics outstrip metals and polymers in their favorable melting points, ability to withstand high temperatures, strength and thermal expansion properties, but due to their brittleness they are often unsatisfactory as structural materials. This lead to the exploration of composites. One may define a composite as material as a materials system which consists of a mixture or combination of two or more micro constituents mutually insoluble and differing in form and/or material composition. Examples of composites are steel reinforced concrete (metals + ceramics), vinyl-coated steel (metals + polymers), fiber reinforced plastics (ceramics + polymers).

Emergence of strong and stiff reinforcements like carbon fibre along with advances in polymer research to produce high performance resins as matrix materials have helped meet the challenges posed by the complex designs of modern aircraft. The large scale use of advanced composites in current programmes of development of military fighter aircraft, small and big civil transport aircraft, helicopters, satellites, launch vehicles and missiles all around the world is perhaps the most glowing example of the utilization of potential of such composite materials.

II. THE AEROSPACE STRUCTURES AND FEATURES

Important requirements of an aerospace structure and their effect on the design of the structure are presented in table 1.
Further, the structure has to meet the requirements of fuel sealing and provide access for easy maintenance of equipments. Passenger carriage requires safety standards to be followed and these put special demands of fire-retardance and crash-worthiness on the materials and design used. For spacecraft the space environment—vacuum, radiation and thermal cycling—has to be considered and specially developed materials are required for durability.

Two key developments in scientific-technological world have had a tremendous influence on the generation and satisfaction of the demands raised by the aerospace community: one, the advances in the computational power and the other, composites technology using fiber reinforced polymeric materials.

### III. Use of Composites in Aerospace Structure

It is to be realized that in order to meet the demands in table 1, it is necessary to have materials with a peculiar property-set. The use of composites has been motivated largely by such considerations.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Applicability</th>
<th>Effect</th>
</tr>
</thead>
</table>
| Light-weight | All Aerospace Programmes | * Semi-monocoque construction  
* Thin-walled-box or stiffened structures  
* Use of low density materials:  
* Wood  
* Al-alloys  
* Composites  
* High strength/weight, High stiffness/weight |
| High reliability | All space programmes | * Strict quality control  
* Extensive testing for reliable data  
* Certification: Proof of design |
| Passenger safety | Passenger vehicles | * Use of fire retardant materials  
* Extensive testing: Crashworthiness |
| Durability-Fatigue and corrosion Degradation: Vacuum Radiation Thermal | Aircraft  
Spacecraft | * Extensive fatigue analysis/testing  
* Al-alloys do not have a fatigue limit  
* Corrosion prevention schemes  
* Issues of damage and safe-life, life extension  
* Extensive testing for required environment  
* Thin materials with high integrity |
| Aerodynamic performance | Aircraft  
Reusable spacecraft | * Highly complex loading  
* Thin flexible wings and control surfaces  
* Deformed shape-Aero elasticity  
* Dynamics  
* Complex contoured shapes  
* Manufacturability: N/C Machining, Moulding |
| Multi-role or functionality | All Aerospace Programmes | * Efficient design  
* Use: composites with functional properties |
| Fly-by-wire | Aircrafts, mostly for fighters but also some in passenger a/c | * Structure-control interactions  
* Aero-servo-elasticity  
* Extensive use of computers and electronics  
* EMI shielding |
| Stealth | Specific military aerospace applications | * Specific surface and shape of aircraft  
* Stealth coatings |
| All-Weather operation | Aircraft | Lightning protection, erosion resistance |

The composites offer several of these features as given below:
- Light-weight due to high specific strength and stiffness
- Fatigue resistance and corrosion resistance
- Capability of high degree of optimization: tailoring the directional strength and stiffness
- Capability to mould large complex shapes in small cycle time reducing part count and assembly times: Good for thin-walled or generously curved construction
- Capability to maintain dimensional and alignment stability in space environment
- Possibility of low dielectric loss in radar transparency
- Possibility of achieving low radar cross-section

These composites also have some inherent weaknesses:
- Laminated structure with weak interfaces: poor resistance to out-of-plane tensile loads
- Susceptibility to impact damage and strong possibility of internal damage going unnoticed
- Moisture absorption and subsequent degradation of high temperature performance
- Multiplicity of possible manufacturing defects and variability in material properties.
Even after accepting these weaknesses, the projected benefits are significant and almost all aerospace programmes use a significant amount of composites as highlighted in the figure below.

