STRENGTH ANALYSIS TECHNIQUE FOR HIGH LOADED ELEMENTS OF COMPOSITE AIRFRAMES

E. Dubovikov, V. Fomin
Central Aerohydrodynamic Institute named after Prof. N.E. Zhukovsky (TsAGI)

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Abstract

The main problems connected with performing confident analysis of strength of composite structures are considered for:

- *non-conventional layouts of aircraft and load-bearing scheme of wing and fuselage section structures,*
- *all spectrum of external factors for airframe,*
- *conditions of long-term service of airframe regarding degradation of composite materials properties.*

The results of investigations presented in the paper allow to reveal on a macrolevel and on a microlevel the features of loading of the basic typical load-bearing elements of composite structure, such as multilayered skin, unidirectional ribs, crossings of the ribs, "skin-to-rib" and "rib-to-rib" interfaces, and to define methods of the strength analysis with the account of these features.

1 General Introduction

The main reasons of low weight efficiency of application of composite materials in load-bearing (primary) structures for commercial aircrafts have been established basing on results of numerical and experimental detailed analyses of composite structure elements at microlevel, with consideration of behaviour of a composite material as a heterogeneous medium. The basic reasons are the following:

– In frames of traditional composite packages of skins, the high-strength carbon fibres cannot be loaded more than on 25-30 % from ultimate values. It is caused by the low strength characteristics of matrix in composite materials.

– Composite structures are extremely sensitive even to the impact of relatively small energy. In a combination with climatic factors, it can lead to fast and considerable degradation of strength properties of composite material and to radical decrease (in 2-2.5 times) of load-bearing capability of structures elements.

– Composite structures have a number of strict technological constraints, which do not allow providing a practical implementation at manufacturing of such structures for the large range of rational values of design parameters.

– Realization of joints and cut-outs in traditional composite structures of type «Black metal» is much more difficult problem, than for metal structures, and is connected with considerable weight penalties.

The result of these researches was the conclusion about necessity of developing the new (multilevel) approach to designing of composite primary structures of a fuselage of new generation of the civil plane. This approach was based on the developed methodic of designing of composite fuselage structures with the formulated recommendations for designing and manufacturing of these structures.

Besides, the conclusion has been made about necessity of application of new approaches to use of composite materials in the primary structures. The conclusion was based on taking into account of the features of the composite materials, connected with their heterogeneous structure [1, 2, 3]. The most reasonable way to achieve high efficiency of use of composite materials in the primary structures of fuselages and wings is the development of new layout schemes for airframes (so-called "pro-composite") with use of nonconventional ("discrete") constructive layouts. The pro-composite layout provides decrease of stress concentrations in the structure sections, and the discrete constructive layout provides to the composite material the most favourable conditions of its deformation regarding realization of high specific strength properties of fibres.

It has been shown in the project ALaSCA (FP7 EC) that by the current moment the most favourable discrete scheme in the weight relation for a composite fuselage with new (pro-composite) configuration is the lattice structure layout. As a result of the researches carried out in the project, new technical solutions have been obtained for the lattice structures, considering specificity of long-term service of aircraft and the safety requirement. The lattice structure of the composite fuselage section developed in the project ALaSCA has shown high weight efficiency. The weight benefit was 20% in comparison with weight of the traditional metal fuselage section. Experimental researches have confirmed the results of the design calculations, and the manufacturing techniques have shown reduction of manufacture cost in comparison with the «black metal» composite fuselage section.

2 Strength analysis of lattice section structure

Strength of the composite structure, as a rule, differs from traditional definition of strength for the structure made of homogeneous materials. For example, strength of a metal structure is defined by values of load which causes collapse of the elements of this structure, and the structure cannot further carry out its functions, that is, the structure loses its load-bearing capability. In the composite structure, the loss of load-bearing capability is more complex process, than in the metal structure. This process begins with occurrence of barely visible cracks in resin (in matrix) of a composite package. The cracks can propagate under the influence of different factors (a moisture, temperature, alternative loads) and it finally lead to loss of integrity of composite structure (so-called «matrix critical destruction»). Such damage cannot affect load-bearing capability during the initial moment, however during long-term service it, as a rule, leads to destruction of the whole structure. This process was named «structure degradation».

