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Materials for rotationally dynamic components: rationale for higher performance rotor-blade design

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Abstract

The design of rotating components demands a good understanding of the effect on materials under dynamic stress conditions. Depending on the operating conditions, the components have to possess appropriate stiffness and strength properties to ensure stresses are kept within acceptable limits, and geometrical stability is maintained to ensure correct functioning. The loads may also fluctuate throughout the rotational cycle, inducing fatigue in the component. In addition, any adverse effects of environmental impact have to be taken into consideration. The design is clearly complicated and utilising the most appropriate material or materials is challenging. This paper discusses the design decision-making involved for a rotationally dynamic component using the example of a helicopter rotor blade. The specification and outline design provide the context for evaluating and comparing metallic and composite constructions.

Keywords: Engineering design; Materials selection; Optimisation; Rotor blade

1. Introduction

The helicopter is a rotary wing aircraft as apposed to a conventional fixed wing aircraft. The wings or blades of a helicopter are part of a larger dynamic system called the rotor, which is designed to provide the lift, thrust and control [1]. In a conventional fixed wing aircraft, the lift, propulsion and control are handled separately. It is therefore apparent that the safety of the helicopter is highly dependent on the reliability of the rotor and its blades. The blades are connected at their centre of rotation by a hub. In operation, as the helicopter flies forward the blade on the advancing side experiences high relative air speeds giving rise to possible compressibility problems while on the retreating side the opposite is true and low speed, high angle of attack stall can result; as a consequence of the rotor flapping to balance itself. Therefore, the forces on the rotor blades are cyclical; repeating every revolution of the rotor, with fatigue performance a major factor of consideration in the design [2].

A retrospective analysis of rotor blade design has unsurprisingly identified the dominance of materials in the development of rotor blades. A rotor blade is a highly stressed rotationally dynamic safety critical structural component. Achieving an optimal design solution is difficult because the operating parameters are already at or near their ultimate limits. Systematising the design procedure, particularly for the formative stages, ensures appropriate consideration is given to all design requirements [3]. The subject of this case study is not new because composites have replaced metals in rotor blades, even though the basic principles of the rotor have not been changed. This paper examines the key aspects involved in substituting a completely new class of materials to essentially replicate the function of an existing

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design for a demanding application but with enhanced performance capability.

2. Design function requirements

An accurate and detailed specification is critical to the success of any design [4]. The functional requirements for the rotor blades generally reflect the requirements for the whole helicopter and can be summarised as follows [5]:

1. *Stiffness and strength*. A combination of high specific strength and controllable specific stiffness is desirable. This is necessary because the forced vibration from the rotating blades have to be separated from the natural frequencies in the airframe. Also, because of the periodic loads experienced by the blades, high fatigue strength coupled with enhanced strain properties are desirable in a material.
2. *Weight*. It is important to keep the weight of the helicopter low to either increase the payload or performance. However, the weight of the blades is determined by the moment of inertia necessary to achieve autogyro-rotational landings in the event of engine failure and by the assignment of natural frequency.
3. *Safety*. To maintain safety in the blades it is necessary to apply high safety margins. Predictable performance and confidence in the materials used allow designers to apply realistic safety margins.
4. *Impact resistance*. The blades have to be resistant to foreign body impact or damage tolerance such as bird strike, as well as a certain amount of mishandling in the field and during servicing. The erosion and corrosion resistance is an integral part of damage tolerance.
5. *Erosion*. The rotor blades travel through the air at high speed, particularly the tips of the blades, and as a result, particles in the air (dust, sand, hail, etc.) are very abrasive. The erosion effect is particularly intense at take off and landing when the down draught from the rotor picks up loose materials from the ground. Abrasive resistant materials are therefore necessary for all the leading edges of the blades.
6. *Corrosion*. To control the effects of corrosion allows smaller safety margins to be applied and reduces maintenance. Corrosive resistant materials are therefore necessary for the whole of the blade.
7. *Cost*. The main requirement is to achieve a functional design at minimum cost. The easiest way of analysing cost is to consider the cost of ownership, because this encompasses all the factors that make up the total cost. The two broad issues for blades are low initial cost of acquisition by mechanising/automating the production process and low operating cost by reducing the maintenance.
8. *Performance*. Aerodynamic efficiency of the blades allows the performance of the helicopter to be maximised, increasing payload capability, range or speed, depending on the design priority. The accuracy of manufactured shape and quality of surface finish are therefore important parameters.
9. *Endurance*. The life of the blades has important implications on operating cost and must be maximised to ensure economic viability. The dominant effect results from fatigue but in service conditions such as corrosion and erosion also have detrimental secondary effects. Improvements in these areas leads to increased reliability and reduced maintenance.
10. *Lightening strike protection*. An electrically conductive path is required along the blade length to discharge any high voltage lightening strikes that may occur.
11. *De-icing*. A facility for locally heating the leading edge of the blade is required for de-icing purposes.

