30th Congress of the International Council
of the Aeronautical Sciences
DCC, Daejeon, Korea ; September 25-30, 2016

NUMERICAL AND EXPERIMENTAL STRENGTH ANALYSIS OF LATTICE COMPOSITE FUSELAGE STRUCTURES

Alexander Dzuba, Alexander Shanygin, Ivan Kondakov
Central Aerohydrodynamic Institute (TsAGI), Russia
Alexander Razin, Valery Vassiliev
Central Research Institute for Special Machinery (CRISM), Russia

Abstract

The present work is dedicated to validation of numerical methods for solving new tasks of strength of lattice composite fuselage structures. The validation was performed based on comparative analysis of results of the numerical calculations and experimental data, obtained during full-scale testing of lattice composite fuselage barrel. The barrel was designed in accordance with the requirements formulated in FP7 ALaSCA project and manufactured by CRISM on the basis of winding technology. Experimental testing was performed on a special test rig designed and created in TsAGI for experimental investigations of static and cyclic strength of lattice composite fuselage structures.

1 General Introduction

The experience of development of high-loaded composite aircraft structures have shown that the conventional approaches to strength analysis and design widely used for metallic airframes do not allow to obtain good enough solutions for composite airframes and achieve considerable weight benefits as compared to conventional structures. The main reason is that the conventional methods of strength analysis and design do not account heterogeneous nature of composite materials and interaction between fibers and resin inside composite packages.

Conventional methods have been created as a result of a long history of development of metallic airframes and meant particularly for metallic structures, taking into account their main advantages, the main of which is combination of high strength and high elasticity properties of aluminum metallic alloys (about 50 kg/m^2 ultimate strength together with about 20% ultimate strain). Unlike metals, current CFRP composite materials do not have such advantages. The weak point of CFRP’s is polymer resins, for which the combination of strength-elasticity properties is dramatically lower (6-8 kg/m^2 ultimate strength together with 2-3% ultimate strain). Such low strength characteristics of resins lead to a number of critical strength problems: appearance of numerous micro-cracks in the zones of resin-fiber interaction leading to significant degradation of strength properties of composite packages under repeated loads, low impact resistance of layered composite skin, low reparability etc.

The experience shows that these problems cannot be solved for conventional semi-monocoque load-bearing composite structures keeping high weight efficiency of such structures. But these problems can be taken into account and minimized for a novel type of aircraft structures - so-called “pro-composite” structures, allowing to realize potential of composites to a maximal extent [1]. In order to create novel pro-composite aircraft structures with high weight efficiency, novel methods of strength analysis and design are needed.

This work is dedicated to validation of numerical methods for strength analysis of lattice pro-composite fuselage structures, which have been developed in frames of a number of projects ALaSCA, PoLaRBEAR and a number of Russian projects [2][3]. These methods are based on multilevel approach to strength analysis of composite airframes [4]. According to this approach, the strength analysis of fuselage structure is performed simultaneously on 4 main levels of detailing: level of section, level of fragments, level of elements and microlevel. On each level of detailing the corresponding strength tasks are solved using parametrical FE and analytical models. These parametrical models are built automatically on the basis of universal database, which includes all parameters of the fuselage structure.

The advantage of the method is the possibility to perform complex strength analysis of lattice composite fuselage barrel, including analysis of fiber-resin interaction on microlevel.

The validation of the method, described in this paper, have been provided on the basis of experimental investigations carried out in TsAGI on the full-scale lattice composite fuselage barrel having 4m diameter and about 6 m length. The lattice barrel was designed in accordance with the requirements (including strength requirements) formulated in FP7 ALaSCA project for a composite fuselage section of perspective civil aircraft. The barrel was manufactured by CRISM on the basis of winding technology, well proven for cylindrical structures of space rockets' adapters. For experimental study of strength of the lattice barrel the special test rig have been designed and built in TsAGI.

2 Method of numerical strength analysis of lattice composite fuselage structures

The method of numerical strength analysis of lattice composite fuselage sections is based on the multilevel approach [4], dividing strength tasks on 4 groups, corresponding to different levels of detailing of the structure (Fig. 1). On each level of detailing different fully parametrical FE models are used for solving corresponding strength tasks. In order to provide reliable strength analysis all these models are built automatically on the basis of a universal database, which includes all structure parameters [5]. For FE models included in the method the principle of nesting is applied, when the nodes of FE model of lower levels of detailing are directly used for building models of higher levels of detailing.

