Actual methods of full-scale metal-composite aircraft structures static testing with the use of information systems

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Annotation. Strength testing of aircraft structures made of polymer composite materials requires improving methods and procedures for conducting experimental research. The paper presents a computational and experimental approach applied in the laboratory of static strength tests of FSUE “TsAGI”. The effectiveness of this approach is demonstrated on the example of testing the structure of medium-range aircraft. Before the tests, a computational model was created, based on which critical strength zones were determined. Additional strain gauges were installed in these areas, which allowed conducting thorough monitoring of the stress-strain state. The use of specialized software “Tensometry visualization module”, developed at FSUE “TsAGI”, made it possible to analyse the readings of ~10,000 strain gages during testing in real-time, which significantly increased the information value of the experiment and reduced the risks of unintentional destruction of a full-scale specimen. Based on the results of the experiment, the calculation model was validated.

Key words: strength, static tests, deformations, strain measurement, finite element method, computational and experimental approach, software.

1. Introduction and problem statement

One of the modern trends in aircraft construction is the introduction of polymer composite materials (PCM) into the load-bearing elements of aircraft [1–4]. Testing the strength of PCM structures is an expensive and laborious process [5,6]. Therefore, any delays or mistakes made at the stage of preparation as well as directly in the course of carrying out full-scale tests turn into a difficultly predictable increase in the costs of the project as a whole. As a consequence, the cost of experimental studies of full-scale structures containing composite materials increases [7,8]. Also, recently there has been a significant increase in the productivity of computers; computational methods and methods of computer modeling are being improved, and automated control systems for experiments are being developed [9]. The introduction of modern information and measuring systems in the testing complex opens up new opportunities for the development of an experimental base [10]. Meanwhile, it should be taken into account that the amount of information obtained during testing is increasing.

The factors described above explain the need to improve the methods of strength testing. The aim of this work was the development of computational-experimental approach, its integration into the testing process, as well as the creation and verification of a computational finite element (FE) model on the example of full-scale tests of a medium-range aircraft. Special attention is paid to monitoring structural zones critical in terms of strength and stability, obtained based on the results of mathematical modeling, as well as comparing the calculation data with the experiment directly during the tests.
2. General concepts of the computational-experimental approach
When performing static strength tests at TsAGI, the well-proven concept of experiment-calculation-analysis is used. It is based on the principle of close relationship between calculation and experiment (Figure 1) [11–13].

To support the experimental studies, a computational FE-model is prepared, on which a virtual simulation of the upcoming loading case is carried out. The most loaded areas are identified, as well as structural elements that are critical in strength and stability. This stage plays an important role as it helps to sufficiently reduce the risk of unintentional destruction of the test specimen and allows, if necessary, to correct the test program.

After performing the computational support, testing for the previously analyzed case of loading is carried out [14]. During the experiment, it is important to watch for the most loaded areas of the structure, track the areas of discrepancy between the calculated and experimental data, and monitor the sensor readings. In the case of emergencies, one should promptly stop the experiment and unload the specimen.

Based on the test results, the data obtained are analyzed, the places of the greatest discrepancies between the calculated and experimental values are determined, and the previously created models are corrected and refined. An advanced mathematical model is used to perform virtual simulations of subsequent load cases, thus providing more reliable data. As a result, the computational-experimental approach is a continuous and interconnected process, which is used to fulfill each individual loading case using previously obtained experimental and calculated data [15,16].

3. Strain measurement visualization module
The key aspect to reduce the risks of unintentional premature destruction of the specimen is processing, express analysis and systematization of experimental data in real-time during the testing. The number of sensors installed on a specimen during testing of full-scale aircraft structures can reach 10,000 pieces. It is obvious that the perception of such a huge amount of information is extremely
difficult for a human. At the same time, in order to make a reasonable decision about stopping/continuing loading, it is necessary to take into account all these data in aggregate.

To solve the problems described above, in the static laboratory of TsAGI “Tensometry Visualization Module” is applied. This is a special software developed by TsAGI specialists, which is used to present and organize information in the course of testing, to provide comprehensive analysis of the stress-strain state during and after loading, as well as to compare calculated and experimental data. This software has proven to be a useful and reliable tool while conducting numerous tests of aircraft structures [17]. The interface of the “Tensometry Visualization Module” is shown in Figure 2. The strain measurements are displayed on the sensor layout diagrams, which are prepared in advance in the AutoCad environment and converted into a graphic format.

![Figure 2. The interface of “Tensometry Visualization Module”](image)

When working with the Module, it is possible to select the required specimen scheme and monitor the strain gauges data during testing in real-time. Depending on the settings, the values of the deformation or the stresses of the structure are displayed in the places where the strain gages are installed. The Module allow to systematize the entire volume of strain measurements obtained, analyze them, identify the most loaded areas, and predict the zones of structural failure during the testing. In preparation for experiment, one can set up the critical deformation values, upon reaching which the Module gives a warning and displays the sensor and the area of the structure in which this value was exceeded. The functionality of the Module also allows in real-time:

- represent graphs of stress (strain) dependence on the applied load for the strain gauges of interest;
- calculate and visualize the predicted stress values for the maximum design load using the internal extrapolation algorithms;
- compare the calculated model with experimental data.

