Aircraft composite structures integrated approach: a review

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Abstract. This paper presents a comprehensive program for modelling airframe structures made of composite materials using the finite element method. The purpose of this study is to apply the comprehensive approach to the creation of models in accordance with the main directions of numerical modelling. The "computational and experimental research pyramid" and its relationship with the complex modelling program are presented. Methods for calculating aggregates and structures using micromechanics, static, dynamic and resource strength methods are described, as well as the influence of the manufacturing cycle on the final performance of a product made of a composite material. This integrated approach allows one to optimize all the stages in the design process of the aircraft. Using this approach, one can replace part of the certification tests with modelling according to the "computational and experimental research pyramid", which will reduce the cost of certification tests.

1. Introduction

Today, perhaps, it is impossible to name the areas of technical systems where composite structures are not used. The aircraft industry is considered an advanced industry in terms of the rate of composite materials implementation. A large number of research programs aimed at introducing new composite technologies into various types of structures are being conducted all over the world. Among them are Wing of Tomorrow (FACC, Republik Osterreich) concerning technologies of RTM-manufacturing of a wing [1, 2], Next Generation Multifunctional Fuselage Demonstration (Clean Sky, European Comission), the project on elements of a fuselage, systems, cargo compartments and a cabin integration improvement along with reduction of fasteners number) [3, 4], Advanced Constructions Technology (Advanced Construction Technology Services, United Arab Emirates), [4, 5], assuming reduction of production cost to 30%.

Improving the effectiveness of such structures requires a deep understanding of the types and principles of their work, the use of comprehensive approach, as well as conducting multidisciplinary research. The creation of a unified scientific environment that would allow us to use the approaches and achievements obtained in the development of various types of structures, in solving various tasks, will accelerate the process of implementing composite structures in actual programs and projects. The use of such approach in modelling was shown in papers [6-9].

The main feature of this approach is integration of all existing project areas into large programs (figure 1). The described approach not only describes the methodology for global programs, but also
takes into account all local levels, including the introduction of special studies on early Technological Readiness Levels (TRL).

![Figure 1. The comprehensive approach scheme.](image)

The development of composite structures has powerful technological trends that largely determine the prospects for composite structures development and implementation. Aviation and cosmonautics accumulates advanced experience in the composite material application. The experience gained is further used by other areas [10, 11], so the field of composite structures application is cross-disciplinary and is not limited exclusively to aviation.

The computational and experimental approach presented in this paper is applicable to other industries: in helicopter construction, shipbuilding, automotive industry, in the design and production of wind blades, sports equipment, and in many other areas.

The aim of this paper is to review the proposed comprehensive approach to composite structures.

2. Computational and experimental research pyramid
Moscow Aviation Institute (MAI, Moscow, Russia) implements numerical modelling methods in the certification process by solving related problems in the design of the wing and the integration of the wing into the overall airframe design. The results obtained show that the use of numerical modelling methods makes it possible to significantly reduce the loads, weight of composite structures, to significantly improve the quality of analysis and the pace of implementation of the composite structures characteristics in the certification and modelling process.

Digital twin technology [12-17] has become the most widely used in the industry, which is not surprising, since digital twins allow you to optimize all the processes in the supply chain dramatically. This allows engineers to model and evaluate the features of the product depending on the established requirements for it. With the help of a digital twin, one can pass certification tests in advance according to the “computational and experimental research pyramid”.

The basic technologies of virtual modelling should first be divided into static, dynamic and fatigue (which in turn include environmental tests modelling) (figure 2). They differ from each other both in the input data required for modelling, and in the principle of performing the calculation. The studies on composite structures damage [18-21] and studies on aircraft units test [20-24] are usually referred as dynamic ones. At the same time studies on fatigue [25,26] use different approach.
Figure 2. Virtual modelling branches.

