aerospace

MDPI

Article

Manufacturing Aspects of Creating Low-Curvature Panels for Prospective Civil Aircraft

Evgeny Dubovikov *,†, Danil Fomin †, Natalia Guseva †, Ivan Kondakov †, Evgeny Kruychkov †, Ivan Mareskin † and Alexander Shanygin †

Central Aerohydrodynamic Institute (TsAGI), 1, Zhukovsky St., Zhukovsky, Moscow Region 140180, Russia; Danil.Fomin@tsagi.ru (D.F.); gus_nata2014@mail.ru (N.G.); Ivan.Kondakov@tsagi.ru (I.K.); Ivan.Mareskin@tsagi.ru (I.M.); Alexander.Shanygin@tsagi.ru (A.S.)

* Correspondence: evgeny.dubovikov@tsagi.ru

† These authors contributed equally to this work.

Received: 11 November 2018; Accepted: 30 January 2019; Published: 14 February 2019

Abstract: For this study, structural and manufacturing schemes for low-curvature pressurized fuselage panels were proposed, making it possible to provide high weight efficiency for the airframes of prospective civil blended wing-body (BWB) aircraft. The manufacturing scheme for low-curvature panels helped to achieve high strength characteristics of the composite details as well as decreased the labor input necessary for manufacturing and assembling. The beneficial features of the proposed structure are that the panels have a low weight, incur low manufacturing costs, and satisfy the demands of repairability.

Keywords: manufacturing; low-curvature panels; pressurized fuselage; blended wing-body aircraft

1. Introduction

Due to certain benefits, the blended wing-body (BWB) concept is considered to be one of the prospective concepts for the next generation of civil aircraft, especially for long-range airliners.

Estimating the effectiveness of applying the BWB concept to civil aircraft with high and extra high-passenger capacity has been the scope of several works undertaken by the Central Aerohydrodynamic Institute (TsAGI) within the framework of the European FP6 NACRE [1,2] project. Work under a number of contracts for Boeing and Airbus [3–5] has also been performed on this topic. In the course of that work, high aerodynamic characteristics and new feasible solutions concerning an aircraft's layout were obtained and substantiated. However, the question of the BWB concept's high weight efficiency remains because the application of conventional metallic and composite ("black metal") structural layouts do not provide an adequate weight efficiency. Consequently, the benefits related to the BWB concept, as compared to conventional analogues, have not been obtained.

The root of the problem of the BWB concept's low weight efficiency are the expenses related to high weight efficiency, namely, the costs needed to ensure the proper strength characteristics of high-loaded pressurized low-curvature (flat) panels. One solution to this problem was proposed in [6–8] based on double-lattice composite panels.

The main load-bearing elements of double-lattice pressurized panels are high-strength axisymmetric metal-composite rods that form a spatial frame. The frame, together with two composite lattice grids (inner and outer), is capable of effectively bearing both in-plane and out-of-plane loads (Figure 1). The panels also include low-loaded elements such as elastic skins (pressurized skin, shape-forming aerodynamic skin, and protective layers). These elements, despite their insignificant role in bearing mechanical loads, are important parts of the structure as they provide the high reliability of the structure, saving load-bearing elements from impacts and environmental factors.

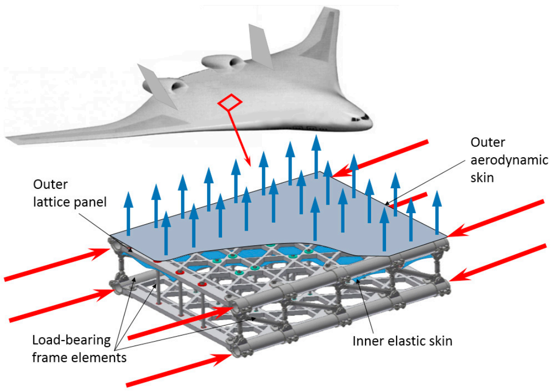


Figure 1. Principal scheme of bearing loads by the pressurized double-lattice flat panel.

In [6,7], it was shown that double-lattice pressurized panels, as described above, could create a low-weight airframe for the BWB with a high operational reliability. The application of such panels can therefore become the solid foundation for significant improvement in the transport efficiency of future aircraft by using the BWB concept.

For this work, the manufacturability of double-lattice panels was investigated and a manufacturing model was proposed and substantiated. In this paper, we present the results of the weight efficiency analysis of the double-lattice flat panels of a hypothetical BWB aircraft, taking into account the manufacturing aspects.

The main objective of the work was to show that the manufacturing requirements and constraints as well as the requirements related to operations and repairs do not drastically decrease the benefits related to the weight of this type of panel.

2. Critical Strength Tasks of BWB Airframes

Integral aircraft concepts, like the BWB concept, as applied to long-haul aircraft with high-passenger capacity, have a number of potential benefits when compared to conventional aircraft concepts [1,4,5]. The benefits of the BWB concept are created by higher aerodynamic characteristics and the possibility of using novel advanced layout solutions.

However, the BWB concept has a number of shortcomings caused mainly by two problems:

(1) The large area of the outer surface, which leads to the appearance of large underloaded zones; and
(2) The presence of large zones with a flat surface, subjected to considerable in-plane and out-of-plane loads.

This work focused on the second problem. The investigation centered on the upper flat pressurized panel, located in the most critical zone of the hypothetical civil BWB aircraft, where the mechanical and internal pressure loads are at a maximum. The panel covering this zone has the following dimensions: length A = 3.8 m, width B = 3.84 m, height H = 0.42 m.

