# Review of Aeronautical Fatigue Investigations

# in Russian Federation

# 2017-2019

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Moscow, Russia

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CONTENT

## 1. Introduction

This paper presents the overview of scientific and engineering research activities related with fatigue and structural integrity issues in aviation industry of Russian Federation. It gives some understanding of the key problems in this field, and outlines some results of experimental and computational studies on fatigue and damage tolerance of airplane structures that had been carried out during 2017-2019 period.

The aeronautical investigations highlighted in the review are devoted to the problems of the failure regularities of structures and their components (for both metal and composite materials cases); experimental studies on specimens tested in accordance with test standards; the full-scale structural tests and tests of subcomponents;

Included in review are some test approaches that had been formulated to provide the equivalent programs for metal-composite structures loading under full-scale test on fatigue and damage tolerance with further recommendations on service-life tests.

Basing on the set of the results of experimental studies the methodological approaches had been developed for evaluation and analysis of design values of structural fatigue characteristics and characteristics of fracture of the given type of the structure.

It also includes the approach ad methods to provide the safe operation of Russian airplanes structures with high-time service lives (aging airplanes).

This review does not cover all the activities of Russian research organizations, universities and institutes on the topic of aeronautical fatigue and is based on the information contributed by organizations and individuals.

This review contains the information permitted for public release or taken from open sources with no limitations for publication or presentation while ICAF 2019 Symposium and Conference.

# 2. Aviation regulations

## 2.1. New version of AR, part 21

In order to renew the version of AP 21 regulations, as well as to take into account the proposals and notes by aircraft developers, the Scientific - Expert Council of the Aviation Board of Government of the Russian Federation continue the work on draft of the Federal Aviation Regulations of RF regarding certification of aviation equipment, development organizations and manufacturers. Part 21.

Some changes will be related with requirements to Certification centers, their accreditation the authorized body and testing laboratories (centers), as well as working bodies participating in the certification of a specific type of AT. More attention will be payed for the role of the designated Certification Centers and the Independent Inspectorate in the Applicant's organization related to certification tests, qualification tests etc.

## 2.2. Recommendations on compliance with Aviation Rules of Russian Federation, part AP-25.571

Gvozdev S.A.[1], Glagovsky A.A., Dubinsky V.S., Dubinsky S.V., Feygenbaum Yu.M.[2], Konovalov V.V.[1], Nesterenko G.I.[1], Pankov A.V.[1], Sadikov D.A., Strizhius V..E.,[3], E. S Metelkin.[2], Ordyntsev V.M.[1], Zhelonkin S.V.[1]
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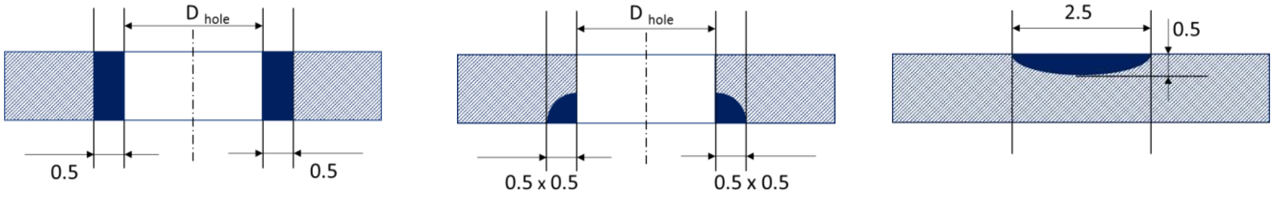
The computational-experimental studies of fatigue of aircraft structures cited in recent years were carried out in order to fulfil the requirements set out in the RC-AP-25.571-1A advisory circular "Assessment of damage tolerance and fatigue strength of a structure".

This circular was developed by the above-mentioned specialists of TsAGI, GosNII GA and design companies in 2015. The circular contains recommendations for ensuring the safety of long-term operation of the aircraft during the development of its design at the design stages, the testing of elements, parts and full-scale design as a whole and during the maintenance of the aircraft's airworthiness during the entire period of its operation up to decommissioning.

The aircraft structure refers to the design of the airframe, engine mount, landing gear and mechanical elements of their cleaning-release, the mechanical elements of the control system and the configuration of the elements that provide mutual power docking of the parts of the airframe and units. The airframe structure is assumed to be made from both metal and composite materials.

The recommendations set out in the local circular RC-AR-25.571-1A are mainly harmonized with the recommendations outlined in the FAA advisory circular AC No: 25.571-1D. But there are a number of sufficient differences in these two advisory circulars.

In the local RF advisory circular it is recommended to use the principle of a gradual increase in the values of permissible operating practices (flights, flight hours, calendar life). Basic conclusions on the operation of the fleet and individual Conclusions on each side of the aircraft are issued at intervals of 4-5 years and 2 years, respectively. Local reference circular gives sizes of initial manufacturing defects for structures made of metallic materials:




Through cracks on both sides of the hole at thin sheets with a thickness of t ≤ 2 mm

Quarter-corner cracks on both sides of the hole at thick sheets, plates, plates

Surface crack at fillet transitions

Figure 2.1 Typical damages or initial manufacturing defects recommended for considerations while analysis

For structures made of metallic materials, the specified damage is shown in the figure below. The survivability of structures with regulated damages (duration of crack growth and residual strength) is checked at the end of a full-scale test of a full-scale aircraft. In the local Russian advisory circular AC-AP-25.571-1A, recommendations are also given on how to provide the safe operation of airplanes that have primary structure and \or load bearing elements made of polymer composite materials (RFPs). They include methodology basis for the formation of a multitask experimental studies of composite structures; the main additional requirements for the method of conducting fatigue (service life) tests of structures made of composites; categorization of composite structure damages.

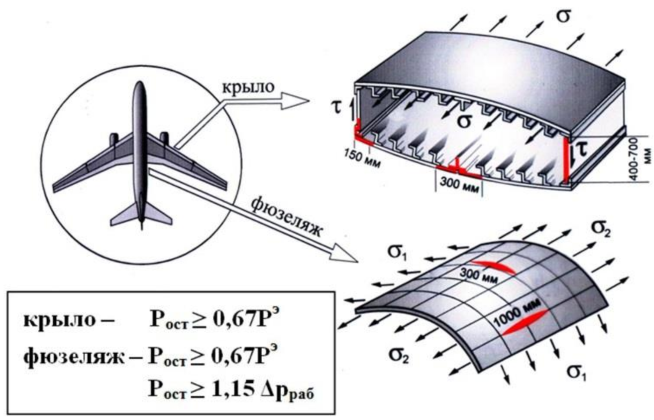



Figure 2.2 Airframe regulated damages

# 3. Aluminium alloy and streel fatigue research

## 3.1. Comparison of fatigue and crack resistance characteristics of contemporary aluminium alloys

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Aviation aluminum alloys currently remain the main structural material of transport aircraft. To ensure high weight efficiency in combination with a large service goal and high characteristics of damage tolerance of aircraft structures, aluminium alloys should have the following set of necessary characteristics: high resistance to variable loads, low development rate of fatigue cracks, required residual strength, good corrosion resistance.

The research was performed mainly as the experimental studies of fatigue and crack resistance of contemporary advanced aluminium alloys, developed in Russian Research Institute of Aeronautical Materials (VIAM) and at ALCOA (USA). Experimental studies were carried out in TsAGI. Characteristics of materials are determined by testing standard samples on electro-hydraulic machines. These materials are used in the structure of most operated airplanes.

Given below are some results on these studies.

