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OPTIMIZATION OF LIGHT AIRCRAFT ENGINE COVER CONFIGURATION

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Abstract

Trends in the civil aircraft market in recent years indicate an increased demand for light aircraft with high efficiency, minimum weight and long service life. However, the development, tests and certification of a new aircraft is a painstaking, time-consuming and expensive process that can cost from several hundred thousand to several million dollars. One way to overcome this problem is to modify the existing certified aircraft through the process of modernization. Modernization, which implies the introduction of a new, stronger and often lighter engine, ensures a simultaneous increase in efficiency and a reduction in the overall weight of the aircraft. Weight reduction can also be achieved through the use of modern, lighter materials, as well as through the use of new methodologies in the design of parts of the structure.

This doctorate was created during work on the modernization of the basic version of the "UTVA-75" aircraft, which was achieved by installing a new LYCOMING IO-390 engine. For the new engine, a new engine cover had to be designed, which led to the possibility of using composite materials for the purpose of additional mass reduction. Composite materials are obtained by joining two or more materials in order to achieve significantly better mechanical characteristics. The advantage of a well-designed composite is reflected in better characteristics compared to the materials from which it is made, sometimes possessing properties that those materials do not have. Some of the key benefits of using composites in aircraft design include weight reduction (from 20 to 50%), increased strength at lower weight in the case of so-called "single shell" molded structures, high impact resistance, high thermal stability, resistance to fatigue and corrosion. A composite engine cover would therefore represent a significant improvement in overall light aircraft efficiency.

The engine cover, in addition to being used to cover the engine and aggregates in order to reduce aerodynamic resistance, is also used for: providing the necessary mass of cold air in order to cool the engine (it is also important that the engine is not undercooled), supplying the engine with air in order to sustain combustion, provide oil filter cooling, alternator cooling, provide air supply for air conditioning and ventilation, etc. In the case of the UTV aircraft in this PhD, the engine is located in front of the first frame, which represents the main determinant according to which the engine cover is designed. In addition to its primary purpose, which is related to the engine and aggregates, the lining must also fulfil other requirements. When designing the engine cover, the requirements of aerodynamics, strength, installation of engines

and engine aggregates, exploitation and production are considered. In addition to the above requirements, the application of appropriate standards and recommendations is also necessary.

Modernization is also reflected in applying new numerical methods and techniques in all the processes mentioned earlier. Being developed and improved over the years, in some cases over decades, numerical methods (primarily finite element method (FEM) and finite volume method) have recently become – as a part of modern software packages – a necessary tool in aircraft design.

The subject of research in this thesis was the multidisciplinary process of designing and optimizing a composite engine cover which must be constructed in such a way that it can withstand all the loads acting on it during exploitation. This procedure implies the implementation of several types of analysis, experimental methods, and especially numerical methods. Considering several conflicting design requirements, through a detailed design process, an algorithm was arrived at that could be used for designing and improving other parts of the structure of the UTVA aircraft in question, but also of other similar aircraft.

The data and results obtained in the analyses presented in this dissertation enabled the production of a composite engine cover and its installation on a light aircraft. In this way, this thesis contributed to the improvement of the design and optimization of composite aircraft elements, and based on its results, verified numerical models and the adopted methodology, it will be possible in the future to effectively modify and improve other aircraft (or parts of the aircraft) that are already in use.

Keywords: Composite design, aircraft design, finite element analysis

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Резиме

Трендови на тржишту цивилних ваздухоплова последњих година указују на појачану потражњу за лаким летилицама високе ефикасности, минималне тежине и дугог експлоатационог века. Међутим, развој, увођење у оперативну употребу и сертификација нове летилице представља мукотрпан, дуготрајан и скуп процес који може да кошта од неколико стотина хиљада до неколико милиона долара. Један од начина превазилажења овог проблема је модификација постојећих сертифицираних летилица путем њихове модернизације. Модернизација која подразумева увођење новог, јачег и често лакшег мотора обезбеђује истовремено повећање ефикасности и смањење целокупне масе летилице. Смањење масе је могуће остварити и кроз примену савремених, лакших материјала као и кроз примену нових методологија у пројектовању делова структуре.

Овај докторат је настао током рада на модернизацији основне верзије авиона „УТВА-75“ која је остварена уградњом новог мотора LYCOMING IO-390. За нови мотор је требало пројектовати и нову моторску облогу (капотаж) чиме се отворила могућност коришћења композитних материјала у сврху додатног смањења масе. Композитни материјали се добијају спајањем два или више материјала у циљу постизања знатно бољих механичких карактеристика. Предност добро пројектованог композита огледа се у бољим карактеристикама у односу на материјале од којих је сачињен, поседујући понекад и особине које ти материјали немају. Неке од кључних предности коришћења композита у ваздухопловству укључују смањење тежине од 20 до 50%, повећану чврстоћу при мањој тежини у случају тзв. „single-shell“ обликованих структура, високу отпорност на удар, високу термичку стабилност, отпорност на замор и корозију. Моторска облога израђена од композита би стога представљала значајно побољшање што се тиче целокупне ефикасности лаке летилице.

Моторска облога, осим што се користи за покривање мотора и агрегата како би се смањио аеродинамички отпор, служи и за: обезбеђивање потребне масе хладног ваздуха у циљу хлађења мотора (битно је и да се мотор не потхлађује), напајање мотора ваздухом у циљу обављања сагоревања, хлађење филтера уља, алтернатора, напајање ваздуха за климатизацију и вентилацију, итд. У случају авиона из овог доктората мотор се налази испред првог оквира који представља главну одредницу према којој се врши пројектовање моторске облоге. Поред своје основне намене која је везана за мотор и

агрегате, облога такође мора да испуни и друге захтеве. Код пројектовања моторске облоге води се рачуна о захтевима аеродинамике, чврстоће, уградње мотора и моторских агрегата, експлоатације и израде. Осим наведених захтева неопходна је и примена одговарајућих стандарда и препорука.

Посебан аспект модернизације огледа се и у примени нових нумеричких метода и техника у наведеним процесима. Развијане и унапређиване дуги низ година, па и деценија, нумеричке методе (на првом месту метода коначних елемената (МКЕ) и метода коначних запремина) имплементиране у софтверске пакете у последње време су постале неопходан алат у пројектовању.

Предмет истраживања ове тезе је мултидисциплинарни поступак пројектовања и оптимизовања композитне моторске облоге која мора бити конструисана тако да издржи сва оптерећења која на њу делују током експлоатације. Овај поступак подразумева имплементацију неколико типова анализа, експерименталних метода и нарочито нумеричких метода. Разматрајући више међусобно супротстављених пројектних захтева, кроз детаљан поступак пројектовања дошло се до алгоритма који би могао послужити за пројектовање и извођење побољшања других делова структуре код предметне летелице УТВА, али и код других сличних летелица.

Подаци и резултати добијени у анализама представљеним у овој дисертацији омогућили су израду композитне моторске облоге и њену уградњу на лаку летелицу. На тај начин је ова теза допринела унапређењу пројектовања и оптимизовања композитних ваздухопловних елемената, а на бази њених резултата, верификованих нумеричких модела и усвојене методологије бити могуће у будућности ефикасно извршити модификацију и унапређење и других ваздухоплова који су већ у експлоатацији.

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1 Introduction and Literature Review

1.1 Background and Motivation

Trends in the civil aircraft market in recent years indicate an increased demand for light aircraft with high efficiency, minimum weight, and long service life. However, the development, introduction into operational use and certification of a new aircraft is a painstaking, time-consuming and expensive process that could cost millions of dollars. One way to overcome this problem is to modify existing certified aircraft through modernization. In this sense, modernization, which implies the introduction of a new, stronger, and as a rule, lighter engine ensures a simultaneous increase in efficiency and a reduction in the overall mass of the aircraft. Further modernization is possible through the application of modern, lighter materials as well as through the application of new methodologies in the design of existing and improved parts of the structure.

The modernization of the basic version of the "UTVA-75" aircraft was accomplished primarily by installing a new LYCOMING IO-390 engine. This opened the possibility of further improvement of the aircraft in question by designing a new engine cover that would be made of composite materials, which would further reduce the mass.

One of the most important innovations in the aviation industry is the use of composite materials. Composite materials are obtained by joining two or more materials in order to achieve significantly better mechanical characteristics. The advantage of a well-designed composite is reflected in better characteristics compared to the materials from which it is made, sometimes possessing properties that those materials do not have.

Some of the key advantages of using composites in aerospace include weight reduction of 20 to 50%, increased strength at lower weight in the case of so-called "single shell" molded structures, high impact resistance, high thermal stability, resistance to fatigue and corrosion. Having all this in mind an engine cover made of composite material would therefore represent a significant improvement in overall light aircraft efficiency.

The engine cover, in addition to being used to cover the engine and aggregates in order to reduce aerodynamic resistance, also serves to: provide the necessary mass of cold air in order to cool the engine (it is also important that the engine is not undercooled), supply the engine with the air in order to carry out combustion, cool the oil filter,

alternator, provide air supply for the air conditioning and ventilation, etc. In this case, the engine is located in front of the first airframe, which represents the main determinant according to which the engine cover is designed.

In addition to its basic purpose, which is related to the engine and aggregates, the engine cover must also fulfill other requirements. During the realization of the engine cover, the requirements of aerodynamics, strength, installation of engines and engine aggregates, exploitation and production have to be considered. In addition to the above requirements, it is also necessary to comply the prescribed standards and recommendations.

A special aspect of modernization is reflected in the application of new, primarily numerical methods and techniques in the mentioned processes. Developed and improved for many years, even decades, numerical methods such as the finite element method (FEM) and the finite volume method, implemented in commercial software packages, have recently become a necessary tool in design in general.

The subject of research in this thesis is the multidisciplinary process of designing a composite engine cover, which must be constructed so that it can withstand all the loads which occur during the operation. This procedure implies the application of several different analyses, experimental and especially numerical methods. Considering several mutually opposing design requirements, the objective of this thesis is to create an algorithm through a detailed design process that could be used for designing (and improvements implementation) of the other parts of the structure of the same aircraft, but also for other similar flying vehicles.

1.2 Literature review

Composite materials are formed by the combination of two or more materials with different mechanical properties. These newly created materials have improved structure and hence they usually have significantly improved stiffness, strength, wear, corrosion, and fatigue resistance. It has to be noted that composite materials are very well known, since wood and animal bone as natural composites were used for hunting and farming from the earliest days of human history [1, 2]. One of the first man-made composite

material is concrete, which was described in detail 2500 BC by Vitruvius in his ten books on architecture [3].

But the modern term composite, was established in the aircraft industry in 1940's, in the sense of using plastics and fibers in aircraft construction [4]. The original fiber reinforcement of modern composites is made of fiberglass [5]. To be more specific, when we think of composite as we know it today, we think of fiber reinforcement. American company 'Owens Corning' and their employees by Games Slayter, John Thomas and Dale Kleist, between 1933 and 1937 gave several patents which enabled production of continuous glass fibers on commercial scale [2, 3]. Around the same time, in 1936 the polyester resin was invented by Carlton Elis from American company 'Du Pont' [6].

The main components of composite materials used in aircraft industry are fibers (usually glass or carbon) and matrix (usually epoxy). The fibers provide most of the stiffness and strength while the matrix binds the fibers together, providing load transfer between fibers. These composites are so-called 'fiber-reinforced composites' (FRCs). They have low density, high strength, and high stiffness, and these properties are the reason why the composites are used in literally every type of engineering industries, even in the design of advanced energy systems [7] and in the production of electromagnetic shielding structures [8]. It is obvious that their mechanical properties strongly depend on fiber orientation, fiber distribution in the matrix and layer sequence. This the reason of continuous interest of the scientists in composites: their development, improvement but also in the mathematical and theoretical modeling of this type of material. Previously mentioned concrete, which has been in use for more than 4500 years, is still the topic of many scientific studies because the material model of steel reinforced concrete – which is nowadays widely used – is not completely established yet. For example, to describe the failure of fiber-reinforced concrete, a fundamentally stochastic fiber bundle model was applied in [9 and 10] to present the bond-slip behavior between fiber and concrete during the pull-out of the fiber. Many other papers deal with this topic, but in this thesis the focus is on the composite materials mostly used in the aircraft industry.

The dynamic behavior of composite structural parts and materials, such as thermal effects, blast loading, crash absorbing, and low velocity impact were analyzed in [11] and [12]. These numerical and experimental analyses included application of composites in hydropower, automotive and aerospace engineering industry.

The use of composites is evident in the innovative approaches in the hydropower plants construction from composite coating for turbines [13, 14] to turbine itself [15] and other hydro-mechanical equipment [16,14].

To make use of all the advantages of the composite material, but also to avoid its weaknesses, it is necessary to determine composite's mechanical properties: elasticity modulus, tensile strength, bending strength, and stress and strain at failure. A detailed review of carbon fiber-reinforced polymer composites' mechanical properties and their performance are presented in [17]. Authors of this review studied more than 70 scientific papers in which they analyzed mechanical properties which were obtained experimentally. However, experiments require manufacturing a number of different FRCs' specimens, and therefore can make them expensive and time-consuming. As computer technologies became more available in recent years, numerical methods, in the first-place finite element method (FEM), have started to be usual methods for analysis of mechanical behavior of composite materials. Bussetta, P., and Correia, N. [18] presented a great effort of the scientific community in a review paper from 2018, which is dealing with numerical modeling of continuous fiber reinforced composite (FRC) material. They analyzed 230 references that were published over 20 years, with a focus on the numerical forming processes based on FEM at the macro-scale level. According to this review, three numerical methods are used to model continuous FRC panels: the continuous approach, the discrete or mesoscopic, and the semi-discrete approach. Based on the presented data authors concluded that the continuous approach, as well as the semi-discrete, are suitable for the modeling of phenomena at the macro-scale and the computation of full structure problems, while the discrete approach and the semi-discrete are more appropriate to model the phenomena at the meso-scale. They also pointed out that numerical modeling of the FRC is still a subject of investigation and it will continue to be so in the future.

The application of FEM is inseparably linked to the computer resources and computing time, since it is well known that the computed results depend on the comprehensiveness of the analyzed model. Many researchers conducted analyses based on a numerical homogenization technique with a representative volume element or a unit cell model within FEM to overcome this issue, as presented in [19-22]. The FEM method is used by some researchers for validation of their theoretical and analytical models [23,

24, 25] while others validated their FEM based analysis results of the composite materials by comparison with experimentally obtained results [24, 25, 26].

However, it has to be pointed out once more that because of its specific structure, unstandardized manufacturing, various fiber orientations, fiber distribution in the matrix, layer sequence, etc., experimental tests of composite material cannot be avoided.

It was already mentioned that the term composite, as we know it today, was established in the aircraft engineering industry in the middle of the last century. Since then, the number of published scientific and research papers in this field has been enormous. A review paper [27] summarizes developments and advancements in composite materials for aircraft applications from 1994 to the present day, including several review articles [28 -32]. The mentioned review is focused on composite materials specially designed for aircraft application, but also on composites' properties, manufacturing procedures, and their utilization in different aircraft structures. Authors separately considered metal matrix composites, ceramics matrix composites, and polymer matrix composites. Based on the presented data polymer matrix composites are the lightest of the three above-mentioned (they have high specific strength and modulus), but in their nature polymer matrix composites are brittle. Their fracture toughness is lesser than the metal matrix composites, but fatigue resistance is the highest of the three mentioned composite materials. They have higher wear resistance compared to metal matrix composites, higher creep resistance, and low density. Polymer matrix composites are used for air brakes' structure, wing boxes, fuselage, window frames, different types of brackets, bulkheads, fittings, blades, vertical fins, tail assemblies, etc. and their operating temperature is up to 200°C. Since polymer matrix surrounds the fibers, they are well protected from environmental influences.

In real laminated composite structures, stresses generated as a result of external mechanical loads are commonly called mechanical stresses. The second source of external loads can be attributed to environmental factors such as extreme operating temperatures resulting in so-called thermal stresses. A typical example is an aircraft, having structural parts made of laminated composite material, exposed to extremely low (below -50°C) or high temperatures (over 50°C). These conditions may contribute to the reduction of composite structure strength in two ways. As a first issue, the reduction of composite structure strength is attributed to the fact that additional thermal stresses can

significantly decrease estimated composite structure strength which is usually determined analytically, using Classical Lamination Theory (CLT). The second issue is associated with the fact that composite lamina strength and stiffness is determined by calculations that involve elastic properties of composite material obtained by laboratory experiments conducted at standard temperature (usually 20°C). As it is well documented in the literature, elastic properties of the matrix, in some cases, are strongly dependable on temperature changes [33]; therefore, elastic properties of composite material must also depend on temperature changes.

Since operating temperatures could be significantly different from standard laboratory tests temperature, it is clear that exposition of the composite structure to extremely low or high temperatures may lead to a notable change of composite lamina mechanical properties and, consequently, change of lamina strength. Recently, several studies have been carried out regarding the influence of temperature on the mechanical properties of composite materials.

In [34] an experimental investigation of the effects of low temperatures on the mechanical, fracture, impact, and dynamic properties of carbon- and E-glass-epoxy composite materials has been conducted. The objective of the study was to quantify the influence of temperatures from 20°C down to -2°C on the in-plane (tensile/compressive) and shear material properties, static and dynamic Mode-I fracture characteristics, including impact/residual strength. It was found that nearly all characteristics of the mechanical performance of the laminates are temperature dependent. In [35] authors evaluated the temperature effect on the mechanical properties and damage mechanisms of a Glass/Elium 150 laminate composite. Quasi-static indentation tests have been carried out at different temperatures to highlight the temperature dependency of different parameters of the composite samples, including stiffness. The influence of temperature was analyzed, and it was shown that mechanical properties and the severity of damage were strongly temperature dependent. The most comprehensive experimental study of the temperature effect on the mechanical properties of composite materials is presented in [36]. The effect of constant and cyclic temperature influences (from -196°C to 120°C) on products made of composite materials was observed. The ring samples have been used and the data on the changes in the linear expansion coefficient values, strength, rigidity, and residual stresses with the change of temperature and the number of thermal cycles,

are given. All above-mentioned studies can be used to evaluate results obtained by numerical evaluations of the elastic properties of carbon fiber reinforced composite material which, surprisingly, cannot be found in the recent literature in the greater number [37].

It was already mentioned that trends in the civil aircraft market in recent years indicate an increased demand for light aircraft with high efficiency, minimum weight, and long service life. This is confirmed in the studies presented in [38] and [39] in which authors analyzed the need for the use and modernization of light aircraft, where the emphasis is set on the use of composite materials and the implementation of new methodologies in the design. According to many studies [40-45], the application of different composite materials in the aviation industry has been present for many years, which led to the fact that today 50% of the new aircraft components are made of composites, from rudder, spoiler, and air brakes to engine cover, wing ribs, blades of turbofan engines, etc. The primary advantage of composite components is their reduced weight and easy assembly. In the available literature, the lack of research that deals with a comprehensive approach to the design of composite aircraft structures is noticeable. This approach includes computational fluid dynamics and structural analysis carried out simultaneously with an emphasis on the future manufacturing of composite parts and experimental verification, where the main goal is to replace the existing metal components with composite parts with significantly lesser mass. The improvement (optimization) of the composite structure using a numerical approach, validated and verified by experiments, is also not noticeably covered in the analyzed literature, although the combination of numerical and experimental approaches is unavoidable in the design of modern aircraft.

1.3 Objective and thesis organization

1.3.1 *Objective*

The main goals of this thesis are:

- Micromechanical analysis of the designed composite material.

- Determination of mechanical properties of designed composite material by numerical methods and their validation by experimental methods.
- Evaluation of high and low-temperature influences on mechanical properties of the composite material in question.
- Determination of aerodynamic loads to which the composite engine cover is subjected during exploitation using computational fluid mechanics (CFD) analysis.
- Analysis of the composite's numerical model and the optimization of its layering sequence to reduce the mass and displacements of the structure under given loads.
- Structural analysis of the composite engine cover by FEM, with special reference to the determination of critical areas which might be the source of failure.
- Determination of possible areas on the engine cover that need reinforcement and design of these reinforcements.
- Design of the production processes and final manufacturing of the composite engine cover.

The data and results obtained during the work on this thesis will enable the creation of a composite engine cover and its installation on a specific light aircraft. It is also expected that this thesis contributes to the further improvements of the design of composite aircraft elements, in the sense that based on its results, verified numerical models, and adopted methodology it would be possible to effectively modify and upgrade the aircraft which are already in use.

1.3.2 Thesis organization

This thesis is comprised of eight chapters.

Background of the thesis topic, literature review, and the thesis objectives and content are presented in the first chapter.

In the second chapter, the theoretical background necessary for thesis research is presented: the background of composite material, its classification, micromechanics of the composites, and macro-mechanical analyses of the composites.

Experimental and numerical analyses of the designed composite material, including fabrication of test specimens, are carried out in the third chapter.

Engine cooling analysis, which includes calculation of mass air flow for engine cooling and other requirements, dimensioning of the engine cover front opening, and calculation of cross-section surface of air filter are conducted in the fourth chapter.

In the fifth chapter numerical determination of aerodynamic loads is carried out through CFD simulations based on the $k - \epsilon$ turbulence model.

Numerical and computational models of composite engine cover are defined, and the results obtained in the previous chapters are used for structural analysis conducted and presented in the sixth chapter.

In the seventh chapter, the production processes' framework and final manufacturing of the composite engine cover are presented.

Finally, in the eighth chapter, the conclusions, and guidelines for further research, together with the thesis's achieved contributions, are given.

2 Determination of mechanical properties of composites

As emphasized in the previous chapter, composites may have excellent mechanical properties (compared to other materials used in construction) and enable the unusual possibility of simultaneous structure and material design. The composite properties are defined not only by the choice of the reinforcement and the matrix but also by their volume fraction, and method of production. Material properties that can be improved by “creating” (i.e. producing) and using the composite material are:

- Strength
- Rigidity
- Weight reduction
- Acoustic insulation
- Corrosion resistance
- Wear resistance
- Thermal insulation
- Thermal conductivity.

It is not possible to achieve all the above-mentioned properties in one composite material, nor it is necessary. Some properties are in collision with the others. The objective is to create material that will serve a specific purpose.

2.1 Classification and properties of composite materials

In brief, based on [46] there are two criteria for the classification of composite materials. The first is based on matrix component type. According to this criterion, there are:

- Organic matrix components (refers to two classes of composite materials: polymer matrix composites and carbon matrix composites),
- Metal matrix composites, and
- Ceramic matrix composites.

The second criterion is based on the reinforcement material. According to this criterion composites can be:

- Fiber-reinforced composites (with discontinuous or continuous fibers), and

- Particulate composites.

This research is based on the use of fiber-reinforced composites (FRC) with continuous fibers and their properties will be described below.

2.1.1 Fiber properties

Fibers are used in composites because they are light (low in mass) and may have high strength. The most commonly used fibers in composite structures are glass, carbon, and aramid fibers. Organic (Kevlar), pine, silicon carbide (SiC), aluminum, and other fibers are used for special purposes. The fiber type is selected according to the structure's application.

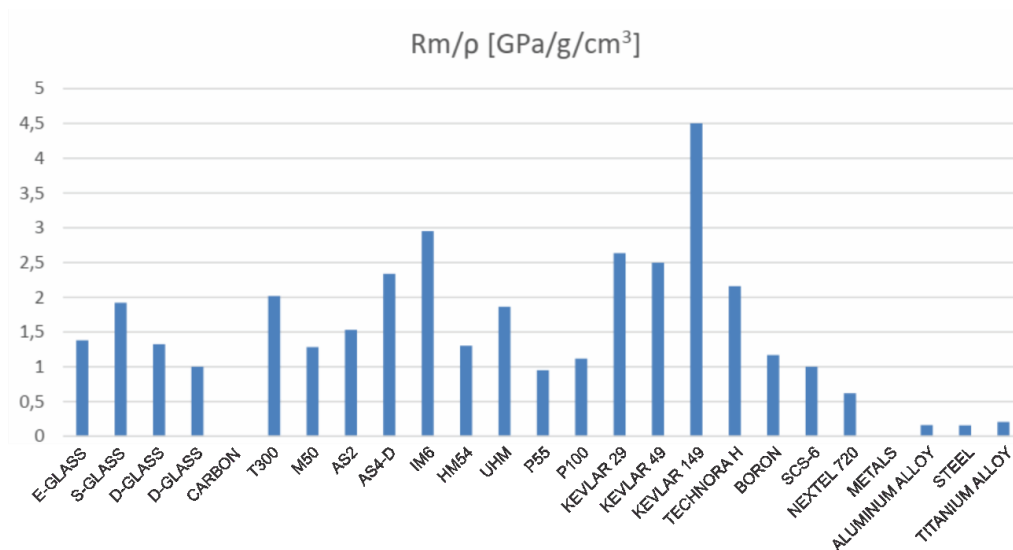


Figure 2-1 Specific dependencies between tensile strength and density of different types of fibers

Due to their small density (ρ), high specific tensile strength (R_m/ρ) (Figure 2-1), and high specific elasticity modulus (E/ρ) (Figure 2-2), composite materials (Table 2-1) are at a great advantage over “classic” metal materials such as aluminum, steel, and titanium commonly used in aircraft production (Table 2-2).

Table 2-1 Physical and mechanical properties of some fibers used in composites

FIBER TYPE	ELASTICITY MODULUS [GPa]	TENSILE STRENGTH [GPa]	COMPRES. STRENGTH [GPa]	ELONGATION [%]	DENSITY [g/cc]	LONGITUDINAL THERMAL EXPANSION [10-6/°C]	TRANSVERSAL THERMAL EXPANSION [10-6/°C]	POISSON COEFFICIENT	THERMAL CONDUCTION [W/m/°C]	MAXIMUM OPERATING TEMP. [°C]	RESISTANCE [micro ohm·m]
E-GLASS	72,345	3,45	-	4,4	2,5-2,59	5,04-5,4	-	0,22	1,05	550	-
S-GLASS	85	4,8	-	5,3	2,46-2,49	1,6-2,9	-	0,22	1,05	650	-
D-GLASS	69	3,31	-	4,8	2,56	6,3	-	-	1,05	600	-
D-GLASS	55	2,5	-	4,7	2,14	3,06	-	-	-	477	-
CARBON											
T300	230	3,53	-	1,5	1,75	-0,6	7,0-12	0,2	3,06	-	18
M50	490	2,45	-	0,5	1,91	-	-	-	54,43	-	8
AS2	227	2,756	-	1,3	1,8	-	-	-	8,1-9,3	-	15-18
AS4-D	241	4,134	-	1,6	1,77	-0,9	-	-	8,1-9,3	-	15-18
IM6	275,6	5,133	-	1,73	1,74	-	-	-	8,1-9,3	-	15-18
HMS4	317	2,343	-	0,8	1,8	-	-	-	64-70	-	9,0-10
UHM	441	3,445	-	0,8	1,85	-	-	-	6,5	-	120
P55	379	1,9	-	0,5	2	-1,3	-	-	120	-	8,5
P100	758	2,41	-	0,32	2,16	-1,45	-	-	520	-	2,5
KEVLAR 29	62	3,792	-	-	1,44	-	-	-	-	-	-
KEVLAR 49	131	3,62	0,72	2,8	1,45	-2	59	0,35	0,04	160	-
KEVLAR 149	179	6,62	0,69	1,9	1,47	-	-	-	-	-	-
TECHNORA H	70	3	0,6	4,4	1,39	-6	59	0,35	-	160	-
BORON	400	2,7-3,7	6,9	0,79	2,57	4,5	0,2	0,2	38	315	-
SCS-6	427	2,4-4	-	0,6	3	4-4,8	-	0,2	10	-	-
NEXTEL 720	260	2,1	-	-	3,4	6	-	-	-	1200	-

Table 2-2 Physical and mechanical properties of some metals

MATERIAL	ELASTICITY MODULUS [GPa]	TENSILE STRENGTH [MPa]	DENSITY [g/cm ³]
ALUMINIUM	69	450	2,8
STEEL	200	1230	7,87
TITANIUM	110	926	4,5

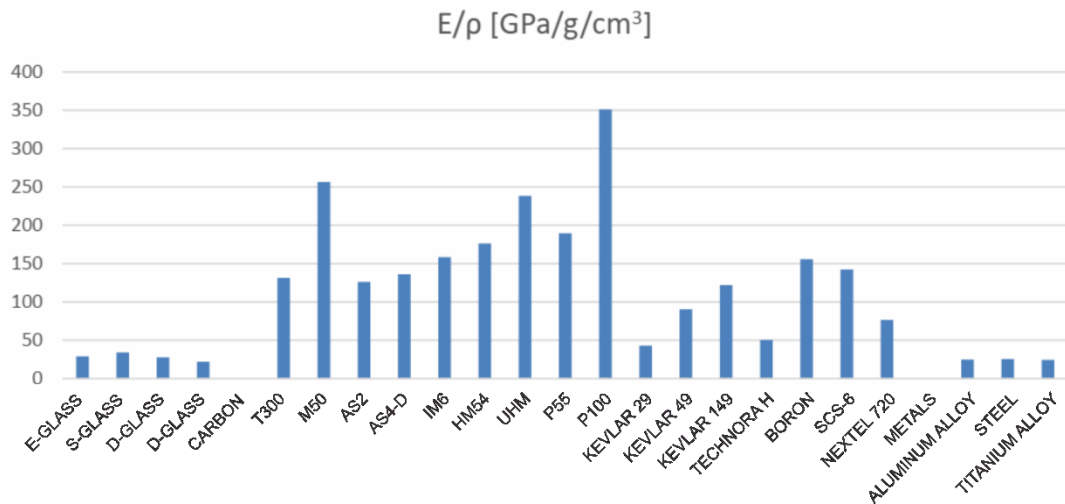


Figure 2-2 Specific dependencies between elasticity modulus and density of different types of fibers

2.1.2 Matrix properties

The matrix joins reinforcement elements (fibers or particles) in one assembly and transfers the majority of loads to them. Also, its purpose is to protect fibers or particles from the external environment and mechanical abrasion and to carry the part of load. Working temperature is one of the characteristics that has the biggest effect on the choice of composite material constituents. Commonly, matrices are of small density, strength, and rigidity when compared to fibers or particles. With the proper combination of the fibers and the matrix, high strength and rigidity with low density of composite material can be obtained. Matrices can consist of polymers, metals, ceramics, or even carbon. The most commonly used matrices in the aerospace industry are polymers. Their advantage is the simplicity of the production: even the most complex construction elements can be formed relatively easily. However, the costs of making molds could sometimes be high. The polymer matrices can be thermoplastic or thermoset materials (Table 2 3). The most common thermoplastic matrices are nylon, polyethylene, and polysulfide. These matrices can be formed after heating. The thermoset matrices have the biggest use in industry due to the ease of production and low price. This subgroup of matrices includes epoxy, phenol, and polyamide resins. They cannot be formed after hardening unlike thermoplastic matrices.

Table 2-3 Characteristics of polymer matrices

MATRIX TYPE	TENSILE ELASTICITY MODULUS [GPa]	TENSILE STRENGTH [MPa]	COMPRESS. STRENGTH [MPa]	TENSILE ELONGATION [%]	BENDING MODULUS [GPa]	BENDING STRENGTH [MPa]	SHEAR STRENGTH [MPa]	POISSON COEFFICIENT	THERMIC EXPANSION [10 ⁻⁶ /°C]	MAXIMUM OPERATING TEMP. [°C]	DENSITY [g/cc]
THERMOSETS											
POLYESTER											
ORTHOPHTHALIC	3,4	55,2	-	2,1	6,9	220,7	-	0,38	-	-	-
ISOPHTHALICBPA	3,4	75,9	177,2	3,3	7,6	241,4	75,9	0,38	30	-	-
FUMARATE	2,8	41,4	103,5	1,4	9	158,6	-	0,38	-	-	-
CHLORENDIC	3,4	20,7	103,5	-	9,7	193,1	-	0,38	-	-	-
VINYL ESTER											
DERAKANE 411-45	3,4	82,7	117,1	5,0-6,0	3,1	124	82,7	0,38	-	-	-
EPOXY											
9310/9360 on23°	3,12	75,8	-	4	-	-	-	0,38	54	185	1,2
9310/9360 on 149°	1,4	26,2	-	5,2	-	-	-	-	-	185	1,2
9420/9470 (A) on 23°	2,66	57,2	-	3,1	-	-	-	-	-	195	1,162
9420/9470 (B) on 23°	2,83	77,2	-	5,2	-	-	-	-	-	155	1,158
HPT1072/1062-Mon 23°	3,383	-	-	-	3,83	131	-	-	-	239	-
THERMOPLASTIC											
PEEK	3,24	100	-	50	-	-	-	0,4	47	143	1,32
PPS	3,3	82,7	-	5	-	-	-	0,37	49	90	1,36
PSUL	2,48	70,3	-	75	-	-	-	0,37	56	190	1,24
PEI	3	105	-	60	-	-	-	0,37	56	217	1,27
PAI	2,756	89,57	-	30	-	-	-	0,37	56	243	1,4
K-III	3,76	102	-	14	-	-	-	0,365	-	250	1,31
LARC-TPI	3,72	119,2	-	5	-	-	-	0,36	35	264	1,37

2.1.3 Multilayered composite materials

Multilayered composite materials are made of *laminas* (thin layers with unidirectional fibers) that are bonded one over the other to create *laminates*, as shown in Figure 2-3. To define and analyze the properties of laminates, two coordinate systems are usually adopted: **local coordinate system** 1-2-3 in which the direction of the fiber is aligned to axis 1 while the direction perpendicular to the fibers is aligned to axis 2, and **global coordinate system** x- y- z, used as reference coordinate system (Figure 2-3). Axes 1 and 2 are usually called *principal material axes*.

