LARGE COMPOSITE FAN BLADE DEVELOPMENT FOR MODERN AERONAVES

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SUMMARY: The state of maturity of contemporary PMC’s after almost 30 years of scientific and technology development has resulted in a capability that far exceeds that available in the late 1960’s, and which, in 1989, prompted General Electric to engage in the notably successful development and flight certification of large PMC fan blades for their GE90 engine. In this paper an accounting of the specific enhancements in (i) constituent (fiber and matrix) property characteristics, (ii) fabrication and processing options, and (iii) design analysis methods combined with computational capabilities will be discussed. However, an equally important aspect is the variation in the design options that has resulted from evolving high by-pass ratio engine technology, which will also be addressed. The GE90 fan blade represents one of these options, being a relatively large blade designed to operate at lower tip speeds, thereby reducing the severity of the impact threat represented by the ingestion of large birds. A comparison between various modern turbofan engine fan blades and other rotor blades serves to indicate the important parameters and the difficulty of establishing a composite threshold range for rotor blades in general.

KEYWORDS: polymer matrix composite, composite fan blade, constituent properties, impact performance, textile reinforcement architectures, engine certification

INTRODUCTION

Since the ill-fated attempt by Rolls-Royce to develop large polymer matrix composite (PMC) fan blades for a large commercial turbofan engine in 1968, i.e., the RB211, this potential application had eluded the engine designer until the emergence of General Electric’s GE90 engine development. But the continuing evolution in turbofan engine design has resulted in a progressive increase in by-pass ratio which has fueled a continued interest in the application of PMC’s for fan blades due to the concomitant increased pay-off for high specific stiffness and strength offered by PMC’s.

The state of maturity of contemporary PMC’s after almost 30 years of scientific and technology development has resulted in a capability that far exceeds that available in the late 1960’s, and which, in 1989, prompted General Electric to engage in the notably successful development and flight certification of large PMC fan blades for their GE90 engine. In this paper an accounting of the specific enhancements in (i) constituent (fiber and matrix) property characteristics, (ii) fabrication and processing options, and (iii) design analysis methods combined with computational capabilities will be discussed. However, an equally important aspect is the variation in the design options that has resulted from evolving high by-pass ratio engine technology, which will also be addressed. The GE90 fan blade represents one of these
options, being a relatively large blade designed to operate at lower tip speeds, thereby reducing the severity of the impact threat represented by the ingestion of large birds. A comparison between various modern turbofan engine fan blades is illustrated for a range of important parameters in Table 1. In addition, the vitally important factor for impact performance, the tip speed, is compared in Figure 1 for a general variety of composite rotor blades. An estimated impact velocity threshold range for composites is also presented in this figure, although many other factors, such as aerofoil profile, angle of projectile incidence and other geometrical features will be discussed later.

Table 1. The evolving fan technology represents a major consideration - some relevant comparisons

<table>
<thead>
<tr>
<th>Blade Type</th>
<th>RB211</th>
<th>TRENT 800</th>
<th>PW4084</th>
<th>GE90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust (lb.)</td>
<td>61k</td>
<td>84k</td>
<td>84k</td>
<td>84k</td>
</tr>
<tr>
<td>Fan Diameter (in.)</td>
<td>86</td>
<td>110</td>
<td>112</td>
<td>123</td>
</tr>
<tr>
<td>No. of Blades</td>
<td>24</td>
<td>26</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Red Line RPM</td>
<td>3900</td>
<td>3264</td>
<td>3045</td>
<td>2386</td>
</tr>
<tr>
<td>By-Pass Ratio</td>
<td>4.5</td>
<td>6.0</td>
<td>7.0</td>
<td>8.5</td>
</tr>
<tr>
<td>Blade Chord (tip)</td>
<td>17.7</td>
<td>19.9</td>
<td>19.5</td>
<td>21.0</td>
</tr>
<tr>
<td>Blade Chord (root)</td>
<td>14.2</td>
<td>16.0</td>
<td>13.9</td>
<td>12.0</td>
</tr>
<tr>
<td>Blade Span</td>
<td>28.4</td>
<td>36.7</td>
<td>34.8</td>
<td>48.0</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>2.0</td>
<td>2.3</td>
<td>2.44</td>
<td>2.57</td>
</tr>
<tr>
<td>Blade Weight (lb.)</td>
<td>19</td>
<td>26.4</td>
<td>35</td>
<td>36</td>
</tr>
<tr>
<td>Tip Speed (ft./s.)</td>
<td>1408</td>
<td>1430</td>
<td>1488</td>
<td>1250</td>
</tr>
</tbody>
</table>

