„POLITEHNICA" UNIVERSITY OF BUCHAREST
FACULTY OF AEROSPACE ENGINEERING
DOCTORAL SCHOOL OF AEROSPACE ENGINEERING

CONTRIBUȚII PRIVIND DESIGNUL ȘI REALIZAREA UNUI ROTOR DE COMPRESOR CENTRIFUGAL DIN MATERIALE COMPOZITE

CONTRIBUTIONS REGARDING THE DESIGN AND DEVELOPMENT OF A CENTRIFUGAL COMPRESSOR ROTOR MADE OF COMPOSITE MATERIALS

PHD THESIS SUMMARY

Author: Eng. Radu MIHALACHE

Scientific coordinator: Prof. dr. ing. Ion FUIOREA

Bucharest, 2021

PHD THESIS CONTENTS

KEYWORDS: centrifugal compressor, composite materials, composite rotor, carbon fibres, prepreg, technology, autoclave

CONTENTS

ABBREVIATIONS, NOTATIONS AND SYMBOLS

ABS	Acrylonitrile butadiene styrene
Al_2O_3	Alumina
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibber Reinforced Plastics
CMC	Ceramic matrix composites
CNC	Computer Numerical Control
CO_2	Carbon dioxide
FEA	Finite Element Analysis
FEM	Finite Element Modelling
FFT	Fast Fourier Transform
FRF	Frequency Response Function
FP	Frame Programme
GE	General Electric
MMC	Metallic matrix composites
MW	Megawatt
NASA	National Aeronautics and Space Administration
NOx	Nitrous oxide
PEEK	Polyether ether ketone
PMC	Polymer matrix composite
RANS	Reynolds-averaged Navier-Stokes
RMS	Root Mean Square
RPM	Rotation per minute
RTM	Resin Transfer Moulding
SiC	Silicon carbide
SNECMA	Societe National D’Etude et de Construction de Moteurs D’Aviation
SST	Shear Stress Transport
UE	European Union
VARTM	Vacuum Assisted Resin Transfer Moulding

INTRODUCTION

The present doctoral thesis entitled "***CONTRIBUTIONS REGARDING THE DESIGN AND DEVELOPMENT OF A CENTRIFUGAL COMPRESSOR ROTOR MADE OF COMPOSITE MATERIALS***" is a contribution to theoretical, technological and experimental research in the field of aerospace engineering. As the advanced research in conjunction with state-of-art technological developments lead to promising results in terms of space exploration, the technological needs are becoming more complex and interdependent.

All these technological requirements must take into account the rules and directives on environmental protection and the reduction of pollutant emissions, so as to comply with the United Nations Convention aimed at limiting global temperature rise to 2°C to avoid the effects of climate change.

The general objective of the doctoral thesis is to contribute to the development and implementation of state-of-the-art technologies in bladed rotary machines, obtaining results that can be easily translated into better efficiency and lower energy consumption for such machines. Therefore, the author uses low-mass composites such as carbon fibre for the development of a centrifugal compressor rotor using the autoclave technology, thus exceeding the boundaries of the current level of development in the field. Moreover, specific research into the possibility of using composite materials for the development of a centrifugal compressor rotor was decided due to the significant mass input of power generating machines that have integrated aerodynamic compressors. Reducing the overall mass would lead to a significant impact on reducing fuel consumption and energy to decrease pollutant emissions.

To this end, the author performed specific analyses on composite materials available on the market and applicable for the development of a centrifugal compressor rotor using autoclave technology, performed comparative analyses based on results from an extensive mechanical characterization campaign to select the most suitable material, determined the physical-mechanical properties for the selected material in order to use this information in subsequent numerical simulations, modelled, manufactured, balanced and tested the centrifugal compressor rotor made of polymeric composite materials reinforced with carbon fibres, thus obtaining its own and novel results in the aeronautical field.

The following are the specific objectives of the current doctoral thesis:

- in-depth analysis of commercially available composite materials for the development of a centrifugal compressor rotor using autoclave technology;
- performing a comparative analysis based on preliminary mechanical characterization tests to select the most suitable material for the present application;
- determination of the physical-mechanical properties for the selected material in order to use this information in the subsequent numerical simulations;
- dynamic balancing studies for components which operate at high speeds and have low mass;

- obtaining the geometric model of the centrifugal compressor rotor suitable for manufacturing using autoclave technology based on complex aerodynamic and mechanical studies, respectively dynamic balancing studies;
- defining the technological process of manufacturing the centrifugal compressor rotor, an objective that also involves the geometric modelling of the moulds related to the proposed technology;
- validation of the proposed technology by manufacturing the centrifugal compressor rotor and experimenting with it through a complex testing campaign.

In view of the above, the next logical frontier in the use of composite materials in aircraft systems is their integration into rotating moving subassemblies in propulsion systems, specifically in the compressor. The propellers of small aircraft, as well as the nacelles of large aircraft are already made of composite materials. Reducing the mass of rotating components is very important because it has a double global effect, it increases the mass-to-payload ratio, and lower inertial moments in the engine, which leads to a decrease in pollutant emissions and noise, especially for take-off and landing regimes.

The development of the technology of manufacturing a centrifugal compressor rotor from composite materials is a complex task, representing a new type of approach, both nationally and internationally, but offering undeniable advantages.

ACKOWLEDGEMENTS

There was nothing I could do on my own. The combined contribution of all was decisive in terms of completing the doctoral thesis. There are many people I want to thank - people who helped me concretely or with a word of encouragement, to complete this work. I remain grateful and extend sincere thanks, from the bottom of my soul, to all the people involved.

I want to thank my scientific coordinator, Prof. Dr. Ion FUIOREA, for guidance, support and encouragement during the period of doctoral preparation, thesis development, as well as in professional activity. I would also like to emphasize the motivating capacity of the professor that was instilled in me throughout the doctoral internship. Without your support, I would not have been able to complete my doctoral thesis.

I would also like to thank Prof. Dr. Virgil STANCIU, who contributed significantly to my training and guided me through the entire period spent at the Faculty of Aerospace Engineering.

I want to thank also the National Institute for Research and Development of Gas Turbines COMOTI for the logistical support offered, a support that significantly contributed to obtaining the results and elaborating this doctoral thesis.

Thank you to all colleagues and management within COMOTI who had a significant contribution in obtaining the results presented that led to the completion of this work.

I would like to thank all the teachers and instructors who trained and guided me in all my professional activity.

Last but not least, I thank and am deeply grateful to my family for their constant encouragement, support, understanding and patience, helping me to complete this thesis.

CHAPTER 1
MOTIVATION OF THE TOPIC AND THE OBJECTIVES OF THE DOCTORAL THESIS

The fabrication of the centrifugal rotor from composite material was initiated within the ManuCFBlade - Lightweight carbon fibre compressor impeller / blade manufacturing research project study funded in the frame of the MANUNET program. The project was coordinated by the National Institute for Research and Development of Gas Turbines COMOTI between 2013 and 2015. In the period following the completion of the aforementioned research project, the author continued the study by manufacturing the entire rotor assembly and performing specific tests on the centrifugal compressor test bench within COMOTI, thus achieving the guidelines and directives on environmental protection and reduction of pollutant emissions, by substantial reduction of the mass of the rotor assembly, leading at the same time to the decrease of pollutant emissions.

The doctoral thesis "Contributions regarding the design and development of a centrifugal compressor rotor made of composite materials" is structured in 7 Chapters, Annexes and Bibliography. **Chapter 1,** entitled **Motivation of the topic and objectives of the doctoral thesis**, highlights the need for research on reducing pollutant emissions and the benefits of composite materials in bladed machines. **Chapter 2**, entitled **Current state of use of composite materials in the aeronautical industry and bladed machines**, presents a complex analysis of the research carried out so far on the main directions of development of the aeronautical industry, the use and applicability of composite materials in this leading industry, respectively the manufacturing of components using autoclave technology. **Chapter 3**, entitled **Studies and analyses on the selection of composite materials for the realization of the centrifugal compressor rotor**, is intended for the selection of the optimal composite material for the manufacturing of a centrifugal compressor from composite materials. Based on the study, a comparative analysis of the identified materials was performed, and four of them were subjected to a test to determine the mechanical characteristics, thus leading to the material which was used to manufacture the compressor rotor. **Chapter 4**, entitled **Defining the geometric model and numerical validation of the centrifugal rotor considering the autoclave technology**, includes aeroelastic design studies and the definition of the geometric model of the centrifugal compressor rotor. Based on these studies, the particularities of the centrifugal compressor rotor regarding the aerodynamic, mechanical and aeroelastic characteristics and a preliminary study on the dynamic balancing of the rotor made of polymeric composite materials reinforced with carbon fibres were determined and optimized. **Chapter 5**, entitled **Manufacturing technology development for the composite material centrifugal rotor**, presents the design of the moulds needed for the autoclave technology, as well as the methods by which the moulds were manufactured. Using the designed and fabricated moulds, the manufacturing of the centrifugal compressor rotor continued in three distinct stages: independent manufacture of the seven rotor blades, integration of the blades in the rotor structure, defining of the rotor disk and of the machining area for the balancing process and in the last stage the machining technology for the interface of the rotor with the drive shaft and for its outer diameter was defined. **Chapter 6**, entitled **Experimental investigations and validation of centrifugal compressor rotor**, consists in performing numerous experimental tests which have the purpose to evaluate and validate the centrifugal compressor rotor, respectively the new manufacturing technology developed in this thesis. In this chapter, experimental verifications were performed consisting in determining the rotor mass and checking the dimensional and geometric deviations, validating the dynamic balancing and performing a modal vibration analysis to determine its natural frequencies and resonance regimes, as well as integrating the rotor on a test bench to perform a partial verification of its functionality. **Chapter 7**, entitled **Personal contributions and future research directions,** contains the general conclusions resulting from the scientific research carried out, highlighting the author's own contributions undertaken in the doctoral thesis, the novelty of the doctoral thesis, and a series of subsequent research proposals.

CHAPTER 2
CURRENT STATE OF USE OF COMPOSITE MATERIALS IN THE AERONAUTICAL INDUSTRY AND BLADED MACHINES

The aeronautical industry is one of the emerging sectors of global industry, benefiting from the latest technologies in areas such as materials and manufacturing technologies, the ultimate goal being to provide the safest, most reliable and least impactful means of transportation. Since the first commercial passenger aircraft, the design and manufacturing of aircraft has evolved considerably, with the trend to reduce fuel consumption as well as pollutant emissions, mainly carbon dioxide (CO_2) and nitrogen oxides (NO_x), with direct implication on climate change or global warming. There are several solutions which can be successfully applied to reduce pollutant emissions, namely:

• Improving the combustion process in propulsion systems (jet engine);

• Use of alternative fuels (i.e. biofuels such as camelina, hydrogen, bioethanol in combination with kerosene etc.);

• Reduction of aircraft mass by using materials with superior mechanical properties and low weight.

Among the solutions presented above, the doctoral thesis aims to reduce the mass of the propulsion system, by using composite materials, with high mechanical properties (similar to metals) and low density. Manufacturing of a centrifugal compressor rotor from composite materials, using autoclave technology, is a complex task, representing a new type of approach in this field, both nationally and internationally, but offering undeniable advantages. The development of such component is addressed in the following chapters.

The use of composite materials is not limited to the structure of the aircraft, they can be successfully implemented for various components of propulsion systems, reducing weight by up to 25% and costs by about 20% for an engine. An important step in this area was the development of the largest dual-flow turbojet engine, the General Electric GE90, which equips the Boeing 777 aircraft. The first attempts at implementing composite materials in fan blades were made in the 1980s for an experimental propane-type turboengine model, GE36. The generation of large dual-flow turbojet engines from General Electric continued with the GEnx model, which introduces CFRP composites for the first time in the fan housing, thus saving up to 160 kilograms for a turboengine. With the introduction of the new version of Boeing 777, called 777X, General Electric developed a new version of the GEnx engine, called GE9X. Unlike its CFRP predecessor blades, the new ones will be a carbon fibre-glass fibre hybrid, incorporating both types of fibres in the same resin.

Romania has also been involved in such programs to improve the performance of turboengines by using composite materials. The OPENAIR project, carried out under FP7, aimed to develop a fan stator blade made of composite materials with polymer matrix reinforced with carbon fibres and foreseen with titanium inserts. An important feature of these is the fact that, in addition to the usual structure, the stator blade is provided with an active system for controlling the noise level, having as source the aircraft engine, its role being to reduce the level of noise pollution.

PERSONAL CONTRIBUTIONS

CHAPTER 3
STUDIES AND ANALYSES ON THE SELECTION OF COMPOSITE MATERIALS FOR THE REALIZATION OF THE CENTRIFUGAL COMPRESSOR ROTOR

3.1. Identification and selection of application-specific composites

This chapter aims to conduct an in-depth study in order to identify and select the most suitable composite materials for the manufacturing of the centrifugal compressor rotor.

The selection of composite materials was made starting from a set of preliminary requirements (as thermal, mechanical and environmental loads) that must be met by the compressor rotor, respectively by the materials that will be used for its manufacturing, such as:

- the need for a high ratio between mechanical strength and density (strength-to-weight ratio - R_m/ρ);
- working temperature (minim 120°C);
- resistance to dynamic loads (centrifugal forces of approximately 11 kN);
- crimp properties.

Considering the requirements of the application, the identification and selection of specific polymeric composite materials was performed in two steps.:

- in the first stage, the materials available on the market were identified considering their field of applicability and the requirements imposed on the application taking into account the autoclave technology;

- in the second stage, from the previously identified materials, four materials were selected, having specifications and characteristics in accordance with the application, which were analysed and compared by mechanical tests. In the selection process of the four materials, the delivery times, the possibility of obtaining a minimum delivery quantity (60 ÷ 100 m^2 material), and also the acquisition cost were taken into account.

Based on materials information, four materials were selected and compared from mechanically point of view:

- M49/42%/200T2X2/CHS-3K (further defied as M49);
- GG245TSE-DT121H-42 (further defied as GG245);
- ER450/CC402 (further defied as CC402);
- ER450/CC370 (further defied as CC370).

3.2. Determination of mechanical properties for selected materials

The four previously selected materials were subjected to a static mechanical test (tensile tests) aiming to determine and evaluate the following parameters: tensile strength, elongation at break, ultimate strength, Young's modulus, yield strength. All the mechanical tests presented in this chapter were repeated on at least five specimens to determine the mechanical properties of the material as accurate as possible. Following the SR EN ISO 527-4:2000 standard, Type 3 specimens were selected for the tensile tests, with tabs as indicated in Figure 3.1 intended for testing thermoplastic and thermosetting materials reinforced with multidirectional fibres.

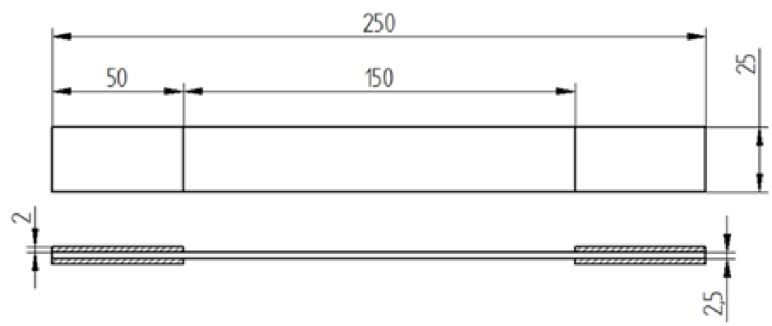


Figure 3.1. Type 3 standard specimen dimensions

Specimen fabrication

For the fabrication of Type 3 specimens, a composite plate (laminate) was manufactured from each of the four materials previously selected, 10 specimens being subsequently cut (5 longitudinal and 5 transverse), using water jet cutting.

The number of layers and the parameters of the curing process differ for each material, depending on the thickness of their layer. Table 3.1 presents the layer configurations for each laminate fabrication, together with the processing parameters in the autoclave The manufacturing process as well as the four manufactured laminates are shown in Figure 3.2.

Table 3.1. Curing parameters for Type 3 specimens

Material	Layer thickness [mm]	Specimen thickness	Layer configuration	Curing parameters
CC370	0.36		$[0°/90°]_9$	Heat: 3°C/min; Temperature: 135°C; Curing time: 120 min.; Cooling: 4°C/min; Pressure: 7 bars; Vacuum bag pressure: 0.9 mbar
CC402	0.42		$[0°/90°]_8$	
GG245	0.23	2.5	$[0°/90°]_{13}$	Heat: 3°C/min; Temperature: 135°C; Curing time: 40 min.; Cooling: 4°C/min; Pressure: 7 bars; Vacuum bag pressure: 0.9 mbar
M49	0.24		$[0°/90°]_{12}$	Heat: 3°C/min; Temperature: 140°C; Curing time: 90 min.; Cooling: 4°C/min; Pressure: 7 bars; Vacuum bag pressure: 0.9 mbar

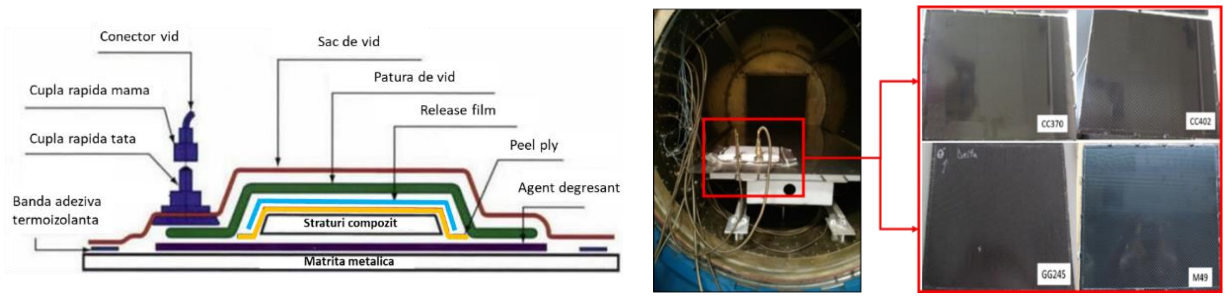


Figure 3.2. Representation of the laminates fabrication process a) layout of the materials for the autoclave curing process; b) laminates after curing cycle

Tensile testing of composite specimens

From each composite laminate, five longitudinal and five transversal specimens were cut, and tabs were added after dimensional accuracy validation.