The structure, which contains the directions of virtual modelling (static, dynamic, resource and technological ones), in turn, consists of the so-called “computational and experimental research pyramid” (figure 3). It is identical in its structure for each direction of virtual modelling. Approaches for organization of the analytical and Finite Element Models were considered in the following papers [7, 20, 27-31].

Figure 3. Computational and experimental research pyramid.

The base level of the pyramid is micromechanical samples simulation [32]. This model should take into account the phase structure of the material within elementary cell (micromechanical cell) [27]. Modelling of this stage can be used to develop the failure criteria and to derive the mechanical properties of the material ply [33]. There are several ways to translate the information obtained via micromechanical modelling to the next level of material samples, i.e. coupon samples. Among most
reported methods are homogenization of the properties received from isolated representative volume element (RVE), which is also known as sequential or hierarchical [34-38]; and parallel simulation of meso- and micro-scales with latter used for quantifying the damage state at a material point at meso-scale, in other words it is concurrent simulation strategy [39-43]. One of the forms of concurrent method is discussed in the section 3 of this paper.

The characteristics obtained in the virtual testing of micromechanical samples are taken into account when modelling the next stage of the pyramid, which is coupon tests simulation [32, 44-47]. Modelling of these samples repeats the "general material qualification" - a certification document confirming the characteristics of the material package. The result of this simulation confirms the correctness of the model, which takes into account various factors (boundary conditions, interactions, fracture/delamination criteria, etc.).

The characteristics obtained in the coupon test simulation are taken into account when modelling the next level of the pyramid, which is details test simulation. This simulation repeats the special qualification of the material. This certification document takes into account standard structures, such as spars, reinforced panels, and skin panels with cut-outs as well as fasteners. Here, in addition to delamination and failure checks, checks for buckling, fasteners crumpling, shear-out and pull-through are carried out. Detailed modeling of structurally similar samples was carried out in the work by Linde [27].

During the simulation process, in order to obtain input data and confirm all output data, it is necessary to conduct certification tests in accordance with approved regulatory documents (ASTM, EN, etc.).

Computational and experimental researches are carried out on the basis of the following approved documents:

- Programs and methods of computational and experimental work, containing a description of the operational sequence and strength criteria;
- Regulatory documents on experimental research;
- List of test samples;
- Coupon and details test programs.

The implementation of tests and simulations in accordance with the “computational and experimental research pyramid” allows confirming or gaining basis for improvements regarding:

- Material selection;
- Composite materials manufacturing technologies;
- Design solutions;
- Strength criteria;
- Methods of calculated strength.

Only after carrying out the pyramid levels described above, one can proceed to the components tests simulation and subsequently the entire structure of the aircraft simulation [21, 31, 48-50].

Figure 3 shows that each stage of the computational and experimental research pyramid is closely related to the certification process through field tests. At the first stage, when there is no approved database of material characteristics and modelling techniques, each stage of modelling is confirmed by field tests. In the process of creating a database, modelling will reduce the number of necessary tests (as well as the number of samples per batch per test unit) carried out at the stage of aircraft design and certification, which in turn will reduce the cost and time of product development.

To compare the modelling approaches used in the MAI with the current world (foreign) experience [21, 31, 48-50], it is necessary to compare them with the global research directions (static, dynamic, resource and technological ones) presented in figure 2. It should be noted that a micromechanical cell approach to modelling is involved at each stage of the computational and experimental research pyramid (the global model takes into account the model of micromechanics).

Approaches to modelling static and dynamic loading at different stages (figure 3) and levels of detail (layer-by-layer solid-body modelling, the use of additional user programs) comply with national and international standards, for example [51], creating mathematical models of aircraft structures, their subsystems, components, aggregates, parts, samples (coupon and details), monolayers, as well as
composite micromechanical cells. The modelling of the manufacturing process (technological factors) is carried out by the world community on relatively small structural elements due to requirements for the computational capacity. In the study [52], a simulation of the molding process for the leading edge rib of the Airbus A-380 wing is presented, in the study [53], experimental and numerical modelling of warping on the example of a structurally similar spar sample is carried out. It is worth noting that along with the pseudo-viscoelastic Svanberg model [54] and the most common elastic model [55], viscoelastic models [56] also appear. Thus, the global models that are developed and considered at the upper stage of the pyramid, taking into account thermal warpage and residual stresses on structures after passing through manufacturing operations and being part of aircraft components, provide a detailed and more accurate picture of stresses distribution during their operation.

