Optimisation of the loading structure for Propulsive Fuselage Concept

Zdobysław Goraj, Mariusz Kowalski and Bartłomiej Goliszek
goraj@meil.pw.edu.pl
Warsaw University of Technology
Faculty of Power and Aeronautical Engineering
Warsaw
Poland

ABSTRACT

This paper presents activities performed for structural integration of the Propulsive Fuselage Concept, being studied within the European Commission founded collaborative research project CENTRELINE ("ConcEpt validation sTudy foR fusElage wakefiLIng propulsioN integration"). Project aims to demonstrate the proof of concept for the aft-fuselage mounted electric propulsion unit that ingests part of the fuselage boundary layer. The paper focuses on the design and optimisation aspects of the fuselage fan load-carrying structure integration. Structure made entirely of composites is analysed considering the most crucial load cases. Methodology for composite structure modelling using Finite Element Method are outlined, and the promising results of structure optimisation are presented and discussed.

Keywords: Composite Structure; Optimisation; FEM; Propulsion System Integration

NOMENCLATURE

ACARE	Advisory Council for Aviation Research and Innovation in Europe
APU	Auxiliary Power Unit
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CENTRELINE	ConcEpt validatioN Study foR fuselage wake-fiLling propulsion integration
EC	European Commission
FEM	Finite Element Method
FI	Failure Index
FF	Fuselage Fan
MPC	Multiple Point Constraint
PFC	Propulsive Fuselage Concept
SR	Strength Ratio
SRIA	Strategic Research and Innovation Agenda
WUT	Warsaw University of Technology

1.0 INTRODUCTION

The future of aviation will be driven by ecological and economic constraints. As air traffic increases year by year, airlines in response to growing demand increase the frequency of flights, open new routes and operate using bigger number of commuter and large aircraft. Airplanes are responsible for a large part of gases emitted to the atmosphere, such as CO_2 or NO_x. It is very important from an ecological and economical point of view to design and create effective solutions that will help to reduce the emission of harmful gases into the atmosphere. Organizations such as the European Commission (“Flightpath 2050”) [1] or ACARE (“SRIA”) [2] in their documents impose more and more stringent standards and restrictions, what accelerates the creation of new technological solutions. One of the solutions aiming, among others, to reduce fuel consumption and, hence, the emission of harmful gases into the atmosphere, is presented in the EC-funded Horizon 2020 collaborative project CENTRELINE (ConcEpt validatioN sTudy foR fusElage wake-filLIng propulsion integration) [3]. Project aims to demonstrate the proof of concept for the so-called Propulsive Fuselage Concept (PFC). Evaluation of the future propulsion system will be based on a selected R2035 reference aircraft. For the purposes of the CENTRELINE project a parametric 3D Computer Aided Design (CAD) model of the structure for the whole aircraft was created [4]. Model takes into account changes in relation to the conventional design of the reference aircraft R2035. The main changes are related to the rear mounted propulsor. Adapting this technology enforces some adjustments in the aft-fuselage load carrying structure and horizontal and vertical stabilizers arrangement. The use of an innovative solution being the object of research within the CENTERINE project, in addition to the potential benefits brings a number of factors that can affect the final performance of the aircraft in a negative way. One of the consequences of using an additional propulsion system is the increase in weight of the supporting structure. This subject is invested in the project at the Warsaw University of Technology. As the activities carried out within the consortium influence aircraft shaping, the prepared parametric model was a very important element affecting the efficiency of work on the concept of aircraft structure. One of the main responsibilities within the structural task is to prepare the concept of fuselage fan support structure, ensuring proper strength and stiffness while maintaining the lowest possible weight of the structure. Because it is predicted that the analysed technology has a chance to be introduced in use in 2035, it was assumed that the structure will be made entirely of advanced composite materials. Apart from utilising additional propulsion, CENTRELINE project also assumes the use of other innovative technologies, such as, for example, a geodetic fuselage [5]. This paper describes the aspects of working on the optimal structure supporting a fuselage fan. The initial structure was subjected to gradual modifications that resulted in a combination of optimal strength, stiffness and weight. Figure 1 shows the 3D model of the PFC Initial Design structure prepared by the WUT’s researchers.