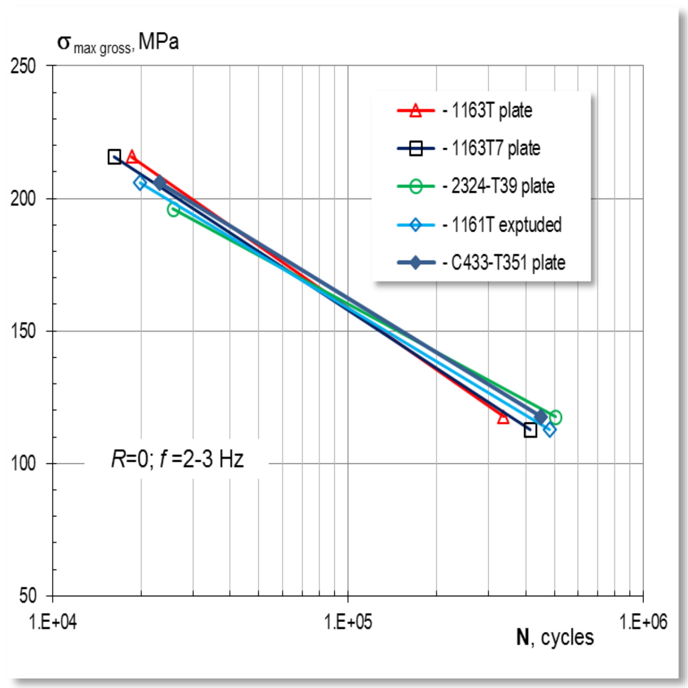


Figure 3.1.1 Fatigue curve of the wing lower surface material

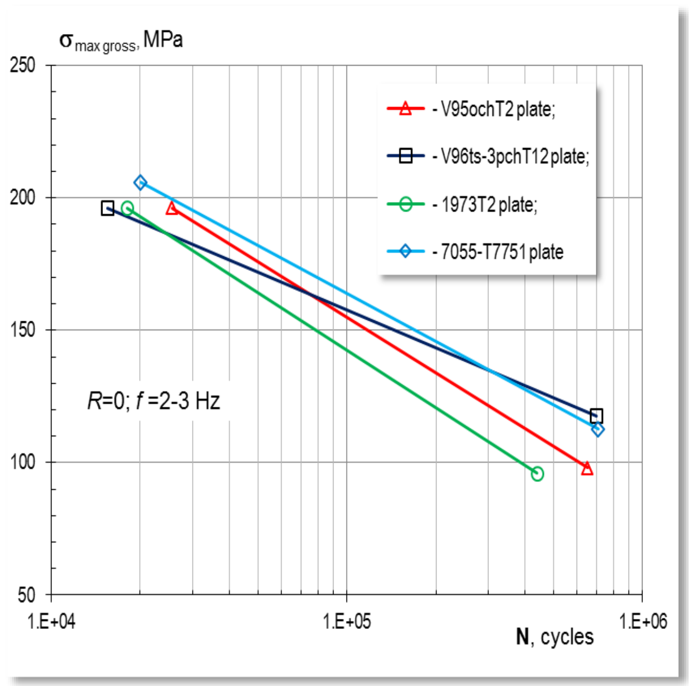


Figure 3.1.2 Fatigue curve of the wing upper surface material

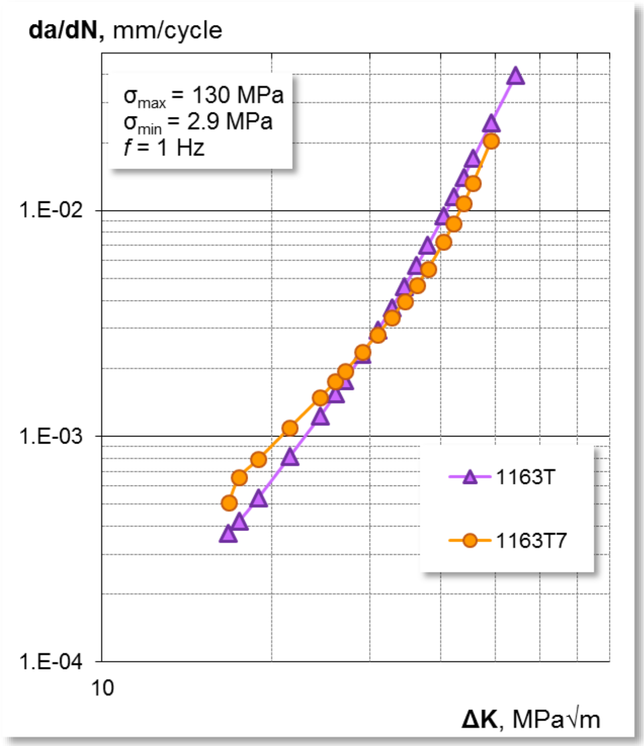


Figure 3.1.3 Crack growth curve of the wing lower surface material

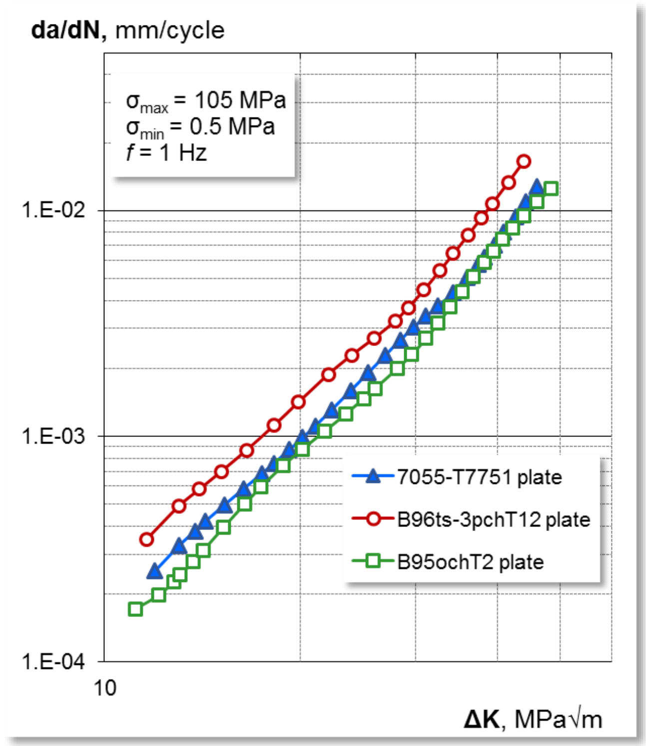


Figure 3.1.4 Crack growth curve of the wing upper surface material

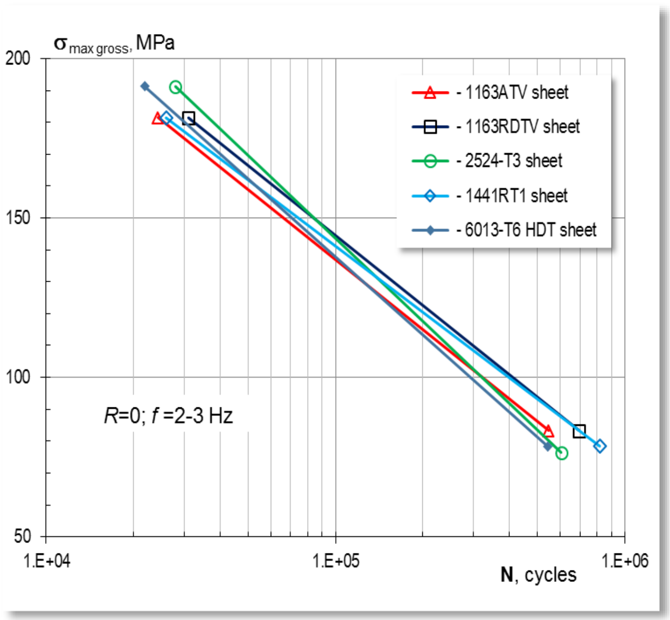


Figure 3.1.5 Fatigue curve of the fuselage skin material

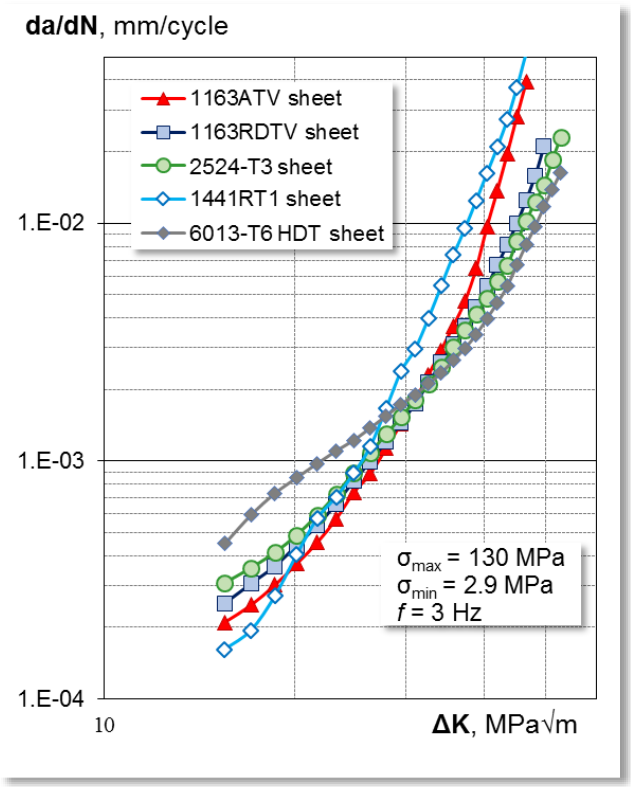


Figure 3.1.6 Crack growth curve of the fuselage skin material

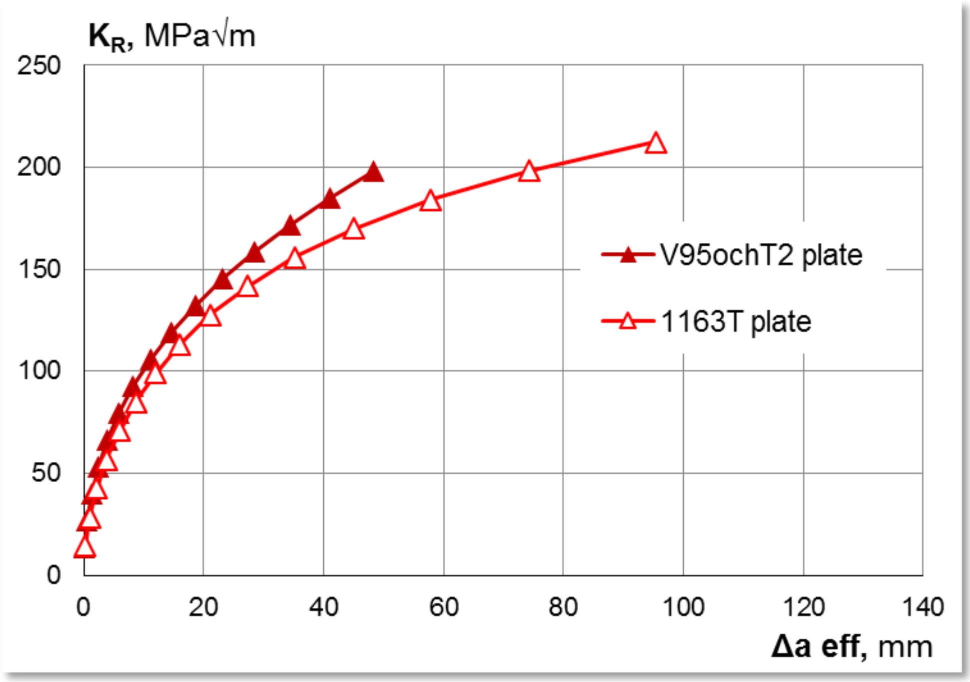


Figure 3.1.7 R-curves of the wing upper and lower surface material

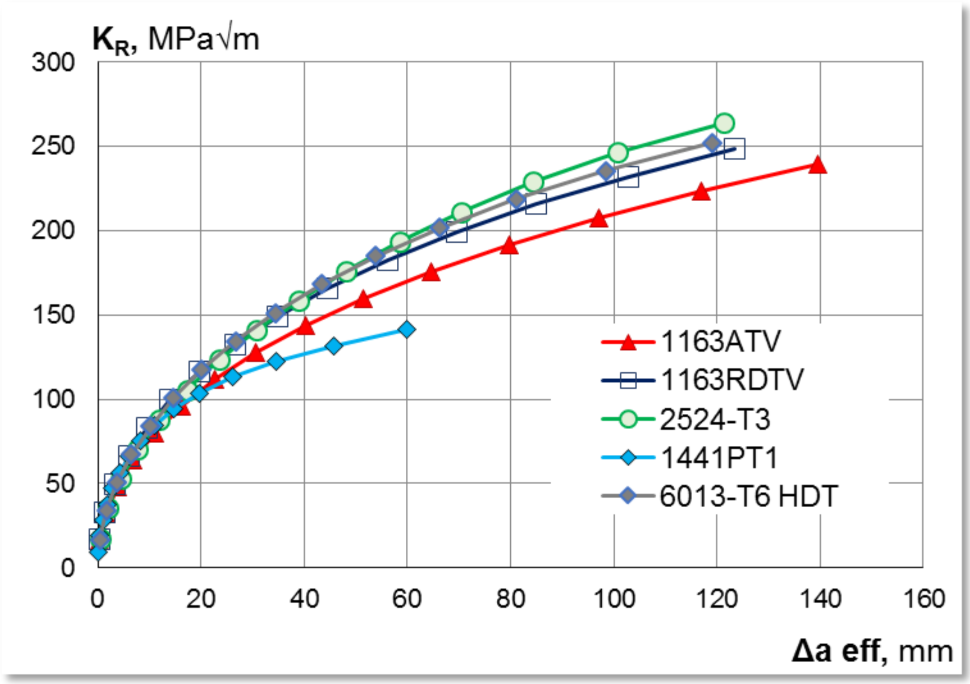


Figure 3.1.8 R-curves of the fuselage skin material

## 3.2. Multi-approach study of crack-tip mechanics on aluminium 2024 alloy

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This joint work presents a comprehensive study for characterizing the crack-tip mechanics and fatigue crack propagation in an aluminium 2024-T351 alloy. It combines information obtained from three different sources: fullfield displacement information from digital image correlation, analytical modelling of the crack-tip field and SEM fractographies. The displacement data measured around the crack-tip are fitted to a Williams' series development in order to evaluate singular and non-singular terms of the crack-tip field. The procedures also allows rigid body motion to be corrected and the crack-tip coordinates and crack orientation to