It is obvious that for performance of requirements of long-term strength at designing of composite section structure it is necessary to consider possibility of occurrence of cracks in a matrix of composite elements during the service period. For this reason, it is necessary to have results of calculations of the stress-strain state for the structure and for its elements at different levels of detailing. For the lattice structure of fuselage/wing sections it is proposed to investigate strength characteristics of the composite structure at following three levels (fig.1):

- Macrolevel (level of section),
- Level of a composite element (level of rib),
- Microlevel (level of fibre).

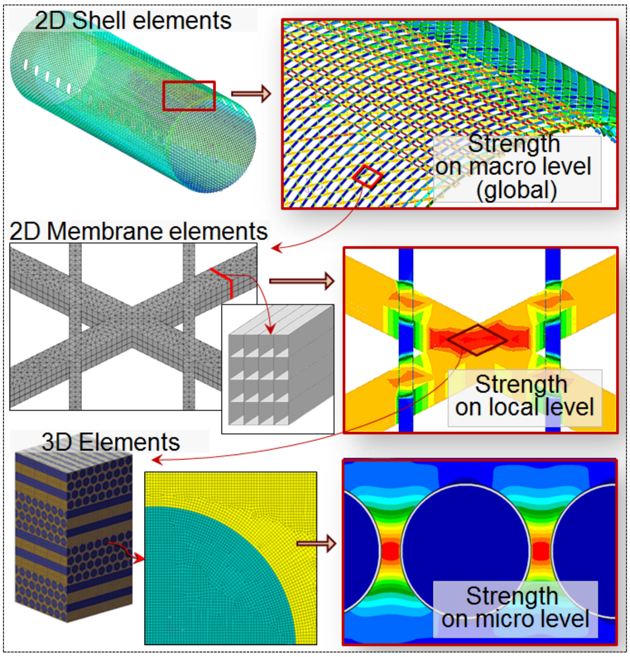

Fig.1 Three levels of strength analysis

At the macrolevel, the global stress-strain state is investigated for the whole section structure and the critical zones of the structure are determined. At the level of lattice element (ribs structure fragment) the local stress-strain state of the structure in the critical zone is determined. At the microlevel, the parameters of strength criteria for elements of the composite lattice structure are defined for given parameters of fibre and matrix (including their specific volumes).

3 Multilevel modeling at strength analysis

3.1 Model on structure level (macromodel)

In the strength model of the primary structure of the lattice composite fuselage section, as a rule, 2D finite elements are used (fig.2).

