PROJECT FINAL REPORT

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Project acronym: **ALaSCA**

Project title: **Advanced Lattice Structures for Composite Airframes**

Funding Scheme: **Collaborative project**

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Period covered: from to **Month 1 – Month 36**

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate) [3]:

  ☒ has fully achieved its objectives and technical goals for the period;

  ☐ has achieved most of its objectives and technical goals for the period with relatively minor deviations.

  ☐ has failed to achieve critical objectives and/or is not at all on schedule.
- The public website, if applicable

  ☒ is up to date

  ☐ is not up to date
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 3.4) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 3.2.3 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: Dr.-Ing. Christian Hühne

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For most of the projects, the signature of this declaration could be done directly via the IT reporting tool through an adapted IT mechanism.

[3] If either of these boxes below is ticked, the report should reflect these and any remedial actions taken.

NOMENCLATURE

ALaSCA	Advanced Lattice Structures for Composite Airframes

	ALaSCA – Consortium - Partner Abbreviations
DLR	*German Aerospace Centre - EU*
TsAGI	*Central Aerohydrodynamic Institute - RU*
CRISM	*Central Research Institute for Special Machinery - RU*
TU Delft	*Technical University of Delft - EU*
SMR	*S.A. Engineering and Development - Switzerland*
AIRBUS	*Airbus Operations GmbH - EU*
EADS-IW	*European Aeronautic Defence and Space Company – Innovation Works - EU*
ULeeds	*University of Leeds – EU*
ESEC	*Educational Scientific and Experimental Centre of Moscow Inst. of Physics and Technology – RU*
MUCTR	*Mendeleev University of Chemical Technology of Russia - RU*
Radar	*JSC Scientific and Production Enterprise Radar-mms - RU*
NIK	*Research Engineering Centre - RU*

Content

1 Executive Summary

State of art fuselage design and Origin of project idea

In order to improve safety and efficiency of air transport, new composite materials such as carbon fibre reinforced polymer and novel primary structure design architectures are being considered to replace traditional sheeting. Lattice structures used for spacecraft rocket interstages and fairings preserve high strength and safety, and are thus an attractive option for composite airframe structures.

Aiming to analyse the potential of Lattice structures for fuselage airframes, several major aerospace companies are working together in a collaborative framework to develop such lattice structures for mass production. Their efforts are funded by the European Commission and Russian Government as part of the 'Advanced Lattice Structures for Composite Airframes' (ALaSCA) project, as a level 1 project.

Starting with the definition of requirements and specification for civil aircraft fuselages, a number of aeroplane configurations are compared for optimal fuselage barrel design and manufacturing efficiency. Identifying the most suitable aircraft design, the fuselage section loads are provided for the fuselage barrel section design process. Herein two pro-lattice and two reference barrel design concepts for the barrel section has been developed, sized and compared in terms of weight and manufacturing costs. On component level, design solutions for a lattice structure have been performed for window cut-outs, barrel-floor interfaces and barrel-barrel interfaces. Despite the design concept development for a suitable pro-lattice barrel section, an important aspect of EU-ALaSCA is the lattice sizing method development, which is done on barrel, component and element level.

The ALaSCA project is showing the potential of lattice design for novel airframe architectures, to significantly reduce the weight and costs of manufactured aeroplane parts, without compromising on safety or efficiency.

KEYWORDS: Lattice structure, aeroplane parts, safety, efficiency, weight reduction, fuselage barrel

Diagrams and photographs – for illustration and promotion; list of partners

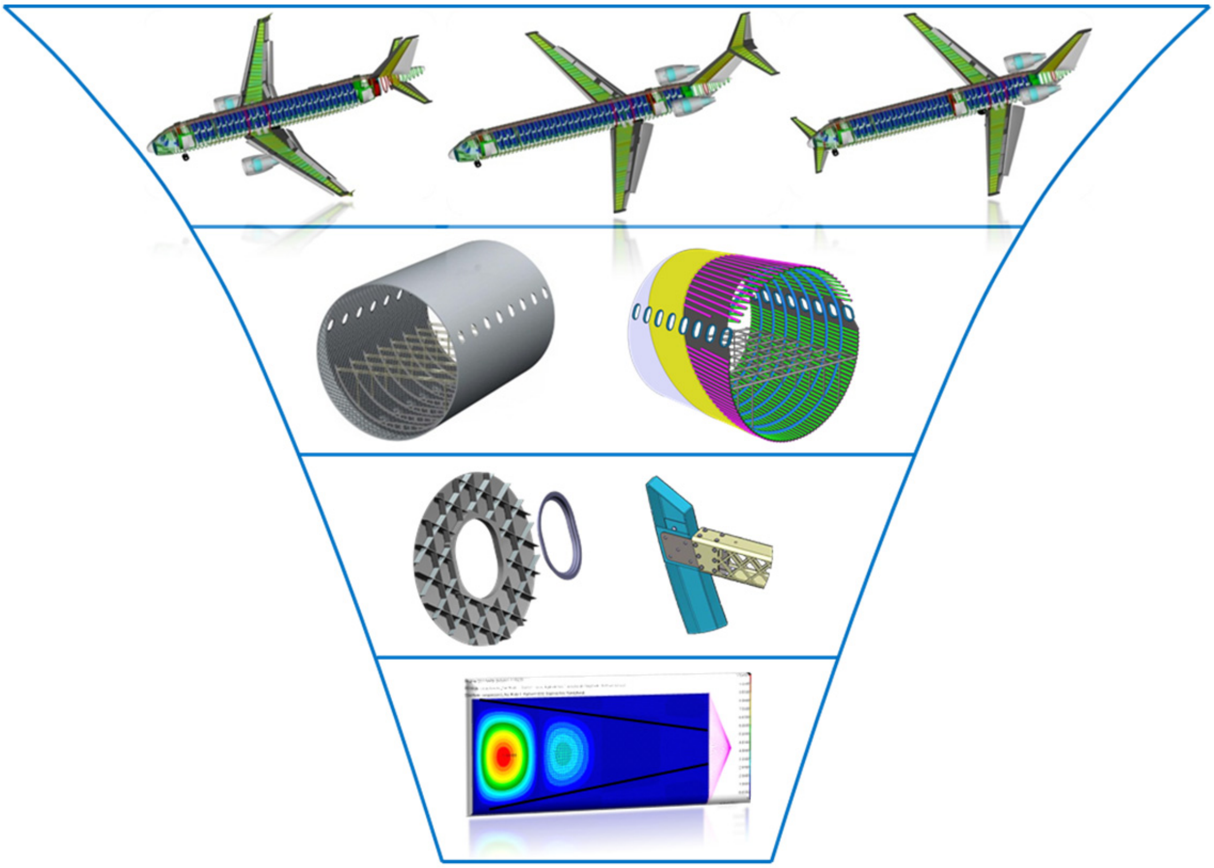

Fig. 1: EU-ALaSCA Workflow

Fig. 2: EU-ALaSCA Pro-Lattice Aircraft Configuration

2 Summary Description

The ALaSCA project focuses on maximum weight and cost reduction significant in airframes by developing manufacture-optimized lattice fuselage structures fulfilling fundamental aspects of airworthiness.

Composite lattice filament-wound tubular structures have been successfully applied for years in Russian rocket technology for their excellent strength and stiffness to weight ratio. Environmental and economic issues force future aircraft designs to strive for maximum efficiency. As metal designs have reached their climax after 90 years of development, further potentials are seen especially with extremely lightweight but high-strength fibre reinforced composites. These materials, however, demand a sophisticated layout, design, and manufacture in order to fully exploit their immense potentials and to be significantly advantageous to metal designs.

Hitherto existing as well as currently being developed composite fuselage designs hardly address this comprehensive approach so that the expected weight and cost benefits of composite airframe designs have not been achieved so far. The full potential of the new material is not exploited as the design is very similar to that based on metal.

Pro-composite design in general and composite design in particular always means carefully considering of material, structural and manufacturing aspects in a closed-loop process chain for reasons of their close interaction. A composite-friendly or pro-composite design incorporates:

- Continuous fibres without any interruption (structural mechanics, material).
- Integral construction, no or very low number of joining / fitting elements (structural mechanics, manufacture).
- Fully automated manufacture yielding high output (manufacture).
- Damage tolerant design by providing redundant load paths around area of destruction (structural mechanics).

Only comprehensively covering these subjects, the potentials of composite materials will be fully exploited resulting in significant weight and cost reductions. Regarding these aspects lattice structures are very close to a pro-composite design.

Fig. 3: CFRP Fuselage Demonstrator, DLR 2002

Taking this situation into account, the idea behind the ALaSCA project is to perform a comprehensive investigation starting with the beneficial geodesic design well-proven in space technology and transferring it to composite aircraft fuselage designs.