be estimated. Fatigue striations from the fracture surface were analysed with SEM in order to estimate the crack growth rate for different boundary conditions. Representation of all the results together with the Paris law data of the alloy allows the procedures to be cross-validated and to fit with a good agreement micro-scale measurements with continuum mechanics estimations.

Compact Tension specimens were used in this work. Samples were made of Al 2024 T351 material (Young's modulus, E=73.4 GPa, Poisson's ratio, υ=0.33, yield strength σy=325 MPa). The geometrical parameters are as follow: W=50 mm, B=12mm . All samples were fatigue pre-cracked. The pre-cracking was implemented by applying ΔKI of 10 MPa√m and load ratio of 0.1. The crack length was monitored with the help of alternating current drop potential system . The crack length was taken as the maximum running ACPD value at a rate of 200 data/cycle over 20 cycles. Once the three experiments were fatigue pre-cracked, the crack was grown by applying a constant load (i.e. increasing ΔKI). The resulting crack lengths were 25.5, 34.9 and 37.6mm for specimens S1, S2 and S3, respectively. An 8-bit black and white camera with 5 mega-pixels was used to record the data with a close-up lens with a working distance of approximately 93 mm. The area of interest was illuminated with fibre optic ring light attached to the lens. Different crack lengths (a) and different loads (F) were studied in this work. Figure 3.2.1 shows the displacement fields measured by DIC (uexp and vexp) for a specimen with crack length a=25.5mm subjected to a 4.95 kN load.