**Boeing 757-200**

All this is, of course, not without its share of hassles. Challenges of using composites on such a large scale are many. The composites are not only new but also non-conventional: they are anisotropic, inhomogeneous, have different fabrication and working methods and also different controls for quality assurance. They have a complex material behavior under load requiring new and complicated analysis tools. Moreover, the behaviour is not always predictable by analysis and this makes reliance on several expensive and time consuming tests unavoidable.

The routes to meet these challenges have evolved around use of the advances in computer technology and analysis methods to implement schemes based on computer aided design, computer aided engineering, finite element methods of analysis and building computer interfaces amongst all aspects of development, namely, design, analysis and manufacturing. These should provide fast transfer of information including graphics and accurate analysis methods for a reasonable prediction of complex behavioural patterns of composites. It is only by harnessing the vast computational power for various purposes that the aircraft structural design of today can meet the challenges posed by the required performance.

**IV. MATERIALS FOR AEROSPACE COMPOSITES**

The materials systems which have been considered useful in aerospace sector are based on reinforcing fibers and matrix resins given in table 2 and 3, respectively. Most aerospace composites use prepregs as raw materials with autoclave moulding as a popular fabrication process. Filament winding is popular with
shell like components such as rocket motor casings for launch vehicles and missiles. Oven curing or room temperature curing is used mostly with glass fibre composites used in low speed small aircraft. It is common to use composite tooling where production rates are small or moderate; however, where large number of components are required, metallic conventional tooling is preferred. Resin injection moulding also finds use in special components such as radomes. Some of the popular systems are given in table 4 along with the types of components where they are used in a typical high-performance aircraft.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Density (g/cc)</th>
<th>Modulus (GPa)</th>
<th>Strength (GPa)</th>
<th>Application areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-glass</td>
<td>2.55</td>
<td>65-75</td>
<td>2.2-2.6</td>
<td>Small passenger a/c parts, aircraft interiors, secondary parts; Radomes; rocket motor casings</td>
</tr>
<tr>
<td>S-glass</td>
<td>2.47</td>
<td>85-95</td>
<td>4.4-4.8</td>
<td>Highly loaded parts in small passenger a/c</td>
</tr>
<tr>
<td>Aramid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low modulus</td>
<td>1.44</td>
<td>80-85</td>
<td>2.7-2.8</td>
<td>Fairings; non-load bearing parts</td>
</tr>
<tr>
<td>Intermediate modulus</td>
<td>1.44</td>
<td>120-128</td>
<td>2.7-2.8</td>
<td>Radomes, some structural parts; rocket motor casings</td>
</tr>
<tr>
<td>High modulus</td>
<td>1.48</td>
<td>160-170</td>
<td>2.3-2.4</td>
<td>Highly loaded parts</td>
</tr>
<tr>
<td>Carbon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard modulus (high strength)</td>
<td>1.77-1.80</td>
<td>220-240</td>
<td>3.0-3.5</td>
<td>Widely used for almost all types of parts in a/c, satellites, antenna dishes, missiles, etc.</td>
</tr>
<tr>
<td>Intermediate modulus</td>
<td>1.77-1.81</td>
<td>270-300</td>
<td>5.4-5.7</td>
<td>Primary structural parts in high performance fighters</td>
</tr>
<tr>
<td>High modulus</td>
<td>1.77-1.80</td>
<td>390-450</td>
<td>2.8-3.0</td>
<td>Space structures, control surfaces in a/c</td>
</tr>
<tr>
<td>Ultra-high strength</td>
<td>1.80-1.82</td>
<td>290-310</td>
<td>4.0-4.5</td>
<td>Primary structural parts in high performance fighters, spacecraft</td>
</tr>
</tbody>
</table>
Table 3. Polymeric matrices commonly used in aerospace sector.