Areas of the structure, in which the maximum values of deformations are observed, as well as the zones of discrepancy between the experimental and calculated data, are of the most interest during testing [18,19]. The identification of such zones is performed in a semi-automatic mode using the “Tensometry Visualization Module”. These areas are monitored interactively continuously during the experiment, current and predicted stress values are analyzed. During the tests, visual monitoring of the
most loaded parts of the structure is carried out.

4. Mathematical modeling
The test object was a full-scale specimen of an aircraft, in the load-bearing structure of which layered PCMs are widely used. One of the most difficult from the point of view of the experiment, and also responsible in the sense of the applied loads, close to critical, was the case of a maneuver with a maximum vertical overload. In addition, the important feature of testing the medium-range aircraft was a large number of installed strain gauges (about 10,000), so it was important to show the functionality of the “Tensometry Visualization Module”, as well as its high performance when processing a large amount of data.

To accompany the static tests, a computational model was created, which included a detachable wing, center section, central fuselage, and a number of other elements. The general view of the computational model is shown in Figure 3.

![Figure 3. View of the finite element model](image)

In the course of computational studies, the stress-strain state of the structure was predicted for the specified loading case, the most loaded zones were identified, and an analysis of possible places of buckling was carried out using nonlinear methods. The computational analysis showed that under maximum design loads, the occurrence of dangerous residual deformations is not expected in the structure, and the loss of stability of individual elements could occur only in local areas.

After carrying out the computational research, it was decided to continue with the loading of a full-scale aircraft sample for the case studied. In the structural elements with the highest deformation values, additional strain gauges were installed, which made it possible to conduct a detailed analysis and monitoring of these zones.

5. Full-scale testing
During the tests for the case considered, the aircraft was loaded in stages up to the maximum design loads [20]. Continuous monitoring and analysis of the structural stress-strain state was carried out. A schematic diagram of the loading process using the above described “Tensometry Visualization Module” is shown in Figure 4. This process includes several stages.
Figure 4. The process of carrying out static strength tests using the “Tensometry Visualization Module”

1) Test loading.  
In the course of this stage, the correct functioning of the structure loading systems and measuring equipment is checked. A preliminary stress-strain state analysis of the specimen is performed.

2) Loading up to the operational load.  
After loading to the operational load level, the analysis of strain measurement data is performed, the most loaded zones of the structure are identified, the calculated and experimental data are compared, and critical load forecast is made. Based on the analysis performed, a decision to proceed to the next stage of loading up to the design load level is made.

3) Loading up to the maximum design load.  
Upon completion of loading up to 100% of design load, the test results are analyzed, visual inspection of the specimen is carried out, identification of zones of buckling, destruction is performed, data obtained are processed. The calculation models are validated.

The stress-strain state of the structure was controlled by strain gauges installed on the surface of the specimen. They were located over the entire surface of the sample, while in the critical zones, according to the calculation performed, their number and density were increased to obtain a complete picture of stress-strain state. The total number of strain gauges was about 10,000 pieces. Stress-strain state analysis and monitoring were carried out using the “Tensometry Visualization Module”.  
As a result of the tests, areas of local buckling and small residual deformations of individual structural elements were recorded. These results were predicted in a computational model and correlate well with experimental data. In some areas of the structure, there were discrepancies between the strain gauges readings and the calculation data of about 10%. The largest discrepancies were observed in areas with local stress concentrators, associated in particular with the presence of rivets and fasteners. In these zones, the detail of the computational model was insufficient, but in general this did not affect the results of its validation.
On the whole, the computational model showed good agreement between the calculated and experimental data. The analysis of the stress-strain state of the structure at the operational level of the load, as well as the forecast conducted at this stage of loading, made it possible to make the right decision to continue testing up to the maximum design load. The overall integrity of the specimen for subsequent stages of testing was maintained.

6. Conclusion
The paper presents some aspects of the computational and experimental approach to static testing of metal-composite aircraft structures. Before testing the structure, a computational model was created, the numerical results of which determined the zones with possible occurrence of plastic deformations of the material, or loss of stability of individual elements. Additional strain gauges were installed in these areas, which made it possible to conduct a thorough monitoring of the stress-strain state of the structure. The use of specialized software “Tensometry Visualization Module”, developed at FSUE "TsAGI", provided interactive processing of the readings of ~10,000 strain gages during the tests. This made it possible to analyze the experimental data in real-time, which significantly increased the information value of the experiment and reduced the risks of unintentional destruction of a full-scale specimen. Based on the results of the experiment, the calculation model was validated.

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