It is well known that in most applications engineers work with 3 basic types of materials. Isotropic materials (Figure 2-4a) have the same properties in all directions and are almost completely defined with two of three basic elasticity coefficients:

- Elasticity modulus (E),
- Shear modulus (G), and

- Poisson coefficient (ν).

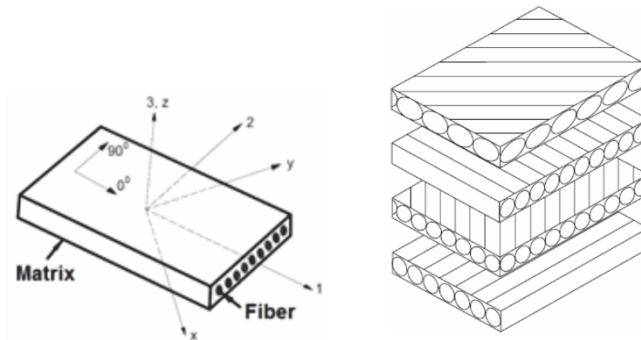


Figure 2-3 Coordinate systems of multilayered composite (laminate)

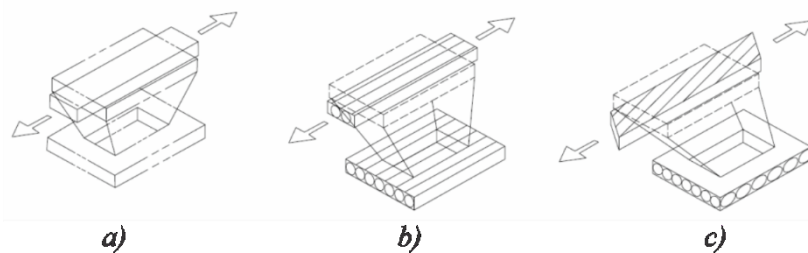


Figure 2-4: a) Isotropic material; b) orthotropic material; c) anisotropic material

On the other hand, orthotropic materials (Figure 2-4b) have three mutually perpendicular planes of material symmetry. *The lamina*, as a basic building block of multi-layered composites, *is usually considered an orthotropic material*.

For plane stress cases, orthotropic materials can be described by four basic elasticity coefficients:

- Elasticity modulus in fibers direction (E_1),
- Elasticity modulus in a direction perpendicular to fibers (E_2),
- In-plane Shear modulus (G_{12}), and
- The major Poisson ratio (ν_{12}).

Orthotropic materials have twice as many independent elasticity coefficients as isotropic materials due to different characteristics in the planes of symmetry. Furthermore, many multilayered composite constructions may exhibit anisotropic material behavior. Unlike isotropic and orthotropic materials, anisotropic materials (Figure 2-4c) have different properties in arbitrarily chosen directions. If orthotropic

material is loaded in a direction that does not overlap with any of the principal material axes, then that orthotropic material will behave as an anisotropic material.

However, methods for the design and analysis of anisotropic material are more complex than methods used for orthotropic materials. Besides the right choice of layering sequence which can enhance (or reduce) anisotropic behavior, there is a problem with stress and safety margins definition. It is important to emphasize that the main task of composite structure designers is to enable optimal layering sequences for predefined loads and predict deformations and stresses under that load. Deformations and stresses are calculated based on layering sequences. Thus, it seems reasonable to consider composite material orthotropic in this thesis since assumed anisotropic behavior could lead to numerous problems in design. The goal is to choose optimal layering sequences leading to laminate properties that fulfill the requirements of strength and rigidity.

2.2 Composite material analysis

Methods of mechanical testing of composite materials are based on procedures defined by ASTM standards. Since the mechanical properties of composite as heterogeneous material are sensitive to the production process, mechanical testing has significant importance in establishing the true characteristics of the produced composite.

However, from the point of view of analytical and numerical analysis, composites can be examined from two aspects:

- Micromechanics – examination of mutual influence of fibers and matrix based on constituents' behavior so mechanical behavior of the lamina can be estimated. Micromechanics creates relations between the properties of fibers and matrices on one side and the composite lamina on the other side. This method is mainly used for the determination of physical characteristics of material (like density, modulus of elasticity, etc.)
- Macromechanics – determination of properties of multilayered composite (laminate). Examination of the mechanical behavior of multilayered composite is based on the known behavior of each layer. Macromechanics establishes dependency between layer characteristics and multilayered composite as a whole. It is based on the continuum mechanics which considers each layer homogenous and orthotropic. However,

experiments are necessary for the verification of the properties of the composite obtained using macromechanics.

2.2.1 Micromechanical analysis

Here, a typical approach used in the micromechanical analysis will be presented through an example. This approach connects longitudinal and transversal characteristics of unidirectional composite with characteristics of the chosen fiber and matrix. Equations used to determine the longitudinal modulus of elasticity and strength of the material are obtained based on *a general rule of mixtures* (weighted mean) [47]. The approach starts with a determination of the volume fraction of fibers.

The volume fraction of fibers is calculated using formula:

$$V_f = \frac{w}{\rho_f \cdot t} = \frac{163}{2500 \cdot 0.11} = 0,6 \quad (2.1)$$

where w is surface density of fibers (Table 2-4),

$$w = 163 \left[\frac{\text{g}}{\text{m}^2} \right]$$

ρ_f is density of fibers (Table 2-4),

$$\rho_f = 2500 \left[\frac{\text{kg}}{\text{m}^3} \right]$$

and t is thickness of fibers (Table 2-4):

$$t = 0,11 \text{ [mm]}$$

(Note: In this example, properties of fiber and matrix used were taken from the database of available materials in the company where the engine cover was produced).

Now, the volume fraction of matrix will be:

$$V_m = 1 - V_f = 0,4 \quad (2.2)$$

The elasticity modulus of fibers in direction 1 is (Table 2-4)

$$E_{f1} = 19[\text{GPa}]$$

while the elasticity modulus of fibers in direction 2 is (Table 2-4)

$$E_{f2} = 18[\text{GPa}]$$

Since the elasticity modulus of matrix (Table 2-4) is

$$E_m = 3,1[\text{GPa}]$$

the elasticity modulus of lamina in direction 1 can be calculated as follows:

$$E_1 = E_f \cdot V_f + E_m \cdot V_m = 12,64[\text{GPa}] \quad (2.3)$$

The elasticity modulus of lamina in direction 2:

$$E_2 = E_m \cdot \left[\frac{1+\xi \cdot \eta \cdot V_f}{1-\eta \cdot V_f} \right] = 8,55[GP a] \quad (2.4)$$

where η and ξ are empirical parameters:

$$\eta = \frac{\left(\frac{E_{f2}}{E_m}\right)^{-1}}{\left(\frac{E_{f2}}{E_m}\right)^{-1} + \xi} = 0,62 \quad (2.5)$$

$\xi = 2$ for fibers of circular and square cross-section.

Poisson coefficient v_f of fibers is taken from Table 2-4:

$$v_f = 0,22$$

as well as Poisson coefficient of matrix (Table 2-6):

$$v_m = 0,38$$

The major Poisson coefficient of lamina is then calculated using equation:

$$v_{12} = v_f \cdot V_f + v_m \cdot V_m = 0,28 \quad (2.6)$$

The shear modulus of fibers is:

$$G_f = \frac{E_{f1}}{2 \cdot (1+v)} = 7,79 [GP a] \quad (2.7)$$

while the shear modulus of matrix:

$$G_m = \frac{E_m}{2 \cdot (1+v)} = 1,12[GP a] \quad (2.8)$$

In plain shear modulus is given by the following formula:

$$G_{12} = \left[\frac{(1+V_f) + V_m \cdot \frac{G_m}{G_f}}{V_m + (1+V_f) \cdot \frac{G_m}{G_f}} \right] = 2,95[GP a] \quad (2.9)$$

while interlaminar lamina shear modulus can be calculated in the following manner:

$$G_{23} = G_m \frac{V_f + \eta_{23} \cdot (1-V_f)}{\eta_{23} \cdot (1-V_f) + V_f \cdot \frac{G_m}{G_f}} = 2,78[GP a] \quad (2.10)$$

Finally:

$$\eta_{23} = \frac{3-4 \cdot v_m + \frac{G_m}{G_f}}{4 \cdot (1-v_m)} = 0,65 \quad (2.11)$$

$$G_{13} = G_{12} \quad (2.12)$$

and tensile strength will be:

$$F_{1t} = F_{1f} \cdot \left[V_f + \frac{E_m}{E_{f1}} \cdot V_m \right] = 222,86[MP a] \quad (2.13)$$

The equation (2.13) assumes that fiber strain and matrix strain are the same which is true if a connection between them is ideal. However, the strain-to-failure of matrix cannot be achieved in reality since the fibers are more brittle and fail at a lower strain. The matrix itself cannot carry the load after break of the fibers appears.

The constitutional components of composite material considered for an engine cover design in this research were glass fiber and epoxy resin (these fibers and matrix were at the company's disposal at the moment when work on the engine cover started). Fiberglass is woven perpendicularly ($\theta_1=0^\circ$, $\theta_2=90^\circ$), and it is produced by standard **8.4548.60** in accordance with **LN9169**, producer **Interglass**. Epoxy resin is **Araldit M** [48] with hardener type **HY-956**. This resin type joins well with the glass and is used for the production of molds and tools. In the following tables (Table 2-4 and Table 2-5) mechanical properties of fibers are presented, as well as their chemical composition.

Table 2-4 Mechanical properties of weaving

PROPERTY	VALUE	O.M.J.
FIBERS DENSITY	2500	[kg/m ³]
THICKNESS OF LAYER (CYB)	0,18	[mm]
SURFACE MASS	163	[g/m ²]
TENSILE STRENGHT F _{1T}	335	[MPa]
ELASTICITY MODULUS E ₁	19	[GPa]
ELASTICITY MODULU E ₂	18	[GPa]
POISSON COEFFICIENT ν	0,22	
SHEAR STRENGHT F ₁₂	50	[MPa]
SHEAR STRENGHT F ₂₁	45	[MPa]
BENDING STRENGHT F _{11F}	495	[GPa]
BENDING STRENGHT F _{22F}	460	[GPa]

Table 2-5 Chemical composition of glass fiber

CHEMICAL COMPOSITION	SHARE [%]
SILICON – OXIDE	52-56
ALUMINIUM (III) –OXIDE	12-16
BORONE (III) – OXIDE	5-10
SODIUM(I) - OXIDE AND POTASSIUM(I) - OXIDE	0-2
MAGNESIUM(II) – OXIDE	0-5
CALCIUM(II) – OXIDE	16-25
TITANIUM(IV) –OXIDE	0-1,5
IRON(III) – OXIDE	0-0,8
IRON	0,1

Properties of epoxy resin are presented in Table 2-6:

Table 2-6 Mechanical properties of mixed resin

PROPERTY	VALUE	O.M.J.
DENSITY	1200	[kg/m ³]
TENSILE STRENGTH, R _m	55-65	[MPa]
ELONGATION, ε	3-4	[%]
TENSILE ELASTICITY MODULUS, E	2,5-2,8	[GPa]
TENSILE STRENGTH, R _F	85-100	[MPa]
BENDING ELASTICITY MODULUS, E	3-3,3	[GPa]
POISSON COEFFICIENT ν	0,38	

Now, basic theory of multilayered composites known as Classical Lamination Theory (CLT) will be used to establish a connection between stresses, strains and fracture criteria for each individual layer. The CLT is the basic mathematical tool for determining macro-mechanical behavior of composite formed from arbitrary homogenous orthotropic layers. The most common is the two-dimensional theory of multilayered composites while the most complex is the three-dimensional theory of higher order.

Based on definition of plane stress load for orthotropic thin plates in coordinate system (1, 2, 3) (Figure 2-5), Hooke's law can be written in the compact form:

$$\{\varepsilon\} = [S]\{\sigma\} \quad (2.14)$$

or in extended form:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_6 \end{Bmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & 0 \\ 0 & 0 & 1/G_{12} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix} \quad (2.15)$$

where $\nu_{21}/E_2 = \nu_{12}/E_1$.

Similarly:

$$\{\gamma\} = [S^*]\{\tau\} \quad (2.16)$$

$$\begin{Bmatrix} \gamma_4 \\ \gamma_5 \end{Bmatrix} = \begin{bmatrix} 1/G_{23} & 0 \\ 0 & 1/G_{13} \end{bmatrix} \begin{Bmatrix} \tau_4 \\ \tau_5 \end{Bmatrix} \quad (2.17)$$

When $\sigma_3 = \tau_4 = \tau_5 = 0$ only four properties (E_1 , E_2 , G_{12} , and ν_{12}) are needed. When $\sigma_3 = 0$ but τ_4 and τ_5 are not zero, then the additional property G_{23} is needed (also $G_{13} = G_{12}$, Eq. 2.12). $[S]$ is the 3×3 compliance matrix, and $[S^*]$ is the 2×2 intralaminar

compliance matrix [47]. Obviously $S_{11} = 1/E_1$, $S_{22} = 1/E_2$, $S_{12} = S_{21} = -\nu_{12}/E_1$, $S_{66} = 1/G_{12}$, $S_{44}^* = 1/G_{23}$, and $S_{55}^* = 1/G_{13}$.

The inversion of the matrix [S] gives the following equation:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix} = \begin{bmatrix} E_1/\Delta & \nu_{21}E_2/\Delta & 0 \\ \nu_{21}E_2/\Delta & E_2/\Delta & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_6 \end{Bmatrix} \quad (2.18)$$

where $\Delta = 1 - \nu_{12}\nu_{21} = 1 - \nu_{12}^2 E_2/E_1$. Similarly for matrix [S*]:

$$\begin{Bmatrix} \tau_4 \\ \tau_5 \end{Bmatrix} = \begin{bmatrix} G_{23} & 0 \\ 0 & G_{13} \end{bmatrix} \begin{Bmatrix} \gamma_4 \\ \gamma_5 \end{Bmatrix} \quad (2.19)$$

which in compact form can be written as:

$$\{\sigma\} = [Q]\{\varepsilon\}$$

$$\{\tau\} = [Q^*]\{\gamma\}$$

where [Q] is the 3×3 reduced stiffness matrix and [Q*] is the 2×2 intralaminar stiffness matrix. However, above stress-strain equations are limited to the case when stresses and strains are oriented along lamina coordinates (1, 2, 3). In practice, it is convenient to relate stresses and strains in laminate coordinates (x, y, z) shown in Figure 2-3. For that purpose, the following equation is used:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad (2.20)$$

where $\bar{Q}_{ij}$ are the coefficients of the transformed reduced stiffness matrix. The detailed derivation of expressions for coefficients $\bar{Q}_{ij}$ is presented in [47]. Here, these equations are given without derivation:

$$\bar{Q}_{11} = Q_{11} \cdot \cos^4\theta + 2 \cdot (Q_{12} + 2 \cdot Q_{66}) \cdot \sin^2\theta \cdot \cos^2\theta + Q_{22} \cdot \sin^4\theta \quad (2.21)$$

$$\bar{Q}_{12} = (Q_{11} + Q_{22} - 4 \cdot Q_{66})\sin^2\theta \cdot \cos^2\theta + Q_{12} \cdot (\sin^4\theta + \cos^4\theta) \quad (2.22)$$

$$\bar{Q}_{22} = Q_{11} \cdot \sin^4\theta + 2 \cdot (Q_{12} + 2 \cdot Q_{66}) \cdot \sin^2\theta \cdot \cos^2\theta + Q_{22} \cdot \cos^4\theta \quad (2.23)$$

$$\bar{Q}_{16} = (Q_{11} - Q_{12} - 2 \cdot Q_{66})\sin\theta \cdot \cos^3\theta + (Q_{12} - Q_{22} + 2 \cdot Q_{66}) \cdot \sin^3\theta \cdot \cos\theta \quad (2.24)$$

$$\bar{Q}_{26} = (Q_{11} - Q_{12} - 2 \cdot Q_{66})\sin^3\theta \cdot \cos\theta + (Q_{12} - Q_{22} + 2 \cdot Q_{66})\sin\theta \cdot \cos^3\theta \quad (2.25)$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2 \cdot Q_{12} - 2 \cdot Q_{66}) \cdot \sin^2\theta \cdot \cos^2\theta + Q_{66} \cdot (\sin^4\theta + \cos^4\theta) \quad (2.26)$$

$$\bar{Q}_{44}^* = Q_{44}^* \cdot \cos^2\theta + Q_{55}^* \cdot \sin^2\theta \quad (2.27)$$

$$\bar{Q}_{55}^* = Q_{44}^* \cdot \sin^2\theta + Q_{55}^* \cdot \cos^2\theta \quad (2.28)$$

$$\bar{Q}_{45}^* = (Q_{55}^* - Q_{44}^*) \cdot \sin\theta \cdot \cos\theta \quad (2.29)$$

where θ is the angle between axis 1 and axis x .

Mechanical properties of the lamina previously determined, using micromechanics equations for uniaxial fibers (Eq. 2.1–2.12), will now be adjusted using the above equations since woven fiberglass was chosen with fibers extending in two mutually perpendicular directions; thus, the angles in this case are $\theta_1=0^\circ$ and $\theta_2=90^\circ$.

For the purpose of finding approximate mechanical properties of selected woven composite, the following assumptions will be used:

- The fibers in direction $\theta_1=0^\circ$ and direction $\theta_2=90^\circ$ separate lamina into two sub-layers of equal thicknesses ($t/2$), and
- Using values obtained with **micromechanical calculations**, coefficients of the stiffness matrix for the unidirectional material can be calculated using the transformed reduced stiffness matrix for $\theta = 0$, i.e. $[Q]_{UNI} = [\bar{Q}]_{\theta=0^\circ}$.

Now, the value Δ and the coefficients of matrices $[Q]$ and $[Q^*]$ can be calculated:

$$\Delta = 1 - \nu_{12}^2 E_2 / E_1 = 1 - 0.28^2 \cdot 8.55 / 12.64 = 0.945 \quad (2.30)$$

$$Q_{11} = \frac{E_1}{\Delta} = \frac{12.64}{0.945} = 13.37 [GPa] \quad (2.31)$$

$$Q_{12} = Q_{21} = \frac{\nu_{12} \cdot E_2}{\Delta} = \frac{0.28 \cdot 8.55}{0.945} = 2.6 [GPa] \quad (2.32)$$

$$Q_{22} = \frac{E_2}{\Delta} = \frac{8.55}{0.945} = 9.04 [GPa] \quad (2.33)$$

$$Q_{66} = G_{12} = 2.95 [GPa]$$

$$Q_{44}^* = G_{23} = 2,78[GPa]$$

$$Q_{55}^* = G_{13} = 2,95[GPa]$$

In the matrix form:

$$[Q]_{UNI} = [\bar{Q}]_{\theta=0^\circ} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} = \begin{bmatrix} 13,37 & 2,6 & 0 \\ 2,6 & 9,04 & 0 \\ 0 & 0 & 2,95 \end{bmatrix} \quad (2.34)$$

$$[Q^*]_{UNI} = [\bar{Q}^*]_{\theta=0^\circ} = \begin{bmatrix} Q_{44}^* & Q_{45}^* \\ Q_{54}^* & Q_{55}^* \end{bmatrix} = \begin{bmatrix} 2,78 & 0 \\ 0 & 2,95 \end{bmatrix} \quad (2.35)$$

As stated above, any lamina is orthotropic in its own coordinate system (1, 2, 3). A lamina is *specialy orthotropic* when it is also orthotropic in the laminate coordinate system (x, y, z) which happens only for orientations $\theta = 0^\circ$ and $\theta = 90^\circ$, or for laminas reinforced with balanced fabrics [47]. In our case lamina is separated in two sub-layers that are mutually perpendicular. Similar to equations (2.34) and (2.35) the stiffness matrix for the unidirectional material can be calculated using the transformed reduced stiffness matrix. This time $\theta = 90^\circ$ since there is a fiber in perpendicular direction. Equations (2.21) to (2.29) are used to calculate the values of coefficients of the transformed reduced stiffness matrix.

Consequently:

$$[Q]_{UNI} = [\bar{Q}]_{\theta=90^\circ} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & 0 \\ \bar{Q}_{21} & \bar{Q}_{22} & 0 \\ 0 & 0 & \bar{Q}_{66} \end{bmatrix} = \begin{bmatrix} 9,04 & 2,6 & 0 \\ 2,6 & 13,37 & 0 \\ 0 & 0 & 2,95 \end{bmatrix} \quad (2.36)$$

$$[Q^*]_{UNI} = [\bar{Q}^*]_{\theta=90^\circ} = \begin{bmatrix} Q_{44}^* & Q_{45}^* \\ Q_{54}^* & Q_{55}^* \end{bmatrix} = \begin{bmatrix} 2,95 & 0 \\ 0 & 2,78 \end{bmatrix} \quad (2.37)$$

After transformed reduced matrices have been determined, we can average them to get the stiffness matrix for the fabric:

$$[Q]_{fabric} = \frac{w}{w} \cdot [\bar{Q}]_{\theta=0^\circ} + \frac{w}{w} \cdot [\bar{Q}]_{\theta=90^\circ} = \begin{bmatrix} 11,21 & 2,57 & 0 \\ 2,57 & 11,21 & 0 \\ 0 & 0 & 2,95 \end{bmatrix} \quad (2.38)$$

$$[Q^*]_{fabric} = \frac{w}{w} \cdot [\bar{Q}^*]_{\theta=0^\circ} + \frac{w}{w} \cdot [\bar{Q}^*]_{\theta=90^\circ} = \begin{bmatrix} 2,86 & 0 \\ 0 & 2,86 \end{bmatrix} \quad (2.39)$$

Based on previously obtained results and above-presented formulae, the mechanical properties have been determined and presented in Table 2-7:

Table 2-7 Calculated fabric's mechanical properties

PROPERTY	VALUE	O.M.J.
ELASTICITY MODULUS E_1	10,62	[GPa]
ELASTICITY MODULUS E_2	10,62	[GPa]
POISSON COEFFICIENT ν_{12}	0,28	
TENSILE STRENGTH F_{1T}	222,86	[MPa]
ELONGATION ϵ_1	2	[%]
PLAIN SHEAR MODULUS G_{12}	2,95	[GPa]
INTERLAM. SHEAR MODULUS $G_{23} = G_{13}$	2,86	[GPa]

Values shown in Table 2- can also be obtained using modern software packages based on the finite element method (FEM). The problem is that most of these packages are commercial and not always available. Besides, the procedure for securing fabric's mechanical properties presented in previous pages shows that off-the-shelf software is not necessary since all required calculations can be implemented through Excel spreadsheets easily and then shared with other people (this is especially important when the job is done within the firm).

However, there are some free FEM-based software like Code Aster which can be used for the micromechanical and macromechanical analyses of defined composite. In section 3.2 the Code Aster was used for estimating the mechanical properties of carbon fiber-epoxy lamina (during the work on the engine cover this combination was also considered; eventually, the decision was made to proceed with the glass fibers).

Nevertheless, "handy" calculations of the mechanical properties of laminate could be challenging, and the FEM-based software is of great value for that purpose. Thus, in Chapter 6 the macromechanical analysis of the fiberglass composite laminates was carried out in Ansys Workbench using lamina's mechanical properties from Table 2-7.

3 Experimental and numerical analyses for composite material characterization

3.1 Experimental analysis

After the analytical analysis of the chosen fabric presented in Chapter 2, experimental analysis was carried out to obtain the actual mechanical properties of the material which then can be used for further numerical analyses, upgrades, and/or quality assurance. However, one must be aware that the experimental results are influenced by several factors including:

- Mechanical properties of components
- Method of production of test specimens
- Testing environment
- Method of fixing the specimen in a testing machine
- Speed of testing
- Temperature
- Humidity
- Volume share of fibers and matrix in laminate, etc.

Tests presented here were performed following ASTM (American Society for Testing and Materials) standards namely:

- Tensile tests, under ASTM 3039,
- Bending tests (three-point bending tests), in accordance with ASTM 7264.

Details regarding these standards can be found on the ASTM website. For example, reference [49] defines the ASTM D7264/D7264M-15 standard.

The mechanical properties of laminate determined using these testing methods are:

- Tensile strength
- Bending strength
- Elasticity moduli.

The manufacturing process was the same for both tensile and bending test specimens and is presented below.

3.1.1 Fabrication of test specimens

Test specimens were made for tensile test (standard ASTM 3039) and three-point bending test (standard ASTM 7264). The manufacturing method used was the same for both. The fabrication method of fiberglass epoxy composite plates was hand layup, using the aluminum mold tool. The tool is comprised of two aluminum parts (upper and lower), along with elements for fiberglass assembling positioned between aluminum parts. The upper and lower plates are tightened by the clamps for better achievement of the required pressure for laminate forming (Figure 3-1).



Figure 3-1 Laminate forming tool

The fabrication process can be divided into several phases:

1. **Tool preparation:** The tool was cleared of all mechanical and chemical impurities. The Teflon plate was placed on the lower part of the aluminum tool to protect it and to ensure easy removal of the composite plate from the tool.
2. **Preparation of the materials used in the fabrication process:** The preparation of structural elements is performed by cutting the fiberglass fabric according to previously determined orientation. Also, the mixing of resin and hardener is performed (ratio 1:5). The Teflon plate was placed on the lower part of the aluminum tool to protect it and to ensure easy removal of the composite plate from the tool.
3. **Production:** Over the Teflon plate positioned in the lower part of the aluminum tool, after being coated with a separator, the required number of layers of fiberglass were

placed, with appropriate fibers' orientations. Along the edge of the assembled fiberglass, two aluminum limiters were positioned to enable the desired thickness of the samples. The leakage of excess resin is achieved from both sides of the tool. On such a prepared base, the mixture of epoxy resin and hardener of a certain ratio is added evenly and material formed in this manner was covered with the upper part of a tool protected with a Teflon plate coated with a release agent. All the time special care was dedicated to preventing the appearance of air bubbles in the material by squeezing out the remaining air with brush and roller. In that manner, better soaking of the glass fibers with resin was achieved, along with better quality of the final product. (Figure 3-2).



Figure 3-2 Assembling of fiberglass in tool

After placing the upper part of tool on the lower part, and tightening the clamps, required pressure for forming was achieved (Figure 3-3). Then, the material was left at room temperature ($\sim 20^\circ$) for 24 hours for the purpose of hardening.



Figure 3-3 Forming of the composite plate in the tool

After the hardening had been finished and the tool opened, the laminate was easily separated from the Teflon plate, and it was checked did obtained surfaces have appropriate quality. As the polymerization process required three days, the obtained composite plate remained at room temperature for that period. After that, samples were cut out from the laminate plate according to the standard test specimens' dimensions (Figure 3-4).



Figure 3-4 The laminate plate used for making the tensile test specimens

3.1.2 Tensile tests

Figure 3-5 shows tensile test specimens produced (in accordance with ASTM 3039 standard) for the purpose of obtaining tensile strength and elasticity modulus of the chosen fiberglass-epoxy composite material (fiber orientation 0°).

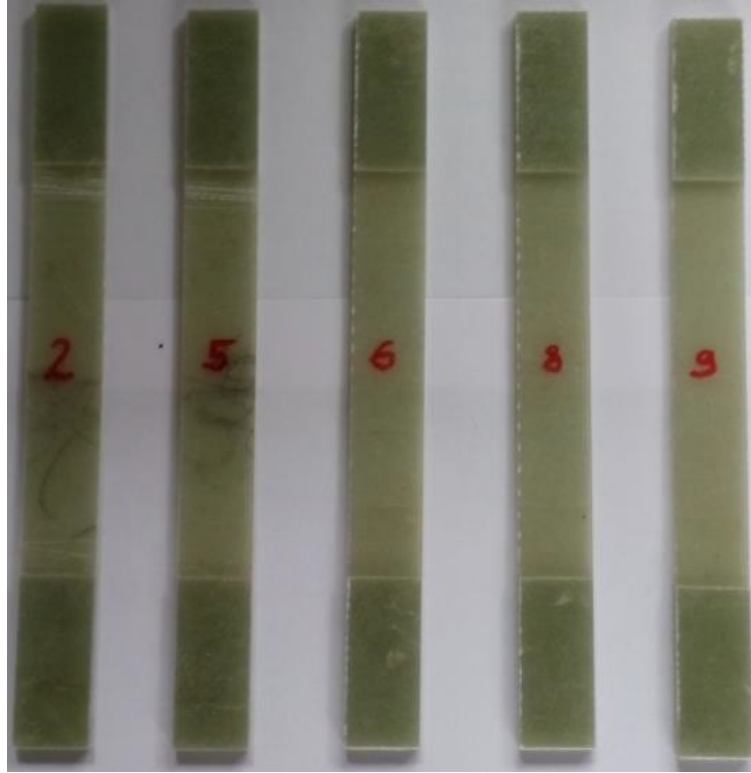


Figure 3-5 Tensile test specimens in accordance with standard ASTM 3039

Dimensions of the tensile test specimens are given in Figure 3-5. Before testing, the width and thickness of specimens were checked with a precision of $\pm 1\%$.

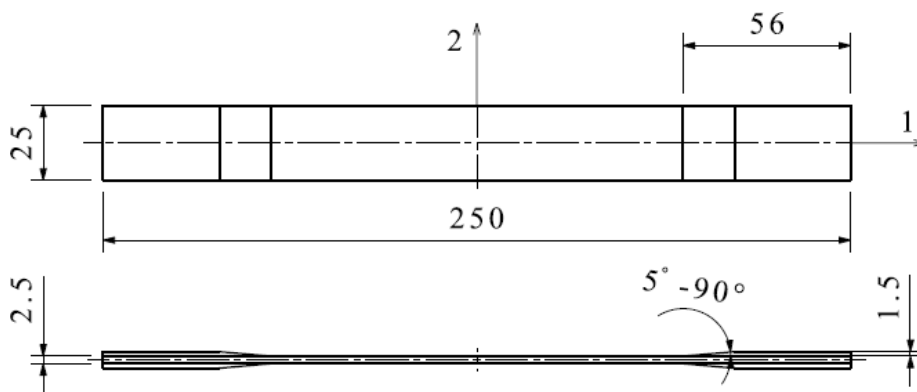


Figure 3-6 Tensile test specimen's dimensions in [mm]

The tensile tests were carried out on a machine SCHENK TREBEL RM 200 (Figure 3-7). During tensile tests, force F and displacement Δl were continually recorded. The range of extensometer measurement was +2.5mm (accuracy ± 0.05 mm), while the load rate was 2 mm/min.



Figure 3-7 Electro-mechanical testing machine SCHENK TREBEL RM 200 (tensile test)

Results of the tensile tests, after standard data processing, are presented in Table 3-1, where MV stands for mean value, SD stands for standard deviation, and CV stands for coefficient of variation.

The tensile strength R_m is calculated according to the equation:

$$R_m = \frac{F_{max}}{b \cdot d} \quad (3.1)$$

where F_{max} is the maximum tear force, b is the width of the test specimen while d is the thickness of the test specimen.

The tensile elasticity modulus E_t can be calculated using the equation:

$$E_t = \frac{\Delta \sigma}{\Delta \varepsilon} = \frac{\Delta F}{\Delta \varepsilon \cdot b \cdot d} \quad (3.2)$$

where σ is the normal stress, and ε is the strain. In this case, the elasticity modulus was determined using the stress-strain diagram created after the experimental data were collected and processed (the strain was calculated using measured values of specimen's

elongation). Using the line of best-fit method (linear regression) the linear correlation between stress and strain was obtained and the gradient of the line was taken as the value of elasticity modulus.

Mechanical properties obtained in tensile tests with 5 specimens showed small spread of values around calculated means with one exception: specimen K-2 strain value at failure was significantly different from other specimens' values (Figure 3-8). The stress-strain graph in Figure 3-8 suggests the omission of results obtained with K-2 since it is obvious that obtained strain during the experiment was not what could be expected and is probably a result of some of the factors mentioned at the beginning of this chapter.

If values obtained in tensile test with specimen K-2 are omitted, to some extent lower mean values are obtained ($E_t = 11.61$ GPa, $R_m = 209.29$ MPa, and $\varepsilon = 2.22\%$).

Table 3-1 Tensile test results.

Specimens n = 5	E_t [GPa]	F [daN]	R_m [MPa]	ε [%]
K-2	12,50	1355,13	218,73	3,17
K-5	12,50	1300,91	217,55	2,28
K-6	11,35	1294,49	208,25	2,21
K-8	11,25	1300,72	204,29	2,19
K-9	11,34	1256,30	207,07	2,21
MV	11,79	1301,51	211,18	2,41
SD	0,65	35,25	6,53	0,42
CV [%]	5,52	2,71	3,09	17,57
Without specimen K-2				
MV	11,61	1288,11	209,29	2,22
SD	0,60	21,41	5,75	0,04
CV [%]	5,13	1,66	2,75	1,76

The fractured specimens (Figure 3-9) show that the brittle fracture of a glass/polymer composite system occurred. However, the same Figure 3-9 indicates that all fractures occurred near the specimens' grips which is – according to the standard ASTM 3039 – a result of a not completely well carried out experiment. The fracture is expected to occur in the middle of the specimen when everything is well done; thus, values presented in Table 3-2 must be taken with caution, but it is reasonable to conclude that they are not far away from actual values.