The configuration and a list of the main parameters of the aircraft are presented in Figure 2. This hypothetical BWB aircraft is considered to be one of the prospective variants of the next generation of civil aircraft. Its maximal take-off weight equals 230,000 kg and its passenger capacity is 325 persons.

Parameter	Value
MTOW, kg	230000
PAX	325
Thrust, N	2x350000
Structure weight, kg / %	66150 / 28.76
Payload, kg	33500
Fuel, kg	70050
Aerodynamic quality	23.5
Specific fuel consumption, 10^{-4} kg/kg*s	1.44
Range, 10^3 m	12550

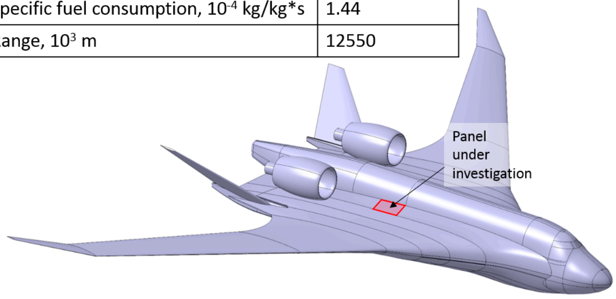


Figure 2. One of the prospective blended wing-body (BWB) configurations.

For this aircraft, the following three variants of pressurized panels with different layouts were investigated and compared: conventional metallic (variant 1), conventional composite (like "black metal") (variant 2), and double-lattice composite (variant 3) (Figure 3). For the first two variants, the weight characteristics were estimated by taking into account the layouts of the aircraft panels used in current civil aircraft. With respect to the third variant, the weight estimation was performed in parallel with the development of a manufacturing model of the double-lattice panel.

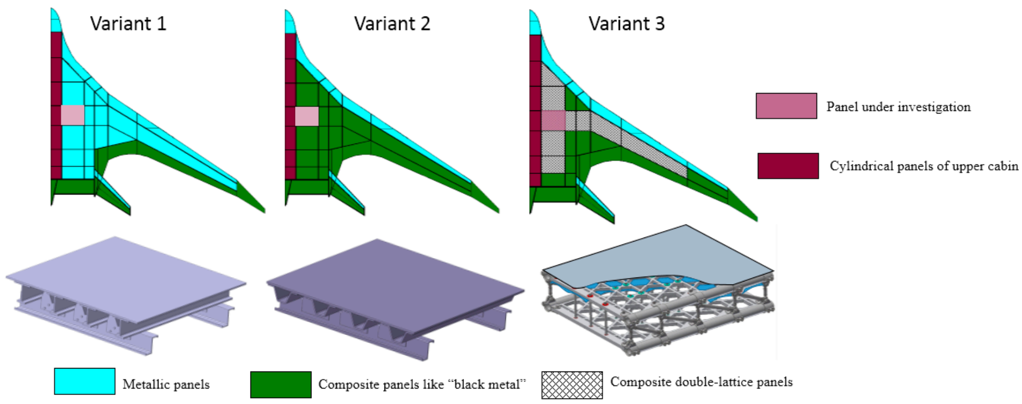


Figure 3. Alternative structure concepts for pressurized flat panels of the hypothetical BWB aircraft.

The weight of a square meter of the metallic panel was 70–75 kg, whereas the weight for the composite "black metal" variant of the panel was 65–70 kg. According to [9], the weight efficiency of a BWB structure turned out to be low, and practical possibilities to increase it significantly were not found.

In the present work, a comparative analysis of the weight characteristics of the above-mentioned panel variants was performed, taking into account the manufacturing aspects for the double-lattice panel.

3. Double-Lattice Pressurized Flat Panels

3.1. Specific Features of the Double-Lattice Concept

In a double-lattice pressurized flat panel, the main part of the primary structure is the spatial frame, consisting of axisymmetric rod elements. The other parts of the primary structure are two composite lattice grids (outer and inner). Additional elements are the elastic pressurized skin and the external shell (skin). The main structural elements of the double-lattice panel are represented in Figure 4.

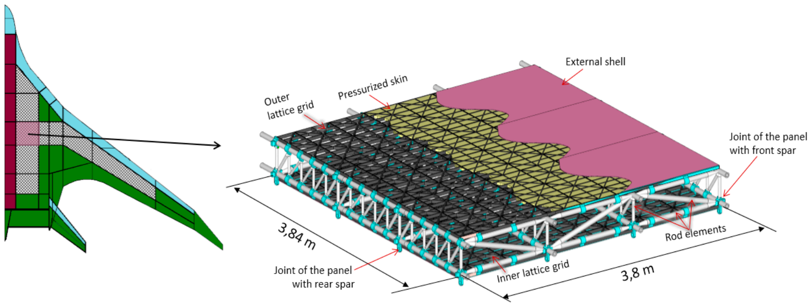


Figure 4. Double-lattice flat pressurized panel.

The main advantage of the double-lattice panels is related to its rational structural layout, allowing composite materials to work more effectively due to the unidirectional stacking of primary structural composite elements and their protection against impacts and environmental factors. Protective elements of the panel such as elastic skins and protection layers are used. Moreover, the lattice grids have high survivability due to their topology [10]. This makes it possible to significantly increase the allowable stress–strain level for primary structural elements of the flat pressurized panels and, as a consequence, increase their weight efficiency.