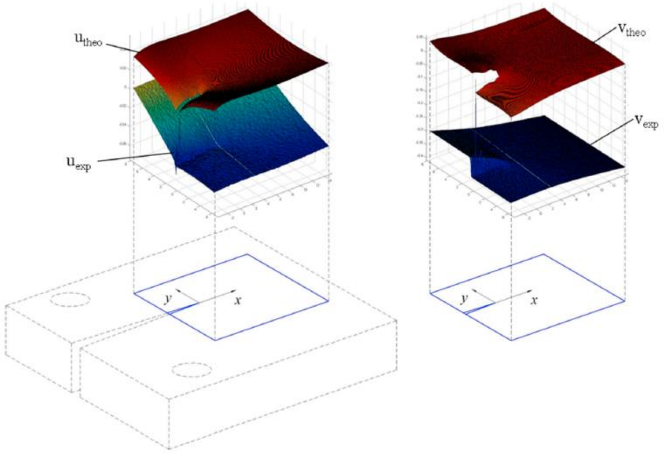

Table 3.2.1 shows the results of calculations of the state parameters for the three specimens. In addition, biaxiality parameter, b and the ratio a/W are included in the table for assessment of T-stress depending on specimen geometry . Similar to previous works, the biaxiality parameter increases in magnitude as the a/W ratio is increased . The differences observed with the literature data might be due to experimental error. This suggests a larger sensitivity to experimental error of T-stress compared to the SIF.

Table 3.2.1

Comparison of the results of the crack-tip location.

| Specimen | S1 | | S2 | | S3 | |
|---|---|---|---|---|---|---|
| | Optical | Algorithm | Optical | Algorithm | Optical | Algorithm |
| $X_0$ [mm] | 1.70 | 1.7178 | −2.66 | −2.5832 | −2.07 | −2.0542 |
| $X_0$ difference [mm] | −0.0178 | | −0.0768 | | 0.0158 | |
| $Y_0$ [mm] | 0.21 | 0.17944 | 0.27 | 0.30981 | 0.12 | 0.18547 |
| $Y_0$ difference [mm] | 0.03056 | | −0.03981 | | −0.06547 | |
| Total difference [mm] | 1.17 | | 0.51 | | 1.59 | |

Comparison of the results of the SIF computation.

| Specimen | S1 | | S2 | | S3 | |
|---|---|---|---|---|---|---|
| | ASTM | Algorithm | ASTM | Algorithm | ASTM | Algorithm |
| $K_I$ [MPa√m] | 18.38 | 19.55 | 10.01 | 10.52 | 9.80 | 11.39 |
| Error in $K_I$ [%] | −6.36 | | −4.85 | | −16.22 | |

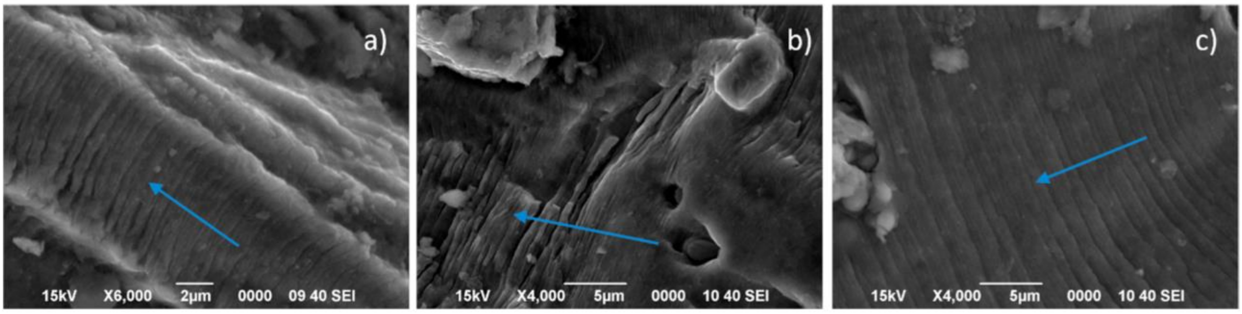


Figure 3.2.1 SEM fractographs of samples (a) S1, (b) S2 and (c) S3. The blue arrow indicates the direction of crack growth.

The average striation spacing for samples S1, S2 and S3 was 0.43, 0.55 and 1.19 µm, respectively. Assuming the main mechanism for crack propagation to be crack-tip blunting and re-sharpening, it is possible to infer the propagation rate based on the striation spacing. In order to use the fracture surface observations as a benchmark for the estimated SIF, the nominal SIF was computed for the crack lengths where the striations were found. These are plotted together with some Paris law data available in the literature for the same alloy and load ratio . Figure 3.2.2 shows the results of the estimated SIF described in the previous sections (green squares). It is observed that all the propagation rate estimations agree well with the literature. A slight offset is observed in the SEM data, probably due to the scattering often observed in striation spacing. Such scattering is often caused by the changing orientation of the striation alignment. Nevertheless, the overall good agreement between the estimated SIF values, the SEM measurements and the data from the literature is useful as a validation. The very small scattering in the data suggests that a combination of SEM fractography and DIC analysis could be used to estimate Paris law data for other alloys. Such estimation would be feasible for cases where striations are created during the propagation. Nevertheless, further analysis would be required to verify the validity of this approach through a larger ΔK range.

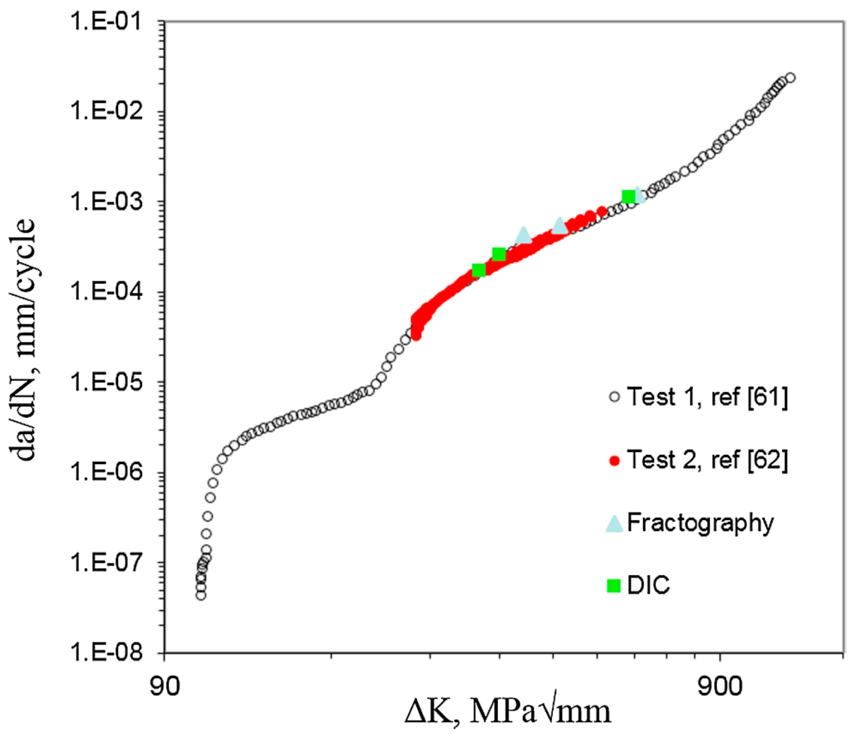


Figure 3.2.2 Crack propagation data from different sources plotted together with data obtained the SEM fractographies and the DIC estimations of the SIF.

As a conclusion to the work it could be stated that a new algorithm for mathematical processing of the experimental displacement fields was obtained by DIC. The method allows automatic evaluation of the crack-tip position and the crack orientation through a set of geometrical parameters. The new method has a great potential for application on full scale objects because the methodology accounts for the shifting and rotation of the region of interest studied. The displacement field measured by DIC was used to extract singular and non-singular terms of crack-tip field, the crack-tip coordinates and the crack orientation. The efficacy of the approach has been demonstrated on real fatigue crack and therefore makes the approach particularly useful for fatigue crack growth studies. The methodology allows automatic tracking of a fatigue crack with simultaneous determination of the fracture mechanics parameters without additional corrections from standard DIC surface observations. Comparison between the different approaches has allowed validation of the mathematical tool and also micro-scale observations (SEM) to be matched with continuum mechanics analysis at the crack-tip.

