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Structural evaluation of a composite centrifugal rotor

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Abstract

The steady increase in the use of composites has brought benefits in many areas. Polymer Matrix Composite (PMC) is a material consisting polymer (resin) matrix combined with a fibrous reinforcing dispersed phase. Polymer Matrix Composites are very popular due to their low cost and simple fabrication methods. This paper aims to validate thru finite element method the structural integrity of a composite gas turbine rotor and establish its benefits and disadvantages compared to a steel alternative. Composites provide the advantages of lower weight, greater strength and higher stiffness and the advantage of prepreg technology.
Keywords: Composite materials, FEM, rotor, CAD modelling

1. Introduction

Fiber-reinforced polymeric matrix composite, CFRP materials, have enormous potential in the construction, transport, aerospace and energy sectors because of their durability, lightweight and ability to be manufactured in complex shapes. The steady increase in the use of composites has brought benefits in many areas. Polymer Matrix Composite (PMC) is a material consisting of polymer (resin) matrix combined with a fibrous reinforcing dispersed phase. Polymer Matrix Composites are very popular due to their low cost and simple fabrication methods. Likewise, within the three classes of composites, the CFRP is the lightest.

The use of composite materials in military and transport aircraft has increased constantly. Initial applications of composite materials to aircraft structures were in secondary structures such as fairings, small doors, and control surfaces. As the technology matured, the use of composite materials for primary structures such as wings and fuselages has increased.

Their applications in industries like aerospace are not only related to high thrust-to-weight ratio, but also their corrosion and fatigue resistance. Stiffness to weight ratio optimization, thermal and environment resistance for high performances, fuel efficiency consume, are issues that are still unsolved. Major efforts are made on providing revolutionary high temperature (up to 425°C in service), mechanical and environment resistant composite materials. Composites provide the advantages of lower weight, greater strength and higher stiffness [1].

2. Paper Contents

The manufacturing of the rotor blade of the axial compressor from composite material is a complex task, and represents a new approach, at both national and international level, offering several advantages. Starting from an existing design, providing a complete cycle of manufacturing of a gas turbine blade is inherently multi-disciplinary and encompasses three main areas: material science, fluid mechanics, and solid mechanics/dynamics. The three areas usually interact more or less intimately in an iterative fashion during the process. Nevertheless, the most important issues of the research work are the application of the autoclave technology for the project impeller blades manufacturing. Design, geometry optimization of the compressor impeller (blades) along with aeroelastic design studies on such complex geometry in strong relation to the manufacturing process using the autoclave technology is the first step of the development cycle. Then, starting from the functioning parameters of the structure (the compressor impeller blade) selection of the materials (prepreg, precursors), related to the established technology (the autoclave), is an important step. The materials selection (composite precursor-prepregs), will be performed starting from the requirements set of the functioning conditions for the compressor impeller/blades. Table 1 summarizes the requirements set for the first step in the selection of the composite materials (precursors, prepregs). The selected materials will be done based on both Table 1 and the highest maximum strength to density ratios obtained for all candidates.

Table 1. Material selection for rotor blades

Material	E (GPa)	σ (GPa)	ρ (Kg/m^3)	E_{SR}
E-glass fiber (typical)	70	3.5	2540	1.1
Aramid fiber (Kevlar 49)	127	2.6	1470	3.4
Polyethylene fiber	100	3	970	4
High-strength carbon fiber	230	3.6	1800	5
Intermediate modulus carbon fiber	300	5.8	1800	6.5
Mild Steel (typical)	200	0.2	7800	1
Alloy steel (typical)	200	1	7800	1
Aluminum alloy	72	0.8	2700	1

E-Young modulus, σ-maximum tensile strength, ρ-density, E_{SR}-normalized specific stiffness, σ-n

The equation 1 sets the base formula for the centrifugal forces calculations, in the present case the first iteration of calculus takes into account a volume element (i.e. ΔV is 2x104 mm3,ρ is taken for the woven High Strength Carbon Epoxy composite as 1.47 g/cm3, the acceleration ω is taken at 17x103 rot/min. and the radius R is 121,48 mm), the centrifugal forces acting on the composite materials structure taken into account within the first iteration is around 11,3 kN.