In the present work, a rational manufacturing concept for the double-lattice composite panel was investigated. For this purpose, the complex strength/weight numerical analysis and design of the upper panel of the hypothetical BWB's central pressurized wing box (Figure 4) were carried out. This analysis considered the factors of static loading, impacts, and environmental conditions.

Structural parameters of the double-lattice panel details were defined by taking into account the manufacturing constraints for the following composite manufacturing processes: fiber placement and wet winding. The design analysis was carried out using a four-level algorithm, developed at the TsAGI for the strength analysis and design of such metal-composite structures [6,11]. The algorithm was validated within a number of Russian (domestic) and European FP6-FP7 projects.

3.2. Four-Level Algorithm of Strength and Weight Analysis

The main specific feature of the four-level algorithm is that the design process is performed within a one complex iterative procedure including a number of global cycles. Within each global cycle, four sequential local actions are performed (Figure 5): aerodynamic analysis (level 1), structure layout analysis (level 2), manufacturing analysis (level 3), and strength analysis (level 4).

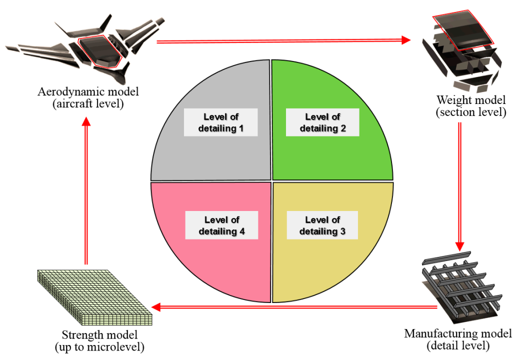


Figure 5. Scheme of the four-level algorithm.

To resolve the aerodynamic tasks (level 1), simplified finite element (FE) models are used to define the aerodynamic parameters and loads of the entire aircraft. The results obtained at this level are transferred to level 2 for the calculation of the structure parameters, weight characteristics, and aeroelastic characteristics. At this level, more detailed FE models are used for the airframe component. The obtained results are correspondingly transferred to level 3 for the definition of rational (feasible) manufacturing concepts. At this level, the manufacturability is checked and the manufacturing constraints are developed. FE models of level 3 are built for the details (subcomponents) of each component. Finally, at level 4, a strength analysis of the fragments/details is carried out.

Subsequently, the results of the global cycle are analyzed, the design parameters are changed, and the next iteration is launched. The iterative procedure stops when the values of the criteria become less than a defined value. As a rule, the main criterion is weight. More complicated criteria can also be used.

To significantly decrease the labor input and time needed for the calculations, the following principles were realized within the four-level algorithm [11]:

- Nesting principle for the FE models of all levels;
- Automated generation of auxiliary analytical models for each of the four FE models;
- Full automation of the iterative procedure;
- Application of specialized databases of prototypes for the weight analysis; and
- Application of specialized databases of available manufacturing processes for the definition of the manufacturing constraints.

4. Main Elements of the Double-Lattice Panel and Their Manufacturing Realization

4.1. Primary Structural Elements of the Flat Panel

4.1.1. Hybrid Rods

The main load-bearing elements of the frame structure of a double-lattice panel are hybrid (metal-composite) axisymmetric rod elements. The rod element (Figure 6) contains three parts: a cylindrical part and two conical parts. Additionally, the structural layout of such rods is also shown in Figure 6. The load-bearing part of the rod element is a composite shell with layers oriented close to its longitudinal axis. The inner space of the shell is filled with a lightweight material, which is used as a mandrel within the manufacturing (winding) process. The conical parts have metallic fittings at the ends. To save the weight, the metallic conical parts can have a porous structure with variable density, which could be maximal at zones of fittings, and considerably low at zones of attachments of metal and composite parts [12].

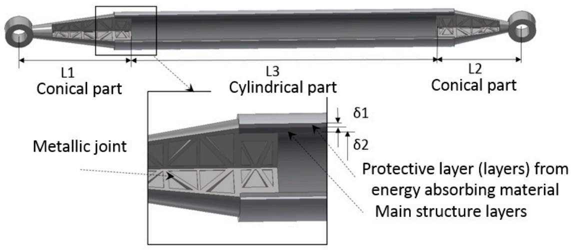


Figure 6. Main elements of the metal-composite rod.

Using a porous structure not only allows the ability to decrease the weight of the rod element, but can also balance the stiffness of the metallic and composite parts in zones of attachment [13].

The rod elements can sustain axial, torsion, and bending loads. However, they are most effective at longitudinal forces. The structure of the rod can have a special layer for impact and moisture protection, which can give a synergetic effect and also provide higher buckling margins of such rods. The manufacturing method for the rod elements combines winding for the composite parts and additive manufacturing (AM) for the metallic parts. It should be noted that for the length of a rod less than ~0.25 m and with a radius less than ~0.05 m, the metallic variant of the rod element is more effective.

At the first stage of the manufacturing process, the conical parts of the rod element are made using AM and are attached to the mandrel. At the second stage, winding is used for the final production of the rod element.

The assortment of the rod elements is defined by the following list of parameters:

L—length of the rod element;
$L1$, $L2$—length of the conical part;
$L3$—length of the cylindrical part;
$R0$—radius of the cylindrical part;
$R1$—radius of the conical part near fitting;
$\delta 1$—thickness of the protective layer;
$\delta 2$—thickness of the composite layer.

