MAIN BENEFITS OF PRO-COMPOSITE LAYOUTS FOR WING AND FUSELAGE PRIMARY STRUCTURE UNITS

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Keywords: *pro-composite structures, composite airframes, fuselage structures*

Abstract

Novel structures for high-loaded wing/fuselage sections based on pro-composite layouts allow to obtain weight benefits in comparison with conventional metallic and composite structures. These benefits are based on the four basic principles allowing to harmonize these structure layouts with physical properties of current CFRP. Robust designing of pro-composite structures requires novel approach to design based on solving multidisciplinary tasks of different stages of design within the one integrated procedure. The multilevel algorithm developed in TsAGI on the basis of this approach allowed to get reliable and promising results for a number of perspective aircraft wing and fuselage structures based on frame/lattice pro-composite concepts.

1 Pro-composite aircraft structures

The problem of weight and cost saving for the airframe structure is remaining relevant through all the history of aviation and it is substantially one of the most important factors in providing the development of aviation vehicles.

The experience gained by TsAGI in frames of a number of Russian and international projects on composite topics, such as NACRE, ALCAS, MAAXIMUS, CM-Fuselage etc., together with leading Russian and European companies, have shown, that the main difficulties in increasing weight and cost efficiency of composite airframes are caused, first of all, by the absence of a new effective approach to analysis, development and manufacturing of high-loaded composite structures [1].

At the present time most of state-of-the-art and currently developing composite airframes do not go beyond the frames of conventional metallic (Black metal) layouts. This does not allow to realize to a full extent the potential of high-strength carbon fibers. The situation is akin to those at the middle of 19th century in the ship building industry, when metallic alloys were beginning to be implemented in the structures of ship hulls.

Fig.1 – SS Great Britain – first ship with a metallic hull

The first ship with an iron hull «SS Great Britain» (Fig.1), has been built by I. Brunel in 1843. Potential advantages of metallic hulls had not been realized for this ship, because its development and manufacturing was carried out according to the methods, conventional for that time. Metallic structure of the ship was almost identical to structures made within the frames of "wooden" layouts. The launch of the ship was accompanied by a wide advertising campaign. SS Great Britain became a first screw steamer to cross the Atlantic ocean. However, its future turned out to be not so brilliant despite of many optimistic predictions. In 1846 the ship was retired due to its low efficiency caused by high weight and other design shortcomings.

The history shows that the change of structure material inevitably leads to new layouts. Hence, for the further progress of composite airframes it is necessary to search for new layouts, different from Black metal, and new structure concepts. This task was the subject of investigation in the European FP6 NACRE project and also in Russian CM-Fuselage project. Searching for so-called "pro-composite" concepts, i.e. concepts allowing to realize potential advantages of composites, is now considered by many Russian and European scientific schools as one of perspective and promising directions of development of up-to-date aircraft structures [2-5].

Fig.2 – Lattice composite structure of a rocket adapter

One of the most promising types of pro-composite aircraft structures is lattice/frame structures (Fig.2). Implementation of lattice layouts for rocket structures has allowed the Russian company CRISM to obtain significant weight benefits for such composite structures in comparison with metallic analogues. For serial produced structures of adapters for the Proton-M rocket these benefits are from 25 up to 50% [6-9]. These impressive results became a basis for a number of investigations dedicated to the development of lattice composite structures for fuselages of up-to-date civil aircrafts.

The results of investigations carried out in frames of Russian and international projects have shown that using lattice composite structures of fuselage sections allow to increase significantly weight efficiency of aircraft primary structure. Lattice grid of unidirectional (UD) ribs allows to sustain all possible loads by the means of tension-compression of UD-ribs only, and that gives a higher level of maximum allowed stresses/strains for composite elements in comparison with laminated composite packages.

2 Main principles for high weight efficiency of lattice airframes

As a result of numerous investigations, the four basic principles, defining high weight efficiency of lattice pro-composite structures in comparison with conventional ones, have been formulated. These principles are:

1. Replacing the conventional stiffened panel by a lattice structure in the primary structure elements of wing and fuselage.

