STRATEGY AND IMPLEMENTATION OF A PARAMETRIC CAD MODEL FOR R2035 AIRCRAFT STRUCTURE AND EXTERNAL CONFIGURATION

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Abstract

The proof-of-concept for a novel propulsion system integration concept – the so-called Propulsive Fuselage Concept (PFC) – is performed in the CENTRELINE project. The PFC aircraft design is based on two selected reference aircraft: R2000 baseline aircraft and R2035 reference aircraft.

This paper is focused on the development of a parametric CAD model for the advanced reference aircraft R2035. The CAD model will include the external geometry of the whole clean (flaps and slots undeflected)/ unclean (flaps and slots deflected) aircraft and an internal structure of the main wing, rear part of fuselage and the empennage. The CAD model is a useful tool for changing internal topology, internal and external flow simulation, stress, strain and displacement assessment, checking if lifting surfaces can be displaced without any geometrical constraints, assessment of structure weight and many other more or less important tasks. In CENTRELINE, the CAD model is used as part of a detailed benchmarking of the optimized PFC aircraft design and performance properties, including geometry, weights and fuel burn for typical missions against the R2035 reference aircraft. Based on this CAD model, advanced numerical methods will be used to assess the state of strain, stress and local displacement for certification-relevant load cases according to CS-25 for the fuselage and nacelle aero-structural pre-design. The pre-design activity and numerical simulation will be iteratively repeated and directly fed into the aircraft sizing and optimization process. In this paper two sets of fuselage samples ("classic" and "lattice" composite structures) have been designed: the "classic" concept with longerons, frames and skin, and the "lattice" concept with helical ribs, hoop ribs and skin. Both samples have been analysed using FEM, loaded with a synthetic load scenario. *Sensitivity of these models versus the angles between ribs, helical and hoop ribs numbers, frame weights and other parameters has been performed for 6 different versions. The carried out analysis proved that increasing the number of hoop ribs and reducing an angle between helical ribs has the most beneficial impact on the fuselage stiffness. It was found that the maximum displacement of the lattice grid can be reduced almost on 25% in comparison to the reference case.*

1. General Introduction

According to "Flightpath 2050" [1] and *SRIA* issued by ACARE [2], great challenges are posed for aviation in order to sustainably protect the natural environment. Among many of targets for future aircraft, some are being put on the reduction of harmful gaseous emissions. Comparing year 2050 and 2000, CO_2 emission should be reduced by 75%, and NO_x emission by 90% [1,2]. Another environmental aspect that needs to be improved is noise generated by flying aircraft. According to the documents [1,2] the noise should be reduced by 65% until year 2050. To meet these objectives declared by the European Commission (EC), every field of Air Transport System needs an improvement. Let focus for example on aerodynamics, propulsion and structure design. The CENTRELINE project [3] aims at the prove-of concept for a wake-filling propulsion system integrated with the aft fuselage section [4] – the so-called Propulsive Fuselage Concept (PFC) – as illustrated in Fig. 1.

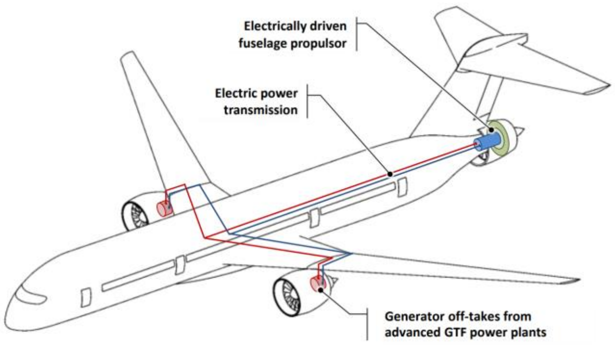

Fig. 1. Turbo-electric Propulsive Fuselage Concept (PFC) investigated in the CENTRELINE project [3]

The project targets 11% CO_2 reduction for a PFC aircraft design against an advanced conventional aircraft with turbofan propulsion, suitable for an entry into service in the year 2035 – the R2035 reference aircraft [5].