4.1.2. Main Joints

Three types of joints are used for the attachment of the rod elements: "end-to-end", "end-to-body", and "small end-to-body". First, two types are used to connect the rods, while the third is used to connect the rods with the lattice grids. The simplest variant of the joints, when only two rods are connected in one point, is shown on Figure 7. For the connection of more than two rods in one point, more complex joints are used. Connections of the rods with the lattice grid based on a "small-end-to-body" joint are shown in Figure 8.

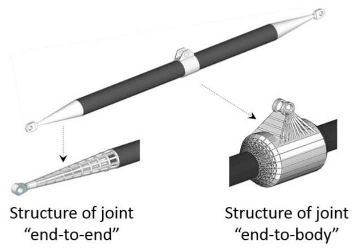


Figure 7. Examples of structural solutions for the attachment of hybrid rods.

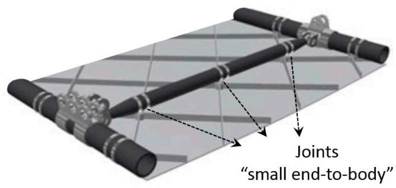


Figure 8. Example of the structural solution for the attachment of the aerodynamic skin and rod elements.

4.1.3. Lattice Composite Grids

The panel includes two lattice composite grids (outer and inner) with the same topology (Figure 9). The outer one is used for forming the aerodynamic shape and transferring aerodynamic loads to the frame, while the inner one is to sustain the internal pressure. The grids are attached to the load-bearing rods by means of "end-to-body" and "small end-to-body" joints using the attachment elements, and embedded into the grids. The number of such attachment elements is about 15–20 per square meter. The maximal load on a "small end-to-body" joint does not exceed 1 kN. For composite ribs of the inner grids, more elastic resins can be used, as the inner grid mostly sustains tension and bending.

For the outer grids, stronger and less elastic resins need to be used because the upper grid sustains bending and compression.

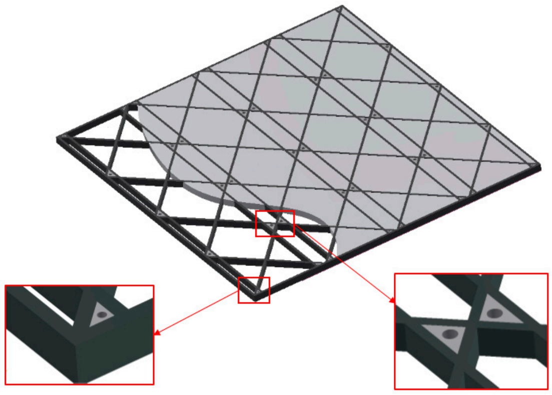


Figure 9. Lattice grid with a protective layer and embedded elements.

Manufacturing of the composite lattice grids can be performed using fiber placement or winding methods. In the frames of these conventional methods, the fibers are usually put into the grooves machined in the special foam coating. The foam coating is removed after curing. This manufacturing method was developed and validated in CRISM (Russia). For several high-loaded sections of the Russian Proton rockets, the weight benefits of lattice composite structures with respect to metallic prototypes were up to 25–50% [14].

In the manufacturing model proposed for the double-lattice panels, the foam coating is not removed as it serves as a protective layer. Such a manufacturing solution not only decreases the labor input and manufacturing costs and increases the quality of the grids (as the grid is not disturbed while removing the foam coatings), but also increases the strength characteristics of the panel.

The geometrical parameters and shapes for the inner and outer grids are different, but the pitch and angles of the orientation of the ribs for the grids are the same.

4.2. Low-Loaded Elements of the Flat Panel

4.2.1. Elastic Waveform Pressurized Skin

The structure of the double-lattice panel includes a thin elastic waveform pressurized skin. The pitch of the spherical segments of the skin coincide with the pitch of the ribs of the lattice grid. The wavelike form of the skin allows for a significant decrease in the tensile stresses in the skins caused by the internal pressure of 1 MPa, down to a level of 30–50 MPa, as the curvature radius of the "waves" is only 0.08–0.15 m (Figure 10).

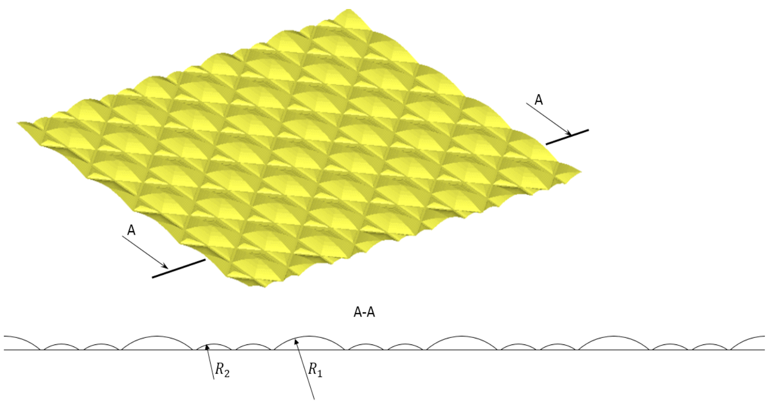


Figure 10. Waveform elastic skin.

As the pressurized skin only sustains tension loads, it is better to make it by means of braiding methods by using cheap low-strength elastic fibers and resins. Thermoplastic composites could be a good variant for such skins.

