INVESTIGATION OF SYNERGETIC EFFECT INFLUENCE ON STRENGTH CHARACTERISTICS AND WEIGHT EFFICIENCY OF LOAD-BEARING AVIATION STRUCTURES

E.A. Dubovikov, M.C. Zichenkov, I.V. Mareskin, A.V. Chernov, A.N. Shanygin

Central Aerohydrodynamic Institute (TsAGI)

Keywords: *synergetic effect, composite structure*

Abstract

The basic principle based of usage of synergetic effect of designing of effective in term of weight composite structures is researched in article.

1. Introduction

Prospects for creating a new generation of aircrafts depend on the use of composite materials in load-bearing aircraft structures. However, first examples of highly loaded composite structures of passenger aircrafts based on traditional structure layout of "black metal" type did not demonstrate expected high weight efficiency, revealing, in addition, a number of critical strength problems in such structures.

This for the most part is due to the fact that structure layout of first composite structures do not differ in principle from traditional metal, where main load-bearing element is thin-walled reinforced skin. However, composite skins unlike metallic ones prove to be not so effective load-bearing element due to serious problems associated with impact and climatic influences during long-term operation.

Certainly, reinforced metal skin used as the main element of modern aircraft structures has a number of unique synergetic properties:

- high strength and deformation characteristics
- high hermeticity and impact resistance
- fracture toughness and fire resistance
- electrical conductivity and corrosion resistance

This synergy was a result of long evolution of structural materials and structure layout and allowed to obtain high weight efficiency of load-bearing metal structures.

Unfortunately, composite layered skin does not have above-mentioned synergistic properties, in general, because of low characteristics of modern binders.

For this reason, despite high strength and rigidity characteristics of modern fibers, it is not possible to obtain gain in weight for modern aircrafts.

Since in the near future one should not expect radical improvement in characteristics of composites and, consequently, the efficiency of skin composite load-bearing structures, search for new rational structure layout, on the basis of which composite structure can work more efficiently, becomes one of the most prospective branches of aircraft construction [3].

Within the framework of European projects FP7 ALaSCA and FP7 PoLaRBEAR [1][2][5][6] a series of successful studies on the development of "pro-composite" wing and fuselage designs in order to create new structure layout with good synergy for composite and hybrid structures of prospective civil aircraft was carried out. This work was realized by Laboratory of Innovative Constructions of Strength Department with domestic and foreign partners (TsNIISM, VIAM, Mendeleyev University of Chemical Technology, DLR, Airbus, EADS, TUDelft, University of Leeds).

2. Specifities of new generation hybrid structures design

2.1 Requirements for searching algorithms for non-traditional composite structures.

The research of new generation hybrid structures was based on the results obtained in the framework of Russia-EU international projects devoted to examination of frame structures[5][6].

One of the main results of this research were dependencies of allowable deformations that can be realized in layered composite packages from the values of allowable deformations in binder (see Figure 1) for different orientations of layers in the package [5].

On the graphs (Figure 1) it can be seen that unidirectional composite packages have gain in weight compared to layered packages with different layer orientations. Using the principle of unidirectionality, it is possible to obtain effective in weight and practically realizable composite structures based on mesh and frame structure layouts [7].

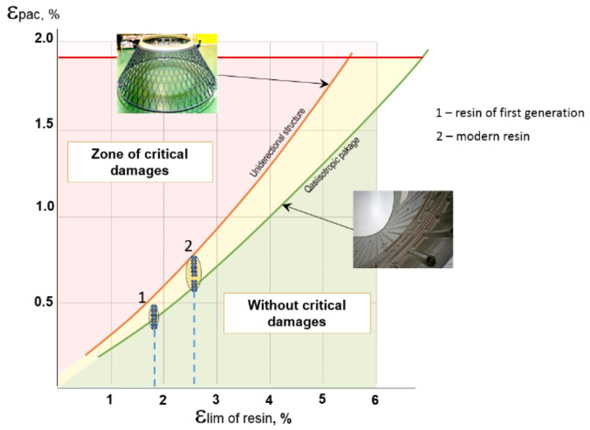

Figure 1 – Dependence of critical package deformations from critical deformations of binder.

