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SPECIALIZED SOFTWARE DEVELOPMENT FOR BUILDING BLOCK APPROACH INTEGRATION IN FULL-SCALE STATIC TESTS

E. M. Kolman, D. V. Kurulyuk, E. A. Levchenko, M. V. Limonin

Central Aerohydrodynamic Institute named after N.E. Zhukovsky, Zhukovsky, Zhukovskogo st. 1, Russia

Abstract

The paper considers the main concepts of the ‘Building Block’ approach to strength testing of aircraft structures. Specialized software ‘TensoVis’ was developed. It is intended for visualization and analysis of strain gauge data in real-time during the tests. The integration of the created software into the measuring and computing complex (MCC) for testing was performed. The advantages and some aspects of its use were shown in the example of a complex loading case of passenger aircraft. The number of installed strain gages was about 10,000 pieces; loads applied to the aircraft reached the values close to critical. The application of software ‘TensoVis’ in addition to the concepts of the ‘Building Block’ approach allowed successfully conducting tests, preserving the overall integrity of the structure. In conclusion, the paper provides the results and analysis of software integration.

Keywords: static strength tests, Building Block approach, strain measurement, software

1. General Introduction

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 and directly in the process of carrying out full-scale tests turn into a barely predictable increase in the costs of the project as a whole. As a result, the cost of experimental studies of full-scale structures containing composite materials increases [7].

Computational methods, computer simulation software, and automated control systems show considerable progress in the past ten years [8]. The introduction of modern information and measuring systems in the testing complex opens new opportunities for experimental base development [9].

Full-scale tests of aircraft structures produce a large volume of measurement data from various recording sensors of different types. The main ones are strain gauges, force sensors (dynamometers), linear and angular displacement sensors, pressure sensors.

Strain gauges distributed over the structure monitor the stress-strain state (SSS). The number of them in full-scale tests of an aircraft is ~10,000 pieces. At the same time, the number of installed dynamometers for measuring the forces applied to the specimen can reach more than 100 pieces in complex loading cases. Also, the number of sensors that measure structural deflections and angular displacements is several tens [10]. The collection, processing, and displaying of the received data are carried out in special measuring and computing systems. Then it is necessary to analyze the entire amount of information received in real-time to make reasonable decisions about the continuation or stop of loading. This role falls on the team of specialists who carry out the test. The perception of such a massive flow of information is extraordinarily complex for one or even several people. It is necessary to develop specialized software tools that provide systematization, analysis, processing, and visualization of the experimental data during the experiment to solve the stated problems.

In the course of this work, modern approaches to static strength testing were analyzed. Specialized software for strain gauge data visualization and processing during the tests was created. It was integrated into the measuring and computing complex in the TsAGI Static Strength Laboratory. The developed software proved its efficiency in the course of full-scale tests of the passenger aircraft. The results of virtual modelling were compared with the test data directly in the process of loading.

2. General concepts of the 'Building Block' approach

The use of composite materials in the structural elements of modern aircraft significantly complicates the process of substantiating the strength characteristics of the product. Developing the design and proving the durability of composite components, as a rule, consists of a complex relationship of testing and analysis [11–13]. The use of a purely experimental approach is prohibitively expensive due to the number of samples required to work out all the necessary conditions for geometry, loads, environmental factors, and failure modes. On the other hand, the analysis methods used separately from the tests are usually not complex enough to adequately predict the results for each set of conditions mentioned above. A combination of tests and calculations provides testing analytical forecasts experimentally, while the test program is guided by the calculation performed. That reduces overall project costs while increasing reliability.

The development of this approach lies in conducting analysis and related tests at various levels of structural complexity, often starting with small samples and moving up the structural ladder through elements, sub-components, and components to a full-scale product. Each level is based on the knowledge gained in the previous, less complex levels. This process of strength substantiation, using a combination of experimental and computational methods at various levels of structural design, is known as the 'Building Block' approach.