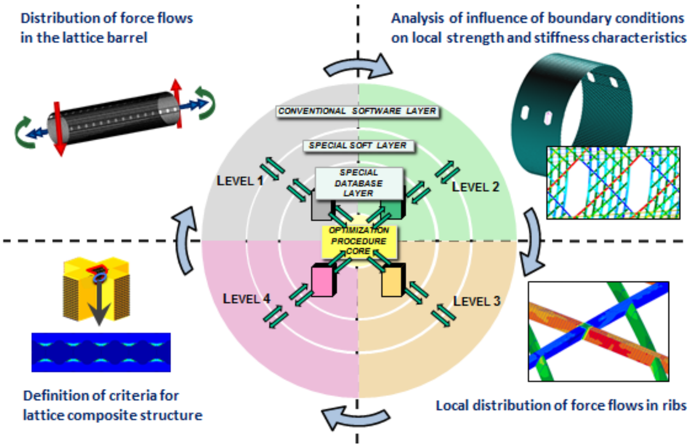

Fig. 1 – Method of strength analysis of lattice composite fuselage sections on the basis of multilevel approach

For complex strength analysis of lattice composite fuselage structures the following main tasks are solved on different levels:

Level 1 - Analysis of general distribution of force flows throughout the lattice composite fuselage barrel.

Level 2 - Analysis of influence of boundary conditions on the distribution of force flows (window cut-outs, joints etc.)

Level 3 - Analysis of local distribution of force flows in lattice ribs in critical zones of the structure.

Level 4 - Analysis of strain state on microlevel (resin-fiber) and definition of strength criteria.

The main advantage of the method is the capability to solve all main strength tasks of lattice composite fuselage structure (including strength of resin on microlevel) with high operability of the strength analysis keeping required accuracy of results.

One of the key features of the method is the technique of modeling for local strength analysis of ribs on level 3. The ribs are modeled on the basis of special "box" structure of 2D membrane elements. Such modeling technique allows to analyze local stress distribution in ribs without using 3D elements, that radically decrease dimensionality of models and simplify the analysis of results of calculations.

According to this technique, rib is modeled as a "box" structure consisting of flanges (horizontally located elements) and webs (horizontally located elements). Flanges are modeled by triangle membrane elements, webs – by rectangular membrane elements.

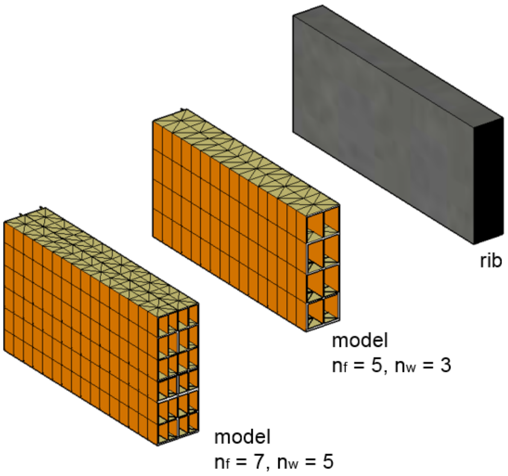

Fig 2 – Modeling of ribs with "box" models

The width and height of cross-section of the "box" model is equal to the real rib. Numbers of flanges (n_f) and webs (n_w) are parameters defining the level of accuracy of modeling (Fig.2). Thicknesses and stiffness parameters of flanges and webs are calculated automatically from the assumption of equality of stiffness characteristics of real rib and the model (Fig.3).