Tensile tests were performed using a universal mechanical testing machine type Instron 8802 (Class A according to ISO 5893) with a hydraulic drive and a force cell of 150 kN. A test-mounted extensometer was used during the tensile tests to measure the lengths. A constant traverse speed of 2 mm / min was used, the tests being performed at room temperature, humidity 45% in the test chamber (4 hours of conditioning before testing). For each tested specimen, the characteristic curve was plotted, which results in the elastic and mechanical parameters. The results of the tensile tests of the four composite materials are presented below. Material selection for the centrifugal compressor rotor was based on Young modulus and tensile test results.

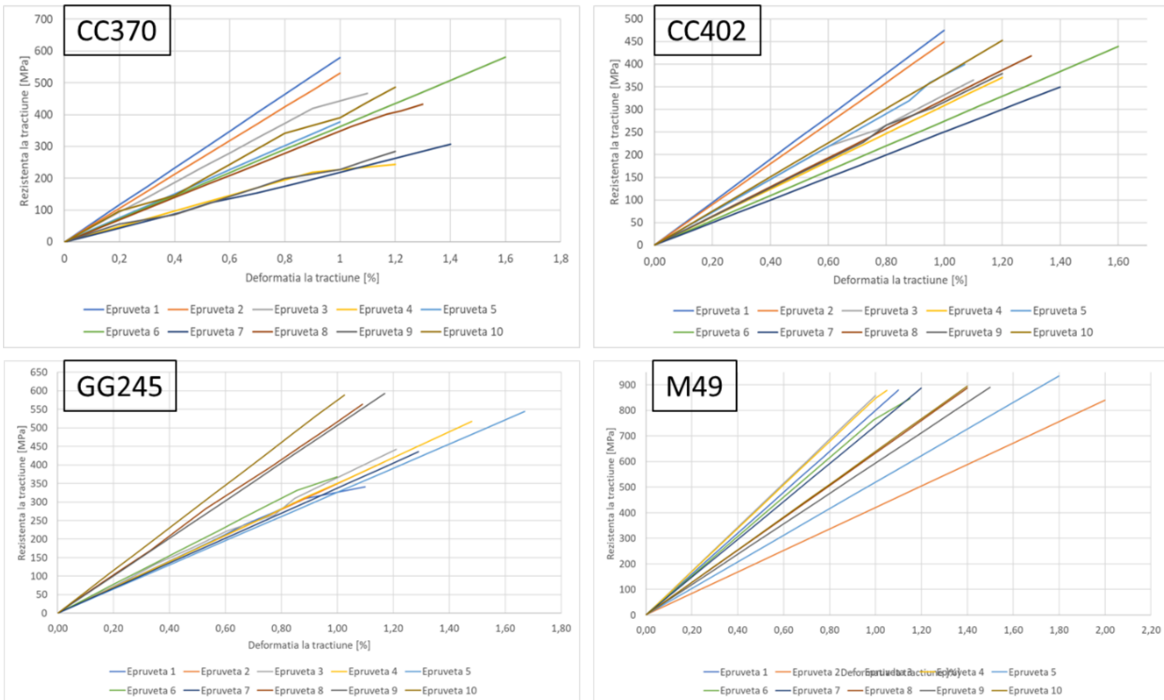


Figure 3.3. Graphical representations of the tensile test results of the four selected materials

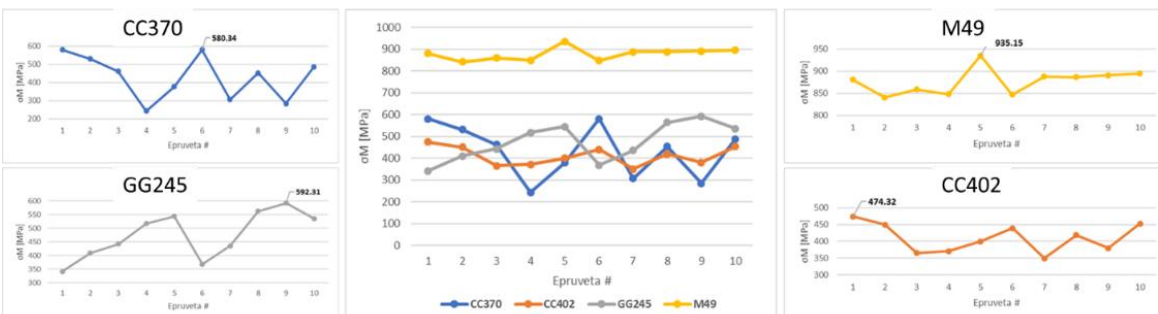


Figure 3.4. Comparative representation of the maximum values obtained after tensile tests

For a more rigorously analysis of the tensile test results, the values of the tensile strength were extracted and a series of statistical analyses were performed. Thus, Figure 3.5 presents the values of tensile strength, highlighting the maximum and minimum values for each material. For each material the mean value and standard deviation were calculated (presented as histogram in Figure 3.5).

Material			
CC370	CC402	GG245	M49
Rezistența la tracțiune σ_M [MPa]			
580.18	474.32	341.35	880.58
530.22	449.44	409.14	840.65
462.79	365.52	442.35	858.55
243.28	371.08	517.37	848.26
377.97	399.4	544.33	935.15
580.34	439.03	368.13	846.72
306.67	349.82	435.29	887.88
452.7	418.74	563.13	886.92
285.17	379.84	592.31	890.87
487.13	452.7	535.37	894.82

	CC370	CC402	GG245	M49
Valoare Medie	430.65	409.99	474.88	877.04
Deviatie Standard	121.93	42.91	86.95	28.92
Valoare Maxima	580.34	474.32	592.31	935.15
Valoare Minima	243.28	349.82	341.35	840.65

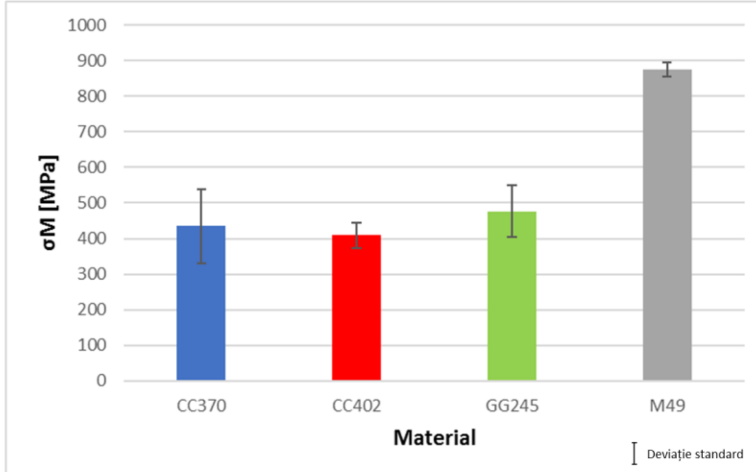


Figure 3.5. Statistical analysis of the tensile test results for each of the four composite materials

For a more comprehensive comparative analysis, the frequency of tensile strength results for the four materials is shown in Figure 3.6. Value ranges have been defined for tensile strength and it is observed that for the M49 material six results fall within a single measuring range (850-900 MPa), which confirms a stable mechanical character for this material. Following the mechanical behaviour of the M49 material and considering that the values of tensile strength are almost double compared to the other analysed materials, it was decided to use this material in the process of developing / manufacturing the blades / rotor of the centrifugal compressor.

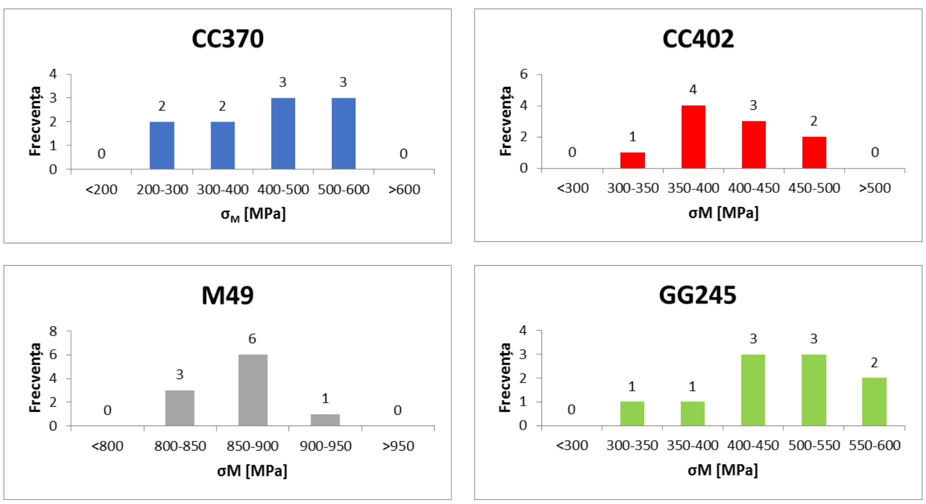


Figure 3.6. Statistical analysis of the tensile strength as a function of results frequency

3.3. Physical-mechanical characterisation of M49/42%/200T2X2/CHS-3K material

The physical-mechanical properties of composite materials depend on a multitude of factors, the most important of which are environmental factors, mechanical stress and compatibility between constituent materials (matrix - reinforcing element). These factors represent important data both for the design stages, for the pre-validation of the structure and for the optimization of the structure.

Determination of constituents in M49 composite material

As the fibre and resin content affect the properties and mechanical response of the material, they must be measured for each material tested and considered for the prediction of the mechanical response. Using ASTM D3171: 2006 "*Standard Test Methods for Constituent Content of Composite Materials*", the volumetric fraction (Vf) of the fibres in the composite material was determined experimentally by chemical attack of the matrix. Therefore, a test sample of M49 with an area of 40 mm^2 and a thickness of approximately 0.24 mm was weighed (Mi = 0,1424 g), then immersed in a solution of sulfuric acid (96% to 98% aqueous H_2SO_4 solution) to remove the epoxy matrix. The results showed that there is a difference between the data provided by the data sheet of the material (42% by mass of resin) and the experimental results (38.63% by mass of resin), but these differences are due to the fact that it cannot be admitted that there are zero losses of resin (even in the case of raw prepreg). The results on the constituent content for the non-polymerized material layers are presented in Table 3.2. The same protocol was applied to the polymerized M49 composite material.

Table 3.2. M49 material results

Uncured samples		Cured samples	
Supplier datasheet	Experimental results	Supplier datasheet	Experimental results
ρ_m=1,18g/cm^3 ρ_c=1,47g/cm^3 ρ_f=1,78g/cm^3	M_i=0,1424g M_f=0,0874g ρ_c=1,48g/cm^3	ρ_m=1,18g/cm^3 ρ_c=1,47g/cm^3 ρ_f=1,78g/cm^3	M_i=1,1983g M_f=0,9203g ρ_c=1,48g/cm^3
W_f=58%	W_f=61,37%	W_f=58%	W_f=76.8 %
W_m=42%	W_m=38,63%	W_m=42%	W_m=23.2 %
	V_f= 51,33%		V_r= 68.7 %
	V_r= 48,67%		V_r= 31.3 %

where, M_i = initial sample mass, M_f = sample final mass, ρ_m = cured matrix density, ρ_c= composite density, ρ_f = fibre density, V_m = matrix volume percentage, V_f = fibre volume percentage, W_f = fibre mass percentage, W_m = matrix mass percentage.

Three-point bending tests

By performing this test, a number of mechanical characteristics can be determined such as modulus of elasticity, flexural stiffness, force at maximum load, displacement at maximum load, maximum flexural stress at maximum load, maximum deformation at maximum load, ultimate strength, specific deformation at break or maximum stress at break. Three-point bending specimens were cut from laminated fabricated in the same conditions and parameters as the ones used for the tensile tests. Flexural tests were performed on an INSTRON 3360 equipment equipped with a cell force of 55 kN, following SR EN ISO 14125:2000 standard. Test conditions were as follows:

- Testing speed of 2 mm/min.;
- Room temperature of 24°C;
- Distance between fixing supports of 32 mm.

Figure 3.7 shows a specimen subjected to the bending test together with the corresponding characteristic curves. Following the mechanical tests, it was found that the M49 material has the following flexural properties (average values resulting from the processing of the results given by the test machine):

- Maximum load: 971.4 N;
- Maximum flexural stress: 907.53 MPa.

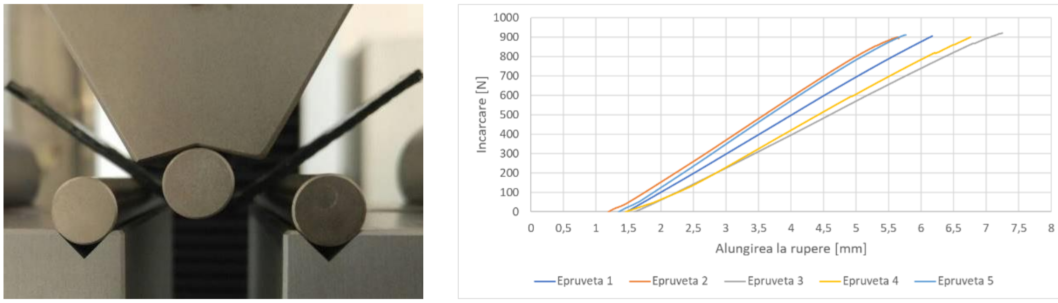


Figure 3.7. Representative image of a specimen during the three-point bending test and their corresponding results

Impact tests

The impact behaviour of structures, the composite centrifugal compressor rotor in this case, is of great interest for both the design phase and the experimental test phase. Impact tests were performed in order to determine the elastic characteristics of the selected composite material, under high deformations velocities, as in the case of its functional regimes, such as impact or shock. Thus, specimens were fabricated according to ASTM D7136/D7136M-07 standard, following the same curing parameters as in the case or previous laminates. Following several trial tests from a height of 3,5 m, 1,5 m, 0,9 m, 0,8 m and 0,7 m, it was concluded that the impact height shall be of 0,7 m to determine the impact strength. Figure 3.9 presents a series if specimens before and after impact tests and the obtained test results.

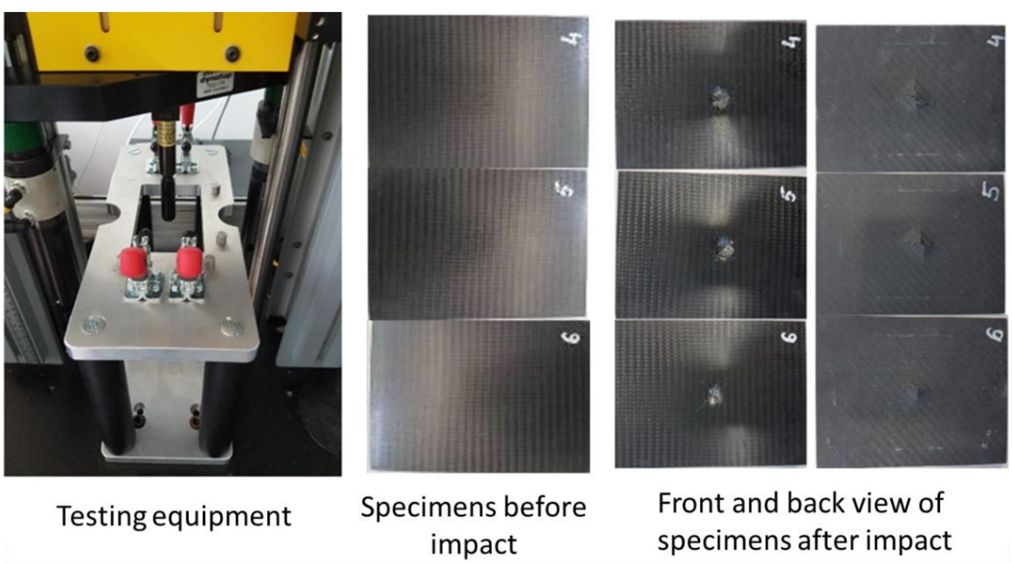
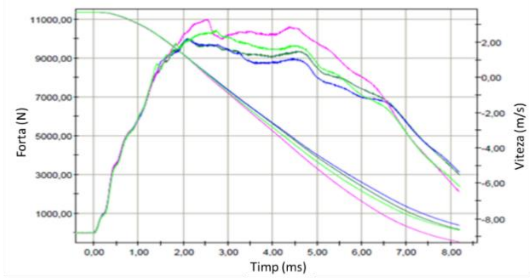


Figure 3.8. Equipment used and specimens before and after mechanical impact tests



Specimen no.	Maximum force [N]	Deformation at max. force [mm]	Energy at max. force [N]	Impact speed [m/s]
1	9980	5,88	30,36	3,69
2	9975,4	5,81	29,80	3,69
3	10980,9	6,08	32,83	3,69
4	10395,4	6,12	32,78	3,69
5	10132,8	5,99	31,95	3,69

Figure 3.9. Results obtained for the impact tests

CHAPTER 4
DEFINING THE GEOMETRIC MODEL AND NUMERICAL VALIDATION OF THE CENTRIFUGAL ROTOR CONSIDERING THE AUTOCLAVE TECHNOLOGY

The objective of the centrifugal compressor rotor design and optimization studies is to define a geometry which is suitable for the autoclave technology, but at the same time to respect the overall dimensions of the reference rotor for a comparative analysis, as well as the aerodynamic and mechanical specifications imposed by the nature of the application. The identified reference centrifugal rotor has a weight of 22 kg, is made of 17-4 PH steel, consists of 17 blades, operates at a speed of 17050 rpm, provides an air flow of 4.25 kg/s, is designed for stage 1 of the CCAE 9-125 centrifugal compressor (discharge pressure - 8.7 bar, flow - 5200 Nm3/h, power - 510 kW, 3 compression stages), having three stages of compression and intermediate cooling, owned by the National Research and Development Institute for Gas Turbines COMOTI. In this chapter, from a geometric point of view, the following conditions were considered regarding the design of the composite rotor manufactured by autoclave technology:

- General dimensions and tolerances;
- Housing profile and compressor outlet;
- triangular profile for transmitting the moment (type K profile which ensures the interface with the shaft).