One of the main goals of the 'Building Block' approach is to reduce the cost and the risks of the test program while meeting all technical, regulatory, and consumer requirements. The idea is to make the design development process more efficient by assessing the technological risks early in the program. Cost-effectiveness is achieved by developing a test program that uses more relatively cheap small samples and requires fewer expensive components and full-scale products. Thus, we significantly reduce the risks of technological defects and miscalculations at the final stage of the test program. Where possible, analytical methods of strength justification are used instead of experimental ones, which also leads to lower costs.

The 'Building Block' process is usually presented in the form of a pyramid, reflecting the main stages of testing the strength of the aircraft elements. The pyramid has an ascending structure, as shown in Figure 1. The results of each level (stage) of the pyramid are the initial data for the implementation of its next level.

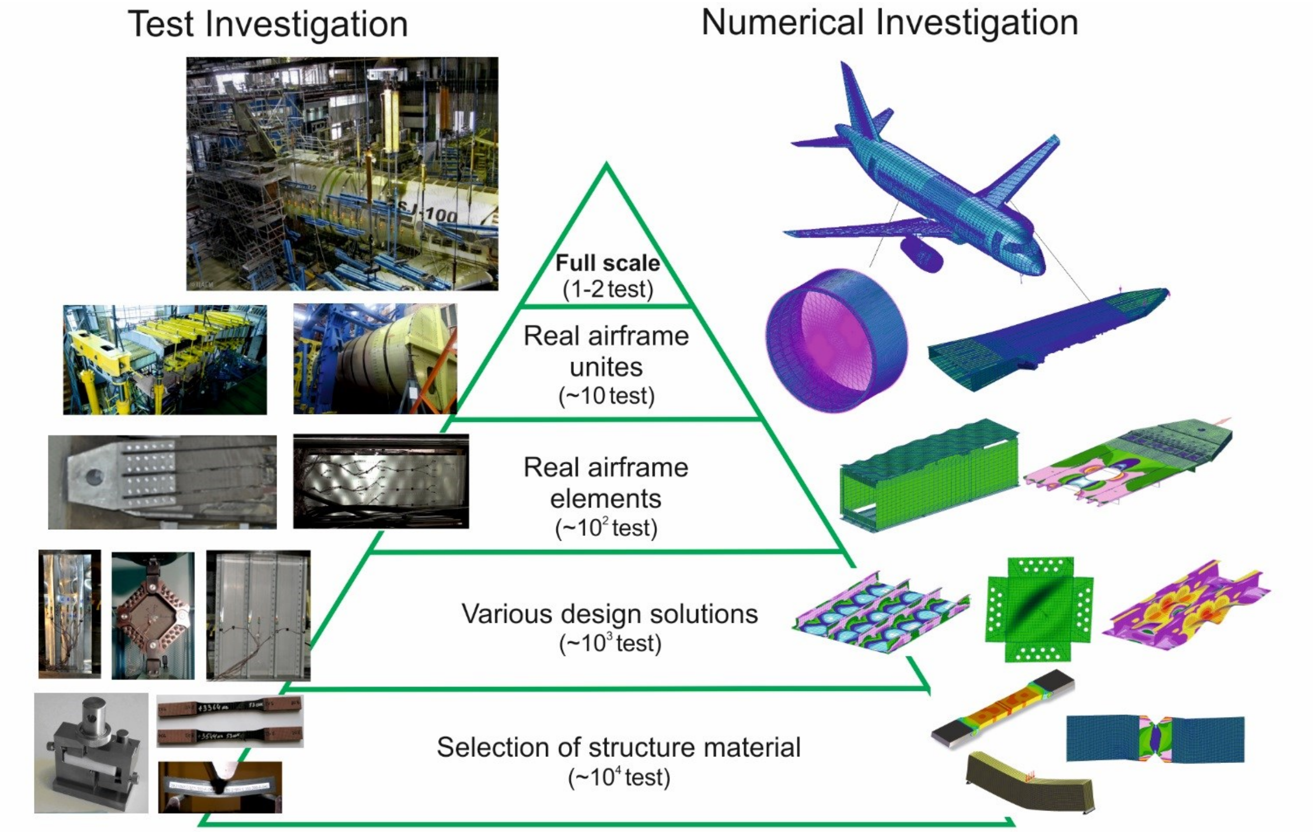

Figure 1 – Pyramid of tests in the design process of an aircraft.