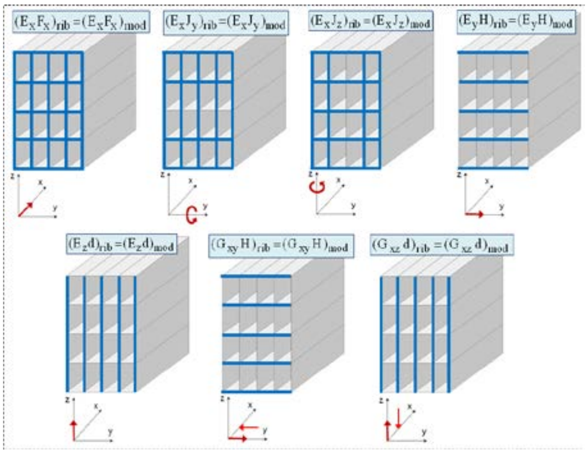

Fig. 3 – Stiffness characteristics of "box" model and real rib

For solving strength tasks on other levels of detailing standard FE models are used: models based on 1D beam elements on level 1 and models based on 2D shell elements on level 2. On level 4 the estimation of strength criteria is performed using models based on 2D or 3D elements.

3 Manufacturing of full-scale lattice fuselage barrel

For validation of the method of numerical analysis of lattice composite structures on the level of section, the real full-scale lattice composite barrel was manufactured and tested.

Manufacturing of the barrel was performed by CRISM on the basis of wet winding technology. The technology developed by CRISM is used for manufacturing of adapters of Russian space rocket-carriers Proton-M and have proven its robustness during about 10 years of serial production of various types of structures for space industry. Detailed description of this technology is given in [6].

The design requirements for the lattice barrel, including loadcases and strength requirements, were selected in accordance with the requirements to the composite fuselage structure of the perspective civil middle-range aircraft, formulated by Airbus within the frames of EU-Russia FP7 ALaSCA project.

Fig. 4 – Winding of lattice composite fuselage barrel (CRISM)

The lattice barrel is a cylindrical shell with diameter of 4 m and length about 6m consisting of the lattice grid of helical and circumferential ribs, reinforced by longitudinal ribs at the bottom of the barrel, and outer composite layered skin for pressurizing. According to the requirements, 12 cut-outs for windows were made, reinforced by special framings made of prepreg composite material. For attachment of the flanges of the test rig, the reinforced frames at both ends of the barrel were made.

Fig. 4 shows the process of winding of lattice grid on the rotating mandrel with silicone substrates attached to its surface. Fig. 5 shows the lattice composite barrel before testing.

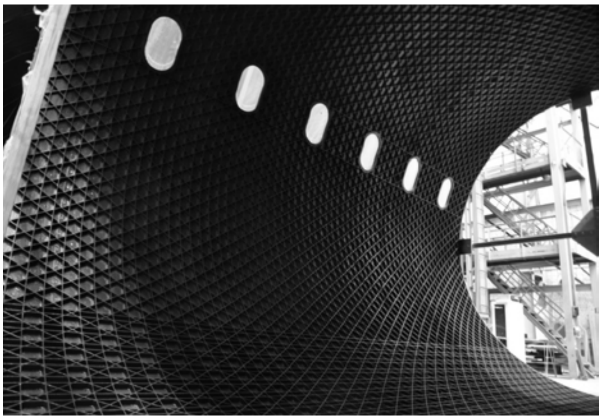

Fig. 5 – Experimental lattice composite fuselage barrel

3 Experimental rig for strength tests of lattice composite fuselage structures

For testing of the full-scale lattice composite fuselage barrel the special test rig have been developed, designed and manufactured in TsAGI (Fig.4). The necessity of creation of such testing facility was driven by extremely high sensitivity of lattice composite structure elements to boundary conditions. That means that in order to get valid results of tests, it is necessary to test a full-scale barrel as correct boundary conditions can be provided only on the ends of fuselage section.

The main elements of the test rig are the following:

- fixing plate, to which the fixed end of the experimental barrel is attached via special flange;
- loading (active) plate, to which the loaded end of the experimental barrel is attached,
- 8 actuators, 4 of which join the loading plate and the fixing plate between each other, and the other 4 joining the loading plate with the load frame and provide transversal displacements of the loading plate;
- measurement system for measuring deformation in the elements (more than 700 strain gauges) of the structure and for measuring displacements in several cross-sections of the barrel.