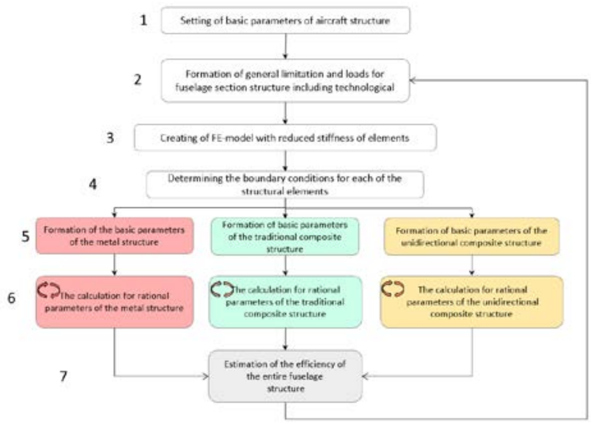

Figure 2 - Generalized flowchart of finding integrated fuselage compartment load-bearing frame optimal parameters

Unfortunately, a lot of "composite" design solutions that are effective in weight cannot be manufactured within the framework of existing composite technologies. For this reason, it is necessary to include technological model in design process at an early stage. The figure (Figure 2) represents flowchart how to search for optimal parameters of airframe hybrid structure consisting of elements with three different structure layout types: traditional metallic, traditional composite and unidirectional composite, allowing to carry out design studies within the framework of multilevel approach developed in TsAGI for multidisciplinary tasks, which makes possible to obtain technologically realizable solutions [10]. The figure shows 7 basic steps of search procedure.

It should be noted that in order to reduce the cost of frame structures strength analysis a number of studies [10] was carried out to find rational way for their modeling using standard FEM software packages. As a result, an operative technique for three-dimensional analysis of frame composite structures on the basis of simple membrane 2D elements was proposed and developed [10]. The use of this technique makes possible to significantly simplify strength analysis and increase the efficiency of associated calculation procedures

2.2 Formation of basic requirements and crateria for new generation hybrid structures development

Another important result obtained in studies mentioned in paragraph 1.1 was the formation of criteria for pro-composite structures' search. It was shown that in order to ensure high weight efficiency and reliability of load-bearing composite as well as hybrid metal-composite structures created on their basis the following requirements should be taken into account:

- to ensure maximum direction coincidence of reinforcing fibers with the direction of main strength flows and the continuity of fibers in load-bearing elements structure;
- to create reliable and light weight power elements protection from impact and climatic influences, integrated with means of technical condition monitoring;
- to exclude binder from joint contact zone between metal and composite structure parts;
- to ensure high maintainability.

3. Hybrid structures for prospective civil aircraft

3.1 Hybrid structures for prospective civil aircraft

In TsAGI has been developed special lattice layout for cylindrical fuselage of civil aircraft on the basis of unidirectional load-bearing ribs. The main components of this structure layout are shown in Figure 3.

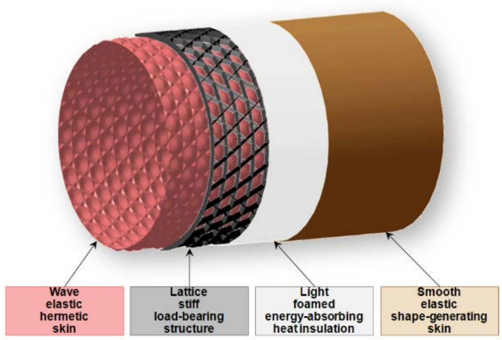

Figure 3 – Main components of lattice structure.

The concept of multilevel protection of load-bearing grid has been offered including as internal and external skins as heat insulation material (Figure 4).