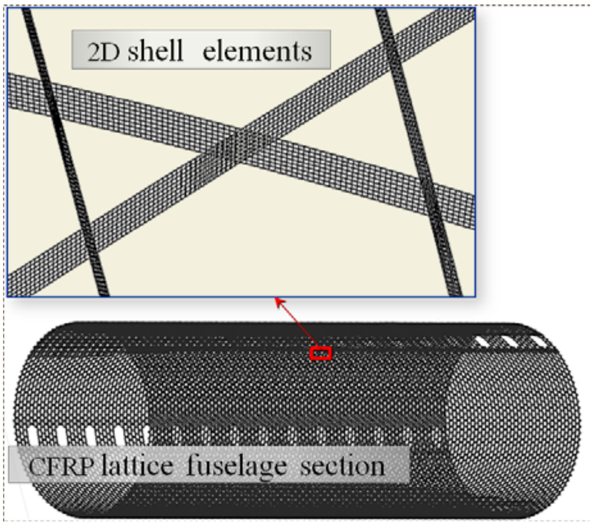

Fig.2 FE model for global stress-strain analysis

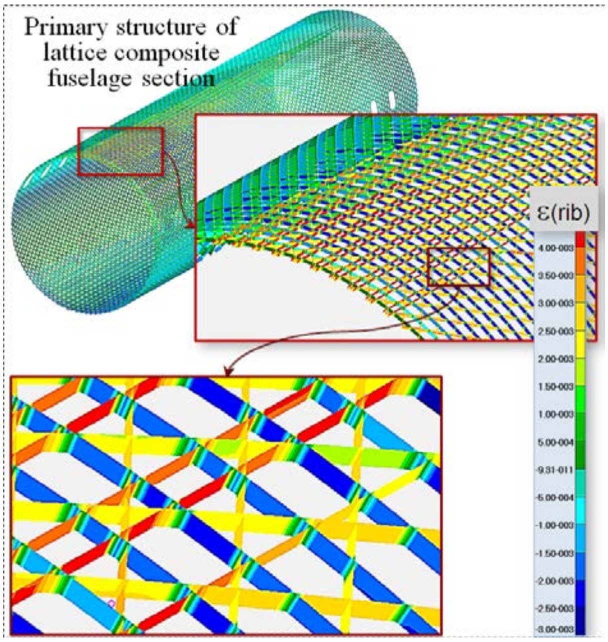

Fig.3 Global deformations of primary structure

Such global model (macromodel) is used for determination of force flows in the lattice structure and for evaluation of global strength of the section structure [4] (fig.3).

3.2 Model on element level (local model)

It is impossible to calculate the local strain state in critical zones by simple reduction of finite elements sizes in frames of the section macromodel because this model does not allow to determine distributions of the strains and stresses on the thickness of the lattice rib, and also to calculate concentration of deformations in zones of ribs crossing. It is because stresses and strains are supposed to be constant on a thickness of the rib, and the crossing of ribs is not modelled at all by finite elements in the macromodel. Therefore, for the analysis of local strains in the lattice ribs and in zones of their crossings it is necessary to use a special model at the level of lattice rib. For creation of such model, it is proposed to use principally other way of modelling which consists in representation of the lattice rib in the form of "box" structure, composed of webs and flanges (fig.4).

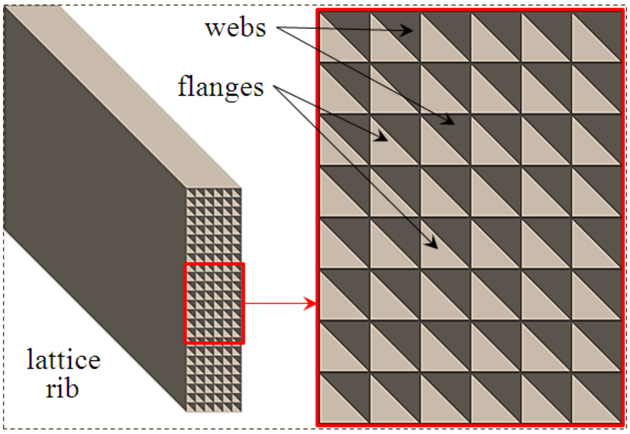

Fig.4 “Box” model of lattice rib

To model the variable deformations along length, height and thickness of the rib, including a zone of ribs crossing, the "box" structure of the rib model was developed. This model consists of webs and flanges with different stiffness parameters. These webs and flanges are modelled by membrane finite elements.
Parameters of the webs and the flanges are defined basing on the conditions of identity of

stiffness characteristics of "box-shaped" structure and the real rib:

$$\left\lfloor E_x F_x \; E_y F_y \; E_z F_z \; E_x J_y \; E_x J_z \; G_{xy} h \, G_{xz} d \right\rfloor_{box} =$$
$$= \left[E_x F_x \; E_y F_y \; E_z F_z \; E_x J_y \; E_x J_z \; G_{xy} h \, G_{xz} d \right]_{rib}$$

Here E is the elasticity modules, G is the shear module, F is the cross-section area, J is the inertia moment, h and d – a height and a width of cross-section of the lattice rib.

The elements of "box" structure, which model the lattice ribs, are divided into rectangular membrane finite elements. Triangular finite elements are used, as appropriate, for modelling zones of the ribs crossing. Membrane elements are chosen for modelling the ribs for the reason that they are simple and convenient for modelling of webs and flanges and for the analysis of the calculation results in the automated mode while bent stiffness of the "box" model are provided by presence of webs and flanges.