$$F_C = R \cdot \omega^2 \cdot \rho \cdot \Delta V \text{ , (N)} \quad (1)$$

Advantages of autoclave processing are related to a very high control of resin content, low void content, control of laminate thickness, lower-cost labor, quality and repeatability, 'clean' process, fabrication of structural composite components with a high fiber volume ratio, high compactness, void-free; it allows production of any fiber orientation, thermoplastics and thermosets resins, various forms and prototypes, high quality, however limited volume parts.
Prepregs are specially formulated resin matrix systems that are reinforced with man-made fibers such as carbon, glass and aramid [1]. The thermoset resin cures at elevated temperature, undergoing a chemical reaction that transforms the prepreg into a solid structural material that is highly durable, temperature resistant, exceptionally stiff and extremely lightweight [2]. The most common thermoset resin is epoxy, probably because the major markets for prepreg materials are in aerospace, sporting goods and electrical circuit boards where the excellent mechanical, chemical and physical properties of epoxies are needed. Epoxy resins can be grouped according to the curing temperatures with typical values being room temperature (commercial applications), medium temperature cure (sporting goods and medical applications) and high-temperature cure (aerospace applications) [3-6]. In some instances, a resin film is placed upon the lower mold and dry reinforcement is placed above. Auxiliary materials are also used for resin excess extraction, vacuum uniform distribution. The assembly

(mold/materials) is vacuumed bagged and placed into an autoclave for the polymerization process. This process is generally performed at both elevated pressure and elevated temperature. The use of elevated pressure facilitates a high fiber volume fraction and low void content for maximum structural efficiency.

Manufacturing compressor impeller/blade through autoclave process by using CFRP composites, will generate weight reduction of the total rotary assemble better performances related to fuel consumption and pollutant emission reduction [7]. In this respect preliminary study was performed to establish the feasibility and technological issues to be solved concerning the manufacturing of the composite parts using autoclave technology.

3. Finite element analysis

The finite element model was created and solved in SolidWorks. The initial model used for these analyses was the steel-based part. In order to define the numerical calculus a mesh was created using 3D tetrahedron elements as depicted in figure 1.

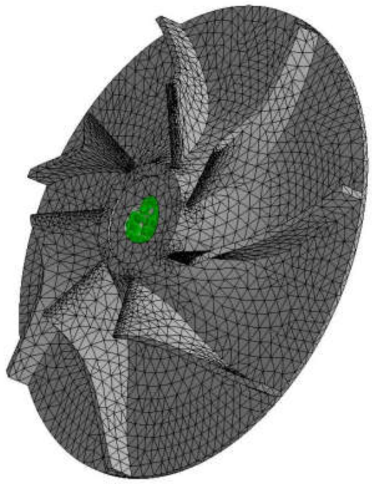
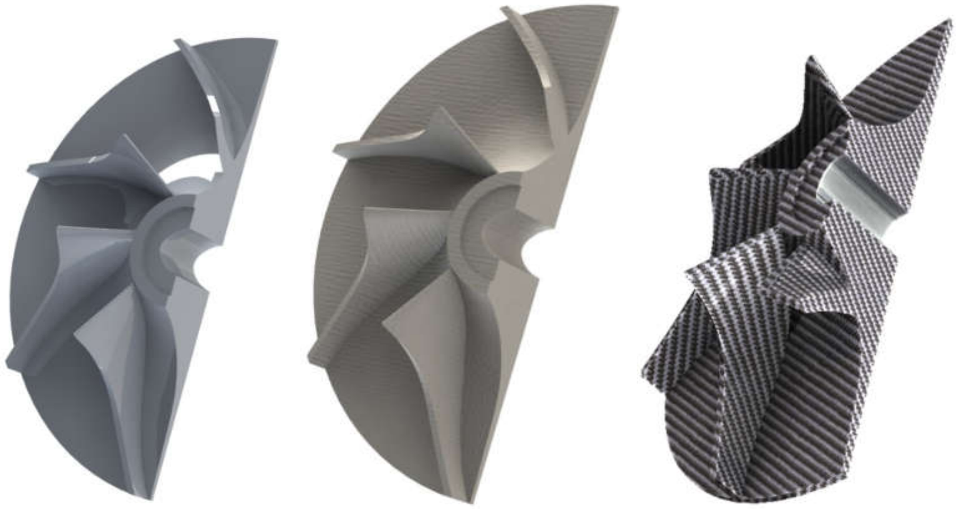


Fig. 1 Meshed model.

For accurate analyses, a curvature-based mesh was imposed on the 3D model, using 44052 nodes and 24762 elements with 4 Jacobian points. Same mesh was applied in all three cases of materials, steel, carbon fibre composite and glass fibre composite. The boundary conditions, as fixed support, for the frequency analyses are also shown in figure, represented by the green area.



a) b) c)

Fig. 2: 3D models for rotor with different materials

Depictions for the three separate models are presented as follows in figure 2: a) steel turbine rotor; b) glass fibre composite rotor; c). carbon-fibre composite turbine rotor.
The mechanical characteristics for the three materials (Alloy steel, E-glass fibre and High-strength carbon fibre) used are presented in table 1