### 3.3. Influence of the biaxial loading regimes on fatigue life of 2024 aluminum alloy and 40crmnmo steel

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The work studies the fatigue life of metallic materials under various schemes of multiaxial non-proportional loading which lead to the occurrence of a complex stress-strain state. We present the results of the experimental study of the fatigue life of 40CrMnMo structural alloyed steel and 2024 aluminum alloy under biaxial cyclic loading. Cyclic tests were carried out on the Instron ElectroPuls E10000 biaxial electrodynamic test system under joint tension-compression and torsion of solid cylindrical corset-type samples. The methodological issues of conducting cyclic tests with a mixed modes loading are considered and the corresponding new experimental results are obtained. The experimental data were presented in the form of points on the graphs and corresponding approximating lines which reflect the dependence of the number of cycles to failure on the relative values of the constant components of the tangential and normal stresses. In all the tests, the specified values of the additional parts of the stress components did not exceed the values of the corresponding conditional yield strengths, which were previously determined in the quasistatic tensile and torsion tests for each material. Based on the test results, the influence of the constant component of tangential stresses on the fatigue life of the materials under cyclic tension-compression was evaluated, and the effect of the constant component of normal stresses on the fatigue life under cyclic torsion was considered. It is shown that because of the constant stress components, both under cyclic tension-compression and cyclic torsion, there is a decrease in the number of cycles before the specimens break. The obtained data demonstrate the necessity to estimate the allowable limits of the constant parts of the stress components, which will not lead to a significant reduction in the fatigue life of structures operating under cyclic loading conditions.

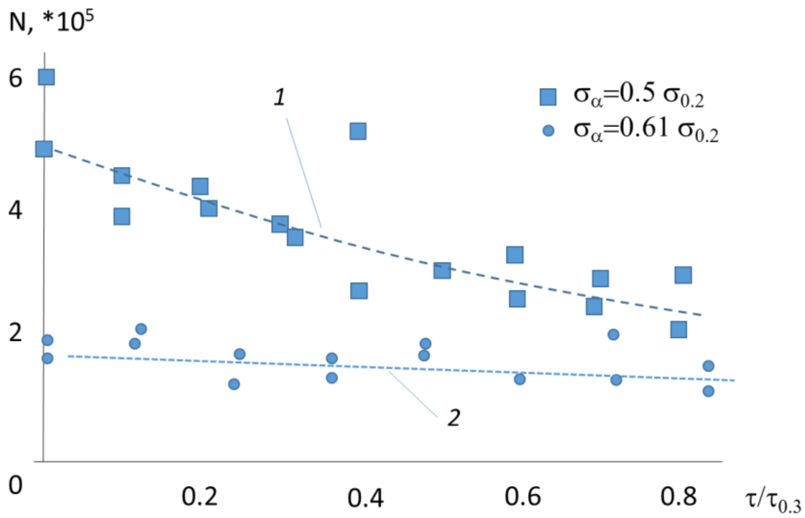


Figure 3.3.1 Dependence of fatigue life of 2024 alloy ta cyclic tension with amplitudes $\sigma a = 0.5\sigma_{0,2}$ (1) and $\sigma_a = 0.61\sigma_{0,2}$ (2) versus constant component of shear stresses

### 3.4. Mechanical behavior of x15crni12-2 structural steel under biaxial low-cycle fatigue at normal and elevated temperatures

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The results of the experimental studies of the low-cycle fatigue characteristics of heat-resistant structural X15CrNi12-2 steel for aircraft purposes (chemistry: C – 0.13%; Cr – 12.5%; Si – 0.05%; Ni – 2.05%; Mo – 1.50%, W – 0.70%; Nb – 0.20%; V – 0.20%) under biaxial cyclic loading are presented. For cyclic tests a specialized Instron 8850 two-axes testing system was used which allows the planning of cyclic and static tests with an arbitrary stress sequence under the conditions of tension and torsion. The Epsilon 3550-010M dual-axis dynamic strain sensors for testing at normal temperatures and the Epsilon 3550HT-025M for testing at high temperatures were used to determine the values of axial and shear strains during the experiments. The test methods for biaxial cyclic loading under normal and elevated temperatures are described which allows to analyze the mechanical behavior and structural steel destruction processes under plane stress conditions. The tests results of X15CrNi12-2 heat-resistant alloy under low-cycle fatigue at different temperatures and cyclic strain paths with proportional and non-proportional changes in axial and shear deformations are presented. For different types of tests hysteresis loops are rep-resented in the form of dependences of normal and shear stresses on axial and shear defor-mations, respectively. It is shown that the durability of X15CrNi12-2 steel in these parameters significantly depends on the cyclic strain path, the shape of the cycle and the test temperature. In the case of non-proportional deformation, the fatigue life of X15CrNi12-2 steel decreases 1.5-2 times as compared with the proportional loading at different test temperatures. Depending on the strain path, a significant decrease in fatigue life at a temperature of 600 ° C by 17-44% in comparison with the room temperature was observed.

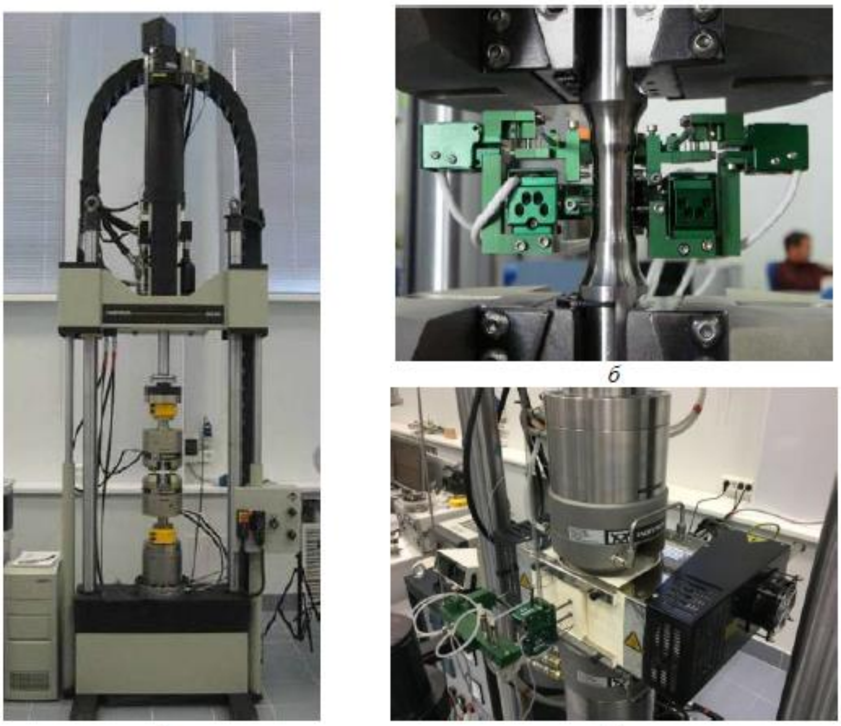



Figure 3.4.1 Servohydraulic test system Instron 8850 (a). Dual-axis strain sensors installed on the sample for testing at normal (b) and high temperatures (c)


Figure 3.4.2 Samples with attached thermal couples (a) and heat insulation laid down on the upper surface of the high-temperature furnace (b)