The main objectives of this research programme are:

- Maximum weight and cost reduction by using lattice designs for fuselage structures.
- Development of manufacture-optimized lattice designs satisfying airworthiness requirements.
- Verification of airworthiness by manufacture and testing of representative lattice components.

Since structural requirements and boundary conditions in rocket technology are quite different from those in aircraft fuselage design, the scope of this project covers the specific aspects of design, sizing, manufacture and testing of lattice structures that follow from aircraft requirements. The objectives will only be achieved when solutions to the following issues in terms of lay-out, design, sizing, manufacture and testing are found:

- Pro-lattice aircraft configurations for maximum weight and cost savings i.e. extended length of fuselage section with minimized number and size of cut-outs by analysing the interaction between aircraft configuration and fuselage design. In addition, investigation of perspectives of industrial exploitation (evaluation on A320 basis).
- Aircraft specific components treated in the lattice fuselage design, i.e. cut-outs, floor grid integration and interfaces.
- Lattice elements, i.e. examination in the aircraft-specific detailed design of loads from internal pressure Δp, impact and service requirements.

In order to achieve these objectives following work steps has been worked on, which are summarized in this report:

- Determination of a requirements and specification document on aircraft level as well as on fuselage barrel architecture level
- Aircraft configuration study for configuration with long undisturbed fuselage section and determination of barrel section loads for different aircraft load cases
- Sizing of barrel section for four designs: two pro-lattice concepts, two semi-monocoque concepts
- Comparison of barrel concept weights as well as estimated barrel manufacturing costs
- Summarizing and explanation of different sizing methods, used and developed for the sizing process
- Presentation of the future needs and next steps to work on

The consortium of EU-ALaSCA consists of six European funded partners and six Russian partners, funded by the Russian government. All partners operate in the field of aeronautical structure development and are a balanced mix of industry, research and university.

3 Requirements and Specification

Creating the same basis for all barrel concept development groups a specification and requirements document has been agreed by all partners. The document is organized to start with demands on aircraft level deriving to local requirements on element level.

The document contains the following requirements for designing lattice composite fuselage structure:

- *Certification requirements (JAR/FAR) applicable for lattice composite fuselage;*
- *Requirements for the up-to-date middle-range aircraft configuration and fuselage section;*
- *Static load cases on the fuselage;*
- *Fuselage sizing criteria, including strength, stiffness, buckling, delamination, impact, reparability and other constraints;*
- *Manufacturing constraints and material properties.*

As stiffness demands minimum bending stiffness's around Y- and Z-axis and torsional stiffness for the barrel section are used. For buckling criteria, a no-buckling-policy has been agreed. For the strength analysis of the composite and metal structures, two main differences are considered in this study. On the one hand main principal strains are analysed for composite materials instead of Van-Mises stresses for aluminium. On the other hand strain cut-off values are defined for the composites, which includes hot/wet and damage tolerance demands, and yield and fatigue stresses are used for the metal variant.

4 Airframe Configuration and Fuselage Section Loads

Three airplane configurations has been analysed in the ALaSCA project, see Fig. 4. The selected ALaSCA configuration is based on the NLF forward swept wing configuration developed in the DLR LamAiR project [1]. The forward swept wing offers a superior potential for natural laminar flow due to the lower leading edge sweep in comparison with the conventional backward swept wing. The known static aeroelastic stability problem of the forward swept wing is addressed in the LamAiR project [1].

Fig. 4 shows the preliminary aircraft design models of the ALaSCA configurations. The selected ALaSCA configuration has a low wing, rear mounted engines and a T-tail. This engine arrangement allows a relatively short landing gear, but leads to higher loads for the wing structure under maneuver flight conditions.

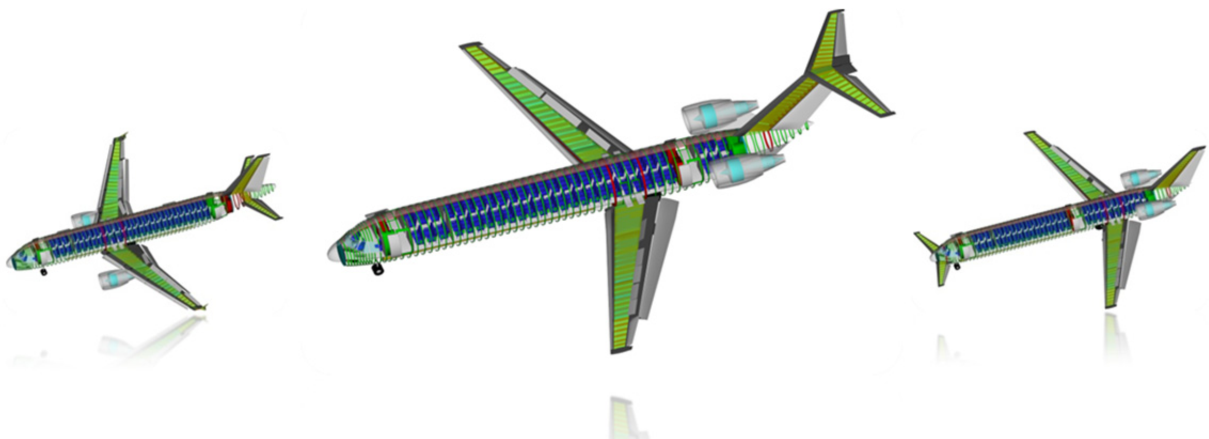

Fig. 4: PrADO model of the analysed ALaSCA configurations (middle one selected)

The ALaSCA configuration combines the aerodynamic benefits of the NLF wing with the potential for future engine concepts (ultra high bypass ratio turbofan, open rotor) with larger dimensions. In addition, the long undisturbed fuselage section is suited for the usage of carbon fiber reinforced plastic materials, for which reason this configuration was selected for the detailed investigations on the lattice structure fuselage design.

The structural sizing of the fuselage is dependent on the selected load cases. While selecting load cases, all expected structural loads in the flight envelope over the life time of the aircraft have to be considered. The structural loads in the fuselage are dependent on the total mass, the mass distribution, the boundaries of the center of gravity, the accelerations on ground and in the air, and the aerodynamic forces of the aircraft. This includes all settings of the high lift devices, deflections of control surfaces, engine thrust settings, and retraction of the landing gear. From this huge number of load cases, the usually unknown critical load cases have to be selected. In the preliminary aircraft design, a limited number of the critical load cases are considered. This selection is based on results of similar aircraft configurations and the corners of the maneuver and gust load diagrams. In the selected critical load cases for the ALaSCA configuration are described.

Load case	Load factor	Aircraft mass	Payload	Fuel mass	Altitude
1	3.469	$m_E + m_P$	$m_{MTO} - m_{F,max}$	0 kg	0 m
6	-1.0	m_{MTO}	$m_{P,max}$	$m_{MTO} - m_{P,max}$	0 m
10	2.5	$m_E + m_F$	0 kg	End of cruise	Hmax
2 Δp_{max}	1.0	m_{MTO}	$m_{P,max}$	$m_{MTO} - m_{P,max}$	0 m

The load case 1 is the critical flight load case corresponding to the maximum positive load factor n for the given aircraft, payload and fuel masses. In load case 6 the maximum negative load factor is considered for the given aircraft masses. Only the load case number 10 included the cabin pressure at the maximum reached altitude under cruise flight conditions.

Internal loads from critical lateral motion load cases have been added to make the sizing of the fuselage more realistic. These internal fuselage loads in terms of torsional moment M_x and shear force Q_y are derived from a known aircraft configuration.

5 Fuselage Barrel Design Concepts

For the development of the barrel design concepts, the barrel section in front of the wing from frame 17 until frame 42 has been chosen (see Fig. 5). For this barrel section two Pro-Lattice concepts and two Semi-monocoque concepts has been developed. Main difference of the two Pro-Lattice concepts is the position of the skin and the design integrity. The two Semi-monocoque structures differs in the material which is used.