The automated building up of the finite-element model of ribs structure provides correct modeling the ribs crossings (under various angles).

The minimum quantity of finite elements is about 50 million at use of the "box" model of lattice ribs for the fuselage section structure 11-11.5 m in length and 4-4.2 m in diameter. For calculation of the stress-strain state and strength of the fuselage section structure on the modern personal computer with use of the model of such dimensionality, not less than 15 hours are required. Therefore, the most rational is the modelling of relatively small fragments of the lattice section containing critical zones, which are defined at the analysis of the global stress-strain state obtained for the macromodel of the fuselage section. For calculation of the stress-strain state and strength for such local models, the most difficult is the automated modeling of correct boundary conditions and loads.

3.3 Model on fibre level (micromodel)

Strength criteria for composite elements of the lattice structure contain values of allowed (ultimate) deformations for a concrete composite package. The most confident data concerning these values can be obtained experimentally. However, the variety of the parameters for the composite package used at designing of the lattice fuselage section leads to necessity of numerical determination of the value of ultimate deformations. To determine the parameters of the global deformation of the composite element, which correspond to the moment of matrix critical destruction (the beginning of degradation of the composite material), it is necessary to obtain results of parametrical calculations of the stress-strain state for resin in zones between fibres for typical loading. Such results can be obtained only at use of finite-element micromodel at a level of monolayers of the composite package. This micromodel considers heterogeneity of the composite material.

In the composite packages of the lattice elements (ribs and their crossings), the fibre diameter, as a rule, is ~10 microns, and their relative volume is ~40% in a regular rib and ~80% in the ribs crossing (fig.5). For determination of stresses concentration in the matrix resin between fibres, the size of finite elements should be no more than 1 microns. At the same time, it is not reasonable to have the size of the finite elements less than this value because of large enough sizes of molecules of the resin (~0.1 microns).

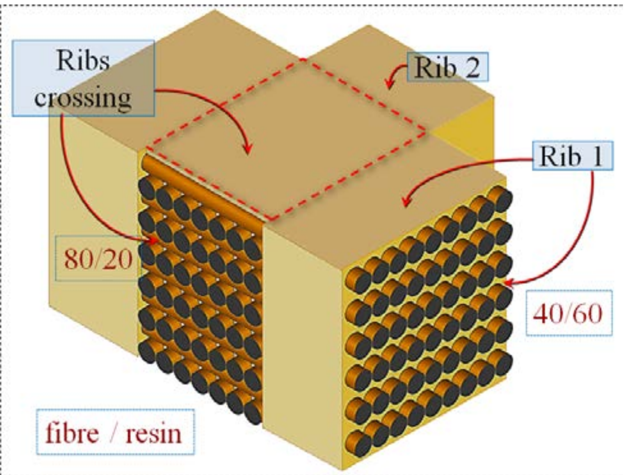

Fig.5 Different volume of fibres in regular ribs and in their crossing

The rib model would have too large dimensionality if the size of finite elements equaled of ~1 microns. Therefore, the modeling of relatively small part of the composite package is used for analysis of the stress-strain state basing on such micromodel.

In the given work, the simple and comprehensible FE micromodel is suggested. In the model the adhesive layer is not considered, i.e. rigid connection of fibres with matrix is supposed. Properties of the fibres and the resin are modelled by isotropic 3D finite elements. The example of micromodel of composite package in a small zone of lattice ribs crossing is shown in fig.4. The model includes 4 monolayers (4 layers of fibres in each monolayer).

For the correct analysis of the stress-strain state and concentration of stresses in the resin, the zone of resin between the next fibres in the monolayer should include not less than 5 finite elements. Fig.6 illustrates the model in which area between fibres contains 15 finite elements.