This paper describes the parametric CAD model of the R2035 reference aircraft. To enable execution of CFD analysis, design of load carrying structure arrangement or provide a FEM analysis, a suitable 3D CAD model is needed. The model developed in the present context is mainly tailored for the needs of structural design. Basic geometric features were derived from manufacturer's 3-view drawings of an Airbus A330 aircraft [6]. The resulting CAD representation was parametrized to the greatest possible extent, what enables easy modifications both when it comes to external geometry features and internal load carrying structure concept.

This article describes the overall design process and presents an example of using the model to analyze the impact of some parameters on the stiffness of composite geodetic [7] fuselage structure.

2. Aircraft model

The initial concept of load carrying structure of the reference aircraft have been designed in Siemens NX integrated software. The baseline aircraft representing a year 2000 state-of-art in the CENTRELINE project, the R2000, is related to Airbus A330-300 with slightly increased payload and range [8]. While the fuselage was stretched to be able to accommodate 340 PAX [8], all other geometric properties remain the same as for A330-300 geometry [6].

The reference R2035 and PFC aircraft in CENTRELINE will have similar configurational layouts as the baseline R2000 aircraft. Only the PFC aircraft layout features a T-tail arrangement and the boundary layer ingesting propulsive device at the aft-fuselage.

Modelling of the aircraft was divided into a few phases related to wing, fuselage, horizontal stabiliser and vertical stabiliser so the parametrisation was easier to be done. In all these phases the main component was selected (wing, fuselage, horizontal and vertical stabilizer) and its main dimensions were predefined. For example, in the case of wing there were: 2D geometry of wing section, chord length, wing twist and span. Then those parameters were used in sketches and functions in model history. Of course, these functions must be used in a proper order so as the model could update automatically after changing dimensions without any mistakes.

Main components were later combined in a file in order the assembly with element's positions might be also parametrized.

Visualization of R2000 baseline aircraft and its external geometry is presented in Fig.2.

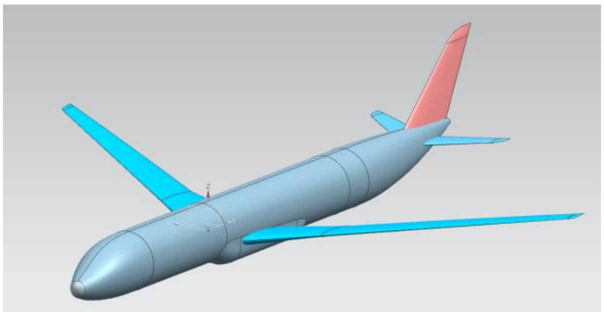

Fig. 2. R2000 baseline aircraft and its 3D model in NX, state of the art technology based on year 2000

The external geometry of R2000 aircraft model was later used to create R2035 with advanced turbofan propulsion as well as the PFC aircraft at a limited amount of effort (in terms of programmer work and computing time).

3. Fuselage structure concept

Nowadays the most common fuselage structure in commercial aircraft has a form of composite stringer structure, see an example shown in Fig. 3. That concept consists of a skin, frames and longerons [9-10].

Fig. 3. Airbus A350 stringer fuselage structure [11]

CENTRELINE project aims the market entry at 2035 [5] and therefore the considered technologies must correspond that time. Currently an old type of design for the airframes is reconsidered in connection with progress of maturity of composite technology. Aeronautical experts believe that the lattice composite structure would be a good design selection for such a structure [7,12-14]. Lattice structure consist of skin and the helical and hoop ribs made from unidirectional carbon fibre reinforced plastics (CFRP). An example is presented in Fig. 4

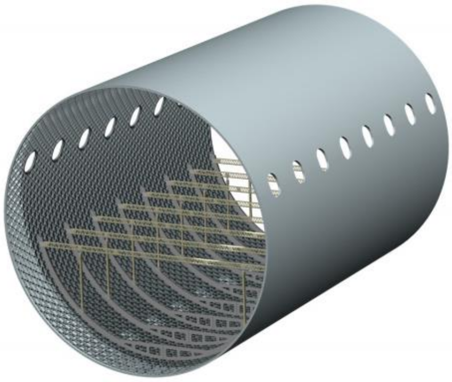

Fig. 4. Example of fuselage lattice structure [15]

Based on the cylindrical part of R2000 fuselage, two sets of the composite structures samples (Fig. 5) have been designed: the “classic” concept with longerons, frames and skin, and the “lattice” concept with helical ribs, hoop ribs and skin.