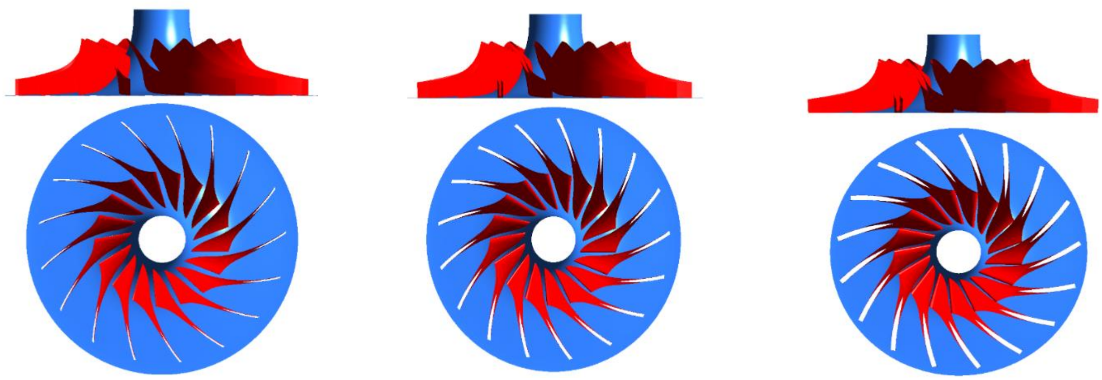
In the following are presented the results of aerodynamic studies which were performed using Ansys CFX software, leading to the definition of the number of blades and their geometry so that the composite rotor can be manufactured using autoclave technology. The resulting geometry was mechanically optimized and validated, considering the material characteristics obtained experimentally and presented in Chapter 3. Summarizing the results of the two complex studies, as well as the balancing method identified to be applicable for a composite centrifugal compressor rotor, the final geometry (CAD model) of the rotor was obtained.

4.1. Aerodynamic analysis regarding the definition of the geometry of the centrifugal compressor rotor

During this study, a different number of blades with variable thicknesses were considered in order to obtain a design suitable for the targeted manufacturing technology. Preliminary tests have established that the minimum thickness of the centrifugal compressor rotor blades cannot be less than 6 mm, for technological reasons, and the number of blades has been varied between 7 and 17, considering their different thicknesses.

Geometrical modelling of the blades

Figure 4.1 shows the influence of stiffness on the efficiency of the centrifugal rotor. Thus, keeping the same number of blades and the same fixing angles, the thickness of the blades was doubled or even tripled. This operation was necessary to make the connection between the rotor geometry and the intended production technology. The increase of blade thickness was followed by reducing the number of blades from 17, to 15, to 13 and to 7 blades.



a) Blade model 1x *b) Blade model 2x* *c) Blade model 3x*

Figure 4.1. Modelling of the thickened blades shape and their intersection with the peak flow channel curve

Numerical model definition

Following the preliminary results obtained, it was decided that the model having a total of 7 blades should be investigated in more detail. Thus, for this case, the blade thickness was varied to determine the influence of geometric changes on the rotor performance. A structural type grid was used for the analysis, made in Ansys ICEM, with 539,248 elements (Figure 4.2).

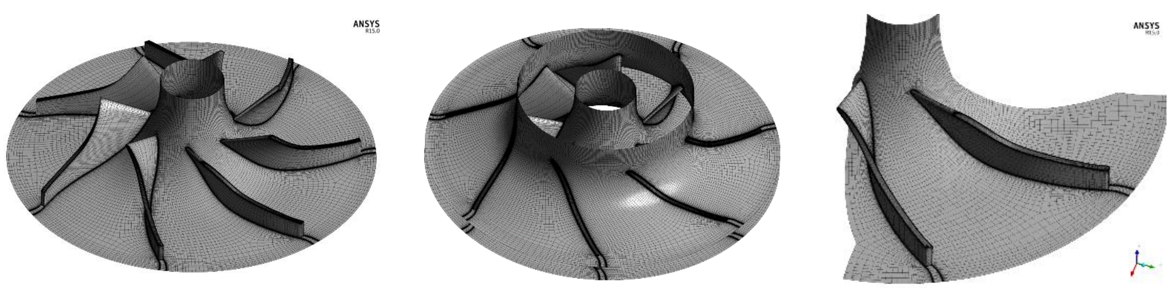
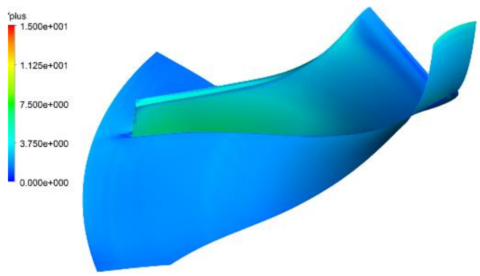


Figure 4.2. Grid used for the analysis of the composite centrifugal rotor

Discretization is one based on topological isomorphism, having the first cell height corresponding to a value of the dimensionless thickness y + ~ 1. Another criterion considered was the discretization with high finesse up to a distance y + = 30, above the limit y +> 30, the k-epsilon model was applied. For the present rotor it was taken into account that the y + value should be as small as possible, its values on the suction side and pressure side of the blade being presented in Figure 4.3. A small as possible value helps to define and/or capture the phenomena around the blades, while also indicates the quality of the grid.



- **Inlet:**
  - Total pressure: 101353 Pa;
  - Total temperature: 288 K;
- **Outlet:**
  - Debit: 4.25 kg/s;
- **Wall:**
  - “No slip” conditions (rest of the domain).

Figure 4.3. Distribution of y+

Aerodynamic numerical simulations analysis

Of the total cases calculated, the case presented in Table 4.1, the composite centrifugal rotor having 7 blades with a thickness of 2x was selected for further use in the thesis, based on the difference in scores compared to the metallic reference rotor. The scores were calculated based on the formula below:

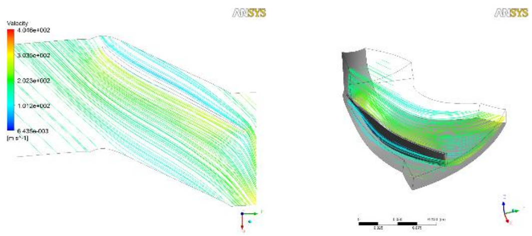
$$S = \sum \left(100 \cdot \frac{\frac{\pi_c}{2.067} + \frac{P}{310.4} + \frac{\eta}{91.80}}{3} \right) \tag{4.2}$$

Table 4.1. Scores obtained for calculated geometries

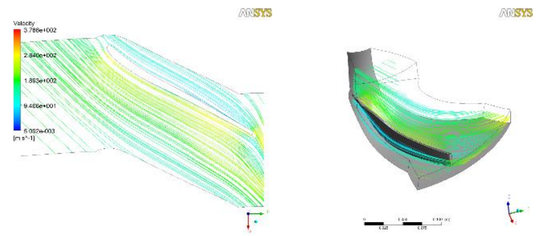
Case/S Core	7 blades			13 blades			15 blades			17 blades		
	1x	**<u>2x</u>**	3x	1x	2x	3x	1x	2x	3x	**1x**	2x	3x
***S* [%]**	/	**<u>95.34</u>**	109.66	/	94.38	88.27	/	93.31	-	**100**	89.07	-

It can be seen that the thickening of the blades in the case of a smaller number of blades leads to an increase in performance. On the other hand, blade thickening for a multi-blade rotor has negative effects. Thus, considering the imposed limit conditions, speed and flow from a gas dynamic point of view, as well as the minimum thickness of the blades, from a technological point of view, it was concluded that the rotor consisting of 7 blades with a thickness of 6 mm is the most suitable for this application.

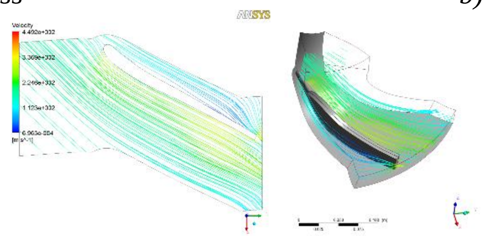
The following figures show the current lines together with the pressure variations in the meridional plane, as well as the pressure variation from the inlet to the outlet of the rotor for the case with 7 blades studied and used further in the thesis.



a) 1x thickness

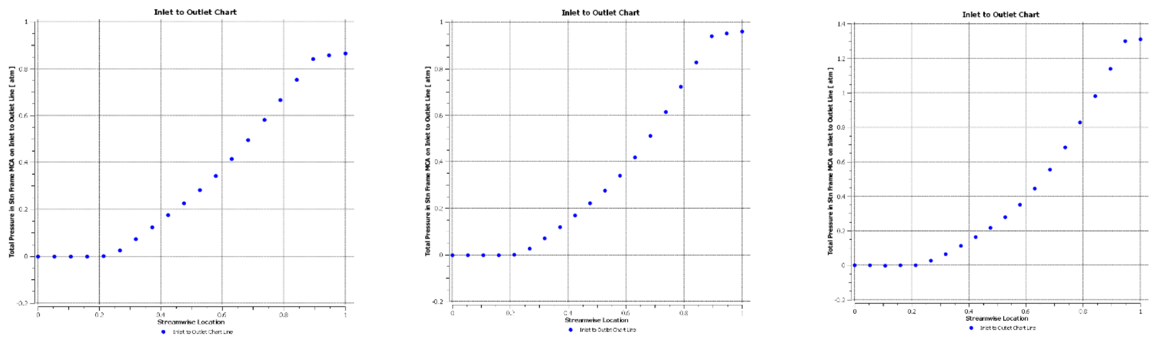


b) 2x thickness



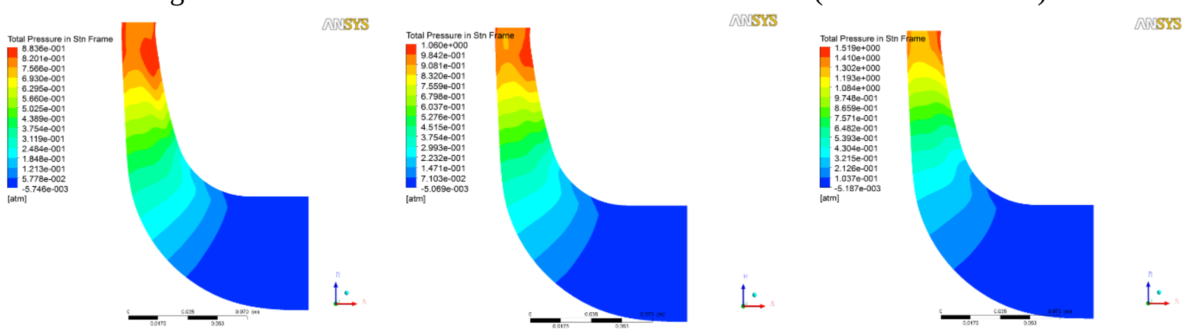
c) 3x thickness

Figure 4.4. Current lines for the rotor case with 7 blades



a) 1x thickness *b) 2x thickness* *c) 3x thickness*

Figure 4.5. Pressure variation from the inlet to the outlet (case with 7 blades)



a) 1x thickness *b) 2x thickness* *c) 3x thickness*

Figure 4.6. Pressure variation in the meridional plane (case with 7 blades)

4.2. Numerical analysis and structural optimization of the rotor

The static and dynamic analyses were performed to validate the solution adopted for the composite centrifugal rotor manufacturing technology. The structural analysis was performed using finite element method, with MSC NASTRAN and MSC PATRAN solver and processing programs.

The failure criteria of laminates can be defined as a generalization of the von Mises criterion. To verify the mechanical strength requirements, both Tsai-Wu and Chang criteria were used for the analyses performed with 2D type finite elements, and Hashin-Fabric for the analyses performed with 3D type finite elements, respectively. Numerical analyses were done as follows:

- Static analysis:
  - Structural analysis for the rotor blades, iterations corresponding to different construction configurations. The objective of this step was to determine the most adequate configuration of the blades;
  - Structural analysis for the composite rotor, iterations performed to define the most suited constructive design for the rotor in terms of disc, blades, balancing metallic rings, etc.);
- Analysis for identifying the eigenmodes and frequencies of the composite rotor;
- Analysis of the frequency response for the shaft-rotor assembly, in order to compare the theoretical and experimental results obtained through a Ping test.

The following criteria were used to evaluate the mechanical characteristics of the 3D finite element model: the von Mises criterion for metal parts and adhesives, the maximum tangential stress criterion for adhesives and the Hashin-Fabric criterion for composite parts (disc and blades).

Constructive configuration definition

Figure 4.7 presents the geometry of the composite centrifugal rotor and the blades used for the preliminary calculation. This geometry, a 7-blade rotor with a blade thickness of 6 mm, resulted from the numerical simulations presented in the previous chapter. The blade modelling was made with 2D type elements (4-node shell), and the layers (laminate) were defined by the material properties and the corresponding elements. Based on the model presented, Figure 4.8 shows the boundary conditions which were used for the iterations presented below. The boundary conditions are shown for the rotor flow surface area geometry. This consists in fixing in the Z=0 plane and imposing axial symmetry conditions on the circular contour in the rotor inlet region. These conditions were established taking into account the mechanical characteristics of the assembly. Based on this numerical model, several iterations were made and analysed in which the number of layers for the blades varied.

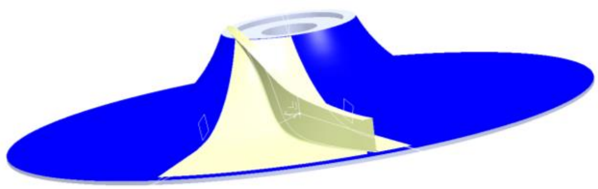
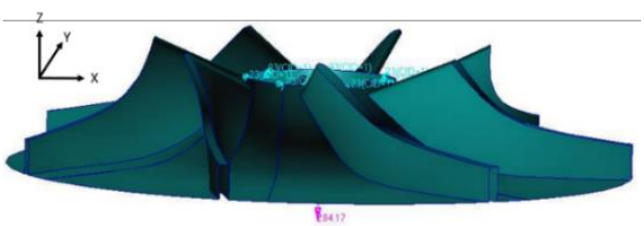
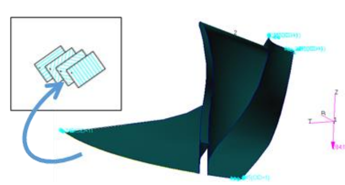


Figure 4.7. Geometry used for the 2D finite element model



a) Rotor blades



b) Blade sector and arrangement of composite material layers

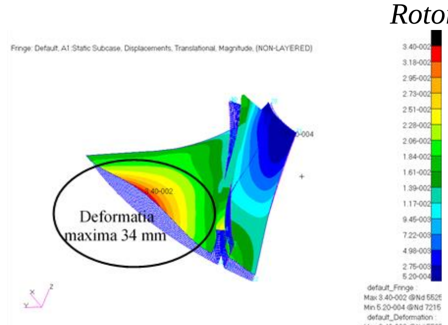
Figure 4.8. Boundary conditions and composite layers pattern

Subsequently, analyses were performed on the blades and on the disk formed by the "n" layers of the blades. It was also analysed whether the composite centrifugal rotor withstands mechanical stress considering a number of layers equal to that imposed for the blades. Thus, in the following figures, total displacements distribution of the blades and the Tsai-Wu failure index are represented for the blade models composed of 4, 6 and 8 layers, respectively. For the 4-layer case, according to the Tsai-Wu criterion, the blade fails from the mounting area, where the maximum value of the failure index is 33.6 (failure appears for FI> 1). It is also observed that on the lateral areas the failure index is higher than the rupture limit. In the case of the 6-layer blades, a maximum deformation of 20.5 mm can be observed, in the area highlighted in red. According to the Tsai-Wu criterion, the blade failure in the mounting area, where the maximum value of the failure index is 23 (the break occurs for FI> 1). For the rotor blades consisting of 8 layers of prepreg, a maximum deformation of 14.1 mm can be observed, in the area highlighted in red. According to the Tsai-Wu criterion, the blade failure in the mounting area, where the maximum value of the yield index is 32 (the rupture appears for FI> 1).