It is known, that the main goal of implementation of composite materials into primary aircraft structures is to realize high specific strength of carbon fibers. Lattice layouts allow to provide sustaining all loads exclusively by the means of tension and compression of UD composite ribs. UD-ribs, that are loaded only by compression/tension allow to realize higher level of allowed stresses/strains in comparison with composite packages consisting of monolayers with different orientations of fibers. The values of ultimate stresses in UD-ribs can reach 650-700 MPa at compression and up to 850-900 MPa at tension.

2. The principle of dividing the primary structure into two elements, responsible for taking different types of loading.

In the lattice structure of a composite fuselage the main load-bearing element that takes external forces and moments, is the rigid lattice grid of UD-ribs. At the same time, the role of skin in such structure is only to provide hermeticity of the cabin, and therefore it is placed from the inner side of the lattice grid. The advantage of such skin is that it is loaded mainly by tension, so it can be made of elastic lightweight material.

Fig.3 shows the concept of the lattice fuselage structure. Besides the lattice grid and the internal skin, it also has the outer ("aerodynamic") skin and the filler, located between two skins, that can serve both for insulation and protection of composite ribs from the environmental factors.

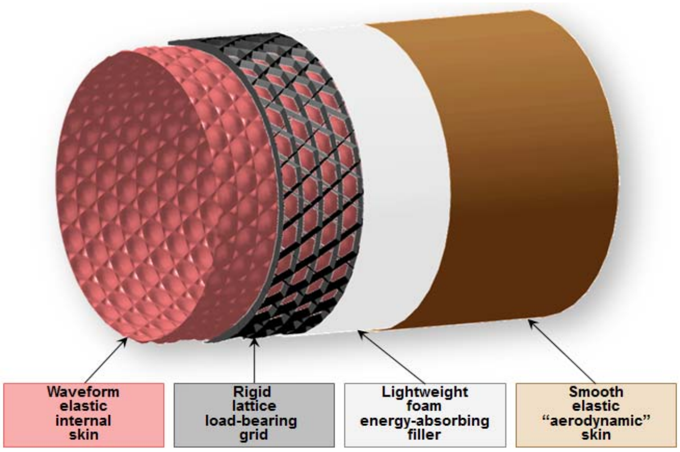

Fig.4 – Structure concept for a lattice composite fuselage barrel

3. The principle of providing durability of the composite structure by the means of using multi-level protection system for composite ribs.

The problem of durability of composite structures is one of the crucial problems for development and creation of composite airframes. In frames of the lattice structures this problem can be cardinally solved by minimizing the possibility of degradation of strength properties of load-bearing composite elements by the means of the special protection system. In the lattice structure concept, described above, the main load-bearing element is the grid of UD-composite ribs, so the protective system is built, first of all, to protect these ribs, but not the whole surface of the fuselage section. As the total area of surface of ribs is significantly smaller than the area of the entire surface of the section, the protection can be effectively realized with slight weight penalty.

Fig. 4 shows the main components of the proposed protection system. As follows from the Figure, inner and outer skin of the lattice structure are serving also as protective elements.

4. Possibility to realize lightweight and robust joints for lattice composite structures.

The state-of-the-art lattice structures have joints based on the phenomenon of "fiber-to-fiber" interaction in the crosses of UD-ribs. Investigations have shown that in these zones, due to very high volume ration of fiber, the contact between fibers of different orientation occurs. The contact is akin to "cold welding", and it allows to avoid concentrators in resin for the zone of ribs' crossings and provide strong connection between fibers of crossing monolayers [10].

Joints based on this effect have low weight, but there is a number of opened questions of using them for aircraft structures, first of all, questions of fatigue. This is one of the reasons to develop new structures of composite-metal joints, based on joining fibers directly to the metallic parts of the joint, allowing to provide strength of the joint during long operation life.

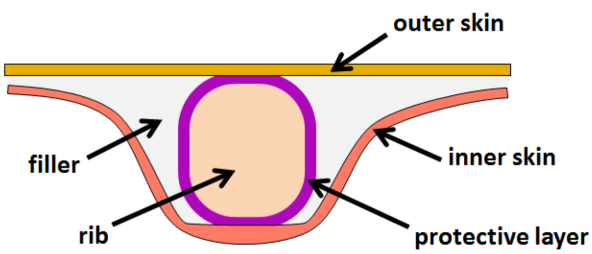

Fig.4 – Concept of multi-level protective system for the lattice structure

3 Multilevel algorithm for designing pro-composite airframes

Building structures using new materials needs not only the changing of structure layouts, but also changing the approaches for designing for the novel structures.