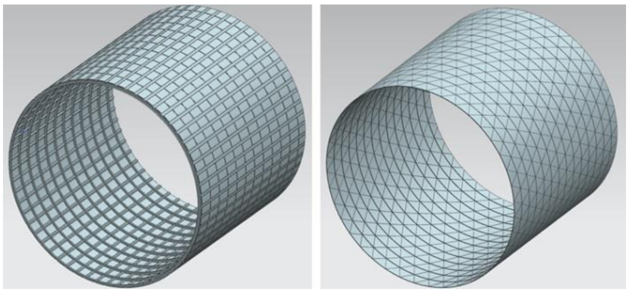

Fig. 5. CAD model of a “classic” and “lattice” structure

Both samples have been analysed using FEM within Nastran module. The structure was fixed from one side (all displacements at the boundary surface perpendicular to tube axis were assumed to be equal to zero), while on the other side of the tube the shear forces were applied. Both structures were also loaded with internal pressure of 0.0763 MPa.

In both cases the constrains, forces and geometrical parameters (tube length and diameter) were assumed to be the same. So, among variables needed for the reference model parametrisation there are thickness, number of plies in the tube structure and other parameters. For both samples those parameters were subject of changing to obtain similar level of stress in the range of about 500 MPa.

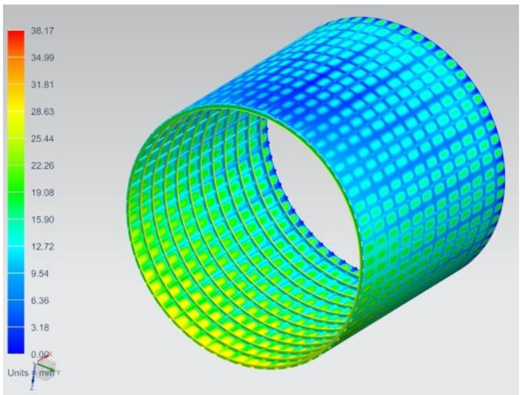

Fig. 6. Classical structure displacement (in the range of 0 to 36 mm)

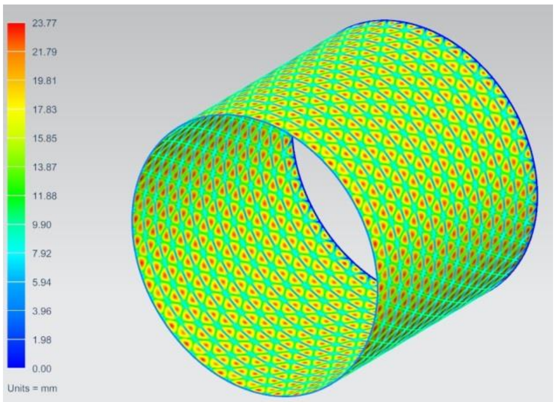

Fig. 7. Lattice structure displacement (in the range of 0 to 24 mm)

Table 1. Comparison of analytical results - max displacement and max stress for classical and lattice structure reference model

Structure	Max. displacement [mm]	Max. stress [MPa]
Classic	38.17	478
Lattice	23.77	509

Results in presented in Table 1 show that for the same level of applied forces and the same level of stress in the airframe, the lattice structure has better stiffness properties. Weight calculation performed for this case shows that lattice structure weight is 22% lower than the corresponding weight of the classical structure.

4. CAD/CAE basic optimization

Having confirmed better strength, stiffness and weight properties of the lattice structure, in the next step one prepared a proper **associative CAD model**, so to be able transfer the model parameters automatically to CAE module in NX.

Length and diameter of sample of the associative CAD model are the same as in the previous cases. For basic optimization the following variables are defined:

- Number of hoop ribs,
- Number of helical ribs,
- Angle between helical ribs.

Those parameters have been defined as separate expressions in NX, see Table 2.

Table 2 Parameters (names, values, units, types) needed and useful in parametrisation process

	Name	Value	Unit	Dimensionality	Type
1	angle between ribs	60	deg	angle	Num.
2	no helical-ribs	80	-	constant	Num.
3	no hoop	24	-	constant	Num.