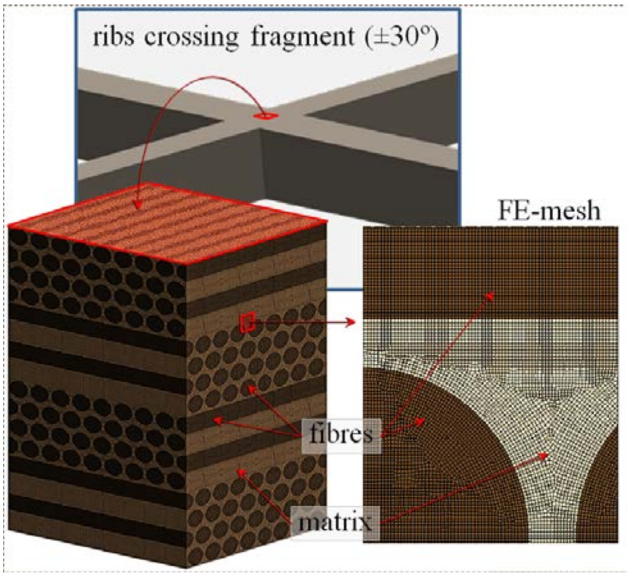

Fig.6 Micromodel for layers stacking in lattice ribs crossing

Basing on the generated micromodel the problem of degradation of properties of composite materials can be solved. One of the reasons of the degradation is a growth of primary damages in resin between fibres in a monolayer located at an angle to action of external force. It leads to weakening of bonds between the fibres and the resin. Growth of the primary damages is simulated by an exception of those finite elements in which the deformations exceed the limiting values.

4 Examples of strength analysis

As a demonstration in figs 7-10, the example of the strength analysis for lattice structure of composite fuselage section with use of models of three levels is shown.

At first, the calculation of the global strain state of the section structure is carried out (fig. 7). After that, the ultimate deformations for ribs and their crossings are calculated (for the given angles between the ribs, fig. 8). These deformations are processed (with taking into account conditions of long term service) and then used in parameters of the strength criteria used at the analysis of the local strain state (figs. 9, 10).