The algorithm containing a set of computational and experimental procedures is used at each stage, as shown in Figure 2 [14]. The results obtained at the previous level supplemented with the performance requirements provide the initial data to make calculations and tests at the next stage [15,16]. If an analytical result is not acceptable, we improve the structural design, and (or) modify the calculation until the outcome is favorable. As soon as the desired analytical result is achieved, we proceed to the tests. If the experimental results do not meet the expectations predicted by the analysis, we may repeat the tests if faults occurred, or improve the design and (or) analytical models. In addition, we can repeat the tests or calculations of the previous stage for verification. The corresponding actions are performed until the test results confirm the analytical forecast. When this is achieved, the test program moves to the next level of complexity.

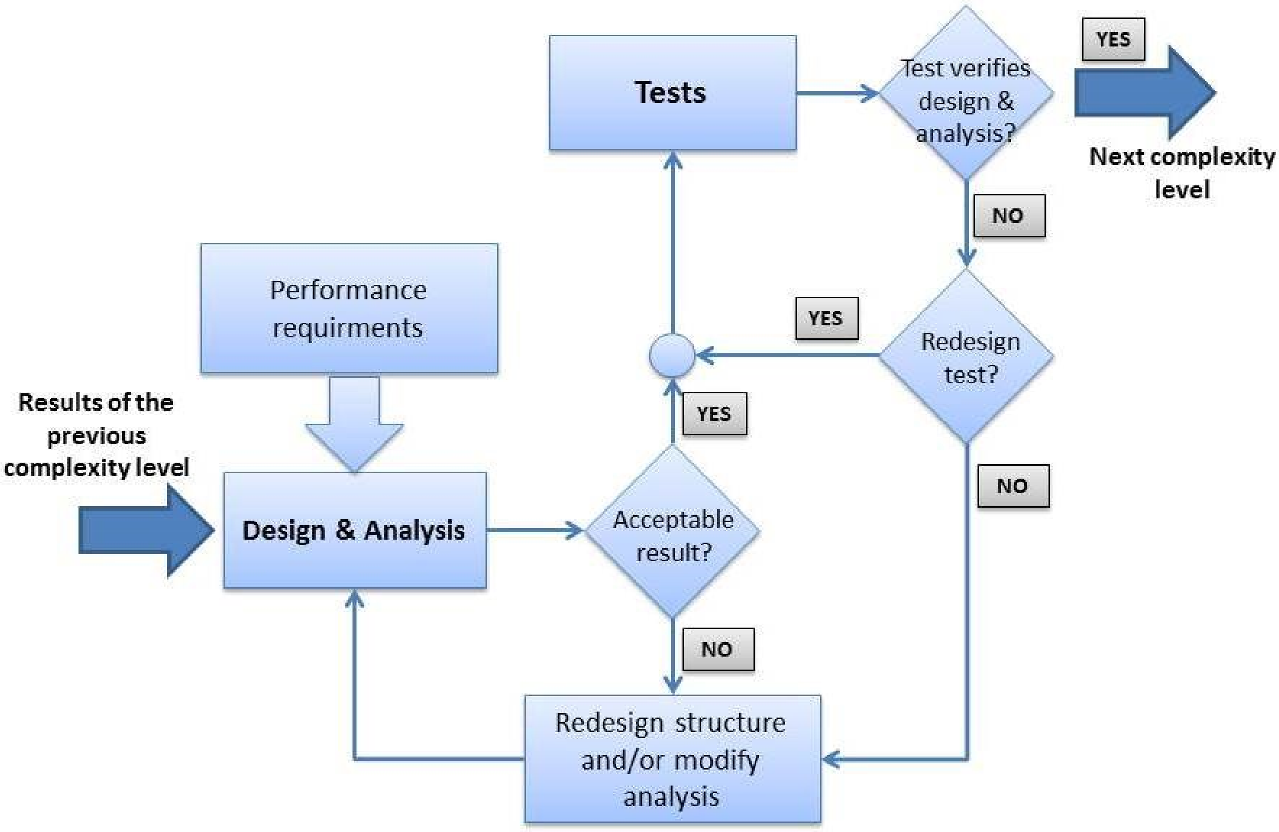

Figure 2 – The algorithm of the ‘Building Block’ approach at one structural design level.

3. The creation of specialized software ‘TensoVis’

3.1 Some technical features of the software implementation

For practical implementation of the concepts of the ‘Building Block’ approach, a specialized software for visualization and analysis of strain gauge data during static strength tests ‘TensoVis’ was created in the course of this work. Software development was conducted in the C++ programming language using object-oriented programming approaches. The software architecture and algorithms were designed based on the requirements for maximizing the performance of the end application.

As the character of the main tasks associated with the visualization and representation of a vast amount of information, we paid close attention to the design of the graphical user interface.

In our case, we may define the graphical user interface as the external shell of the program, consisting of a set of indicators, windows, buttons, and other components that provide interactive interaction between the user and the computer program. Many works are devoted to the theory of interface development (see, for example, [17,18]). By itself, the design of a functional, well-thought-out interface implies meeting a large number of requirements. For our purposes, it is advisable to take into account the most basic of them:

- **Intuitiveness.** The functionality of the final program should be familiar and intuitive for the new user, contain standard methods and approaches to data visualization and interaction with the operator. Thus, the learning time for the new interface will be minimal, speeding up the training process for specialists who work with the system.