It is important to create such a parametric CAD model that would be automatically updated when the independent model variables are changed with a guarantee that no errors in geometry are introduced. It was done by complete parametrization of every function or sketch used in the model history and a proper use of those functions in a proper order.

This way the prepared 3D model has then been transferred into the NX CAE module. In the traditional approach to FEM analysis all the geometric parameters must be prepared from scratch, so using the parametric CAD model the FEM analysis can be initiated automatically by “one click”.

5. Structure parametrization

The same procedures were applied to all wing’s elements (main wing, horizontal tailplane and vertical stabiliser). For the wings the classic composite structure was chosen because it is well known, widely proven by experience and reliable enough. The wing structure consists of skins, spars and ribs. Structure modelling is based on previously created external aircraft geometry [16-18].

The first action for wing element type is to define the division for fixed and movable parts (main parts, slats, flaps, ailerons for main wing and main parts, elevators and rudders for tailplane and vertical stabiliser). Having all wings parametrized the proper wing structures modelling procedure could be initiated.

When starting the structure of fixed wing part parametrisation one has to define how the thickness and number of plies made of unidirectional CFRP are changing versus wingspan.

For the description of the wing skin the following main variables could be used:

- Thickness of a single carbon composite ply,
- Number of plies in the wing root section,
- Number of plies in the wing tip section,
- Change of skin thickness along wing span.

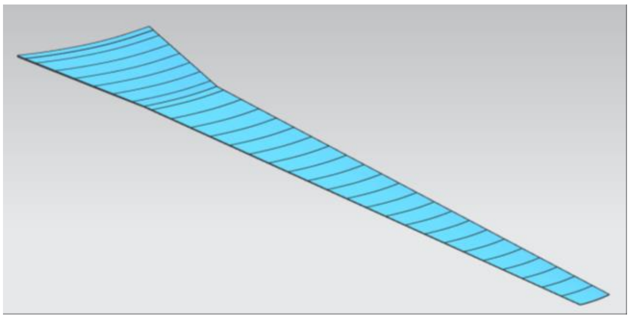

Fig. 9. Model of wing skin (it is assumed that numbers of plies between lines shown at the figure are constant)

The second step in the wing structure modelling is a spar design. In the case of R2035, as it is relatively big aircraft, a two spar structure has been chosen. As the structure is fully composite, the C-shape spar cross sections was selected, because such a shape can be easier manufactured by the automated fibre placement machines. Basing on previously defined wing division, the spars placement has been parametrized.

For the spars, the main parametrized variables were selected as follows:

- Spar placement,
- Thickness of a single carbon composite ply,
- Spar cap width and its change versus wingspan (both for front and rear spar),
- Number of carbon composite plies in upper spar cap and its change versus wingspan (both for front and rear spar),
- Number of carbon composite plies in lower spar cap and its change versus wingspan (both for front and rear spar),
- Number of carbon composite plies in web spar and its change along wingspan (both for front and rear spar),

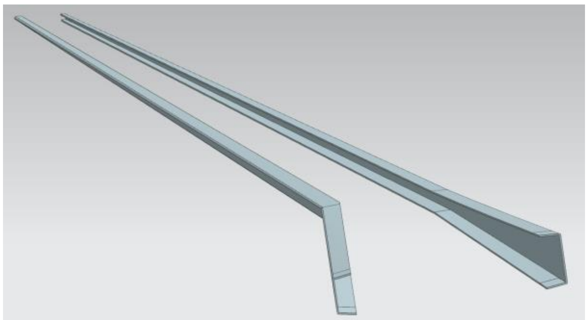

Fig. 10. Models of wing spars (left kink-spar and right main spar create the so-called “spar plane”)

The third group of important element of wing design are stringers, see Fig.11. They are designed as flats made of an unidirectional carbon composite and are attached to the skins.

For stringers one assumed the following independent variables:

- Number of stringers,
- Angle between stringers and wing leading edge,
- Flat thickness,
- Height of each stringer (the closest to the fuselage) and its change versus wingspan.