4.2.2. Outer Skin of the Panel

The panel includes an outer aerodynamic skin. The role of this element is to form the aerodynamic shape and transfer the aerodynamic loads to the outer lattice grid. It also serves as an impact-resistant protective layer. The skin is attached to the lattice grid by the means of bolts/pins.

The skin can be manufactured by means of fiber placement or braiding technologies. RTM-method (resin transfer molding) can also be applied.

Parameters of the skin are mostly defined by the stiffness requirements.

4.2.3. Thermal and Impact Protection Layers

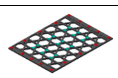
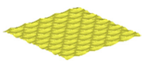
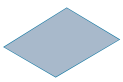
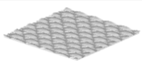
Thermal/impact protection layers are the secondary parts of the panel and serve to:

- Form the local stiffness,
- Add thermal and impact protection,
- Attachment function (additionally, the outer skin can be connected to these layers by means of an adhesive joint),
- Foam coating for manufacturing.

4.3. Assortment of the Main Structural Elements

Table 1 shows a list of the main structural elements of the flat pressurized double-lattice panel and feasible variants of their manufacturing.

Table 1. Assortment of the main structure element of the panel.

Figure	Element	Material	Manufacturing Method
	Horizontal axisymmetric rods	Carbon fiber composite prepreg	Automated fiber placement/winding on special foam preform
	Transversal (diagonal) and vertical axisymmetric rods	Metal for ends and composite prepreg for tube	Automated fiber placement/winding on special foam preform
	Lattice grids	Carbon fiber composite prepreg	Automated fiber placement
	Joints for axisymmetric rods and lattices	Metallic alloy	Additive manufacturing (3D printing)
	Wave elastic pressurized skins	Fabric prepreg	Fiber placement /braiding
	Outer aerodynamic skins	Fabric prepreg	Fiber placement /braiding
	Wave foam covering	Foam	Cutting
	Attachments (pins, bolts, screws)	Metallic alloy	Conventional metallic technologies

5. Multilevel Principle of Manufacturing and Repair of the Flat Double-Lattice Panel

Three following main units can be distinguished in the structure of the double-lattice panel:

1) Spatial frame skeleton including the rod elements and joints;
2) Outer subpanel including the outer lattice grid, wave elastic hermetic skin, wave foam covering, foam covering with embedded elements and outer elastic skin; and
3) Inner subpanel including the inner lattice grid, flat foam covering with embedded elements.

5.1. Main Stages of Manufacturing of the Panel

The double-lattice panel is manufactured in three main stages (levels). At the first stage, the foam coverings for the rod elements and the subpanels (Figure 11) are manufactured by means of turning and cutting. In parallel, the metallic conical parts for the rod elements and other attachment elements are manufactured using AM and conventional methods.

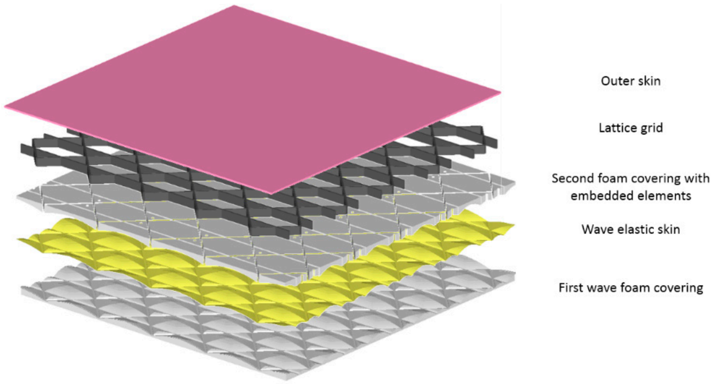


Figure 11. Main structural elements of the upper subpanel of double-lattice panel.

At the second stage, the rod elements and the subpanels are manufactured using wet winding and fiber placement. The second stage contains a number of substages for manufacturing both the rod elements and the lattice subpanels.

With regard to the rod elements, there are three substages. During the first substage, a cylindrical foam covering is connected with metallic conical parts. During the second substage, a number of layers (including load-bearing and protection layers) are winded. During the third substage, the rod elements are cured. This manufacturing process of the second stage can be automated to a high extent.

For the outer lattice subpanel, there are three substages. During the first substage, a wave elastic skin is manufactured by means of fiber placement using the first wave foam covering. At the second substage, the second foam covering is put on the wave skin and pressed. Next, the ribs of the lattice grid are placed into the grooves of the second foam covering and the attachment elements are embedded. At the third substage, the outer skin is placed and connected to the subpanel using bolts/pins and adhesive joints. Finally, the subpanel is cured.

For the inner lattice subpanel, which has no skin, only one substage is needed. Within this substage, the lattice grid is placed into the grooves of the foam covering and is cured.

At the third stage, the double-lattice panel is finally assembled in three substages. At the first substage, the spatial frame is assembled from rod elements using "end-to-end" and "end-to-body" joints. At the second substage, the outer lattice subpanel is connected to the frame by means of bolted joints. At the third substage, the inner lattice subpanel is attached.

5.2. Multilevel Protection System for Primary Structural Elements of the Panel

The sensitivity of the primary structural composite elements to impacts and environmental damage significantly decreases their weight efficiency. One of the methods against impact damage is through the protection of the primary structural elements from impacts by means of the application of special impact-absorbing materials.

Investigations dedicated to the development of special protection for unidirectional composite high-loaded rod elements were carried out in TsAGI [15].