Fig. 1: A general comparison of composite vs. hollow titanium rotor blades blades. An estimated impact velocity threshold range for composites is also presented in this figure, although many other factors, such as aerofoil profile, angle of projectile incidence and other geometrical features will be discussed later.
The GE90 blade design, Figure 2, also serves to illustrate the critical importance of a multidisciplinary posture that enables the effective exploitation of a new technology in key hardware items for revenue generating products. The current strategies based on integrated product development teams which evidence this trend are emphasized in the discussion. Ultimately, the successful application of PMC’s for large fan blades will contribute to higher aerodynamic efficiency, with lower specific fuel consumption, in concert with environmentally friendly, lower engine noise. Technology advances discussed in the paper will also focus on enhancements in analysis capabilities that facilitate high rate, large displacements and strains, together with three-dimensional (out-of-plane) modeling of severe soft body impacts inflicted during bird ingestion. Much improved simulations of both the PMC fan blade target and the soft body (bird) projectile have become feasible with the advent of supercomputing technology. This has culminated in greater insight for the engineer and subsequent improvement in composite design for higher impact resistance and reliability with less extensive, and less expensive, experimental commitments. Collectively, such capabilities will lead to a reduction in the time necessary to develop new technology-driven products.

Fig. 2: The GE90 Composite Fan Blade

In the concluding section, the challenge of developing certification strategies and economics-driven issues of repairability and airline customer acceptance and confidence will be addressed.
The potential advantage of polymer matrix composites (PMC’s) to the evolving development of the high by-pass ratio turbofan engine was first recognized in the late 1960’s by Rolls-Royce. A major contributor to the Rolls-Royce decision of embarking on an extensive composite fan blade development program for the RB211 at that time was the emerging carbon-fiber production capability. The background of experience gained from earlier work on small glass-fiber/epoxy compressor blades provided a useful foundation and, together with the additional specific stiffness available with carbon-fiber reinforcement, also satisfied the demanding dynamic environment. Indeed, the possibility of developing a large fan blade with vibration characteristics that would eliminate the need for midspan shrouds (or “snubbers”) that were necessary with similar solid titanium fan blades of that era represented a further significant incentive, i.e., these benefits translate into high aerodynamic efficiency, lower noise and improved fuel consumption.

Unfortunately, the severe bird ingestion environment presented a major obstacle and the lack of ductility and toughness characterized by the very low strain-to-failure and inferior interlaminar shear strength of early carbon fiber composites were shown to be totally inadequate. Use of metallic leading edge sheaths necessary for contributing erosion and hard body as well as ice impact resistance were subsequently shown to offer insufficient improvement in soft body impact (bird ingestion) performance.

Continuing evolution in turbofan engine design has resulted in progressive increases in by-pass ratio over a range from 3 to 9 and projections for future advanced engines indicate the possibility of significantly larger ratios. As a consequence, the potential payoff with PMC’s for the resulting large fan blade application has become even more attractive, as illustrated by General Electric’s excursion into PMC fan blade development for the GE90 engine, with a by-pass ratio of 8.5. Another advanced technology product, the hollow, superplastically formed and diffusion bonded (SPF/DB) titanium fan blade currently offers the only viable alternative to PMC’s. Interestingly, the initial development of the hollow-titanium fan blade by Rolls-Royce, began at the same time as the original carbon fiber/PMC RB211 fan blade design was replaced by the shrouded solid titanium design. Rolls-Royce’s Trent 800 engine now utilizes the proven hollow titanium version which was originally introduced over 12 years ago for the RB211-535 engine as discussed recently by Miller [1].

It will be explained more fully, later, that the fate of the original Rolls-Royce PMC fan blade for the RB211 was mainly due to its inability to satisfy the demanding bird-ingestion requirement. Further, the technological advancements in composite constituent property characteristics (fiber and matrix), fabrication options and design analysis methods, in addition to the changing requirements created by the evolution in high by-pass ratio fan technology will be described in accounting for the revitalized interest in PMC fan blades.