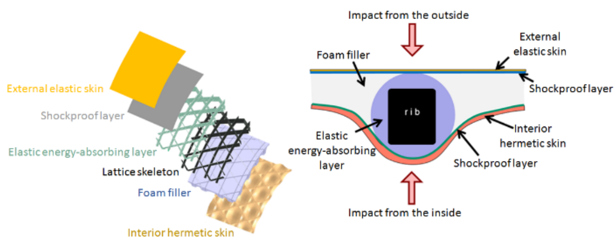

Figure 4 – Multilevel protection of lattice load-bearing grid concept.

Such protection allows to receive significant synergy synergetic effect due to one structural element carries out several functions at once:

- load-bearing grid protection;
- overpressure sustain;
- aerodynamic loadings sustain;
- heat insulation.

Also such type protection positively influences on the load bearing capacity and robustness of unidirectional ribs (Figure 5) [11].

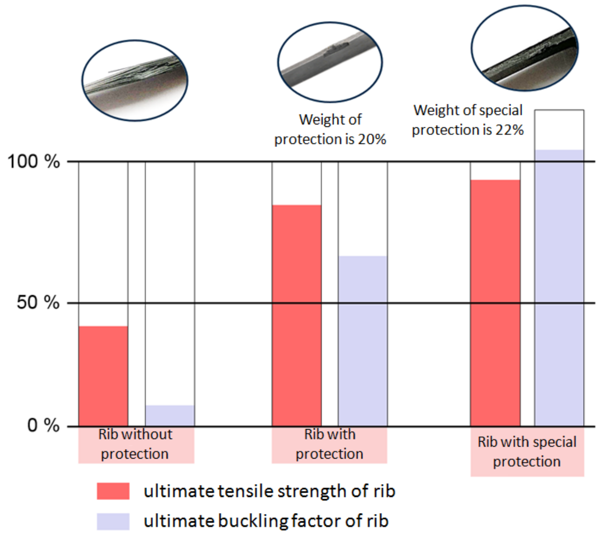

Figure 5 - Decrease of rib strength characteristics after the certificated impact with 30 J energy.

3.2 Frame structure layout on the basis of hybrid rods.

The structure of axisymmetric hybrid rods is designed at the same time to developing of lattice layout by TsAGI.

A hybrid rod structure is an axially symmetric and consists of cylindrical and conic parts. Each of these rod parts is hollow (tubular) with circular cross section. Conic parts of a rod are executed from metal and come to an end joint providing hinge joints in frame structure (Figure 6).

Hybrid rod elements can sustain as axial, as torsion and bearing loads. However, they are more effective in case of longitudinal efforts. The main part of unidirectional monolayers in a cylindrical part of a hybrid rod has lay up close to a longitudinal axis coinciding with load stream direction from external loads on a rod for effective application of high specific strength properties of composite materials

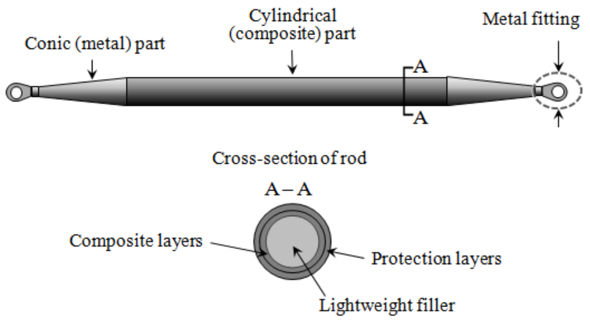

Figure 6 – Basic parts of hybrid rod structure/

The composite cylindrical part of a rod connects with metal conic parts using joints. The structure of such joints can be various using bonding, winding and other technologies the choice of which depends on the geometrical sizes of rods and from level of loading.

The multicomponent protection concepts is offered presented on Figure 7 to provide rod elements protection.

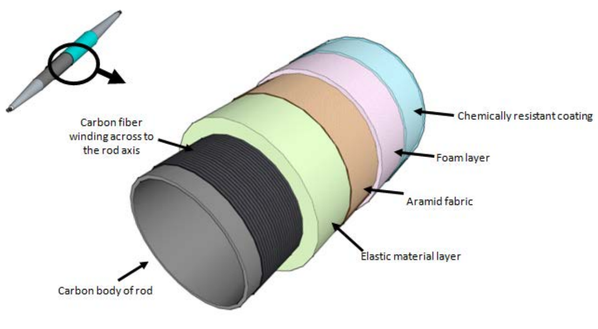

Figure 7 – Multicomponent protection concept.