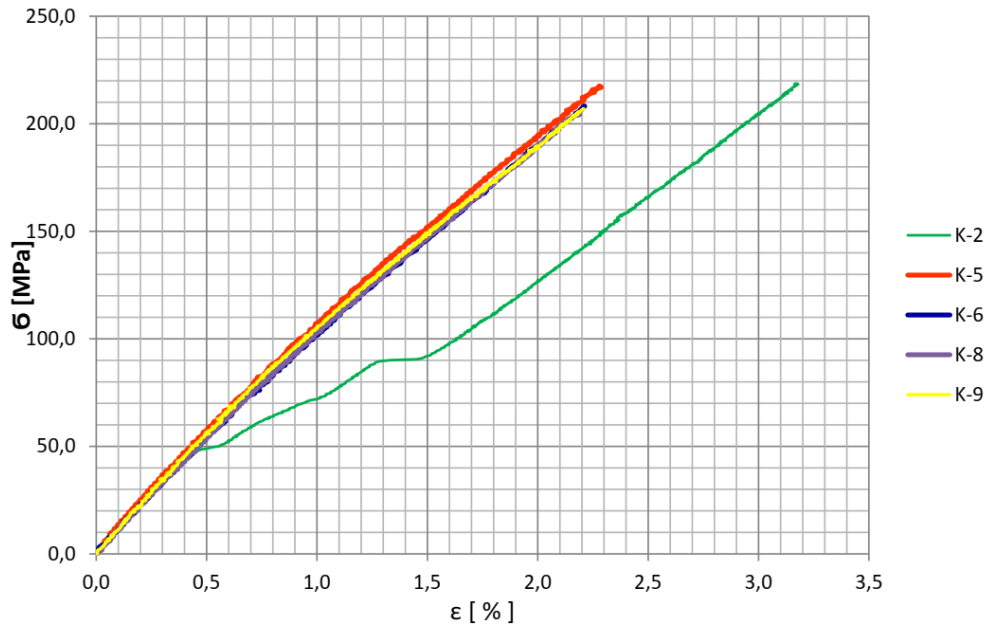


Figure 3-8 Obtained stress-strain diagrams for tensile specimens

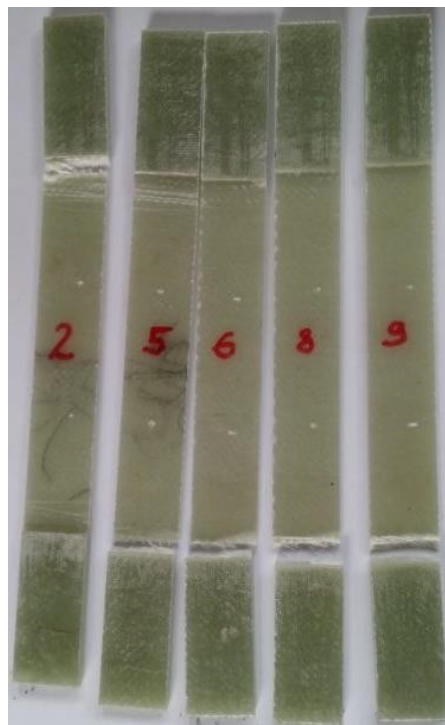


Figure 3-9 Fracture of tensile test specimens

Based on observation of the fractured specimens after experiments, it was arguably assumed that the critical strain state and fracture were the consequence of the separation of connection between fibers and matrix (i.e. debonding). The brittle fractures of fibers

are usually the result of the matrix's “absence”. In that case, the fiber fails immediately since there is nothing around the fiber to “protect” it from fracture.

3.1.3 Bending test

The three-point bending tests were also carried out on the SCHENK TREBEL RM 200 but with a different set-up (i.e. different loading conditions). The set-up can be seen in Figure 3-10.



Figure 3-10 Electro-mechanical testing machine SCHENK TREBEL RM 200 (Bending test)

Contrary to tensile test specimens, the bending specimens were made without grip sections (Figure 3-11).

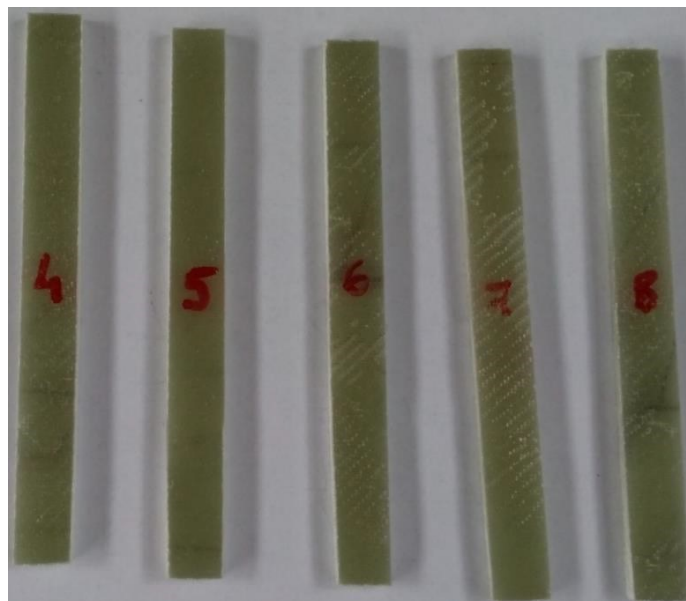


Figure 3-11 Bending test specimens according to standard ASTM 7264

To determine the flexural strength of the chosen glass/polymer combination, the standard ratio of the distance between the supporting pins and specimen thickness was chosen - $L:h=32:1$. The distance between supporting pins was 106.6 mm. The total length of the test specimen was 128 mm (Figure 3-12). Before testing, the width and thickness of the specimen were measured with a precision of $\pm 1\%$. The load was applied through the upper loading pin positioned at the middle of the specimen length.

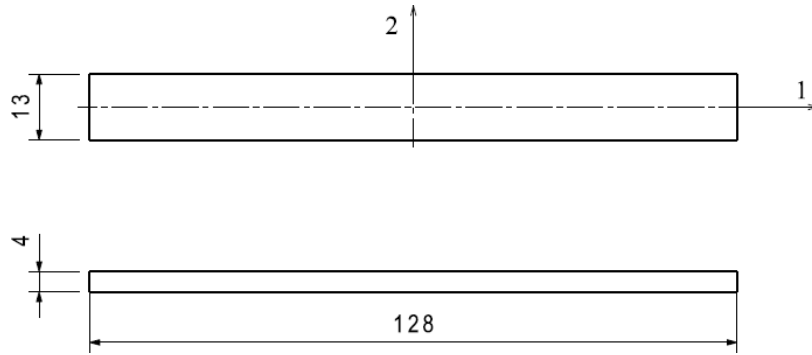


Figure 3-12 Bending test specimen's dimensions [mm]

During the three-point flexural tests, applied force P was continuously monitored, as well as the deflection δ of the specimen, with the same range of extensometer measurement $\pm 2.5\text{mm}$ (accuracy $\pm 0.05\text{ mm}$). The load rate of 2 mm/min was the same as in the previous tests.

The bending strength σ_{smax} at the middle of the specimen's length can be calculated using the equation:

$$\sigma_{smax} = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot h^2} \quad (3.3)$$

where P is the applied force, L is the distance between supports, b is the specimen's length, and h is the specimen's thickness.

The flexure elasticity modulus E_f is calculated using the equation:

$$E_f = \frac{\Delta \sigma_s}{\Delta \varepsilon} \quad (3.4)$$

where σ_s is the normal bending stress while the strain ε and the deflection δ are connected through the equation:

$$\varepsilon = \frac{6 \cdot \delta \cdot h}{L^2} \quad (3.5)$$

The elasticity modulus was, as in the case of tensile tests, determined by using the line of best-fit method (linear regression) applied to the obtained stress-strain diagram. Results of the three-point bending tests are presented in Table 3-3 and in Figure 3-13.

Table 3-3 Bending test results

Specimens	E_f	P	σ_s	δ	ϵ
n=5	[GPa]	[daN]	[MPa]	[mm]	[%]
KC-4	9,32	32,82	252,46	15,40	3,27
KC-5	11,10	34,78	267,54	14,01	2,96
KC-6	11,02	34,59	266,08	14,16	2,99
KC-7	11,42	35,58	273,69	14,03	2,96
KC-8	10,58	32,30	248,46	13,79	2,91
MV	10,69	34,01	261,65	14,28	3,02
SD	0,82	1,39	10,70	0,64	0,14
CV	7,65	4,09	4,09	4,49	4,79

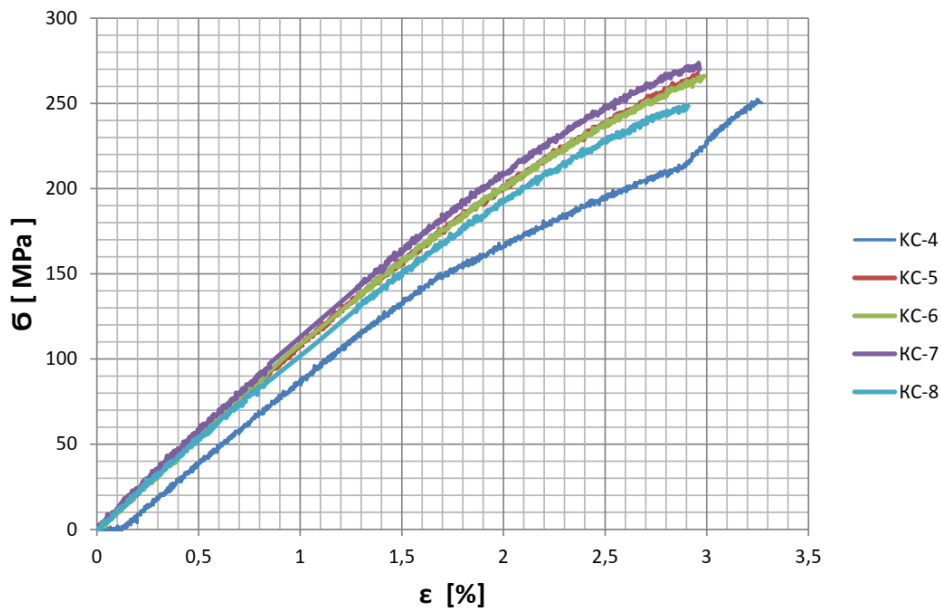


Figure 3-13 Stress-strain diagrams for bending specimens

Figure 3-13 shows that specimen KC-4 exhibited considerable deviation in strain values compared to other specimens (similar to the K-2 specimen in the tensile experiments). By omitting the values obtained with KC-4, the following mean values were obtained: $E_f = 11.03$ GPa, $\sigma_{smax} = 263.94$ MPa, and $\epsilon = 2.95\%$. The fractured

specimens can be seen in Figure 3-14. Fractures occurred in the middle of the specimens as expected.



Figure 3-14 Fracture of bending test specimens

3.2 Numerical analyses of the composite material at low and high temperatures

Since the composite material should be used for designing the engine cover, it is expected that it will be exposed to wide range of temperatures, changing from -18°C , which is the ambient temperature of the outside air, up to 224°C which is the maximum cylinder head temperature during high performance cruise operation [51].

In order to investigate the influence of high and low temperatures on elastic properties of the composite material, micromechanical analysis was performed [52]. Here, micromechanical analysis uses the concept of a representative volume element (RVE) or sometimes referred to as unit cell. An RVE is the smallest portion of the composite material that contains all of constituents (part of the fiber and part of the matrix) and, therefore, is considered as representative of the material as a whole. In this analysis carbon fiber-epoxy composite (commonly named carbon fiber reinforced plastics or CFRP) was used. In order to evaluate elastic properties of CFRP, micro-mechanical analysis of RVE has to be done numerically using the finite element method (FEM). This

method was successfully used for evaluation of elastic properties and strength of different types of structural materials in the presence of porosity [53 and 54] and without it [55].

3.2.1 Modeling procedure

As mentioned in section 2.1.3, the elastic properties of the lamina are usually defined according to principal axes (1, 2, 3) (Figure 3-15). The 1-axis is defined to be parallel to the fibers, the 2-axis is defined to lie within the plane of the plate and is perpendicular to the fibers, and the 3- axis is defined to be normal to the plane of the plate.

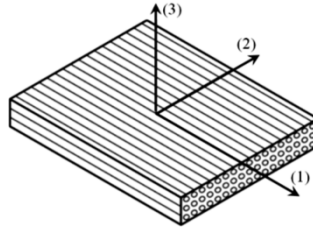


Figure 3-15 Single lamina with principal axes

The fibers are arranged symmetrically about the 1-3 and 2-3 planes. For two-dimensional analysis, elastic properties of composite lamina are usually defined through following constants: modulus of elasticity in direction 1 - E_1 , modulus of elasticity in direction 2 - E_2 , shear modulus in plane 1–2 - G_{12} and major Poisson ratio - ν_{12} , while minor Poisson ratio - ν_{21} is defined through following expression: $\nu_{21} = \nu_{12} E_2 / E_1$. In case of three-dimensional analysis, additional elastic properties are defined through following constants: modulus of elasticity in direction 3 - E_3 ($E_3 = E_2$), shear modulus in plane 2–3 - G_{23} , shear modulus in plane 1–3 (G_{13}), and Poisson ratios - ν_{23} , ν_{32} , ν_{13} , and ν_{31} .

In order to obtain elastic properties of carbon fiber-epoxy composite lamina, a numerical analysis has been performed using Code Aster [56], the open-source finite element analysis software. RVE of carbon fiber-epoxy composite lamina having 60 % volume fraction of fibers is represented through Multi-Phase Unit Cell (MPUC) model as shown in Figure 3-16. MPUC model is modeled as a 3D continuum using FEM and first-order hexahedral elements. The assumptions for constituents (the fiber and the matrix) are:

1. the constituents have linear elastic material properties at given temperature,
2. the fiber is assumed to be a transversely isotropic material, while the matrix is assumed to be an isotropic material,

3. the fiber and the matrix will not fail at the prescribed loads, and
4. the constituents are assumed to be non-porous materials.

Due to the symmetry of the unit cell and the applied loads, as well as adopted isotropic material properties, the models were reduced to one fourth of the unit cell, as shown in Figure 3-16b. Dimensions of reduced unit cells are $5 \times 5 \times 5 \mu\text{m}$ while radius of the fiber is $4.37 \mu\text{m}$.

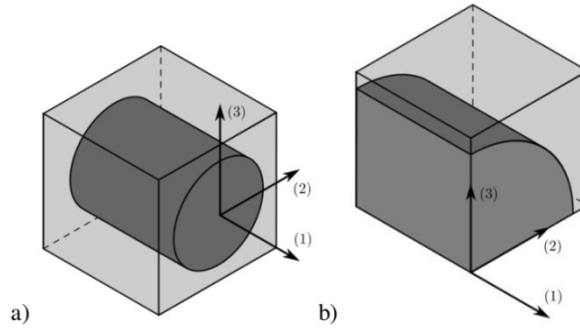


Figure 3-16 Representative volume element: MPUC with 60 % of fiber volume fraction
(a) full size MPUC, (b) one fourth of the MPUC

For carbon fiber, used material properties are assumed to be constant through the full temperature range (from -60°C to 120°C) and are presented in Table 3-4.

Table 3-4 Material properties of analyzed carbon fiber

Properties	Carbon Fiber T300
Longitudinal Young's Modulus E_1 (GPa)	230
Transverse Young's Modulus E_2 (GPa)	15
Longitudinal Shear Modulus G_{12} (GPa)	15
Transverse Shear Modulus G_{23} (GPa)	7
Major Poisson's Ratio ν_{12}	0.2
Transverse Poisson's Ratio ν_{23}	0.07

For epoxy matrix, the modulus of elasticity is temperature-dependent through full temperature range (from -60°C to 120°C) and is adopted from the literature [33], as well as the other material properties. All MPUC models are considered by introducing boundary conditions, which in case of evaluation of modulus of elasticity and Poisson's

ratio, constrains the MPUC to remain in its original shape. The MPUC is loaded in compression along principal directions: 1, 2, 3 respectively. After loading, the sides of the MPUC remain parallel and orthogonal, but there are changes in length. The local coordinate system aligns with the global one. Evaluation of shear modulus involved boundary conditions which forced small shear angle in plane 1–2. In this case, despite the MPUC changed its original shape, it is considered that its volume remains the same.

In order to be easily compared with values at the room temperature (at $T = 20^\circ\text{C}$), all of obtained results for lamina properties, showed in the next figures, are expressed through their normalized values: $\bar{E}$, $\bar{G}$, $\bar{\nu}$. Values obtained in finite element analysis of lamina's mechanical properties at different temperatures showed that the value of elasticity modulus $\bar{E}_1$ is not influenced by temperature change (Figure 3-17).

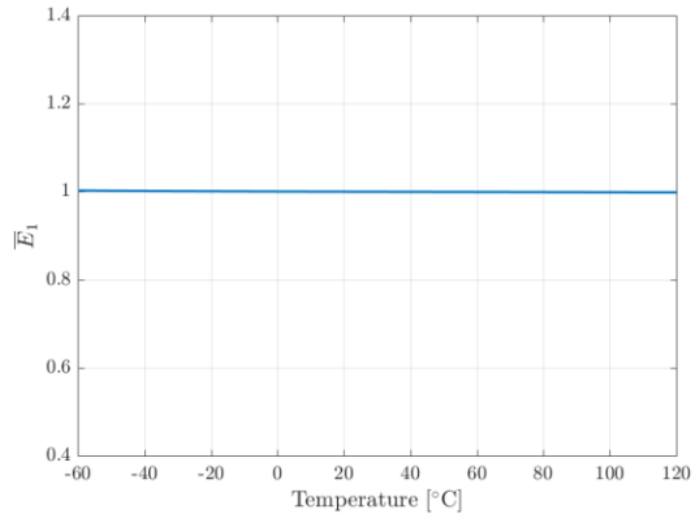


Figure 3-17 Change of normalized $\bar{E}_1$ within temperature range

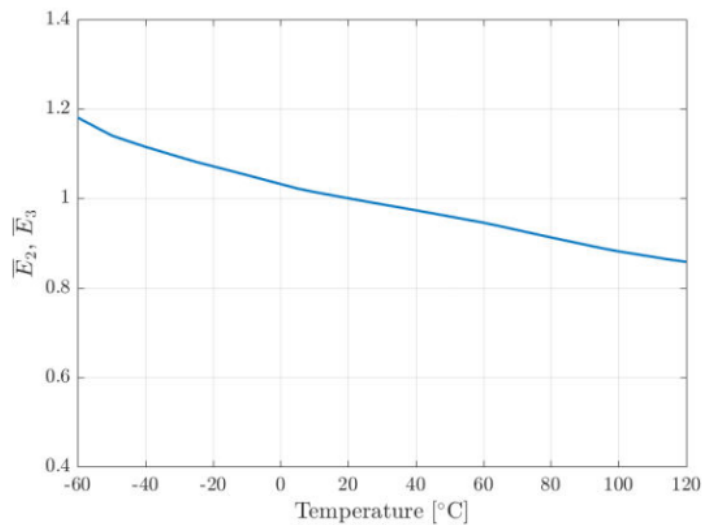


Figure 3-18 Change of normalized $\bar{E}_2$ and $\bar{E}_3$ within temperature range

On the other hand, values of E_2 and E_3 show notable change with the change of environmental temperature (Figure 3-18). With increasing temperature, when the temperature reaches $+120^\circ\text{C}$, values of $\bar{E}_2$ and $\bar{E}_3$ decrease by 15 % when compared with room temperature values. When temperature decreases and reaches -60°C , values of $\bar{E}_2$ and $\bar{E}_3$ are 18 % higher than at the room temperature.

Shear moduli slightly change when the temperature is decreasing (at -60°C values of $\bar{G}_{12}$, $\bar{G}_{13}$ and $\bar{G}_{23}$ are higher by approximately 1%), whereas with an increasing temperature, changes of shear moduli are negligible up to 120°C (Figure 3-19 and Figure 3-20).

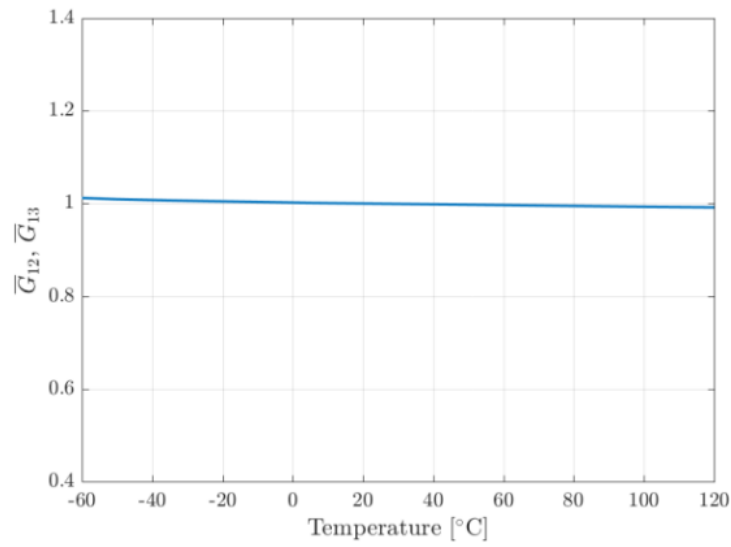


Figure 3-19 Change of normalized $\bar{G}_{12}$ and $\bar{G}_{13}$ within temperature range

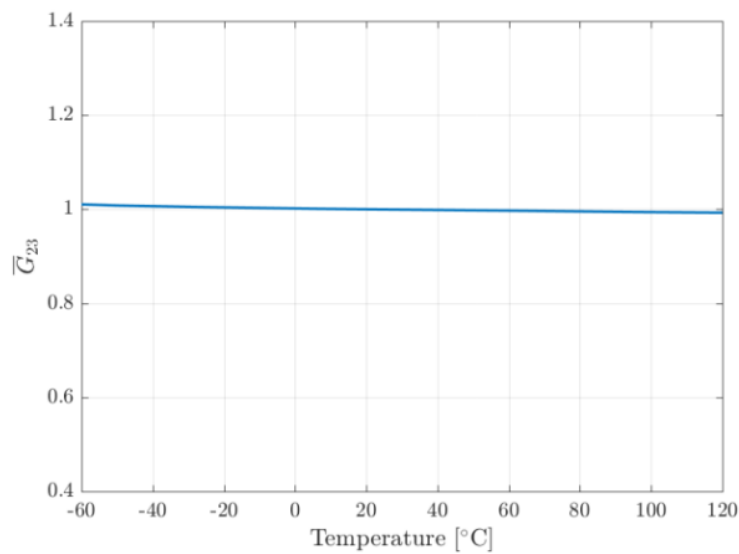


Figure 3-20 Change of normalized $\bar{G}_{23}$ within temperature range

Changes of values of Poisson's ratios ν_{12} and ν_{13} are negligible within temperature range (Figure 3-21), but ν_{23} experiences increase of approximately +4 % when temperature reaches +120°C, and decrease of 7 % when temperature is -60°C (Figure 3-22).

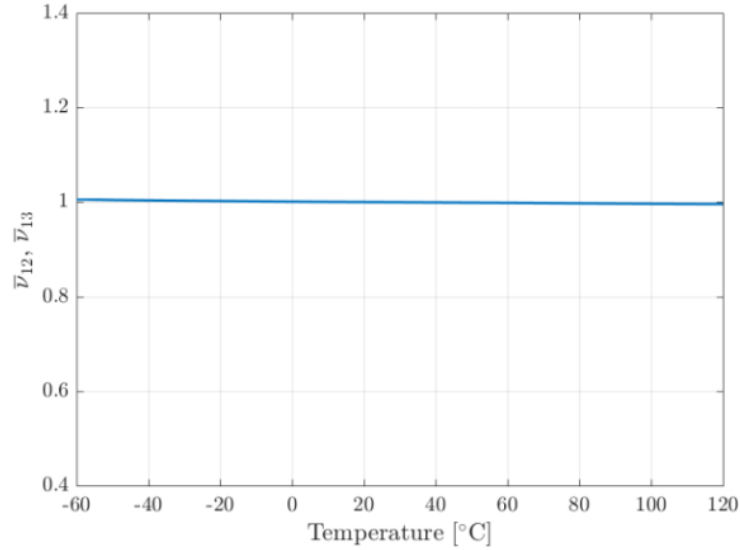


Figure 3-21 Change of normalized $\bar{\nu}_{12}$ and $\bar{\nu}_{13}$ within temperature range

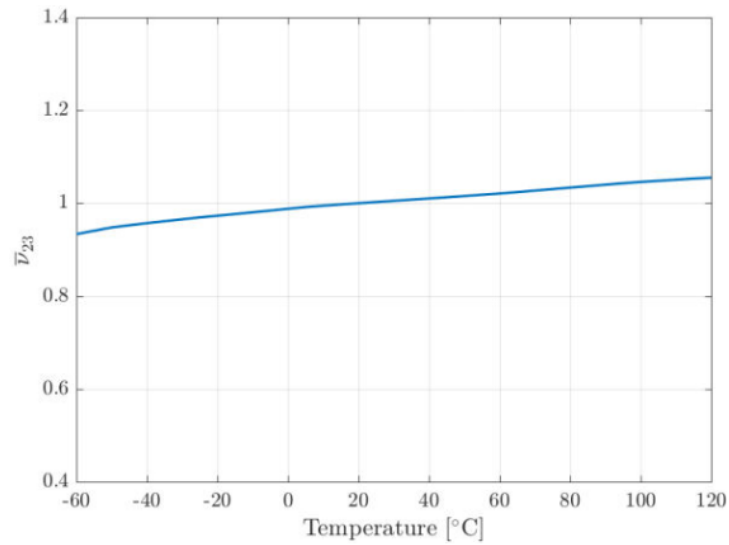


Figure 3-22 Change of normalized $\bar{\nu}_{23}$ within temperature range

In order to quantify the influence of temperature dependent elastic properties on generated thermal stresses, a simple case of an unconstrained carbon fiber-epoxy [0/90/90]_s symmetric laminated plate (6×6 mm) is considered (Figure 3-23).

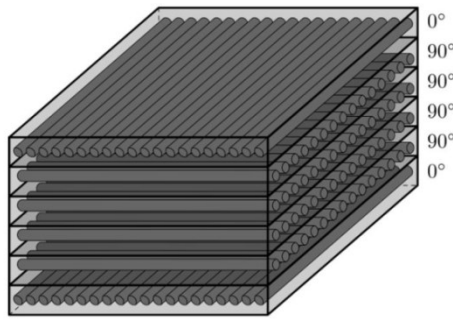


Figure 3-23 Symmetrical laminate with 6 plies (laminas) - $[0/90/90]_s$

Symmetrical lay-ups are widely used in the industry nowadays since geometrical and material symmetry help to avoid thermal twisting of parts as they cool down after curing. In considered laminate, the thickness of each lamina is 0.2 mm. The plate is thermally loaded by different temperature changes, in range from $\Delta T = -80^\circ\text{C}$ (which simulate that laminate is exposed to temperature of -60°C) to $\Delta T = +100^\circ\text{C}$ (which simulate that laminate is exposed to temperature of $+120^\circ\text{C}$). The size of the numerically modeled plate is assumed to be large enough so that the free-edges effects are negligible at the symmetry plane of the plate. Since there are no other external loads, such as external forces and moments, the plate is considered to be stress free at standard (room) temperature of 20°C . Due to the fact that in directions 1 and 2 each lamina has different coefficients of thermal expansion, applied temperature changes induced thermal loads which consequently generated thermal stresses.

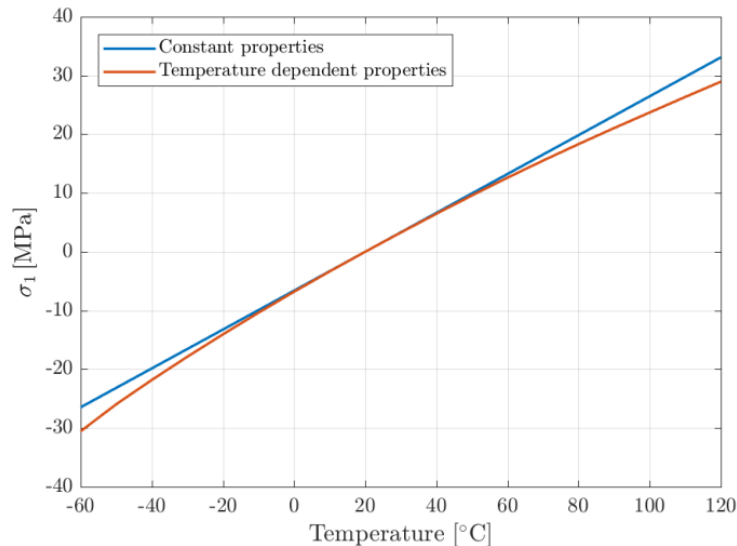


Figure 3-24 Variation of σ_1 with temperature change (values in lamina oriented at 0°)

These thermal stresses have been determined numerically using open-source software Code Aster [56]. Values of obtained stresses in direction 1 (σ_1) and in direction 2 (σ_2), in lamina oriented at 0° , are shown in Figure 3-24 and Figure 3-25.

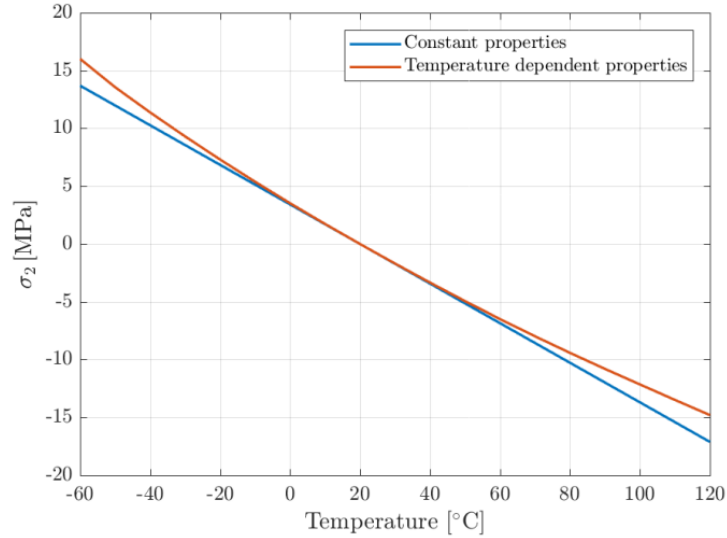


Figure 3-25 Variation of σ_2 with temperature change (values in lamina oriented at 0°)

Mentioned figures show that in case of lamina's temperature-dependent elastic properties values of stresses: σ_1 and σ_2 are different than the values of those stresses calculated with constant material properties (at $T = 20^\circ\text{C}$). These differences are not small and must not be ignored. At -60°C differences between these stresses is 15.4 % for stress σ_1 and 16.9 % for stress σ_2 , while at $+120^\circ\text{C}$ these differences are: 14.3 % for stress σ_1 and 15.6 % for stress σ_2 .

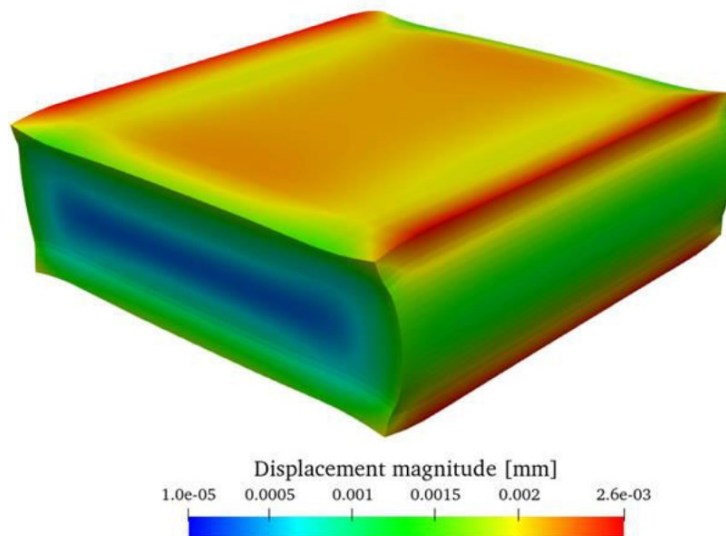


Figure 3-26 Displacement field in lamina (0°) at 120°C (scale factor 100)

Finally, Figure 3-26 shows non-homogenous displacement field of laminate exposed at temperature of +120°C ($\Delta T=100^\circ\text{C}$). As can be seen, since laminate is an anisotropic material, a displacement is not uniform (as can be expected in case of isotropic plate).

Obtained results clearly indicate that in case when lamina properties are temperature dependent, those ones must be considered in composite design process if such composite structure is going to be exposed to considerable temperature changes – extreme operating temperatures.

4 Sizing of engine cooling system

The engine installation has to ensure the engine's maximum performance is obtained within the required working conditions (given by the engine manufacturer), which enables safe and long usage of the engine.

The amount of air used to cool the engine's cylinders, engine supply, and oil radiator are the most important parameters that effect right engine installation. The position and shape of the air intake, as well as the position and size of the outlet opening, greatly influence proper engine cooling.

Engine cooling is achieved by introducing cold air into the area over the engine (Figure 4-1). Obviously, the position of the engine, engine mount, all necessary equipment, and required space for the unobstructed flow of the air will also influence the shape of the engine cover.