- **Easy to use or ergonomic.** The concept of ergonomics borders on the concept of intuitiveness. The performance of basic and simple actions should be quick, easy, and convenient. The most common operations should be easily accessible for their use. Working with ergonomic interfaces leads to reducing the time to complete a specific action and the entire task.
- **Focus on the end-user and specific tasks.** Under this term, we will understand the

optimization of the human interaction process with a computer program to solve the tasks set. That also includes minimizing data interpretation errors which user makes due to an inconvenient and crude interface.

- **Unification.** In terms of creating user interfaces, unification implies that any actions and objects that look the same should be executed in the same way. When working with the program, a user will encounter a large flow of the same type of information related to the readings of strain gauges. It is necessary to ensure a unified display of all this data.

Among other things, the GOMS model (The model of goals, objects, methods, and selection rules) developed by Card, Moran, and Newell [19] is an effective approach for various quantitative assessments of user interface performance. It is based on a set of time intervals required to perform separate operations. Although the time to complete the same action can significantly vary for different users, this model is helpful for comparative analysis and general quantitative estimates when developing user interfaces. The time intervals of the GOMS model are:

- K = 0.2 s – time required to press the key;
- P = 1.1 s – the time it takes for the user to point to a particular position on the monitor screen;
- H = 0.4 s – the time it takes to move the hand from the keyboard to the mouse (or from the mouse to the keyboard);
- M = 1.35 s – mental preparation, the time it takes for the user to prepare mentally for the next step;
- R – the waiting time for the computer response (depends on the current task in progress).

3.2 Basic functionality and key features of the software

The basic concepts described above, together with the quantitative estimates to analyze the effectiveness of the user interface, formed the basis for the design and creation of software for visualization and analysis of strain gauge data 'TensoVis'. The developed software provides the solution of essential tasks, such as:

- organizing a large volume of strain gauge data in a convenient and visual form;
- grouping of strain gauge data on the specimen schemes, sorting by values;
- color marking of sensors using a gradient transition from light green to bright red, depending on the current value;
- plotting the stress/strain-load relationships for any selected sensor;
- comparison of the calculated model with the experimental data directly during the test.
- the ability to predict the location of structural failure.