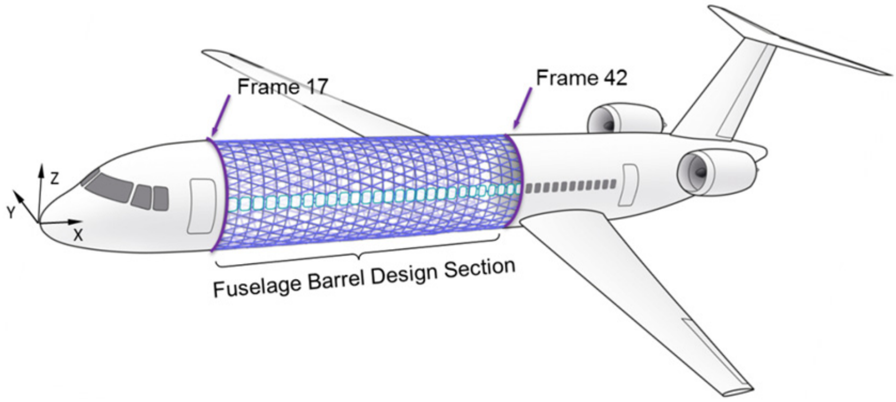

Fig. 5: ALaSCA fuselage barrel section

5.1 Pro-Lattice Skin-Outside Concept

In geodesic, integral lattice structures developed in CRISM, the primary load bearing elements are monolithic ribs, made of unidirectional carbon composite material by continuous automatic filament winding, whereas the skin is not treated as load-carrying element and transfers only internal pressure to the ribs. Technology of lattice structures involve as the basic operation formation of ribs by automatic winding with impregnated tows of carbon fibers laid into the grooves with the ribs profiles made in elastic material, which covers the mandrel. End rings, illuminator frames and the places loaded with locally applied forces are formed using the layers of pre-impregnated carbon fabric inserted into the structure in the process of winding. The skin is a Hybrid material compound under development, made of two unidirectional Prepreg layers and an elastic material layer in between. The fabrication is assumed in a final stage winding process. After completion of the winding process, the structure is cured and is forming an integral barrel structure with ribs and skin, which gets removed from the mandrel. The panels of elastic material are removed from the structure. The final operations are machining of end rings, cutting illuminator holes and doors. [2], [3]

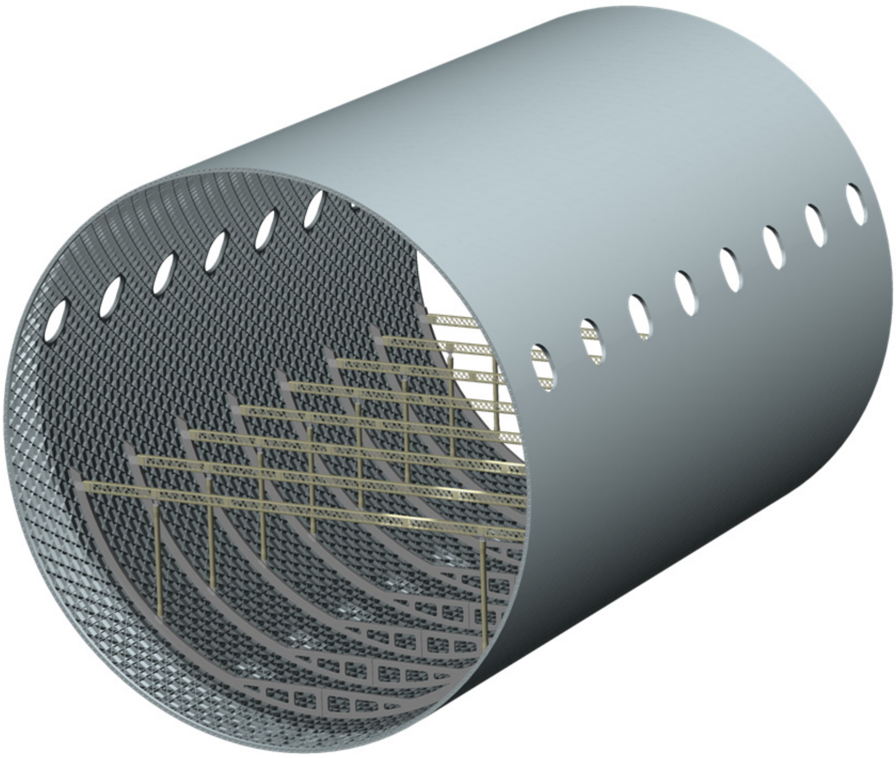

Fig. 6: View of a finite element model of the fuselage section

High weight efficiency of composite material in the lattice structure is achieved because the forces acting in the ribs coincide with the direction of carbon fibers. Transverse and shear stresses in the ribs of lattice structures are very low and do not result in cracking of the matrix. Stability of lattice structure is provided by the height of the ribs. Mechanical characteristics of the rib material depend on the volume content of the fibers, characteristics of the fibers and resin, as well as of the parameters of the manufacturing process. Lattice fuselage section made by automatic winding has constant thickness of helical, longitudinal and hoop ribs, rib spacing and the angle of orientation of helical ribs.

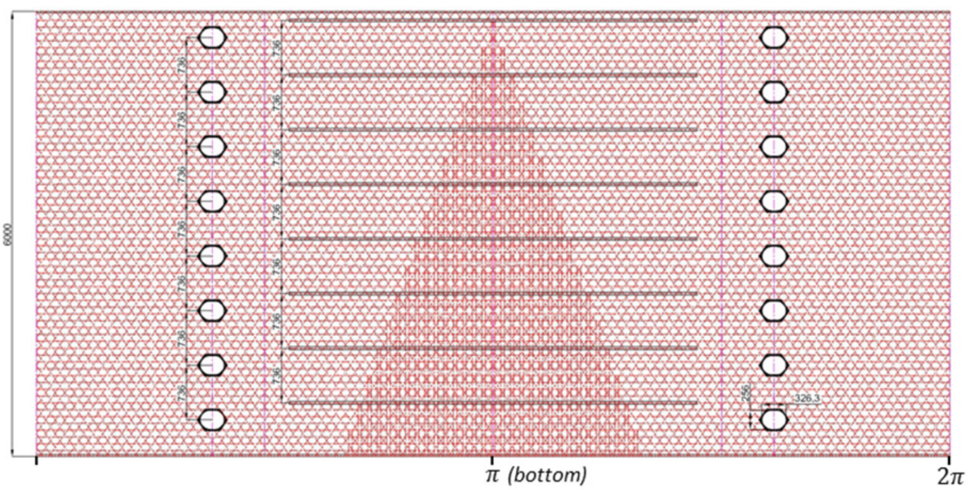

Fig. 7: Tailored Pro-Lattice Rib Structure

At the first stage of the sizing a section with 6 m length was considered (see Fig. 6 right). A tailored pro-lattice rib-structure has been invented with axial ribs because of the very high bending moment loads at frame 42. Tailored means that the axial ribs are not running through the whole section. Calculation shows that the minimum mass for the ALaSCA barrel section is reached if the barrel is split into four subsections with the optimal lattice structure for each subsection [3].

5.2 Pro-Lattice Skin-Inside Concept

This design concept is based on a load carrying skin, stiffeners in a net structure and frames as circumferential stiffeners. The stiffeners are placed as geodesic lines on the cylindrical skin (also helix-stiffeners called), so that non-rectangular skin bays are generated, which increase the stability properties of the skin. To avoid intersections of the stiffeners, they are placed on two sides of the skin. Due to the load bearing skin on the inside and the need of an aerodynamic skin, this concept is called the Skin Inside concept. For closing the space between the two skins, a foam core with low density is considered as not load carrying in dimension process. See Fig. 8 for the concept illustration. This concept shows in contrast to the Skin Outside concept a high differential approach, which means that most components are manufactured separately and assembled afterwards. [4], [5]

The primary structure consists of frames with C-shape and stiffeners with Omega-shape (hat shape). Due to the position of the stiffeners with an angle and the loss of axial panel stiffness, CFRP-Steel-Hybrid material is assumed for the stiffeners because of the increased axial stiffness properties and the fulfilment of repair, joining and damage tolerance demands at the same time [6], [7]. The foam and the aerodynamic skin are multifunctional elements for the concept. The foam is filling the space between the skins, but is also acting as thermic insulating for the cabin as well as protecting the primary structure elements from outside impacts. The aerodynamic skin layer is assumed to be an aluminium layer to provide lightning strike protection in addition to the aerodynamic shape.