<table>
<thead>
<tr>
<th>Thermosets</th>
<th>Thermoplastics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Epoxies</strong></td>
<td><strong>Polymer</strong></td>
</tr>
<tr>
<td><strong>Phenolics</strong></td>
<td><strong>Polyester</strong></td>
</tr>
<tr>
<td><strong>Forms cross-linked networks in polymerization curing by heating</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Most popular</strong></td>
<td><strong>Cheaper</strong></td>
</tr>
<tr>
<td><strong>80% of total composite usage</strong></td>
<td><strong>Lower viscosity</strong></td>
</tr>
<tr>
<td><strong>Moderately high temp.</strong></td>
<td><strong>Easy to use</strong></td>
</tr>
<tr>
<td><strong>Comparatively expensive</strong></td>
<td><strong>High temp usage</strong></td>
</tr>
<tr>
<td><strong>Low shrinkage (2-3%)</strong></td>
<td><strong>Difficult to get good quality composites</strong></td>
</tr>
<tr>
<td><strong>No release of volatile during curing</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Can be polymerized in several ways giving various structures, morphology and wide range of properties</strong></td>
<td><strong>Inherent stability for thermal oxidation</strong></td>
</tr>
<tr>
<td><strong>Good storage stability to make prepreg</strong></td>
<td><strong>Good fire and flame retardance</strong></td>
</tr>
<tr>
<td><strong>Absolute moisture (5-6%) causing swelling and degradation of high temp properties</strong></td>
<td><strong>Brittle than epoxies</strong></td>
</tr>
<tr>
<td><strong>Also ultra violet degradation in long term</strong></td>
<td><strong>Infinite storage life. But difficult to prepreg</strong></td>
</tr>
</tbody>
</table>

V. CONCERNS WITH COMPOSITE USAGE

The concern in use of composites arises mainly due to demands of high degree of reliability and safety of aerospace structures as against the complexity of composite behaviour and consequent difficulties in building prediction models. This creates an excessive reliance on testing at all stages; design and development, proving and certification, and in-service inspection and repairs. The costs of such testing are sometimes enormous and this had led to some skepticism in use of composites. Two major issues in this regard are briefly discussed below.

5.1(a) Simulation

In this study, the simulation was undertaken in framework of ABAQUS commercial finite element package. Finite element modeling of composites is depending on the purpose of the analysis. In ABAQUS, there are several techniques for composite modeling such as microscopic modeling, macroscopic modeling, mixed modeling, discrete reinforcement modeling and sub modeling. However, the most common use in finite element simulations of composite material are layered shells, layered-solids, stacked solid elements and stacked or layered continuum shells.

The objective of ABAQUS analysis and simulation of unidirectional E-glass is to predict the mechanical properties and mechanical response of unidirectional E-glass such as tensile, compression and thermal response and then will be compared and verified with experimental results.

This option is for orthotropic materials and used specifically for plane stress, such as in laminated shell. It requires specification of E1, E2,  $\nu_{12}$, G12, G13 and G23 where E1 represent the Longitudinal Modulus, E2 is Transverse Modulus, $\nu_{12}$ is major Poisson’s Ratio and G12, G13 and G23 are in-plane Shear Modulus.
<table>
<thead>
<tr>
<th>Material</th>
<th>$E_1$ (GPa)</th>
<th>$E_2$ (GPa)</th>
<th>$\nu_{12}$</th>
<th>$\nu_{23}$</th>
<th>$G_{12}$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass 21xK43 Gevetex</td>
<td>53.48</td>
<td>17.7</td>
<td>0.278</td>
<td>0.4</td>
<td>5.83</td>
</tr>
<tr>
<td>Silenkra E-glass 1200tex</td>
<td>45.6</td>
<td>16.2</td>
<td>0.278</td>
<td>0.4</td>
<td>5.83</td>
</tr>
</tbody>
</table>

It is typically unspecified that a unidirectional E-glass fiber or lamina can be treated as transversely isotropic. For transversely isotropic lamina, the independent elastic constant becomes five because $E_2 = E_3$, $G_{12} = G_{13}$ and $\nu_{12} = \nu_{13}$.