Figure 3 shows the interface of the developed software.

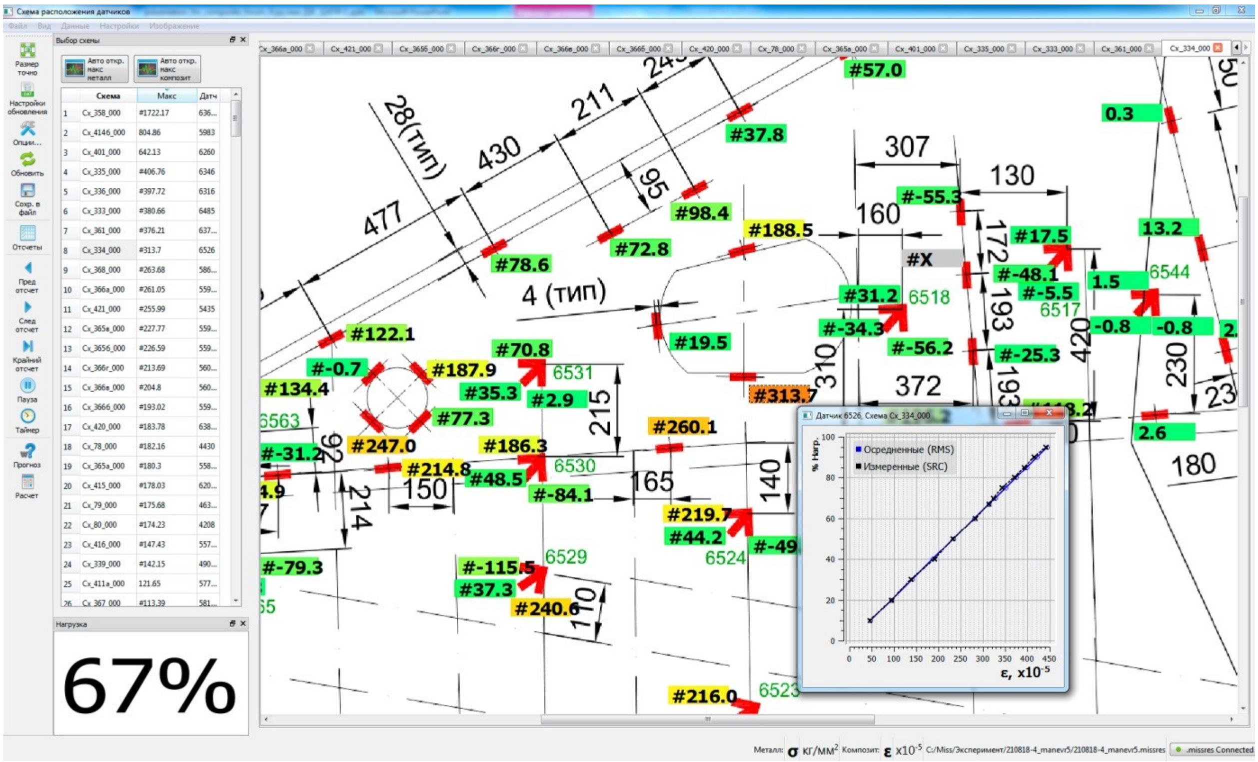

Figure 3 – Graphical user interface of specialized software ‘TensoVis’.

The software provides processing, analysis, and visualization of sensor readings stored in the database of the MCC for testing. One of the main concepts of the ‘TensoVis’ is to display strain gauge data on specimen schemes, which are prepared for each specific item and transformed into a graphical format. As a rule, the preparation of such electronic drawings is a part of the workflow when installing strain gauges on the specimen.

When working with the ‘TensoVis’ software, it is possible to select the desired specimen area and observe the strain gauge data during the tests in real-time. Depending on the settings, the values of the strain or stress of the structure are displayed. The location of the sensors in the diagrams corresponds to their actual place on the test item. That ensures the visibility of the output information and grouping by the position of the sensors on the product. In addition, strain gages are marked with a color depending on their current value: light green for relatively small values, bright red for large values.