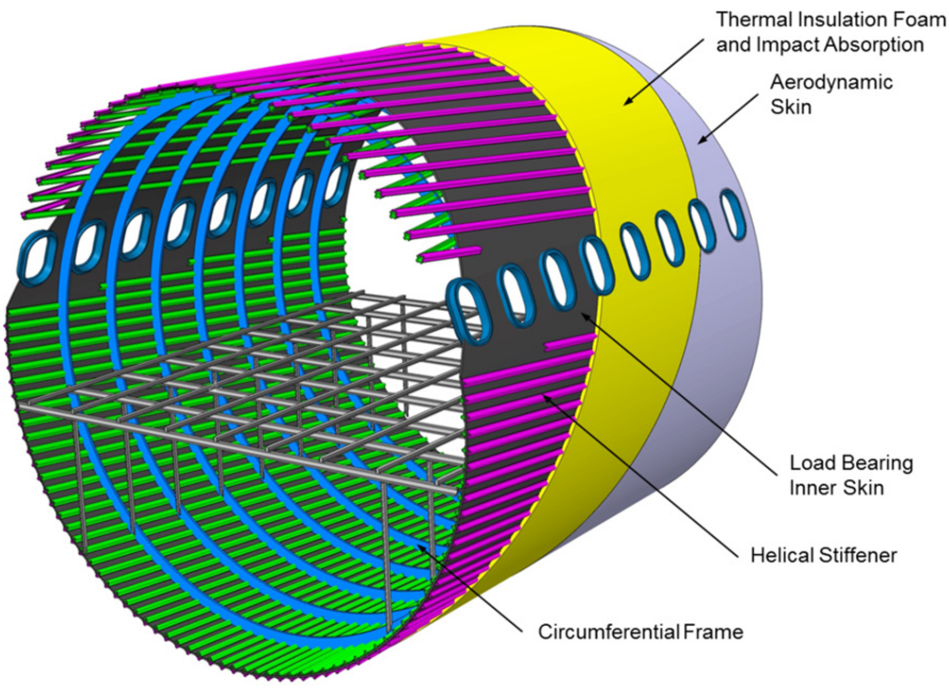

Fig. 8: Pro-Lattice Skin Inside Concept Overview

The concept has been dimensioned analytical, getting start values for the numerical concept analysis. This analytical pre-dimensioning process has been performed with conventional methods like beam theory, methods of reduction coefficients and classical laminate theory. The process considered the complete barrel section and result in sized parameters for the skin with constant thickness and frames and stiffeners with different thicknesses and distance on the top and bottom panel. For the prediction of the buckling load of the non-rectangular skin bays numerical local skin field models have been used to get a correction buckling load factor in comparison to rectangular skin fields.

In parallel to the analytical sizing process an automated numerical sizing tool has been developed and successfully used in combination with a multi parameter optimization algorithm (see chapter 7.2). Both methods the analytical sizing process and the optimisation algorithm showed good alignment of the optimum result, deriving in low stiffener angles and thin frame and stiffener profiles [8].

Due to the strongly differing of the barrel loads along the length of the fuselage barrel, starting with relative low loads at frame 17 and highly increased section loads at frame 42 in front of the wing, a so called stringer run-out concept has been assumed for the barrel (see Fig. 8 bottom picture). This means that stringers get cut along their length, when the loads have been decreased enough. This design has been analyzed and optimized numerically with different FE-modelling techniques. [9]

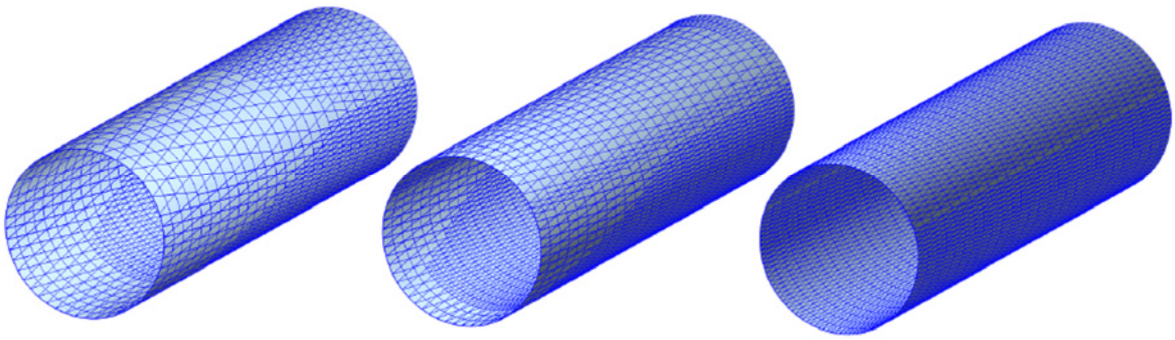

Fig. 9: Picture of analysed stiffener cut-off configurations (by SMR)

Because of the antimetric arrangement of the stiffeners on the inside and outside of the load bearing skin, also a study has been performed to analyse such antimetric structural behaviour of the barrel. It has been shown, that the relative thick skin is dominating the deformation behaviour of the barrel and the antimetric design has no critical effect in static strength and deformation analysis.

5.3 CFRP-Semimonocoque Reference Concept

For a benchmark of the newly developed advanced lattice structures in the project ALaSCA, a composite frame/stringer configuration is defined and sized according to the project specific criteria and loads. The design incorporates state-of-the-art assumptions and includes recently gathered experience with these kinds of structures in aircraft applications.

The conventional frame/stringer architecture permits a relatively strict functional separation for the major structural components: skin, stringers and frames. The stringers provide the necessary bending stiffness against local skin and panel buckling and carry a significant amount of axial compressive and tensional loads. The skin is the major load-carrying component for the membrane forces; especially shear forces are carried solely by the skin. The frames provide the necessary bending stiffness for contour accuracy and against global buckling and share circumferential loads originating in internal pressure. Additionally they serve as attachment elements for floors, overhead compartments and various system and cabin elements.

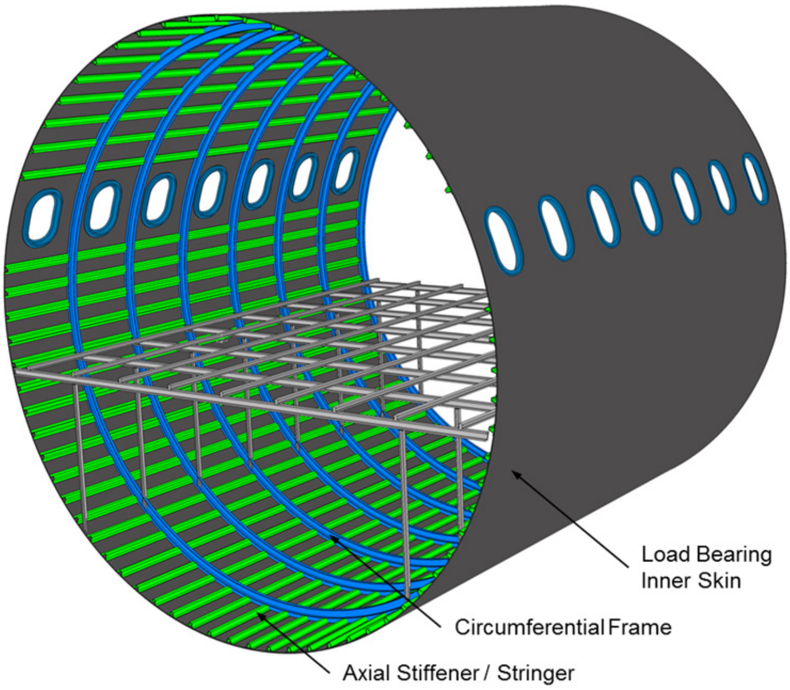

Fig. 10: Semi-monocoque architecture for primary airframe structure

In this concept C-shape frames are considered, which are joined with the load bearing skin via clips, and stringers with an omega shape, see Fig. 10.

As result out of structural analysis, carried out with FEA software developed by MSC, three fuselage barrel weights as specific mass per meter fuselage has been derived. These are the so called ALaSCA Baseline, which considers exactly the requirements specified, the ALaSCA Reference, which considers current buckling policy for airframe structures and the ALaSCA No-minimum-skin-thickness, which considers a possibly lower skin thickness as used as state of art. For the comparison of the concepts the Baseline concept has been used. [10]

5.4 Metal-Semi-Monocoque Reference Concept

A primary structure of a semi-monocoque fuselage section rests on a stiffened panel concept. The panels contain the following load-bearing elements: a skin and stiffeners (stringers and frames). As a rule, in a semi-monocoque structure these stringers and frames are placed orthogonally to each other. The frames do have a Z-shape with mouse holes for the stringers and an additional L-profile as second flange. The stringer profiles also have a Z-shape, see Fig. 11.