Currently in aircraft design, margins of safety for static strength are set, reaching up to 4 according to AMC 25.571 in order to avoid calculating the fatigue strength margin of safety.

In turn, some researchers have developed the finite element fatigue modelling of structures made of polymer composite materials in the last few years. In 2002, the thesis of the Belgian scientist Wim Van Paepegem [57] was defended, which analytically described the behavior of CM material during long-term operation, was experimentally confirmed and was added to the Siemens software as a method of finite element modelling.

3. Modelling of micro-scale level

First stage of computational and experimental research pyramid, which is micro-scale modelling, allows for conducting the analysis and obtaining estimates of material properties for next level of testing pyramid Here the solutions for different local problems, such as deriving laminate properties from ply properties, influence of fiber-matrix interface on ply properties, defects onset and accumulation in the material are considered.

Today’s growth of computational resources extends the range of possible micro-scale wise tasks. Conventional technique known as “homogenization” is used to build the properties of the layer based on properties of its constituents: matrix, fibres and interface [58-62]. Received results usually show reasonable accuracy in mechanical properties, but not in strength properties, which do not appear coincident with the results of testing in laboratories. Within domain of computational micromechanics using Finite Element Method, accurate mechanical material constants may be calculated as well as strength values under simple and complex loading configuration [33, 44]. Achieved results invest in the development of the so-called “Virtual Test Laboratory”, which is called for supplementing or even replacing real testing of the samples, thus minimizing the cost of testing program [32, 44].

An illustrative example of micro-scale modelling is a RVE of material, consisting of matrix, fibres and interface between matrix and fibres. Computational resources allow for conducting the analysis of sufficiently large cells with hundreds of fibres and this way size-effect from the cell choice might be estimated (figure 4). The results, delivered during one of the on-going projects in MAI show, that longitudinal tensile strength results converge only from the side of the cubic cell of material equal to 80 µm. With fibre volume fracture of 50% and mean radius of filament of 3.5 µm such RVE incorporates about 100 fibres. The results of the analysis also give complex and comprehensive damage state of the model (figure 5). The proper solution for described RVE requires about 1.5 million of finite elements, which clarifies, that even such simple task needs certain computational power.

![Figure 4. Undirectional ply’s cubic RVEs in the range of 20…175 µm.](image-url)
Figure 5. RVE model cut with damage state, received from longitudinal tensile test.

One of the most promising lines in using micromechanics is irregular zones modelling (ply drop-off, joints etc.) These regions are normally responsible for structure overweighting, which comes from the use of conservative failure criteria herein. Analysis of irregular zones dictates the need for new approaches that may overcome modelling of isolated RVE. One of the possibilities here is direct approach (figure 6 a, b, c) (which might be thought as some extent of embedded cell method [63-67]) developed at present in Moscow Aviation Institute. The idea of the method is the insert of detailed on micro-scale level unit in the zone of interest in homogenized material. This approach is applicable on both mono-layer and laminate level [68-70], with latter forming the laminated RVE (figure 7). It is worth mentioning, that to authors knowledge there are only few studies, where the multidirectional laminate cell is modelled explicitly with oriented material cells [69,71,72].

Figure 6. Direct approach verification models: (a) – homogenised layer with embedded cell (b) – full micromechanical cell (c) – homogenized layer. Micro-scale units in the body of homogenised layers of laminate.
4. Micro-scale level modeling
The second stage of the pyramid, which is coupon tests simulation, serves mainly for the repetition of the material general qualification. At this stage, the physical and mechanical properties of the composite material package are checked by comparing them with the results obtained during certification tests according to approved methods and standards. An example of the characteristics obtained on an elementary sample is the tensile ultimate stress (figure 8).