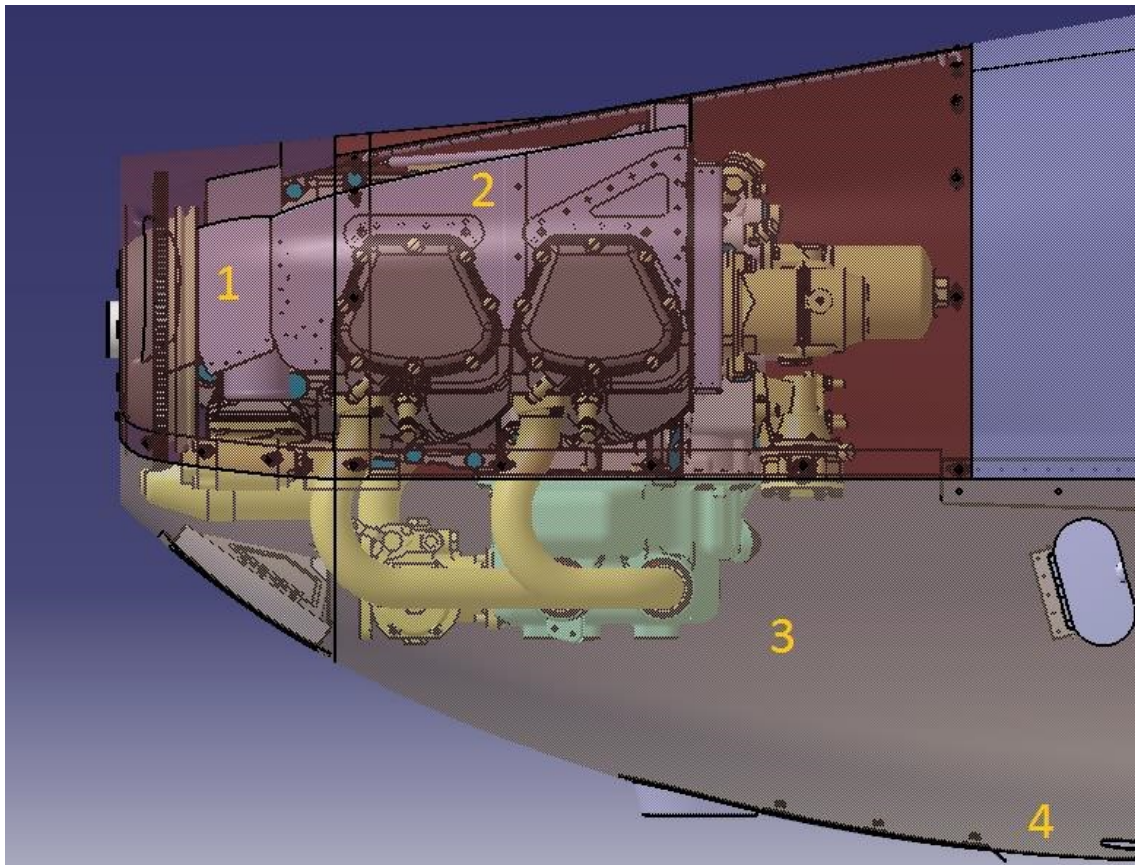


Figure 4-1 Cooling of the engine area inside the engine cover (1- air intake; 2- area of higher pressure; 3- area of lower pressure, and 4- air outlet)

4.1 Calculation of cooling openings on the engine cover

In this part of the thesis, the analysis and dimensioning of the cooling opening on the engine cover are presented. Due to the necessity for the installation of the new improved engine, it is necessary to determine the required surfaces of engine cover openings for engine cooling. The service experience with the aircraft UTVA-75 (designed and built in the seventies of the last century in the same firm) showed the need for detailed analysis and proper opening dimensioning for engine cooling to achieve the optimal working temperature of the engine.

The analytical calculation of the engine cooling openings is conducted. The obtained values were used as input parameters for later computational fluid mechanics (CFD) analysis. The results obtained by analytical and numerical methods are compared and they are presented in this thesis. The elaboration of methods used to dimension the surfaces of a cross-section of the cooling engine openings is also given.

The analysis of the elements in the engine area and beneath the engine cover is conducted to define the required airflow necessary for engine and engine aggregates cooling (oil radiator, alternator, and magnets). Besides, proper airflow to the engine must be provided since the air is necessary for the combustion process too, as well as for the cabin cooling/heating.

Thus, the required quantities of air for the engine operation (and other installations) must be determined first, and based on this result the shape and size of the front cooling opening on the engine cover are determined.

4.1.1 Calculation of the mass air flow for engine cooling

The method of determining the required quantity of air for engine cooling is based on obtaining the mass air flow (MAF) and the pressure drop through the deflector from the diagram provided by the engine manufacturer.

Required air quantity depends on many factors, such as the ambient air temperature T_{amb} , flight height H and engine power P . The diagram in metric units was created according to diagram No.13580 of the engine Lycoming IO-390-A1A6 [51] selected to be used with the new aircraft.

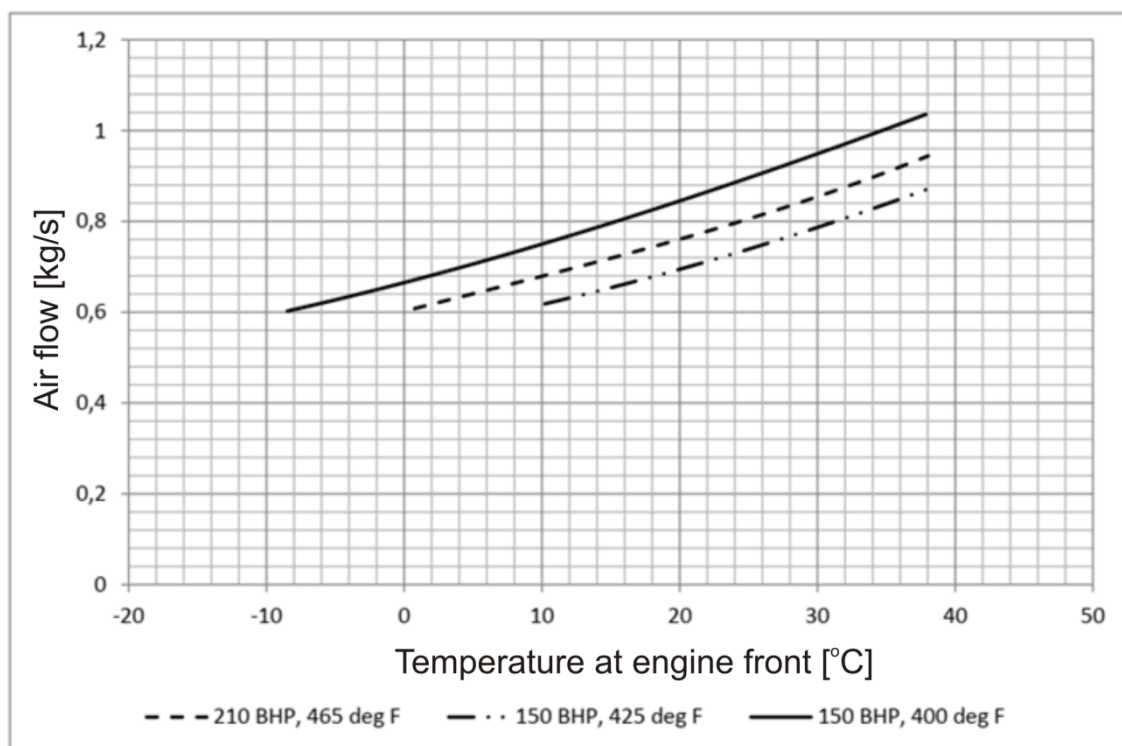


Figure 4-2 Mass air flow change with the temperature (SI units) - engine Lycoming IO-390-A1A6 [51]

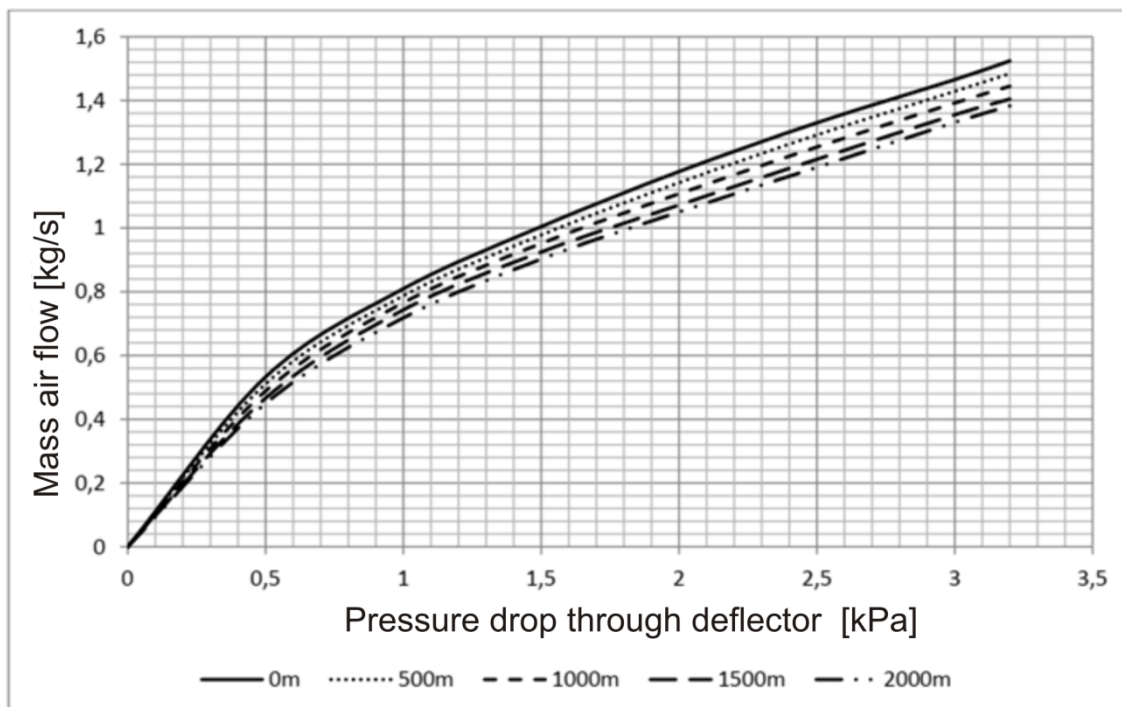


Figure 4-3 Mass air flow change with the pressure drop through deflector (SI units) - engine Lycoming IO-390-A1A6 [51]

Mass airflow (MAF) change with the temperature and change with the pressure drop through the deflector are presented in Figure 4-2 and Figure 4-3, respectively. Values of mass airflow and pressure drop through the deflector are given for the case of climbing (Table 4-1) and for the case of horizontal flight (Table 4-2) for both, summer and winter conditions.

Table 4-1 MAF and pressure drop through the deflector in a case of climbing

H		P	T _{amb}		m _v		Δp _d	
[m]	[ft.]	[BHP]	[°C]	[°F]	[lb/s]	[kg/s]	[in.H2O]	[kPa]
1	2	3	4	5	6	7	8	9
<i>SUMMER CONDITIONS</i>								
0	0	210	38	100,4	2,07	0,94	5,34	1,33
500	1640	210	35	95,0	1,99	0,90	5,22	1,30
1000	3281	210	32	89,6	1,93	0,87	5,06	1,26
1500	4921	210	29	84,2	1,86	0,84	5,02	1,25
2000	6562	210	26	78,8	1,79	0,81	4,94	1,23
<i>WINTER CONDITIONS</i>								
0	0	210	-5	23,0	1,34	0,61	2,49	0,62
500	1640	210	-8	17,6	1,34	0,61	2,61	0,65
1000	3281	210	-12	10,4	1,34	0,61	2,77	0,69
1500	4921	210	-15	5,0	1,34	0,61	2,93	0,73
2000	6562	210	-18	-0,4	1,34	0,61	3,09	0,77

Table 4-2 MAF and pressure drop through the deflector in a case of horizontal flight

H		P	T _{amb}		m _v		Δp _d	
[m]	[ft.]	[BHP]	[°C]	[°F]	[lb/s]	[kg/s]	[in.H2O]	[kPa]
1	2	3	4	5	6	7	8	9
<i>SUMMER CONDITIONS</i>								
500	1640	150	35	95	1,85	0,84	4,54	1,13
1000	3281	150	32	89,6	1,78	0,81	4,42	1,10
1500	4921	150	29	84,2	1,71	0,78	4,38	1,09
2000	6562	150	26	78,8	1,65	0,75	4,30	1,07
<i>WINTER CONDITIONS</i>								
500	1640	150	-8	17,6	1,13	0,51	2,01	0,50
1000	3281	150	-12	10,4	1,10	0,50	2,09	0,52
1500	4921	150	-15	5,0	1,10	0,50	2,21	0,55
2000	6562	150	-18	-0,4	1,10	0,50	2,33	0,58

The calculation of the required air quantity for engine cooling is performed for extreme flight conditions (climbing with maximum engine power) and for cruising (for an altitude range of 500 m to 2000 m). The MAF and the pressure drop through the deflector obtained here will be used for the front opening of the engine cover dimensioning.

4.1.2 Calculation of mass air flow for other requirements

The engine manufacturer has defined permitted temperatures of engine components as following:

- Permitted magnet temperature: $225^{\circ}\text{F} = 107^{\circ}\text{C}$
- Permitted alternator temperature: $360^{\circ}\text{F} = 182^{\circ}\text{C}$

The same air that is used for the engine cooling is to be used for cooling of the above-mentioned devices. For this purpose, the recommended MAF is:

$$\dot{m}_v = 0.03 \frac{\text{kg}}{\text{s}}.$$

For the purpose of cabin heating, design solution predicts usage of the air from the front region of the engine cover. The MAF necessary for heating of cabin space is:

$$\dot{m}_v = 0.05 \frac{\text{kg}}{\text{s}}.$$

For the purpose of oil cooling (for selected oil radiator and predefined oil temperatures) the required MAF is:

$$\dot{m}_v = 0.45 \frac{\text{kg}}{\text{s}}.$$

4.1.3 Dimensioning of the engine cover front opening

Dimensioning of the engine cover front opening for airflow inside the engine area is performed tabularly (Table 4-3). The columns in this table are defined as follows:

- Column 1 – Flight altitude: $H[\text{m}]$
- Column 2 – Engine power: $P[\text{BHP}]$
- Column 3 – Speed in the flight direction: $V \left[\frac{\text{km}}{\text{h}} \right]$
- Column 4 – Speed in flight direction: $v \left[\frac{\text{m}}{\text{s}} \right] = \frac{V}{3.6}$
- Column 5 – Temperature of the outside air – standard atmosphere: $T[^{\circ}\text{C}]$
- Column 6 – Temperature of the outside air: $T[\text{K}] = t + 273.15$

- Column 7 – Ambient temperature of the outside air: $T_a[^\circ\text{C}]$
- Column 8 – Ambient temperature of the outside air: $T_a[K] = t + 273.15$
- Column 9 – Air density – standard atmosphere: $\rho \left[\frac{\text{kg}}{\text{m}^3} \right]$
- Column 10 – Ambient air density: $\rho_a \left[\frac{\text{kg}}{\text{m}^3} \right] = \rho \cdot \frac{T}{T_a}$
- Column 11 – Dynamic pressure at the inlet: $p_{in}[Pa] = \frac{1}{2} \cdot \rho_a \cdot v^2$
- Column 12 – Dynamic pressure at the engine front: $p_{dc}[Pa] = 0,75 \cdot p_{in}$
- Column 13 – Total pressure at the engine front: $p_{tot}[Pa] = P_{amb} + p_{dc}$
- Column 14 – Temperature increase due to charge pressure: $\Delta t[^\circ\text{C}]$
- Column 15 – Temperature on the engine front: $t_c[^\circ\text{C}] = t_a + \Delta t$
- Column 16 – MAF for cooling: $\dot{m} \left[\frac{\text{kg}}{\text{s}} \right]$
- Column 17 – Pressure drop through the deflector: $\Delta p_d[Pa]$
- Column 18 – Overpressure under the engine: $p_2[Pa] = p_c - \Delta p_d$
- Column 19 – Required pressure decrease: $p_d[Pa]$

The requirement is to find a constructive solution that creates under-pressure from outside the engine cover to provide sufficient difference of pressures and enable the airflow through the deflector. This parameter is obtained by calculation of airflow around the “apron” of the engine cover using numerical analysis.

- Column 20 – Temperature under the engine: $t_2[^\circ\text{C}] = t_c + 83,33$
- Column 21 – Temperature under the engine: $T_2[K] = t_2 + 273,15$
- Column 22 – Air density at the outlet: $\rho_2 \left[\frac{\text{kg}}{\text{m}^3} \right] = \rho_a \cdot \frac{T_a}{T_2}$
- Column 23 – Air speed at the outlet: $v_2 \left[\frac{\text{m}}{\text{s}} \right] = \sqrt{\frac{2 \cdot (p_2 - p_{dc})}{\rho_2}}$
- Column 24 – The outlet flow: $\dot{v} \left[\frac{\text{m}^3}{\text{s}} \right] = \frac{\dot{m}}{\rho_2}$
- Column 25 – Area of the outlet opening: $A_2[\text{cm}^2] = \frac{\dot{v}}{v_2} \cdot 10^4$
- Column 26 – Air speed at the inlet: $v_{in} \left[\frac{\text{m}}{\text{s}} \right] = 0,5 \cdot v$
- Column 27 – Required flow at the inlet: $\dot{v}_{in} \left[\frac{\text{m}^3}{\text{s}} \right] = \frac{\dot{m}}{\rho_a}$
- Column 28 – The area of the inlet opening: $A_{in}[\text{cm}^2] = \frac{\dot{v}_{in}}{v_{in}} 10^4$

- Column 29 – The assumed area of the inlet opening – iteration 1: $A_{in1}[m^2]$
- Column 30 – Air speed at the inlet – iteration 1: $v_{in1} \left[\frac{m}{s} \right] = \frac{\dot{v}_{in}}{A_{in1}}$
- Column 31 – Ratio of the inlet speed and speed of horizontal flight (should be between 0,4 – 0,6) – iteration 1: $\Delta v_{in1} = \frac{v_{in1}}{v}$
- Column 32 – The assumed area of the inlet opening – iteration 2: $A_{in2}[cm^2]$
- Column 33 – Air speed at the inlet – iteration 2: $v_{in2} \left[\frac{m}{s} \right] = \frac{\dot{v}_{in}}{A_{in2}}$
- Column 34 – Ratio of the inlet speed and the speed of horizontal flight (should be between 0,4 – 0,6) – iteration 2: $\Delta v_{in2} = \frac{v_{in2}}{v}$

4.1.4 Calculation of cross-section area of air filter

For the calculation of cross-sectional area of air filter, the method of filter manufacturer Brackett Aero Filters will be used.

Filter manufacturer has defined the required quantity of air for the purpose of combustion $\dot{V} = 1500PPH$. Mass flow required for combustion is:

$$\dot{m} = 326,75 \frac{ft^3}{min} = 0,15 \frac{m^3}{s}$$

Flow speed through the air filter is in the range of $600 - 1200 \frac{ft}{min}$. The adopted flow speed through filter is:

$$v = 900 \frac{ft}{min} = 4,12 \frac{m}{s}$$

The ratio of air volume in engine cylinder and working volume of cylinder at cruising is:

$$\frac{\dot{V}_{vaz}}{\dot{V}_{uk}} = 0.7$$

It follows that the required area of cross-section for air filter is:

$$0.7 \cdot \dot{V}_{uk} = 0.7 \cdot \frac{\dot{m}}{v} = 0.7 \cdot \frac{0.15}{4.12} = 0.0255m^2 = 255cm^2$$

Table 4-3 Dimensioning of the engine cover front opening

5 Numerical determination of loads on engine cover during flight

In the last few decades, numerical methods (finite volume and finite element method) became a necessary tool for the analysis of complex structures, especially with computer development.

Computational Fluid Dynamics (CFD), based on finite volume method (FVM) is the part of fluid mechanics that uses numeric analysis in order to solve and analyze the problem of air flow. Computers are used as tools for calculation, and they simulate interaction between fluids and solid boundary for the defined set of boundary conditions.

Basic equations of fluid dynamics are:

- Continuity equation (differential form):

$$\frac{d\rho}{\rho} + \frac{dv}{v} + \frac{dA}{A} = 0 \quad (5.1)$$

- Law of momentum conservation for viscous fluid (Navier-Stokes equations):

$$\rho \frac{Dv_i}{Dt} = \rho \left(\frac{\partial v_i}{\partial t} + v_j \frac{\partial v_i}{\partial x_j} \right) = \rho F_i - \frac{\partial p}{\partial x_i} + \eta \frac{\partial^2 v_i}{\partial x_j^2} \quad (5.2)$$

- Law of energy conservation:

$$\rho \frac{D}{Dt} \left(e + \frac{v^2}{2} \right) = \rho F_i v_i - \frac{\partial}{\partial x_i} (p v_i) + \frac{\partial}{\partial x_i} (v_j \tau_{ij}) - \frac{\partial q_i}{\partial x_i} \quad (5.3)$$

- Second law of thermodynamics:

$$\delta q = T ds \quad (5.4)$$

The aerodynamic load is the main load that engine cover is subjected to. So, CFD will be used for the development of flow field and determination of mentioned aerodynamic load. The CFD analyses were carried out by ANSYS Fluent [57 and 58]. The knowledge of the speed and pressure fields, which is obtained in these analyses, will enable the solution of the problem of additional intake trim under engine cover from the previous chapter.

5.1 Fluid flow modeling

The most frequent form of fluid flow is turbulent fluid flow, whether it is natural or enforced, while the laminar flow represents the exception. In this case the turbulent flow is considered. For the calculation of turbulent flow, the system made of Raynold's equations and continuity equation is applied (in total four equations) [59]. There are ten unknowns: three components of averaged speed, pressure and six turbulent stresses,

which means that there are more unknowns than equations, so this system of equations is not closed. The cause of uncertainties of problems is the time averaging of Navier-Stokes equations where there are additional members of turbulent stresses, six in total, that are unknown. This situation requires that turbulent stresses should be determined, i.e., modelled.

Raynold's equations are made by the transformation of Navier-Stokes equations that represent the equations of averaged turbulent movement of fluids:

$$\rho \left(\frac{\partial \bar{v}_i}{\partial t} + \bar{v}_j \frac{\partial \bar{v}_i}{\partial x_j} \right) = \rho \bar{F}_i - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_i} \left(\eta \frac{\partial \bar{v}_i}{\partial x_i} - \rho \overline{\bar{v}_i \bar{v}_j} \right), \quad (5.5)$$

where $\eta \frac{\partial \bar{v}_i}{\partial x_i}$ represents viscous stresses and $\rho \overline{\bar{v}_i \bar{v}_j}$ represents turbulent stresses.

Averaged equation of continuity for incompressible flow:

$$\text{div } \vec{v} = 0, \quad \text{div } \vec{v} = \frac{\partial \bar{v}_i}{\partial x_i} = \frac{\partial \bar{v}_i}{\partial x_i} + \frac{\partial \bar{v}_i}{\partial x_i} = 0, \quad (5.6)$$

where $\frac{\partial \bar{v}_i}{\partial x_i}$ represents time averaged flow and $\frac{\partial \bar{v}_i}{\partial x_i}$ represents fluctuation flow.

Base system of equations for study of turbulent flow:

$$\rho \left(\frac{\partial \bar{v}_i}{\partial t} + \bar{v}_j \frac{\partial \bar{v}_i}{\partial x_j} \right) = \rho \bar{F}_i - \frac{\partial \bar{p}}{\partial x_i} + \rho \frac{\partial}{\partial x_i} \left(\nu \frac{\partial \bar{v}_i}{\partial x_i} - \overline{\bar{v}_i \bar{v}_j} \right), \quad \frac{\partial \bar{v}_i}{\partial x_i} = 0. \quad (5.7)$$

There are numerous models of turbulence. In this research turbulence model of second order that is based on direct determination of turbulent stresses, more precisely so-called $k - \varepsilon$ model [60] is applied.

5.1.1 $k - \varepsilon$ model

Model $k - \varepsilon$ is the most used as engineer model of turbulence.

Assume that turbulent kinematic viscosity $\nu_t \left[\frac{m^2}{s} \right]$, depends on kinetic energy of turbulence $k \left[\frac{m^2}{s^2} \right]$ and energy dissipation $\varepsilon \left[\frac{m^2}{s^3} \right]$. The dimensional analysis than gives:

$$\nu_t = f(k, \varepsilon) = C_\varepsilon k^a \varepsilon^b \xrightarrow{a=2; \quad b=-1} \nu_t = C_\varepsilon \frac{k^2}{\varepsilon} \quad (5.8)$$

Model coefficient $C_\varepsilon(Re)$ depends on Raynold's number and for turbulence when $Re \rightarrow \infty$ its value is: $C_\varepsilon = C_\eta = 0.09$. This model is also called Lauder-Spalding $k - \varepsilon$ model where two transport equations are required, one for kinetic energy of turbulence k , and the other one for dissipation ε , and this is the reason why this model is called model with

two transport equations. Additional equation for ε is obtained by multiplying Navier-Stokes equations with speed fluctuation and by applying the averaging rule.

So, two transport equations of $k - \varepsilon$ model are obtained:

$$\rho \left(\frac{\partial \varepsilon}{\partial t} + \bar{v}_j \frac{\partial \varepsilon}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} P - \rho C_{\varepsilon 2} \frac{\varepsilon^2}{k}, \quad (5.9)$$

$$\rho \left(\frac{\partial k}{\partial t} + \bar{v}_j \frac{\partial k}{\partial x_j} \right) = P - \rho \varepsilon + \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right], \quad (5.10)$$

where the member of turbulent stresses and gradient of averaged field $P = \rho \overline{v'_i v'_j} \frac{\partial \bar{v}_i}{\partial x_i}$ represents the production of turbulent energy. In standard $k - \varepsilon$ model, the constants in transport equations are:

$$C_\eta = 0.09; \quad \sigma_\varepsilon = 1.3; \quad C_{\varepsilon 1} = 1.44; \quad C_{\varepsilon 2} = 1.92; \quad C_k = 1.$$

These values of coefficient are also used in this research (Figure 5-1).

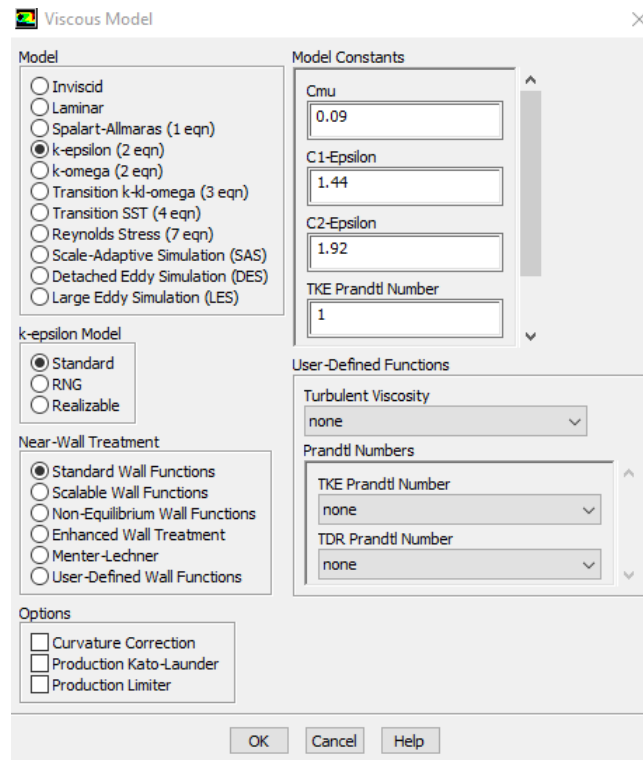


Figure 5-1 Constants for standard $k - \varepsilon$ model

5.2 CFD simulation

The basic approach is the same for each problem. Procedure for the preprocessing is:

- Preparation of the geometry model (physical boundary).

- Determination of the fluid control volume and mesh generation.
- Applying the boundary conditions (behavior of the fluid).

When the computer calculation and simulation is finished, the phase called postprocessing is started. The mentioned phase is used for the analysis and visualization of the obtained results.

5.2.1 Preparation of the geometry model

The geometry model is imported in ANSYS Fluent (CAD model) in order to create the fluid domain where the engine cover analysis is performed. In order to properly model the flow field (with streamlines) around the engine cover, the effect of the fuselage of the aircraft has to be considered. The analyzed fuselage contour includes engine cover, spinner, nose leg and exhaust pipe and it represents the physical boundary between fluid volume and impermeable environment (the wall). The geometry is designed in accordance with the previous chapter, in CATIA program package (Figure 5-2).

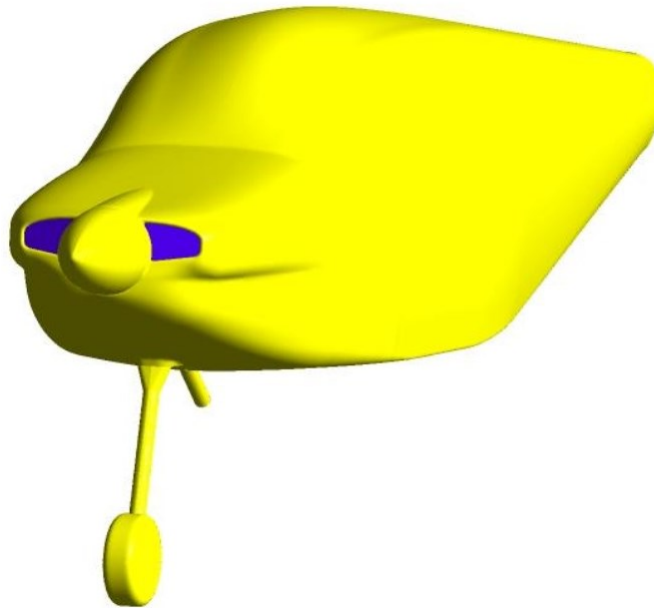


Figure 5-2 CAD model of analyzed fuselage contour

5.2.2 Determination of the fluid control volume and mesh generation

Determination of the fluid control volume is performed in accordance with the recommendations from experience in order to obtain the best results. The half of the fluid domain is modeled due to the assumption of flow field symmetry (Figure 5-3). After

dimensioning of the control volume, the conditions to start making CFD mesh are created. The mesh is created in ANSYS-Mesh workbench tool using tetrahedron cells.

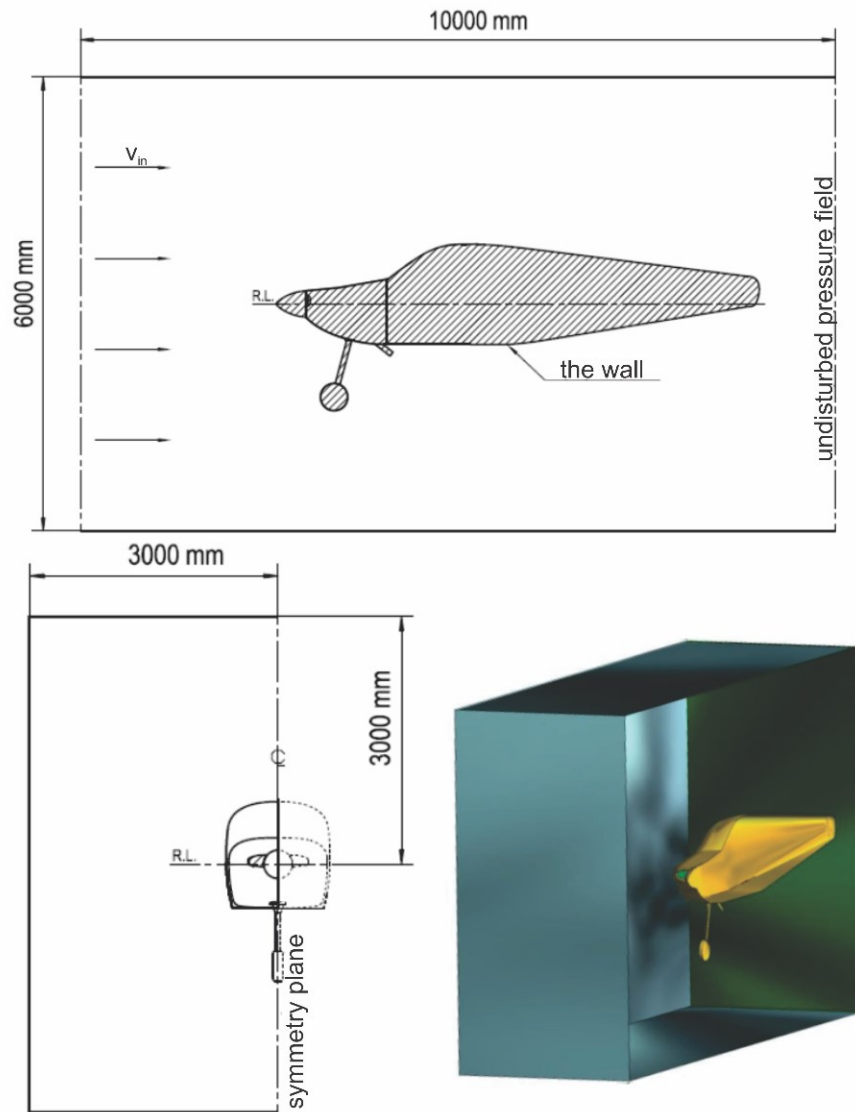


Figure 5-3 Fluid control volume

The automatic mesh generation created 628 002 cells. Mesh quality checking is necessary in order to avoid problems in simulations. This feature is a part of the Global Mesh Controls and represents so-called rough tuning which is applied to the whole mesh. After rough tuning the mesh cells are automatically optimized. Next, the local mesh improvement can be applied if needed. This is carried out through the Local Mesh Controls.