In general, the requirements for fiber reinforcement in a composite fan blade should comprise:

(i) Adequate stiffness in flexure and torsion to provide resonant frequency characteristics that avoid undesirable vibration responses. It follows that flexural stiffness calls for axial (0°) fiber reinforcement preferably at aerofoil surfaces, whereas torsional stiffness similarly calls for ±45° reinforcement as close to the outer surfaces as practicable. Adequate chordwise flexural stiffness is also required for blades of low aspect ratio and this requires a reasonable percentage of transverse (90°) fiber reinforcement.
(ii) The dominant consideration of bird (soft body) impact translates into high dynamic interlaminar shear stress in the blade root region and, probably, at the impact sites. Furthermore, for the highest level (8 lb.) bird impact interlaminar damage must be anticipated but containment of the damage by suppressing the propagation of this damage may benefit from some through-thickness fiber reinforcement. Consequently, some compromise between acceptable in-plane stiffness and strength properties and adequate interlaminar toughness would then be sought.

ENHANCEMENTS IN TECHNOLOGY

Since the early attempt at utilizing the first-generation PMC’s in the form of a carbon fiber/epoxy matrix system in the late 1960’s, Goatham [2, 3], Kedward [4], there have been several substantial enhancements in the properties of the fiber and matrix constituents. More reliable manufacturing technologies with a greater range of options for producing reliable products at lower cost have also matured and been applied in production. Finally, assisted by the advent of supercomputer technology a much improved range of sophisticated design analysis methods have been developed and are now on-line. In the following sections a specific explanation of the impact that these enhancements have had on the development of high performance composite fan blades is presented.

Improvements in Constituent Properties

With the early polyacrylanitrile (PAN) based fibers, the statistical variability, particularly in fiber strength properties was significant as well as the limited general quality standards available from early production processes. In the past twenty-five years both the strength and stiffness of available fibers have increased significantly. Moreover, the capability to obtain fibers with both high strength and high modulus has been developed, whereas the composites designer was previously forced to choose between one or the other. An appreciation of these enhancements in fiber properties can be gained from the historical data presented in Table 2.

Clearly, the benefits in strength, strain-to-failure and modulus of contemporary carbon and graphite fibers translate into major gains in the in-plane properties of multidirectional laminates of interest in highly efficient structurally loaded components. Similar benefits in transverse and interlaminar matrix dominated properties are realized from the gains in polymer matrix ductility, toughness and the improved understanding of the influence of the fiber-matrix interface.

Table 2. Carbon/graphite fiber property enhancements

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Fiber</th>
<th>$F_{tu}$ ksi</th>
<th>$E_f$ (Msi)</th>
<th>$\varepsilon_{tu} (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967 Rolls Royce</td>
<td>“HYFIL”</td>
<td>300</td>
<td>30</td>
<td>0.94</td>
</tr>
<tr>
<td>1978 Amoco</td>
<td>T300</td>
<td>450</td>
<td>34</td>
<td>1.30</td>
</tr>
<tr>
<td>1980 Hercules</td>
<td>AS4</td>
<td>570</td>
<td>34</td>
<td>1.60</td>
</tr>
<tr>
<td>1985 Hercules</td>
<td>IM6</td>
<td>740</td>
<td>40</td>
<td>1.73</td>
</tr>
<tr>
<td>1986 Hercules</td>
<td>IM7</td>
<td>770</td>
<td>40</td>
<td>1.81</td>
</tr>
<tr>
<td>1987 Hercules</td>
<td>IM8</td>
<td>790</td>
<td>44</td>
<td>1.67</td>
</tr>
</tbody>
</table>
Substantial gains have evolved through the development of tougher polymer matrix systems which, in conjunction with a more extensive scientific characterization of the effect of fiber/matrix interface phenomena, has provided much needed increases in interlaminar toughness, see Table 3 and Figure 3.

Table 3. Fracture Energy of Bulk Polymer Matrix and Composite Interlaminar Cleavage

<table>
<thead>
<tr>
<th>Date (Ref)</th>
<th>Bulk Polymer System</th>
<th>Matrix Fracture Energy $G_{IC}$ (kJ/m$^2$)</th>
<th>Interlaminar (Mode 1) Fracture Energy, $G_{IC}$ (kJ/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974 [5]</td>
<td>Shell 818</td>
<td>0.18</td>
<td>0.55</td>
</tr>
<tr>
<td>1980 [6]</td>
<td>Hexcell 205</td>
<td>0.27</td>
<td>0.60</td>
</tr>
<tr>
<td>1986</td>
<td>AS4/PEEK</td>
<td>*3.80</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>(Thermoplastic)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>IM7/8551--7</td>
<td>*1.10</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>(Toughened Eposy)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3: Translation of Polymer Matrix Toughness into Interlaminar Composite Toughness
Much has been learned regarding the methods of toughening bulk polymer matrix materials such as the use of elastomeric particles for example. More significant is the ability to translate the enhanced toughness of the bulk polymer into improved interlaminar toughness in the composite. In first generation, relatively brittle, epoxy systems (Table 3) toughness enhancement of the matrix resulted in substantial increases in composite interlaminar (toughness particularly in Mode 1 (interlaminar tension). This effectiveness is illustrated in Figure 3 for the relatively brittle epoxy matrix systems with typical values of Mode 1 strain energy release rates, $G_{IC}$, given in Table 3. It is also clear, from Table 3 and Figure 3, that the translation of bulk matrix toughness into composite interlaminar can be much less effective for the tougher polymer systems. We now appreciate that the general principle accounting for the reduced effectiveness of composite toughening is associated with the high degree of constraint imposed by the stiff reinforcing elements in PMC’s with high reinforcement volume fractions.