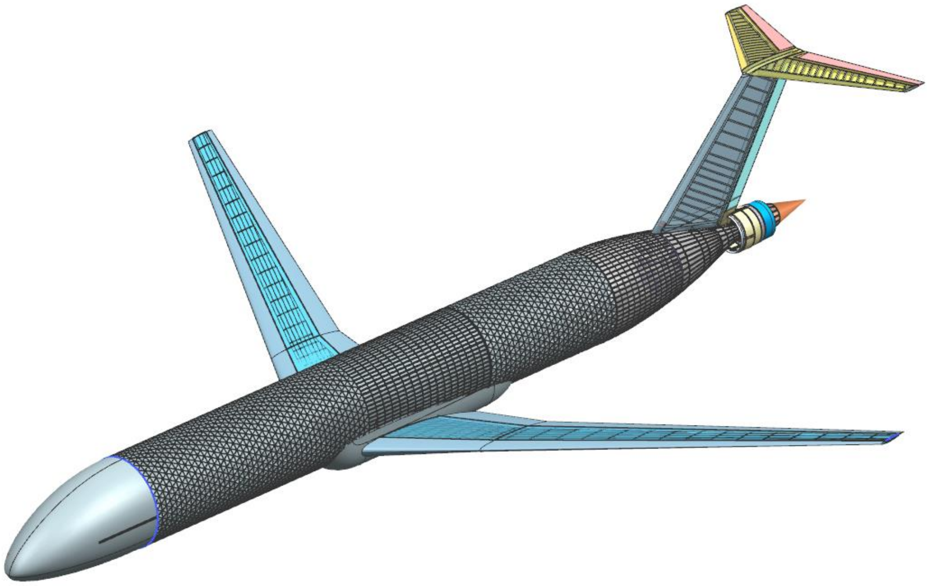

Figure 1 PFC Initial Design load-carrying structure concept

2.0 COMPOSITES MODELLING

The purpose of modelling is to examine the strength of a composite structure that transfers loads from the propulsor mounted in the aft-fuselage section. It is necessary to determine the relationship between the load applied to the multi-layer shell and the state of strain and stress in each layer. Knowledge of even an approximate state of stress or at least strain is necessary to assess the laminate ultimate strength. The shell made of the composite is modelled in general as an anisotropic material, composed of layers with orthotropic properties. In order to investigate the task of transferring loads in curved shells, a number of different theories have been derived. The example presented in this paper assumes usage of a generally recognized and experimentally confirmed statement that each shell can be approximated with a set of connected, flat elements, small enough that the curvature of the shell within them creates negligible imperfections [6]. The so-called classic laminate theory was used, applied to the Mindlin plate model [7].

The direct cause of the destruction of the composite shell is due to applying loads distribution that causes exceeding the strength of one of the layers. The purpose of the analysis is to determine the condition of the shell fragment for which permanent deformation or damage to one of the layers of the composite structure will take place. The condition of the composite may be expressed by means of stress or strain. Based on them, several strength hypotheses regarding the destruction of a single layer were formulated. Each of them formulates one or more inequality conditions in form $FI \leq 1$, where FI means Failure Index.

The Failure Index is calculated for each laminate layer and is a function dependent on the state of strain or stress and on the strength parameters of the material. Among classic strength hypotheses based on the assumption of homogeneity of the composite layers and a flat state of stress (deformation), one can distinguish [8]:

- Maximum deformation hypothesis;
- Maximum stress hypothesis;
- Hill's hypothesis;
- Hoffman's hypothesis or
- Tsai-Wu hypothesis.

At present, hypotheses considering load configuration are developed, which are based on many models that take into account the microstructure of the composite and the mechanisms of its destruction such as: propagation of microcracks, propagation of delamination, deviations from straightness of fibres and their microwaving at compression, fracture of fibre strands causing local warping. An example of such a hypothesis is LaRC03 [9]. Taking into account the limitations and the lack of some parameter's values, the Hoffman hypothesis was used in this analysis. It should be noted that the FI destruction index is not a reliable figure in the assessment of ultimate strength. In general, it can be said that during destruction its value exceeds 1. Therefore, the factor called Strength Ratio (SR) is introduced, through which the components of the stress state should be multiplied in order to obtain a state of destruction. The strength factor SR is inversely proportional to the material stress (analogous to the safety factor). Exceeding ultimate strength and susceptibility to delamination are not the only mechanisms that can lead to destruction of the structure. It must be mentioned about the loss of stability also, which is a dangerous phenomenon. In thin-wall, composite aircraft structures, it occurs in the form of buckling of coatings under the action of compressive and/or shearing forces. When analysing composite structures, the structural stability is a very important aspect and is often treated as the starting point for sizing of the structure, which greatly affects the final structural weight.

3.0 CONSIDERED LOAD CASES

The initial PFC design is a new configuration of an airplane and current regulations do not state conditions for the application of a fan at the aft-fuselage. However rationally analysing the CS-25 regulations [10], the FF can be treated according to rules that applies to engines and Auxiliary Power Units (APU). According to the regulations, the structure of the aircraft must withstand the maximum loads to be expected in service as well as the ultimate loads (limit loads multiplied by the safety factor - in general 1.5). For the PFC, the main load factor is the "limit manoeuvring load factor", which according to CS 25.337 equals to 2.5 for positive direction and -1 for negative direction. The analysed structure of the rear part of the fuselage consists of the following elements:

- Nozzle;
- Section A;
- Section B with APU installed inside;
- Nacelle;
- Stator and
- Fuselage Fan.

The aft-fuselage structure elements in exploded view are presented in the Figure 2.