The protection configuration to provide a maximum level of protection from external loads is shown on the figure. The protection structure can change for different service conditions.

Application of such "encircling" protection leads to synergy effect appearance, consisting in simultaneously:

- a critical force of primary element buckling increases;
- an impact strength indicator indicator of a rod element improves;
- protection against chemical exposure is provided.

3.3 Hybrid structure of cylindrical fuselage

Analysis of efficiency using of different structure layouts of a mid-range passenger aircraft cylindrical fuselage structure has been carried out on the basis of the developed method.

As a result of investigations a rational structure layouts have been defined (Figure 8) for basic fuselage sections and weight efficiency of hybrid fuselage structure consisting of sections with different structure layouts have been estimated. The rational scheme of sections arrangement with different structure layouts for a mid-range passenger aircraft fuselage structure is shown on Figure 8. Three structure layout types were considered:

- conventional metal;
- composite thin-walled (black type metal);
- lattice composite.

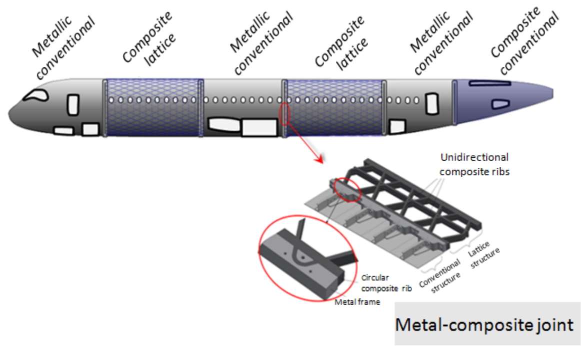

Figure 8 – Rational aircraft fuselage sections structure layout of conventional configuration.

Technical decisions have been used to organize high-strength joints developed in TsAGI [12] to couple lattice structure layout sections.

To choose structure layout and material for each separate section provides the decision of several tasks simultaneously:

- load-stream sustaining;
- reliable and safety operation providing;
- cut-outs with the minimum weight losses realization;
- regular fuselage section processability.

Thus the new synergetic effect appears at the airframe aggregate level.

Investigation results have shown that application of lattice structure layouts in regular fuselage zones together with composite materials application within of conventional structure («black metal») in some other airframe sections, can give a weight efficiency about 5 % in comparison with all-metal analogue [13].

3.4 Hybrid structure of oval fuselage

Within carried out investigation the hybrid structure for civil aircraft with load bearing fuselage not having cylindrical form of cross section has been studied. The main features of this structure are shown on Figure 9.

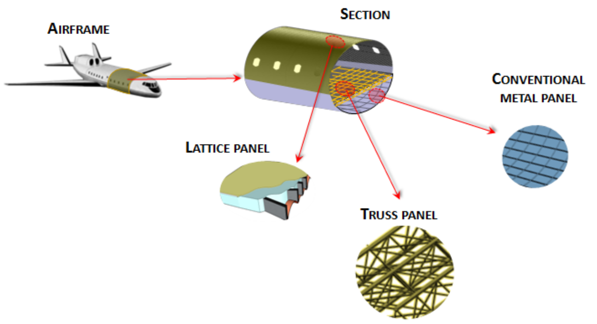

Figure 9 – Main details of an integrated fuselage structure.

Application of conventional metal and composite structure layouts are inefficient for such type of configurations. However, using new hybrid structure layout, developed in TsAGI (Figure 4) for such configuration has allowed to realize a number of synergetic effects and to receive as high weight efficiency as reliability in operation. The structure on the basis of given structure layout consists of three main parts: a top composite section of lattice structure layout, a bottom metal section of conventional structure layout and a transfer section including a load-bearing floor.