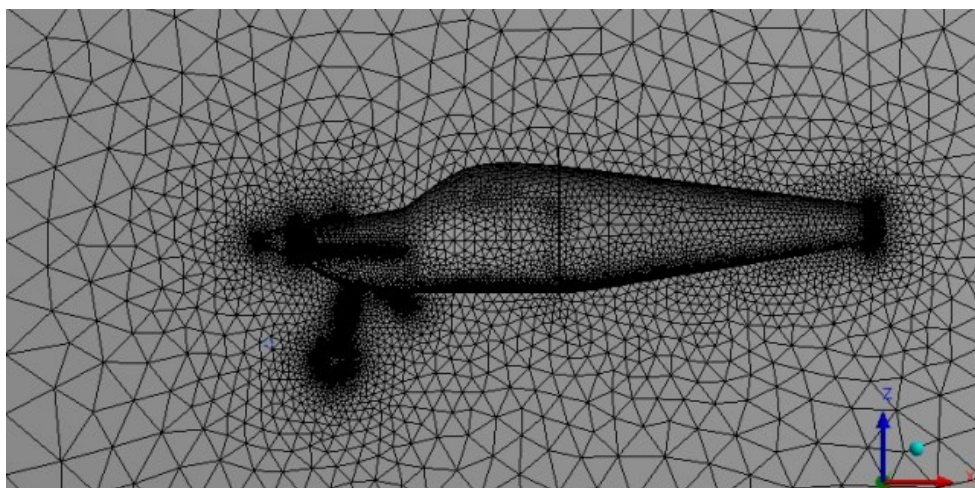


Figure 5-4 Automatically generated mesh

In Figure 5-4 it can be seen that the improvement of mesh is required in the proximity of the body, especially on the areas with complex geometry. For that reason, the uniform cell size of 15 mm on the surface of the body on areas with complex geometry was adopted by using the option Sizing. The boundary layer near the wall was also adopted by using the option Inflation.

The properties of the fluid control volume and mesh can be seen in the Table 5-1.

Table 5-1 The properties of the fluid control volume and mesh

Basic geometric measures		
length	10 m	
width up to CL^1	3 m	
height	6 m	
fluid volume	177,4 m ³	
engine cover volume	2,6 m ³	
statistics	<i>fine</i>	<i>rough</i>
number of nodes	566.936	115.026
number of cells	2.084.860	628.002

The difference between fine and rough mesh can be seen in Figure 5-5.

¹ The central line is marked as CL. It represents symmetry plane of the aircraft.

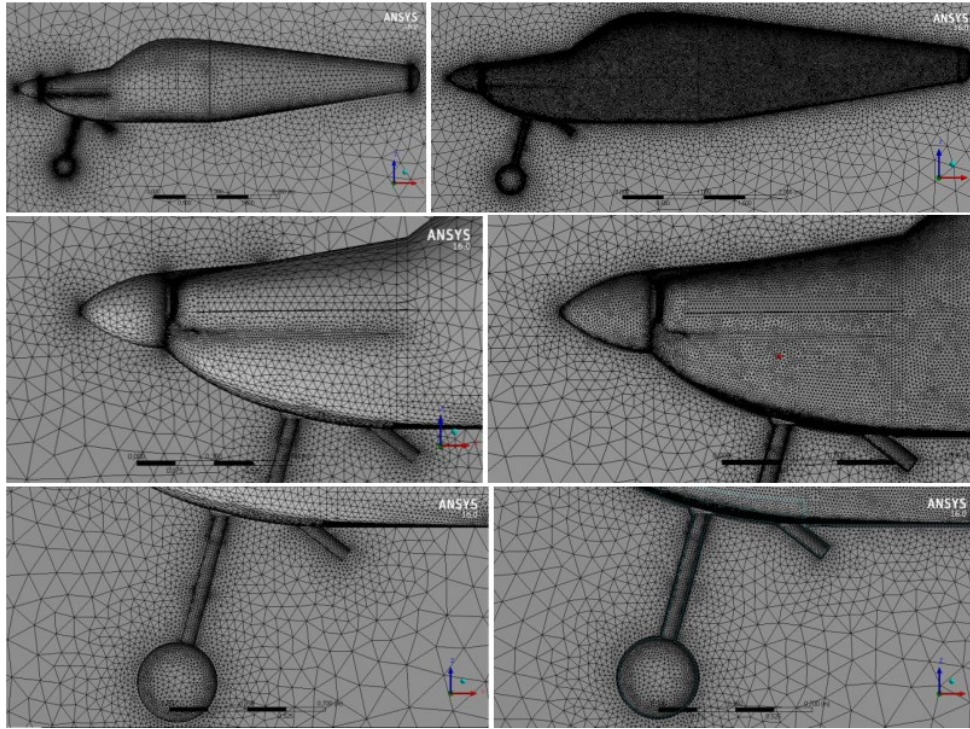


Figure 5-5 Comparison between rough (left) and fine mesh (right)

The generation of mesh of good quality is a crucial step which leads to obtaining more accurate results. But it has to be noted that the increase of mesh quality, as always, resulted in an increased number of cells (70% more), which inevitably leads to increased computational time.

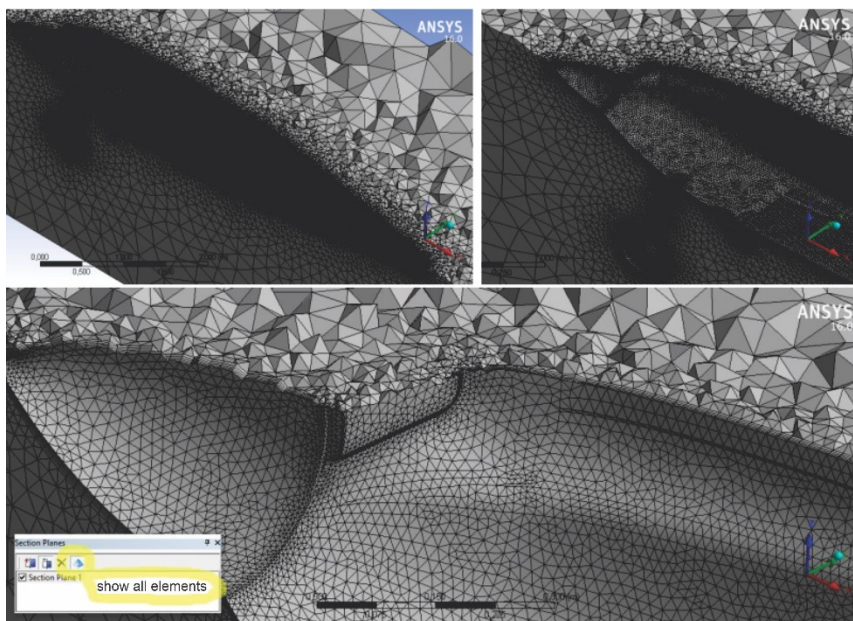


Figure 5-6 Visual inspection of the mesh

As one of the methods for mesh quality check the visual check can be performed by using the option Selection Planes (cross-section). This option enables the visual inspection of cells around the fuselage contour at the desired cross-section.

Based on this visual inspection, it can be observed (Figure 5-6) that the mesh looks quite “clean”, i.e., that there are no big deviations between cells, and that they are not too much chamfered. So, it can be concluded that the mesh is of appropriate quality.

Also, Ansys Fluent offers several different options for mesh quality control within “Mesh diagnostics” [57 and 58], such as:

- **Skewness** – is one of the key options for mesh quality control. This method determines how much elements of newly created mesh are close to ideal geometry (one-sided tetrahedron and isosceles tetrahedron). According to definition, the value of 0 represents considered element as ideal. On the other hand, for the value 1 consider the element is completely degenerative and it is of the worst quality.
- **Orthogonal quality** – domain for calculation of orthogonal quality of elements (cells) are from 0 to 1. The value 0 represents the worst quality and the value 1 for the element of the highest quality. The minimum value of this method cannot be smaller than 0,01 while the average value has to be as close to 1 as possible.

Both of these options were used for mesh quality control (Figure 5-7 and Figure 5-8).

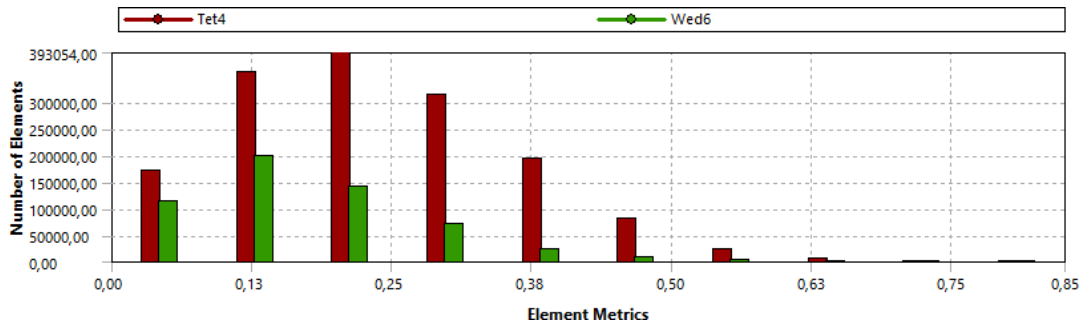


Figure 5-7 Mesh quality verification using the options *skewness*

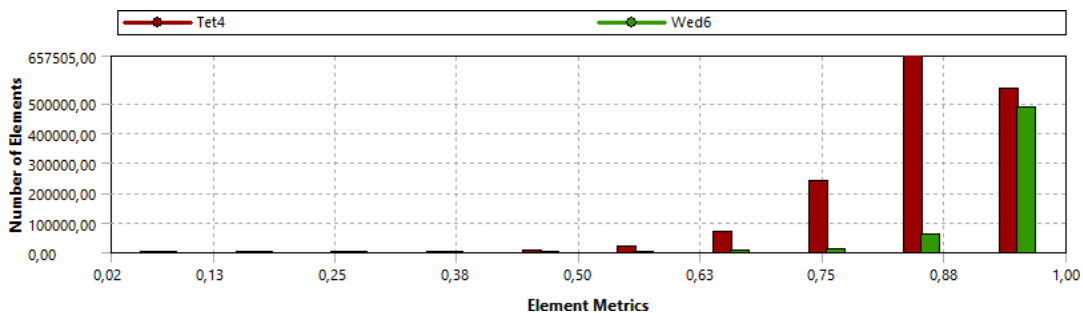


Figure 5-8 Mesh quality verification using the method *orthogonal quality*

In accordance with shown results of mesh quality inspection, it can be determined that the good quality mesh has been generated.

5.2.3 Boundary conditions

After importing geometry and mesh modelling, the boundary conditions are defined. Boundary conditions represent engineering assumptions of real conditions and therefore they have to be properly considered. Considering their importance, the following types of boundary conditions for problem solving are used:

- Input – open boundary that enables entry of fluids into control volume,
- Output – open boundary that enables the output of fluids from control volume,
- Opening – open boundary where the fluid can enter or exit the control volume,
- Wall – represents closed physical boundary between fluid volume and impermeable environment, where there is no fluid flow,
- Symmetry – closed boundary on symmetry plane that is used for simplifying the test model.

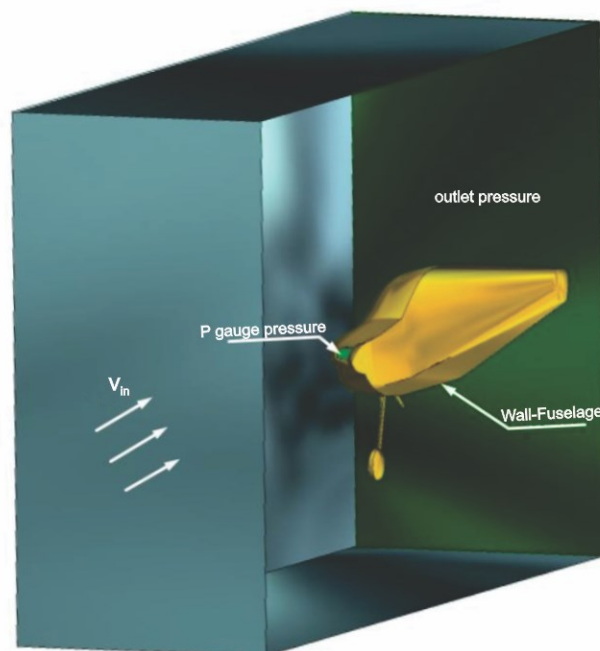


Figure 5-9 Applied boundary conditions

Figure 5-9 shows the geometry of flowing model specially labeled. Each of those elements of geometry represents some type of boundary conditions that describes model through engineering assumptions.

In accordance with the model, the following set of boundary conditions is defined:

- Inlet section –undisturbed air flow velocity $V_{in}= 53 \text{ m/s}$, which is the speed of aircraft movement through the fluid environment on cruising height of 2000 meters for summer period (Table 4-3).
- Inlet boundary surfaces– undisturbed air flow on boundaries of control volume that is used in same way and has the same properties as air flow on entry section, i.e. it has the speed V_{in} .
- Outlet section – it is represented with the pressure outlet, whose value corresponds to the value of atmospheric pressure of the international standard atmosphere on the sea level for the referent cruising speed. The relative value of the pressure on outlet pressure is adjusted to 0 Pa in comparison to absolute value of the working pressure of 79482 Pa on that height.
- Intake for engine cooling – we also represent it with outlet pressure from control volume, whose value is determined in previous chapter of this paper. From Table 4-3. column 12 we take the value of dynamic pressure $p_c= 966 \text{ Pa}$.
- Wall – includes contour of the aircraft's fuselage: engine cover, spinner, nose leg and exhaust pipe.

5.3 Results of CFD analysis

All the input parameters have been adopted for cruising height of 2000 meters of horizontal flight from the Table 4-3, at summer conditions. This referent value has been selected because the aircraft will be majority of its lifespan on this height, so the engine cover has been designed in accordance with these conditions. After designing the geometry, mesh, input parameters, turbulence model, boundary conditions, CFD analysis of the engine cover was conducted. The convergence to the solution has been reached after 1500 iterations. The verification of the obtained results was carried out through residuals. Residuals are the indicators of how much solutions satisfy given equations. As the solution converged towards an exact solution for generated mesh, the residuals advanced to the adopted constant value of $1e^{-06}$. The results did not converge below this criterion. However, after 800th iteration, the residual sum starts oscillating around constant value, so it can be concluded that the solution has converged (Figure 5-10).

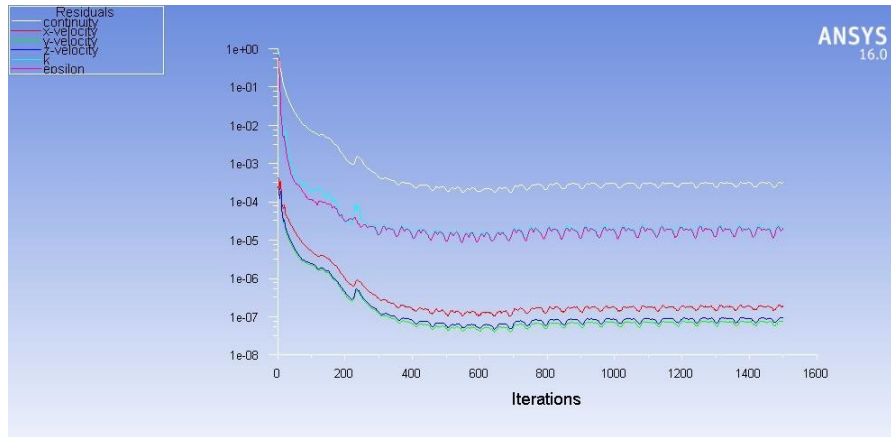


Figure 5-10 Convergence of the results

In this case velocity field and pressure field around the engine cover with associated influence of effect of fuselage, spinner, nose leg and exhaust pipe are very important for the purpose of modeling as much real flow conditions as possible. The simulation results (Computational Fluid Dynamics) are shown in the following figures.

5.3.1 Velocity field

The velocity field around the model can be seen in Figure 5-11, in which speeding up of fluid flow can be observed on areas above and below the aircraft, while in the proximity of the aircraft's surface, in the zone of the boundary layer, the slowing down of the fluid flow occurs.

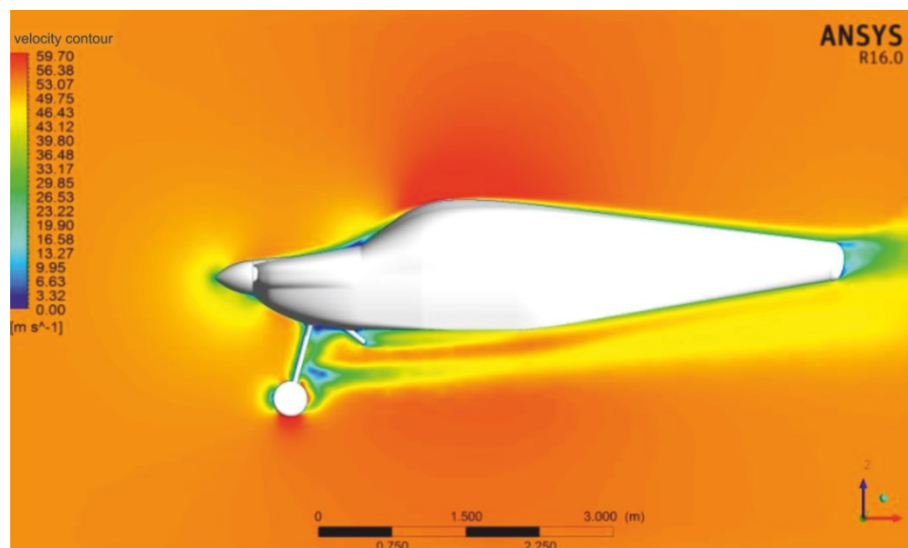


Figure 5-11 Velocity field around the aircraft in symmetry plane

Areas where air flow separation occurs can also be spotted in the zones at the end of the fuselage, nose leg, exhaust pipe. Inside the fuselage there is no fluid flow, while the flow through the engine cover is defined by leaking from the control volume or air intake in the engine cover for the value of dynamic pressure that is previously defined by analytical calculation.

Visualization of fluid flow by the streamlines is shown in Figure 5-12.

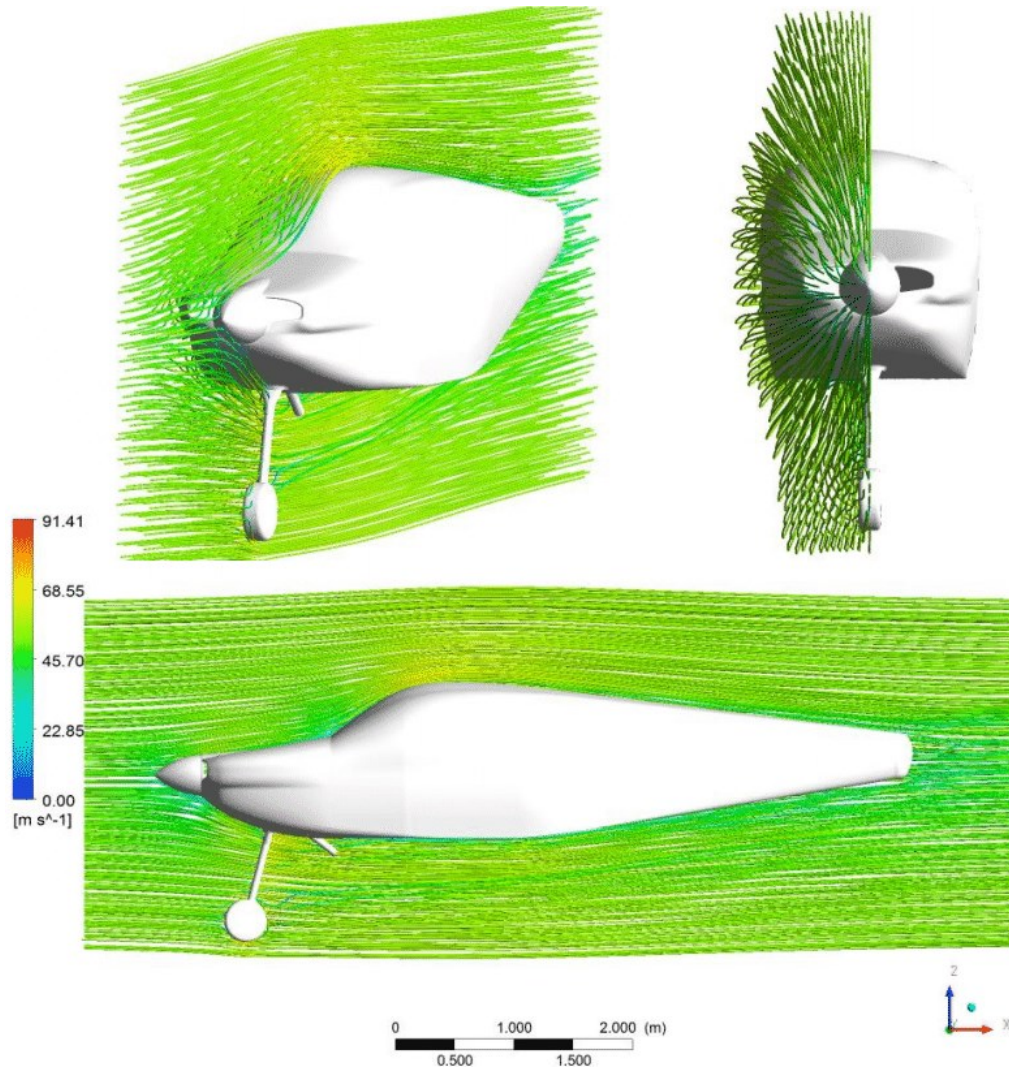


Figure 5-12 Flow field visualization

5.3.2 Pressure field

The pressure field around the model can be seen in Figure 5-13 and Figure 5-14. It can be observed that the pressure is larger in the stagnation points on the top of spinner, nose leg and exhaust pipe. Smaller pressure values occur at the areas of air flow separation, behind nose leg and exhaust pipe.

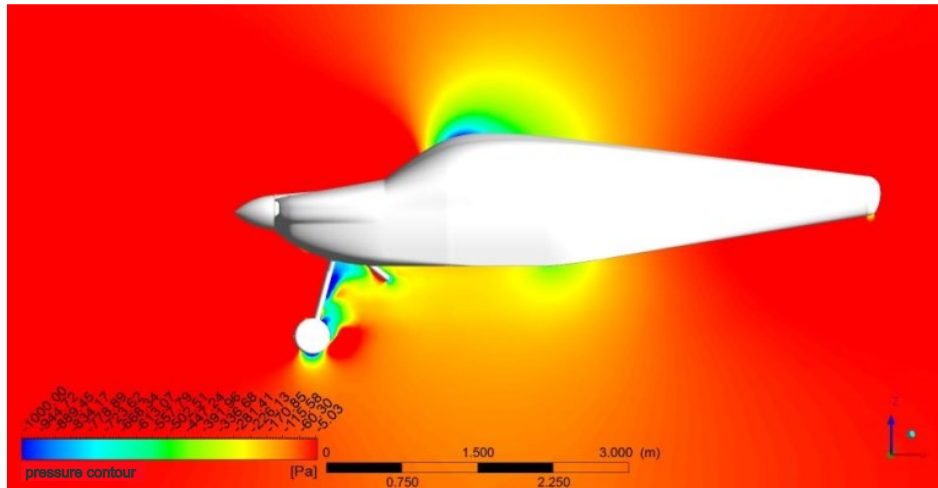


Figure 5-13 Pressure distribution

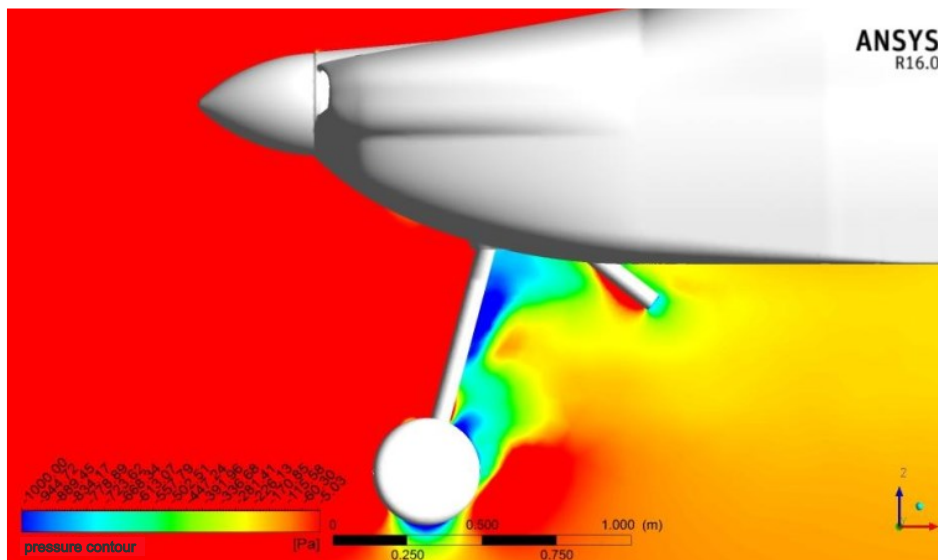


Figure 5-14 Pressure distribution (enlarged detail)

For constructive design of the engine cover opening, it was required to provide sufficient difference of pressures from intake to outlet (outlet 1 and 2) in order to enable free flow through the deflector and inside the engine (Table 4-3). It was determined by analytical calculation, that for the intake pressure on the engine front of 966 Pa, where the intake surface is 450 cm², the additional intake trim is required, in the amount of -650 Pa for calculated value of outlet surface of the exhaust of 455 cm².

The constructive design of “apron” is selected, which is situated directly in front of the exhaust, whose function is to block the opening by its shape and draws air flow around it, creating the zone of sub-pressure, and enabling the undisturbed air outflow from engine area. The position of nose leg has conditioned the “apron” position with two exhaust

openings. Following figures (Figure 5-15 and Figure 5-16) show streamlines in symmetry plane and in space on exhaust points 1 and 2.

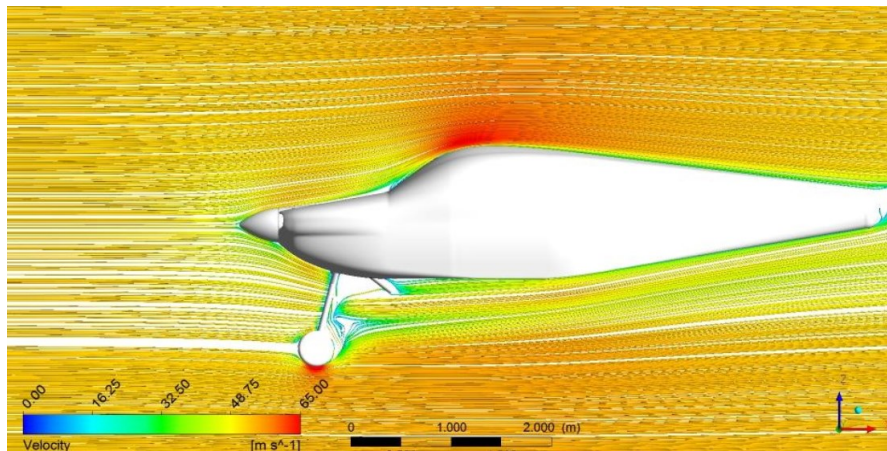


Figure 5-15 Streamlines in symmetry plane

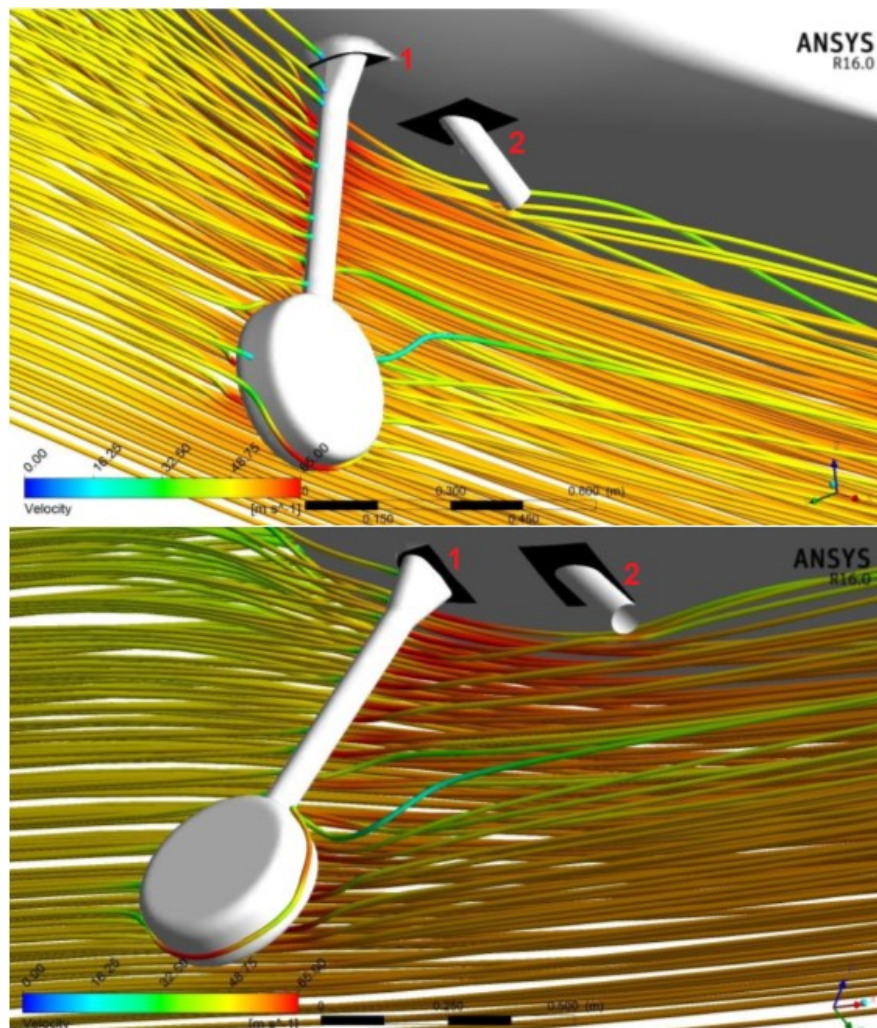


Figure 5-16 Streamlines on exhaust points 1 and 2

But for the aerodynamic load, which is necessary for the following analyses, the pressure distribution on the fuselage and on the engine cover is of the most importance (Figure 5-17).

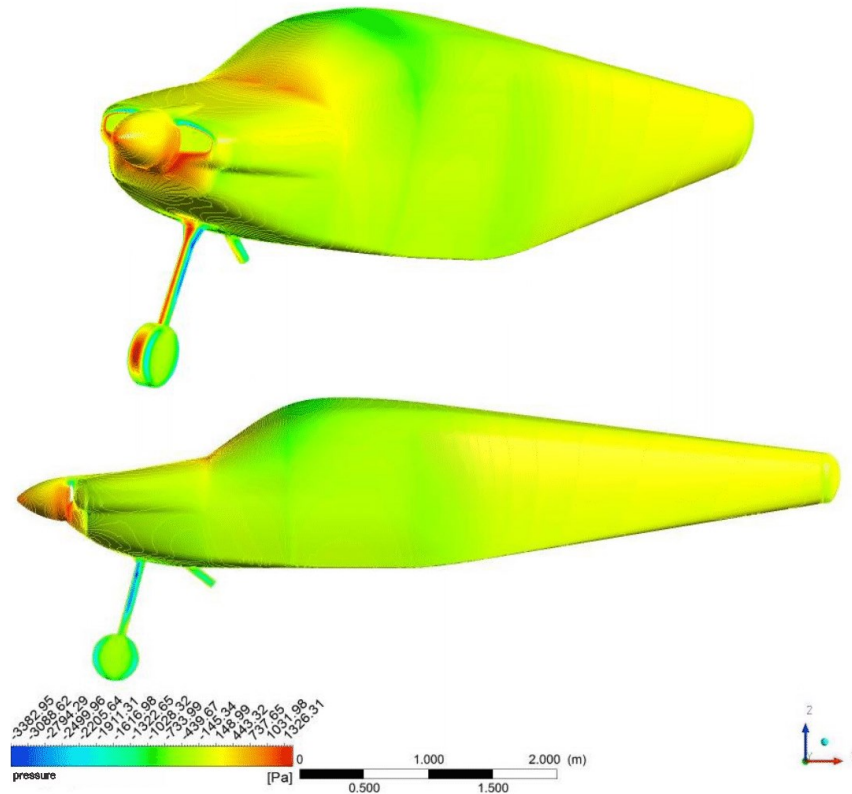


Figure 5-17 Pressure distribution on the fuselage model

The pressure distribution is also important for designing of the engine cover openings (Figure 5-18 and Figure 5-19).

The results of the conducted analysis showed that on the surfaces of outlet openings there is an average value of pressure of -630 Pa. More approximate values can be achieved with additional iterations, surface modification depending on pressure. However, since in this case the error amounts to 3% the analyzed design is adopted as satisfactory.

It has to be noted that CFD analysis of air flow through the engine cover i.e., engine area, was not included in this research. This would require definition of new control volume, generation and inspection of a new mesh and setting of new boundary conditions that would present more precisely engine area, whose entry parameters would correspond to the results of previous analysis (entry/intake, outlet/exhaust). Within new control volume air flow around the engine and its aggregates would be performed in order to obtain contour images of pressure distribution and air velocities inside engine area.