For a high-loaded rod element, a special protection system against impacts and environmental factors was proposed that consisted of a combination of protective layers winded on the rod element (Figure 12):

- Layer of carbon fibers,
- Layer of elastic impact-absorbing materials,
- Layer of aramid fabric, distributing the impact energy on a larger area,
- Layer of chemical-resistant material.

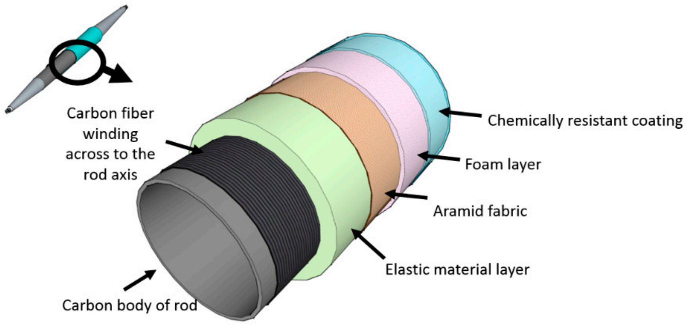


Figure 12. Concept of the special protection system for rod elements against impacts and environmental factors.

The materials used for these layers had low moisture absorption, high impact resistance, and high energy absorbing properties. The results of the investigations also showed that increasing the strength of high-loaded composite rod elements was more effective when adding material to the protection system, instead of adding the material to the element itself, by taking into account the degradation of its properties caused by the environment and impacts (see Figure 13).

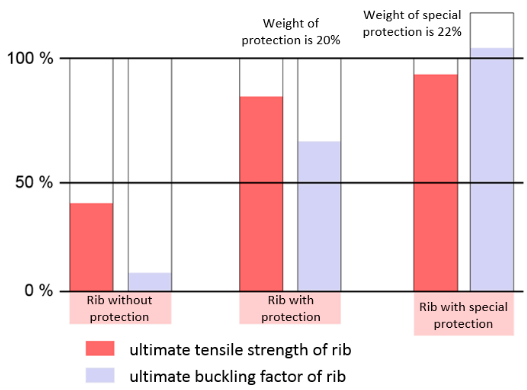


Figure 13. Influence of different variants of the protection on the residual strength and buckling properties of the composite rod elements.

Figure 14 shows the diagrams characterizing the strength parameters of cylindrical rods with various extents of protection after impact loading with energy ~20 J. It is shown, that spending ~20% of weight of the rod element on its protection makes it possible to not only fully maintain its strength characteristics after 20 J of impact, but even increase them due to synergetic effects. In particular, using the special multilayered protection (Figure 12) with a weight of 22% of the rib weight increased the buckling factor of the rib by ~5% due to squeeze caused by the wrapping layer of carbon fibers. Such results were also obtained for the lattice grid.

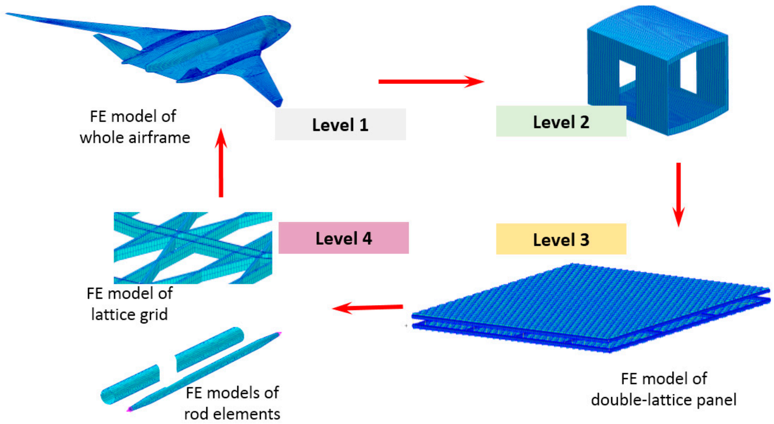


Figure 14. FE models of different levels for the weight estimation of the double-lattice panel.

Another method of decreasing the influence of impact loads on the performance of the structural elements is the location of the element inside the structure and the creation of a "natural" protective system for it. The "natural" protective system consists of both impact-absorbing layers and structural elements, naturally protecting this element from impacts.

In the structure of the pressurized double-lattice panel, both of the above-mentioned methods are used. For example, the main elements of the panel, the rod elements of the frame, are protected against external impacts by means of an aerodynamic skin with an impact-protection layer, upper lattice subpanel, and the rod elements of the upper frame. By this reason, there is no need to create a special protection system for these elements.

The lattice grid of the outer subpanels is protected from impacts, correspondingly, by means of an aerodynamic skin with an impact-protection layer. The lattice grid has a multi-path layout, so the impact damage is less dangerous for its load-bearing capacity.

Finally, the aerodynamic skin is subjected to direct impact and can be damaged. However, the damage will be even less critical than the damage of the lattice grid as the skin is not a primary structural element.

For the double-lattice panel, a simple and cheap enough repair scenario can be realized. Three types of repair of the panel, depending on the level of damage, can be classified:

1. Minor damage repair: Repair of the skin and several ribs of the lattice grid. This is an in field type of repair and only requires standard equipment. The damaged skin is repaired using patches by means of bonding. The damaged zone of the lattice grid is filled with a polymer compound.
2. Medium damage repair: Replacement of the skin and lattice for a significant part of the panel. Such types of repairs presume the replacement of the upper lattice sub-panel with a new one. The lattice sub-panel is connected with the frame by bolts and so can easily be removed.
3. Hard damage repair: Replacement of the skin and one to two elements of the upper frame.