An algorithm of sizing, constraints, methods of strength and buckling analyses, and numerical models were specified according to the main aim of the research: to determine rational parameters for alternative variants of the fuselage section and to obtained weight parameters for the comparative analysis. Special requirements for sizing, constraints, modelling and methods for strength and buckling analyses have been formulated to provide comparability of the results of weight analyses for different structures. These requirements were based on the ALaSCA requirements document. The 4-level program algorithm developed in TsAGI for designing airframes with different configurations of layout was chosen as the basic one. [11], [12]

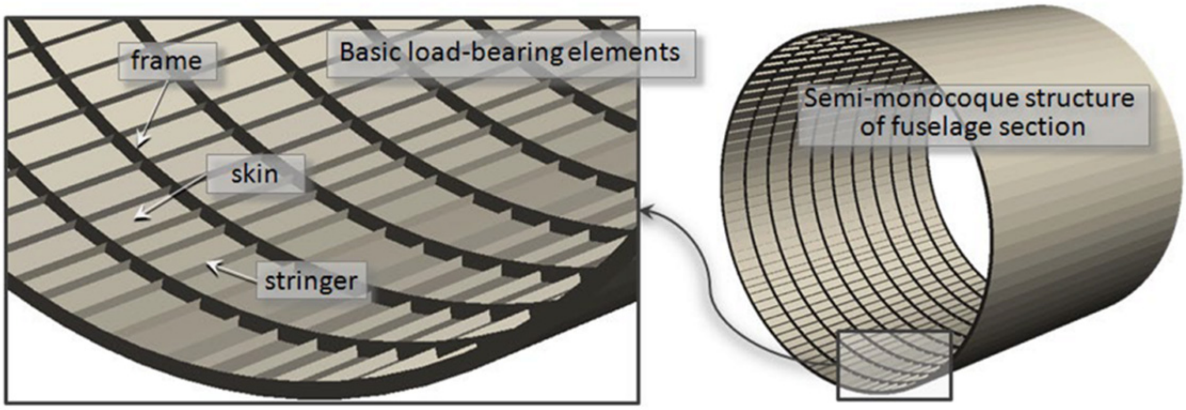

Fig. 11: Semi-monocoque architecture for metal primary airframe structure

5.5 Comparison of Fuselage Design Concepts

It has been determined that three main groups of features have to be compared:

- Weight data for the structures of the different concepts
- Cost analysis of materials and manufacturing process
- Level of application of requirements e.g. of robustness and repair.

The concept weights have been provided by all partners responsible for the concept sizing. It has been shown that it is suitable to differentiate the primary concept structure and the overall concept weight. As primary structure only load bearing elements got considered, which are grid structure, stringers, skin and frames. In the overall structure weights, additional elements have been included like window frames, circumferential and longitudinal interfaces, thermal insulation and lightning strike protection.

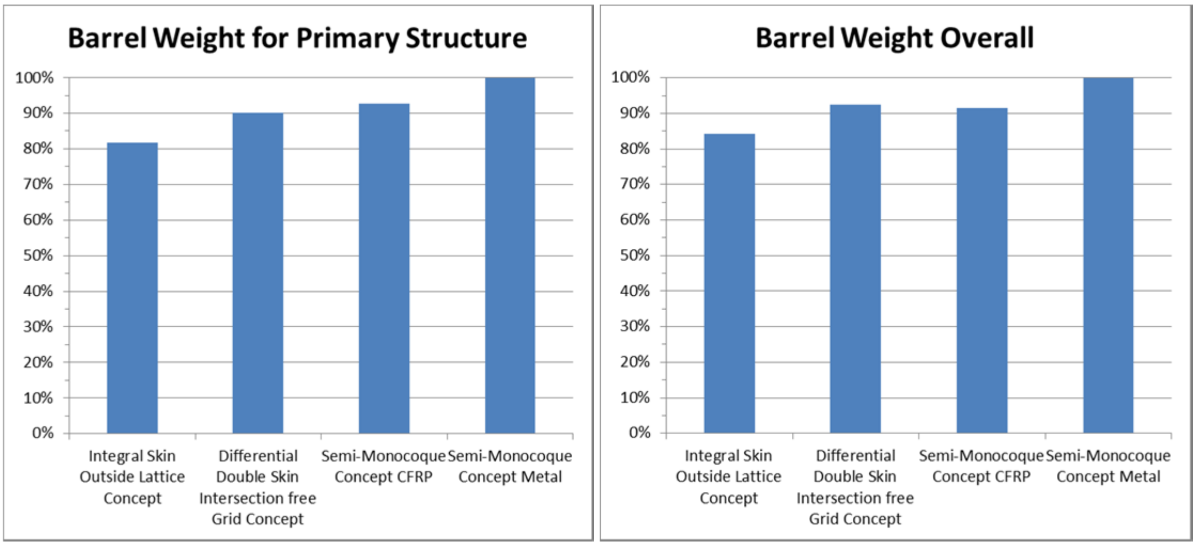

Fig. 12: Result of Concept Comparison of Primary Structure (left) and Overall (right)

Comparing only the weight of the primary structure (skin, stiffeners and frames), the CFRP fuselage designs result in a decreased barrel weight of -7% for the Semi-monocoque CFRP Concept, -10% for the Pro-Lattice Skin Inside and -18% for the Pro-Lattice Skin Outside concept in comparison to the semi-monocoque metal concept. Considering also additional weights like window frames, barrel-barrel-interfaces, lightning strike and thermal insulation, the overall barrel weight results in -8% for the Semi-monocoque CFRP Concept, -7% for the Pro-Lattice Skin Inside and -16% for the Pro-Lattice Skin Outside concept in comparison to the semi-monocoque metal concept.

6 Concepts on Component Level for Pro-Lattice Design

In addition to the barrel concept development, described in the chapter before, design solution on component level has been worked out. Because of the novelty of the integral pro-lattice Skin-Outside concept, the focus has been laid on solution for this concept design. Fig. 13 shows the components, which are window cut-outs, barrel-floor interface and barrel-barrel-interface.

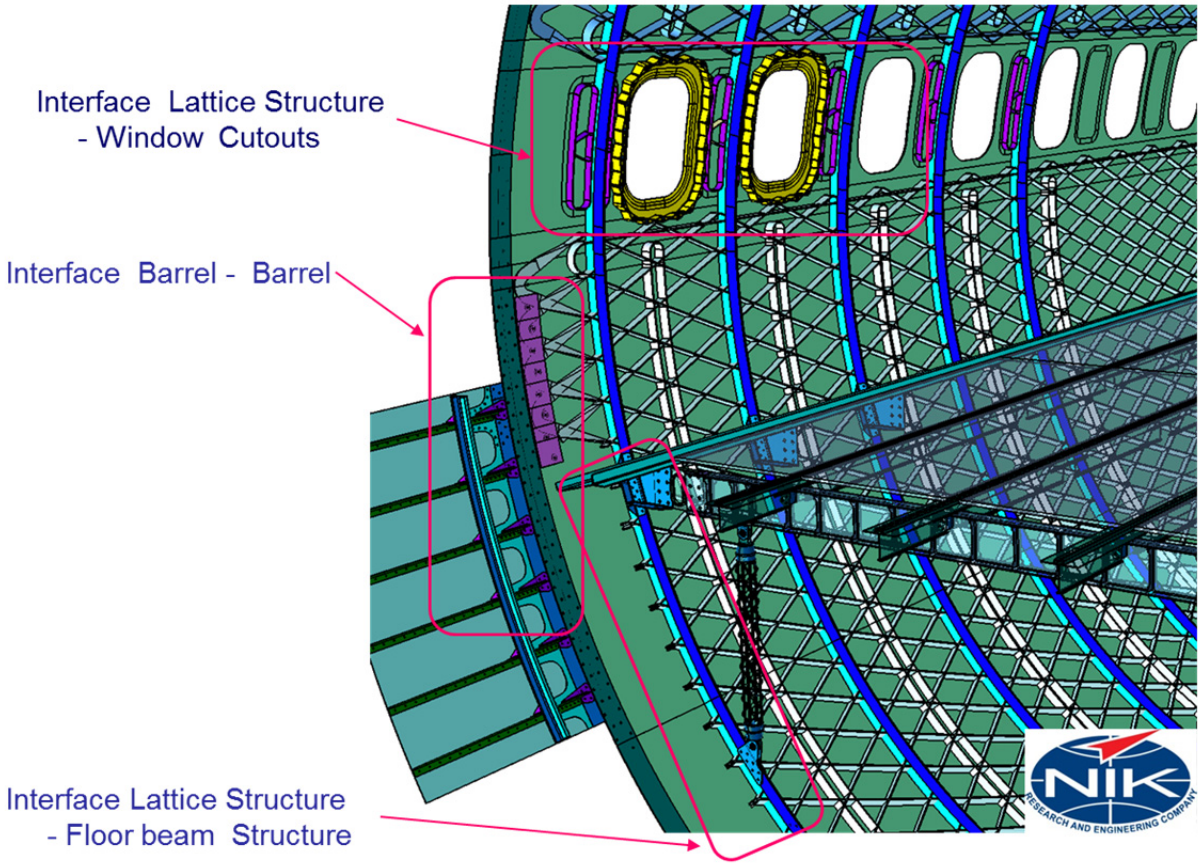

Fig. 13: ALaSCA Development Focus on Component Level

6.1 Window Cut-Outs

The composite lattice structure significantly differs from the barrel made of traditional materials and from a semi-monocoque barrel design. So, the design of window frames used currently can't be applied to the lattice structure without changes.