With regard to the general subject of damage tolerance and the macroscopic structural behavior of composite structures it is also acknowledged that the proportional increase in toughness may be significantly different for Mode I (interlaminar tension) vis-à-vis Mode II (interlaminar shear). Typically the gains in Mode 1 ($G_{IC}$) are significantly higher than those realized for Mode II ($G_{IIC}$) for most candidate toughening methods. From a structural designer’s viewpoint the relative importance of these factors must be interpreted from the aspect of structural configuration and loading. In the event of the high velocity impact threat the damage resistance can be strongly dependent on the Mode II toughness of the composite but this may vary for composite structural configurations subjected to hard body projectiles, e.g. ice, runway stones, etc. vs. soft body (bird ingestion) projectiles. On the other hand the damage tolerance of composite structures may be more dependent on Mode I toughness particularly for damaged structures that are loaded in compression following an impact event. For the composite fan blade application, of interest herein, the latter is probably of lesser importance than for, say, that of a composite upper wing skin for a commercial transport aircraft.

More recently the rate-dependent behavior in both Mode I and II fracture has been studied for both untoughened and toughened epoxies, see Cairns [8,9]. Although the conditions representing only low velocity impact have been addressed indications of significant rate dependence specifically for Mode II fracture properties of toughened epoxy systems are of direct interest and relevance. It is particularly noteworthy that the corresponding results pertaining to Mode I fracture are relatively insensitive to strain rate [9]. Qualitative rationalization of these observations refer to tortuosity of crack path development in the non-homogeneous toughened epoxy matrix system, local crack tip sliding deformation as well as inherent matrix toughness increases.

During the past four or five years it has been demonstrated that the interlaminar toughness of laminated composite systems can be effectively increased, at least in Mode I, by the inclusion of a small percentage of through thickness reinforcement by stitching of dry fiber preforms [10] followed by resin infiltration processing as discussed next.

**Alternative Reinforcement Architectures for Toughening and Manufacturing Advantages**

Recent NASA-funded research and development work at McDonnell Douglas Aerospace, Long Beach, California has demonstrated that effective toughening of laminated polymer
composites can be realized by use of a small percentage of stitched reinforcement [10]. Using the Compression-After-Impact (CAI) strength as an indicator of toughness, it was shown that only 3% of Kevlar stitch reinforcement is necessary, using the relatively brittle Hercules 3501-6 resin matrix system to attain a toughness equivalent to that of the toughened epoxy system, Hercules 8551-7. The latter is a considerably more expensive matrix material but, more significantly, the possibility of utilizing resin infiltration method such as Resin Transfer Molding (RTM) or Resin Film Infusion (RFI) methods of processing net shape structures offers potential economic advantages for manufacturing. At least for commercial transport upper wing skin and related applications this approach is most attractive and is now has serious consideration for such applications. A tolerable reduction in the critical in-plane properties must be accomodated in utilizing relatively-lightly stitched PMC systems however.

Other candidate approaches for effective interlaminar toughening are widely available through the exploitation of textile technology. One specific example is some form of “angle interlock” architecture, often defined as “2.5D fiber architecture”. The need for adequate in-plane stiffness and strength properties generally precludes consideration of a full 3D-type of fiber reinforcement architecture.

As mentioned the ability of stitched fiber arrangements to suppress or contain interlaminar damage has been demonstrated, for the McDonnell Douglas transport wingskin application now under development. There is also a limited amount of data that indicates that "2.5D" or angle-interlock architectures can similarly suppress or contain damage although the impact on in-plane properties has been less well characterized as are meaningful comparisons of interlaminar tensile and shear properties of these systems.