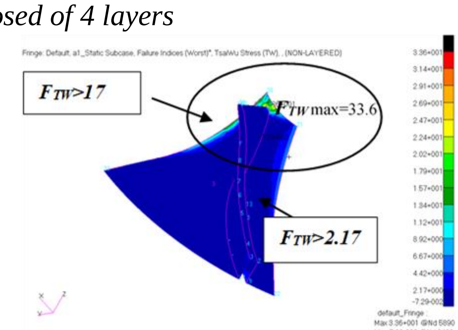
It was observed that, by increasing the number of composite material layers, the distribution of the failure index decreased, obtaining the following maximum values: 33.6 for the 4-layer model, 23 for the 6-layer model, 32 for the 8-layer model. There was also observed a decrease in total displacement distribution correlated with increasing the number of layers. The values of the total displacements are high which significantly change the flow channel of the rotor. The failure of the rotor blades is caused by the fact that the disc modelled with 4, 6, and 8 composite layers does not withstand the mechanical loads.

In this regard, a new iteration was performed by modelling a more complex disk. The Chang criterion was used to ensure the transition to the Hashin-Fabric criterion appropriate for 3D composite structures.

Rotor blade composed of 4 layers

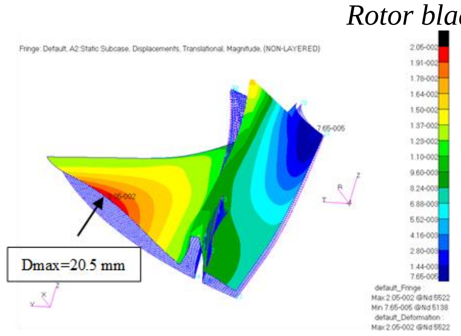


Total displacement distribution [m]

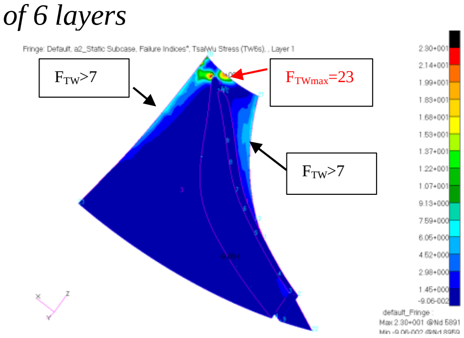


Failure index distribution

Rotor blade composed of 6 layers

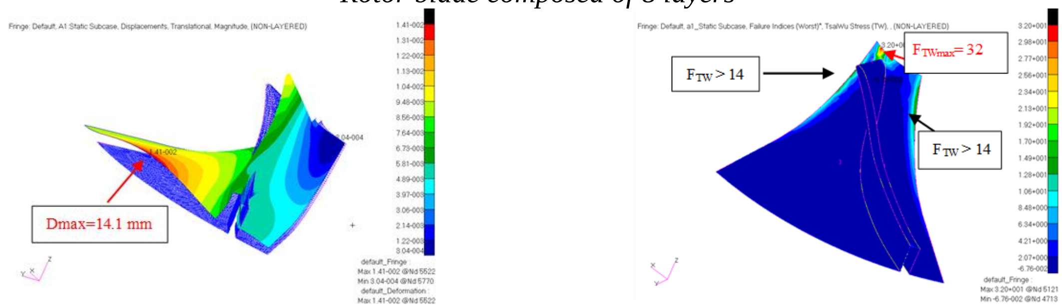


Total displacement distribution [m]



Failure index distribution

Rotor blade composed of 8 layers



Total displacement distribution [m] *Failure index distribution*

Figure 4.9. Total displacement distribution and Tsai-Wu failure index for rotor blades composed of 4, 6 and 8 composite layers

It was concluded that the rotor consisting only of blades and the disc layers for 4, 6 and 8 layers does not withstand the stresses caused by centrifugal forces corresponding to a nominal speed of 17050 RPM. Given the results obtained regarding the definition of the constructive configuration, in order to consolidate and optimize the rotor geometry from a structural point of view, a new iteration was performed in which the rotor disc modelling was performed with median surfaces and shell elements. Axial symmetry of the part, from mechanical properties point of view, was ensured by alternating the composite layers orientation, from 5° to 5° orientation, specifically for the disc. Each composite layer is a prepreg composed of epoxydic resin and carbon fibres, with a thickness of 0.246 mm before curing, and 0.23 mm after curing.

In this regard, three comparative numerical analyses were performed for three different cases:

- Disc modelled with 22 layers and 7 layers on the blades;
- Disc modelled with 22 layers, 7 layers on the blade bottom and 5 layers on the top;
- Disc modelled with 44 layers.

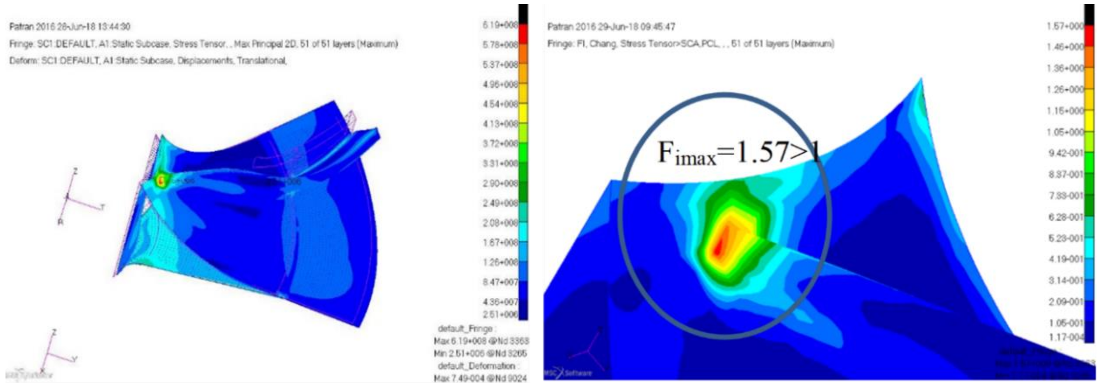
For the first case, the stress state caused by the rotating motion is shown in Figure 4.10, resulting that the maximum stress is 619 MPa. This one is located in the region of the leading edge and the minimum stress is 248 MPa, being located in the same region.

Strength evaluation was based on the Chang criterion and it is presented also in Figure 4.10. The maximum failure index value was found at 1.57 and it is due to blade’s bending stress.

For the second case presented in Figure 4.11, it was observed that the mass reduction from the top of the blade had the effect of reducing by 25% the distribution of the maximum failure index for the 5-layer model, to a value of 1.18. Strength analysis indicated a maximum main stress of 619 MPa located in the region of the blade leading edge. According to the Chang criterion, a region appears where the blade fails, at a maximum failure index of 1.57.

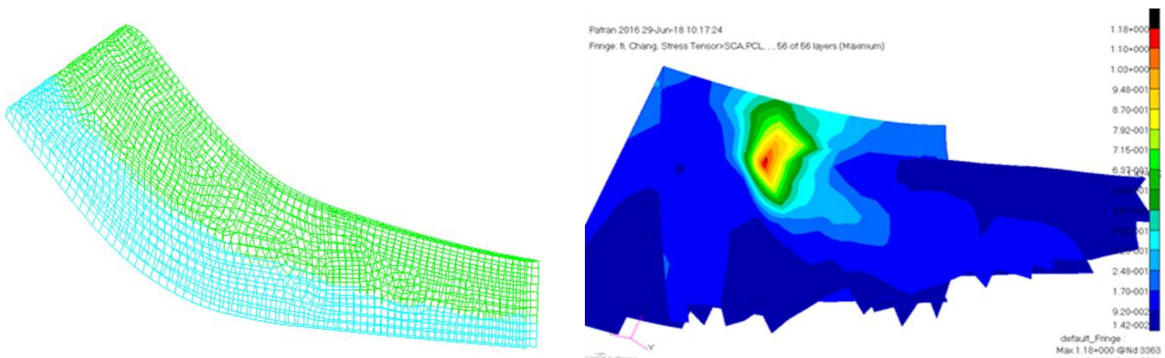
For a constant cross-section of 2 mm, the experimentally determined maximum bending strength was 907.53 MPa. Consequently, it was considered that the failure caused by the blade bending stress may be due compatibility difference between the disc (22 layers) and the blade (7 layers), but also due to a uniform mass distribution on the blade which increases the inertial forces values and the strain caused by the bending stress. For a distribution of 5 and 7 layers (for blades), respectively 22 layers (for disc) it can be observed that the maximum failure index is 1.18, 25% lower than in the case of the blade model with 7 layers.

For the third case, the main stress distribution and failure Chang index is 0.97, and it is shown in Figure 4.12. The maximum failure index value is 1.68, and the failure region is located on the coupling of the layers of the disc with the hub.



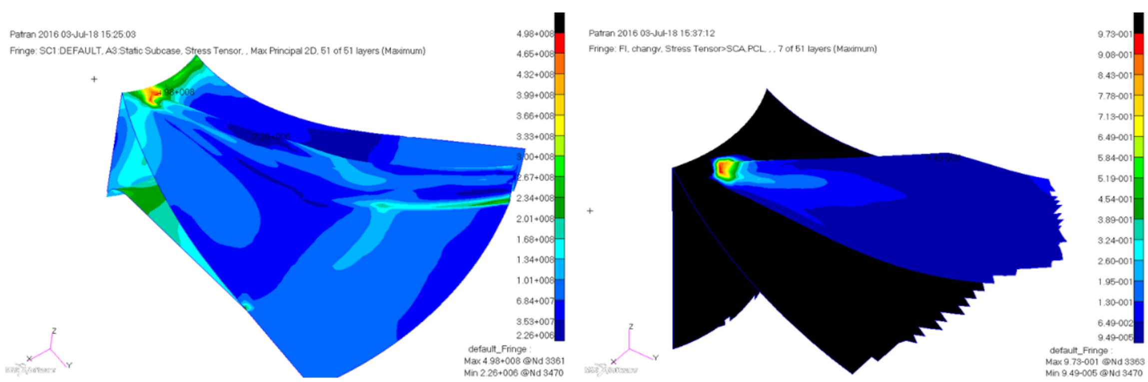
Main maximum stress [Pa] – maximum global value on all the layers *Chang failure index distribution*

Figure 4.10. Maximum main strain and Chang index distribution



Blade structure: blue – 7 layers, green – 5 layers *Chang failure index distribution*

Figure 4.11. Distribution of new prepreg layers and Chang index distribution

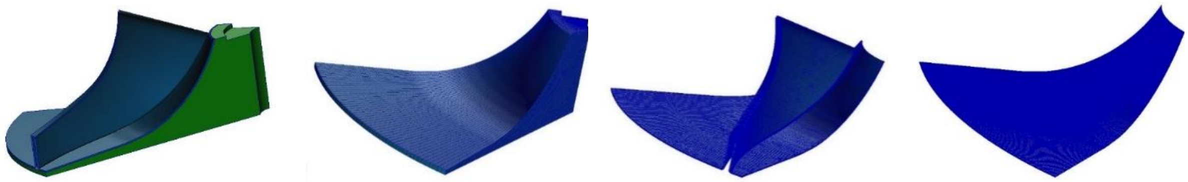


Main maximum stress [Pa] – maximum global value on all the layers *Chang failure index distribution – maximum on the blade's layers*

Figure 4.12. Distribution of main strain and failure index

Figure 4.13 presents the centrifugal rotor geometry, highlighting its specific parts: blade elements modelled with CHEXA (parallelepipeds), composite material (PCOMPLS), disc modelled with orthotropic material and interface modelled with CHEXA elements and isotropic material. Numerical analysis was performed on a rotor sector, taking into consideration axial symmetry of the rotor. Blade layers were modelled as follows:

- Layer 100001 – the outer layer of the rotor (in contact with the working fluid) consisting of the prepreg layers oriented at 45° to the direction of the sectors median plane;
- Layers 100002...100007 consisting in prepreg layers oriented at 0°/-45°/-0°/-45°/-0°/-45°;
- Layer 100008 consisting of resin (isotropic material) in which the orientation is irrelevant.

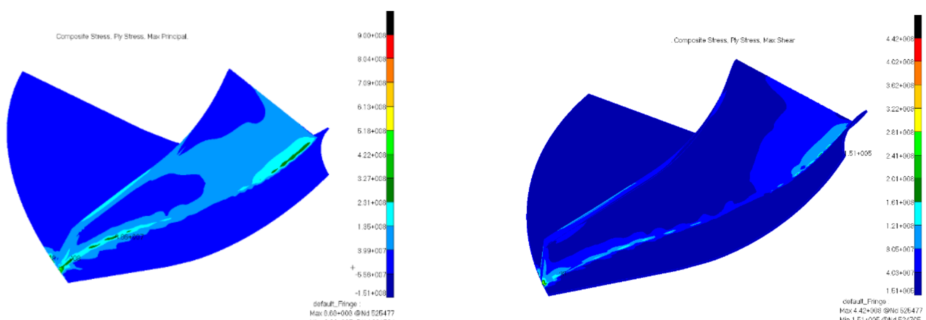


a) Rotor assembly and blade element | *b) Blade – finite element model* | *c) Disc and blade element* | *e) Interface between disc and blade*

Figure 4.13. Rotor elements geometry

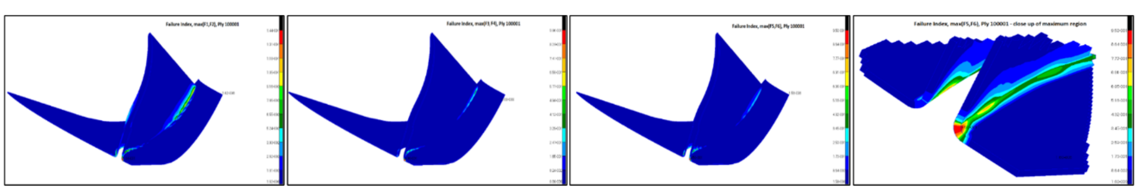
A. Strength analysis

Stresses resulting from the non-linear numerical simulation are shown in Figure 4.14. The maximum value of the main stresses is 868 MPa and it is located on the layer 100001 region from the disc to the trailing edge of the blade. The maximum value is less than the tensile strength of the material, of 900 MPa. The maximum value of the shear stress is 442 MPa and it is located on the layer 10001 in the same node, shown in Figure 4.15.



a) Maximum main strain [Pa] – maximum value for all layers | *b) Maximum shear strain [Pa] – maximum value for all layers*

Figure 4.14. Tension distribution in the blades



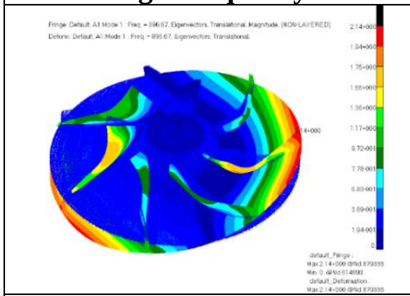
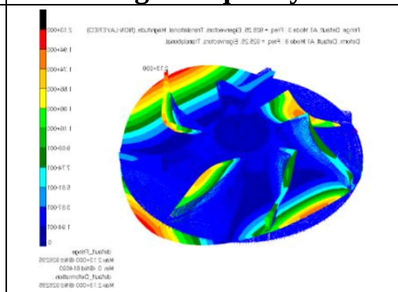
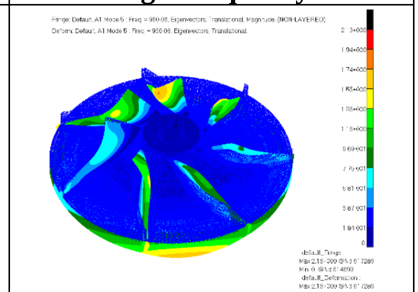
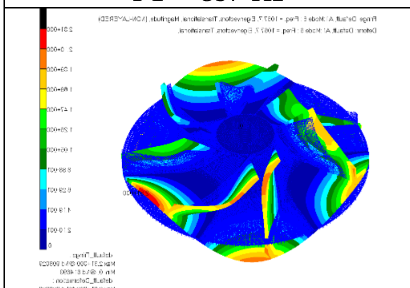
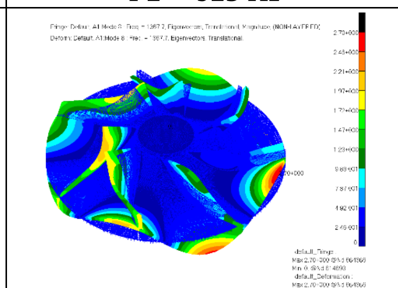
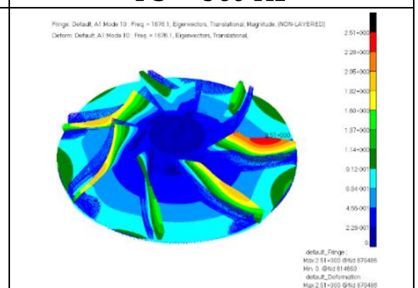
Hashin Fabric Index –max F1 | *Hashin Fabric Index –max F3* | *Hashin Fabric Index –max F5* | *Hashin Fabric Index –max F5 pe muchie racordare*

Figure 4.15. Hashin-Fabric failure index distribution – maximum values on layer 100001

B. Vibration and eigenvalues analyses

The fixing conditions of the rotor used in the analysis to identify the vibration modes are those used in the analysis to determine the states of deformation and strain. The eigenmodes occurring when the centrifugal rotor is in steady state are presented in Table 4.2. It was observed that the main eigenmodes characterized by the disc bending (first 3 Nodal Diameters) have also a consistent blade participation.

Table 4.2. Vibration modes – Eigen values – rotor in steady state

Eigenvector – [mm] / Eigenfrequency	Eigenvector – [mm] / Eigenfrequency	Eigenvector – [mm] / Eigenfrequency
		
F1 = 897 Hz	*F2 = 925 Hz*	*F3 = 960 Hz*
		
F4 = 1068 Hz	*F5 = 1368 Hz*	*F6 = 1676 Hz*

C. Ping test simulation

An analysis of the frequency response of the rotor assembly modelled with 1D elements was performed), and the theoretical results obtained by this simulation are compared with the experimental results. The frequency response of the rotor assembly is shown in Figure 4.16, for a 0-1000Hz frequency band. A critical frequency F1 = 660 Hz was observed, which can be identified by the Ping test. It was concluded that the centrifugal composite rotor withstands the load caused by a rotational motion at 17250 RPM. The rotor Eigen values are presented in Table 4.3.