The software functionality allows displaying the stress (or strains) dependences on the applied load for the gages of interest. Also, using the embedded extrapolation algorithms, the predicted stress values for the ultimate load can be calculated. The software provides its visualization. Such a forecast can be fulfilled at any of the intermediate loading stages to estimate the stress strain-state of the structure for the higher load levels.

An essential feature of ‘TensoVis’ software is its ability to compare the analytical model with the experimental data directly during the tests. In a virtual experiment, the strain values are calculated at the places of strain gages allocation. ‘TensoVis’ uses these data for visualization and comparison with real experimental data. The error between the calculated and measured values is also defined.

The areas of the structure with the maximum values of stresses (strains), and the areas of the large discrepancy between experimental and calculated data, are of the most interest during testing. Identification of such zones is performed in semi-automatic mode using the ‘TensoVis’ software. As an additional option, we may set critical values for strains. Then the program issues a warning when reaching it, displaying the target sensor and its location on the product. To sum up, critical areas of the structure are monitored continuously during loading using the functionality of the developed software: current and predicted stress values are analyzed, stress-load graphs for sensors with the highest values are monitored, warnings about exceeding pre-set critical values are processed.

4. Integration of the developed software into the MCC for strength tests

Software initial approbation was carried out in tests of individual aircraft units on isolated stands. In such tests, the number of strain gages installed on the product was several dozen pieces, and the applied loads were far from critical. That made it possible to debug the main functionality of the software, integrate it into the measuring and computing complex in the static strength laboratory of TsAGI [20]. Afterward, the performance and efficiency of the 'TensoVis' were confirmed in full-scale aircraft tests with relatively small loads applied to the structure. The number of strain gages installed on the tested structure reached several thousand pieces. The final stage of validation, during which the developed software has fully demonstrated its effectiveness, was the passenger aircraft testing for a complex loading case simulating a maneuver with maximum vertical overload. This case was the most complicated and also responsible in terms of the applied loads close to critical. The number of strain gages controlling the stress-strain state of the structure was about 10,000 pieces.

Further, the paper describes the process of testing for the mentioned loading case using the 'Building Block' approach, demonstrates the effective use of the developed software during testing, and shows its advantages.

4.1 Passenger aircraft testing. Virtual modeling

The test object was a full-scale specimen of an aircraft with layered PCMs in the load-bearing structure. One of the most complicated and 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 feature of testing was a large number of installed strain gauges. So it was significant to show the functionality of the 'TensoVis' software and its high performance when processing a large amount of data.

For the static tests support a computational model was created, which included a detachable wing, center section, central fuselage, and several other elements. Figure 3 shows the general view of the model.