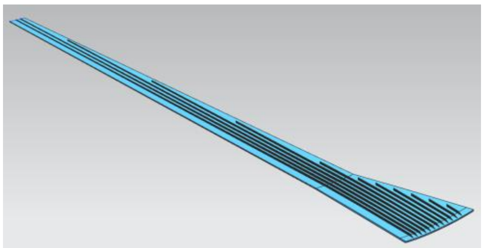

Fig. 11. Stringers in the form of flats, attached to the lower skin surface

Finally, a model for the wing ribs needs to be built. The geometry of each rib results from the geometry of spars, skins and stringers.

For the ribs the following independent variables were selected:

- Number of ribs,
- Distance between adjacent ribs,
- Thickness of each rib.

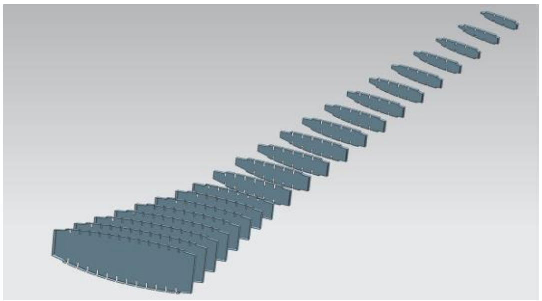

Fig. 12. Wing ribs distributed versus wingspan

Parametrization of the fuselage has been also conducted. Having two versions of structure (classical and geodetic) already parametrized, combination of both was used to create an aircraft fuselage. There are 2 reasons that combination both the classical and geodetic structure are used [19]. First of all, in the wing-fuselage section the classical structure must be used instead of geodetic one because of complication in joining wing-center box just to geodetic structure. It must be underlined that the lattice structure cannot be used on non-developable surfaces. Fig. 13 shows where the lattice structures (see the crosshatched area) are used.

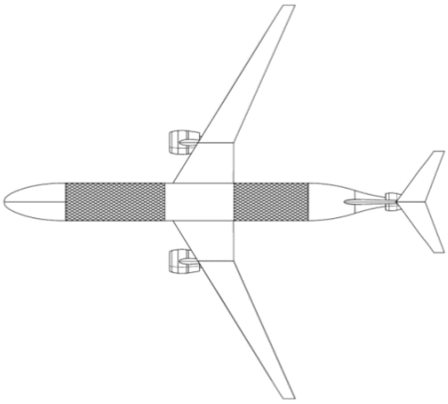

Fig. 13. Usage of lattice structure for the model of PFC, crosshatched areas show where geodetic structure are applied for fuselage design

Fig. 14 presents the PFC aircraft structure model that was created on the basis of the prepared parametric structure, the so-called R2000 baseline model. Of course, some adjustments to baseline model had to be implemented, for example due to change of a type of the empennage. However prepared earlier the associative 3D R2000 structure model, definitely speeds-up work on PFC structure.

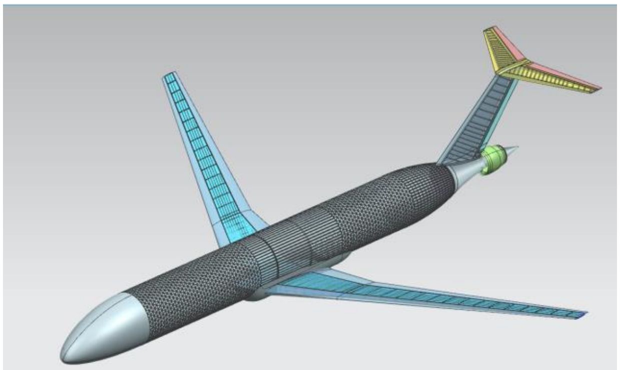

Fig. 14. PFC – the selected details of aircraft structure are shown

6. FEM analysis

Finite Element Method analysis of a cylindrical section of the geodetic fuselage structure is a good example of using the reference aircraft model. The prepared parametric CAD 3D model was used to investigate the impact of geodetic grid configuration on the stiffness of fuselage section. Model of fuselage section had length of 10 m and diameter equal to 6.4 m. The parameters that were being changed in FEM simulations included the number of hoop ribs, number of helical ribs and the angle between hoop ribs. Ribs have the square cross sections, 10 by 10 mm for every one version. Laminate layup was the same in every case as well. External shell consists of 4 carbon fibre woven fabric plies and 1 mm polyurethane core layer in following scheme: 0/90 deg, +-45 deg, PU, +-45 deg, 0/90 deg. In the geodetic fuselage concept, the external shell is responsible mainly for transferring the internal pressure to load carrying composite rib grid.