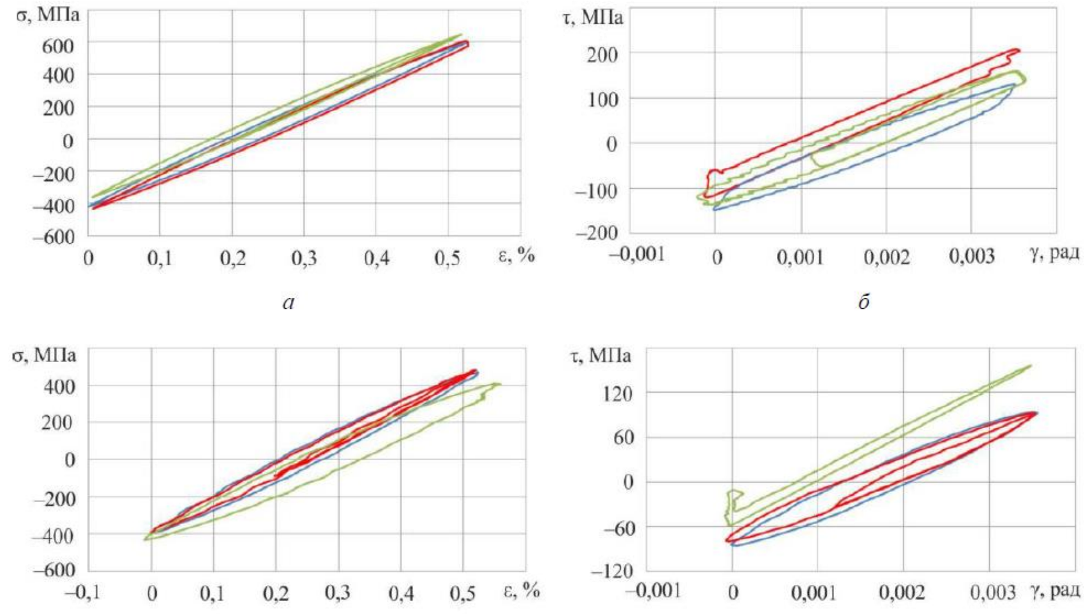
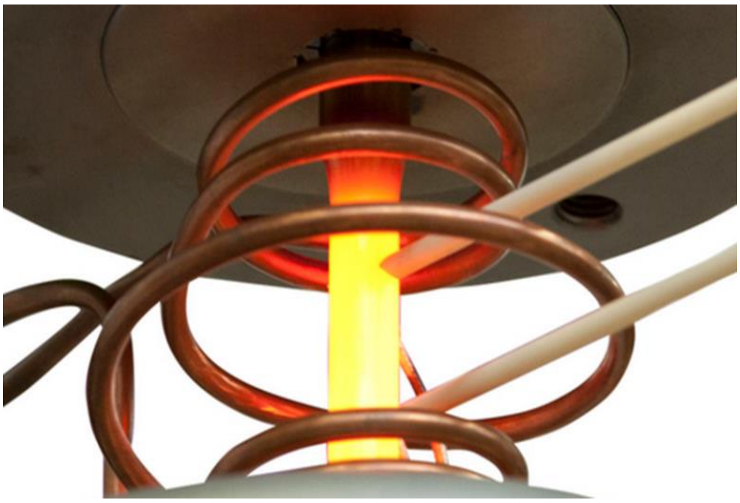



Figure 3.4.3 Characteristic hysteresis loops of low-cycle fatigue at room (a and b) and high temperatures (c and d) and three different cyclic deformation diagrams (blue – simple loading with a triangular cycle mode, red is simple loading with M- the figurative cycle mode, green color – complex loading)

The work is a part of research performed in related work with aviation engine manufacturer “UEC- Aviadvigatel”, aimed for experimental studies of thermomechanical fatigue structural steels at increased heating and cooling rate. That includes investigation of the resistance characteristics of low-cycle thermomechanical fatigue of structural steels and alloys under conditions of cyclic heating to 1000 ° C in air at heating rates and cooling the samples to 25 ° C/s and testing at different phases and laws of stress, axial deformations and temperatures.



## 4. Studies of fatigue behavior of reinforced polymer composite materials (FRPs)

In recent years, reinforced polymer composite materials (FRPs) had been widely and intensively introduced in aircraft structures produced in Russian Federation. Key application of advanced composites are related with MC-21 program, where the airframe and load bearing structures of MS-21-300 airplane are made of so called “power composite”.  In this regard, numerous studies on composite material behaviour and composite structure performance were conducted by Irkut Company jointly with TsAGI and other research and industrial partners. TsAGI conducted extensive research on the patterns of FRP destruction.

For example, in 2017, about 800 elementary samples and 60 structurally similar samples were tested for fatigue. Based on the results of such tests, certain regularities of FRPs destruction were established. Below are some of the results of the research.

Figure 4.1 Full scale composite structures under experimental studies at TsAGI on structural integrity

## 4.1. Influence of irregular loading parameters on durability of composite polymer specimens having typical stress concentrators

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Currently, this work is limited to the studies of the fatigue and durability of the most common type of stress concentrator, namely an open hole at regular (constant) and irregular (random , quasi random) loading.

Using the results of additional experimental research, verification of the developed model for assessing durability under irregular fatigue loading was carried out. The model is based on the use of fatigue curves for several loading asymmetries corresponding to different failure modes, a modified Oding formula for reducing asymmetric cycles and a hypothesis of linear summation of damage. In addition, the effect of the key parameters used in the formation of the loading spectrum for the field test programs on the fatigue characteristics was evaluated.

In this work, at the first stage of research, the nonlinearity of the summation of durability under irregular loading was revealed, which is expressed by a significant difference in the sum of fatigue damage from 1. This is due to the fatigue behaviour of existing FRPs, which is a high value of the fatigue curve (fatigue) index. In this case, the significant contribution to fatigue accumulation and durability is defined by rare cycles with maximum load level. The destruction of the investigated element at the loading spectrum that corresponds to the real one can be obtained only by increasing the maximum load values corresponding to the durability range from 10 cycles to several thousands, for which a linear approximation of the curve fatigue may not be applicable.

Therefore, to study the effect of such parameters as the sequence of loads, loads with small amplitudes, "air" loads, four special experimental research programs were formed.

As a result of the research conducted, a study of experimental durability and calculated durability was carried out in accordance with the developed calculation model, all necessary experimental data were obtained, including fatigue curves for regular loading with different asymmetry, a generalized fatigue curve was constructed and sums of fatigue damage were obtained for all experimentally obtained durability irregular loading. The amounts of fatigue damage of all four programs lie in the range of variation in the range from 0.8 to 1.1.

It was concluded that the use of the proposed calculation model, which uses the linear hypothesis of damage summation, makes it possible to obtain elements acceptable to justify the fatigue strength of FRPs, provided that they are calculated for loading levels at which the durability exceeds 50,000 cycles. The applicability or validity of the findings and method developed for the cases of other types of structural elements and elements with impact damage requires further experimental studies.

## 4.2. Correlations to estimate the fatigue durability of components of composite airframes

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The research is carried out in order to provide the fatigue calculation method for one of the most relevant in engineering practice design cases of quasi-random loading program by uniaxial tension-compression of the elements of the longitudinal set of a composite wing of a transport aircraft.

According to the results of the review of currently available open data on the fatigue strength of laminated composite materials at uniaxial tensile-compression cyclic loading, the author identified four of the most well-known today fatigue strength models of such elements:

- model of Trunin Yu.P. (TsAGI);
- model Kassapoglou;
- Sendetsky model;
- the model of Mendell

In order to find the equation that most accurately approximates the experimental data of layered FRPs, on the basis of experimental data published in foreign work, the author conducted a comparative analysis of the accuracy of approximation of experimental data using the fatigue curve equations in the 4 models listed above. Figure 4.1 shows examples of approximation for open hole specimens of carbon-fiber AS4-PW loaded by a symmetric cycle (R = -1).

According to the results of data analysis showed in Fig. 4.1 the author made the following main conclusion: the fatigue curve constructed using the Mendell model equation,

$$\sigma_{max} = a + b*lgN$$

shows the highest level of accuracy of approximation of the experimental data "σ-N" for the considered elements of the FRPs.

In view of this, the Mendell equation can be considered the most suitable for further use in the design estimates of the fatigue life of layered FRPs operating under conditions of regular uniaxial cyclic loading by tension-compression.