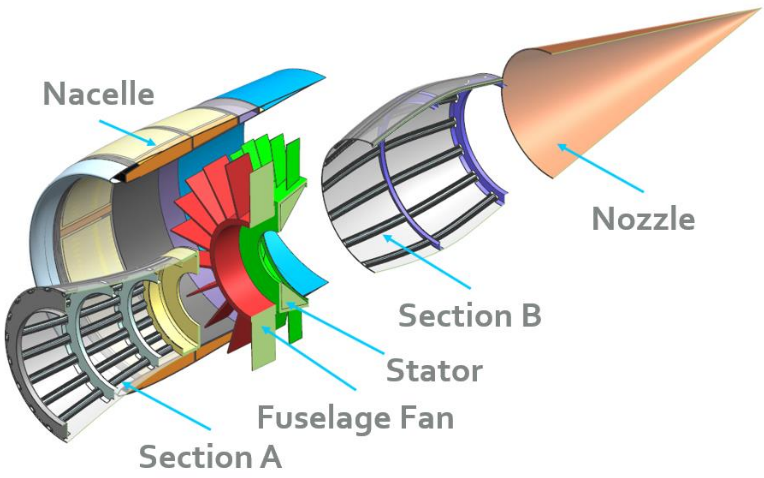

Figure 2 Aft-fuselage assembly

The main sources of loads that affect the above structure are:

- Inertia loads coming from the structural weights;

- Torque coming from rotating parts of FF;
- Aerodynamics loads on the nacelle and
- Gyroscopic loads of FF and APU rotating parts.

Of course, the above-mentioned load sources do not work individually. Considering the innovative placement of the propulsor as well as the nature of the operation of the entire assembly, the CS-25 regulations were analysed. The following load cases were selected as critical:

Table 1
Considered load cases

Load case	**Regulation**
Emergency landing	CS 25.561
Side load	CS 25.363
Maximum torque	CS 25.361
Gyroscopic loads	CS 25.371

Let’s consider these four load cases in details:

- CS 25.561 – Emergency landing

During operation, in extreme hazardous situations, the aircraft may be damaged, however, it must be crafted to protect its passengers as much as possible. Both APU and FF are large masses mounted in the fuselage, what is not a desirable solution from the security point of view. According to CS 25.561(c)(2) their supporting structure must withstand the following ultimate inertia forces acting separately in case of emergency landing:

1. CS 25.561(b)(3)(i) Upward 3.0g
2. CS 25.561(b)(3)(ii) Forward 9.0g
3. CS 25.561(b)(3)(iii) Sideward 3.0g
4. CS 25.561(b)(3)(iv) Downward 6.0g
5. CS 25.561(b)(3)(v) Backward 1.5g

- CS 25.363 - Side load on engine and auxiliary power unit

Mounting and supporting structure of APU and FF must be designed for lateral loads with a maximum limiting factor in yawing condition but not less than 1.33. In the case of the PFC aircraft, the smallest possible limit factor was adopted.

1. CS 25.363 n_y (g)= 1.33

- CS 25.361 - Engine and auxiliary power unit

The following regulation describes a complex load case. When considering FF in the case of CS 25.361(a)(1)(i) the mounting and supporting structure must be designed to transfer a limit engine torque corresponding to take-off thrust, acting simultaneously with 75% of the maximum limit load. In the case of CS 25.361(a)(1)(ii) limit engine torque corresponding to the maximum continuous, acting simultaneously with the maximum limit load. In case CS 25.361(a)(3)(i) mount and supporting structure must withstand 1-g level flight and limit engine torque imposed by a sudden engine deceleration due to malfunction.

Table 2
Fuselage Fan Loads

CS 25.361	**torque [kNm]**	**n_{z+}(g)**
CS 25.361(a)(1)(i)	35,88	1,88
CS 25.361(a)(1)(ii)	20,86	2,5
CS 25.361(a)(3)(i)	11,95	1

The mount and support structure of the APU must be designed to withstand the 1-g flight load and limit engine torque imposed by a sudden engine deceleration due to malfunction-CS 25.361(b)(1) or maximum acceleration of the APU CS 25.361(b)(2).

Table 3
Auxiliary Power Unit Loads

CS 25.361	**torque [kNm]**	**n_{z+}(g)**
CS 25.361(a)(3)(i)	2,50	1
CS 25.361(a)(3)(ii)	1,35	1

- CS 25.371 – Gyroscopic loads

During flight rotating parts of FF and APU generate gyroscopic loads arising from different conditions. According to CS 25.371 to prove compliance of this regulation the pitch manoeuvre must be carried out until positive limit manoeuvring load factor

Table 4
Fuselage Fan Gyroscopic Loads

CS 25.371	**M_y [kNm]**	**n_{z+}(g)**
CS 25.331(c)(1)	4,91	2,5

Table 5
Auxiliary Power Unit Gyroscopic Loads

CS 25.371	**M_y [kNm]**	**n_{z+}(g)**
CS 25.331(c)(1)	1,03	2,5

4.0 LOAD-PATH CONSIDERATIONS

The case analysed under the CENTRELINE project is not a typical solution for aircraft currently in use. Due to an innovative design, the case should be analysed for the occurring loads. One of the fundamental problems in the design of the structure was the issue of transferring loads from the nacelle to the main supporting structure (mainly section A). An unwanted operation from the aerodynamic point of view would be to place additional structural elements in the front part of the nacelle, which would cause a flow disruption in front of the fan and thus a decrease in its efficiency. However, it is possible to use the stator as a load bearing element, provided that its geometry allows it and the stresses occurring in it do not exceed the critical values. To avoid reducing the aerodynamic efficiency of the fan, the transfer of loads from the nacelle through the stator vanes is the most advantageous solution. In CENTRELINE project, the aerodynamic optimization of the stator vanes is the subject of a separate task, conducted by University of Cambridge [11]. The analysis described in this article was carried out for geometry that is not the final version. As mentioned, the aerodynamic loads generated on the outer surface of the nacelle are meant to be transferred by the stator vanes. The two-dimensional pressure distribution has been converted to the 3D version by revolving relative to the symmetry axis of the structure. The pressure distribution is presented in the Figure 3. It shows that the maximum overpressure occurred just behind the fan, which verifies the correctness of the pressure application.