![Figure 8. Coupon tensile test model.](image)

In the process of confirming the obtained characteristics in the simulation, an extensive database of chemical and mechanical properties of materials is created. The obtained data primarily serve as a justification for the choice of materials (fiber, matrix, honeycomb structure, etc.) for further structures design and manufacturing.

When modelling elementary samples, the choice of the manufacturing process (Pre-Preg, Vacuum Injected Molding, Resin Transfer Molding, etc.) is taken into account, the relationship between the characteristics of the composite material and the parameters of the manufacturing process is revealed, and the configuration of the sample and tooling during testing is also taken into account.

A distinctive feature of the models prepared and calculated in MAI is the layer-by-layer modelling of solid-state structural elements (coupon, details, components), which take into account both the interlayer failure (delamination) and the formation of cracks in the layers [73, 74]. In addition user-defined subroutines are used that being loaded into software packages allow supplementing finite element models with local criteria and, as a result, increase the accuracy of the results obtained.

5. Detail tests simulation
The third and fourth stages of the pyramid are structurally similar samples of details that confirm the special qualification of the material. It takes into account the modelling of structural elements used for
The manufacture of fuselage compartments, wing torsion box, empennage, etc. The values of the material characteristics are determined based on the comparison of the simulation results and experimental data. This stage includes the modelling based on static, dynamic (figure 9), fatigue, environmental testing, the crack resistance characteristics obtained on coupon tests [75, 76] are taken into account as well.

The results obtained by coupon test modelling form an additional materials database. These databases are used at the subsequent levels of the "Pyramid" in the design and manufacture of structurally similar samples, full-scale components, structural units and the entire aircraft airframe and take into account the variation of material properties associated with the imperfection in the specimens due to manufacturing issues.

At this stage, models received at the coupon test stage are approved. Structurally similar samples are checked for impact effects, the occurrence of damage during manufacturing (the occurrence of residual stresses and warpage of the structure during curing (figure 10)), damage received during operation (hail and lightning strikes, etc.) on the residual strength of the structure. The influence of boundary conditions and applied loads is evaluated, design solutions are developed taking into account the influence of the scale factor and further maintainability. Such modelling results in clarifying aggregates and units local zones, creating local strength criteria, and issuing recommendations on accounting for and eliminating the influence of manufacturing defects and external factors in structures.

6. Components tests simulation

The fifth stage of the pyramid (components tests simulation) includes a full-scale simulation of such structural elements as the fuselage compartment, the wing box (figure 11), main and auxiliary control surfaces, landing gear unit, etc. Modelling of aggregates allows not only to obtain information about the properties of the object of research, which will be needed to continue the work on the creation of products, but also to help give a qualitative and quantitative assessment of the design decisions made.

One major difference of component test simulation from coupon and detail simulations is that the study area is restricted not by boundary conditions but other structural elements. The components are modelled in accordance with the requirements of the regulatory documentation (ASTM, EN and Russian GOST standards). Taking into account these requirements allows not only to clarify the object of the study, but also to conduct the study in such a way that its results can become valid in terms of regulatory documents, which will allow you to partially or completely abandon the expensive real tests.
The step-by-step parametric optimization method being developed at the Moscow Aviation Institute takes into account the anisotropic properties of laminate. The parametric optimization of the thicknesses of such wing box structural elements as spars, ribs and skin is carried out, with restrictions on strength criteria, it also considers stringer spacing and spar caps thickness with restrictions on buckling.