As an example of proposed structure layout efficiency, the hypothetical structure of aircraft having parameters, presented on Figure 10 and in Table 1 has been chosen. This structure was compared to alternative aircraft structures of equal passengers' capacity in diameter of ~4 meters (Table 1).

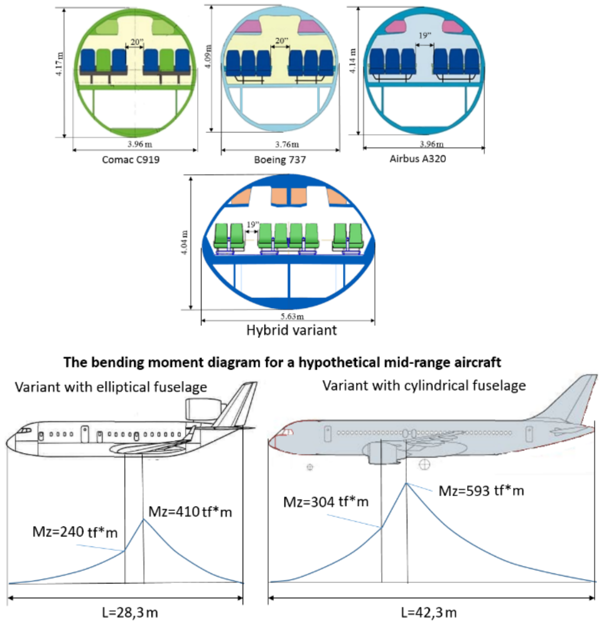

Figure 10 – Alternative fuselage structure parameters.

Table 1– Main parameters of some aircrafts configuration

Aircraft	Airbus A320	Boeing B737-800	Comac C919	Hybrid variant
Take-off weight, kg	77000	79015	77310	65000
Number of passengers , pax	140-180	160-189	168	150-160
S_{mid}, m^2	12,88	12,09	12,97	17,03
$L_{fuselage}$,m	37,6	39,5	38,9	28,3

The proposed structure of a hybrid fuselage consists of three main parts:

- top lattice composite section with curvature radius 3 m;
- transfer section with truss floor frame;

- bottom metal section with a longitudinal and cross-section supporting set in curvature radius of 3.2 m.

The feature of this structure is exception of composite panels of the top section from high-loaded structure elements. In the load-bearing plan the top composite panel is responsible for load sustaining from overpressure, local aerodynamic loads and partially loadings from a torsion moment. A rational structure layout for the top section will be lattice structure layout (mentioned above), having a rigid frame and a set of elastic skins to create an aerodynamic surface and pressurization. Low loading level coupled with multiply connected of lattice structure (Figure 9 and Figure 10) allows to provide high reliability and low weight for this structure.

The transfer section consisting from truss floor frame structure, integrated with metal joint side panels (Figure 11) will be the most difficult and innovative element in a hybrid fuselage. The joint metal side panel consists of stiffened curvilinear sheet with variable curvature in which there are lugs to fasten knees and basic elements of truss frames [7].

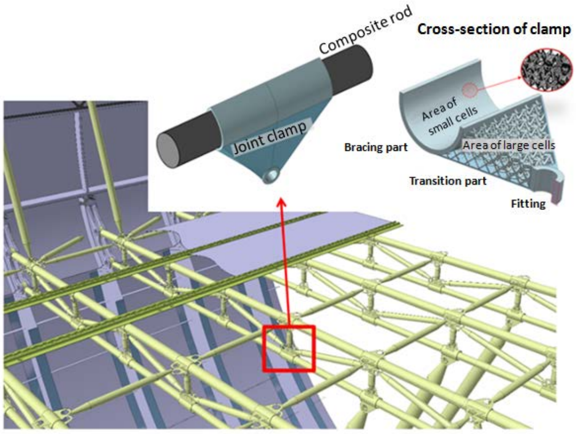

Figure 11 – Transfer section with side metal panel and floor frame structure layout.