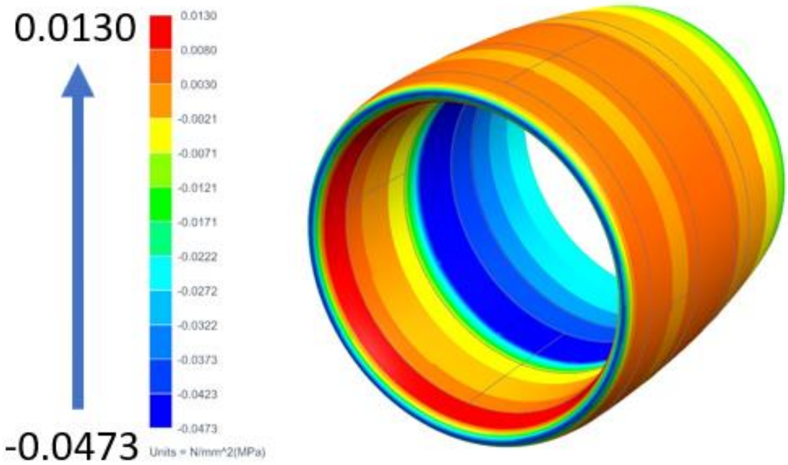

Figure 3 Pressure distribution over the Fuselage Fan nacelle (Ma= 0.82, FL = 350)

During analysis, the degrees of freedom of the nacelle were removed at the stator vanes attachment points. As a result of the carried-out calculations, a verification of the strength and stiffness of the nacelle outer shell were obtained, and a reaction force was derived at the stator mounting location, which made it possible to carry out a preliminary stator strength analysis for the current shape of the stator blades. The obtained reaction force was multiplied by the safety factor and applied to the stator ring model to verify its strength and stiffness. A typical aluminium alloy was used for the analysis, but in the final design other, more advanced material may be used to ensure better strength properties. The maps of stresses and displacements reported in the structure are presented in Figure 4.

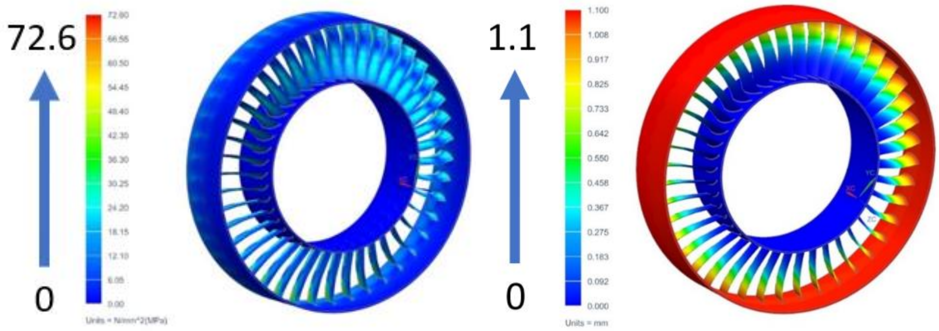

Figure 4 Von Mises stresses (left) and maximum displacement of the stator ring (Ma = 0.82, FL = 350)

From Figure 4, it follows that the maximum calculated von Mises stresses in the structure reaches 72.6 MPa, which, with the properties of the material used, gave a safety factor of about 4. The maximum displacement was 1.1 mm. The analysis shows that stator blades can be treated as both structural and aerodynamic elements. The current shape provides adequate strength and stiffness of the structure, which can be further improved by using a different material. Due to the durability of the stator, additional structural elements are not needed in front of the fuselage fan.

5.0 OPTIMISATION PROCESS

5.1 Initial geometry

In order to carry out the analysis of the load-carrying structure, a geometric model based on the parametric CAD model of the PFC Initial Design aircraft was prepared. To be able to perform the first iteration of strength calculations some assumptions regarding thickness, number of layers or type of structure were made. Both in section A and section B, a semi-monocoque structure was used, consisting of an outer shell, stringers and frames. It was assumed, that the whole structure is made using carbon-epoxy laminates and sandwich structures. Stringers are made of unidirectional carbon composite, the frames are made of a quasi-isotropic multi-directional composite, while the outer shell is a sandwich structure. The frames to which the engine is attached are additionally reinforced to allow a rigid and secure connection. The structures for the initial concept are shown in the Figure 5.