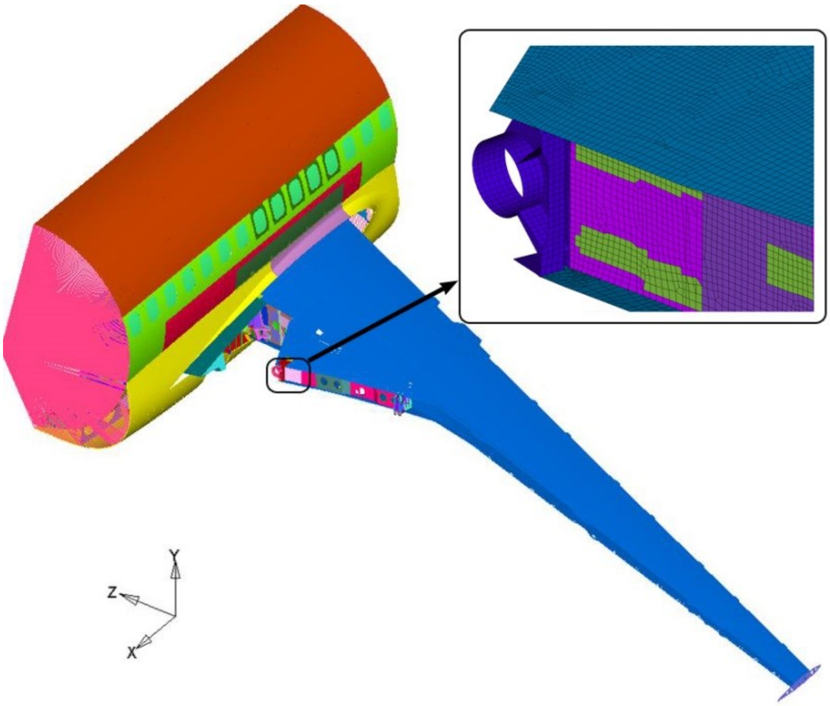

Figure 3 – View of the finite element model.

The goal of computation is to predict the stress-strain state of the structure for the specified loading case taking into account nonlinear behavior. Results analysis identifies the most critical areas. In the case under consideration, the computation showed that: residual strains and buckling takes plays in local areas. In these critical areas, additional strain gauges were installed. That made it possible to obtain more detailed results for monitoring these zones and further analysis.

4.2 Full-scale tests of passenger aircraft

The aircraft was loaded incrementally up to the ultimate load [21] with continuous monitoring and analysis of the structural stress-strain state. Figure 4 shows a schematic diagram of the loading process with the use of 'TensoVis' software. This process includes several stages.