The conventional approach to designing metallic structures has been forming during several decades. The main features of the approach are caused to a large extent by specific physical properties of the aviation metallic alloys:

- homogeneity and high strength properties of the structure material,

- high elasticity of the current aviation alloys,
- high technological realizability of almost any structure of any complexity,
- high insulating properties of metal alloys (impact, fire, moisture/air permeability

The properties of structure materials listed above and rich experience in designing, manufacturing and maintenance of conventional structures allow to divide the designing process into several stages, i.e. to solve the problem separately. As a rule, the conventional approach to structure designing includes 4 stages:

- stage of the draft proposal,
- stage of the draft design,
- stage of detail designing,
- stage of preparation for a serial production.

What about composite structures, this procedure cannot be correctly used and all the design tasks have to be solved simultaneously in frames of one combined stage. This leads to a catastrophic increase of required labour input to solve the design problem. It worth to note that many designers have tried to apply the conventional ("metallic") approach to design composite high-loaded structures, but the results were as a rule rather poor.

In order to solve the problem of designing composite airframes, the multilevel algorithm for designing a pro-composite aircraft structure has been developed and validated in TsAGI [11] and it was proven to be an effective tool to be used at the initial design stage.

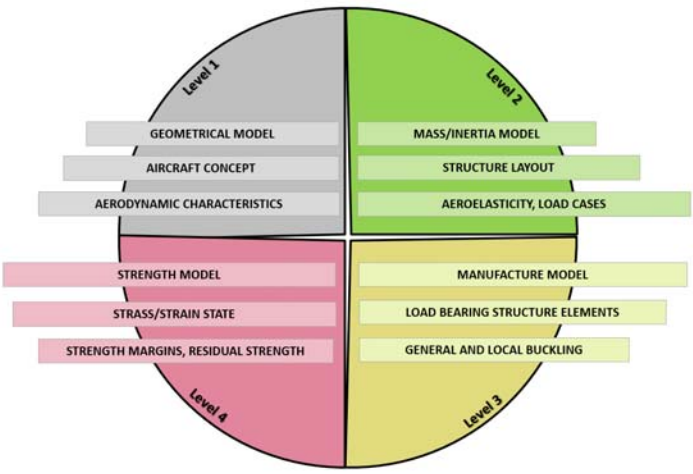

Fig.5 – The main design tasks for different levels of detail

The basis of the multilevel algorithm is the principle of building the general 4 level FE model of the aircraft structure on the basis of the universal specialized database of the design parameters. The specialized database allows to build four FE models of the structure with different levels of detail. Besides all four models represent the single nested structure, i.e. the model of each following level of detail keeps all base parameters of the previous levels and includes new parameters which describe the airframe in more detail. Procedure of solving the problem in frame of the multilevel algorithm consists in the consecutive solving the problems typical for each levels of detail (Fig. 5).

The multilevel algorithm allows to unite the strength tasks of four conventional design stages in the one integrated stage. Thus the consecutive solving of four multidisciplinary design tasks, typical for each design stage, is carried out simultaneously on the basis of the multilevel algorithm. The principle of the new approach is shown on Fig.6.

The main features of the multilevel algorithm are the following:

- In frame of the specialised database the typical multilevel FE model of the airframe is formed *in the automated mode*. The feature of the FE models building procedure is that dimensionality of the finite-element mesh is one of basic varied parameters of the numerical model. The dimensionality of FE model is defined by value of ΔFE [m] - the maximum linear size of FE in the model. The rational value of ΔFE is automatically determined for any structure taking into account required accuracy of calculations and labour input;
- At each level of any aircraft structure FE model the analytical models of aggregates/units/details are formed *in the automated mode* on the basis of the universal specialised database Analytical models are formed in parallel with FE models of each level. These models are effectively used for operative solving of a number of nonlinear tasks including

the analysis of strength, buckling, postbuckling aeroelasticity etc. Use of such parallel (alternative) analytical models allows to decrease essentially labour input and the time necessary for solving the designing task;

- On the basis of generated FE and analytical models the following problems are consequently solved in frame of the one iterative cycle:

Level 1: calculation of aerodynamic loads and aerodynamic characteristics;

Level 2: calculation of inertia loads, definition of load cases, static and dynamic aeroelasticity, weight analysis;

Level 3: calculation of local and global buckling, analysis of post-buckling conditions for different structure elements, calculation of nonlinear stress/strain state of panels, calculation of load-bearing capacity of elements;

Level 4: calculation of general stress/strain state of structure elements, determination of strength margins, residual strength and durability.