To assess the potential of 2.5D systems, in fan blade applications a survey of the existing technology and data base should be conducted. Some relevant data is presented in Table 4, compiled from Ref. [11] but the absence of interlaminar strength properties will be noticed here.
Table 4: Data for Angle Interlock “2.5D” Reinforcement Architectures, [11]

<table>
<thead>
<tr>
<th>Property</th>
<th>Mode</th>
<th>Layer-to-Layer (LTL)</th>
<th>Through-the-Thickness (TTT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Type A (4 layers)</td>
<td>Type B (6 layers)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.22”</td>
<td>0.246”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.22”</td>
<td>0.246”</td>
</tr>
<tr>
<td>$E_1$</td>
<td>Tension</td>
<td>12.3</td>
<td>11.6</td>
</tr>
<tr>
<td>Axial Modulus (ksi)</td>
<td>Compression</td>
<td>12.8</td>
<td>11.8</td>
</tr>
<tr>
<td>Flexure</td>
<td>Flexure</td>
<td>10.4</td>
<td>---</td>
</tr>
<tr>
<td>Ft, ult</td>
<td>Tension</td>
<td>142</td>
<td>136</td>
</tr>
<tr>
<td>Axial</td>
<td>97.2</td>
<td>101</td>
<td>82.7</td>
</tr>
<tr>
<td>Strength</td>
<td>Flexure</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>$E_2$</td>
<td>Transverse (Msi) Elastic Modulus</td>
<td>63.5</td>
<td>6.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.16</td>
<td>6.64</td>
</tr>
<tr>
<td>$E_3$</td>
<td>Thru-thickness (Msi) Elastic Modulus</td>
<td>2.32</td>
<td>2.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0</td>
<td>2.02</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>In-plane shear (Msi) Modulus</td>
<td>0.9</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.81</td>
<td>0.83</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>(In-plane Poisson ratio)</td>
<td>0.06</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.054</td>
<td>0.097</td>
</tr>
</tbody>
</table>

In attempting to summarize the state-of-the-art on the subject as it relates to the fan blade application, the following observations are pertinent:

(a) Typical layer thicknesses for the layer-to-layer angle interlock and through-thickness angle interlock architectures are in the range of 0.040 inch-to-0.060 inch, which is much larger than typically found in tape or fabric laminates. Hence, it may be necessary to "phase out" the interlock layers in the thinner sections of a fan blade.

(b) It is also important to note that typical interlock systems comprise only orthogonal in-plane reinforcement (warp and fill directions) with no ±45° fibers. Incorporating in-plane angle orientations may require some development time on behalf of the preform supplier.

(c) The effectiveness of the interlock arrangement in achieving improvements in interlaminar, tension and shear, characteristics without serious degradation in the in-plane properties demands very careful study. For example, the angle and straightness, in the thickness direction, of the warp weavers and the associated anisotropy in interlaminar property enhancement has not been adequately presented in the literature reviewed to date.

(d) Due to the coarseness of the architecture and the related unit layer thicknesses the tendency for lower flexural stiffnesses, especially for thinner sections of the blade
should be recognized. Some of the data presented in Table 4 illustrates this
tendency. Table 5 provides a concise summary of the general implications of this class
of reinforcement architectures for fan blade applications in terms of some pros and
cons.

Enhancements in Design Analysis Methods

With the enormous expansion of numerical methods development, such as that based on finite
element technology, combined with the utilization of current supercomputing capabilities
there has been phenomenal growth in our ability to conduct complex and detailed analyses.
Advantages in the development and handling of databases that can effectively link the
computer aided design, analysis, manufacturing and tooling functions are also derived from
these developments. Numerous, special purpose software developments and design rules and
systems are now available, examples such as linear and nonlinear laminated plate analysis
codes and out-of-plane methodologies have emerged to support conventional laminated
composite structures. More recently there is a growing capability for treating integral fiber
architectures although generally a less mature design analysis at present.

However, of greater interest and relevance to PMC fan blade design are the sophisticated
analysis methods now developed for soft body impact evaluation than can simulate the
ingestion of large birds and predict the consequences. This particular condition has primarily
been the critical design issue, and most certainly accounted for the failure of the first attempt
to utilize PMC’s for the Rolls-Royce RB211 engine in the late 60’s and early 70’s.