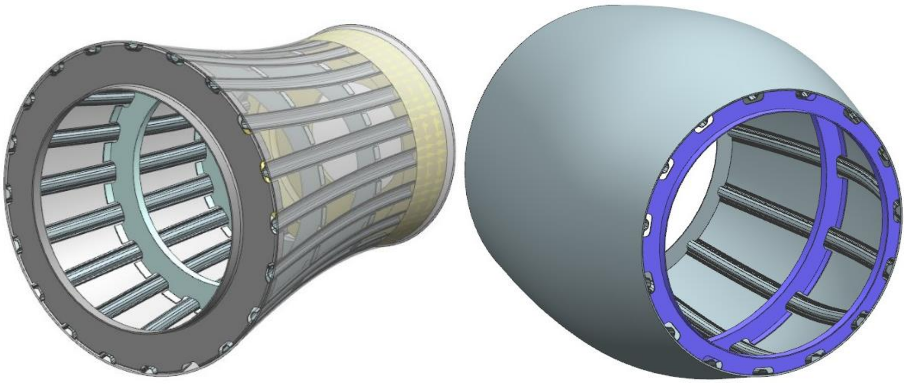

Figure 5 Initial structure design for Section A and B

5.2 FEM Model description

The structure design shown in the previous chapter has been verified using the Finite Element Method. The results of the first iteration gave an idea of the strength of the structure and allowed to identify areas where the weight can be reduced. In the next stage, a number of composite layers was reduced at these points, what resulted in a reduction in the weight of the structure. This process was repeated iteratively to obtain adequate strength, stiffness and resistance to buckling while maintaining the smallest possible weight of the structure.

Because the thickness of the structure is much smaller than its other dimensions, the outer shells and shaping frames were modelled using 2D elements, while the one-dimensional elements were used to model the stringers. The finite element mesh for the model has been prepared using elements with a maximum side length of 20mm. The grid consists of 128214 finite elements. The masses of the parts generating loads in the designed structure have been modelled as concentrated masses and connected to the structure using the Multiple Point Constraint (MPC). For section A, the mass of the APU, located in its centre of gravity, was connected to the structure by means of RBE3 [12] elements, whereas the mass of the assembled fuselage fan by means of RBE2. In the case of section B, RBE3 elements were used to connect the concentrated mass of the APU with the structure. The finite element meshes for the output geometries of sections A and B are shown in the Figure 6.

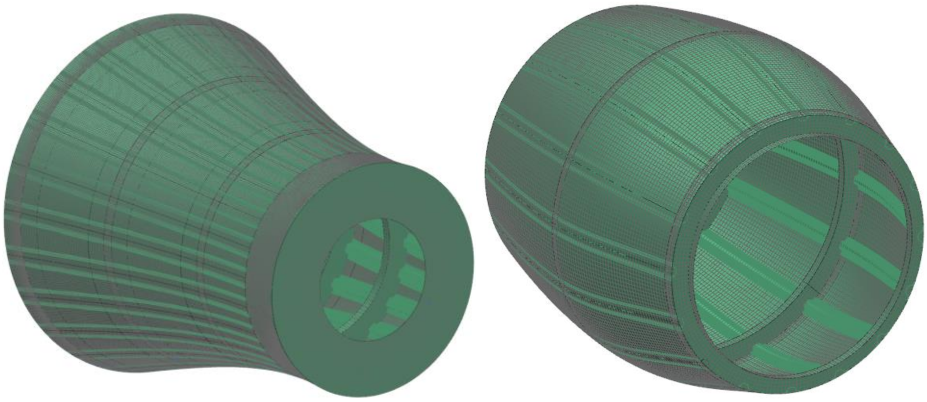

Figure 6 Finite element meshes for sections A and B

Due to the displacement with a significant value in relation to the thickness of the structure, it was decided to use non-linear analysis. A FEM analysis was carried out for all load cases listed in chapter 3. The CAD/CAM/CAE software that was used for the analysis made it possible to generate a report for the laminate, illustrating the state of stress of the structure on the SR coefficient maps. The Advanced Post Report takes into account all calculated load cases and all laminate layers, generating a resultant SR for entire part. The analysis was supplemented with Linear Buckling calculations for the two most demanding load cases.

5.3 Section A analysis

After the first iteration of the calculations, a map of the SR coefficient was generated, which is presented in Figure 7.