Table 3. Angles between ribs, ribs numbers, frame weights and increments/decrements in percent

Ver.	Angle between helical ribs	Helical ribs number	Hoop ribs number	Frame weight [kg]	Total weight [kg]	+/- [%]
1	60	80	24	224.76	658.54	0
2	60	100	24	261.75	695.52	+5.6
3	60	80	41	279.16	712.93	+8.2
4	90	80	24	257.06	690.83	+4.9
4	50	80	24	218.21	651.98	-1
6	50	80	31	240.61	684.38	+4

Table 3 shows differences between different computational versions. First version (Ver.1) was treated as a reference case and it consists of 80 helical ribs and 24 hoop ribs, while the angle between helical ribs is set to 60 deg. Versions 1-5 differ from each other only by one parameter, to check the sensitivity of the model versus the angles between ribs, helical and hoop ribs numbers, frame weights. In Ver. 2, the number of helical ribs was increased to 100, Ver. 3 consists of 41 hoop ribs, in Ver. 4 the angle between helical ribs was increased to 90 deg. and in the Ver. 5 the angle was decreased to 50 deg. Table 3 also shows how the weight of the model was changed due to the performed modifications. External shell weight was the same for all variants, the weight differences were caused only by the geodetic grid modifications. Lattice structure was modelled using one dimensional finite elements with the size of 20 mm, while for modelling of external shell 2D the 4 nodes elements were used. For the reference case, the number of 1D elements was equal to 72760, whereas the number of 2D elements is 599689. Those numbers change insignificantly depending on the computing version. The fuselage part under consideration was loaded with internal pressure of 0.0763 MPa (It is difference between cabin pressure and external pressure according to CS-25) , and with bending moment 1500 Nm (it is a synthetic load scenario – this value corresponds to the typical displacement observed in real flight environment) applied to the ending side of the geodetic cylinder structure. The degrees of freedom were fixed at the unloaded end of the fuselage model. Loads and constraints are presented at Fig.15. In the reference version the maximum displacement of geodetic grid was 21.13 mm (see Fig.16), while the maximum displacement of the external shell was 26.35 mm. This difference is due to internal pressure which pushes the skin outwards. The highest recorded value of stress in ribs reached 770 MPa.

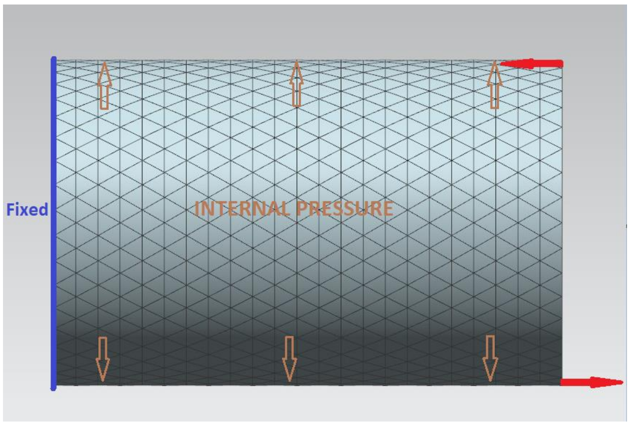

Fig. 15 Loads and constraints applied to the geodetic cylinder structure

Table 4. Results FEM simulation: max skin displacement, max frame displacement, max stress in frame and increments/decrements displacements in [%]

Version	Max Disp. Skin [mm]	Max Disp. Frame [mm]	Max Stress In frame [MPa]	+/-Frame Displacement [%]
1	26.35	21.13	770	0
2	26.01	19.07	856	-9.7
3	22.43	14.89	555.16	-29.5
4	29.55	22.57	721.71	+6.8
5	27.41	18.17	723.28	-14
6	24.73	15.95	706.16	-24.7