The essence of the methodology is to select the geometric parameters of the wing box structural elements by the means of step-by-step optimization. At the first stage, the thicknesses of the spars and ribs and the effective thicknesses of the skin elements, including the cross-sectional area of the stringers, are determined. The mass is selected as the target optimization function. The limits for structural elements made of metal alloys are maximum stress criteria. For parts made of polymer composite materials, maximum strain criteria are set [77]. Next, the stringers spacing and spar caps thickness is optimized with buckling as optimization constrain. The thickness of the stringers is determined based on the effective thickness of the skin and the optimized stringers spacing [78].

At the next stage, the skin is divided into many fragments by lines, as which the projections of the median planes of the ribs are taken, and the compressive (shear) force acting on each fragment is determined (figure 12 a, b). Then, an analytical calculation is performed to determine whether the buckling of this fragment occurs. If it does, the fragment is divided into smaller and smaller pieces until this piece does not cease buckle. The minimum fragment size and should be taken as the optimal stringer spacing [79].

At the end, a check simulation of the wing box model is performed, taking into account the parameters obtained after optimization. The developed technique allows reducing the weight of the wing box structure by 8-15% while maintaining the strength and stiffness characteristics [80].
7. Airframe test simulation

The last and the most important step of the pyramid is the airframe tests simulation. When modelling the entire airframe, a full accounting of databases on materials, technologies for structures structural elements, components and aggregates manufacturing, as well as the history of its loading is carried out.

In the process of modelling, all previously developed techniques related to micromechanics, coupon and structurally similar samples and components are taken into account.

In the course of such studies, the entire airframe with all the structural elements becomes the object for the simulation (figure 13). Some load cases, such as landing of an airplane, do not seem reasonable to investigate on other scales of tests.

![Figure 13. Global model of the aircraft airframe.](image)

The calculation of aerodynamic loads taking into account the aero elasticity of the structural elements of the airframe made of polymer composite materials is an example of a comprehensive study conducted at this level of the pyramid.

Global finite element models of the airframe are used to take into account the influence of the empennage, control surfaces and fuselage, made of polymer composite materials, on the aerodynamic loads of the wing. In the course of the analysis, the loads on wings are refined taking into account the aerodynamic loads, the mass distribution and the rigidity of the structural elements.

In order to optimize the structural scheme, reduce the weight and thickness of the structural elements of the aircraft, a coupled calculations performed to determine the aerodynamic loads. The essence of the coupled calculation is that the structural and aerodynamics modules exchange data at each iteration of the calculation, as the result of which the loads and, accordingly, the deflections of the wing change at each subsequent iteration. To perform this task, a connection is established between the elastic structural model and the aerodynamic one [81]. The result of the work of the aerodynamics module is the pressure field, which is transmitted to the structural solver. At the next step the model is rebuilt again (figure 14).

After that, the obtained aerodynamic pressure fields are interpolated on the wing structural model and the wing box stress-strain state is calculated taking into account the inertial loads. The wing deflection values obtained as a result of the coupled calculation are analyzed and compared with the loads obtained by the "classical" method. The developed technique allows us to obtain a wing structure with a minimum mass while maintaining the necessary stiffness and strength characteristics by taking into account changes in the wing geometry under aerodynamic forces.
8. Conclusion
In this article, an integrated approach to airframe structures made of composite materials design was considered. The basic idea is that the design is investigated starting from the micro level up to the macro level, taking into account the repetition of all the material qualifications. Multidisciplinary virtual simulations are conducted at different levels using the characteristics of materials or structures obtained in the previous ones. This allows one to achieve high simulation accuracy with the least effort and cost of resources.

The approach under consideration involves conducting multidisciplinary research, which means using not only strength Finite Element models, but also aerodynamic ones, as well as conducting coupled calculations and other calculations, including taking into account manufacturing characteristics. A complex of related calculations taking into account a comprehensive study of the design allows one to apply this approach in any field of composite materials application.

The data obtained during the material research allows one to form a part of the digital twin of the product, which is necessary for its further implementation, as well as its support throughout the entire life cycle. This will allow one to quickly respond to changes in the design or repair work during the product operation.

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