In attempting to account for the technology leverage existing today relative to that available in
the 1968-71 era of the RB211 development, the current analysis capability represents a
profound advantage for the engine designer. To put this in perspective it is appropriate to
briefly review historical developments over the period from 1968 through to the present. An
illustration summarizing the key developments in soft body impact analysis methods is
portrayed in Figure 4. Only very crude modeling and analysis techniques for both the soft
body (bird) projectile as well as the composite target (blade) were available in the late 1960’s.
One example of this overly simplistic idealization of the distribution, termed slice mass, of the
bird onto the blade was published by Sayers [12]. Although finite element technology
development, and the application therof, was rapidly growing in the late 1960’s, it was some
time later (about 1975) before advanced composite anisotropic layered structures could be
effectively idealized, recognizing the fact that computational capabilities permitted only
relatively slow run times. The additional data input and output required for large numbers of
composite layers was very cumbersome at that time.
### Table 5: Some Pros and Cons Related to the Selection of Fiber Reinforcement Architecture in Fan Blade Application

<table>
<thead>
<tr>
<th></th>
<th>STITCHED FABRIC BASELINE</th>
<th>LAYER-TO-LAYER ANGLE INTERLOCK</th>
<th>THROUGH THICKNESS ANGLE INTERLOCK</th>
</tr>
</thead>
</table>
| **PROS**         | • Modest dilution of in-plane properties.  
                  | • Flexibility for accommodating all 0/45/90 directions.  
                  | • Order of magnitude improvement in Mode I (Interlaminar Tension Strength) properties.  
                  | • Amenable to selective transverse reinforcement.  | • Well established preform experience.  
                  | • Potential enhancement of Mode II (Interlam. Shear Strength) properties.  
                  | • Good prospects for automated preform development.  | • Well established preform experience.  
                  | • Potential enhancement of Mode II (Interlam. Shear Strength) properties.  
                  | • Good prospects for automated preform development.  | • Potential enhancement of Mode II (Interlam. Shear Strength) properties.  
                  | • Potentially lower cost preform rel. to thru-thickness system.  | • Potential enhancement of Mode II (Interlam. Shear Strength) properties.  
                  | • Less effective reinforcement in filler direction (Anisotropy)  
                  | • Unproven capability for accommodating ±45 in-plane reinforcement.  
                  | • Potentially higher cost preform rel to thru-thickness system.  | • Less effective reinforcement in filler direction (Anisotropy)  
                  | • Unproven capability for accommodating ±45 in-plane reinforcement.  |
| **CONS**         | • Restricted to near-normal fiber reinforcement thru thickness.  
                  | • Limited enhancement of Mode II (Interlam. Shear Strength) properties.  
                  | • Possibility of application to thicker sections.  | • Restricted to near-normal fiber reinforcement thru thickness.  
                  | • Limited enhancement of Mode II (Interlam. Shear Strength) properties.  
                  | • Possibility of application to thicker sections.  | • Restricted to near-normal fiber reinforcement thru thickness.  
                  | • Limited enhancement of Mode II (Interlam. Shear Strength) properties.  
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                  | • Possibility of application to thicker sections.  | • Limited enhancement of Mode II (Interlam. Shear Strength) properties.  
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                  | • Possibility of application to thicker sections.  |

By the mid 1970’s the compatibility for more representative soft body simulations were beginning to emerge such as Pratt & Whitney’s PW/WHAM code. In this simulation, reported and described later by Martin [13] a more accurate distribution of impact load is facilitated by a fluid finite element idealization. “Flow” of the soft body (bird) occurs at impact while the target remains solid. The postulate in such projectile models is that the material density rather than the material strength is the dominant factor and this tended to be substantiated by Barber et al [14,15,16] using metallic targets. Soft body impact was shown [15,16] to be characterized as a four-step process:
(i) initial shock (Hugoniot pressures) caused by a sudden decrease in speed of a soft-body projectile at the initial impact (stagnation) point

(ii) impact shock decay via relaxation waves propagating from the free surface of the projectile.

(iii) steady-state fluid jet flow developing a stagnation pressure.

(iv) finally flow and induced load decay.