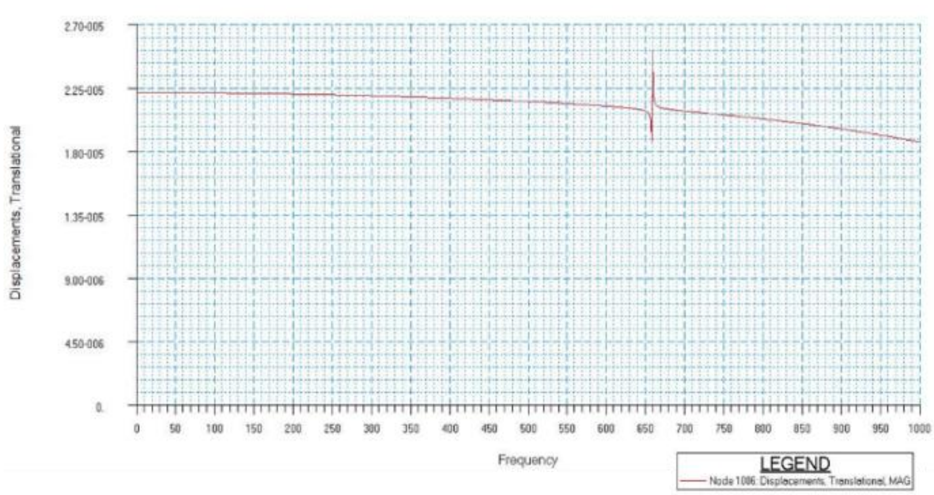


Figure 4.16. Frequency response [m] – Rotor centre of mass radial displacement

Table 4.3. Eigen values determined by numerical simulations

N0.	Frequency [Hz]	Observations
1	660	Eigen modes for rotor shaft assembly Ping test
2	897	First rotor Nodal Diameters
3	925	Second rotor Nodal Diameters
4	960	Rotor flare
5	1068	Third rotor Nodal Diameters
6	1368	Complex vibration mode
7	1676	Complex vibration mode

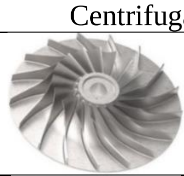
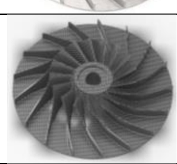
4.3. Study on the implications of dynamic balancing of centrifugal compressor rotor geometry

In this case study, the following analyses were performed regarding the dynamic balancing of a centrifugal compressor rotor made of composite materials.:

1. Centrifugal rotor made entirely of 17-4PH steel - the reference model considered for this work;
2. Centrifugal rotor made entirely of composite materials - great advantage of the lowest mass;
3. Centrifugal rotor made of a mixed structure, composite materials and metallic materials:
    a. With integrated metal hub;
    b. With metal rings disposed at different diameters.

Starting from the reference model, three distinct cases were studied to identify the optimal method for the composite compressor rotor balancing.

Table 4.4. Theoretical results obtained for the dynamic balancing of the rotors

Centrifugal rotor model		$U_{ADM\ A}$ (gmm)	$U_{ADM\ B}$ (gmm)	M_A (g)	M_B (g)
	Reference metallic rotor 17-4 PH	11,349	16,423	4,10	1,49
	Reference composite rotor	2,121	3,182	0,766	0,278
	Composite rotor with 7 blades Composite/ metallic rings	1,34	2,01	0,91	0,68

where, $U_{ADM\ A}$ – allowable unbalance in plane A, $U_{ADM\ B}$ – allowable unbalance in plane B, M_A – Mass removal from plane A, M_B – Mass removal from plane B.

Achieving a lighter and more accurate rotor would lead to much better unbalance corrections to dynamic balancing. Thus, according to the studies performed, by making the rotor from composite material with metal inserts (metal rings), the possibility of dynamic balancing corroborated with the substantial reduction of the rotor mass is ensured. Also, by using two metal rings, the balancing can be performed more easily by removing material from the metallic inserts in order to achieve dynamic balancing of the rotor.

4.4. Design of the centrifugal compressor rotor

In order to manufacture the entire centrifugal rotor from composite materials and with respect to the numerical simulations results, the rotor with 7 blades and 6 mm blade thickness, of which 3 mm representing an empty section and the addition of connecting radii on the contour of the blade was considered.

Thus, the design of the new rotor version started from the redesigning of the surfaces of the reference rotor (Figure 4.17) to reach the geometry with 7 blades, with a two times thickness as those in the reference model. The design model of the centrifugal compressor rotor shown in Figure 4.18 follows the overall dimensions of the reference rotor, as well as the interface with the drive shaft. This geometry was used in defining the moulds needed to validate the autoclave technology and to validate the composite centrifugal rotor by performing experimental tests on a dedicated test bench.

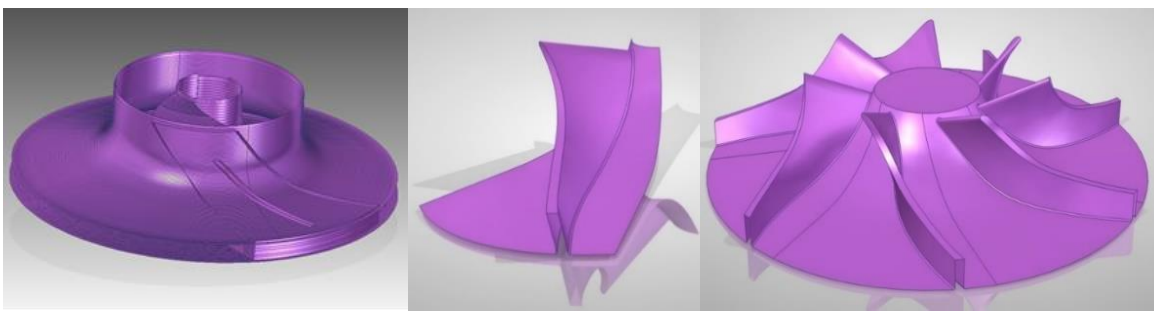


Figure 4.17. Redesign of reference model rotor surfaces

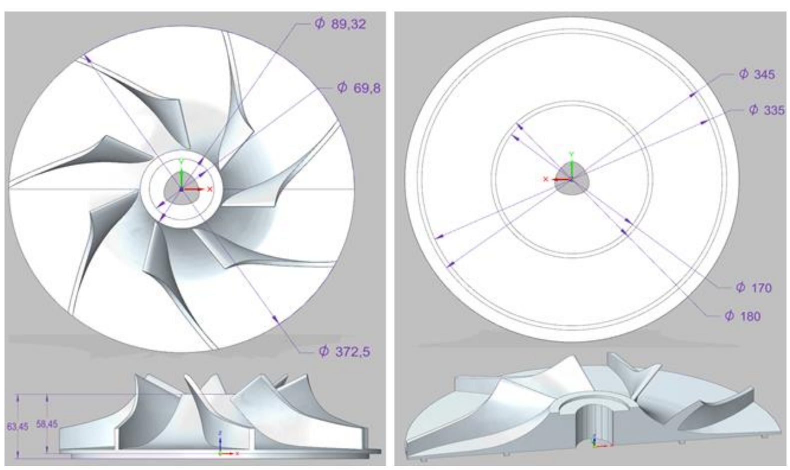


Figure 4.18. Centrifugal compressor rotor design

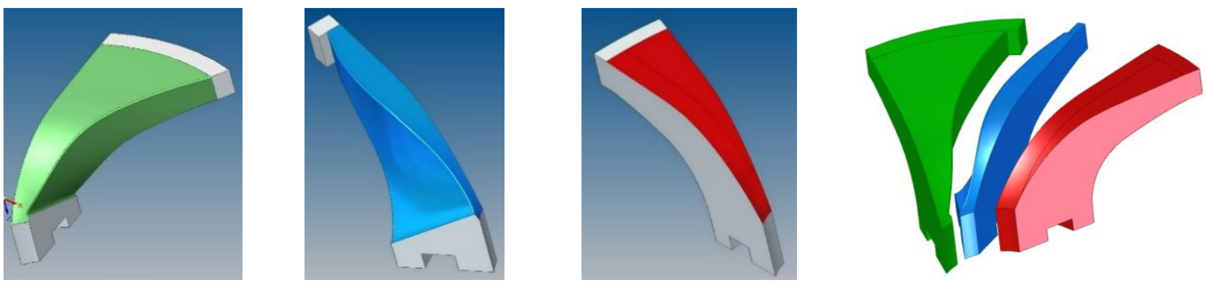
CHAPTER 5
MANUFACTURING TECHNOLOGY DEVELOPMENT FOR THE COMPOSITE MATERIAL CENTRIFUGAL ROTOR

Within this chapter, the necessary moulds were designed and fabricated, following with a series of technological tests that aimed to the preliminary validation of the developed technology and finalizing with the manufacture of the composite rotor which was made in several stages.

5.1. Mould development needed for centrifugal compressor rotor fabrication

Moulds design for the centrifugal compressor rotor fabrication using autoclave

Figure 5.1 presents the geometric models of the moulds which define the suction side and pressure side of each blade. The mould for the suction side of the blade is marked with green and the mould for the pressure side of the blade is marked in blue, highlighting their active surfaces, that will come in contact with the composite material during the curing process and will form the rotor at the end of this manufacturing process. A spacer mould which completes each segment was also designed, coming into contact with both suction side and pressure side moulds, having the active surface marked in red.



CAD model – suction side mould | *CAD mode – pressure side mould* | *CAD model – space mould* | *Mould displacement*

Figure 5.1. CAD models of the moulds used for blade and rotor manufacturing

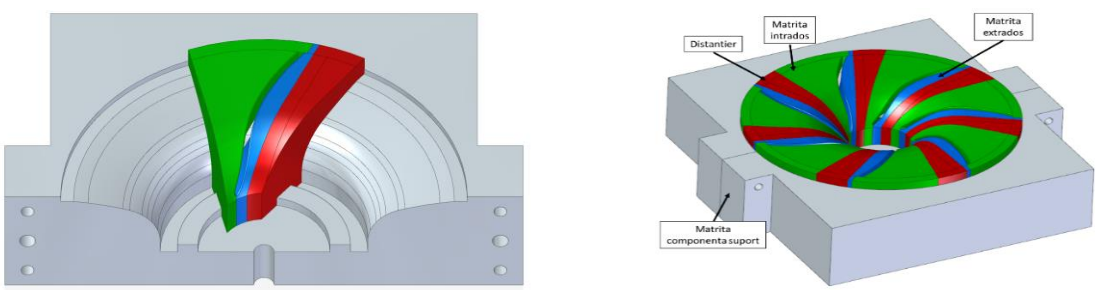


Illustration of one segment moulds that forms one rotor blade on the support component

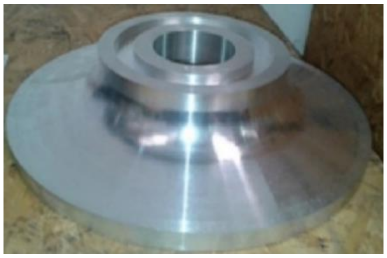
Illustration of all moulds' segments aligned on the support component, representing all the 7 blades of the composite centrifugal rotor

Figure 5.2. Mould displacement on the support component

In order to fix the moulds that make up the rotor, a support component was designed, with a separation plan. The two parts that form the support component are aligned by means of two Ø16 mm pins, and they are tightened in position by means of four M12 screws.

Manufacturing of metallic moulds required for the fabrication of the composite rotor

The first component needed for blade moulds was machined using a carousel lathe at COMOTI, from 2024 aluminium alloy. Also, in order to machine the support component mould, a semi-finished 2024 aluminium alloy slab was used, from which the two semi-moulds were cut. The two semi-moulds are presented in Figure 5.3. Consequently, the blade moulds were machined and presented in Figure 5.3.



Machined block required for blade mould processing.

Support component mould after completion of mechanical operations

Machined moulds needed for blade manufacturing

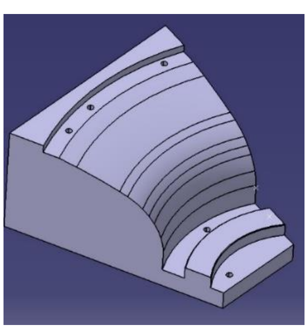
Figure 5.3. Blade mould processing and support component fabrication

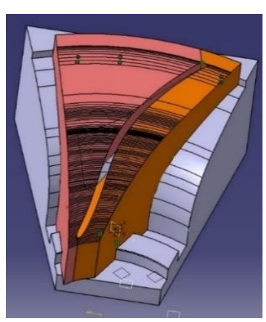
Following the dimensional analysis control, the maximum dimensional deviation identified was 0.247 mm, this value being considered acceptable for this technology and for the manufacture of the composite centrifugal compressor rotor.

Manufacturing of the plastic moulds

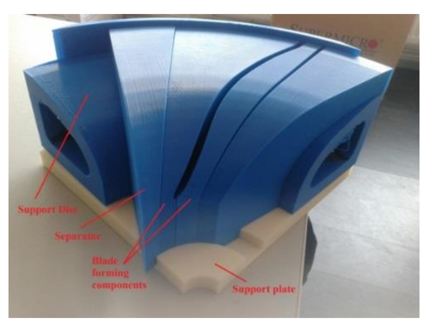
The manufacture of plastic moulds using a 3D printer had two different specific objectives:

- printing a sector of the support component mould, as well as the moulds that define the blade together with the spacer mould. This activity was performed before machining of metal moulds in order to reduce the risks so as to identify possible defects or errors which cannot be observed during the geometric modelling process. Figure 5.4 presents the printed moulds;
- manufacturing the complementary moulds which define the seven blades of the rotor, together with the flow channel, seven pieces for each of the three moulds, suction side and pressure side, as well as the spacer mould.





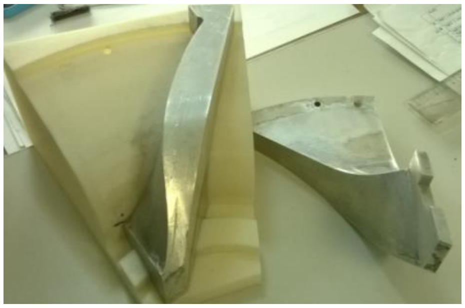
Used CAD models



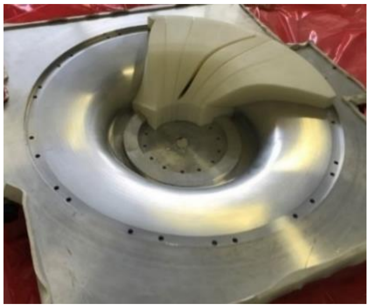
Printed moulds

Figure 5.4. Design and 3D printed moulds

In order to carry out few technological tests, a sector of the support component mould was also made, Figure 5.5. Following these preliminary verifications and tests, it was determined that the curing process must be carried out at a maximum temperature of 80°C so that the 3D printed ABS components won't suffer dimensional changes due to high temperature in the autoclave, but also due to the pressure inside it. Figure 5.5 presents all the 3D ABS printed moulds, assembled on the metallic support component mould.



Metallic mould placed on the 3D printed sector



ABS moulds placed on the metallic support component mould

Placing all the ABS moulds on the metallic support component mould

Figure 5.5. 3D ABS model – used in the fabrication and validation of the blade manufacturing process

Necuron mould manufacturing process

In order to have a preliminary validation of the technology for manufacturing a single composite blade, a small-scale mould (1:2.5) was designed and manufactured using a high-density polyurethane material, Necuron, as a mould. Geometric modelling of the small-scale mould was used as input data for the geometric models of the 1:1 scale mould, but it was necessary to remodel one of the two blade moulds due to the small size of the Necuron material. Images with the separate and assembly components of the mould are presented in Figure 5.6.

Figure 5.6. Machining and assembling of Necuron moulds

5.2. Technology development for the composite centrifugal rotor

Preliminary technology development tests

To define the final manufacturing method for the rotor blades, an intermediate manufacturing step of 1:2.5 scale blades was performed first. In this case, the small-scale Necuron mould was used. Figure 5.7 show the 1:2.5 scaled manufactured blades.

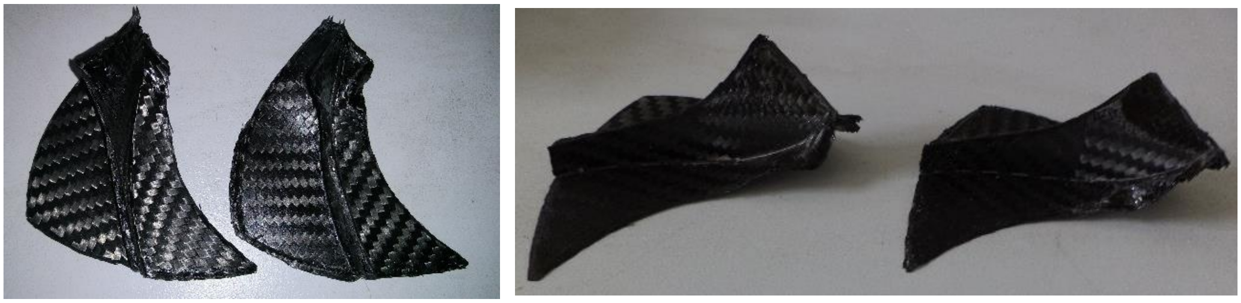


Figure 5.7. Composite 1:2,5 scaled blades

Centrifugal rotor blades manufacturing process

The ABS support component mould was used for the first manufacturing stages of a single composite blade. Prepreg layers were placed on the ABS mould, followed by the auxiliary materials needed for the vacuum bag and inserted in an oven for the curing process. After curing, traces of uncured resin could be observed on the two moulds, due to the low curing temperature (80°C), composite material optimum curing temperature being between 120-140°C.