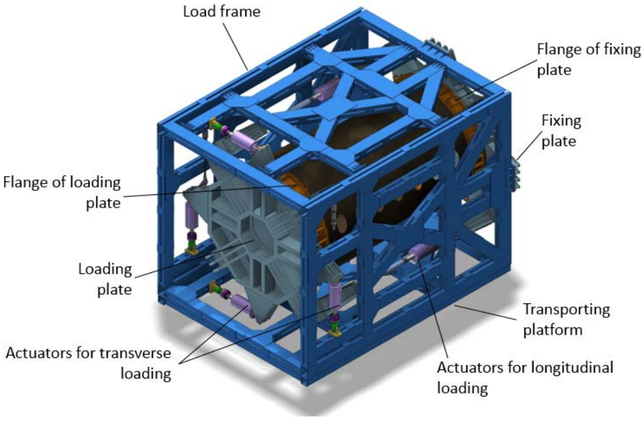

Fig. 4 – Scheme of the test rig for lattice composite fuselage barrels

For experimental investigation of lattice composite barrel the test program was developed. The program included investigation of strength of the barrel on a number of static and cyclic load cases, investigation of strength of the structure with damaged/delaminated ribs. The load cases were defined on the basis on the most critical load cases for regular fuselage barrel of perspective civil aircraft, considered in FP7 ALaSCA project.

The main goals of experimental study were the following:

– Experimental definition of actual static and cyclic strength characteristics of lattice fuselage barrel structure;

– Validation of numerical FE models and methods of strength analysis of lattice composite fuselage structures;

– Definition of boundary conditions for different fragments of the lattice structure for experimental investigations on upper levels of detailing.

The necessity of definition of actual strength properties of the barrel was caused by the special features of winding manufacturing technology, for which the sufficient dependence of strength properties on technological parameters is typical. As the lattice composite fuselage barrel was in fact the first real test prototype of such kind of structures, before testing there was no actual data on strength properties of lattice ribs which can be reliably used in modeling.

Loading of the lattice barrel was performed by the means of corresponding displacements of the loading plate. During the testing procedure, the lattice barrel have been loading by a number of load cases according to the test program. For every step of loading in every loadcase the strains in lattice ribs were measured by the means of strain gauges located on the inner edges of ribs (total number of strain gauges used in the tests exceeded 700) and measuring strains along the orientation of fiber in ribs.

Before testing of the lattice barrel the validation of the test rig was done. In frames of the validation compliances of flanges and attachments of the test rig on typical load cases were estimated. Fig. 5 shows the example of FE-analysis of test rig when testing lattice barrel on vertical bending loadcase.

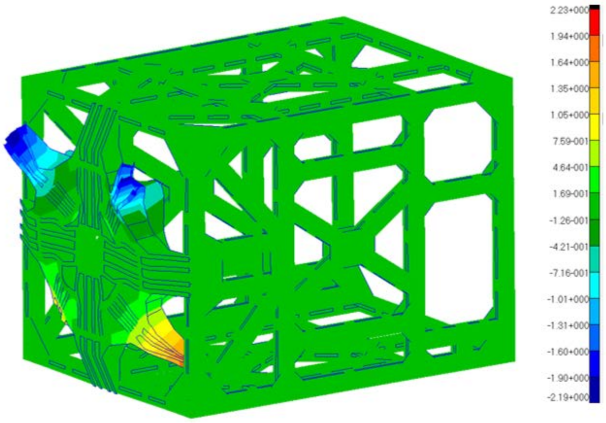

Fig. 5 – Displacements of test rig at vertical bending of lattice barrel

4 Validation of numerical methods using results of tests of full-scale lattice composite fuselage barrel

The experimental data obtained after testing of the lattice composite fuselage barrel was used for the validation of the method of strength analysis. The validation was made for the FE models of levels 1 and 2 of the considered method, corresponding to the level of fuselage section and the level of fragments.

The values measured by the strain gauges were compared with the values of strains at the corresponding finite elements of the FE models.

Fig. 6 shows the comparative analysis of results of numerical strength analysis of the lattice barrel on simplified FE-model of level 2 based on 2D shell elements with the experimental data obtained on strain gauges placed on internal edges of composite ribs. This comparison was made for a high-loaded regular zone of the barrel at the upper “panel” of the lattice structure. The loads applied on the barrel correspond to one of critical landing load cases with vertical bending and vertical shear force, which was taken as one of loadcases for validation of numerical models. As it can be seen at the figure, the differences between numerical and experimental data does not exceed 10% except several point of the structure for which the obtained experimental data was not valid.