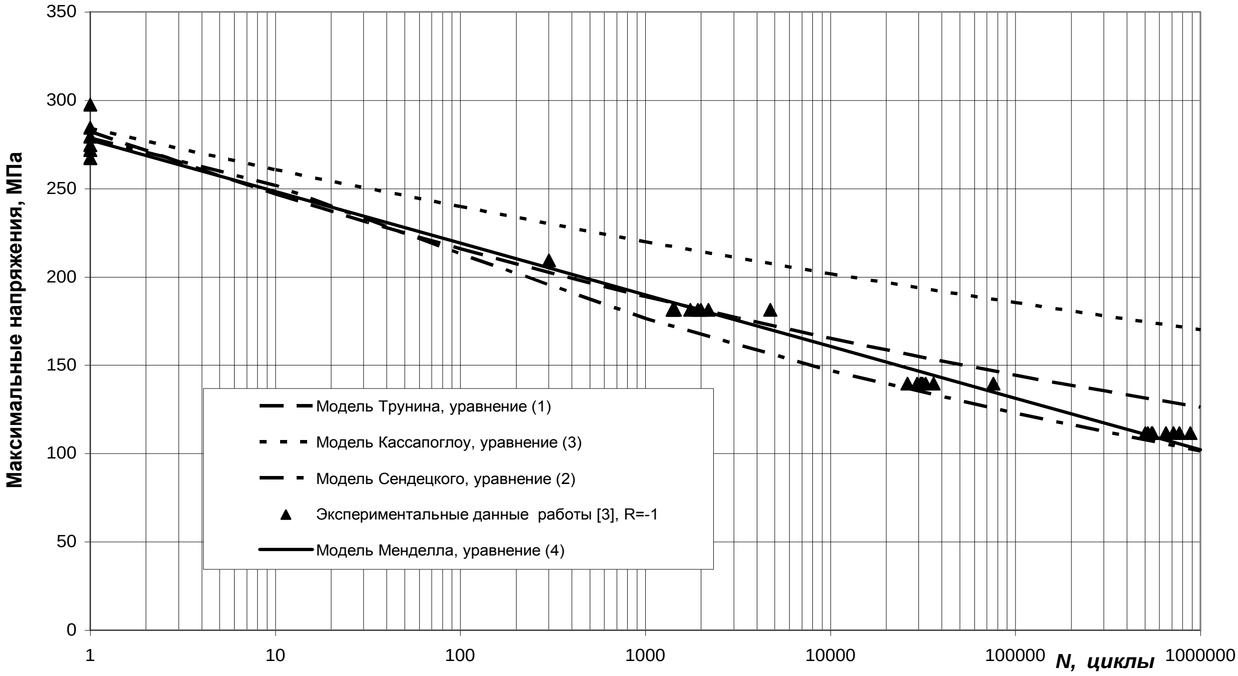


Figure 4.1 Approximation of test data for specimens with open holes. AS4-PW laminate

In order to find the equation of the diagram of limiting amplitudes of the cycle, which most accurately represents the dependence of the fatigue life of laminated PCM on the cyclic loading asymmetry, a review of four currently best known similar equations was conducted:

- modified Gerber equation;
- the modified Goodman equation;
- modified Oding equation;
- Beheshti-Harris-Adam equations.

According to the results of the analysis of diagrams that can be constructed using the above equations, it was concluded that it describes the well-known physical features of such diagrams for the layered PCM Beheshti-Harris-Adam equation most accurately.

In scope of research on fatigue damage accumulation author considered the hypothesis of fatigue summation on the basis of published works analyses and came to the consideration that for engineering calculations and estimations of FRPs fatigue at various loading program , it would be rational to use hypothesis of Haw and Owen in terms of accuracy of results and time consumption

$$\boldsymbol{D} = \sum_{i=1}^{k}[\boldsymbol{A}(\frac{n_i}{N^i}) + \boldsymbol{B}(\frac{n_i}{N^i})^c]$$

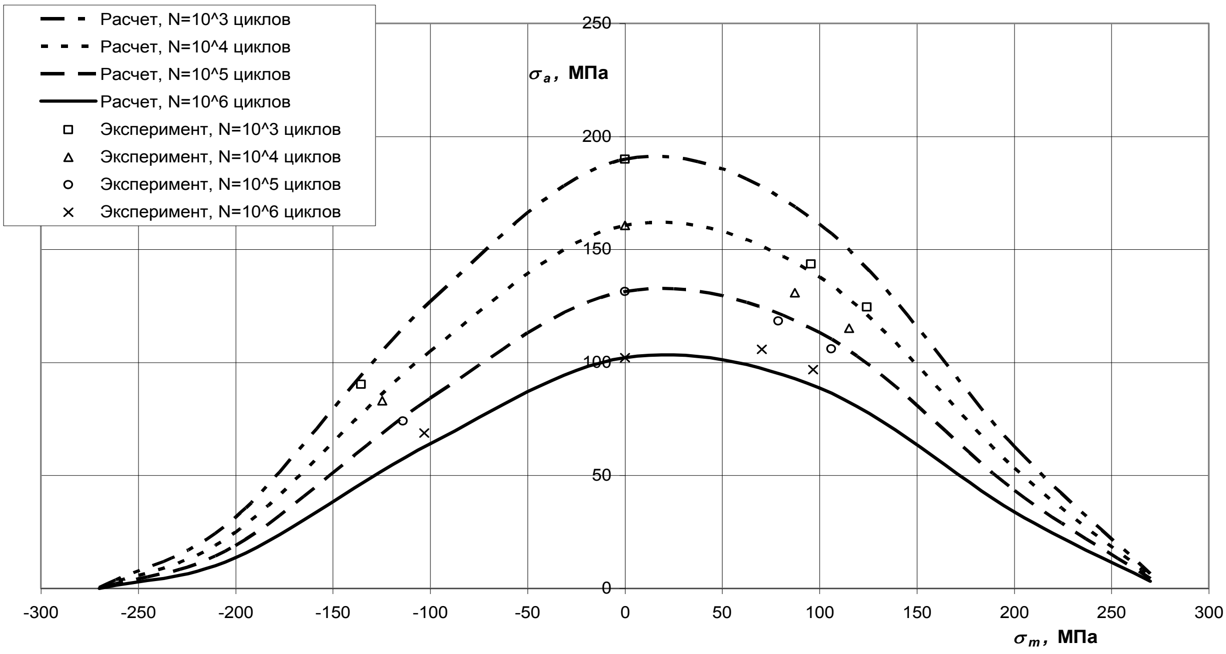


Figure 4.2 Cycle limit amplitude diagrams based on the Beheshti-Harris-Adam equation for the open hole specimen made of AS4-PW carbon fiber

## 4.3. Fracture criterion for FRPs specimens at fatigue tests with tensile loads

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The research on development of fracture criterion for composite material specimens and structural elements was carried out in scope of fatigue tests of composite strip specimens with open holes. Those specimens were fatigue tested at zero-to-tension loading (R = 0).

The application of the "classic" criterion for FRP specimen fracture into two parts, which is successfully applicable for metal specimens, resulted into high scattering of fatigue characteristics. For example, the standard deviation of durability logarithm was within 0.7÷0.9 range. To obtain the reliable data on fatigue life of the structure with consideration of such high scattering values would be significantly time consuming and economically expensive. Thus to solve this task, the failure criterion was developed to allow reduced scattering.

Experimental studies performed by the authors of the work showed that the first damage in the form of longitudinal interlayer cracks and delamination initiated in the hole area, followed by delamination at free edges of the specimens. A similar pattern was found in literature review by the foreign authors.

Figure 4.3 demonstrates the X-ray diffraction patterns of the specimen in the beginning of the tests, during the tests and after applied $10^6$ load cycles with maximum load equal to 80% of ultimate load from static tests.