5.1(b) Experimental

The experimental work is successfully done which consists of tensile test and thermal-stress test. This experiment required only simple rectangular-shape test specimen where it is prepared using hand lay up process. During the experiment, the surface of clean plate flat surface was waxed to facilitate easy removal of the laminate before apply mix of resin on the waxed surface. Then, cut the first fiber layer into required dimension and placed on the top of that and apply the resin again. Make even the resin using serrated roller and brush and removed all trapped air in resin and fiber. Repeat this step for the next layer until 6 layers. Finally, cover the layers with waxed flat surface and put load on the top of it to produce a better surface. Specimen was cured at room temperature for 24h in ambient condition.

Then, it was cut into the specimen dimension which is 25 mm x 250 mm.

The tensile test was undertaken using Material Test System (MTS) machine.

5.1(c) Impact damage and damage tolerance

The laminated structure of the composites and the fiber-matrix interfaces provide weak interfaces for delamination and debonding to take place. This is further aggravated by practical structural features such as discontinuous plies to create thickness changes and sharp bends required in stiffening members. Of particular concern is the proneness exhibited for damage due to impact. The issue is not merely the reduction in strength (particularly in compression) but also that the damage is inside the material and not visible at the structure. This is particularly so where the impact is due to blunt objects at low to medium velocities. Common instances are dropping of tools, hailstones, runway debris and impacts and jolts while handling (even before the assembly of the air craft). Such hidden damage can be extensive- both in terms of planar dimensions and through the thickness. The damage mostly occurs as delamination, but may sometimes be accompanied by fiber-breaks in back plies which are not visible from outside. In the shop, such damages can be found by ultra-sonic C-scan method and ‘a barely visible impact damage’ can cause a reduction in compressive strength by almost 60%. The fatigue resistance of carbon composites stands it in good stead, however, and no further significant reduction in strength or growth of damaged is observed under in-plane loads.

The current philosophy to handle impact damage problem is as follows: (i) design the structure to have alternate load paths to have damage tolerance against impact of moderate severity. This is generally taken care by designing the structure as a framework of stiffening members or as boxes; (ii) lower the design allowable strength values to an extent where the ‘barely visible impact damage (BVID)’ can be sustained even at the highest load and for all the time with no degradation in performance; (iii) any damage that exceeds the BVID level (i.e. visible damage) may lower the intermediate performance and should be repaired immediately. The basic safety of aircraft with damage is ensured due to (i) and (iv) the structure may not cater to very severe impact.

There is, of course, a penalty in lowering the allowables but for the present systems, this is considered to be not too excessive in view of the similar reduction of allowables required for fastener holes. With improved processing to get large parts integral with stiffeners and other complex shapes and with availability of high strength fibres the limitations due to impact damage would be more perceptible and prohibitive.

Another consequence of the impact damage issue which the aeronautical community is, perhaps, not yet fully exposed to is in terms of the inspection intervals and defining levels of repairs etc. when the presently developed aircraft go in full service. Extensive studies and gathering of experience through testing is presently underway to tackle this problem.

5.2 Environmental degradation

The presently used epoxy resins absorb about 5-6% moisture by weight when fully saturated. This leads to about 1.5-1.8% moisture weight gain in carbon-epoxy composites with the usual 60% fiber volume fraction. In practice, under the normal operating conditions, the maximum equilibrium moisture gain in an aircraft component can be about 1.0-1.4%. This moisture gain can cause (a) swelling and dimensional changes, (b) lowering of the gas transition temperature ($T_g$) of the resin matrix, and (c) degradation of matrix dominated properties of composites such as shear and compression strengths.
The dimensional changes and weight gain by itself are generally not significant in many aircraft structures but may be of considerable significance where extreme precision is required such as in antennae panels and in aircraft structures is the degradation of the shear and compressive strength properties-particularly at high temperatures close to $T_g$ which in itself is now reduced due to moisture absorption. The design of a structural component, therefore, generally proceeds by reducing allowables for moisture degradation.

This single issue of environmental degradation due to moisture absorption has made development of composite components for aerospace quite expensive and tedious. Moreover, associated with the already complex behaviour of composites particularly in the long run.

Apart from the moisture absorption, the other significant aspects relate to the UV degradation and radiation effects in the long term. These are particularly important in space structures. The current studies on the subject have provided some solutions to these problems even though the concern about long term behaviour exists.