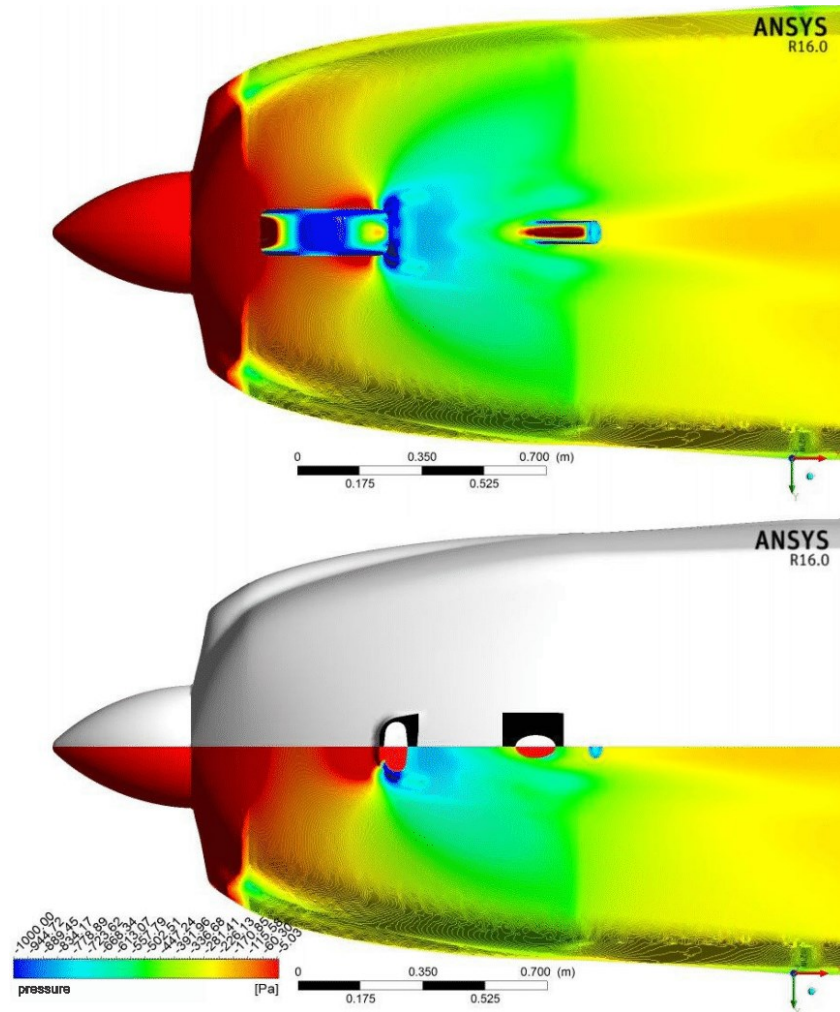


Figure 5-18 Pressure distribution at outlet openings (exhaust 1 and 2)

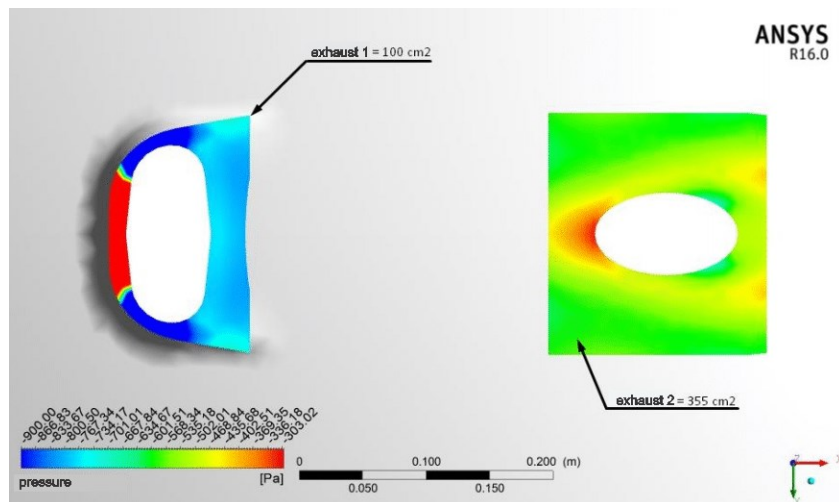


Figure 5-19 Pressure distribution at exhaust 1 and 2 (detail)

The comparison of the numerically obtained results with the analytical ones (Table 4-3) showed a very good agreement between results, which leads to conclusion that initial assumptions were good.

However, complete results validation has to be performed through flight tests and by comparing flight tests results with the ones obtained by calculation. Only in this way one can be sure that the conceptual design of the engine cover with its openings was carried out properly and that overcooling or overheating of the engine will not occur.

6 Structural analysis and optimization of the engine cover shape

To obtain the aerodynamic loads to which engine cover will be exposed to during the flight in previous chapter the computational fluid dynamics (CFD) analyses were carried out in Ansys Fluent. This CFD analysis provided aerodynamic loads which were transformed into pressure distribution and used in the structural analysis performed in the Ansys Mechanical module. Beside this, the assumed inertial loads were also used. It has to be noted that dynamic loads caused by the vibrations of the engine were not considered, since a good damper system was designed to prevent and diminish the dynamic load transfer from the running engine to its cover. As addition to the structural analysis an integrated module of this program called **Ansys Composite Prep – Post (ACP)** was used, which enables definition of cover's composite structure.

All mentioned analyses were conducted and coupled in Ansys Workbench 16 [61].

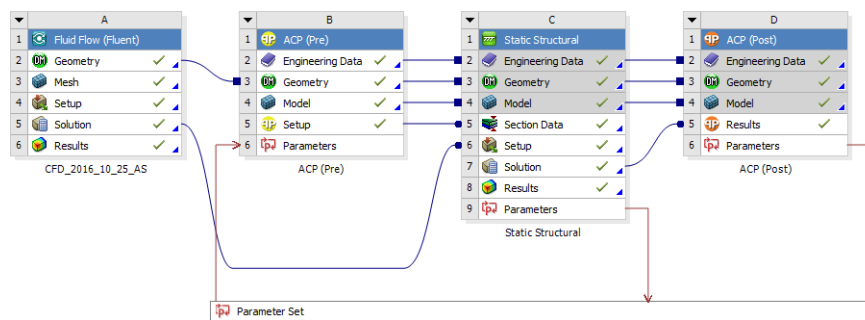


Figure 6-1 Coupled numerical analyses

The structural analysis requires definition of the material and its properties. The values of mechanical properties of lamina which were determined in the third chapter of this thesis are used (Table 2-), along with the values obtained from tensile and bending tests.

The mass of the engine cover is defined by its surface and additional components which are connected to it. The total surface of the engine cover for which the finite element mesh was generated (for the whole model of cover) amounts to 3.5234 m^2 , and having in mind that assumed thickness of laminate is 1mm, the volume of 0.0035234 m^3 is obtained. This thickness shall be achieved in nine layers, where each layer has the

thickness of 0,11 mm. The density of composite is 1980 kg/m³ so computational mass amounts to 6,97 kg.

Properties of Outline Row 3: staklo-epoksi				
	A	B	C	D E
1	Property	Value	Unit	
2	Density	1980	kg m ⁻³	
3	Orthotropic Elasticity			
4	Young's Modulus X direction	1,062E+10	Pa	
5	Young's Modulus Y direction	1,062E+10	Pa	
6	Young's Modulus Z direction	1,062E+10	Pa	
7	Poisson's Ratio XY	0,28		
8	Poisson's Ratio YZ	0,28		
9	Poisson's Ratio XZ	0,28		
10	Shear Modulus XY	2,95E+09	Pa	
11	Shear Modulus YZ	2,86E+09	Pa	
12	Shear Modulus XZ	2,86E+09	Pa	
13	Field Variables			
14	Temperature	Yes		
15	Shear Angle	No		
16	Degradation Factor	No		
17	Tensile Ultimate Strength	2,1E+08	Pa	

Figure 6-2 Mechanical properties used in the numerical simulations

6.1 Finding the optimal layering sequence (Ansys Composite Prep)

First, finite element stress analysis was carried out for the numerical model of the geometry of the laminate with pre-defined (program default setting) layering method for given load conditions. Based on the obtained stress analysis results, the analysis of the layering sequence of the lamina with different orientations was carried out, with the aim of achieving the optimal stress distribution for given load conditions. The lamina with optimal layering sequence was then analyzed with the aim of additional weight reduction of the composite structure without impairing its strength and stiffness.

The analysis of the layering sequence's selection was performed with the variation of the angle of direction of fibers in relation to the reference direction. Four different layering sequences were investigated, and they are defined in Table 6-1. The choice of the investigated layering sequences was limited by the availability of the manufacturing conditions.

Table 6-1 Layering sequences

Laminate No. (Layering sequence)	Layers with fiber orientations								
	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	45	0	45	0	45	0	45	0
3	45	0	45	0	45	0	45	0	45
4	45	45	45	45	45	45	45	45	45

The following figures (Figure 6-3 show the sequence for all four analyzed stacking sequences.

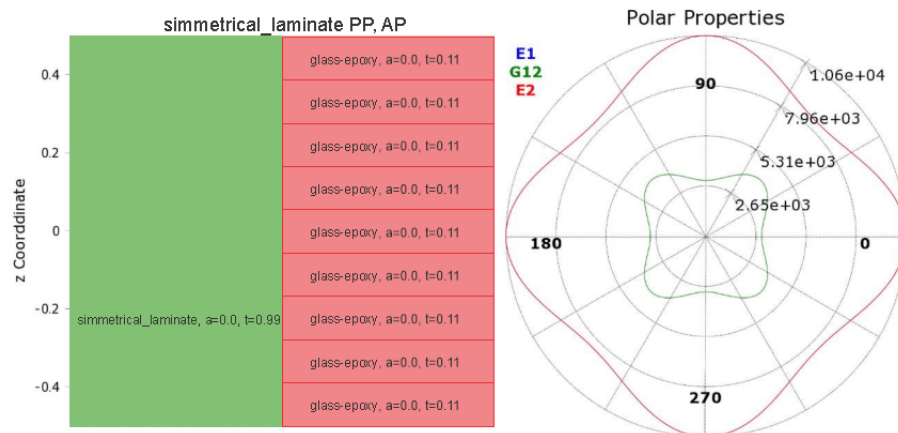


Figure 6-3 Layering sequence 1 (thickness is in mm and elasticity moduli in MPa)

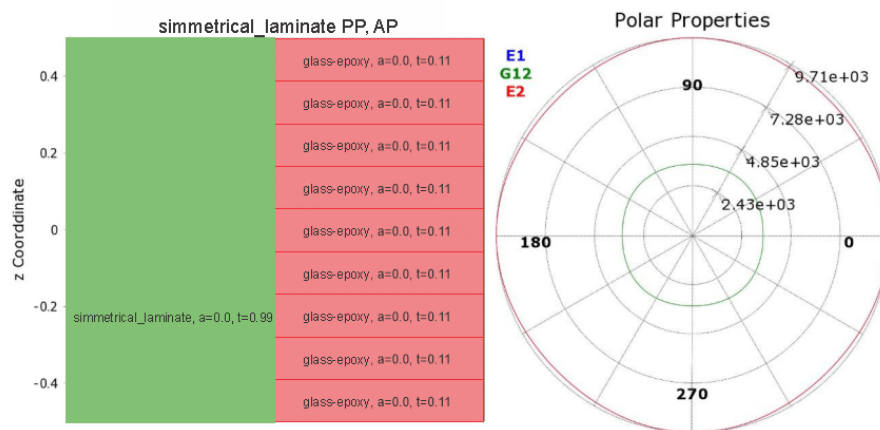


Figure 6-4 Layering sequence 2 (thickness is in mm and elasticity moduli in MPa)

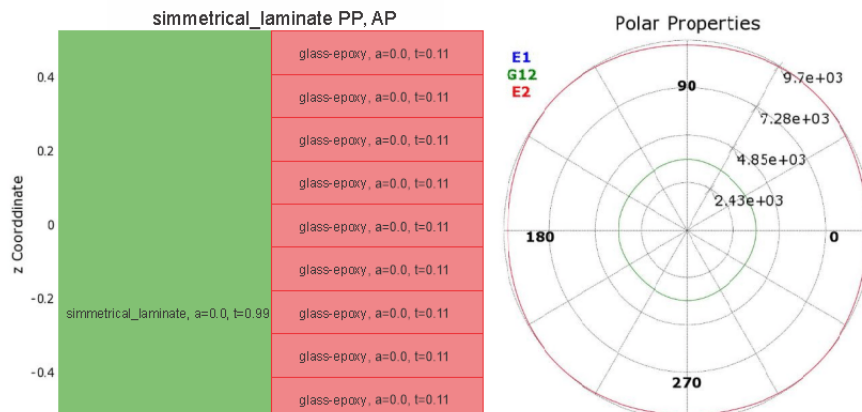


Figure 6-5 Layering sequence 3 (thickness is in mm and elasticity moduli in MPa)

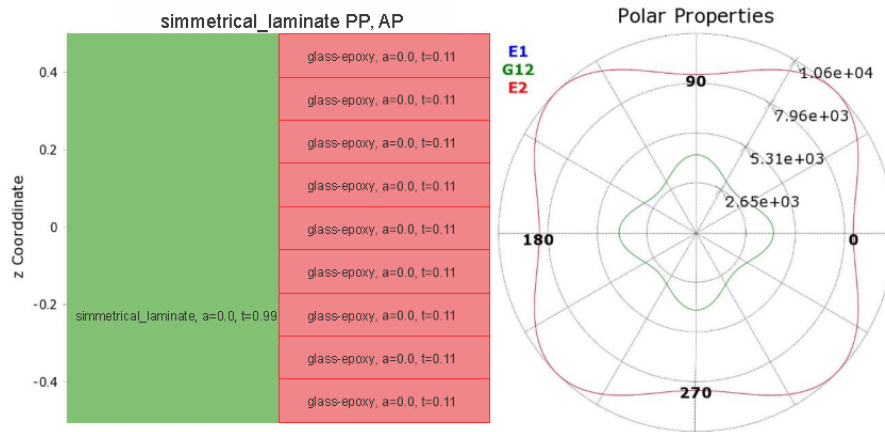


Figure 6-6 Layering sequence 4 (thickness is in mm and elasticity moduli in MPa)

The Figure 6-7 shows layering sequence where fibers are oriented inside the engine cover in the relation to the reference direction. The lamina for layering sequence of 0° is presented. Green arrows represent the longitudinal direction and red arrows represent transversal direction of fibers (direction 2 and 3) in relation to the reference direction, while purple arrows show layering in the direction of thickness. The reference direction is the direction determined by applied Orientation Selection Set (OSS) properties within Ansys APC module and it follows the surface of the model.

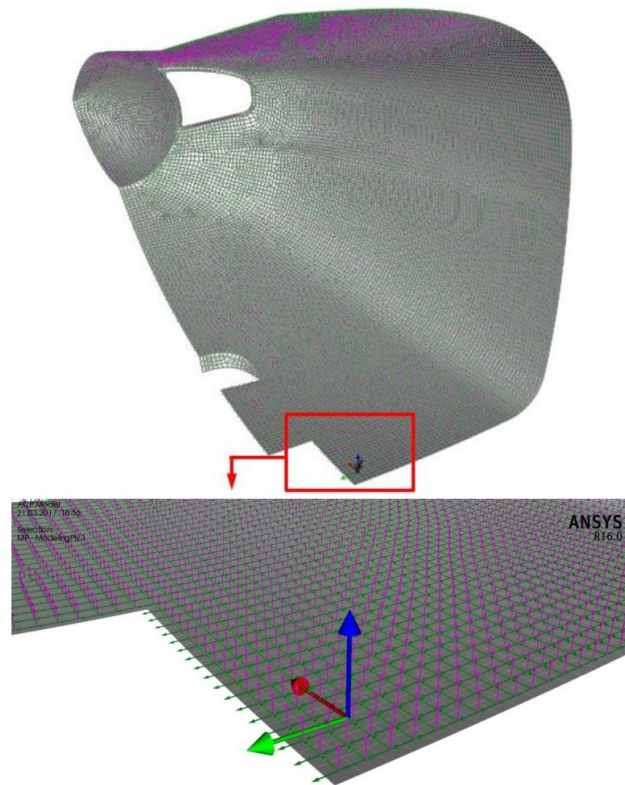


Figure 6-7 Coordinate system for layering inside engine cover

6.2 Structural analysis of the engine cover by finite element method (FEM)

Structural analysis of the engine cover by finite element method (FEM) required import and modification of CAD model which was used in CFD analysis. In order to decrease computational time, the symmetry of the model was used, so only the half of the engine cover model was analyzed.

6.2.1 *Mesh generation*

New mesh was also required. The finite element which was used in this 3D structural analysis was SHELL181 which is well-suited for linear, large rotation, and/or large strain nonlinear applications. According to Ansys Mechanical manual [61], this four-node finite element with six degrees of freedom at each node is suitable for analyzing thin to moderately-thick shell structures, so it is usually used for modeling composite shells or sandwich construction (shell thickness variation is accounted for nonlinear analyses). It took several iterations to generate good quality mesh. The generated mesh had 18061 elements and 18292 nodes (Figure 6-8), which is far less than CFD mesh. Following figures show the final mesh and verification of its quality (Figure 6-9 and Figure 6-10).

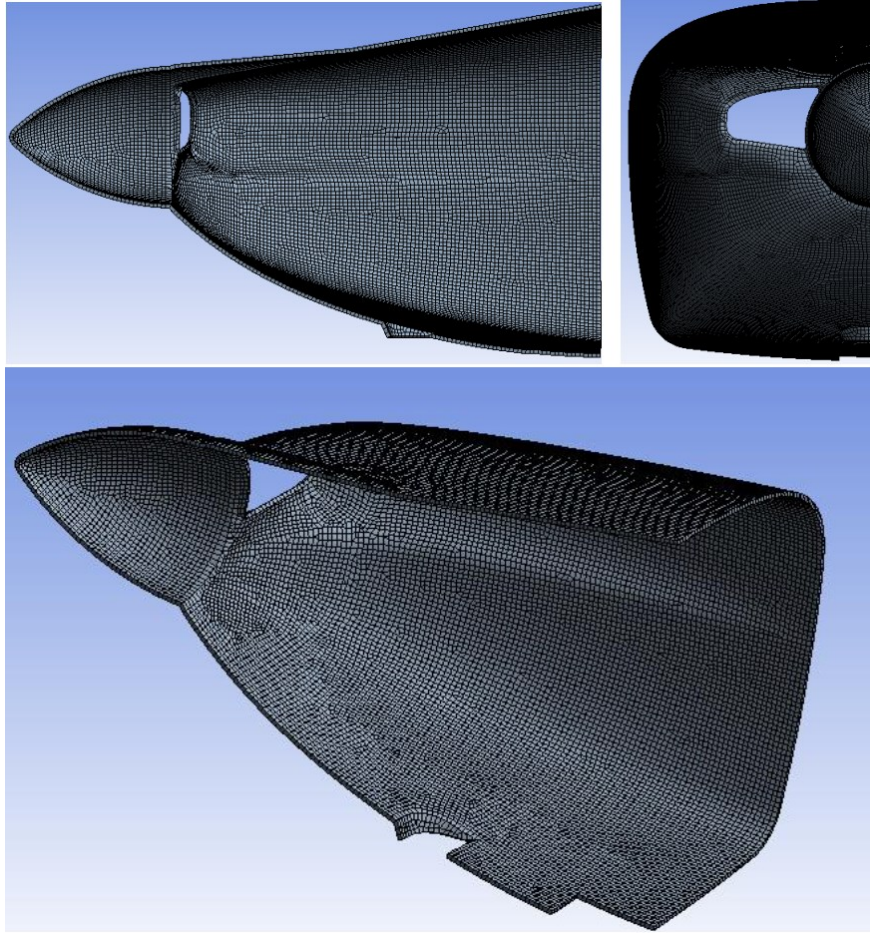


Figure 6-8 Finite element model of the engine cover

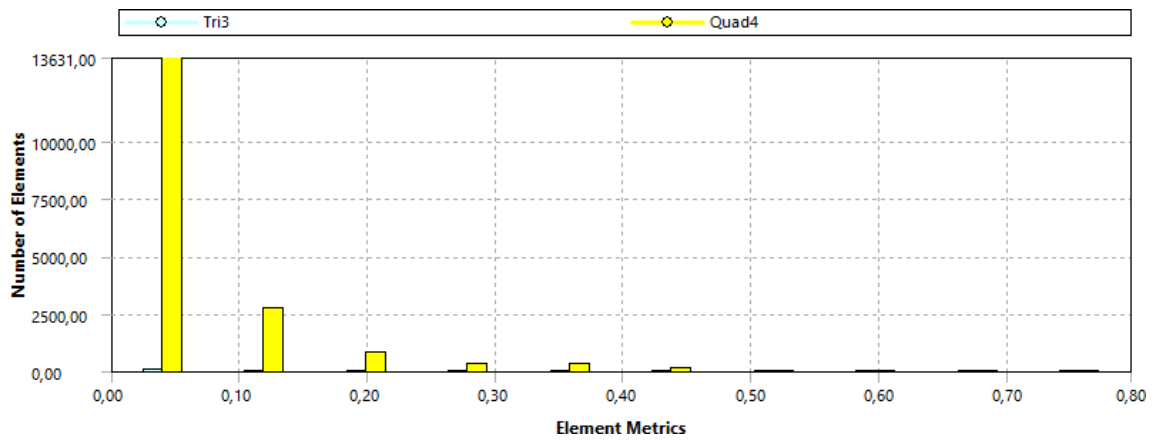


Figure 6-9 Mesh quality verification using the option *skewness*

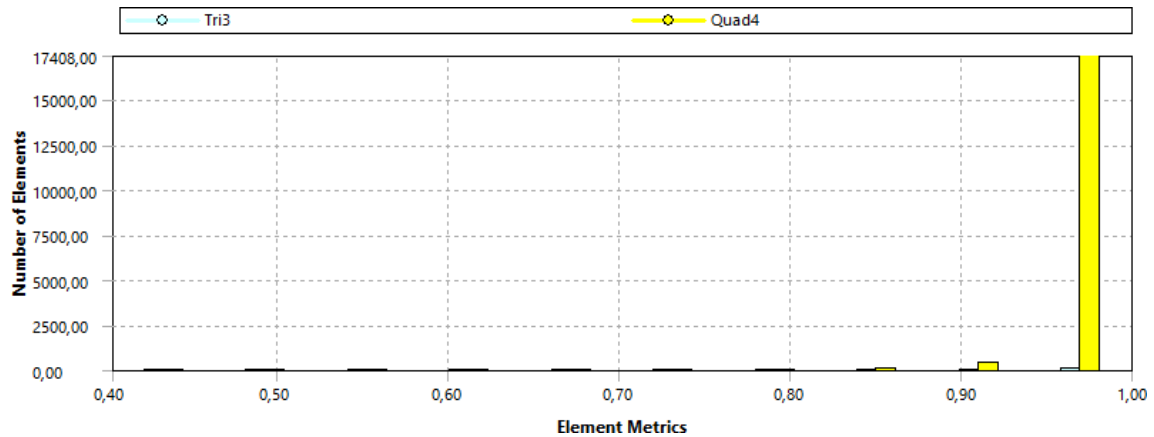


Figure 6-10 mesh quality verification using the option *orthogonal quality*

The same options for mesh quality control used in Ansys Fluent are applied in Ansys Mechanical, within “Mesh diagnostics”: *skewness* and *orthogonal quality*. In accordance with shown results of mesh quality inspection, it can be determined that the good quality mesh has been generated.

6.2.2 Loads and boundary conditions

As already said, CFD analysis conducted in previous chapter provided aerodynamic loads which were transformed into pressure distribution (Figure 6-11) along with the assumed inertial loads. The engine cover was considered as a hollow console which means that fixed support was used.

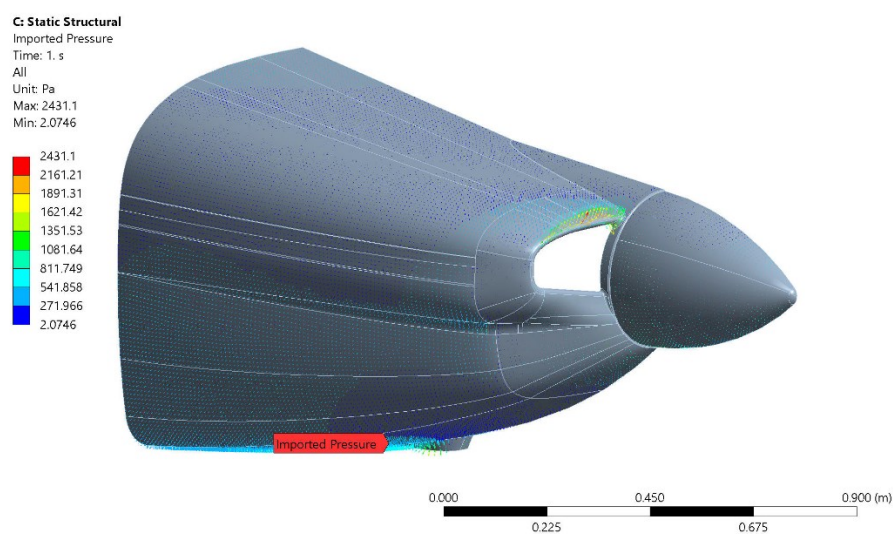


Figure 6-11 Imported aerodynamic load (pressure) of the engine cover

6.3 Results of FEM analysis

After definition of lamina properties, mesh generation, setting up the boundary conditions and import of loads, the finite element analysis was carried out along with the optimization of the layering sequence. The engine cover of thickness of 1 mm, achieved in nine layers was analyzed in the first iteration. The results of these analyses can be seen in Table 6-2 and Here, it has to be noted that Ansys commercial software calculates equivalent stress and strain for orthotropic materials. Equivalent stress is calculated based on principal stresses, while equivalent strain for orthotropic materials is calculated using the effective Poisson's ratio default value of 0.5 [61].

Table 6-3.

Based on the results presented in Table 6-2, it can be concluded that the stresses induced by applied loads are not high enough, since experimentally and numerically obtained tensile and bending strength were above 200 MPa. This means that the lamina failure is not likely to occur under these conditions. (However, the failure analysis of the engine cover was conducted in section 6.4.) Also, it can be observed that laminates of layering sequence 3 and 4 showed optimal results (minimal normal and shear stresses, and minimal values of maximum deflection). Both layering sequences give approximately same results. Sequence 4 has a bit smaller maximum deflection, while stress values are much more favorable for layering sequence 3.

In following figures (Figure 6-12 to Figure 6-18) maximum deflection, stresses and strain distributions are presented for the engine cover model for layering sequence 3, where directions 1, 2 and 3 represent principal material axes.

Table 6-2 Laminate layers optimization and FEA results (deformation and stresses)

Laminate No.	Max deflection	Equivalent strain	Max normal stress	Normal stresses				Shear stresses	
	δ	ϵ_{kv}	σ_{kv}	σ_{1max}	σ_{1min}	σ_{2max}	σ_{2min}	σ_{12max}	σ_{12min}
	mm	mm/mm	MPa	MPa	MPa	MPa	MPa	MPa	MPa
1	11.875	0.00182	16.328	16,589	-14,444	9,558	-14,413	3,819	-2,475
2	11.420	0.00187	16.736	16,720	-14,600	10,065	-14,863	3,608	-2,570
3	11.342	0.00190	16.275	11,509	-9,956	8,535	-11,357	3,486	-4,764

4	11.173	0.00199	16.578	11,424	-10,095	8,785	-11,573	3,630	-5,253
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Here, it has to be noted that Ansys commercial software calculates equivalent stress and strain for orthotropic materials. Equivalent stress is calculated based on principal stresses, while equivalent strain for orthotropic materials is calculated using the effective Poisson's ratio default value of 0.5 [61].

Table 6-3 Laminate layers and FEA results (strains)

Laminate No.	Strain					
	$\epsilon_{1\max}$	$\epsilon_{1\min}$	$\epsilon_{2\max}$	$\epsilon_{2\min}$	$\epsilon_{12\max}$	$\epsilon_{12\min}$
	[-]	[-]	[-]	[-]	[-]	[-]
1	0,00075	-0,00127	0,00079	-0,00091	0,00119	-0,00087
2	0,00082	-0,00132	0,00081	-0,00089	0,00109	-0,00086
3	0,00060	-0,00082	0,00062	-0,00098	0,00152	-0,00099
4	0,00061	-0,00084	0,00066	-0,00095	0,00166	-0,00112