Figure 5.8. Composite rotor blade (1:1 scale) after first technological test

By performing this first technological test, the proposed blade manufacturing technology was partially validated, respectively the layers positioning, the blade interior vacuum (a space with a width of only 3 mm is available), entire assembly vacuum and removal of the two moulds after the curing process. For the manufacturing process of the 7 composite blades, the metallic suction side and pressure side moulds were used, following the same manufacturing steps. After the prepreg lay-up, the moulds were introduced in a vacuum bag and placed in the autoclave for curing at 120°C for 90 minutes with 7 bars pressure. The manufactured composite blades, shown in Figure 5.9, present smooth surfaces and they follow each mould profile.

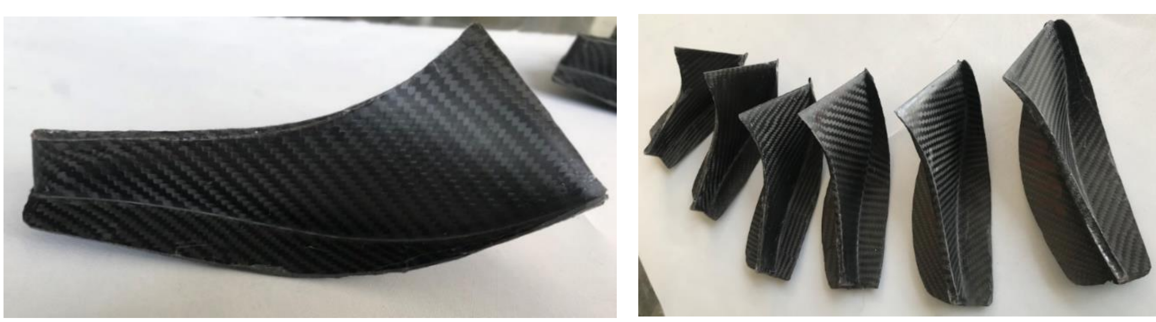


Figure 5.9. Composite centrifugal rotor blades

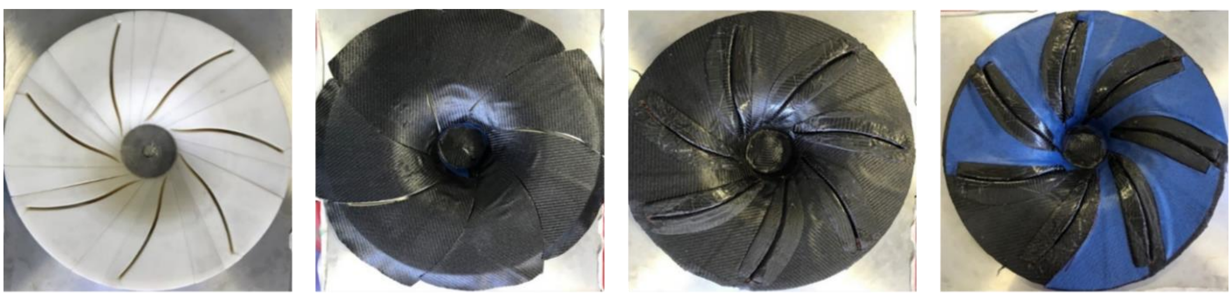
Full composite rotor manufacturing

The composite centrifugal rotor manufacturing process was performed in three stages:

- Stage 1 – **Manufacturing the rotor disc** – All 7 blades are aligned to form the rotor disc and flow channel is defined;
- Stage 2 – **Final composite rotor manufacturing** – formation of the hub that ensured the interface with the shaft, consolidation of the disc and integration of the two metallic rigs for the dynamic balancing process of the rotor;
- Stage 3 – **Machining of the composite rotor** to assess the mechanical interface with the drive shaft and machining the final outer diameter.

A. Stage 1. Manufacturing the rotor disc

Each blade was weighted and the average blade mass was of 47 ±2 g. The blades have been carefully distributed so that the centrifugal rotor shall have an unbalance as low as possible after the fabrication/curing process. In order to ensure a continuous area on the active side of the rotor disc, respectively of the flow channel, 3 layers of prepreg were applied on the ABS moulds consisting of several strips (one layer consists of 7 strips, corresponding to the number of blades), according to Figure 5.10. After applying the 3 layers of prepreg, the integration of the composite blades in the ABS mould followed. Considering the fact that, between the upper surface of the cured blades and the first 3 layers of prepreg placed on the mould there is a difference in thickness equal to the thickness of the blade, it was decided to apply several layers of prepreg between the 7 blades according to the structural analysis performed earlier.



Placing the ABS moulds on the component mould | *Placing the prepreg layers* | *Placing the blades* | *Layers placed to integrate the blades in the main assembly*

Figure 5.10. Integration of rotor blades in the ABS moulds

After the curing process was completed, the assembly was left for 24 hours before opening the vacuum bag, to ensure a gradual cooling in order to easily detach the ABS moulds. Thus, the spacer moulds were detached first, followed by the pressure side moulds and finally the suction side moulds. Figure 5.11 shows the removal of each ABS mould and the composite centrifugal rotor after curing process.

Dismounting of the ABS moulds after the curing process

Centrifugal compressor rotor after the first manufacturing stage

Figure 5.11. Removal of the ABS moulds after the curing process

B. Stage 2. Final composite rotor manufacturing

During this stage, the interface roughness with the shaft (K-profile) was increased to improve the adhesion of the uncured prepreg layers over the ones already cured in the first stage. Also, an important step was to fill the hub area (the area that provides the interface with the drive shaft) with about 400 layers of prepreg with a diameter of 85 mm. The last 20 layers forming the rotor hub were interspersed with layers with a diameter of 110 mm to ensure the flatness of the disc, as seen in Figure 5.12. At the intersection of the 85 mm and 110 mm prepreg layers, several other prepreg strings were placed to ensure a connection between the two diameters and to prevent delamination during the machining process. The next step was to cut and apply 20 layers with a diameter of 400 mm. These layers had the role of consolidating the rotor disc, as well as connecting the previously placed layers. Over the disc layers, the two metal rings were placed, aiding the dynamic balancing process, and, in order to keep them in a fixed position, a series of composite strings were placed. Another 5 prepreg layers with a diameter of 400 mm were applied over the metal rings, each layer being cut so as to allow moulding on the profile of each ring, respectively of the disc.

Placing the prepreg layers in the hub area

Placing the intermediate prepreg layers

Placing the metallic rings and the prepreg strings

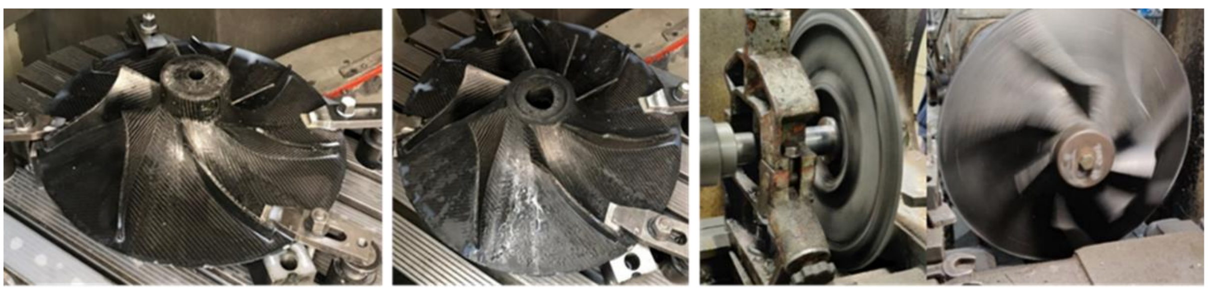
Placing the prepreg layers which make the rotor's disk

Figure 5.12. Steps for final manufacturing stage of the composite centrifugal compressor rotor

The final step was to place the auxiliary materials and vacuum the rotor assembly without using the previously used moulds and autoclave polymerization at 120 ° C, 7 bar for 7 hours.

C. Stage 3. Machining of the composite rotor

The last stage in the development process for the composite centrifugal compressor rotor consisted in its machining, by defining the interface with the drive shaft and the materialization of its outer diameter. The machining of the composite rotor consisted in removing the offset material addition (for technological purposes) from the hub area, excess resulting from the design of the moulds, using a milling cutter with 5 axis CNC machine (Figure 5.13). After removing the offset material, next was the milling of the K profile, ensuring the interface of the centrifugal rotor with the drive shaft. Finally, the composite rotor was machined on the exterior, to reduce the rotor diameter from Ø400 mm to the nominal one of Ø375.5 mm, by turning operations of the offset material resulted in Stage 1 of the manufacturing process. Following three distinct steps presented above for the development and manufacturing process of a composite centrifugal compressor rotor, the final rotor is shown in Figure 5.14.



Creating a through hole for and interface machining

K-profile machining

Machining of the composite rotor outer diameter

Figure 5.13. Machining of the K profile and of the offset material

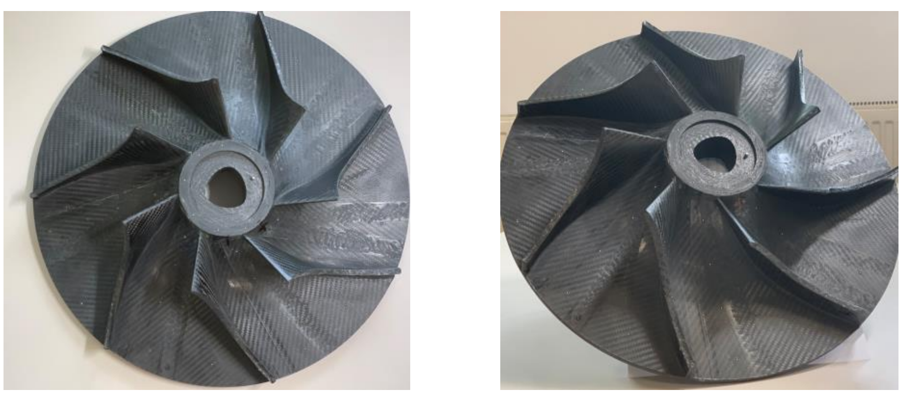


Figure 5.14. Composite centrifugal compressor after all manufacturing stages

CHAPTER 6
EXPERIMENTAL INVESTIGATIONS AND VALIDATION OF THE CENTRIFUGAL COMPRESSOR ROTOR

In this chapter, the verification and testing of the composite centrifugal compressor rotor characteristics were performed as follows:

- determining the centrifugal compressor rotor mass and comparing it with the mass of the reference model;
- verification of the dimensional and geometric deviations of the compressor rotor in different phases of the manufacturing process;
- roughness determination on the active side, the rotor flow channel;
- verification and validation of the rotor dynamic balancing in order to reduce the unbalance;
- performing a modal vibration analysis to determine the natural frequencies and resonance regimes;
- composite rotor integration on the test bench and partial verification of its functionality.

6.1. Centrifugal compressor rotor mass evaluation

As presented in Chapter 5, the composite centrifugal compressor rotor was manufactured in different stages, using a number of 7 independently manufactured blades. There was a difference of 0.1 and 3 grams between the rotor blades, this difference being reduced by applying mechanical adjustments to the surface of the blades disc. The subsequent distribution of the blades was performed in a way that it does not introduce any unbalances at rotor level, respectively radial loads for the hydrodynamic bearings. Following a comparative analysis between the CAD model and the physical model of the first manufacturing stage, it was shown that the difference between the two models is only 7%, the CAD model having a theoretical weight of 0.930 Kg and the physical one of 0.869 Kg. After the complete manufacturing process of the composite rotor, the difference between the mass determined from the CAD model and the effective one was of approximately 3%, the CAD model having a theoretical weight of 2,340 Kg, and the physical one being 2,271 Kg. The difference in weight between the CAD model and the final one can be caused by the processing parameters (7 bar pressure and 0.9 mbar pressure in the vacuum bag, used in the curing process) which influenced the final weight of the rotor. Figure 6.1 shows the comparison in terms of mass for the two rotors. The final mass of the composite rotor, after all the mechanical processing, is 2,340 kg, which represents a reduction of approximately 600% of the mass compared to the one for the metallic reference rotor.

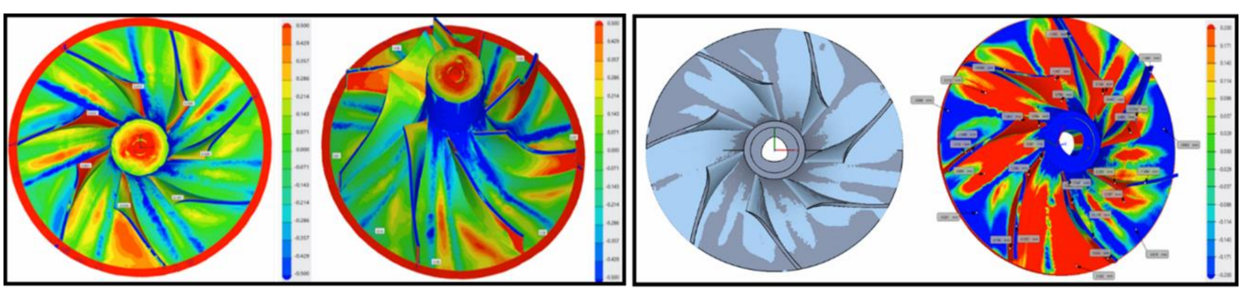
Metallic reference rotor – 13,102 Kg *Composite rotor mass – 2,227 Kg*

Figure 6.1. Mass comparison between the metallic and composite centrifugal compressor rotor

6.2. Evaluation of dimensional and geometrical accuracy of the composite rotor

The centrifugal compressor rotor was evaluated from a geometrical and dimensional point of view by 3D scanning of the rotor from the two manufacturing phases, similar to those of determination and mass evaluation. Thus, in Figure 6.2 the dimensional analyses of the composite rotor after the first manufacturing stage are presented, where the offset material is observed. After the dimensional analysis, it can be observed that the manufacturing technology ensures a good dimensional control with respect to the arrangement of the seven blades and the inner part of the rotor disc (highlighted in green colour). For the dimensional control of the rotor in the final configuration, presented also in Figure 6.2, the rotor was aligned on the outer diameter and on a point defined by the intersection between a blade and the surface of the disc. It was found that the dimensional deviations are larger compared to the initial assessment. This is because the final curing of the rotor was carried out in the absence of the moulds, to be able to process it at a temperature of 120°C. If the metallic mould had been used, the blades deformations during the curing process would not have taken place. Although the dimensional deviations are higher than the imposed tolerances, the experimental model validates the manufacturing technology for a composite centrifugal compressor rotor.

In Figure 6.3 the results obtained from the 3D measurements compared to the ones from the technical drawings are presented. According to these measurements, the centrifugal compressor rotor falls within the imposed limits, highlighting the maturity of the developed technology, as well as the quality and precision of the mechanical processing.



Dimensional accuracy for the first manufacturing stage Dimensional accuracy for the final manufacturing stage

Figure 6.2. Dimensional analysis of the composite rotor manufacturing process

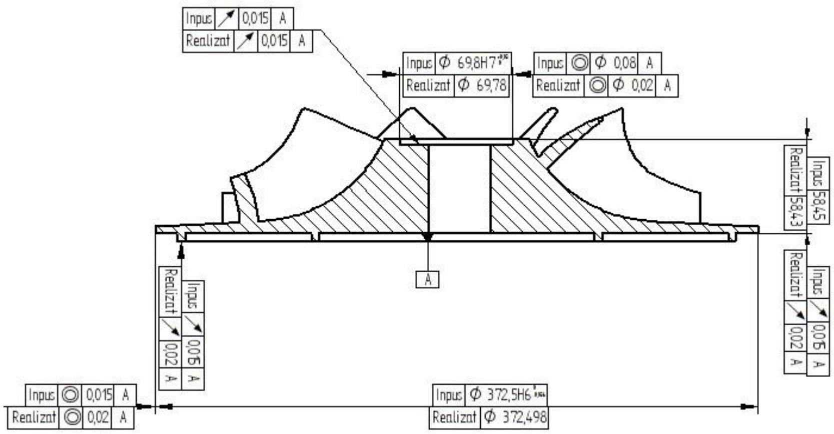


Figure 6.3. Drawing of the composite centrifugal rotor tolerances and overall dimensions (imposed and achieved)

6.3. Roughness evaluation for the rotor flow channel

A rotating component flow channel roughness is very important in terms of equipment performance, as high roughness values can lead to boundary layer detachment or turbulence. Roughness measurements were performed, the results of which are shown in Table 6.1.

Table 6.1. Composite centrifugal rotor roughness values

Iteration	**Disk**		**Blade**	
	Ra [µm]	**Rz [µm]**	**Ra [µm]**	**Rz [µm]**
1	1.306	18.6	1.606	22.206
2	1.303	24.865	1.021	24.336
3	0.991	17.069	1.418	21.89
Average value	**1.2**	**20.18**	**1.34**	**22.81**

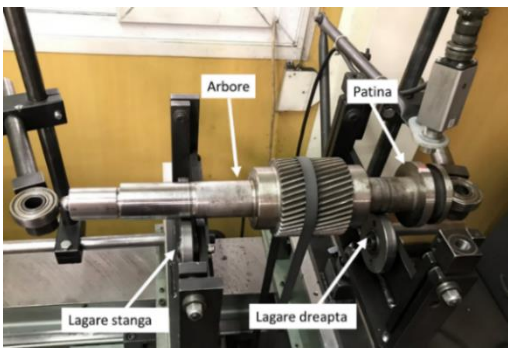
6.4. Dynamic balancing of the composite centrifugal compressor rotor

According to the activities performed in this domain, it was concluded that the dynamic balancing of centrifugal rotors is fundamental to ensure its operational parameters in optimal conditions and maximum safety of any rotary machine. Balancing of the composite rotor was performed using the IRD 246 balancing machine owned by COMOTI.