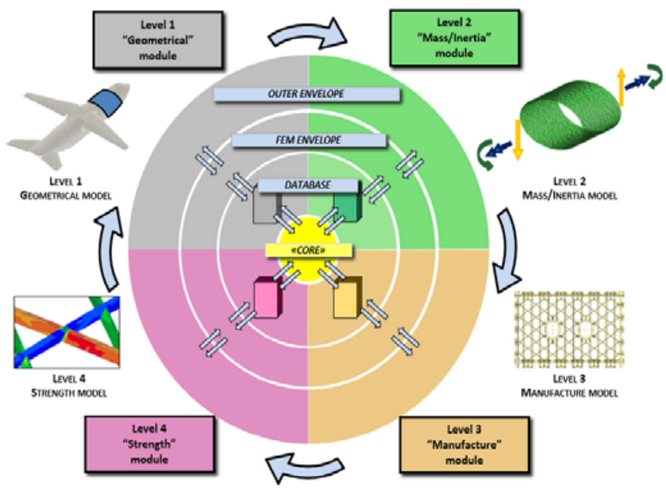

Fig.6 – Block-scheme of the multilevel algorithm for designing composite airframes on the basis of the specialized database

The specialized database was developed taking into account the following requirements:

- The standard form for input of structure design parameters;

- The standard interface intended for considerable reduction of efforts by the user and minimize possible errors;

- Economy of time by the means of the automated procedure of model building and analyzing;

- Possibility of simultaneous use of models of various types with different level of detailing.

The specialised database has the following structure (Fig. 6):

- 4-level principle of data storage (i.e. design parameters are stored in four sectors according to value of an index (1-4), defining an accessory of the given group of parameters to the corresponding level),
- 4-level core providing processing of the data depending on type of the data, and the software of a specialised database.

4-level envelope contains:

- The first (internal) envelope «core» which is responsible for accumulation, storage and processing of the statistical data on structure materials, designs of prototypes, requirements and criteria of an optimality,

- The second envelope «the main layer», responsible for formation of the initial data and the analysis of results of calculations of designed structures,

- The third envelope «FEM layer», responsible for the current solving the design problems of multilevel FE models of an investigated structure,

- The fourth (external) envelope, responsible for supporting the external utilities in relation to «FEM layer».

4 Estimation of weight efficiency of lattice composite fuselage barrel

The multilevel algorithm described above have been successfully applied in a number of projects, devoted to the development of pro-composite wing and fuselage structures of perspective civil aircrafts.

In frames of the FP7 ALaSCA project a comparative weight analysis of alternative structures (metallic, Black metal composite and lattice composite) of fuselage section of an up-to-date airliner have been done. (Fig.7). The geometrical parameters of the section and the requirements were the same for all alternative structures. The weight analysis have been carried out in parallel by the partners of the project, including DLR, EADS-IW, CRISM and TsAGI. The results of weight estimations had only some slight differences, that allowed to validate successfully the multilevel algorithm, developed by TsAGI.