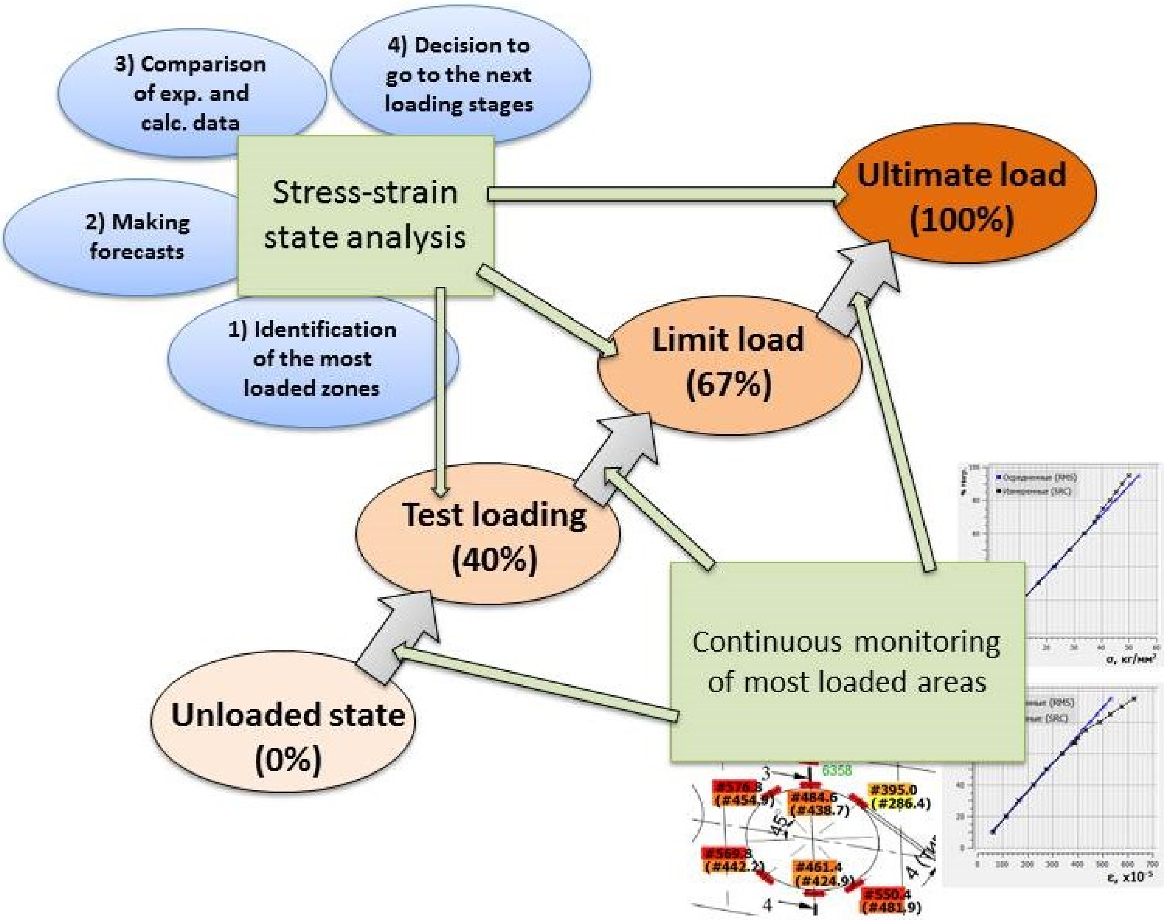

Figure 4 – The process of static strength testing with the use of 'TensoVis' software.

1) Test loading.

In this stage, we check the correct functioning of the loading systems and measuring equipment and perform a preliminary SSS analysis of the specimen.

2) Loading up to the limit load.

Upon loading to the limit load, we analyze strain measurement data, identify the most critical zones of the structure, compare the calculated and experimental data, and make predictions for the critical load. Based on the results, we decide to proceed or not to the next stage of loading.

3) Loading up to the ultimate load.

Upon completion of loading up to 100% of ultimate load, we analyze the test results, carry out visual inspection of the specimen, identify zones of buckling and destruction, and process the data obtained, validating the calculation models.

The SSS of the structure was monitored by installed strain gauges, placed over the entire aircraft with the increasing number and density in the critical zones determined in numerical analysis. The total number of strain gages was about 10,000 pieces. SSS analysis and monitoring were carried out with the use of 'TensoVis' software.

The full-scale static test resulted in local buckling and small residual strains of individual structural elements. These results were predicted in a computational model and correlate well with experimental data. In some areas of the structure, discrepancies between the strain gauge readings and the calculation data were about 10%. The most differences appeared in places 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 model showed good agreement between the calculated and experimental data. We carried out the SSS analysis at the limit level and conducted a forecast for the ultimate level in the course of loading. That helped to make the right decision to continue testing up to the ultimate load, thus, maintaining the overall integrity of the construction for subsequent stages of testing.

5. Results and conclusions

The paper presents some aspects of the ‘Building Block’ approach to static testing of metal-composite aircraft structures. To develop and integrate the concepts of this approach into the MCC for testing at TsAGI, specialized software for visualization and analysis of strain gauge data during static strength tests ‘TensoVis’ was created. This software has passed the procedure of state registration of the computer program.

Debugging of the ‘TensoVis’ software was performed during testing individual aircraft units on relatively simple loading cases with a small number of installed strain gauges. Complete efficiency was demonstrated during the complex loading of the full-scale passenger aircraft, where the number of force points was about 100, and the installed strain gages about 10,000. The developed software showed its performance, sufficient for processing and analyzing such a significant amount of data in real-time. During the loading, the calculated model was compared with the experimental data, which allowed integrating the ‘Building Block’ approach concepts into MCC at TsAGI.

The paper provides a methodology of conducting tests using the developed software, which allowed:

- perform real-time monitoring and analysis of calculated and experimental data during testing;
- reduce the time required to prepare and process the experiment data;
- minimize the risk of making mistakes related to the human factor;
- ensure reliable preservation of the original structure from unintended destruction.

The integration of 'TensoVis' software into the measuring and computing complex for testing allowed to achieve a new scientific and technical level of strength testing in TsAGI laboratories.

6. Contact Author Email Address

Mailto: dmitriy.kurulyuk@tsagi.ru

7. Copyright Statement

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