In order to achieve the dynamic balancing, the rotor was mounted on a drive shaft containing the drive shaft and the skid. The drive shaft together with the skid were independently balanced so that the residual unbalance measured by the machine is mainly the one generated by the composite rotor. The composite rotor was subsequently mounted on the drive shaft of the reference rotor together with the skid (Figure 6.4). The dynamic balancing continued with the following steps:

- The rotor assembly was secured in the axial direction by using a set of metallic balls and fixing bearings at the ends of the shaft;
- A test run was performed at low speed (100-200 RPM) to observe if the rotor assembly is not fully fixed, if different noises are heard during operation or if it shows any axial or radial runouts;

- The rotor correction planes were identified.;
- The balancing machine was calibrated using calibration weights to ensure correct measurement. The calibration speed must be high enough for the self-centering phenomenon to occur;
- The permissible limit of the reference rotor assembly was considered at 17.3 g mm for the left plane and 3.24 g mm for the right plane, and the permissible limit for the composite rotor was required to be lower, respectively 10 g mm for the left plane and 2 g mm for the right plane;
- Values were recorded over a speed range up to 1700 RPM, data were processed and balancing speed was chosen;
- The unbalance was measured at the chosen balancing speed;
- Material has been removed from the areas indicated by the balancing machine;
- The last two steps were repeated until the measured unbalance value was below the calculated allowable limit.



Shaft and skid balancing

Composite rotor assembly

Composite rotor assembly during the balancing process

Removal of mass

Unbalance measuring – balancing planes

Figure 6.4. Mounting and balancing process of the composite rotor assembly

During the dynamic balancing process, approximately 45 grams were removed from the outer metallic ring. If the initial residual unbalance had been greater, it would have been necessary to remove material from the inner metallic ring as well.

6.5. Modal analysis of the composite centrifugal compressor rotor

Modal analysis involves determining the natural (resonant) frequencies and vibration modes of a structure. During the rotational movement, stresses occur in the rotor, due to inertial effects which can change the intrinsic character of the rotor, namely vibration modes and natural frequencies.

Evaluation of Eigen values using the impact hammer method

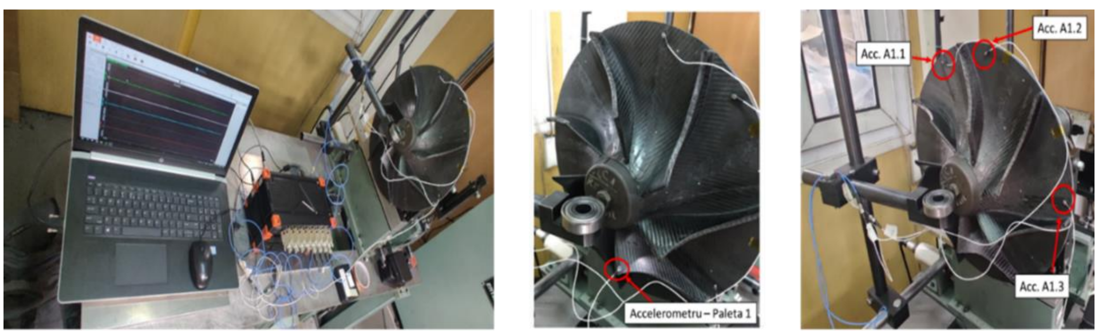
The centrifugal rotor was excited using a special impact hammer, and the response was measured with miniaturized accelerometers weighing 0.5 g. The use of these ultra-light transducers leads to a minimal influence of the frequency response of the blades, respectively the centrifugal compressor rotor.

The modal analysis was performed using the following equipment:

- Dewesoft Sirius multichannel acquisition module;
- Three 3224A1 Dytran accelerometers (0.5g).

The sampling frequency of the vibration signals was set to 50ks/s. Given the mass of the accelerometers, their influence on the frequency response of the rotor is minimal.

The procedure for measuring the rotor's eigen frequencies consisted in mounting an accelerometer/transducer on each blade and then apply three shocks on each blade at different points on the surface of the blade. Firstly, the seven blades were numbered, and, in order to determine the frequencies of each blade, an accelerometer was placed in the top area of each blade. In the second phase of this experimental test, three accelerometers were placed on the top of the rotor disc, approximately 15-18 mm from the outer diameter of the rotor. These investigations are presented in Figure 6.5.



Experimental modal analysis system for the composite rotor

Accelerometer mounting on blades

Accelerometer mounting on disc

Figure 6.5. Eigen frequencies analysis of the composite rotor

Table 6.2 and Table 6.3 summarize the frequencies of the vibration modes and the maximum relative deviation of each blade subjected to the three independent shocks.

Table 6.2. Eigen values for the composite centrifugal rotor blades

	Blade 1				Blade 2				Blade 3				Blade 4				Blade 5				Blade 6				Blade 7			
Frequency	Shock 1 [Hz]	Shock 2 [Hz]	Shock 3 [Hz]	**Avg. freq. [Hz]**	Shock 1 [Hz]	Shock 2 [Hz]	Shock 3 [Hz]	**Avg. freq. [Hz]**	Shock 1 [Hz]	Shock 2 [Hz]	Shock 3 [Hz]	**Avg. freq. [Hz]**	Shock 1 [Hz]	Shock 2 [Hz]	Shock 3 [Hz]	**Avg. freq. [Hz]**	Shock 1 [Hz]	Shock 2 [Hz]	Shock 3 [Hz]	**Avg. freq. [Hz]**	Shock 1 [Hz]	Shock 2 [Hz]	Shock 3 [Hz]	**Avg. freq. [Hz]**	Shock 1 [Hz]	Shock 2 [Hz]	Shock 3 [Hz]	**Avg. freq. [Hz]**
F1 [Hz]	682	687	686	**685**	645	645	645	**645**	684	685	682	**684**	645	645	645	**645**	644	645	686	**658**	644	644	642	**643**	644	643	644	**644**
F2 [Hz]	762	766	765	**764**	764	764	764	**764**	846	846	845	**846**	762	762	764	**763**	684	696	818	**733**	686	685	684	**685**	685	764	764	**738**
F3 [Hz]	813	820	817	**817**	847	847	845	**846**	1135	1136	1135	**1135**	815	815	817	**816**	762	817	1135	**905**	817	816	815	**816**	764	818	818	**800**
F4 [Hz]	1119	850	850	**940**	1121	1121	1118	**1120**	1500	1495	1497	**1497**	1135	1135	1137	**1136**	815	847	1348	**1003**	1121	1121	1116	**1119**	817	1118	1118	**1018**
F5 [Hz]	1304	1122	1121	**1182**	1299	1296	1296	**1297**	2051	2411	2047	**2170**	1345	1345	1347	**1346**	847	1138	1448	**1144**	1440	1301	1301	**1347**	1121	1331	1338	**1263**
F6 [Hz]	1494	1312	1307	**1371**	1448	1448	1448	**1448**	3062	2033	2410	**2502**	2043	2024	1450	**1839**	1135	1348	2939	**1807**	1821	1440	1450	**1570**	1343	1619	1624	**1529**

Table 6.3. Analysis of experimental data on Eigen values for the rotor blades

Frequenc	Avg. Freq. Blade 1-7 [Hz]	Blade 1		Blade 2		Blade 3		Blade 4		Blade 5		Blade 6		Blade 7	
		Avg. freq. [Hz]	Max. dev. [%]	Avg. freq. [Hz]	Max. dev. [%]	Avg. freq. [Hz]	Max. dev. [%]	Avg. freq. [Hz]	Max. dev. [%]	Avg. freq. [Hz]	Max. dev. [%]	Avg. freq. [Hz]	Max. dev. [%]	Avg. freq. [Hz]	Max. dev. [%]
F1 [Hz]	**658**	685	4	645	2	684	4	645	2	658	0	643	2	644	2
F2 [Hz]	**756**	764	1	764	1	846	12	763	1	733	3	685	9	738	2
F3 [Hz]	**876**	817	7	846	3	1135	30	816	7	905	3	816	7	800	9
F4 [Hz]	**1119**	940	16	1120	0	1497	34	1136	1	1003	10	1119	0	1018	9
F5 [Hz]	**1393**	1182	15	1297	7	2170	56	1346	3	1144	18	1347	3	1263	9
F6 [Hz]	**1724**	1371	20	1448	16	2502	45	1839	7	1807	5	1570	9	1529	11

Following this analysis, it was identified that, for the first frequency the maximum deviation is 4%, and for the second frequency the maximum deviation is approximately 12% for the blade number 3, while for the other blades the maximum deviation of 3% was found. It should be noted that the average deviation of the eigen frequencies for blade number 3 is different from the other blades, as the eigen frequencies of this blade are much higher.

Experimental results of the modal analysis on the compressor rotor

To determine the eigen modes of the entire rotor, three accelerometers were placed on the rotor disc (providing three measuring points) and three independent shocks were applied. The different location of each accelerometer favours the identification of several eigen frequencies, so there is the possibility that one of the transducers/accelerometers is located in a node of a vibration mode, and the other two in an antinode.

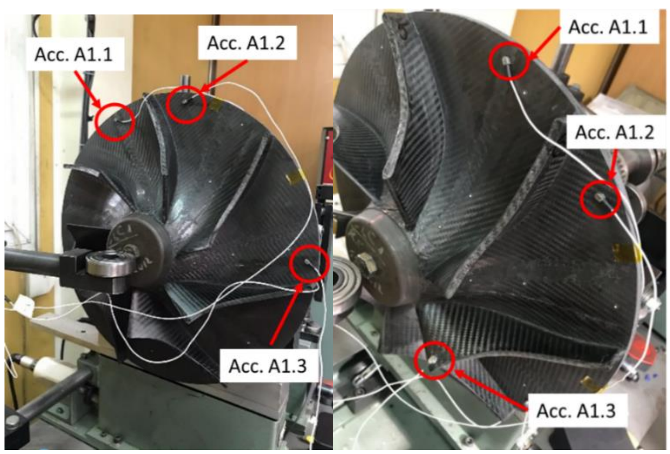


Figure 6.6. Accelerometers placement on the composite centrifugal rotor disc

Taking into consideration the results obtained after the application of the three independent shocks, Table 6.4 presents the identified obtained values together with their average value. For the second shock, the values of the third and fourth eigen frequencies were not identified. Also, Table 6.4 presents a comparative analysis between the critical frequencies determined by the Ping test and the eigen frequencies of the vibration modes calculated by numerical methods (FEA). The table contains the results determined experimentally at rotor level for all three shocks applied, together with the average value, highlighted in blue. Based on the correlations presented above, Table 6.5 highlights the maximum relative deviation between the frequencies of the eigenmodes determined experimentally and by means of numerical simulations.

Table 6.4. Comparative analysis of eigenvalues determined experimentally and by numerical methods

Test Ping rotor					Eigen values	Blades Ping test Avg. freq. (blades 1-7) [Hz]	
Freq.	Shock 1 [Hz]	Shock 2 [Hz]	Shock 3 [Hz]	Avg.freq. [Hz]	Frequency [Hz]	Frequency [Hz]	
F1 [Hz]	455	457	456	**456**	660	F1 [Hz]	**658**
F2 [Hz]	646	645	644	**645**	897	F2 [Hz]	**756**
F3 [Hz]	687	-	682	**685**	925	F3 [Hz]	**876**
F4 [Hz]	769	-	762	**766**	960	F4 [Hz]	**1119**
F5 [Hz]	819	849	845	**838**	1068	F5 [Hz]	**1393**
F6 [Hz]	1121	1123	1136	**1127**	1368	F6 [Hz]	**1724**
F7 [Hz]					1676		

Table 6.5. The maximum relative deviation of the eigen frequencies determined experimentally and by numerical simulations

Ping test on rotor [Hz]	**Numerical simulation (FEA) [Hz]**	**Maximum relative deviation [%]**
F2 = 645	F1 = 660	2.3%
F3 = 685	F1 = 660	3.3%
F5 = 838	F2 = 897	6.4%
F6 = 1127	F5 = 1068	5.5%
Ping test on blades [Hz]	**Numerical simulation (FEA) [Hz]**	**Maximum relative deviation [%]**
F1 = 658	F1 = 660	0.3%
F3 = 876	F2 = 897	2.3%
F4 = 1119	F5 = 1068	4.8%
F5 = 1393	F6 = 1368	1.8%
F6 = 1724	F7 = 1676	2.8%

Concluding, the comparative analysis of the results of the Ping test with that of the vibration calculation shows that the finite element model is adequate to the real one within the limits of the calculated deviations. The deviations related to the test results can be explained by the variation of the constructive parameters (uniform arrangement of the resin, homogeneous mechanical properties) as well as by the influence of the spectral components of the shock stress.

6.6. Testing of the composite centrifugal compressor rotor functionality

For the experimental test, COMOTI's centrifugal compressor test bench was used, shown in Figure 6.7, being composed of the following:

- Electric motor with a 200-kW nominal power and 3000 rpm;
- Compression assembly unit with multiplier, at a ratio of 5,78:1;
- Universal coupling;

- Oil lubrication and cooling system;
- Air barrier system for the radial bearing;
- Command and control system;
- Monitoring system for working parameters.

After assembling and checking all the systems specific to the test bench presented above, the rotor assembly (rotor mounted together with the drive shaft) was integrated into the test bench (Figure 6.8). Natural air was used as a working fluid for the experimental test.

Figure 6.7. Experimental test bench for the validation of the composite rotor

Figure 6.8. Composite centrifugal rotor mounted on the test bench

In order to measure the vibration levels, two accelerometers positioned between the input and the output multiplier have been used. After performing the preliminary steps, the electric motor was started and its speed was gradually increased and the speed of the compressor shaft was measured manually using a tachometer. The speed of the electric motor was manually controlled by a converter, and, during the test, the vibration level of the pinion was monitored, as well as the oil pressure at the inlet to the multiplier (having a multiplication ratio is 5,780).

Further, the RMS values of speed in time correlated with the compressor rotor speed and instantaneous spectral analyses corresponding to the cursor position are presented. Thus, it can be observed that, at the speed of 4400 RPM, in the global vibration graph there is a sudden increase of vibrations as seen in Figure 6.9.

Following an FFT (Fast Fourier Transform) analysis, it was observed that the increase is produced by the spectral component at a frequency of 13.43 Hz (805 RPM) corresponding to the speed of the electric motor. This increase is produced by the critical speed of the rotor/motor-multiplier transmission.

At a frequency of 77 Hz the compressor speed has an amplitude of 0.1 mm/s, recorded by the accelerometer located near the multiplicator output bearing.

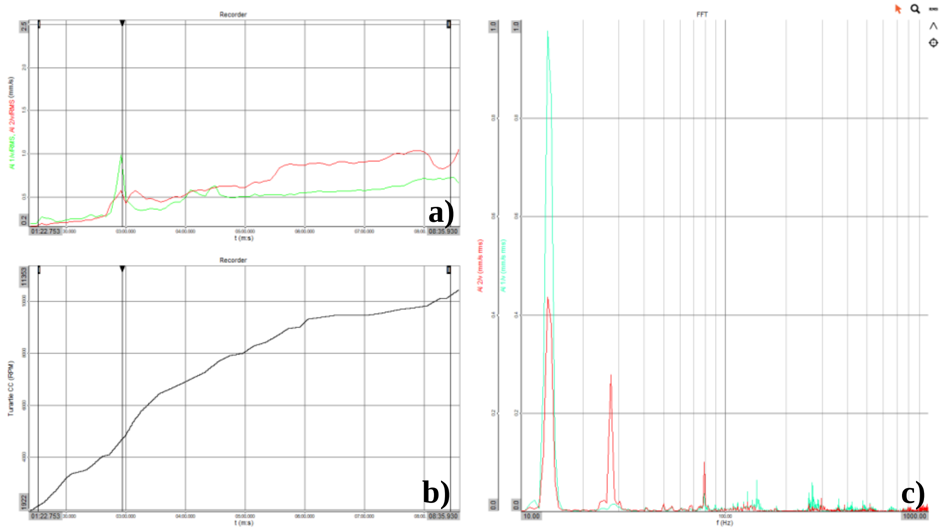


Figure 6.9. a) Variation in time of the overall vibration b) Speed variation in time, c) FFT analysis in the frequency domain corresponding to the cursor timeframe – 4400 RPM

At 8100 RPM both the speed and vibration speed of the compressor are maintained at 0.1 mm/s. Increasing the speed to 9200 RPM increases the level of vibration, being produced mainly by the speed of the electric motor. At the timeframe before stopping the electric motor, the speed of the rotor assembly was 11353 RPM, with a stable vibration level, being within the same limits presented above (Figure 6.10).