As a rational structure layout of the bottom section a conventional metal supported panel including structure elements of a cargo floor wide-body aircraft with fuselage diameter 6,4 meters can applicate.

Such hybrid structure layout due to synergetic confluence of several structure layouts in one section ensures requirements implementation to fuselage structure, namely requirements:

- strength and buckling;
- cut-outs realization;
- impact strength;
- reliability and damage tolerance;
- repairability,

Including structure weight efficiency on 10-15 %.

4 Conclusions

The realization possibilities of new positive synergetic effect in perspective aviation composite structures are shown. Also estimations of weight efficiency increasing of a fuselage structure due to synergetic effect application at different levels are presented including: a load-bearing element, a section, total aggregate.

Increasing of weight efficiency possibility of a mid-range airframe structure the plan on 10-15 % is shown.

References

[1] FP7 NACRE (New Aircraft Concepts Research). Annex I – Description of Work. FP6-2003-AERO-1 Integrated Project. 2005

[2] FP6 ALCAS project [web-resource] // URL:http://cordis.europa.eu/project/rcn/75777_en.html.

[3] Shanygin A. The features of designing pro-composite airframes. In: Proceedings of TsAGI, vol. 2698, 2011.

[4] Shanygin.A. "Investigation of lightweight composite and hybrid primary aircraft structures"m Proceedings of CST Conference, Dubrovnik, Croatia, 2012.

[5] FP7 ALaSCA project [web-resource] // URL: http://cordis.europa.eu/result/rcn/149775_en.html

[6] FP7 PoLaRBEAR project [web-resource] // URL: http://cordis.europa.eu/result/rcn/175990_en.html

[7] Shanygin A, Dubovikov, E, Fomin V, Mareskin I, Zichenkov M. Designing pro-composite truss layout for load-bearing aircraft structures. Fatigue and Fracture of Engineering Materials and Structures. 2017;40:1612–1623. https://doi.org/10.1111/ffe.12695

[8] E. Dubovikov, V. Fomin, I. Kondakov, A. Shanygin Development of rational hybrid fuselage structure for prospective civil aircraft, 7th EASN Conference on Aerostuctures, 26-29 сентября, Варшава, Польша, 2017.

[9] A. Shanygin, V. Fomin, G. Zamula Multilevel approach for strength and weight analyses of composite airframe structures // Proceedings of the 27th International Congress of the Aeronautical Sciences. Nice. September. 2010

[10] Dubovikov E, Fomin V and Kondakov I. FE modeling of lattice composite fuselage elements for general and local strength analyses. In: Proceedings of 3rd EASN association international workshop on aerostructures, Milan, Italy, 9–11 October 2013.

[11] K.D. Potter, F. Schweickhardt, M.R.Wisnom. Impact response of uniderectional carbon fibre rod elements with and without an impact protection layer. Queen's Building University Walk. Bristol. June. 1999.

[12] A. Chernov, D. Fomin, V. Grishin, I. Kacharava, A. Shanygin Development of Lightweight and Reliable Joints for Airframes Based on Unidirectional Composite Elements// Proceedings of the 30th International Congress of the Aeronautical Sciences. Daejeon. September. 2016

[13] E. Dubovikov, V. Fomin, I. Kondakov, A. Shanygin, D. Vedernikov, Development of rational hybrid fuselage structure for prospective civil aircraft. Journal of Aerospace Engineering, June, 2018.

[14] A. Chernov, D. Fomin, I. Kondakov, I. Mareskin, A. Shanygin, Lightweight and reliable metal–composite joints based on harmonization of strength properties of joined parts, Proc Inst Mech Eng Part G-J Aerosp Eng, https://doi.org/10.1177/0954410018778797.

Contact Author Email Address

Mailto:

alexander.shanygin@tsagi.ru

evgeny.dubovikov@tsagi.ru

ivan.mareskin@tsagi.ru

Copyright Statement

Acknowledgements

This work was supported by the Subsidy of Ministry of Education and Science of the Russian Federation, Agreement #14.628.21.0009, project identification number: RFMEFI628180009.