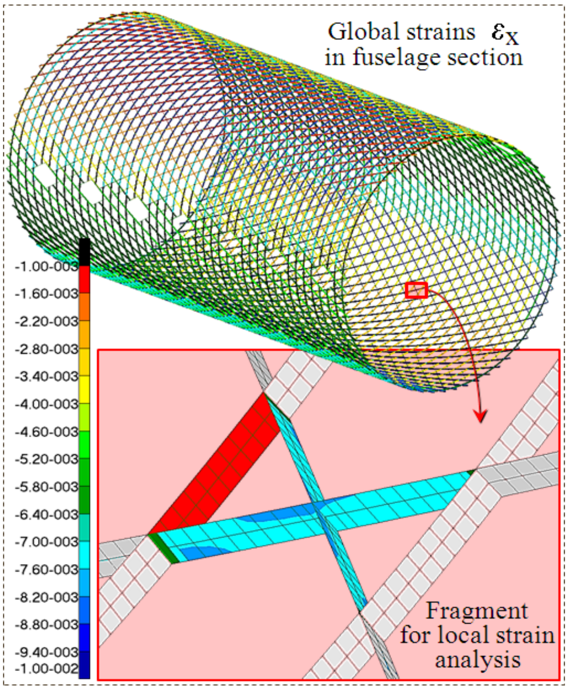

Fig.7 Global deformation of fuselage section

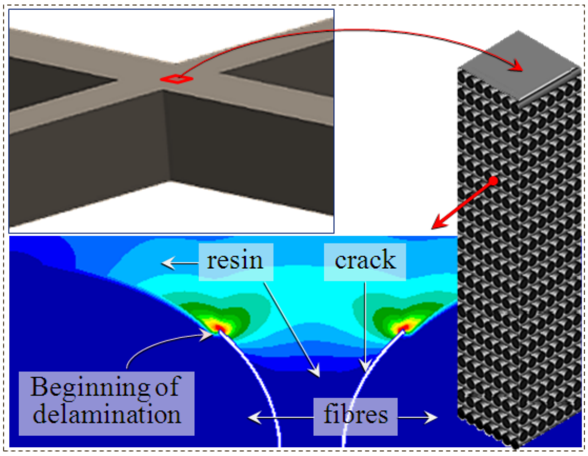

Fig.8 Distribution of deformation on microlevel

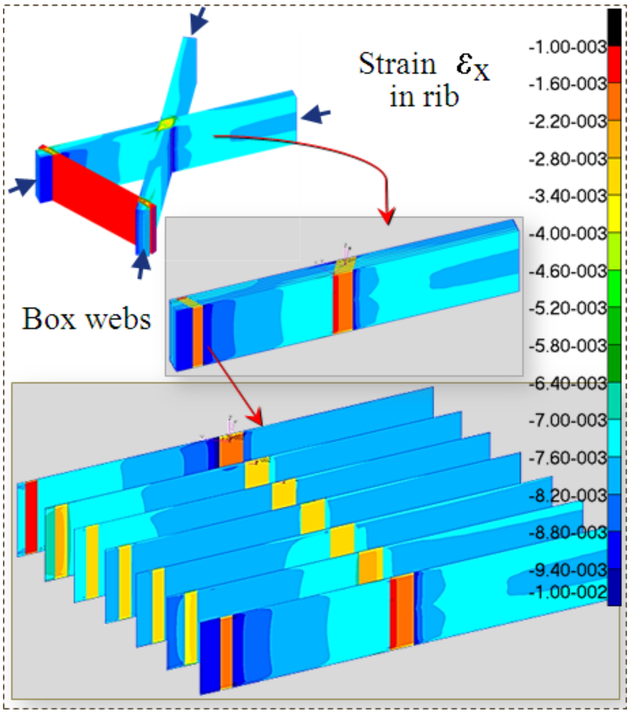

Fig.9 Local deformations of rib (webs of "box" model)

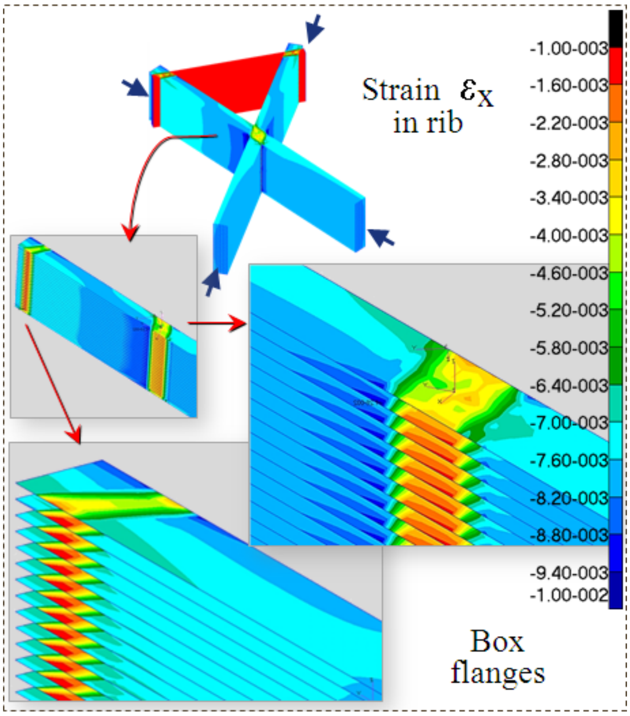

Fig.10 Local deformations of rib (flanges of "box" model)

References

[1] Fomin V., Shanygin A. and Zamula G. Multilevel approach for strength and weight analyses of composite airframe structure**.** *Proc. Of 27th International Congress of the Aeronautical Science*, Nice, France, 2010.

[2] Shanygin A. Main features of designing of pro-composite airframes. *Papers of TsAGI*, 2012.

[3] Chernov A., Fomin V. and Shanygin A. Strength criteria development for composite structures basing on solutions for models of different levels. *Proc. Of 28th International Congress of the Aeronautical Science*, Brisbane, Australia, 2012.

[4] Dubovikov E., Kondakov I. and Fomin V. FE modeling of lattice composite fuselage elements for general and local strength analysis. *Proc. of 3rd EASN Association International Workshop on Aerostructures*, Milano, Italy, 2013.

Contact Author Email Address

Mailto:
alley_59@mail.ru, evgeny.dubovikov@tsagi.ru; victor.fomin@mail.ru, victor.fomin@tsagi.ru.

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