3. Candidate materials selection

From a structural point of view, a blade is essentially a continuous load-bearing member with clearly defined principal stress directions. The major stress path is along the long axis of the blade resulting from centripetal forces [6]. There are no major notches or apertures, therefore any serious stress concentrations, except for the root area where the blade is attached to the hub.

The candidate materials for blades are as follows [7]:

- Metals: aluminium, stainless steel and titanium.
- Composites: glass, aramid, and carbon (high modulus and high strength) fibres in epoxy resin matrices.

Originally, rotor blades were made from wood (a natural composite) glued together in plywood form. However, warping and moisture absorption lead to poor dimensional stability. For this reason metals replaced wood and now composite materials have replaced metals. A similar pattern of use and development can be seen for propellers.

From the list of candidate material properties in Table 1, it can be seen that conventional aerospace grade metals, i.e., aluminium, stainless steel and titanium are limited to specific strengths of 0.17–0.23 MPa and specific stiffness of around 0.025 GPa. The metal with the best mechanical properties is titanium but its use is generally controlled because of its cost and availability. However, composite materials, e.g., glass fibre/epoxy,

Table 1
Candidate material properties

Material	Young's modulus (GPa)	Ultimate tensile strength (MPa)	Density (kg m^{-3})	Specific stiffness (GPa/kg m^{-3})	Specific strength (MPa/kg m^{-3})
Aluminium	70	480	2770	0.025	0.173
Stainless steel	200	1240	8030	0.025	0.154
Titanium	110	1035	4430	0.025	0.234
Unidirectional composite (60% volume fraction)					
Carbon – high modulus	180	1000	1600	0.113	0.625
Carbon – high strength	140	1500	1600	0.088	0.938
Aramid	75	1300	1400	0.054	0.929
Glass	40	1000	1900	0.021	0.526
Woven composite (50% volume fraction)					
Carbon – high modulus	85	350	1600	0.053	0.219
Carbon – high strength	70	600	1600	0.044	0.375
Aramid	30	480	1400	0.021	0.343
Glass	25	440	1900	0.013	0.232

aramid fibre/epoxy, carbon fibre/epoxy have specific strengths of 0.22–0.94 MPa and specific stiffness of 0.01–0.11 GPa. Therefore, the range and higher values of stiffness and strength properties make the use of composite materials more suitable than metals for rotor blades. The fatigue properties of composites are also superior to metals, permitting longer service life [8].

Corrosion is a major problem with any metal aircraft structure especially for highly stressed components such as helicopter blades. The blades are susceptible to stress and crevice corrosion. The problem is particularly severe when operating near the sea. Salt water is particularly aggressive to aluminium; therefore stainless steel and titanium are mostly used. However, these materials are difficult to process and fabricate, especially titanium, which has a high melting point. Composite materials though are not prone to corrosion problems, although prolonged exposure to moisture demands special resins, and relatively not as difficult to process.

Erosion, particularly in the tip region is a major problem in blades. Metals have advantages over relatively softer composite materials. However, it is possible to cover the vulnerable leading edges of the blades with metal erosion shields, which also provide a conductive path for lightening and can contribute to the strength. Titanium is the favourite material for the inboard region of the blade but for the more complex shaped tip region, more advanced metallic materials are employed such as electro-deposited nickel.

The cost of materials used for blade manufacture can be high but the cost of processing and in service costs have to be taken into consideration as well. In general metals are cheaper than composite materials, but mechanising and automating the manufacturing process can bring down the cost substantially. However, the large initial investment in tooling has to be amortised over the expected production run. Therefore, the greater the number of blades manufactured the less the affect of the tooling cost, assuming the tool life is not exceeded [9].

For safety, the fatigue life of a composite blade is much greater than a metal blade because composite materials have endurance limits for certain loading conditions that are a higher percentage of ultimate strength than found in metals. Also, composite components, if designed properly, have a gradual failure mechanism. The failure process normally starts with cracking in the matrix, resulting in a gradual loss of stiffness. This gives helicopter operators plenty of warning with visual indications, rather than rapid loss of structural integrity and catastrophic failure. The Civil Aviation Authority (CAA) in the UK and Federal Aviation Authority (FAA) in the USA approved operating life for metal helicopter blades are around 1500–3000 h. The CAA/FAA approved operating life for composite blades is unlimited, although most operators inspect their blades at regular intervals, typically after 10,000 h. The life of a civil helicopter might be 40,000 plus hours.

The aerodynamic efficiency of a rotor blade is critical to its performance. The use of metals restricts the blade designs to constant section profiles for ease of manufacture and economics. The use of composites and associated moulding processes enables contoured compound curvature blades to be repeatedly produced with accurate profile and excellent surface finish [10]. Blade shapes not possible in metal can be made using composite materials. There is no motivation for reducing the weight of blades by using composites, which high specific stiffness and strength permit. There is a need however to control the moment of inertia for powerless landings and control the frequency of vibration to prevent resonant conditions occurring during the operating frequency range [11].