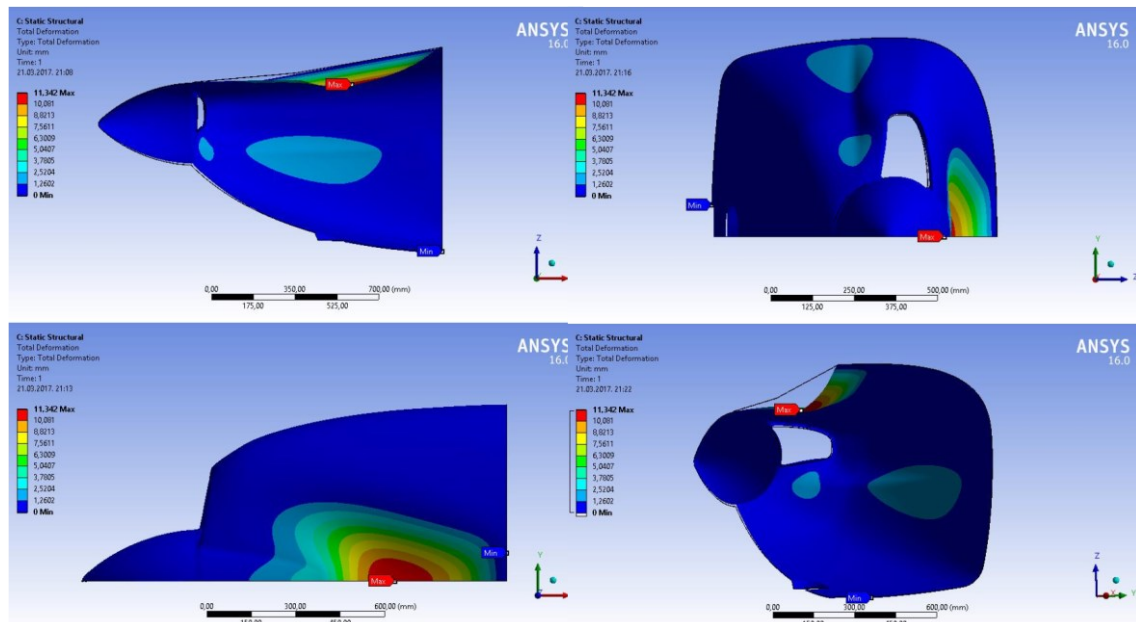


Figure 6-12 The size and position of the engine cover's maximum deflection δ

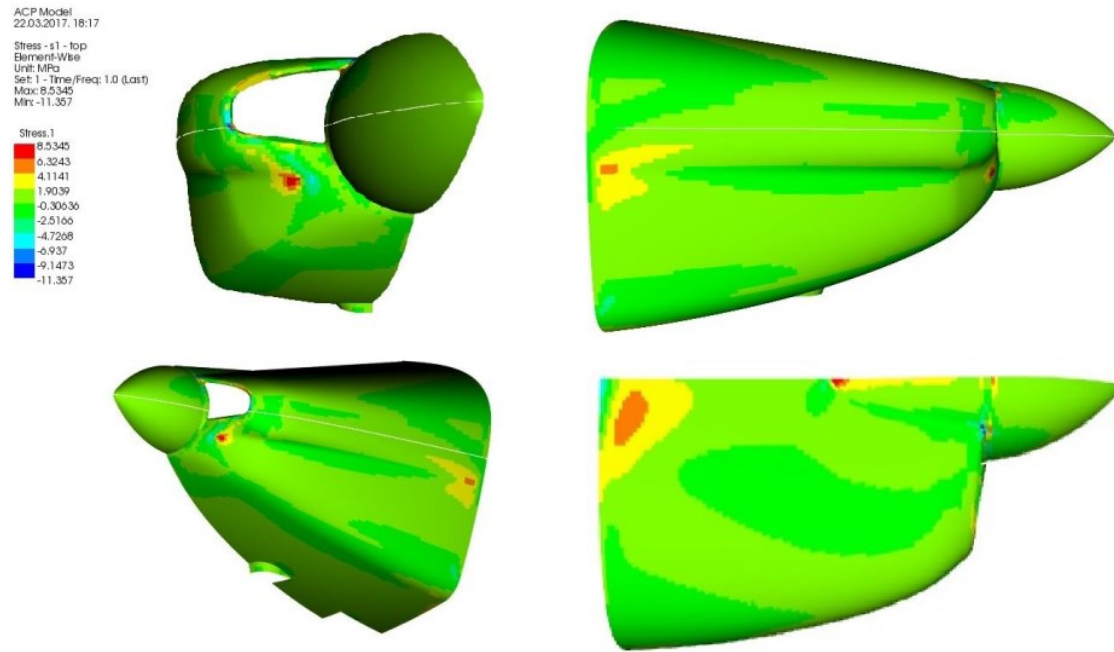


Figure 6-13 Stress distribution of σ_1

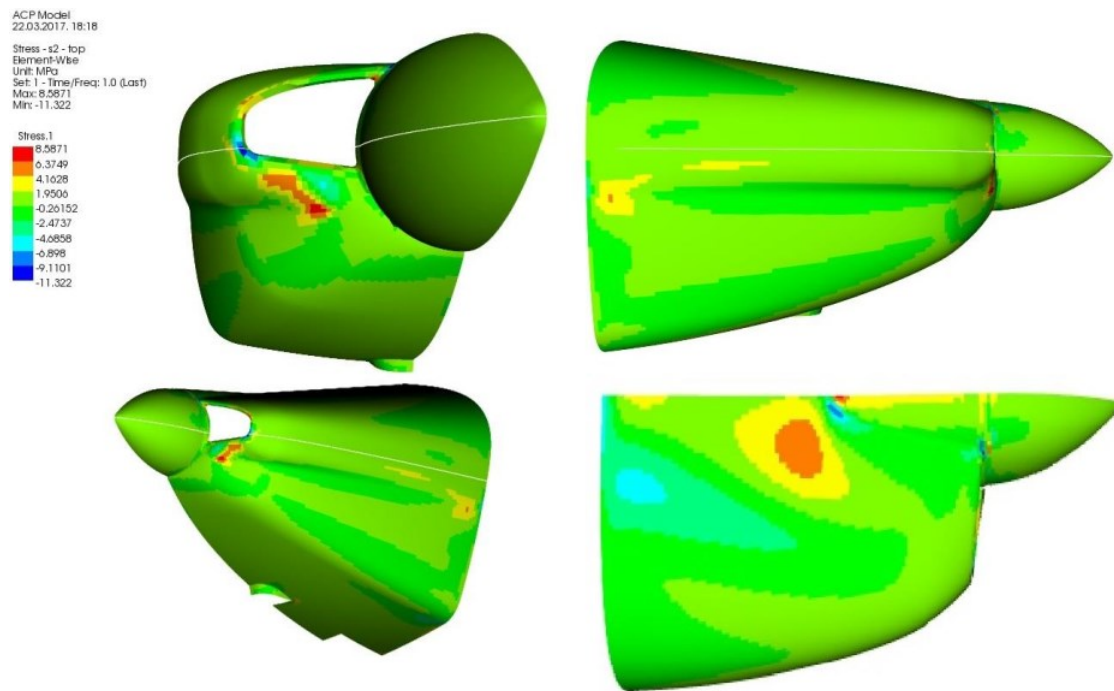


Figure 6-14 Stress distribution of σ_2

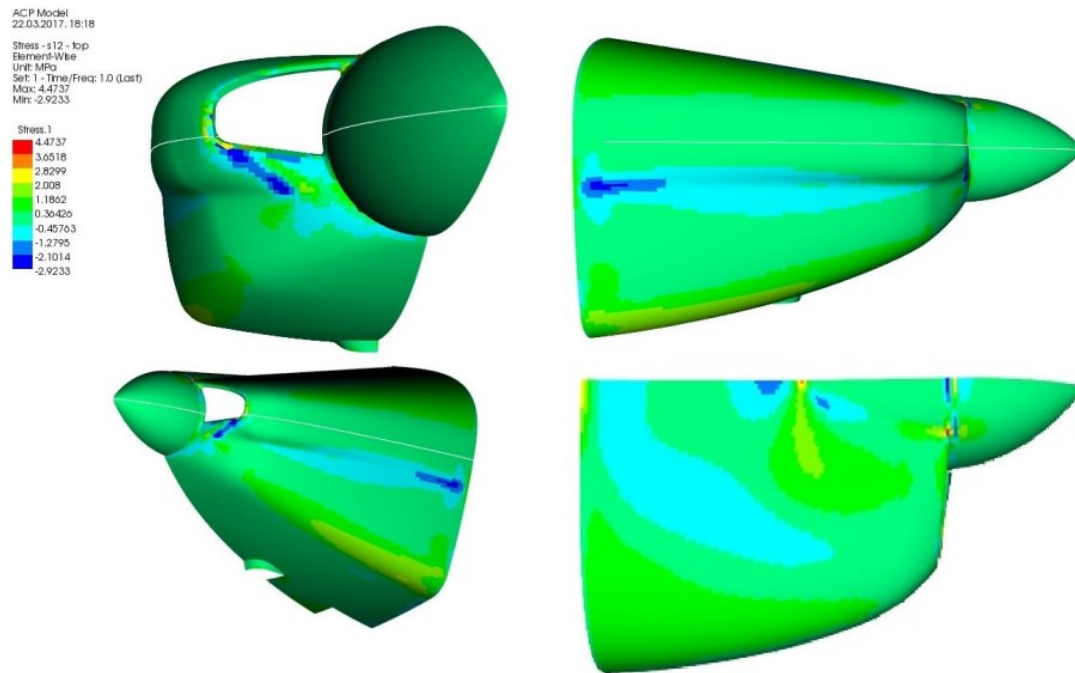


Figure 6-15 Stress distribution of shear stress σ_{12}

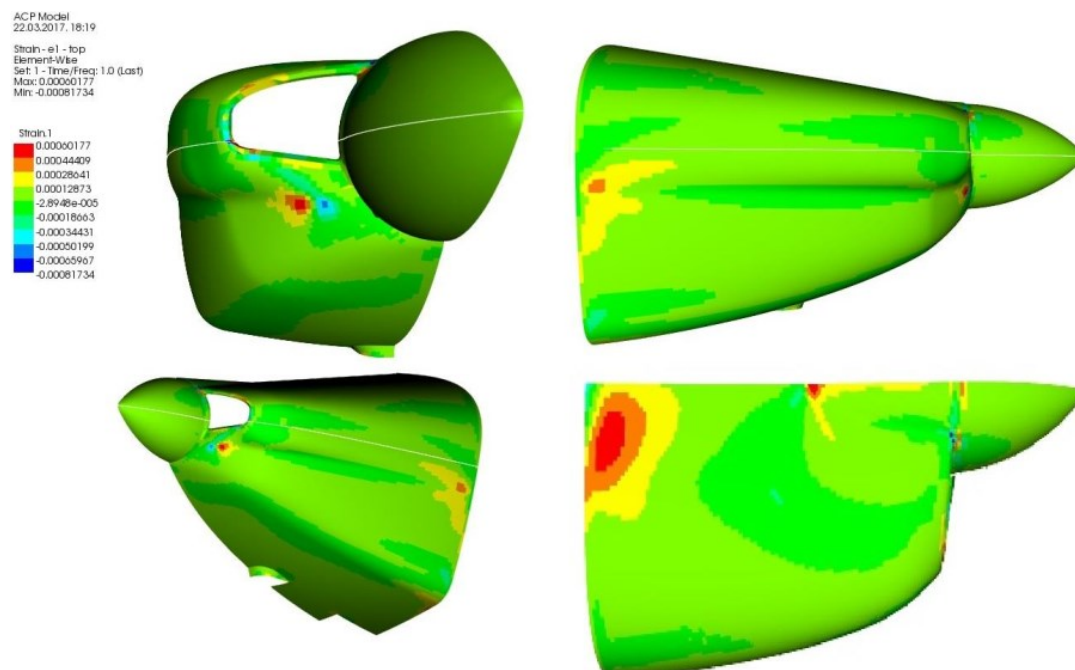


Figure 6-16 Strain distribution of ϵ_1

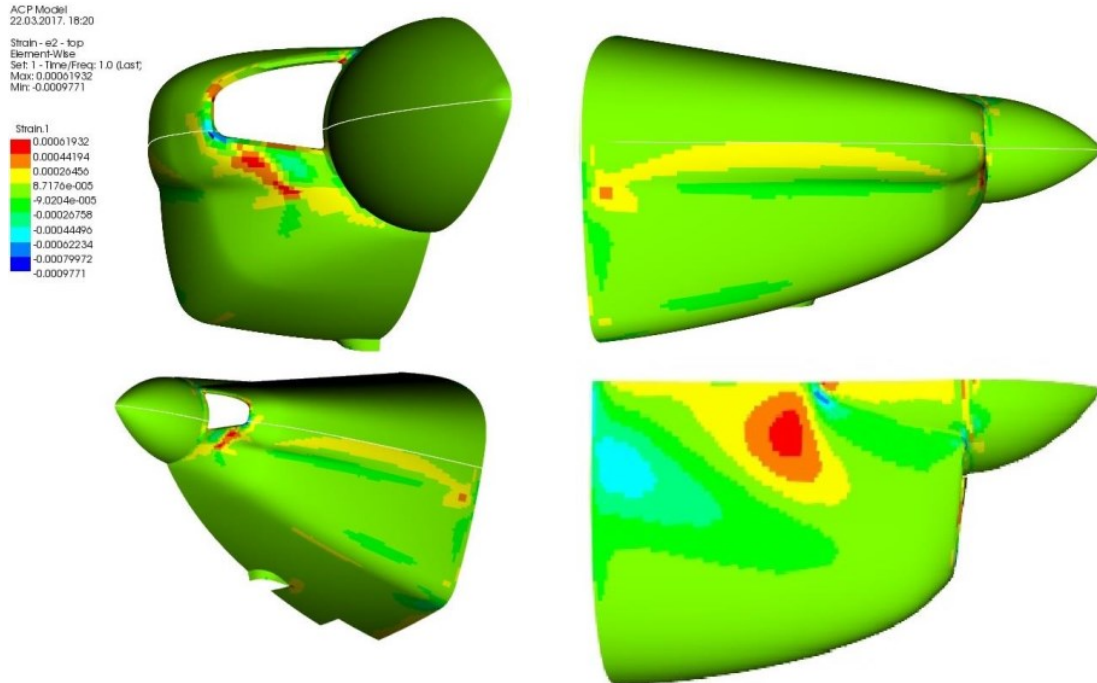


Figure 6-17 Strain distribution of ϵ_2

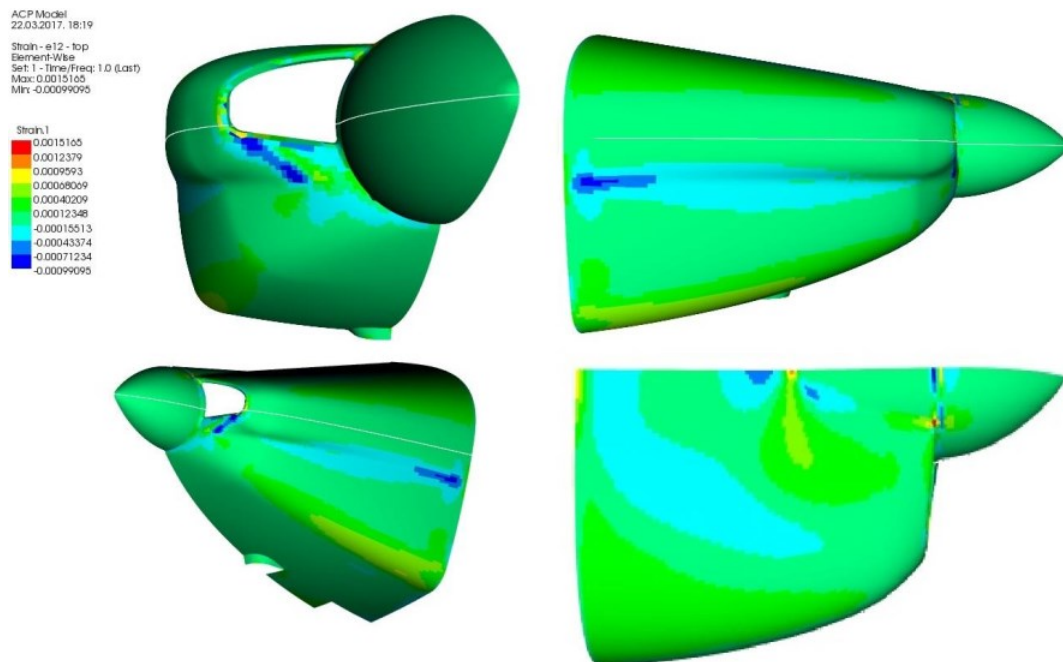


Figure 6-18 Strain distribution of ϵ_{12}

6.4 Failure analysis of engine cover

Next, the failure analysis of engine cover was conducted.

Failures of composite materials can occur in many ways, and some of them include:

- Fiber cracking – due to high tensile loads.
- Occurrence of cracks in matrix – it indicates the occurrence of microscopic damages on matrix. It can be caused by mechanical load, humidity, aging.
- Matrix cracking – similar to previous item with addition that cracks are more distinct.
- Fiber separation – when separation of matrix and fibers occurs.
- Delamination – separation of layers of laminate.

There are many criteria of composite failure [47], to mention the most used ones:

- Criterion of maximum stresses.
- Criterion of maximum strains.
- Tsai – Hill criterion.
- Tsai – Wu criterion.
- Puck criterion.

These criteria represent equations with parameters set to correspond to experimental data of failure of one layer and based on that data, they are used for failure analysis of the laminate. In this thesis Tsai – Hill criterion was applied.

6.4.1 Tsai – Hill criterion

Tsai – Hill criterion of composite material failure [62] is used in the case of triaxial state of stress and belongs to the group of energy failure criteria. That criterion says that the failure of the composite layer will not occur if the following condition is met:

$$(G + H)\sigma_1^2 + (F + H)\sigma_2^2 + (F + G)\sigma_3^2 - 2H\sigma_1\sigma_2 - 2G\sigma_1\sigma_3 - 2F\sigma_2\sigma_3 + 2L\tau_{23}^2 + 2M\tau_{13}^2 + 2N\tau_{12}^2 \geq 1, \quad (6.1)$$

where F, G, H, L, M and N are Hill's yield stresses will be regarded as failure strengths [63]. These parameters were related to the usual failure strengths X, Y, and S for a lamina defined by Tsai [62]. If only τ_{12} acts on the body, then, because its maximum value is S,

$$2N = \frac{1}{S^2} \quad (6.2)$$

When similar procedure is applied to other components from equation (6.1), following terms are obtained:

$$G + H = \frac{1}{x^2}. \quad (6.3)$$

$$F + H = \frac{1}{Y^2} \quad (6.4)$$

$$F + G = \frac{1}{Z^2} \quad (6.5)$$

where the strength in the 3-direction is denoted by Z.

Comminating equations (6.3-6.5) the following relations between F, G, H and X, Y, Z are obtained:

$$2F = \frac{1}{Y^2} + \frac{1}{Z^2} - \frac{1}{X^2} \quad (6.6)$$

$$2G = \frac{1}{X^2} + \frac{1}{Z^2} - \frac{1}{Y^2} \quad (6.7)$$

$$2H = \frac{1}{X^2} + \frac{1}{Y^2} - \frac{1}{Z^2} \quad (6.8)$$

For unidirectional lamina with fibers in the 1-direction, which is the case here (plane stress in 1-2 plane), it will be $\sigma_1 = \tau_{13} = \tau_{23} = 0$, and $Y = Z$ from the obvious geometrical symmetry of the material construction. Considering all this, equation (6.1) becomes:

$$\frac{\sigma_1^2}{X^2} - \frac{\sigma_1\sigma_2}{X^2} + \frac{\sigma_2^2}{Y^2} + \frac{\tau_{12}^2}{S^2} \geq 1 \quad (6.9)$$

In case of only σ_x , acting in direction of angle θ and the stress-transformation equations [63]:

$$\sigma_1 = \sigma_x \cos^2 \theta, \quad \sigma_2 = \sigma_x \sin^2 \theta, \quad \tau_{12} = -\sigma_x \sin \theta \cos \theta,$$

equation (6.9) can be written as:

$$\frac{(\cos\theta)^4}{X^2} + \left(\frac{1}{S^2} - \frac{1}{X^2}\right)(\sin\theta)^2(\cos\theta)^2 + \frac{(\sin\theta)^4}{Y^2} \geq \frac{1}{\sigma_x^2} \quad (6.10)$$

which represents Tsai-Hill failure criterion for uniaxial off-axis strength.

6.4.2 Results of failure analysis

The Tsai-Hill failure criterion function for unidirectional plies used in Ansys is given in the form [61]:

$$f = \frac{\sigma_1^2}{X^2} - \frac{\sigma_1\sigma_2}{X^2} + \frac{\sigma_2^2}{Y^2} + \frac{\tau_{12}^2}{S^2}$$

The value of failure criterion function is determined by applied load.

In Ansys, numeric line search method is used for determining the value of reserve factor (RS) [61], which describes the distance from the point of the applied load to the failure point, for which $f = 1$.

The reserve factor indicates the margin of failure. The reserve factor is obtained when the load at failure is divided by the applied load. The reserve factor that is greater than the value 1 indicates the positive margin of failure while the value smaller than 1 indicates the negative margin of failure [61].

Critical values of reserve factor lie in domain between 0 and 1, while noncritical values are between 1 and $+\infty$. The margin of failure can also be presented by margin of safety coefficient (MoS). MoS is the alternative to reserve factor. It is determined:

$$MoS = Rf - 1 \quad (6.11)$$

Positive MoS indicates how much higher load in percent can structure endure before the material failure occurs.

The results of failure analysis of the engine cover are presented in Table 6-4.

Table 6-4 Failure analysis results

Laminate No.	Layers with fiber orientations									Reserve Factor (RF)	Margin of Safety (MoS) MoS=RF-1
	1	2	3	4	5	6	7	8	9		
1	0	0	0	0	0	0	0	0	0	3,72	2,72
2	0	45	0	45	0	45	0	45	0	3,81	2,81
3	45	0	45	0	45	0	45	0	45	3,69	2,69
4	45	45	45	45	45	45	45	45	45	3,65	2,65

Table 6-2, Here, it has to be noted that Ansys commercial software calculates equivalent stress and strain for orthotropic materials. Equivalent stress is calculated based on principal stresses, while equivalent strain for orthotropic materials is calculated using the effective Poisson's ratio default value of 0.5 [61].

Table 6-3 and Table 6-4 show that laminates numbered 3 and 4 have the optimal properties, although the differences in strains, stresses, MoS, etc., are in fact very small. The laminate number 3 has slightly lower value of MoS but considering all other values from Table 6-2 and Table 6-3, this laminate is selected as optimal. (Figure 6-19).

By observing and comparing the calculated stresses in Table 6-2 and values of tensile strength, it can be seen that values of stresses in the stress field of the engine cover are lesser than critical value. It can be observed that calculated values of MoS are very high (much higher than 1- minimum value is 2.65). For laminate 3 this value is 2.69 (Figure

6-19). This gives the possibility of further improvement of the engine cover with the aim of additional weight reduction (decreasing of thickness).

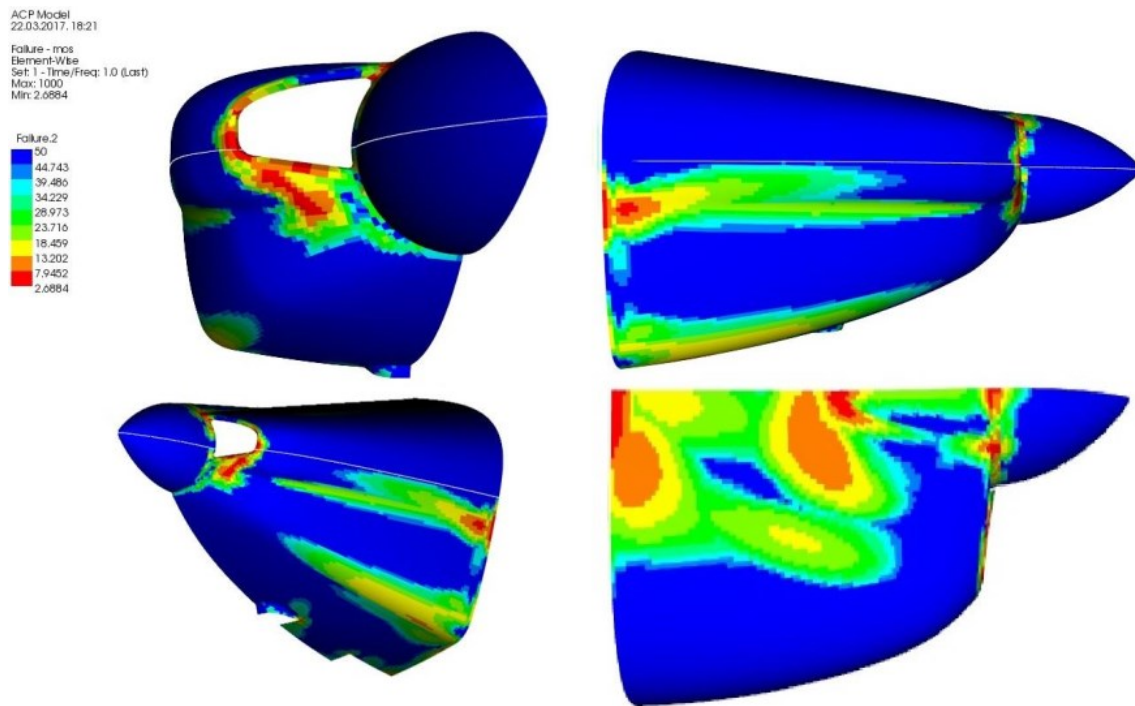


Figure 6-19 Margin of safety for layering sequence 3

6.5 Structural reinforcement

As already mentioned, the value of maximum deflection of 11 mm is high even the failure does not occur because it can cause structural instability. But this large deflection significantly reduces necessary gaps between the engine and the cover which are designed to provide free circulation of the air during the flight. In order to avoid this, laminate structure strengthening is performed in areas where this large deflection is observed. This strengthening consisted of sandwich construction made of previously defined fiberglass composite laminate and polymer foam Airex. This polymer foam has many advantages, like high ratio of strength in relation to mass, it does not absorb the humidity, it possesses the resistance to chemicals. Also, it has great characteristics of joining and it is compatible with most of the resins that are used in production process. For that reason, it represents

adequate material for wide use of light sandwich constructions which are exposed to static and dynamic loads. Its main mechanical properties [65] can be seen in Table 6-5.

Table 6-5 Airex - Mechanical properties

Mechanical properties	Value	Unit
Density	80	[kg/m ³]
Tensile strength, Rm	2	[MPa]
Elongation, ε	18	[%]
Tensile elasticity modulus, E	66	[MPa]
Compressive strength, RF	1,45	[MPa]
Compressive elasticity modulus, E	104	[GPa]

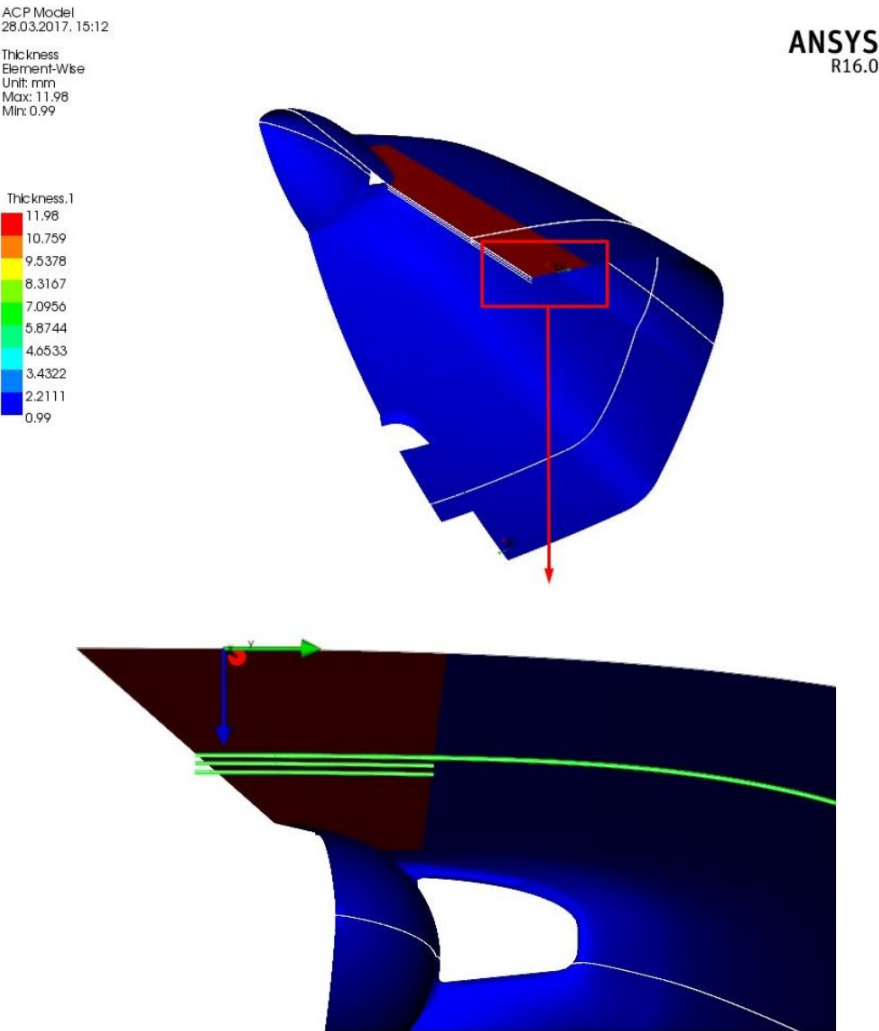


Figure 6-20 Thickness in the area of the engine cover’s reinforcement

Reinforcement is performed on the surface of $0,234 \text{ m}^2$ (both sides), with Airex with thickness of 10 mm and mass of 0,187 kg. Airex is placed in the sandwich of two laminates with 1 mm in thickness, which means that the maximum thickness of sandwich amounts to 12 mm (Figure 6-20). The second laminate that covers the reinforcement is with fiber orientation 0° and its mass on this point is 0,46 kg. This structural reinforcement increased the overall mass the engine cover for 647 gr.

This structural reinforcement required new finite element analysis and creation of a new mesh. This new mesh was generated as a modification of initial mesh in the area of reinforcement in order to maintain the same properties of thickness and quality and to preserve the same number of nodes and elements, as in previous case. It has to be noted that boundary condition, loads, type of element and all other settings and parameters used in finite element analysis also remained the same.

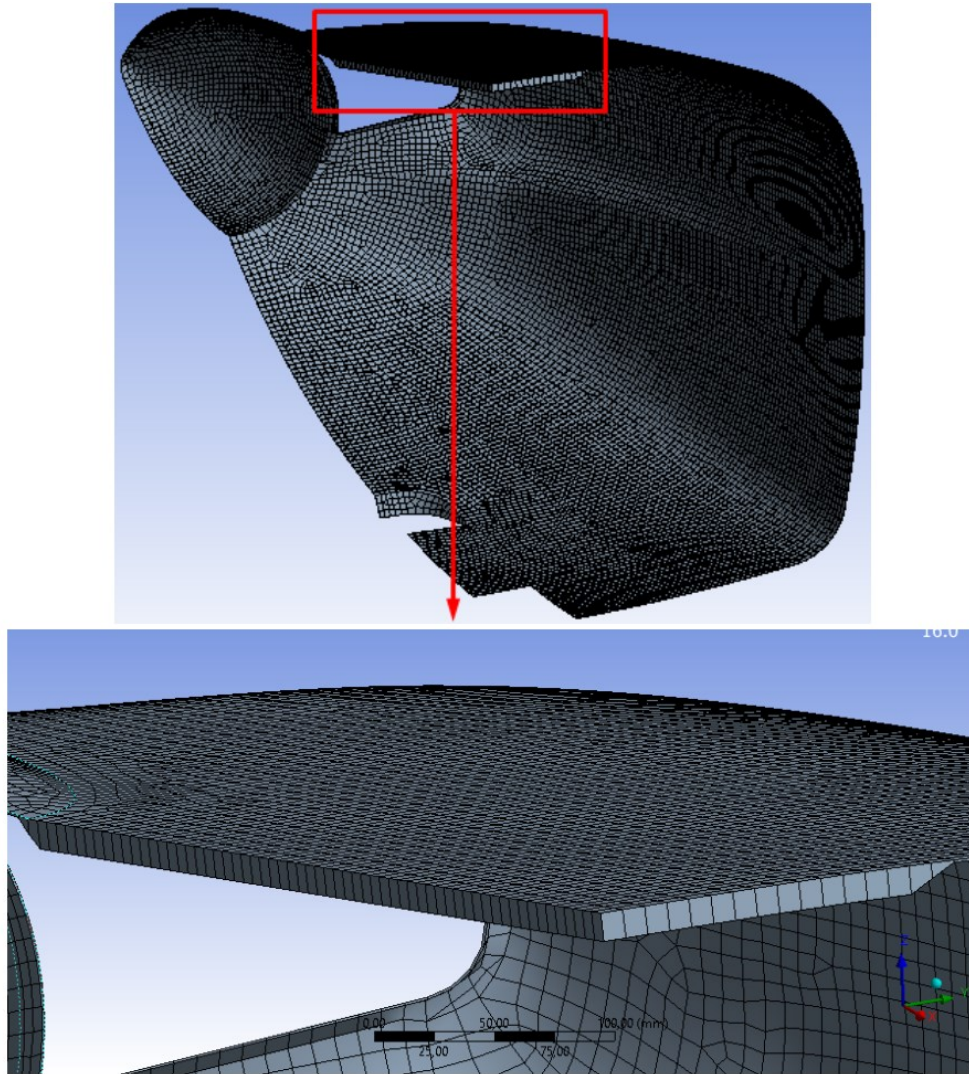


Figure 6-21 Modified mesh in the area of reinforcement

6.5.1 Results of the FE analysis for the reinforced structure

After defining laminate properties, reinforcement, new mesh construction, establishing boundary conditions, importing aerodynamic loads, etc., the finite element analysis was carried out along with the optimization of the layering sequence. The results of these analyses are presented in the following tables (Table 6-6 and Table 6-7).

Table 6-6 Reinforced laminate layers optimization and FEA results (strain and stresses)

Reinforced Laminate No.	Max deflection	Equivalent strain	Max normal stress	Normal stresses				Shear stresses	
	δ	ϵ_{kv}	σ_{kv}	σ_{1max}	σ_{1min}	σ_{2max}	σ_{2min}	σ_{12max}	σ_{12min}

	mm	mm/mm	MPa	MPa	MPa	MPa	MPa	MPa	MPa
1	2,088	0,00197	17,606	8,464	-9,413	8,961	-11,713	4,238	-2,632
2	2,180	0,00202	18,064	8,710	-9,417	9,430	-11,887	4,024	-2,524
3	2,214	0,00205	17,608	7,309	-7,482	7,974	-12,438	3,815	-5,167
4	2,370	0,00215	17,985	7,510	-7,488	8,209	-12,725	3,984	-5,713

Table 6-7 Reinforced laminate layers optimization and FEA (strains) and failure analysis results

Reinforced Laminate No.	Strain						RF	MoS
	ϵ_{1max}	ϵ_{1min}	ϵ_{2max}	ϵ_{2min}	ϵ_{12max}	ϵ_{12min}		
	[-]	[-]	[-]	[-]	[-]	[-]		
1	0,00070	-0,00093	0,00059	-0,00100	0,00111	-0,00096	3,42	2,42
2	0,00076	-0,00093	0,00059	-0,00099	0,00108	-0,00096	3,49	2,49
3	0,00057	-0,00089	0,00058	-0,00108	0,00110	-0,00090	3,60	2,60
4	0,00057	-0,00092	0,00062	-0,00106	0,00118	-0,00102	3,34	2,34

Since there was no laminate failure in the initial structure it is considered that laminate failure will not occur in the reinforced structure as well. All four reinforced layering sequences gave approximately same results. Sequence 1 has a bit smaller maximum deflection while stress distribution is more favorable in layering sequence 3, which also has greater MoS. And that is the reason why layering sequence 3 was selected as the most optimal method of layering in this case.

So, in following figures (Figure 6-22 to Figure 6-29) maximum deflection, stresses and strain distributions, and MoS are presented for the engine cover model for the reinforced layering sequence 3.