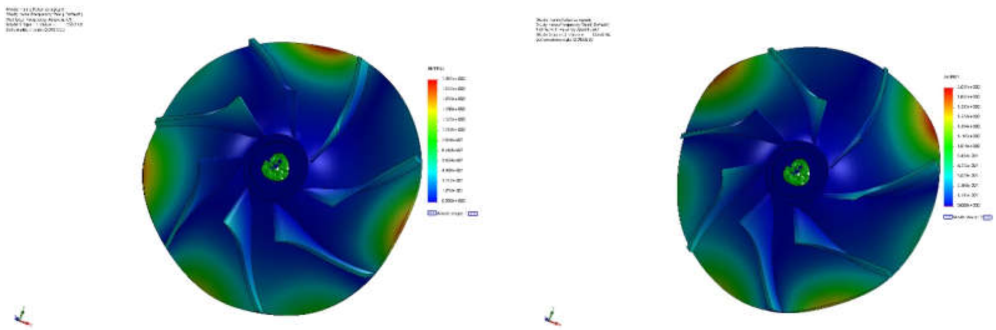


Fig. 3 The first and the second natural frequencies for the steel rotor

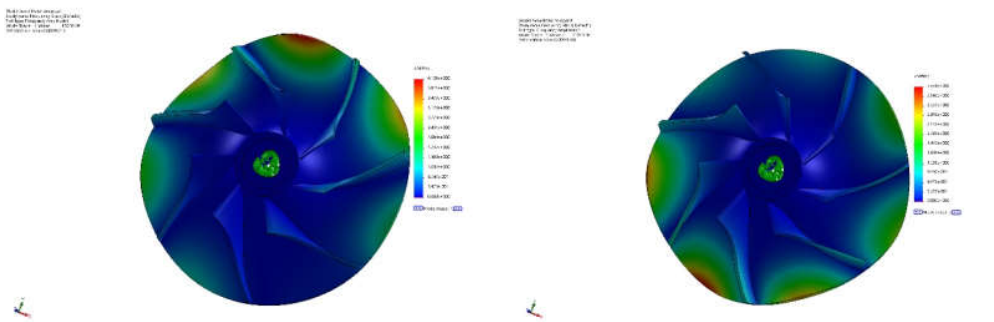


Fig. 4 The first and the second natural frequencies for the fiberglass rotor

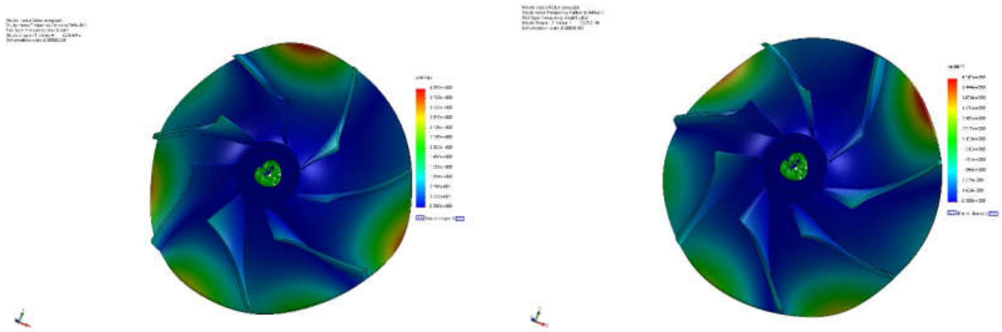


Fig. 3 The first and the second natural frequencies for the carbon fibre rotor

6. Conclusions

The first laboratory tests indicated that despite the low thickness of the blade wall (in the case of an empty blade), a technological protocol related to autoclave technology can be established so as to manufacture the compressor impeller blades out of CFRP composite materials. Other not empty solutions like metallic guards and foam cores will be investigated, the aim being not only reducing weight but also obtaining a strong and high performances compressor impeller. Thus, further laboratory tests will be performed in order to obtain an optimum technological protocol for the future activities of composite compressor impeller blades manufacturing using autoclave technology. The target of the research work is the rotating assembly of aerodynamic compressors since they represent the bigger challenge in weight reduction. By manufacturing compressor impeller/blade through autoclave process by using carbon fiber is that of creating a new lightweight but strong and durable product material. Obtaining this composite material will generate weight reduction of the total rotary assemble, better performances related to fuel consumption and pollutant emission reduction.

The finite analysis shows that the steel model and fiberglass models are similar in behavior, both having the first natural frequency superior to the turbine rotation frequency. The carbon model obtains the highest natural frequencies, almost three times higher compared to steel and glass fiber. Thus, with further research, both the glass fiber and carbon fiber could be a proper replacement for steel in manufacturing this type of turbine rotors.

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