![Fig. 4: Historical development of impact analysis technology](image)

It is characteristically found that predictions based on the above approach generally concur with experimental results specifically with regard to transmitted stresses near the trailing edge several milliseconds after the initial impact. In fact damage or loss of material near the trailing edge tip is typically observed during experimental bird impact simulations and this was indeed the case in GE90 fan blade development testing. Predictions also indicated that impact induced stresses are subsequently transmitted to the root in the trailing edge area several milliseconds later; again this has been confirmed during experimental evaluations. It was also shown that, experimentally, gelatin material was a suitable soft body substitute for bird-like projectile confirming that established and used earlier by Rolls Royce [12] and others [17,18]. Simple one-dimensional analytical predictions are also available such as that of Cassenti [19] who showed that, for perpendicular impacts the Hugoniot pressure is given by the water hammer pressure; i.e.

\[ p_H = \rho_0 C_0 u_0 \]  

(1)
where
- \( \rho_0 \) is the material density at the nominal pressure
- \( C_0 \) is the velocity of sound in the fluid body, for small disturbances
- \( u_0 \) is the nominal initial velocity of the projectile

The stagnation pressure is given by:

\[
p_s = \frac{1}{2} \rho_0 u_0^2
\]  

By application of equations (1) and (2), a rough estimate of the pressures developed at the impact center can be obtained. The possibility that delamination damage may be created by the high, short pulse, Hugoniot pressure remains unproven with regard to its potential significance in degrading the composite target (blade) integrity.

With the advent of supercomputing capability in the mid 1980’s and the development of high rate, large displacement, nonlinear flow modeling and analysis for ductile metals, represented by software developments such as DYNA 3D, growth in soft body impact analysis capability was extensive, see Niering [20]. At about the same time the capabilities for modeling geometrically complex blade targets exhibiting centrifugally load-induced nonlinear deflections and comprised of highly anisotropic, heterogeneous laminated composites had reached a relatively mature level.

Clearly, the growth in sophistication of physical simulations, and associated commercial modeling and analyses of the bird and the composite fan blade target presented a major advantage for GE’s development of the GE90 blade relative to the primitive state-of-the-art existing at the time of the initial Rolls Royce RB211 fan blade development. More significantly, the designer can now conduct more meaningful evaluations of the complete containment event in developing designs for new systems to combat bird ingestion and its consequences.

**INTEGRATED PRODUCT & PROCESS DEVELOPMENT PHILOSOPHY**

The development of the GE90 Composite Fan Blade (Figure 2) serves as a classic example of the successful utilization of concurrent engineering approaches that embody a strong multidisciplinary posture in contemporary industry. With the adverse history of the earlier Rolls Royce experience with the RB211 engine and the negative attitudes that had “shadowed” that era of aggressive composite utilization it was a particularly formidable challenge for General Electric to commit to the GE90 fan blade development. In retrospect it is clear that GEAE had formed the vision that the increased by-pass ratio and thrust, the increased blade size and lower tip speed, see Table 1, presented a scenario that merited revisiting the application of composites. This vision is apparent from a review of the papers presented by Hauser & Elston [21] and by Elston [22] wherein credits are attributed to the excellent execution of component/product design based on the integration of material selection, manufacturing process definition and rigorous development evaluation.

Elston [22] discusses the benefits in overall engine reliability and performance and to customer (airline) acceptance derived, in addition, from the design attention to maintenance and overhaul features. Specifically the high thrust and enhanced fuel economy are introduced together with substantial reductions in noise and emissions. Numerous lessons learned from GEAE development such as the Unducted Fan (UDF) engine developed under the GE/NASA

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Energy Efficient Engine program proved to be invaluable for the overall GE90 engine development.

The initiatives based on integrated product and process development (IPPD) and concurrent engineering was extended to external interactions with the airframe manufacturer, i.e. Boeing’s 777 team, as well as subcontract suppliers and airline representatives.

Interestingly, Miller [1] projects the Rolls Royce philosophy advocated for the development of their advanced line of high by-pass ratio aeroengines, the RB211 and Trent families. Interdisciplinary collaboration between material scientists, design and manufacturing engineers, representative of the same concurrent engineering philosophy utilized by GEAE, was a continuing theme in the recent presentation by Miller [1]. However, Rolls Royce offers an alternative form of fan blade design, i.e. a hollow titanium construction. The engineering and manufacturing development of the wide chord hollow titanium fan blade is described by Miller [1] as, “an excellent example of simultaneous engineering-design for a controllable manufacturing process as well as for product duty”. It is also noteworthy that the hollow titanium fan blade design and development began at the time that the original RB211 PMC fan blade was being abandoned to be replaced by the shrouded solid titanium design configuration, as mentioned previously.

Only time will tell which fan blade, the GE90 Composite or Rolls Royce hollow titanium, will prove to be superior over a long period of service. The comparisons illustrated on Figure 1 indicate that the latter will tolerate higher tip speeds although many other engine parameters and geometrical factors may be responsible for the operational superiority of the two competing engines. Some have expressed concern regarding the long term fatigue/durability of the hollow-titanium construction. Undoubtedly such comparisons, other than the thrust rating and specific fuel consumption (SFC), are exceedingly difficult to determine in quantitative terms.