A screening of current window frame solutions in industry has shown that there are still solutions available like compression moulding of long fibre reinforced matrices or continuous fibre-reinforced parts manufactured in RTM technology. In the concept development phase four window frame concepts has been created. These concepts differ in design philosophy (integral or differential), manufacturing processes and raw materials used. All design concepts also have been analysed with numerical simple models and compared by means of weight, stresses and fabrication process.

As result a differential window frame concept has been favoured with a weight increase for the barrel section of approximately 3.3%. This window frame concept consists of a winding process, impregnated with additional long fibre reinforced thermoplastic matrix. [13]

6.2 Floor-Barrel-Interface

For the barrel-floor interface, a detailed design methodology with a detailed finite element model has been created and optimized for the critical loading condition with a special emphasis on the interfacial regions. From special interest was the question about load distribution in the elements of the floor and primary structure (cross beams, stanchion, and rib structure) and a suitable joining concept of the floor to the primary structure.

The model created in PATRAN/NASTRAN is half of the fuselage cross-section that spans across 3 frames and has a constant radius. Two configurations of this model are investigated. The first one has the frame that spans across only the lower half of the circumference of the fuselage while the second one has the frame that spans across the entire circumference of the fuselage.

As result, a method to design efficient fuselage to floor composite joints has been realized. A Pi-joint was used for connecting the grid-stiffened fuselage to the passenger floor. The method used the vertical struts (stanchion) to optimize the load distribution between the different members. The Pi-joint was analysed for bearing, pull-through, material failure and delamination. The floor beam was designed for material strength, buckling and crippling. Finally, the fuselage skin was designed locally against grid/skin separation at the location where the grid was terminated to accommodate the Pi-joint.

Accounting for load redistribution between different members of a floor-to-fuselage joint, leads to very efficient designs. Pi-joints can be effective in alleviating the load on floor beams and reducing the overall weight of the structure. The optimum weight configuration requires as low a bending stiffness of the floor beams as possible. This is limited by other requirements such as maximum deflection and strength of the floor. Significant weight savings is possible when a Pi-joint is used as opposed to a design relying solely on floor beams to carry the floor loads. [14]

6.3 Barrel-Barrel-Interface

For joining the lattice composite fuselage section with adjacent sections, having conventional semi-monocoque design, the doweled joint with tension bolts is preferable. The experience shows that this type of joint allows the ribs of the lattice grid to transfer loads to the pins effectively, avoiding sufficient stress concentrators. The number of bolts in the joints is a multiple of number of pairs of helical ribs in lattice grid, and this contributes to the decrease of stress concentrations.

Such joint has been tested and is used in the lattice cylindrical shells manufactured by CRISM. As the front and the back ends of the fuselage barrel sustain different loads, the designs of interfaces on the front and back ends of the barrel can have different dimensions of the frame and different number and dimensions of the bolts. The sizing of such an interface has been performed analytically and validated by numerical models. [3]

7 Method Development

All partners developed with different focus numerical and analytical methods to solve their sizing problems for the concepts. On global aircraft level TsAGI implemented successfully a multilevel optimization cycle for the sizing of anisogrid fuselage barrel sections. On component level DLR has implemented a parametric analysis process for the anisogrid barrel section to provide needed Designs of Experiments for a multi parameter optimization algorithm set up by the University of Leeds. A new semi-analytical method has been developed by EADS-IW for calculation of buckling value of grid-stiffened skin shells on element level.

As result, the partners were able to get a high understanding of the structural behaviour of lattice structures, invented new design methods for these structures and performed successfully the sizing of all fuselage barrel design concepts, shown in chapter 5.

7.1 Multi-Level Sizing Procedure for Airframe Barrel Section

This algorithm is based on a multilevel approach to generate the universal parametrical finite element models which includes four FE models (levels) of different discreteness based on the specialized data base for the investigation of non-conventional structure concepts.

The algorithm consists of four main parts, each of which is responsible for its modelling level [12]:

- *Level 1: geometrical model (specifying the geometrical parameters and external loading analysis),*
- *Level 2: constructive model (determination of inertia loads),*
- *Level 3: manufacture model (panels parameters input and solving the buckling tasks),*
- *Level 4: strength model (stress-strain state analysis).*

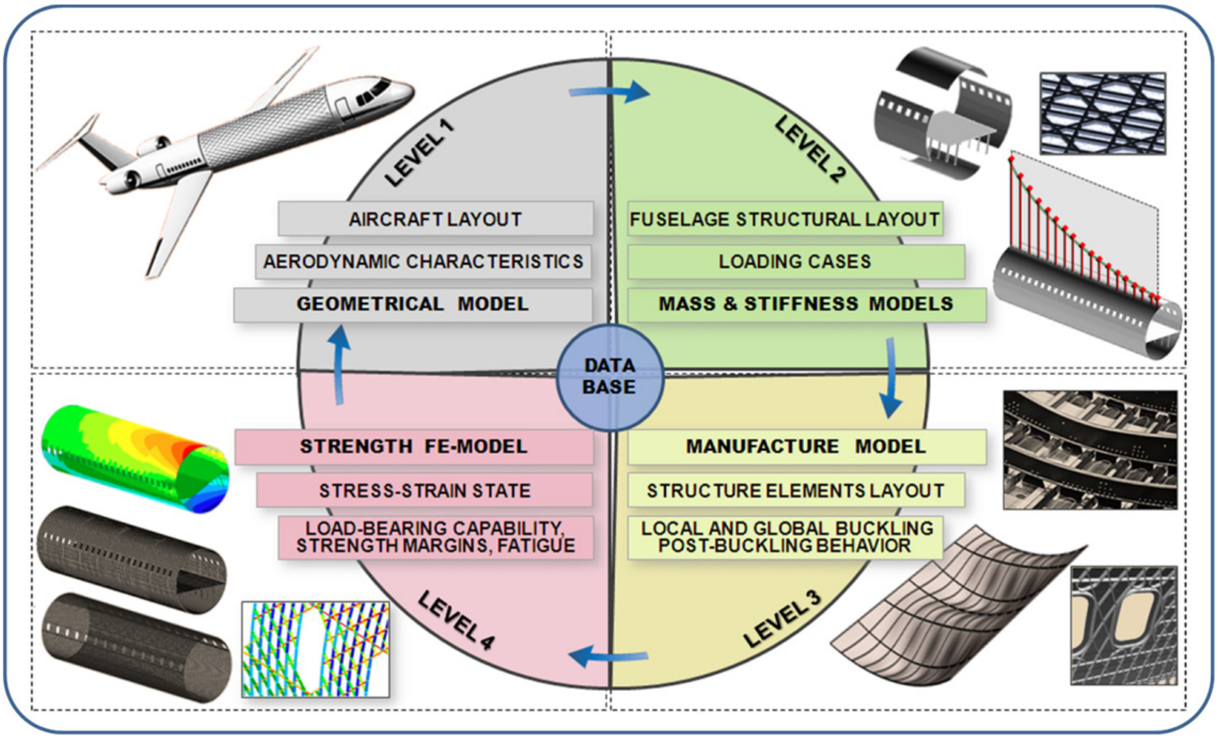

Fig. 14: Multilevel Approach in Structure Designing

Both the approximate semi-analytical methods using numerical-analytical solutions for the model with “smeared” ribs’ stiffness and more accurate (finite-element) models using real (discrete) layout of ribs and skin, can be used for analyses of the lattice structure in frame of the multilevel approach. Approximate methods can be used for express analyses of stress-strain state and buckling of regular parts (panels) of the fuselage unit and for preliminary estimations of critical loads for these parts depending on structural parameters. Methods based on FE approach should be also used for modelling of structural features caused by the presence of the specific components.