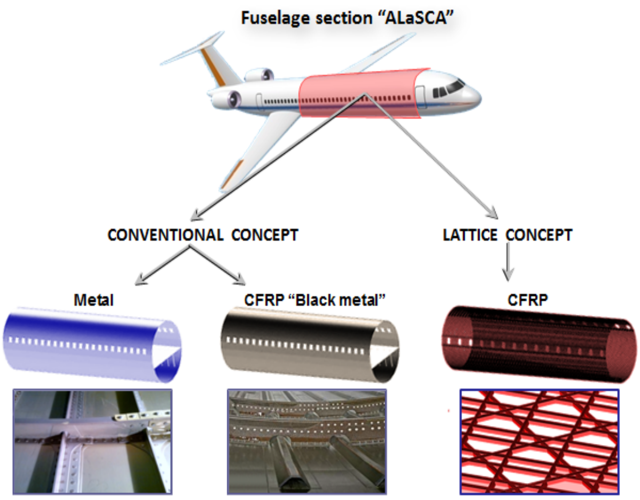

Fig.7 – Alternative structure concepts of a fuselage section of a perspective airliner

The weight parameters of the lattice composite barrel (for the primary structure and its components) relatively to the weights of alternative structures are listed in the Table 1.

Table 1

Variant	Metallic	Composite (Black metal)	Composite (Lattice)
Weight, %	123.9	118.3	100.0

The weight of the lattice composite fuselage section is approximately 84.5% of the weight of the "Black metal" composite barrel and 80.7% of weight of the metallic barrel. The ALaSCA partners made their own weight estimations, close to the results, presented in the table. This fact allowed the partners to make a conclusion about high potential of lattice composite structures in decreasing the weight of fuselage sections in comparison with conventional structures.

The investigations, carried out in TsAGi in frames of some Russian projects have shown that the lattice composite structures have good perspective to be used in the fuselage barrel with oval-form cross-sections (Fig.8).

It is known, that one of the crucial problems of such structures, that does not allow to get proper weight efficiency, is the necessity of keeping the oval form of the cross-section, which tends to turn into circle when pressurizing. In conventional structures the problem is usually solved by implementing the special high-loaded bending frames, but this cause significant decrease of the weight efficiency.

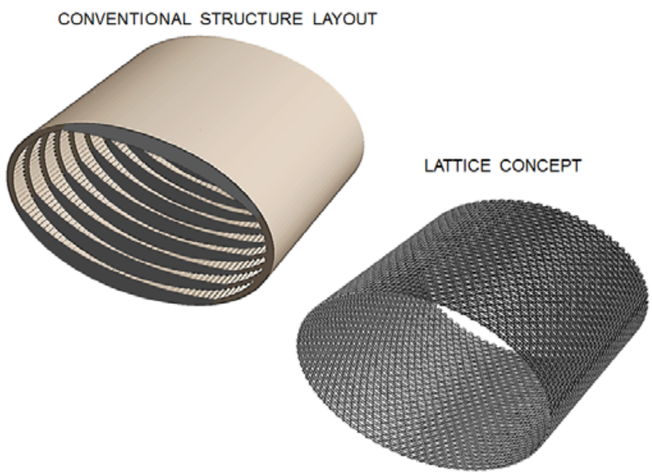

Fig.8 – Conventional and lattice concepts of an oval fuselage section

What about lattice structures, the preliminary calculations have shown, that for these structures the pressurizing loads can be taken by the means of tension of together circumferential and helical UD-ribs, that allows to make a more lightweight structure.

The other perspective direction of research of lattice composite airframes is development of frame-lattice panels for the "Flying wing" aircraft concept. Wing and fuselage panels of such integrated structure can be realized according to the scheme shown on Fig.9. At this scheme two lattice panels, upper and lower, are connected between each other by a system of spatial frames made of lightweight metallic alloy.

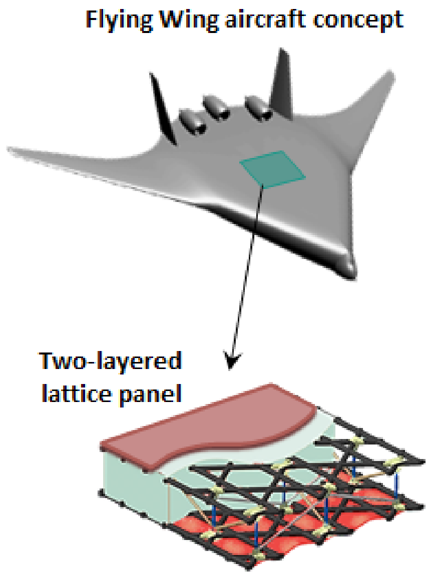

Fig.9 – Two-layered frame-lattice panel concept for the Flying wing aircraft concept

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