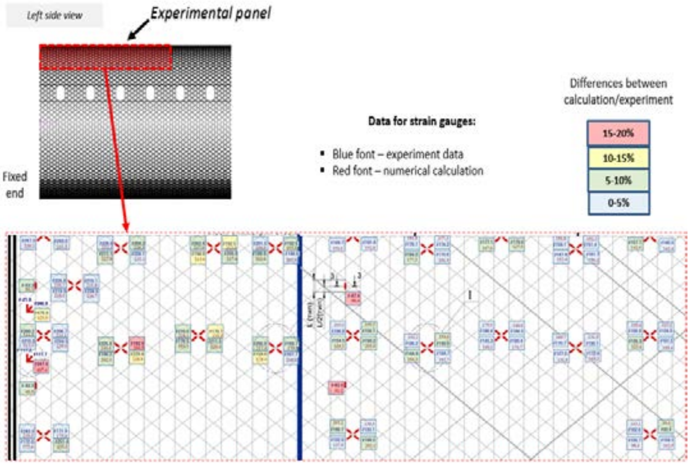

Fig. 6 – Comparative analysis of numerical and experimental data for a regular zone of the lattice barrel

The same comparative analysis was performed for non-regular zones of the lattice barrel (Fig. 7). The errors of modeling here did not exceed 20%, which can be explained by a complex stress-strain state of ribs in non-regular zones. Such stress-strain state is characterized not only by compression-tension of ribs (as in the regular zones) but also by considerable local torsion and bending of ribs. The strain gauges located in the inner edges of ribs allow to measure only local tension/compression of ribs, but do not give a full picture of stress-strain state of ribs in non-regular zones. At the same time, FE-models of levels 1 and 2 give only an average values of strains in ribs, which are in this case considerably different from local strains measured by strain gauges.

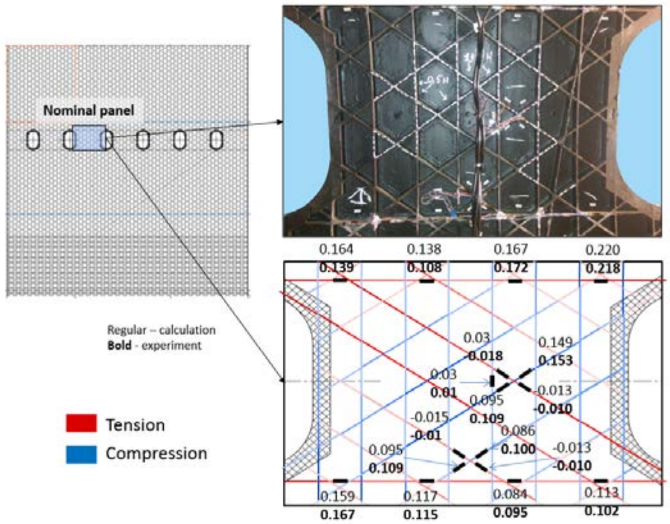

Fig. 8 – Comparative analysis of numerical and experimental data for a non-regular zone of the lattice barrel

For estimation of stress-strain state of ribs in non-regular zones, in several cross-section of ribs 3 strain gauges were installed: at the inner edge and at two side edged of the rib. The experiments have shown that differences in the values of strains for inner and side edges of ribs can reach up to 20-25%.

These results have shown that using of simplified modeling techniques based on 2D shell and 1D beam finite elements is correct for numerical strength analysis of regular zones of lattice structures on the level of barrel, but for the strength analysis of non-regular zones a more detailed modeling technique, such as "box" model of level 3 should be used. Fig. 9 shows the results of strength analysis of a fragment of a lattice barrel made using detailed FE modeling technique of level 3 of the method. As may be seen on the figure, strain concentrators up to 15% can occur even in regular parts of the lattice barrel at certain loadcases, while for non-regular fragments they can be considerably higher.