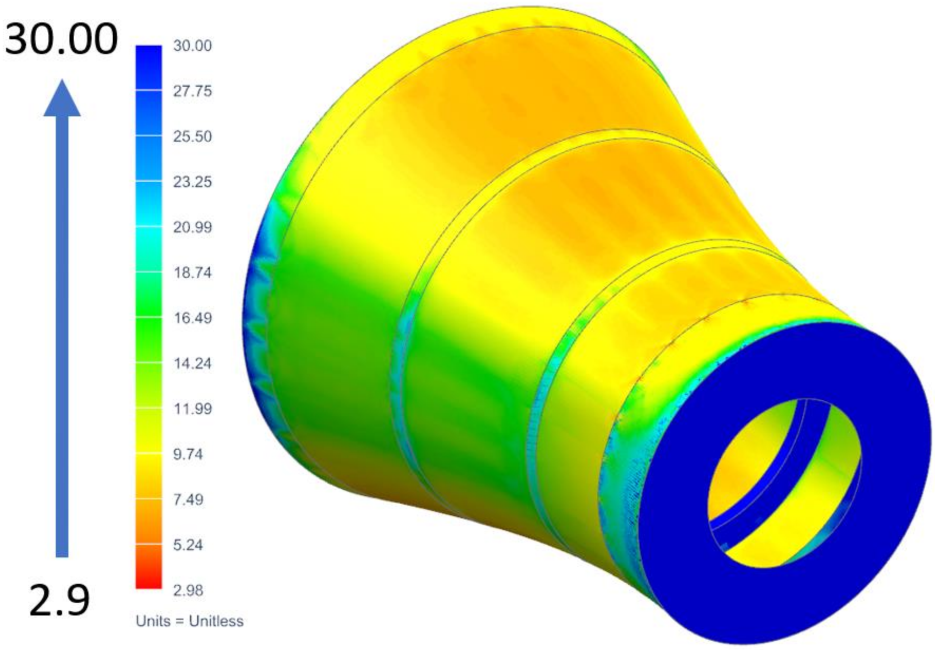

Figure 7 Strength Ratio distribution for Section A

The minimum SR was equal to 2.98 for the case under consideration, which means that the proposed initial structure is able to transfer loads almost three times higher. However, it can be seen that the area of the greatest effort is limited only to small fragments of the structure. In the majority of the structure, the coefficient reached the value of about 9 and above, which means that in these places the structure can be significantly slimmed down. The shaping frames are minimally loaded, the SR was even 30 or more. Very low loads were also observed in the stringers. It should be taken into account that this is a conceptual design that does not consider many aspects to be tackled at a later stage of design studies. In the case of the frames, it is desirable to ensure their adequate strength in order to be sure that potential elements of the aircraft systems attached to them will not cause its failure. The frame to which the fuselage fan is attached is designed with a high margin to allow the introduction of the significant forces generated by FF during its operation. The first stage of the analysis showed that the initial structure concept is not optimal and requires the mass reduction. Due to low stresses occurring in the stringers, it was decided to change the concept from the semi-monocoque to the monocoque structure, composed only of the load transferring outer shell and the forming ribs. After changes involving the removal of stringers and a gradual reduction in the number of laminate layers, subsequent iterations were performed until the SR coefficient the closest to 1 was reached. After achieving the expected results in terms of strength, the mass of structure was 65% less than the initial mass. In the next stage, the buckling strength of the structure was checked. Unfortunately, this analysis showed that the structure is buckling rather quickly, already for loads equal to 34% of the maximum loads. The SR coefficient map for this version of the structure and the first buckling mode are shown in Figure 8.

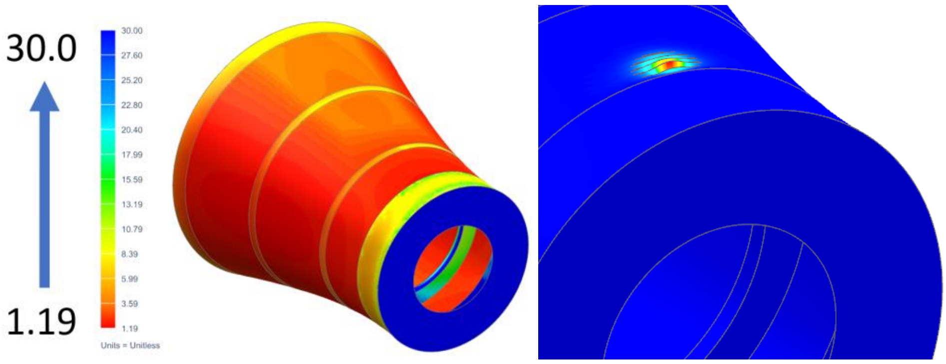

Figure 8 Section A: Strength Ratio (left) and first buckling mode

To improve buckling resistance, a sandwich structure core with a greater thickness was used, as well as additional layers of carbon fabric, which also aimed to stiffen the structure and reduce displacements. These treatments made it possible to obtain an adequate buckling structure resistance, enabling the desired rigidity and strength of the structure to be obtained. The maximum value of the SR coefficient for the final version was 2.38, the maximum stresses according to the von Mises hypothesis were 175 MPa. The contour maps for the SR coefficient and the maximum stresses are shown in Figure 9. The first mode of buckling is observed when loads exceed 110% of the maximum value. The structure meets all the assumed strength and stiffness conditions for the analyzed load cases.

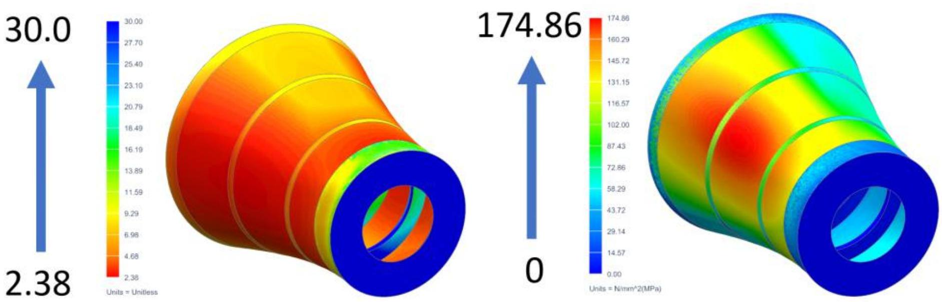

Figure 9 Final design SR (left) and von Mises stresses for Section A

5.4 Section B analysis

Section B of the structure is loaded only with forces generated by the APU, therefore it is expected to have lower stresses level and therefore lower mass than Section A. For the initial version of the structure of the Section B after the first iteration of calculations for all load cases, the map of the resultant SR is shown in Figure 10.