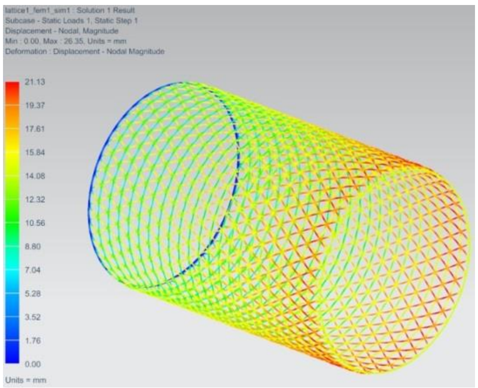

Fig. 16 Ribs displacement, based on results of simulation obtained in Ver. 1

In the reference version the maximum displacement of geodetic grid was 21.13 mm (see Fig.16), while the maximum displacement of the external shell was 26.35 mm. This difference is due to internal pressure which pushes the skin outwards. The highest recorded value of stress in ribs reached 770 MPa.

For the Ver.2, where the number of helical ribs was increased to 100, value of maximum displacement in lattice ribs decreased to 19 mm, what gives almost 10% lower value of displacement comparing to the reference variant. Unfortunately, better stiffness was obtained at the expense of weight increased by 5.6 % compared to the Ver. 1. Another revealed undesirable effect was connected to the increase in stresses observed in load carrying grid. In this case the stress level exceeded 850 MPa, what is almost 100 MPa more than in the reference version. Displacement of the external skin was slightly decreased, what is probably caused by smaller distance between the ribs. For Ver.2 (see Table 3) this displacement is equal to 26.01 mm, what gives about 1.5 % lower value than in the reference version (i.e. Ver. 1). Fig. 17 shows the increased displacement arrows of geodetic skin in a scale of 10 to 1.

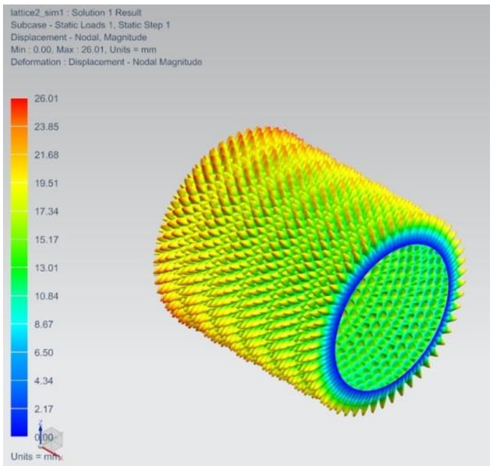

Fig. 17 Geodetic cylinder structure - skin displacement due to bending moment 1500 Nm applied to the ending side, plus internal pressure of 0.0763 MPa, Ver. 2

In the Ver.3, the number of hoop ribs was increased, what resulted with an increase of load carrying grid weight by 8.2 %. Weight increase, however, is compensated by noticeable improvement in stiffness of the load carrying structure. The maximum value of displacement of geodetic grid for Ver.3 is 14.89 mm, what is almost 30% lower than in the case of reference scenario. Significant reduction in maximum stress can be also observed - the maximum stress value in ribs was equal to 770 MPa in the case of reference scenario, whereas it was decreased to 555 MPa in the case of Ver.3. Map presenting the von Mises stresses in the geodetic fuselage load carrying grid is presented at Fig. 18. The maximum displacement in composite skin was decreased also. In the case of Ver. 3 it is under 23 mm, what is 10% lower than in the reference case of geodetic cylinder structure.

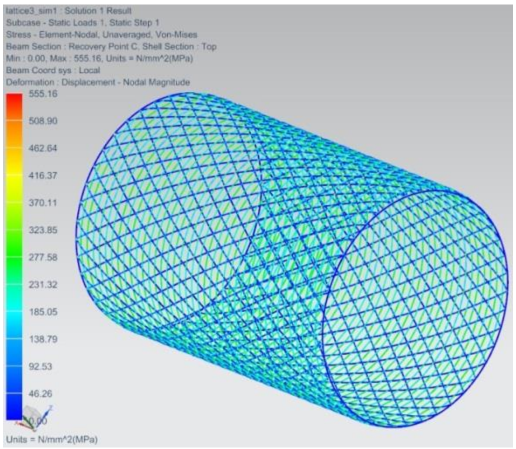

Fig. 18 Geodetic cylinder structure - Stresses in frame structure due to bending moment 1500 Nm and applied to the ending side plus internal pressure of 0.0763 MPa, Ver. 3