7.2 Multi-parameter Optimisation Algorithm

The design process of the composite pro-lattice Skin Inside concept is a multi-parameter optimisation problem, which has been performed with a metamodel-based optimization technique. Using an extended uniform Latin hypercube design of numerical experiments (DOE), 101 barrel designs, corresponding to different sets of design variables, have been created and analysed using the Finite Element method. Therefore an automated programme code has been developed by DLR to pre-process, solve and post-process these 101 finite element models. Global metamodels have been built by ULeeds as explicit expressions of the design variables using Genetic Programming (GP) to predict the structural responses. This was followed by the parametric optimization of the fuselage barrel to obtain the best design configuration in terms of weight savings subject to stability, strength and strain requirements. Since one of the design variables, the number of helical ribs, is integer a discrete form of a genetic algorithm (GA) has been used to solve this integer-continuous optimization problem. [8]

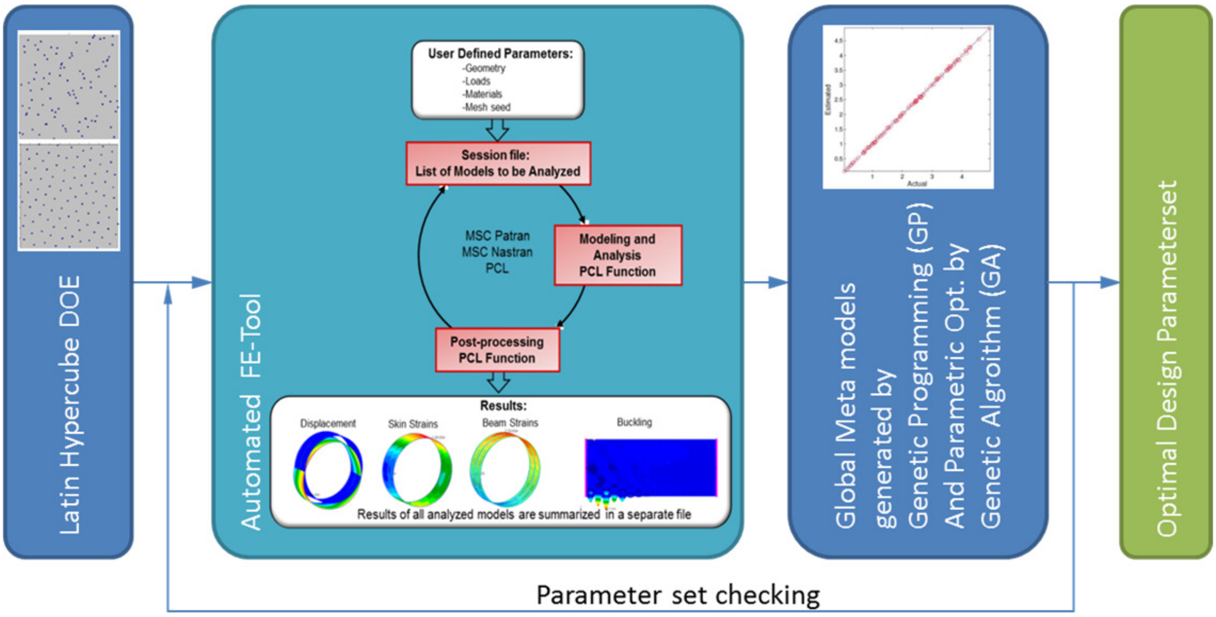

Fig. 15: Indications of the quality of fit of the obtained expression for the shear strain response into the data

The optimal solution and structural responses were verified with finite element simulations of the optimal lattice fuselage barrels. Two optimum structures were obtained. The first structure was optimized only for strength requirement, producing a light weight fuselage with few thin helical ribs and circumferential frames, and large skin bays. The second structure was optimized for strength, stability and stiffness requirements. The fuselage generated was subsequently a heavier structure with smaller skin bays and more stiffeners. The stability criterion became the driving factor for the skin bay size and the fuselage weight. It is concluded that the use of the global metamodel-based approach combined with prior topology optimization has allowed to solve this optimization problem with sufficient accuracy as well as provided the designers with a wealth of information on the structural behaviour of the novel anisogrid composite fuselage design.

7.3 Skin Bay Buckling Value Determination Method

A procedure to analyse the buckling behaviour of curved skin fields in grid-stiffened shells was developed by Weber and Middendorf [15]. As load cases combinations of biaxial compression and in-plane shear are considered. The laminate of the skin is assumed to be symmetric, balanced and orthotropic. Furthermore the material law of the Classical Laminate Theory is applied and the curvature is taken into account by using kinematic relations of Kirchhoff/Love [16] for thin singly-curved shells.

The buckling load is obtained by minimizing the total potential energy of the system according to Ritz and solving the resulting eigenvalue problem. Since the stiffness matrices only depend on the shape functions they only need to be calculated once. This is a major advantage compared to finite element analyses where a change in geometry demands a change of the model. Compared to referencing finite element and analytical results, the method shows a high level of accuracy even in cases were the finite element method encounters numerical problems (Weber and Middendorf [15]).

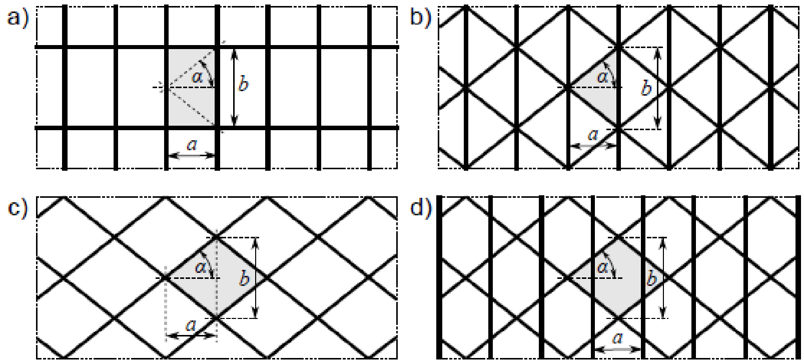

Fig. 16: Stiffening patterns and dimensions of skin segments for a) orthogrid, b) isogrid, c) diamond grid and d) kagome grid [15]

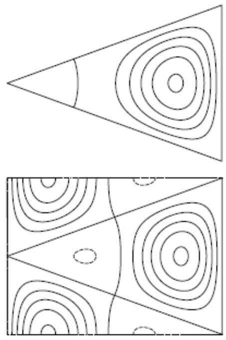

Fig. 17: Buckling mode of single skin segment and skin fields [15]

Four different stiffening patterns are considered (see Fig. 16). It is important to mention that the stiffeners themselves are not part of the mechanical model. Their influence is only reflected by choosing shape functions with zero deflection at the stiffener positions.

Two different types of boundary conditions are investigated. First, simple supports at stiffener positions for a single skin segment. Second, symmetry boundary conditions for simulating skin fields with a theoretically unlimited number of skin bays. Fig. 17 illustrates exemplary a resulting buckling mode for the two different types of boundary conditions.

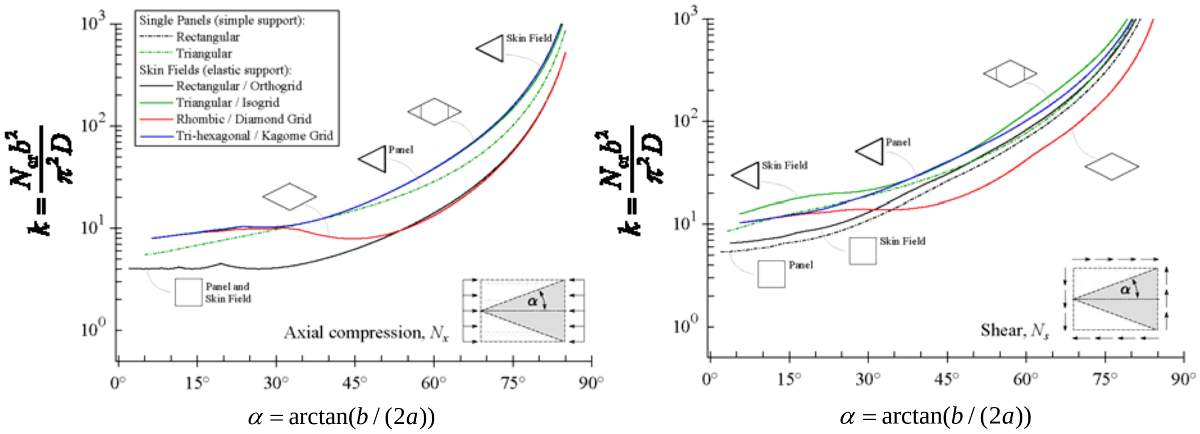

Fig. 18: Buckling factors of different grid patterns for a) axial compression and b) shear [15]

A comparison of buckling factors by Weber and Middendorf [15] for different grid patterns and varying half vertex angle α is shown in Fig. 18. As load cases axial compression and in-plane shear are considered. In case of the skin field model, interaction of adjacent skin segments leads to an increase of the buckling factor compared to the case of a single panel. For orthogrid structures this effect is limited to situations including shear load. Iso- and kagome-grids show considerable higher buckling factors compared to orthogrids for same α.

8 Test Barrel Manufacturing

TsAGI let manufactured a full scale demonstrator and test barrel at CRISM in August 2013, according to the Skin Outside concept development, see Fig. 19. This full-scale barrel section will be tested in the following time after the ALaSCA project.