4. Blade construction

The construction of a typical metal helicopter blade consists of an assembly of around 250 separate components. All these components have to be manufactured

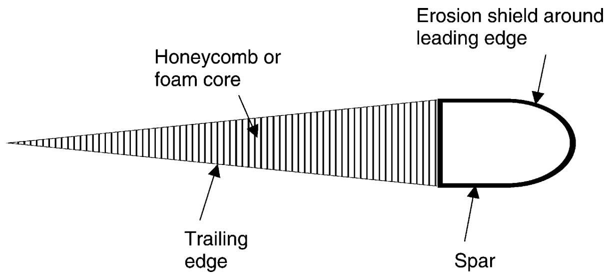

Fig. 1. Cross section through a typical composite rotor blade.

and assembled in jigs, using rivets and bolts. The majority of components are curved skin panels, which have to be individually formed prior to assembly. Blade manufacture in metal is therefore a labour intensive process. Composite blades also comprise of many components, in fact thousands of components if all the plies of composite material are taken into consideration. These plies are long, floppy, thin, tacky and easily damaged or contaminated. Packs of up to 100 plies are often required and it is extremely difficult to control the quality by manual methods. The processing of manufacturing composite rotor blades is therefore highly mechanised to ensure rapid production and consistent quality in order to compete with metal constructions.

The construction of a typical composite rotor blade consists of three major parts: a hollow section spar, a sandwich structure trailing edge, and an erosion shield on the leading edge as shown in Fig. 1. All three parts are consolidated in a jig and bonded together.

4.1. The spar

The spar comprises of a hollow 'D' shaped cross section made up from pre-impregnated unidirectional fibres wrapped with ±45° fibres on the inside and outside surfaces. The fibre is deposited using either a filament-winding machine or a tape laying/placement machine. It is usual to combine glass and carbon fibre in the construction of the spar.

4.2. The trailing edge

The trailing edge comprises a sandwich structure, using either 'Nomex', a paper honeycomb impregnated with phenolic resin, or a structural foam, profiled to shape and skinned with ±45° fibres. A variety of fibre types are used in the trailing edge in woven and unidirectional form.

4.3. The erosion shield

This is usually made from a sheet of titanium and is formed to completely cover the leading edge of the spar.

The torsional stiffness in the blade is derived from the ±45° wrap on the spar and the trailing edge. The longitudinal or bending stiffness is derived from the unidirectional lay-up in the spar. By varying the types of fibre, the lay-up and the position of fibres, the characteristics of the blade can be adjusted [12]. The ability to be able to 'tune' the blade characteristics using composite materials gives a distinct advantage over metals. A carbon and glass fibre hybrid is used for the spar to offset catastrophic failures in thick carbon fibre sections and provides a more fibre dominated failure mechanism but still retain an acceptably high modulus. Glass and carbon fibre combination are also used in the trailing edge skins because aramid fibres have poor compressive properties.

The use of pre-impregnated composite materials is preferred over wet lay-up composite materials because the quality is more controllable, although the materials are more expensive. Using a mechanised manufacturing process, the pre-cut material is placed in position, one ply at a time using a tape laying head on a lay-up table and transferred to a moulding tool [13]. An inflatable mandrel forms the hollow section of the spar. A proven method of attaching the blade to the hub is by using two metal side plates. These are bolted to the spar at the root end where additional woven material is incorporated to provide high bearing strength and load distribution capability around the drilled holes. The use of metal end fittings overcomes the high local loads experienced at the root ends [14].

5. Conclusions and recommendations

The requirements for helicopter blade design have been outlined. The primary candidate materials for blade construction have been cited along with their advantages and disadvantages. It has been demonstrated that composite materials have many advantages over traditional aerospace metals. Their use in helicopter blades has lead to greatly increased service life, better performance and improved safety. The implications on design for dynamically stressed components in general involving material substitution have been emphasised. Whether the motivation for change is for enhanced performance and/or more cost-effective production, the emphasis must be on establishing the critical design parameters that are affected by the bounds of the existing materials and processes used. Highly stressed components are more sensitive to change because they may already be operating at the limitation of certain aspects of material (or process) performance and a material (or process) substitution may necessitate a compromise in certain parameters for an overall gain in performance or process efficiency. For the rotor blade, substituting metals with isotropic properties, for composites with an-isotropic properties leads to variable properties throughout the structure of the component, depending on the fibre direction. In this case, the material substitution can improve the mechanical properties in one direction but may worsen the mechanical properties in another direction. With the drive towards more optimal structures, compromise is necessary in order to satisfy the many conflicting requirements such as high strength and stiffness against poor damage tolerance when using composite materials. Obviously, design solutions exist to overcome material shortcomings but their consequences have to be managed to ensure sympathetic consideration.

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