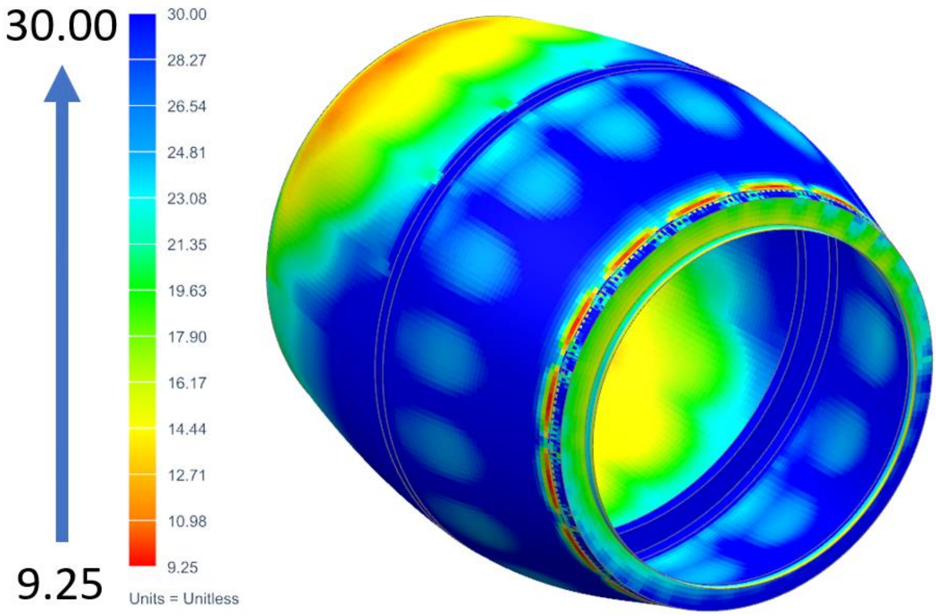

Figure 10 Initial design SR for Section B

The analysis carried out showed, that structure of Section B was also oversized. In this case the minimum SR coefficient was equal to 9.25, but also in this section similarly to section A, the minimum SR occurred only in small areas of the structure. For most areas of the structure, this coefficient has values above 19.

In the first stage of optimization, similarly as for section A, the semi-monocoque structure concept was changed to monocoque and the number of laminate layers in the outer shell was reduced. Also, as in the case of Section A, the shaping frames have been designed with a strength reserve, which slightly increases the mass of the structure, but provides adequate strength when fixing components and systems at a later stage of design. As the safety factor is taken into account at the stage of applying loads, the calculation aims at reducing the SR to the value closest to 1 in the whole structure. After removing the stringers and gradually reducing the number of laminate layers, it was possible to obtain the SR coefficient with a minimum value of 1, which enabled weight saving of almost 60%. It appeared, that after reducing the number of layers the structure buckling was initiated under a load less than the maximum load occurring in the structure. For the case of torque load, a local buckling was recorded for a force equal to about 90% of allowable forces. There were also problems with large displacements in the structure. The SR map and the first buckling form are presented in Figure 11.

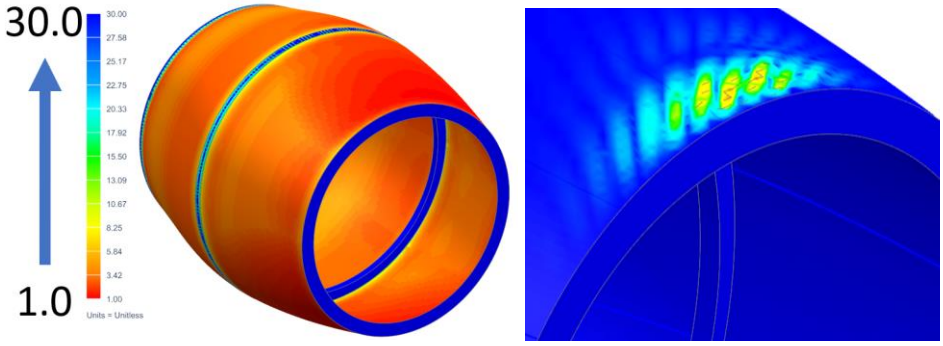

Figure 11 Section B Strength Ratio (left) and first buckling mode

Similarly, in the case of section A, there was a problem with stiffness and buckling in section B. To solve this problem, the thickness of the sandwich core was increased in the first stage. This procedure ensured the improvement of buckling resistance, the first buckling mode appeared then at a load equal to 120% of the allowable. However, to improve the stiffness of the structure, an additional layer of biaxial carbon prepreg was also added.