For manufacturing, the following work has been done:

- *Mandrel for winding test barrel and moulds for elastic matrices have been designed and manufactured;*
- *The test equipment has been prepared according to dimensions of the barrel, loads to be applied and needed measurements.*

The barrel has the following specific components:

- *Rib structure with circumferential, helical and axial ribs*
- *Monolithic CFRP skin*
- *Cut-outs for windows with frames*
- *Barrel-Barrel-Interfaces at the ends of the fuselage section*

The Interfaces at the ends of the barrel section gets used to fix it in the testing machine. The barrel will be used for validation of the developed numerical models to investigate in a detailed testing program strength and stiffness of the barrel.

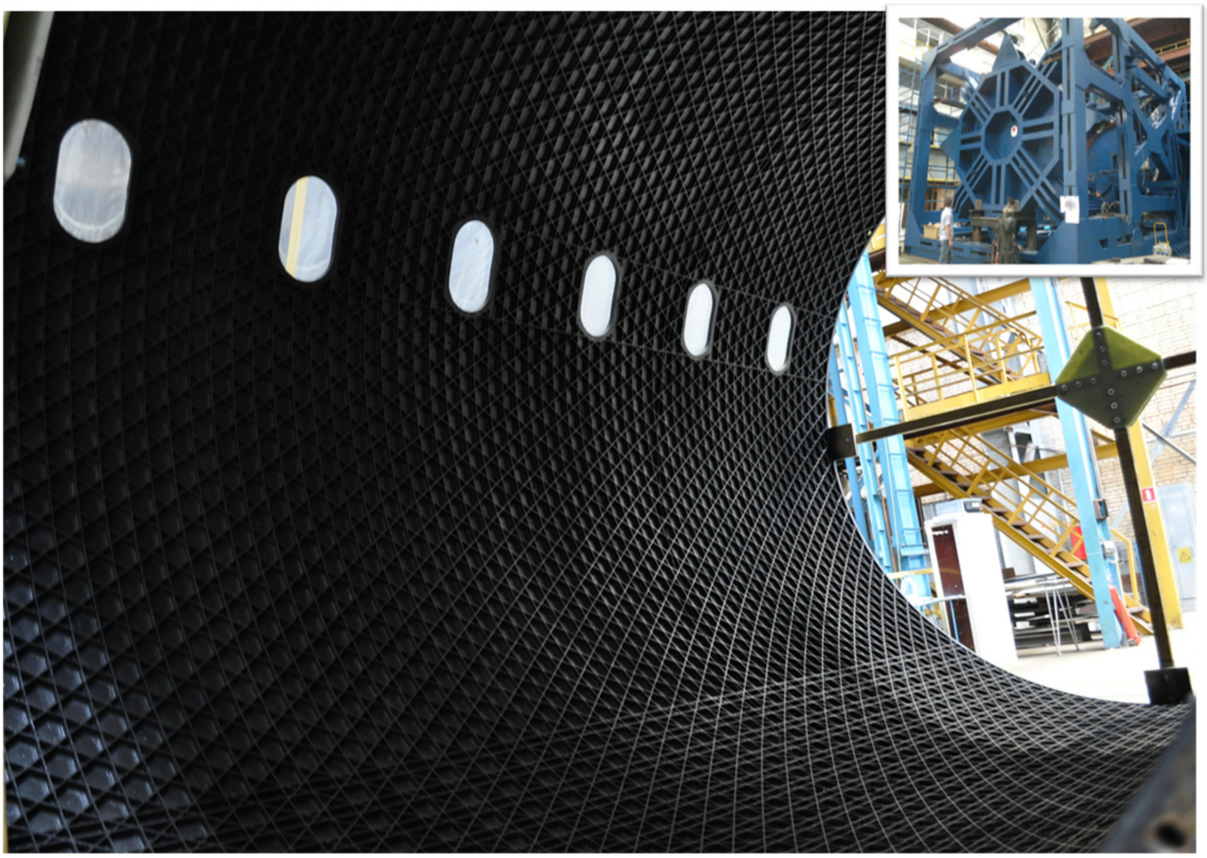

Fig. 19: Full-Size Test Barrel at TsAGI

9 Conclusion and Outlook

In the level 1 project ALaSCA (Advanced Lattice Structures for Composite Airframes) the potential of novel airframe architecture has been demonstrated. Deriving from a spacecraft well proven structure design, two different pro-lattice barrel concepts has been developed. On the one hand a highly integral airframe concept, which can be produced in automated tape laying or winding process. On the other hand a differential design concept with load bearing skin and a multifunctional covering of the primary structure.

Following main innovations could be developed in the ALaSCA project:

- Aircraft configuration with long undisturbed combination of composite and metallic fuselage sections - Patent [4]
- Tailored integral lattice structure for perspective composite fuselage structure - [3]
- Differential airframe design concept with load bearing skin and stiffeners in lattice grid arrangement - [5], [9]
- CFRP-Steel Hybrid material for stiffeners in primary airframe structure – Patent [6]
- Pro-lattice primary structure for aircrafts – Patent [17]
- Semi-analytical method for Skin Buckling of Curved Orthotropic Grid-stiffened Shells - [15]

For an investigation of the impact of the weight reduction on aircraft level, a mass reduction of 10% of primary structure weight has been implemented in the airplane configuration calculation only for the ALaSCA barrel section. Due to scaling effects on other aircraft components, the barrel mass reduction results already in 1% overall fuel consumption reduction for the flight mission of such short and middle range aircraft. These significant design improvements for composite geodesic fuselage structures derived from following findings:

- *The resulting non-rectangular skin bays between the ribs, which show increased buckling coefficients compared to rectangular skin bays with the same weight.*
- *The uniaxial loading of the monolithic ribs, with which a strain allowable increase can be pursued, considering an impact protection of the highly oriented ribs.*
- *Aiming a possibly high axial stiffness for the stiffeners, CFRP-Metal-Hybrid shows the potential achieving a high axial stiffness, while also being damage tolerant.*

Due to the focus of EU-ALaSCA on a global barrel design level, there are open questions on the local level. The successful applied follower project, called EU-PoLaRBEAR, will focus on the above mentioned investigations, relying on a bottom-up approach on local level to increase the technology readiness level of geodesic structures, see Fig. 20.

In parallel work packages the research will be addressed regarding automated manufacturing of a protection layer in winding process, automated manufacturing of geodesic structures with Prepreg technology, buckling analysis of non-rectangular skin bays, damage tolerance and fatigue of the rib-structure and reparability of the elements. Finally to all investigations, Design Rules for geodesic structures will be created.

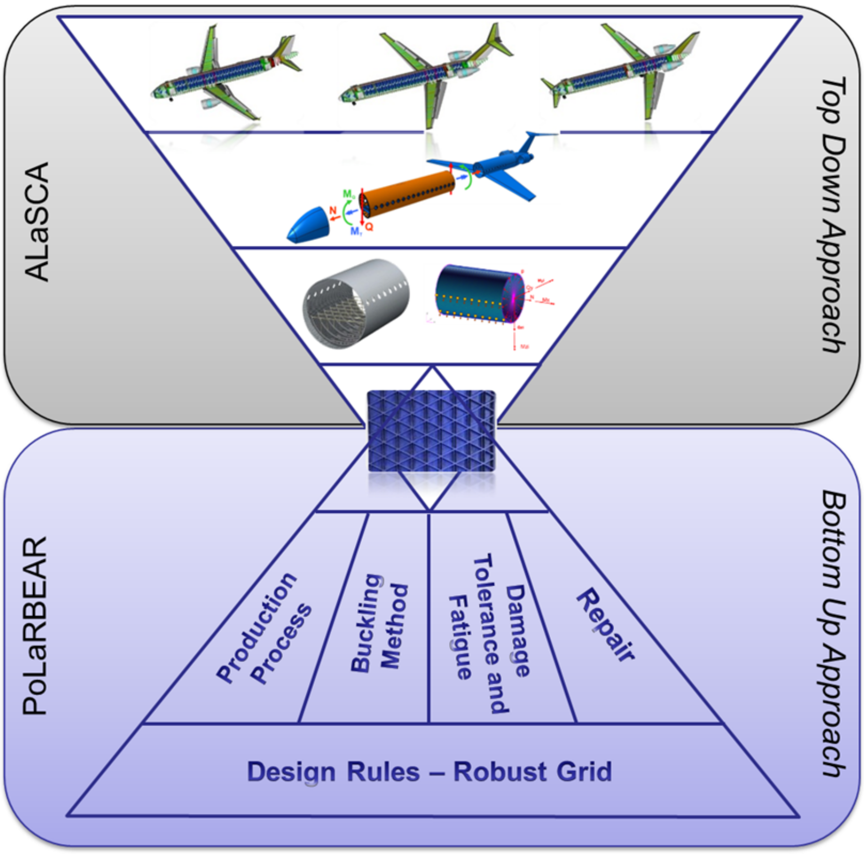

Fig. 20: Focus of ALaSCA and PoLaRBEAR

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