CERTIFICATION AND MAINTENANCE ISSUES

First the general operational requirements associated with large fan blades are significantly different from those for aircraft structures for which the large proportion of data and documentation is available [23, 24]. Moreover, these fan blade requirements also differ from those typical of other components in engine structures that are in use or under consideration regarding projected composites utilization. The differences bear close similarity with the situation for the rotorcraft industry wherein rotor blade engineering development and production receives special treatment relative to typical static, fuselage structures, fairings, etc.

As a consequence it is of no surprise that certification strategies tend to be substantially different for large fan rotor blades vis a vis other aeroengine components. Primary reasons for this situation are also associated with environmental and maintenance considerations for which extreme temperature exposure as well as low velocity damage of relatively thin gage structures represent driving concerns. For the case of large fan blades the bird ingestion criteria usually dominates the overall design approach. The range of temperature experienced by the major proportion of the fan blade configuration high bypass ratio engines does not, typically, cause major concern. This scenario results from the higher impact velocities created at take-off engine rpm in conjunction with moderate aircraft forward speeds.
A striking example of the uniqueness involved with the certification of composite fan blades was provided during the development and certification of the GE90 blade. Although the general airworthiness requirements are detailed in Section 33.77 of the Federal Aviation Regulations (FAR) Part 33 [25] it also became necessary for the Federal Aviation Administration (FAA) to develop a “Special Conditions” document [26] covering the specific design aspects of the GE90. However, as stated reference [26] does not represent a standard for general applicability to other composite fan blades. Nevertheless, future engine developers introducing composite fan blades would be advised to review [26] very thoroughly and should contemplate the possibility of a somewhat different set of special conditions. It is especially noteworthy that GEAE also faced the increased bird ingestion guidelines recently imposed by the FAA which call for a demonstrated capability for ingestion of an 8 lb. bird with a safe engine shutdown. The corresponding large bird requirement was previously 4 lb.

The economics-driven issue of maintenance also poses special challenges for composites. Current attention to related composite repair procedures have identified this subject as critical to future airline acceptance. Surveys have indicated that the cost and time of composite repair and the availability of suitable repair materials are common reasons for the concern. Again most of the surveys apply to secondary aircraft structure (airframe) repairs and therefore, with reference to composite fan blade applications, they should be taken as general operational experiences that do not usually apply directly to rotating, blade components.

Specifically for the composite fan blade scenario, results have shown that damage levels below visual detectability are unlikely to pose a threat to structural integrity. The most susceptible area experiencing moderate damage levels is usually in the vicinity of the leading edge where it has been demonstrated that the metallic leading edge guard in this area can be “dressed” in the instances to provide satisfactory structural performance as well as cosmetic appearance. Naturally, blade replacement would be necessary after incidents such as large bird ingestion.

CONCLUDING REMARKS AND FUTURE OUTLOOK

The above discussion has, hopefully, illustrated that the dramatic advances in materials performance, both fiber and matrix, together with substantial enhances in design, analysis and processing accounts for the notably successful GE90 composite fan blade. Contemporary trends in high by-pass ratio aeroengines has generally supported the introduction of composites on account of larger blade sizes and lower tip speeds. But several items of concern remain; examples being the effort required to certify large composite fan blades and the related prospect of other “special conditions” to be satisfied.

Existing capabilities for soft body impact prediction, now under consideration, should be further enhanced specifically for more rigorously characterizing the composite fan blade structure in both the aerofoil and the blade root region. Failure criteria and progressive damage models that reflect rate dependent behavior must be refined so as to provide improvements to current capabilities [27, 28] now commonly used in the available software systems such as DYNA3D and MSC/DYTRAN. These capabilities should be coordinated with carefully-instrumented experimental programs. To establish refined correlations more extensive use of of-embedded sensor technology should be utilized to effect greater insight and understanding of the characteristics of composite fan blade in operation, particularly under the critical bird ingestion loading.
There is an imminent need for more representative damage modeling and the interrelated failure criteria that are applicable to composite fan blades during the severe soft body impact condition. Better information on the strain rate effects, for which preliminary research has been reported by Cairns [8,9], could provide a useful background for conventional composites. However, the future of integral fiber architecture can only be meaningfully assessed if the analysis methods now evolving are carefully correlated with high quality experimental work.

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