As a result, the minimum SR coefficient reached the value of 2.91 while the maximum von Mises stresses in the structure were equal to 180 MPa. For a structure that meets the strength requirements, the mass reduction relative to the initial version was almost 51%. Resulting SR and von Mises stresses distribution for the optimised Section B structure are presented in the Figure 12.

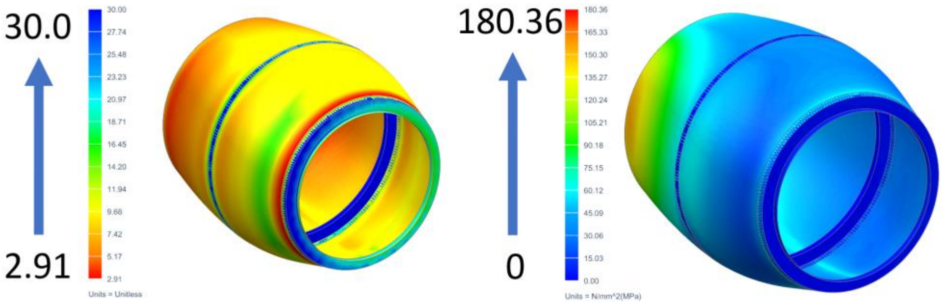

Figure 12 Final design SR (left) and von Mises stresses for Section B

6.0 CONCLUSION

This paper presents a general approach to the optimization of the load-carrying structure at the conceptual design stage. The method of identification of structural loads is presented, the method of modelling composite structures and the hypotheses used to identify areas exposed to destruction are also outlined. A series of calculations have been made for a structure subjected to iterative changes to ensure adequate strength while reducing the weight of the design. The structure under study has been divided into sections to enable an effective iterative process by reducing calculation time. In total, through the changes introduced in the structure, it was possible to reduce the mass of the main elements by almost 51%. In the case of both sections, the sizing of structure was based on requirements for buckling mitigation. Taking into account only the loads and material ultimate strength, the mass reduction was even much higher, but ensuring adequate resistance to buckling caused an increase in weight by about 15%. It should be noted that this type of analysis is useful at the conceptual design stage. Numerous simplifications have been applied, however, at a later stage of the analysis, the case must be supplemented with more detailed information on load-generating elements in the design area and thus affecting the state of stress and strain. The main objective of the CENTRELINE project is to validate the proposed concept of an additional propulsor in the back of the fuselage, so the calculations and knowledge gained thanks to them are very useful in the conducted analysis. The information about the weight increase caused by the introduction of additional forces from the propulsor will be used at further stages of the project to estimate the achievable profits resulting from the application of this innovative solution.

ACKNOWLEDGMENTS

This paper is based on the work performed by the CENTRELINE project consortium. The CENTRELINE project has received funding from the European Union's Horizon 2020 research and innovation program under the Grant Agreement No. 723242.

REFERENCES

[1] European Commission, "Flightpath 2050: Europe's Vision for Aviation", Report of the High Level Group on Aviation Research, Publications Office of the European Union, Luxembourg, 2011

[2] Advisory Council for Aviation Research and Innovation in Europe, "Strategic Research and Innovation Agenda", Brussels, 2012

[3] Seitz, A., Peter, F., Bijewitz, J., Habermann, A., Goraj, Z., Kowalski, M., Castillo, A., Meller, F., Merkler, R., Samuelsson, S., Petit, O., van Sluis, M., Della Corte, B., Wortmann, G., Dietz, M., "Concept Validation Study for Fuselage Wake-Filling Propulsion Integration", 31st Congress of the International Council of the Aeronautical Sciences, Belo Horizonte, Brazil, September 09-14, 2018

[4] Goraj, Z., Goliszek, B., Kowalski, M., Seitz,A. , Peter, F., Meller, F., "Strategy and Implementation of a Parametric CAD Model for R2035 Aircraft Structure and External Configuration", 31st Congress of the International Council of the Aeronautical Sciences, Belo Horizonte, Brazil, September 09-14, 2018

[5] Goraj, Z., Kowalski, M., Goliszek, B., „Stress, strain and displacement analysis of geodetic and conventional fuselage structure for future passenger aircraft" READ Conference, Brno, Czech Republic, 2018

[6] Zienkiewicz, O., C., "Finite Element Method: Its Basis and Fundamentals" ELSEVIER, 2013

[7] Jones, R., M., "Mechanics of Composite Materials", 2nd edition, Taylor & Francis, 1999

[8] Carey, J., P., „Handbook of Advances in Braided Composite Materials", Woodhead Publishing, 2017

[9] Davila, C., G., Camanho, P., P., "Failure criteria for FRP laminates in plane stress", NASA/TM-2003-212663, 2003

[10] European Aviation Safety Agency: Certification Specifications for Large Aeroplanes CS-25, 2007

[11] Castillo Pardo, A., Hall, C. A., "Aerodynamics of Boundary Layer Ingesting Fuselage Fans", ISABE 2019, Canberra, Australia, 2019

[12] SIEMENS, "Element Library Reference", retrieved from: https://docs.plm.automation.siemens.com/data_services/resources/nxnastran/10/help/en_US/tdocExt/pdf/element.pdf, Page accessed: November 2018