The strength analysis of the zones near cut-outs using detailed FE-models have shown that the strain concentrations in these zones due to cut-outs can reach 3.2. Furthermore, these concentrators have a significant influence of adjacent zones of the lattice structure on about 7-10 sized of typical lattice cells.

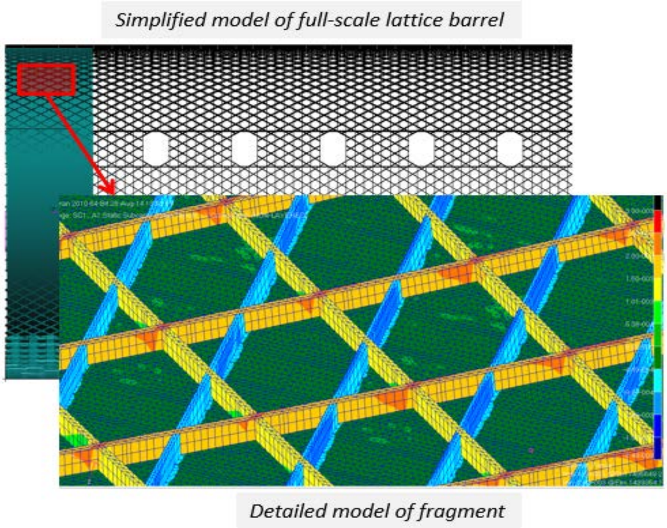

Fig. 9 – Local strength analysis of lattice barrel using detailed modeling technique (level 3).

The other part of experiments was dedicated to investigation of crack propagation inside ribs (due to delamination after damage) and debonding of skin from composite ribs.

The lattice barrel was tested on cyclic loading on a cyclic testcase which included bending and torsion of the barrel. The maximal load on each of cycles corresponded to 50% of limit load for the barrel. The number of cycles according to the test program was about 20 thousands. The results of cyclic loading have shown that the delaminations along damaged ribs are tending to raise very slow, while debonding of skin from ribs goes a lot faster even without any pressurizing. The debonding was most likely caused by a significant local concentrations of shear strains appearing in the skin-rib interface. Due to low strength properties of resin, the concentrations leaded to debonding of skin during cyclic loading. These results have confirmed that the layered composite skin can not be effectively used as a load-bearing structure element in lattice composite structures.

As a result of completing the main issues of the test program of the lattice composite fuselage barrel, the following main conclusions were made:

– lattice composite fuselage structures allow to obtain high level of loading for carbon fibers in unidirectional ribs, that proves their high potential in weight saving;

– lattice composite structures have high characteristics of cyclic strength and damage tolerance, as delamination in lattice ribs grows slowly;

– using of stiff layered composite skin decreases weight efficiency of lattice composite structures, so another type of skin (e.g. elastic skin) should be used in such structures;

– cut-outs in lattice composite structures have significant influence of strength of large zones of the structure.

References

[1] A.Shanygin, M.Zichenkov, I. Kondakov Main Benefits of Pro-Composite Layouts For Wing And Fuselage Primary Structure Units, Proceedings of the 29th Congress of the International Council of Aeronautical Sciences (ICAS-2014), Saint-Petersburg, Russia, 2014.

[2] European Commission, Aeronautics and AirTransport Research 7th Framework Programme 2007-2013, Project Synopses – Volume 2, Calls 2010 & 2011, 2012, http://cordis.europa.eu/result/report/rcn/56403_en.html.

[3] Production and Analysis Evolution for Lattice Related Barrel Elements under Operations with Advanced Reliability (PoLaRBEAR), Project Proposal – FP7-AAT-2013-RTD, 2013.

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

[5] I.Kondakov, E. Dubovikov, V. Fomin FE modeling of lattice composite fuselage elements for general and local strength analyses, Proceedings of the 3rd EASN Association International Workshop on AeroStructures, Milan, Italy, 2013.

[6] V.V. Vasiliev, A.F. Razin. Anisogrid composite lattice structures for spacecraft and aircraft applications. Composite Structures 76, 2006.

Contact Author Email Address

Mailto:
dzuba@tsagi.ru
alexander.shanygin@tsagi.ru
ivan.kondakov@tsagi.ru

Copyright Statement