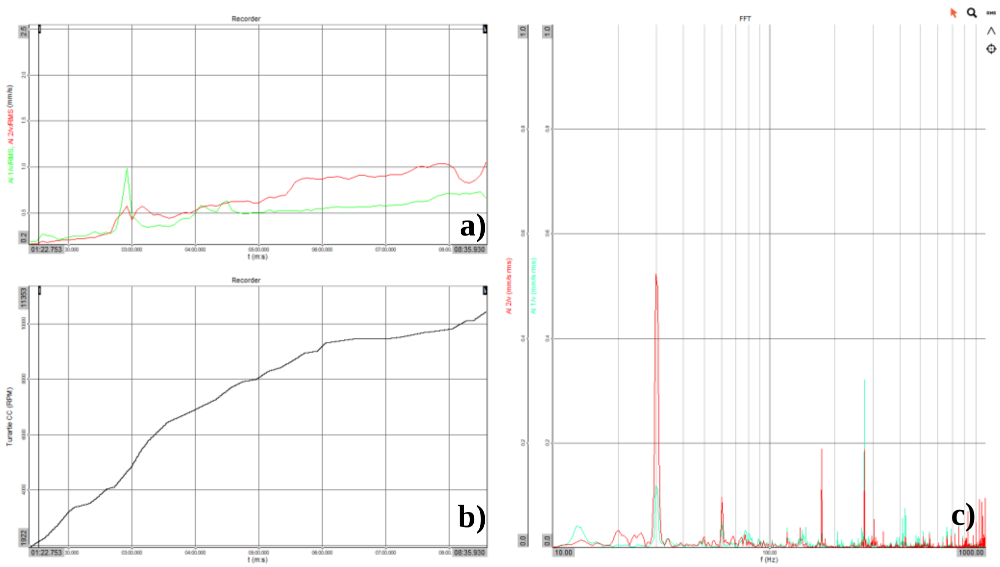


Figure 6.10. a) Variation in time of the overall vibration b) Speed variation in time, c) FFT analysis in the frequency domain corresponding to the cursor timeframe – 11353 RPM

The experimental analysis of the vibrations showed that the rotor, moreover the rotor assembly had a stable behaviour throughout the tests. The low vibration levels of the compressor component, found to be below the limits imposed by the application, indicating that it has been correctly balanced, with no eccentricities leading to dangerous vibrations.

CHAPTER 7
PERSONAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

7.1. General conclusions

The doctoral thesis was structured in seven chapters in order to meet the general objective and the specific objectives defined in Chapter 1, regarding the identification and selection of application-specific materials, rotor and moulds design based on complex aerodynamic and mechanical studies, definition of technology manufacturing of the rotor and finalizing with its experimental validation. Thus, in the following paragraphs the general conclusions regarding the elaborated work, the manufacturing of a component with complex geometry from composite materials using autoclave technology are presented:

1. The selection of a composite material based on carbon fibres in a polymer matrix taking into account the application-specific requirements is a very important step in the process of developing a special component, such as the compressor rotor.
2. Defining the geometric model of the centrifugal compressor rotor considering the autoclave technology. Aerodynamic studies were performed which defined the number of rotor blades and their thickness, structural and mechanical studies which defined the number of layers of composite material in different areas of the rotor, studies on dynamic balancing of the rotor considering its extremely low mass in comparison with other rotors made of metallic materials.
3. Ensuring optimal functionality for a centrifugal compressor rotor by designing and making moulds with good dimensional accuracy. The design and realization of the moulds confirms that the technological stages of manufacturing the rotor are defined, this being one of the specific critical points of this thesis;
4. The manufacturing process of the centrifugal rotor from composite materials by defining the shapes of the prepreg layers based on the geometries of the active parts of the moulds.

The scientific impact consists in achieving knowledge and solving problems in a cutting-edge field, making it possible to continue activities so as to increase the maturity level of the composite rotor, its qualification and integration in equipment used in terrestrial applications or aerospace industry. This knowledge is also a solid basis for carrying out activities or even research projects with even more ambitious objectives in a constantly expanding field.

From a social point of view, a possible technological transfer of the studied topic and developed technology would create new jobs of such a high level of qualification, due to the precision needed to work in the field of compressor rotors, as well as of medium level of qualification due to the need for numerous manufacturing operations within the proposed technology, thus increasing the social impact.

From the point of view of the impact on the environment, it results that the proposed technology has a much lower impact on the environment, which comes from the more judicious use of raw materials, but also from their composition. The proposed technology for making a composite centrifugal compressor rotor is competitive compared to metal rotors, especially if the effects on the environment throughout the product life cycle are taken into account.

7.2. Original contributions

The doctoral thesis contains a comprehensive study on the development of a centrifugal compressor rotor from composite materials, marking its own and original contributions, which bring novelty elements to the topic addressed. These novelty elements are further punctuated:

- The synthesis of information on the current state of research in the field of the use of composite materials in applications specific to bladed machines for rotating elements. Carrying out a study on composite materials based on prepregs available on the market, which meet the specific requirements of the components of the cold part of propulsion systems (high ratio between mechanical strength and density, operating temperature of at least 120° C, resistance to dynamic loads). This study represents a solid and original basis for identifying the optimal material for the current application, but also for other applications or research specific to this field of a high technological level;

- The identification of the optimal application-specific material based on a comparative analysis which included specifications and characteristics of the materials obtained from the material sheets, but also following some experimental determinations. Analysing the material properties presented in the data sheets, performing a comparative analysis based on the application-specific requirements and selecting four materials that were compared following a mechanical test. Interpretation of experimentally obtained results based on statistical analyses and selection of the application-specific composite material. The material which was selected for use was subjected to a complex testing campaign that included mechanical, thermo-mechanical tests and physical-chemical and microstructural analyses. The experimentally determined parameters were considered in numerical analyses with finite elements that aim at mechanical and structural modelling and validation, obtaining a better accuracy for these theoretical simulations;

- Designing the experimental program on determining the physical-mechanical properties for the analysed composite materials, defining the polymerization processes for the laminated plates from which the test pieces used in the test campaign were cut and interpreting the results. Based on these original contributions, the degree of confidence in the accuracy of the numerical simulations has increased, respectively the risks that the centrifugal compressor rotor will not meet the application requirements have decreased;

- Participation in the implementation team to study the aerodynamic effects of the geometry of a centrifugal compressor rotor designed to be made of composite materials using autoclave technology. Through these complex studies, the rotor was predimensioned and an aerodynamic evaluation was performed using numerical methods considering different configurations for the rotor. The strategy of varying the number of blades and their thickness, so as to determine the optimal geometry of the rotor for the selected technology, is one of the original contributions of the author and contributed to the general objective of the doctoral thesis;

- Defining the constructive configuration of the centrifugal compressor rotor made of composite materials considering the autoclave technology and validation by specific analyses with the finite element method to meet the criteria of resistance and vibration. The arrangement of the prepreg layers, as well as the definition of the technological solutions to reduce the mechanical loads at the level of the rotor represent one of the original contributions of the author;
- Determination of a technical solution for balancing a centrifugal compressor rotor made of composite materials based on carbon fibre in a polymer matrix, by integrating two metal rings with different diameters. The technical solution was determined following a large study that contains theoretical considerations on dynamic balancing which apply to all components that operate at relatively high speeds and have low mass, but it also contains practical recommendations related to the design of such components. The combination of composite materials with metallic materials in order to ensure dynamic balancing is an original contribution that led to the validation of the technology studied and defined in this thesis;
- Integration of all available results and information from previous activities and definition of the geometric model of the centrifugal compressor rotor that meets all application requirements and takes into account the specifications and constraints of autoclave technology. The geometric model of the resulting centrifugal rotor is an original contribution because a centrifugal rotor that can be achieved by autoclave technology has been designed, a technology which has not been used until now to make such components;
- Development of the technology for manufacturing the centrifugal compressor rotor from composite materials considering the autoclave technology. In the first instance, the general stages of manufacturing process were established, which allowed the design of the necessary moulds. The design of the moulds, more precisely the definition of the separation plans and the assembly method, respectively disassembly after the completion of the polymerization process represents an original contribution, specific to this doctoral thesis. Based on the geometry of the moulds and the results of the resistance and vibration calculations, the geometric shape of each layer and the number of prepreg layers were defined. The shape of the prepreg layers consists in a series of unfolded surfaces, which, when positioned on the moulds, they define the specific parts of the compressor rotor, the blades or the rotor disk. The shape of the prepreg layers, respectively the establishment of their arrangement must allow the closing / assembly of the moulds before the beginning of the polymerization process. Considering the complex geometric shape of the rotor, the

small thickness of the blades, respectively the large number of moulds necessary to make the entire rotor, the definition of the shape of the layers and the arrangement are a novelty and an original contribution. The design of the moulds, the establishment of the assembly and disassembly steps, the definition of the geometric shape of the layers and the arrangement are part of the development of the production technology and represent an original contribution;

- The manufacturing process of the centrifugal compressor rotor through three distinct stages consisting in the independent manufacturing of the seven blades, their integration in the rotor structure and consolidation of its disc together with the integration of the two metal rings, defining the necessary steps to ensure the mechanical interface with the drive shaft and the outer diameter representing original contributions to the technology and manufacturing process;
- The definition of the testing and verification plan for the rotor which allowed either the comparison of some characteristics of the centrifugal compressor rotor made of composite materials with the reference rotor (weight, dimensional stability), or the validation of the dynamic balancing of the rotor, the determination of vibrations and own modes or checking its functionality;
- Identifying the Eigen frequencies for each blade, but also for the rotor by specific tests and comparing the results with the theoretical ones. These activities represent original contributions and confirm the link between numerical analysis and the structural behaviour of the rotor, respectively validate once again the technology developed in this thesis;
- Determining the mass of the centrifugal compressor rotor made of composite materials and comparing the values obtained with the theoretical model and the reference model. It is highlighted that the developed technology is controllable, by small differences between the real mass of the composite rotor and the theoretical one. Also, the weight of 2.72 kg of the rotor made of composite materials confirms once again the advantage of using such materials in terms of mass;
- Studying the efficiency and accuracy of numerical analyses performed with the finite element method by evaluating the yield criteria specific to the rotor and comparing with the experimental results obtained.

7.3. Perspectives for future development

In order to increase the maturity level of the centrifugal compressor rotor made of composite materials, the following directions of further development are highlighted:

- Identification of possible solution to optimize the design of materials, including aspects related to the improvement of materials through different matrix / fibre combinations, the arrangement of fibres in fabrics or the application of surface coatings.

- fabrication of all the moulds from metallic materials with a thermal expansion coefficient as low as possible so that no dimensional deviations occur at the level of the polymerized rotor and the manufacture of the rotor through a single polymerization process;
- testing the centrifugal compressor rotor in real operating conditions, ensuring the optimal clearance between the rotor blades and the stator ring and obtaining as many experimental data (pressures, temperatures, flow rates) as possible, in order to compare with the theoretical results used in the numerical simulation analysis.

PUBLISHED PAPERS

I. Articles published in Web of Science journals in the field of doctoral thesis

1. Draghici, S., Vintila, I.S., **Mihalache, R.,** Petrescu, H.A., Tuta, C.S., Hadar, A., Design and Fabrication of Thermoplastic Moulds for Manufacturing CFRP Composite Impeller Blades, Mater. Plast., 57 (1), 2020, 290-298, https://doi.org/10.37358/MP.20.1.5338;

2. Maier, R., Vintilă, I.S., **Mihalache, R.,** Vilag, V., Sima, M., Dragan., Decreasing the Mass of Turbomachinery Subansamblies Using Advanced Polymer Composites, Materiale Plastice, 56, no. 4, 2019, https://doi.org/10.37358/MP.19.4.5254;

3. **Mihalache, R.,** Condruz, R.M., Vintila, I.S., Vilag, V., Stanciu, V., Utilizarea unor materiale compozite avansate la proiectarea și fabricarea unor palete de rotor centrifugal (Centrifugal rotor blade: design and manufacturing using advanced composites), Revista Romana de Materiale, Volume: 48 Issue: 4 Pages: 522-528, 2018;

4. Voicu, R., Vintila, S., Vilag, V., **Mihalache, R.,** CAD Modelling: Light Weight Composite Centrifugal Rotor Manufacturing for Energy Efficiency, Materiale plastice, Volume: 53 Issue: 4 Pages: 623-625, 2016.

II. Articles published in BDI journals in the field of doctoral thesis

1. **Mihalache, R.,** Vilag, V., Popescu, J., Voicu, R., Stanica, C., Manufacturing a composite structure with applications in aeronautical field that can absorb displacements on different directions, Proceedings of the 3rd CEAS Air & Space Conference and 21st AIDAA Congress, 24-28 October 2011, Venice, Italy, ISBN: 978-88-96427-18-7

2. Olaru, D., **Mihalache, R.,** Vilag, V., Gabor, D., Light Weight Carbon Fiber Compressor Impeller/Blade Structural Design, 1st International Conference NEW CHALLENGES IN AEROSPACE SCIENCES NCAS 2013, November 7-8, Bucharest, ROMANIA, ISSN 2344-4762, ISSN-L 2344-4762

3. **Mihalache, R.**, Fuiorea, I., Popa, I.F., Deaconu M., Sima, M., Numerical and experimental analyses regarding the eigen frequencies of a centrifugal compresor made of composites, UPB Scientific Bulletin Series D, Submission ID 11363 – în curs de evaluare;

III. Articles published in journals listed Web of Science in fields related to the doctoral thesis

1. Adiaconitei, A., Vintila, I.S., **Mihalache, R.,** Paraschiv, A., Frigioescu, T., Vladut, M., Pambaguian, L., A Study on Using the Additive Manufacturing Process for the Development of a Closed Pump Impeller for Mechanically Pumped Fluid Loop Systems, Materials, Volume: 14 Issue: 4, https://doi.org/10.3390/ma14040967

IV. Articles published in BDI journals in fields related to the doctoral thesis

1. Vintila I.S., Adiaconitei, A., **Mihalache, R.,** Paraschiv A., Frigioescu, T., Condurachi, F., Datcu, D., A study on reducing the adherent dross on additively manufactured closed impeller, Turbo Journal, editat de INCD Turbomotoare COMOTI – în curs de publicare

2. Draghici, S., Jiga, G., Vintila, S., **Mihalache, R.,** Petrescu, H.A., Hadar, A., Structural evaluation of a composite centrifugal rotor, Volume XXIII 2020, ISSUE no.1, Scientific Bulletin of Naval Academy, MBNA Publishing House Constanta 2020;

V. Articles published in journals listed Web of Science in fields not related to the doctoral thesis

1. Mihai, D., **Mihalache, R.**, Popa, I.F., Vintila, S.I., Datcu, D., Ciocan, I., Braic, V., Pana, I., Kiss, A.E., Zoita, N.C., Burlacu, P., Design, analysis and evaluation of titanium antenna reflector for deep space missions, Volume 184, July 2021, pp. 101-118, https://doi.org/10.1016/j.actaastro.2021.04.006;

2. Popa I.F., Andreescu T., Ifrim D., **Mihalache R.,** Mihai D., Cican G., Finite element modelling and performance optimization of an ion thruster depending on the nature of the propellant, CEAS SPACE JOURNAL, Volum: 11, Nr. 2, Pag: 115-122, 2019, ISSN: 1868-2502, WOS: 000465226800001;

3. **Mihalache R**., Mihai D., Megherelu G., Popa I.F., Olaru D., Ifrim D., Sealing Technologies Trade-off for a Phobos Sample Return Mission, Transportation Reseach Procedia, Volum 29, Pag. 244-254, 2018;

VI. Articles published in BDI journals in fields not related to the doctoral thesis

1. Silivestru, V., Cuciumita, C., **Mihalache, R.,** Petcu, R., “COANDA-1910” - the first jet propulsor for airplane, INCAS BULLETIN, Volume 2, Number 4/ 2010, pp. 179 – 187, https://doi.org/10.13111/2066-8201.2010.2.4.23;

2. Popa, I.F., Megherelu, G., **Mihalache, R.**, Mihai, D., Adiaconitei, A., Nutu, E., Stanciu, V., Centrifugal pump breadboard design for a Mechanically Pumped Fluid Loop Cooling System, TURBO Journal, editat de INCD Turbomotoare COMOTI – în curs de publicare;

3. Silivestru, V., **Mihalache, R.,** Silivestru, C., Popescu, J., Stanciu, V., Advanced Strategic Planning Regarding the Development of a Turbopump System for a Liquid Fuel Rocket Engine, The CEAS European Air & Space Conference 2013, 16-19 September 2013, Linkoping University, Sweden,

VII. Participation in conferences

1. Voicu, R., VINTILA, S., Vilag, V., **Mihalache, R.**, Energy efficiency - lightweight composite centrifugal rotor, International Conference on Energy and Environment, 2013, Bucharest, Romania
2. Popescu, J.A., Vilag, V.A., Stefanescu, M., **Mihalache, R.,** Fuiorea, I., Gabor, D., Dynamic Balancing Method for a Carbon Fibre Centrifugal Compressor Impeller, Proceedings of the 5th European Conference of Mechanical Engineering (ECME' 14), Florence, Italy, November 22-24, 2014;

VIII. National patents in the field of doctoral thesis

1. Vintila S.I., **Mihalache R**, Condruz M.R., Vilag V.A., Maier R., Ansamblu Rotatic de Compresor Centrifugal din Materiale Compozite Polimerice Avansate Ranforsate cu Fibre de Carbon, Nr. Patent RO133845-A0, 12 Septembrie 2019;

IX. International patents in fields related to the doctoral thesis

1. MARDJONO J.N., JODET N.B.A., **MIHALACHE R**., PETCU R., SILIVESTRU V., STANICA C.M., VOICU L.R., Insert pour la fixation d'un composant sur un support de turbomachine, Patent no.: FR3070427-A1 (01 Mar 2019); FR3070421-B1 (21 Feb 2020)
2. MARDJONO J.N., JODET N.B.A., **MIHALACHE R.,** PETCU R., SILIVESTRU V., STANICA C.M., VOICU L.R., Pale pour turbomachine et son procède de fabrication, Patent no.: WO2019038500-A1 (28 FEB 2019)