In this case, the upper lattice sup-panel is removed to provide access to the frame. After that, the damaged rods are repaired or replaced. The upper lattice sub-panel is also replaced.

Such repair scenarios can provide for the long-term and reliable operation of the structure with low weight and cost expenses.

6. Estimation of Weight Efficiency of the Flat Pressurized Panel

In this work, the weight analysis of alternative variants of the pressurized panels including the double-lattice panel structure was performed using the four-level algorithm. For all variants, FE models, corresponding to each level of the algorithm, were built, taking into account the special features of each layout. The types of models for levels 1 and 2 were the same for each of the variants, while for levels 3 and 4, different types of models were different. For variants 1 and 2, conventional FE models based on 2D shell elements for the panel (level 3) and its fragments including stiffeners (level 4) were built. Regarding variant 3, special FE models of levels 3 and 4, forming lattice grids and axisymmetric rod elements, were built (Figure 14).

All FE models for all variants were fully automated and the data transfer between the levels during the cyclic procedure of the design analysis was organized without manual operations. In the design analysis, all elements of the BWB aircraft structure were designed and analyzed. However, the comparative weight analysis was performed only for the above-mentioned pressurized panel.

Parameters of the structural materials, used in the FE models, are shown in Tables 2 and 3.

Table 2. Parameters of the structural materials for variants 1 and 2.

Element	Metallic				Black-metal Composite			
	Elastic modulus, GPa	Allowable stresses, MPa			Longitudinal elastic modulus, GPa	Allowable strains		
		Tension	Compression	Shear		Tension	Compression	Shear
Skin	72	350	250	200	57	0.4%	0.3%	0.5%
Stringers/ frames	71	350	250		68.67	0.4%	0.3%	0.5%
Webs of spars/ribs	71			200	68.67	0.3%	0.2%	0.23%

Table 3. Parameters of the structural materials for the double-lattice panel.

Element	Material Name	Density kg/m^3	Longitudinal Elastic/ Shear Modulus GPa	Allowable Strains/Stresses		
				Tension	Compression	Shear
Lattice grids	Hexply M21	1600	90/5.3	0.6%	0.5%	
Composite parts of rod elements	Hexply M21	1600	88.6/8.7	0.8%	0.7%	
Inner skin	Polystyrene	1050	1.3/-	80 MPa		
Outer skin	Hexply M21	1600	57/21.5	0.4%	0.3%	0.2%
Joints	VT6 titanium alloy	4500	105/40.38	900 MPa	900 MPa	600 MPa

Critical loads for the panel were derived on the basis of the FE and analytical models of levels 1 and 2, while detailed manufacturing and the strength analysis of the panel were carried out using FE models of levels 3 and 4. The main design load case for the upper panels was the maneuver case with a load factor of 2.5 and internal pressure of 1 atm. The value of maximal bending moment in the zone of the pressurized cabin (containing the upper panel) was $M_{\text{bend}} \approx 25 \times 10^6$ N·m, torsion moment $M_{\text{tors}} \approx 3 \times 10^6$ N·m. The value of the normal force for the upper panel was $P_{\text{norm}} \approx 7.9 \times 10^6$ N. These load factors are sustained mainly by the longitudinal (along spanwise) rod elements. The lattice grids of the upper panel bear the local loads from the internal pressure and the aerodynamic forces and transfer it to the longitudinal rod elements.

The results of the numerical strength analysis of the panel showed that the values of the structural parameters (Table 4), obtained during the design analysis, satisfied both the strength requirements and the constraints on the out-of-plane displacements of the panel, defined by the aerodynamic constraints (limits for the drag coefficients).

Table 5 shows the values of the weights for the main structural elements for one square meter of the upper panel for all variants of the structure.

Table 4. Rational values of the structural parameters.

Lattice Grids (Outer and Inner)		Rod Elements	
Parameter	Value, m	Parameter	Value, m
Height of ribs	0.03	Outer diameter of the inner horizontal axisymmetric rods	0.1
Width of diagonal ribs	0.006	Thickness of wall of the inner horizontal axisymmetric rods	0.017
Width of perimeter ribs	0.009	Outer diameter of the outer horizontal axisymmetric rods	0.076
Width of ribs orthogonal	0.0025	Thickness of wall of the outer horizontal axisymmetric rods	0.011
		Outer diameter of the transversal (diagonal) and vertical axisymmetric rods	0.02
		Thickness of wall of the transversal (diagonal) and vertical axisymmetric rods	0.003

Table 5. Results of the weight analysis: specific weights of the components of the panels, kg/m^2.