<table>
<thead>
<tr>
<th>Material system</th>
<th>Application area</th>
</tr>
</thead>
<tbody>
<tr>
<td>175°C curing high strength-carbon-epoxy</td>
<td>Structural components of fighter aircraft and helicopters. e.g. wing skins, spars, fin, rudder, elevons, doors, etc.</td>
</tr>
<tr>
<td>– Zero-bleed (neat resin content) UD prepregs&lt;br&gt;- 5 HS or 8 HS bi-directional fabric prepreg&lt;br&gt;- toughness, good out-life and shelf-life</td>
<td></td>
</tr>
<tr>
<td>175°C curing intermediate modulus carbon with epoxy + BMI / cyanate-ester</td>
<td>Frames, stiffeners, rotor blades</td>
</tr>
<tr>
<td>– Zero-bleed (neat resin content) UD prepregs&lt;br&gt;- 5 HS or 8 HS bi-directional fabric prepreg&lt;br&gt;- high toughness, good out-life and shelf-life&lt;br&gt;- low environmental degradation</td>
<td></td>
</tr>
<tr>
<td>120°C curing HS-carbon-epoxy</td>
<td>Structural components of helicopters or transport aircraft. e.g. spars, fin, rudder, elevons, doors, etc. Frames, stiffeners</td>
</tr>
<tr>
<td>– Zero-bleed (neat resin content) UD prepregs&lt;br&gt;- 5 HS or 8 HS bi-directional fabric prepreg&lt;br&gt;- toughness, good out-life and shelf-life</td>
<td></td>
</tr>
<tr>
<td>Aramid fibre in low-loss polyester / cyanate esters</td>
<td>Radome</td>
</tr>
<tr>
<td>Cu-mesh epoxy prepreg</td>
<td>For Lightning Strike protection Wing-skin, others</td>
</tr>
</tbody>
</table>
VI. ADVANCES IN MATERIALS FOR COMPOSITES

6.1 Reinforcements

The carbon fiber technology continues to improve harnessing the versatility of carbon fibre and new varieties in terms of better combinations of modulus and strength are becoming available. The developments seem to be in two directions: one, for aircraft applications, is aimed basically at higher strength (>5 GPa) with concurrent improvements in modulus to a moderate level (>300 GPa) and the other, for space applications, is aimed at high modulus (>500 GPa) with moderate strength (3.5 GPa). The higher failure strain for the
fiber is expected to result in composites with better damage tolerance. The developments in aramid fibers also aim at higher modulus with concurrent increase in strength. However, the major thrust in improving reinforcements for composites comes from the requirements of multidirectional weaving. Several processes (weaving, knitting, braiding) have been developed for this purpose and performs with multidirectional woven fibers have now been made. Simplification and cost reductions appear to be the major motives for further developments.

6.2 Matrix Resins

A significant effort in improving composites is focused on improving matrix materials. The two major concerns mentioned earlier viz. impact damage tolerance and hygro thermal degradation, provide the main motivation for improvement. A major direction of improvement appears to be an improvement in the toughness, which should result in higher resistance in to delamination and against impact. High failure strain of matrix resin would help in translating the higher performance of the improved fiber to the composite. Higher resin shear modulus would help in achieving better transfer of load from fiber to resin and again to fiber and should therefore improve compression strength. For polymeric materials a possible figure of 5 GPa should be achievable as against the current resins with shear modulus of about 2 GPa. As far as hygro thermal degradation is considered, newer systems based on cyanate ester look very promising and some of these have already found some application. Another route being investigated is the use of thermoplastic resins and their blends. Poly-ether-ether-ketone (PEEK) has been considered very promising, but the industry needs to resolve the problems associated with high temperature (> 350 OC) processing of a material. Current approaches to new resins appear to be directed towards producing polymeric systems which can be processed in the way composites industry is used to (such as autoclave curing up to 180 OC).

VII. CONCLUSIONS

Hence we can finally conclude that:

□ Composite materials offer high fatigue and corrosion resistance.
□ Composite materials have high strength to weight ratio.
□ So they are best suited for various aerospace applications.

REFERENCES


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