Variant with more hoop ribs proved to be more beneficial, despite the increase in weight. In the next lattice structure version (Ver. 4), the angle between helical ribs was changed to 90 deg. In this case, the deterioration of stiffness and increase in weight by almost 5% with respect to the reference case, was observed. Maximum calculated displacement in grid was 22.57 mm, what is 6.8% higher than in the reference case. Stresses in geodetic grid decreased slightly compared to the reference Ver.1, but the maximum displacement in skin was raised to almost 30 mm. In consequence the conclusion can be made, that the increase of the angle between helical ribs negatively affects both weight and stiffness of the structure.

In Ver. 5, the spiral ribs are crossing at angles of 50 degrees. Due to that modification, it is possible to achieve an increase in overall stiffness and at the same time to obtain a slight weight loss. Maximum displacement in ribs grid was 18.17 mm, what is 14 % less than in the base variant. The weight of the design model has decreased by 1 %. The only undesirable result of this change is related to the increase in stresses of external shell.

The carried out analysis proved that increasing the number of hoop ribs and reducing an angle between helical ribs have the most beneficial impact on the fuselage stiffness.
Based on that conclusion, an additional version was analysed, in which both above mentioned parameters (i.e. number of hoop ribs and angle between helical ribs) were changed. In Ver. 6 the design model was equipped with 31 hoop ribs, while angle between helical ribs was decreased to 50 deg. The purpose of these changes was to achieve stiffness similar to that of the case in Ver. 3, but with a smaller weight penalty. This goal was successfully achieved.

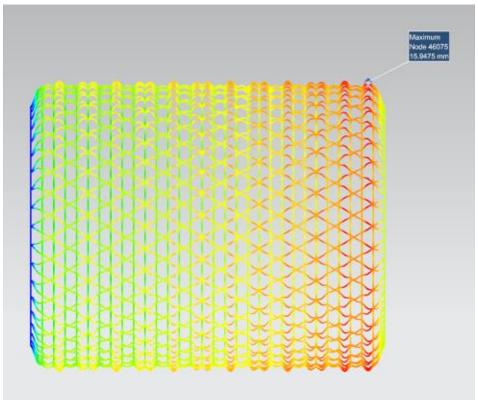

Fig. 19 Ribs displacement in a scale of 10 to 1, based on results of simulation obtained in Ver. 6. The maximum displacement is marked in the picture.

The maximum displacement of the lattice grid was reduced to 15.95 mm, which is almost 25% less than for the reference case. The obtained stiffness is about 7 % worse than that of the Ver. 3, but the weight of the frame only was increased by less than 16 kg, while for Ver. 3 it was equal to 55 kg. Unfortunately, the decrease in the maximum stress values is not so big comparing to that of the Ver. 3, which was 28 % stiffer than in the reference version.

7. Conclusions

Parametric 3D modelling definitely simplifies and quickens the analysis of the geodetic composite fuselage structure. Next steps of research will be focused on further study of stiffness of load carrying structure with angle between helical ribs smaller than 50 degrees. Also, it is essential to verify how ribs cross section affects the frame stiffness and its stress level.

The parametric model developed in this paper also enables the conduct of similar analyses for either the main wing or the horizontal and vertical tailplanes.

The 3D model of the fuselage has a replacement section with “Classic” structure that allows for easy comparison of “Classic” structure with longerons and frames to the geodetic structure model.

Proper parametrization of external geometry with a relatively small amount of work also allows to prepare a model to be used for a flow analysis using a selected CFD software [10-12].

Parametrization of a 3D model simplifies and speeds-up the work of an engineer, however it has to be used in an appropriate way and the results still have be carefully checked and verified. It is essential to outline the fact that not every element can be parametrized and that the process of creating of the parametrized model itself is a time consuming and gives profits only for a series of products and manifold simulations. The CAD model developed and presented in this paper will be used in CENTRELINE project for the PFC aircraft structure optimisation and the main components weight assessment.

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