Metallic Panel Elements	Weight	Composite Panel Elements	Weight	Double-lattice Panel Elements	Weight
Skin	23.7	Skin	24.3	Frame grid	28.7
Longitudinal stiffeners	18.2	Longitudinal stiffeners	16.6	Inner lattice grid with attachment	9.2
Transversal stiffeners	12.1	Transversal stiffeners	11.9	Outer lattice grid with attachment	10.0
Flanges of ribs	4.2	Flanges of ribs	3.9	Inner pressurized skin	0.6
Flanges of spars	4.9	Flanges of spars	4.5	Outer skin with thermal insulation layer	2.2
Attachment elements	5.3	Attachment elements	4.0	Protection of primary structural elements (including foam coverings)	3.0
				Additional attachment elements	2.4
Total	68.4 **(100%)**		65.2 **(95%)**		56.1 **(82%)**

7. Conclusions

The proposed concept of a flat double-lattice panel of the pressurized cabin of the BWB aircraft was analyzed from the viewpoint of the feasible manufacturing methods using currently available processes of aircraft production. A rational and simple manufacturing model for the double-lattice pressurized panel was proposed. Weight analysis showed that the manufacturing demands did not disturb the potential benefits of the double-lattice pressurized panel in weight saving. The weight comparison of the alternative variants made it possible to substantiate up to 18% weight saving of the double-lattice panels in comparison with the metallic analogue and up to 14% in comparison with the conventional composite analogue.

An effective system of multilevel protection and simple and reliable repair scenarios were also substantiated for the double-lattice panel.

The next step of the investigations will be manufacturing and testing the demonstrator of the double-lattice panel.

Author Contributions: Investigation, E.D., D.F., I.K., E.K., I.M., and A.S.; Writing—original draft preparation, E.D., D.F., N.G., I.K., I.M., and A.S.; Writing—review and editing, A.S.; Supervision, A.S.

Funding: This research was funded by the Ministry of Industry and Trade of Russia in the framework of the State program on the development of the civil aviation industry.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. FP6 NACRE Project. Available online: https://cordis.europa.eu/project/rcn/75773/reporting/en. (accessed on 13 February 2019).
2. Okonkwo, P.; Smith, H. Review of evolving trends in blended wing body aircraft design. *Prog. Aerosp. Sci.* **2016**, *82*, 1–23. [CrossRef]
3. Investigations of Technologies, Critical for Implementing an Airplane of Flying Wing Type with Superhigh Seating Capacity, ISTC Project #0548. Available online: http://www.istc.int/en/project/CAA832BC090C56E44325691F0011CAD4 (accessed on 13 February 2019).
4. Denisov, V.E.; Bolsunovsky, A.L.; Buzoverya, N.P.; Gurevich, B.I.; Shkadov, L.M. Conceptual Design for Passenger Airplane of Very Large Passenger Capacity in the Flying Wing Layout. In Proceedings of the 20th Congress of the International Council of the Aeronautical Sciences, Sorrento, Italy, 8–13 September 1996; Volume II, pp. 1305–1311.
5. Bolsunovsky, A.L.; Buzoverya, N.P.; Gurevich, B.I.; Denisov, V.E.; Shkadov, L.M.; Udzhukhu, A.Y. Investigations on possible characteristics of FW superhigh seating capacity airplane. In Proceedings of the 22nd Congress of the International Council of the Aeronautical Sciences, Harrogate, UK, 27 August–1 September 2000; pp. 116.1–116.9.
6. Shanygin, A.; Dubovikov, E.; Fomin, V.; Mareskin, I.; Zichenkov, M. Designing pro-composite truss layout for load-bearing aircraft structures. *Fatigue Fract. Eng. Mater. Struct.* **2017**, *40*, 1612–1623. [CrossRef]
7. Mareskin, I. Multidisciplinary optimization of pro-composite structural layouts of high loaded aircraft constructions. In Proceedings of the 30th Congress of the International Council of the Aeronautical Sciences, Daejeon, Korea, 25–30 September 2016.
8. Dubovikov, E.; Fomin, V.; Kondakov, I.; Shanygin, A.; Vedernikov, D. Development of rational hybrid fuselage structure for prospective civil aircraft. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2018**. [CrossRef]
9. Dubovikov, E.A. Novel approach and algorithm for searching rational nonconventional airframe concepts of new generation aircrafts. In Proceedings of the 28th Congress of the International Council of the Aeronautical Sciences (ICAS 2012), Brisbane, Australia, 23–28 September 2012.
10. FP7 PoLaRBEAR Project. Available online: http://cordis.europa.eu/result/rcn/175990_en.html (accessed on 13 February 2019).
11. Shanygin, A.; Fomin, V.; Zamula, G. Multilevel approach for strength and weight analyses of composite airframe structures. In Proceedings of the 27th Congress of the International Council of the Aeronautical Sciences, Nice, France, 19–24 September 2010.
12. Kondakov, I.; Mareskin, I.; Shanygin, A.; Zichenkov, M. Features of design of hybrid airframes on the basis of unidirectional composite elements and metallic metamaterials. In Proceedings of the 15th Annual Russian-French Seminar TsAGI-ONERA, Sochi, Russia, 4–7 October 2016.
13. Chernov, A.; Fomin, D.; Kondakov, I.; Mareskin, I.; Shanygin, A. Lightweight and reliable metal-composite joints based on harmonization of strength properties of joined parts. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2018**, *232*, 2663–2672. [CrossRef]
14. Vasiliev, V.V.; Razin, A.F. Anisogrid composite lattice structures for spacecraft and aircraft applications. *Compos. Struct.* **2006**, *76*, 182–189. [CrossRef]
15. Dubovikov, E.; Fomin, V.; Hühne, C.; Kolesnikov, B.; Kondakov, I.; Niemann, S.; Shanygin, A.; Wagner, R. Anisogrid design for fuselage primary structures—Results of EU/RU projects ALaSCA and PoLaRBEAR. In Proceedings of the Royal Aeronautical Society's 5th Aircraft Structural Design Conference, Manchester, UK, 4–6 October 2016.