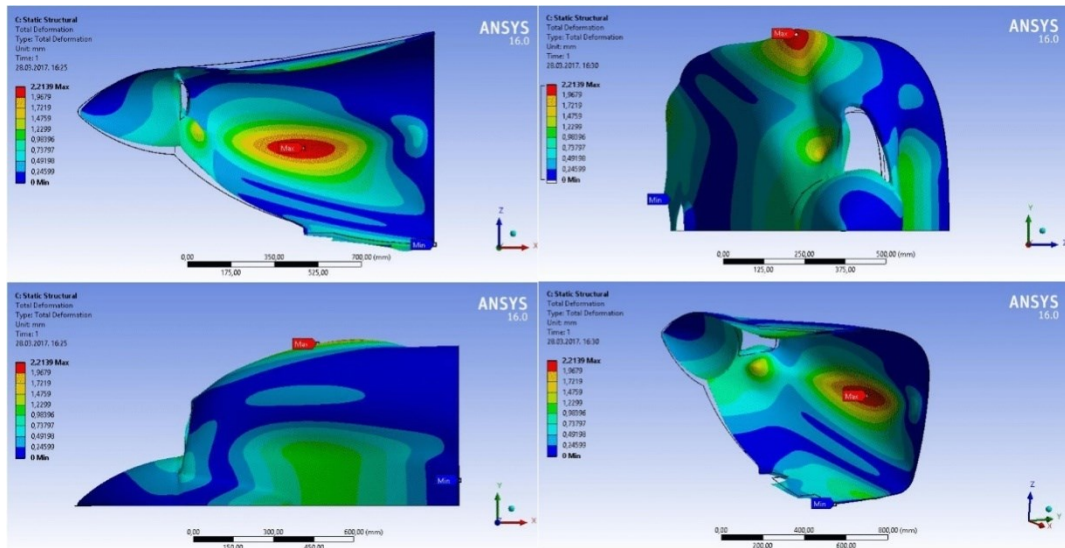


Figure 6-22 The size and position of the reinforced engine cover's maximum deflection

δ

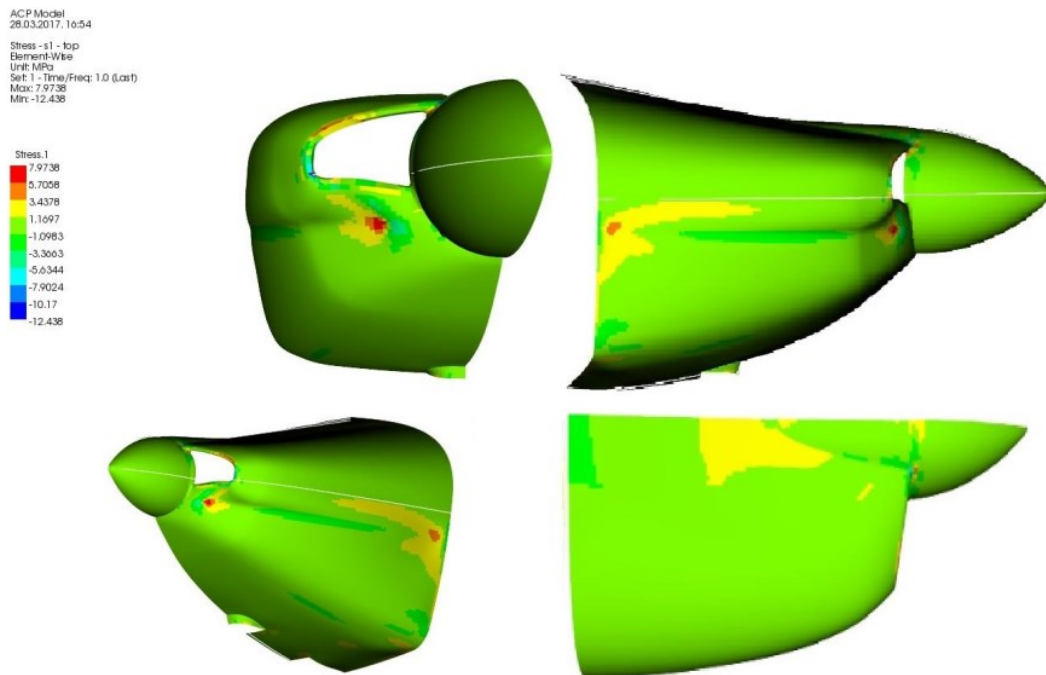


Figure 6-23 Stress distribution of σ_1 (reinforced structure)

ACP Model
28.03.2017, 16:56
Stress - s2 - top
Element-Wise
Unit: MPa
Set: 1 - Time/Freq: 1.0 (last)
Max: 8.1117
Min: -12.517

Stress.3
8.1117
5.8196
3.5275
1.2354
-1.0508
-3.3489
-5.041
-7.9331
-10.225
-12.517

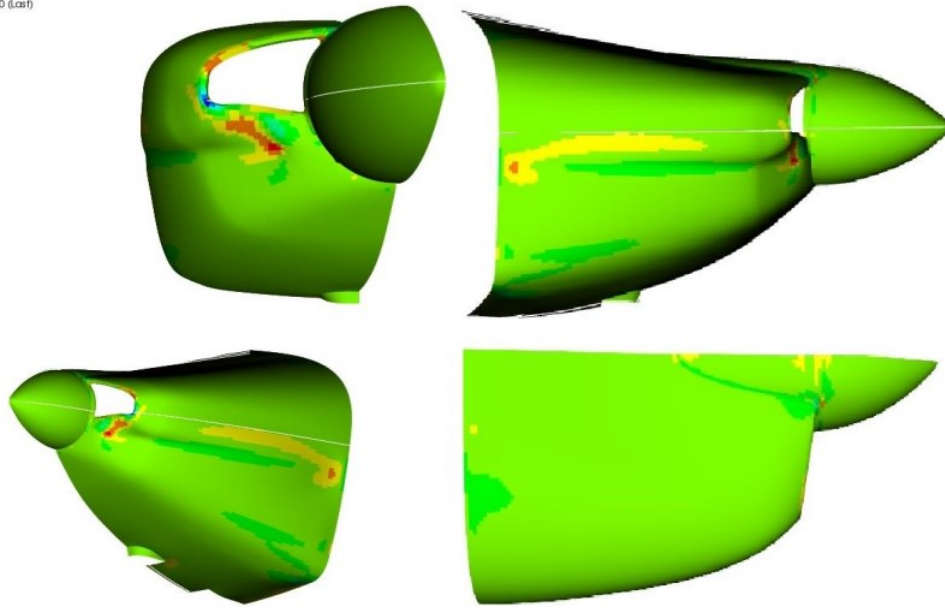


Figure 6-24 Stress distribution of σ_2 (reinforced structure)

ACP Model
28.03.2017, 16:55
Stress - s12 - top
Element-Wise
Unit: MPa
Set: 1 - Time/Freq: 1.0 (last)
Max: 3.2351
Min: -2.0083

Stress.2
3.2351
2.5791
1.9232
1.2673
0.61135
-0.044573
-0.7005
-1.3504
-2.0123
-2.0083

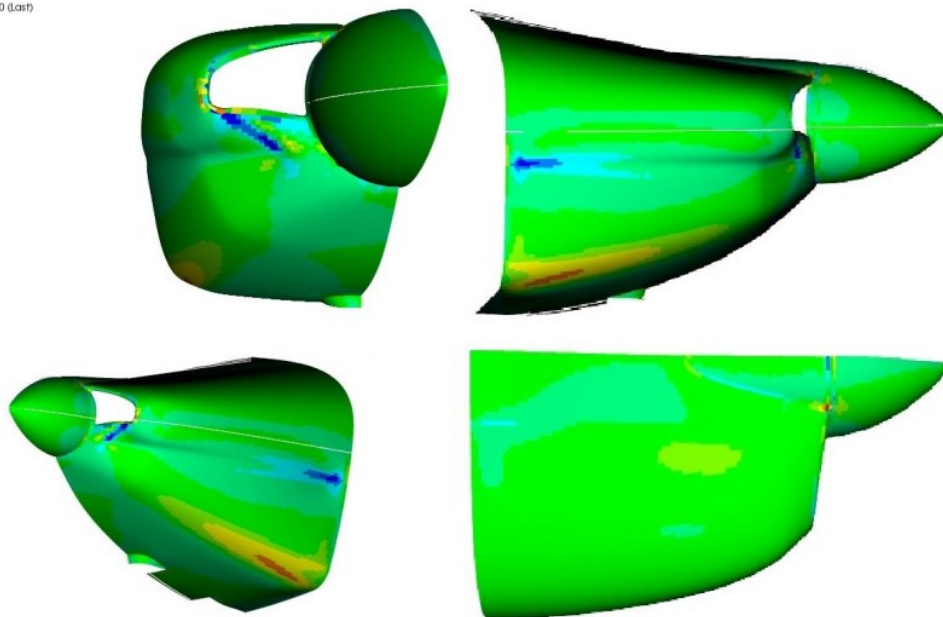


Figure 6-25 Stress distribution of σ_{12} (reinforced structure)

ACP Model
28.03.2017, 16:56
Strain - e1 - top
Element-Wise
Set: 1 - Time/Freq: 1.0 (Last)
Max: 0.00050737
Min: -0.00069491

Strain.1
0.00050737
0.00040489
0.00024242
7.9943e-005
-8.2533e-005
-0.00024501
-0.00040749
-0.00059996
-0.00073244
-0.00089491

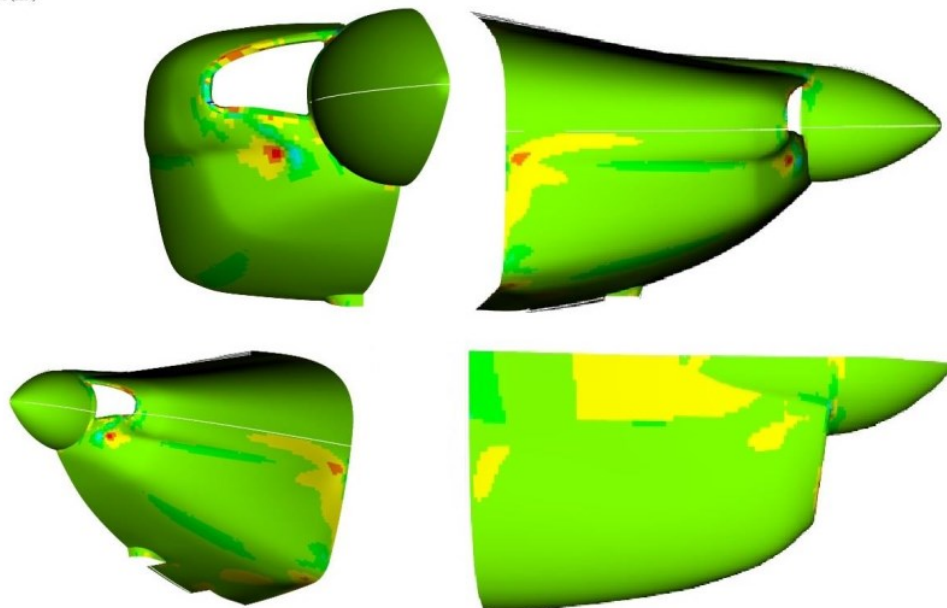


Figure 6-26 Strain distribution of ϵ_1 (reinforced structure)

ACP Model
28.03.2017, 16:56
Strain - e2 - top
Element-Wise
Set: 1 - Time/Freq: 1.0 (Last)
Max: 0.00058206
Min: -0.0010823

Strain.3
0.00058206
0.00039714
0.00021221
2.7281e-005
-0.00015765
-0.00034257
-0.0005275
-0.00071243
-0.00089736
-0.0010823

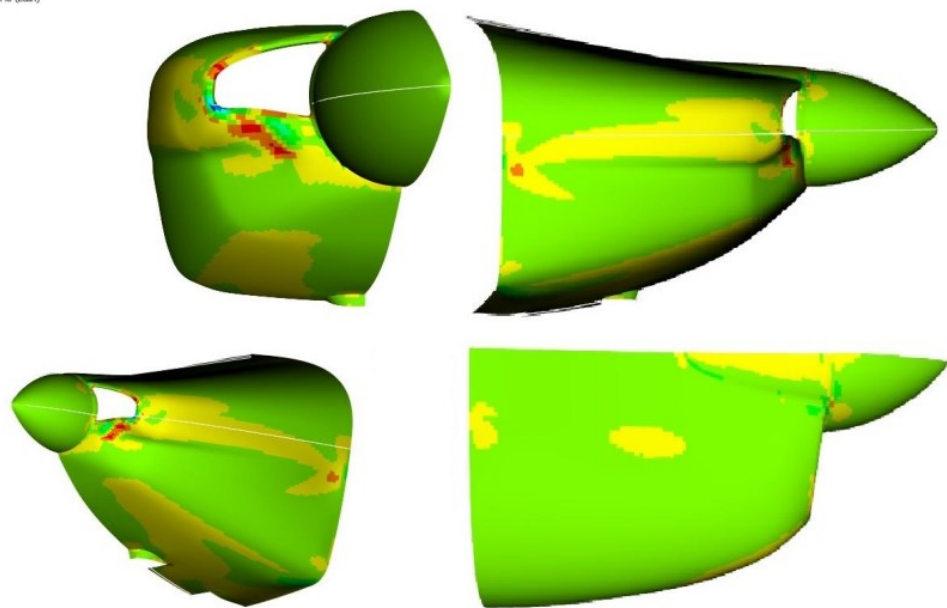


Figure 6-27 Strain distribution of ϵ_2 (reinforced structure)

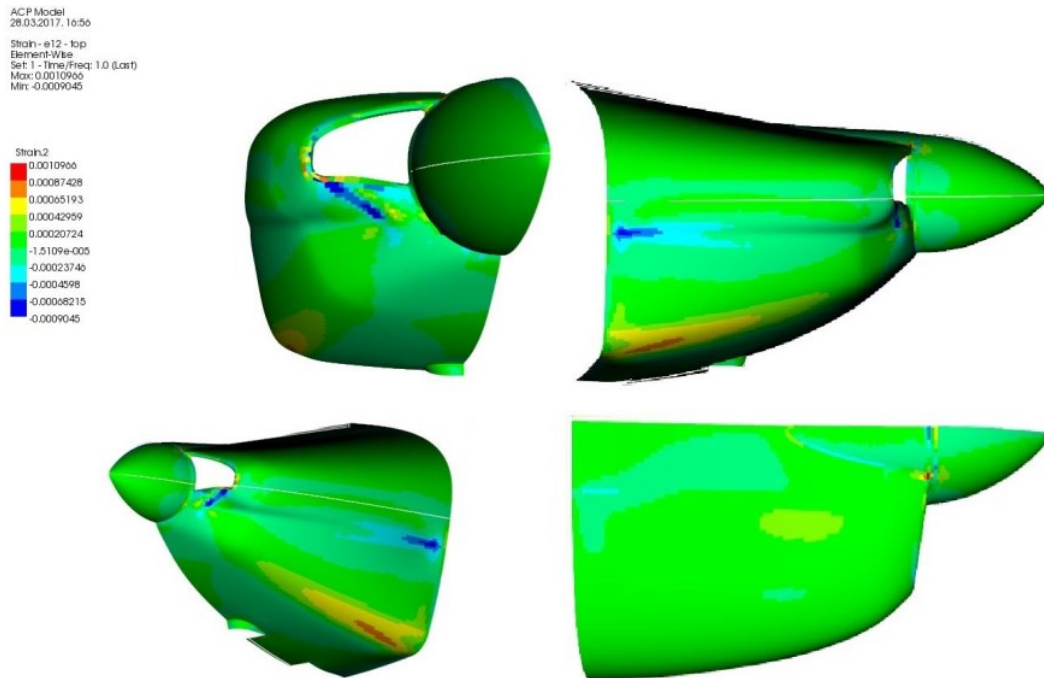


Figure 6-28 Strain distribution in ε_{12} direction (reinforced structure)

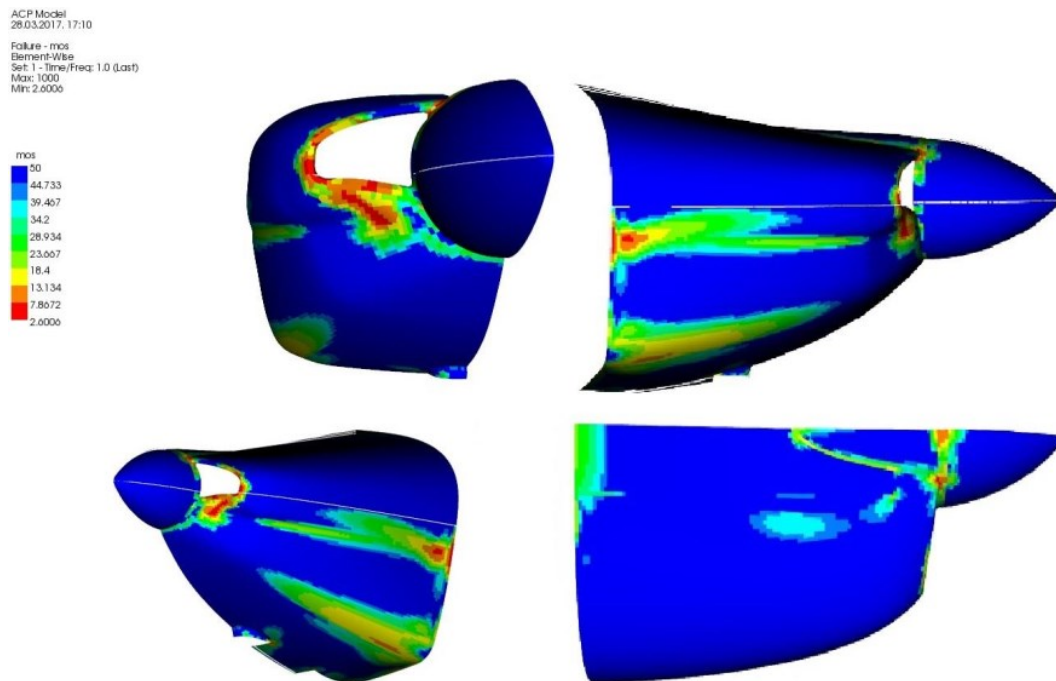


Figure 6-29 Margin of safety for reinforced layering sequence 3

Examination of the structural analysis results from Table 6-2 and Table 6-6, the reinforced structure of the engine cover shows a minor raise of the equivalent stress (around 7.5 %) and of the equivalent strain (7.3%). However, with applied reinforcement,

considerable decrease in the deflection was achieved: from 11,34 mm to 2,21 mm, which is reduction of 80%. It is also noted that the position of the maximum deflection is changed. In this case it is positioned on the lateral side of the cover, as Figure 6-22 shows.

The failure analysis results of the reinforced engine cover show that the minimum value of MoS is 2.6 (Figure 6-29), which confirms that induced stresses are well below critical values.

Presented results show that reinforcement should be applied, and that reinforced layering sequence 3 should be selected for further manufacturing and installation on the aircraft.

7 Production process definition and manufacturing of optimized engine cover

The analyses that were carried out in previous chapters of this thesis enabled the selection of the design of the engine cover that will be eventually manufactured and installed on the aircraft.

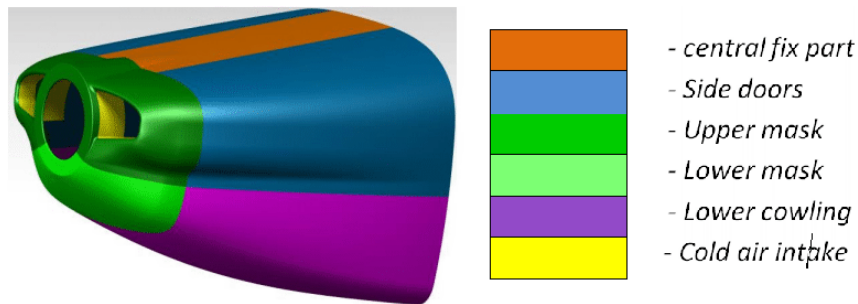


Figure 7-1 The engine cover segments

The engine cover is divided into several segments, as it can be seen in Figure 7-1.

Upper engine cover– is the assembly comprised of central fix part and side doors. The central fix part acts as a support of upper engine cover. It is fixed for the first frame of the aircraft and front mask with screw connections, while side doors are joined by hinges for central fix part and by buckles on the first frame, lower engine cover and upper mask in closed position. This assembly is to be produced in female tool from one shell, followed by cutting into appropriate segments.

Lower engine cover– acts as the support of whole structure of engine cover that is leaning against it (upper mask, lower engine cover). Lower engine cover is comprised of: lower cowl and lower mask. After manufacturing of the elements of lower cowl and lower mask in female tools, their joining is to be performed into integral element in appropriate tool.

Front mask – for operational needs, assembly of the front mask is reduced only to the upper mask. Definition of the line of mask cutting, more precisely the division of mask into upper and lower is performed in order to uninstall the propeller more easily, in order to avoid uninstallation of the whole assembly of the engine cover. The manufacture of the upper and lower mask is performed in one tool. First, the manufacture of the upper mask is performed and then the lower mask. The lower mask is countersunk for the

dimension required to provide enough space for housings of buckles and rivet nuts in order to achieve the link between two elements.

After all the aspects regarding operational capabilities and exploitation of the engine cover are met, production process can be started.

7.1 Manufacturing of the tools

In order to produce the engine cover, first it is necessary to manufacture the appropriate tools. The selected concept of the engine cover's production is based on the application of three female tools. One of the tools is used for front mask production, while the other two are used for the production of the rest of the engine cover.

The production process of tools manufacture is started by transforming the engine cover contour into G-code, the materialization of the engine cover computer design is performed. The G-code is basically computer program used for controlling the CNC machines. Programming is done in the program package on the computer by selecting the tools, method of processing, speed and entering other required instructions to the machine for making of production part. This procedure defines processing operations. Machine used for processing is three-axis milling machine with two spindles V2 2000B Forest Line (working environment $x=3500$ mm, $y=1250$ mm; $z=600$ mm). The material of production part is the Styrofoam of high density, in the shape of the cube, compounded of 50 mm thick plates that are glued together. The manufacturing of female tool is more complex than the male tool due to the existence of negative angles and impossibility of processing them on the three-axis milling machine. For that reason, the process of production of female tool is performed in several steps:

1. Machine processing of Styrofoam and manufacture of male part.
2. Creation of conceptual solution by lamination of male part.
3. Taking imprints of conceptual model for the purpose of manufacturing female tool.

Figure 7-2 show machine processing and manufacturing of the male model over which the conceptual model, made by the lamination of fiberglass and epoxy resin, is to be

placed. This step is done because the Styrofoam is quite porous material, and it is not suitable for direct imprinting for tool manufacturing because the tool surfaces would be of high roughness. The offset contour for measuring the laminate thickness of conceptual design is used and, in this case, it is 0,5 mm. Also, Figure 7-2 shows how machine draws the cutting line, which is previously predicted in the model and put into the G-code. In this way the cutting lines in the tool will be defined before the final imprinting for the female tool, which improves operability at production process.



Figure 7-2 Front mask manufacturing on PHY machine, lamination and creation of conceptual design, female tool

The lamination is performed in same way as already described in this thesis (Section 3.1.1), but in this case, it can be noticed that the tool is covered with pigment of black color that represents Gel-coat resin. This material is used for the purpose of ensuring the high quality of smooth surfaces of the composite materials, and it is applied on surface in

thin layer of 0,5mm. Gel-coat is applied on molds in liquid state and it is used in the combination with fiberglass and epoxy resin.

The rest of the engine cover is manufactured using the same technology which is used for the front mask. This tool (Figure 7-3) is comprised of two parts, for lower and upper engine cover. The tool for the upper engine cover is compounded of two parts connected on the line of the maximum width so the finished part could be easily removed from the tool.

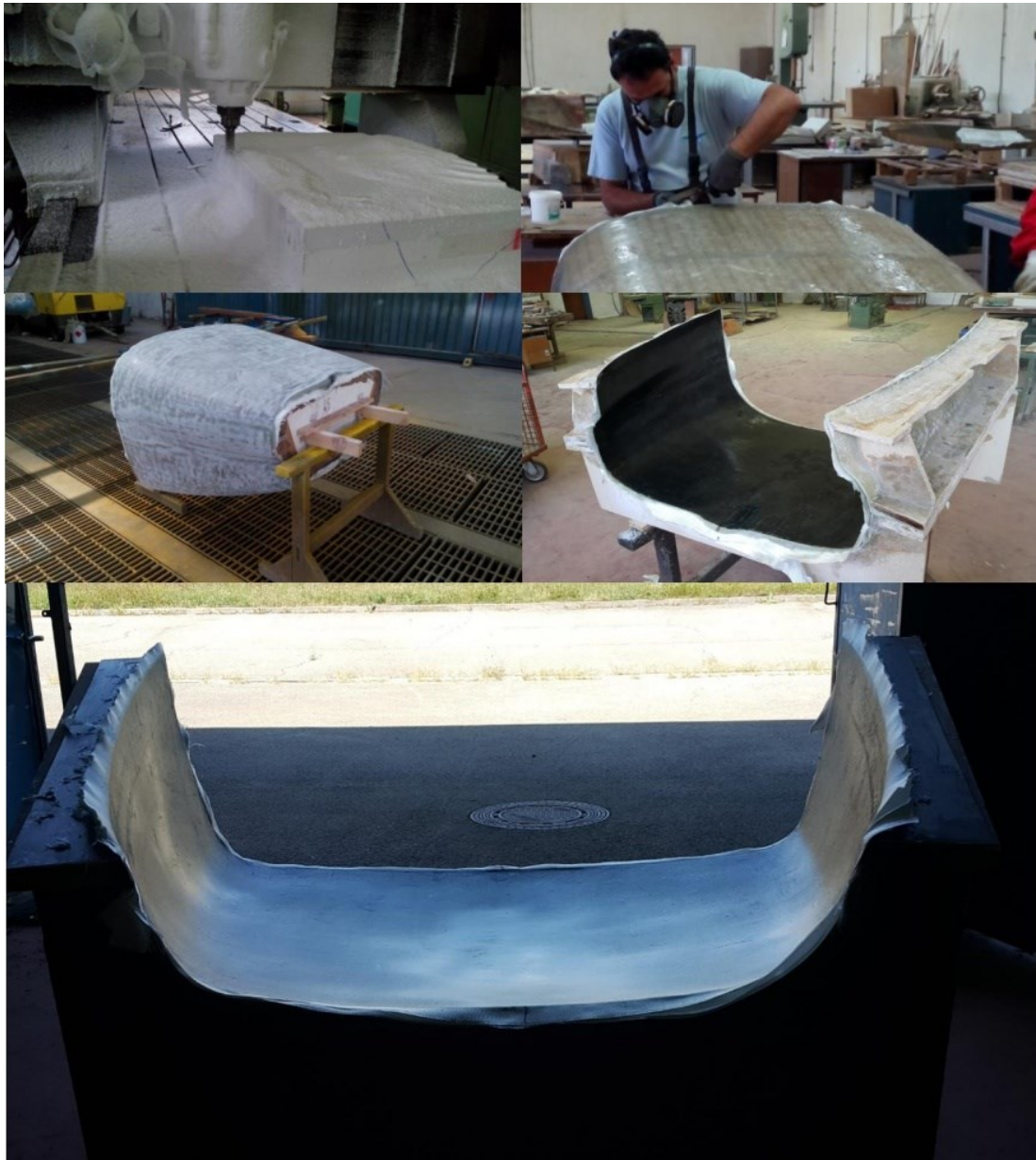


Figure 7-3 Base processing, lamination and creation of conceptual design, female tools

7.2 Production technology

The technology available in this case enables the usage the simplest production process for composite processing: hand layup [66].

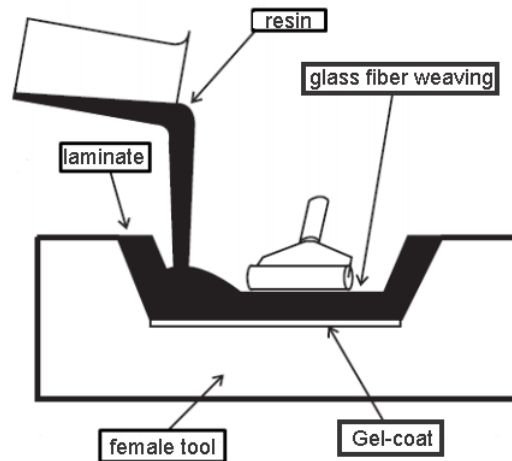


Figure 7-4 Manufacturing process

The processing and manufacturing of the engine cover's composite construction is achieved through the following operations:

1. Tool preparation – is one of the most important steps at manual layering. In order to successfully remove the finished part from the tool, it is required to coat the tool with the separator after eliminating mechanical impurities.
2. Application of paint and surface layer – these operations are done after preparation in order to ensure the highest level of smoothness of the surfaces. Thin layer of Gel-coat is applied before putting fibers in order to create protective outer layer that will not demand later processing. Unfortunately, in this case this operation is skipped but can be applied in the future.
3. Preparation of the base and the auxiliary material – during this phase the cutting of fiberglass is performed and its layering in the tool according to already defined orientation and thickness. Before the process of contouring starts, mixing of resin and hardener must be performed in ratio 1:5.
4. Description of manufacturing process (Figure 7-4) – The mixture of epoxy resin and hardener of appropriate ratio is applied evenly on the prepared base. By using brushes and press rollers, the excess air and resin have been squeezed out on sides of the tool (on the mask on the lowest point) and in this way is achieved better “watering” of fiberglass.

After completing this operation, the material was left at room temperature of 20°C for the next 24 hours until complete hardening. The process of polymerization lasted three days with the finished part kept during that period in the tool at room temperature. After that, the finished part is successfully removed from the tool and sent for final processing and installation into assembly. Some of the key moments of the engine cover production and its installation on the aircraft are presented in Figure 7-5 to Figure 7-9

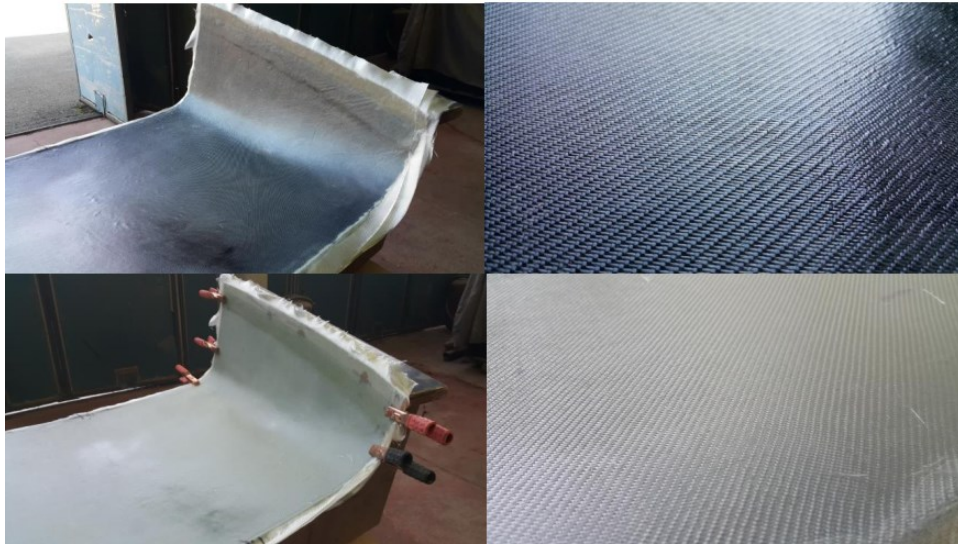


Figure 7-5 Lamination in female tool of the lower engine cover(before and after hardening)



Figure 7-6 Sandwich construction of the lower engine cover in the female tool



Figure 7-7 Finished lower and upper engine cover



Figure 7-8“Gluing” of the lower engine coverwith the front mask



Figure 7-9 The engine cover on the aircraft

8 Conclusion

This thesis presents an efficient methodology combined from analytical, experimental and, most of all, numerical methods, which involves application of composites and enables modification and upgrade of operating aircraft and its parts. This methodology is used in the design of a composite engine cover of light aerobatic aircraft.

Material used for the engine cover construction is fiberglass-epoxy resin type of the composite. Fiberglass is woven crosswise at 90° angle, made according to standard 8.4548.60 in accordance with LN 9169 of the manufacturer Integlass. Epoxy resin the resin Araldit M with hardener type HY-956 of the manufacturer Huntsman. In order to evaluate mechanical properties of the selected composite material, first, analyses were conducted in which composite were investigated from two aspects: micro-mechanics (analytical approach) and macro-mechanics (numerical FEM approach).

However, for the reason of composite's irregular structure and specific production techniques, experimental analysis of produced composite could not be avoided, and it was carried out as well. To reduce the number of experimental tests, which are expensive and time consuming, the numerical analyses were carried out and the evaluation and verification of these results were carried out experimentally. Since selected composite is used for designing the engine cover, which is exposed to wide range of temperature changing, the influence of high and low temperatures on the mechanical properties of the composite, were also investigated by numerical analyses. Those analyses showed significant influence of both low and high temperatures on the composite's mechanical properties and showed that they must be taken into consideration. The effect of elevated and lowered temperatures on the elastic properties of carbon fiber-epoxy composite lamina was studied using multi-phase unit cell (MPUC) numerical model. Obtained results confirmed that elevated and lowered temperature has noticeable influence on some elastic properties of carbon fiber-epoxy composite lamina. The following elastic properties of carbon fiber-epoxy composite lamina appear to be considerably temperature-dependent: transverse moduli of elasticity E_2 and E_3 . As shown on sample of thermally loaded composite plate, this fact may have significant influence on accurate evaluation of generated thermal stresses in real laminated composite structures, exposed to extremely high or low operating temperatures. However, this composite was not used

in the design of the engine cover (due to high costs) but results obtained here might be very useful for some future projects.

The analysis and dimensioning of cooling openings on the engine cover was conducted as well. The obtained values were used as input parameters for the computational fluid mechanics analysis. The results obtained by analytical and numerical method are compared and they are presented in this thesis. The elaboration of used methods for the purpose of dimensioning the surfaces of cross section of the cooling engine openings is also given.

The engine cover is designed in such way so it can endure stresses during the exploitation, which are: aerodynamic loads, dynamic loads caused by the vibration from running engine, and inertial loads. The determination of aerodynamic loads by numerical method (CFD) is presented in detail.

The dynamic loads were not taken into consideration in this thesis, because the selected design of the engine cover does not have direct connection with the engine which is the source of vibrations. It is, in fact, indirectly connected through air intakes whose elastic connection (rubber) absorbs the vibrations.

Next, numerical structural analyses together with the optimization of the layering sequence and failure analysis were carried out. These analyses provided data regarding stress-strain state of the four different layering sequences which through comparison with the experimentally obtained (and numerically verified) mechanical properties of the composite enabled selection of the optimal layering sequence for the engine cover manufacturing. They also showed the need for reinforcement of the upper area of the engine cover due to the rather high deflection value which jeopardized the size of the cooling gap between the engine and its cover. This reinforced structure was analyzed numerically as well, and based on these results the shape and the layering sequence of the engine cover that will be used for manufacturing were adopted. Special attention was paid to the numerical prediction of fatigue life of the damaged engine cover.

Finally, in the 7th chapter manufacturing process of the engine cover was presented, which included the production process of the corresponding tools (molds).

Carefully defined combination of analytical, experimental, and numerical analyses presented in this thesis designed methodology which enabled fast and reliable modernization of the operating aircraft. Accordingly, experimental investigations were

reduced to the necessary minimum. They were replaced with the numerical methods which were implemented through the commercial software. Used software were validated in many scientific research, which can be found in the literature. However, ultimate validation of the adopted design of the engine cover must be performed by comparing flight test results with the results obtained by the calculation conducted in the presented methodology.

The data and results obtained in the aforementioned analyses will enable the production of a composite engine cover and its installation on a specific light aircraft. It is expected that the dissertation will contribute to the further improvement of the design of composite aircraft elements, in the sense that based on its results, verified numerical models and the adopted methodology, it will be possible to effectively modify and improve aircraft that are already in operation. Also, with minor adaptation, it will be possible to use presented methodology for the design and improvement of structural parts and elements of any device.

The methodology itself can be improved by using upgraded numerical methods and software. Improvement of the composite's production process is reflected in future use of vacuum technology. Using uniform pressure effect onto laminate by more flexible diaphragm or bag before it hardens, would improve the joining of the fibers and matrix, eliminating resin excess, air pockets and resin evaporation. This would also enable production of the cheaper components of high quality.

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Изјава о ауторству

Име и презиме аутора Таха Салим Алтир

Број индекса D 34/2014

Изјављујем

да је докторска дисертација под насловом

ОПТИМИЗАЦИЈА МОТОРСKE ОБЛОГЕ (КАПОТАЖА) ЛАКЕ ЛЕТЕЛИЦЕ

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OPTIMIZATION OF LIGHT AIRCRAFT ENGINE COVER CONFIGURATION

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