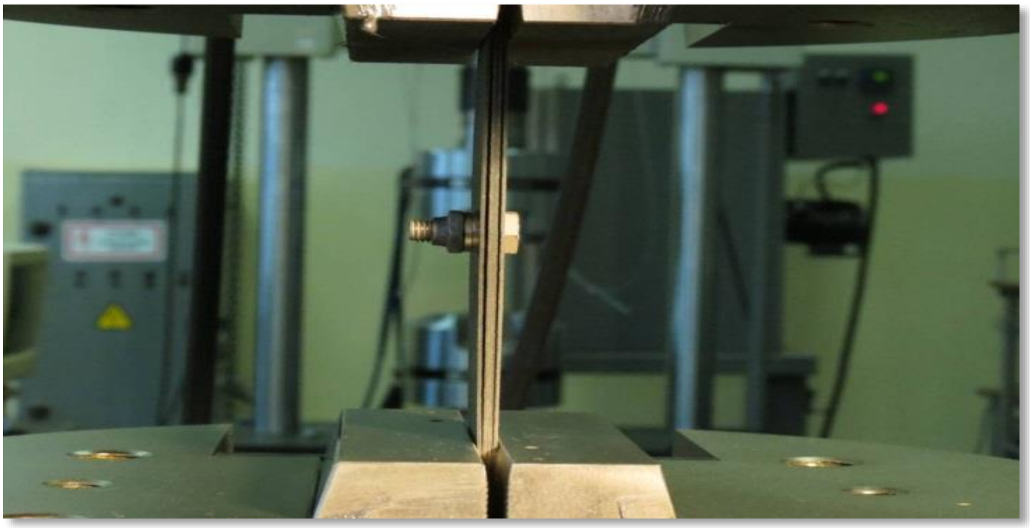

Figure 4.3 Photo of the tested strip CFRP specimen installed in the test rig

The test process was supported by visual and x-ray control, with X-ray inspection allowing to determine the growth of interlayer delamination and longitudinal cracks, while visual inspection provided the control of increase in number and in size of transverse and longitudinal cracks on the specimen surface.

For fatigue tests on tensile testing of composite strips type specimen with an open hole it is proposed to consider the fracture criterion as the time of delamination in the concentrator zone.

TsAGI developed a delamination sensor that was installed in the specimens' holes and detected the beginning of the material delamination in the concentration area in real time.

As a result of studies performed using a delamination sensor device, the critical value of the thickening of the specimen selected during fatigue tensile tests was considered as a fracture criterion – when the value was reached the specimen fracture took place:

$$\Delta_{tens} \geq 0{,}05\ mm$$

This approach to consider thickness criterion provided the standard *Slgn* deviation in allowable range which does not surpass 0.3 and which is acceptable for the current FRPs, and thus does not lead to unjustified safety\reliability factor introduction to fatigue analyses.

Figure 4.3 (cont) Photos of the tested strip CFRP specimens

## 4.4. Validation of methods and determination of crack resistance parameters at static and fatigue loading for FRPs

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The research was performed in TsAGI in scope of methods development program in order to obtained specified parameters for crack resistance model at static and fatigue simulation and analysis. Crack resistance is considered as one of the defining parameters of the strength of structures made of laminated polymer composite materials.

In general approaches for the analysis of crack resistance of composites traditionally three modes of destruction should be considered:

I is the mode of separation, II is the mode of longitudinal shear, III is the mode of transverse shear, as well as mixed modes, which are their combinations.

The analysis of delamination damages and their propagation in the composite package, in general, is carried out in terms of the intensity of release of the elastic energy, and not of stress, since theoretically the stresses at the tip of the crack tend to infinity. The intensity of the release of elastic energy is numerically equal to the change in the elastic energy of the structure with increasing crack area per unit.

For composite elements, the energy release rate can be calculated using the FEM analysis. The most common approaches for such calculations are:

- the methods of virtual crack closure
- the method of cohesive elements.

The initial data for the design estimates of the strength and durability of structural elements with delamination are

- fracture toughness in modes I, II and mixed mode
- “fatigue curves” for a sample with delamination
- kinetic fracture diagrams.

The “fatigue curves” of a sample with a bundle are constructed in the same way as a standard fatigue curve, but a sample with a delamination is used instead of stresses. Durability is defined as the number of loading cycles before the development of the zone of stratification. The criterion for the beginning of the development of delamination is either a visually detectable change in the size of the delamination zone, or a change by some amount of an indirect feature depending on the length of the delamination, for example, the compliance of the sample.

Currently, ASTM standards could be used to determine the fracture toughness by mode I and II and the joint mode I + II. On the basis of these standards, Russian national draft standards have been developed, harmonized with ASTM standards, and draft standards have been developed for fatigue loading in mod II and mixed mod.

According to the those draft standards, tests to define the characteristics of crack resistance on specimens with delamination for advanced polymer composite materials were performed. Tests on mode I were carried out under tension of the samples, tests on mode II — in point bending of samples, tests on a mixed mode — on a special tooling, which allowed simultaneously to carry out the stretching and bending of the sample.

A method for determining the fracture toughness of FRPs under the influence of climatic factors has been developed. It was determined that an increase in temperature (82°C) and moisture saturation of specimens can lead to a decrease in fracture toughness by tens of percent for the mode II.

Table 4.4 shows the ranges of crack resistance values of carbon-fiber reinforced plastics obtained both by the authors of the work and from various open sources.

Table 4.4 Typical ranges of crack resistance values for CFRPs

| | **Fracture toughness, kJ / m2** | **Slope of fatigue curve** | **Slope of kinetic fracture diagram*** |
|---|---|---|---|
| **Mode I** | 0,1÷0,5 | 7,0÷9,0 | 12÷20 |
| **Mode II** | 0,5÷2,5 | 4,0÷6,0 | 4,0÷6,5 |

The values of the slopes of the fatigue curves in terms of "stress-durability" and the kinetic fracture diagram in terms of "stress-growth rate of delamination" will be twice as much, since the intensity of energy release is proportional to the square of stresses.

Figure 4.4.1 below shows the average fracture toughness values of advanced FRPs applied in the airframe and structural elements of transport aircraft. Experimental data obtained from the test results of 140 samples.

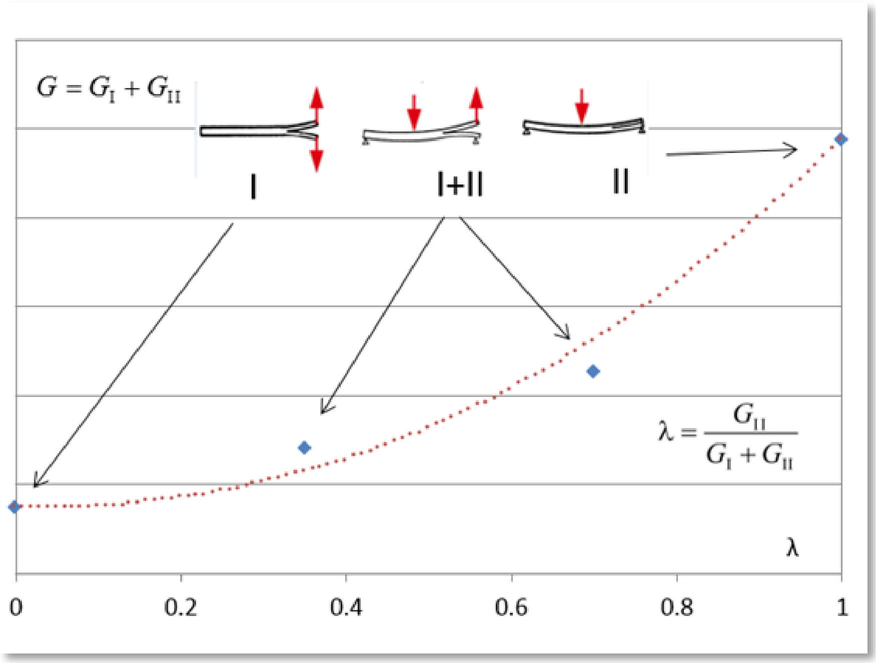


Figure 4.4.1 The average values of fracture toughness for different fracture modes of advanced CFRP material applied in the structure of transport aircraft

Figure 4.4.1 Test rig for fatigue and crack resistance characteristics studies, advanced CFRP material. Mixed mode testing at TsAGI lab.

## 4.5. Nonlinear deformation and failure analysis of laminated composites

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An approach to the characterization of different types of nonlinearity in the behavior of composite materials is proposed. One of them is concerned usually observed in experimental studies the dependence of deformation properties of composite materials on the type of external forces. Another type of nonlinearity lies in the fact that the shear stress-strain curves are nonlinear, though they are linear ones when the load is applied along the reinforcement. To describe these effects, the additional matrix is introduced into the proposed constitutive relations. There are different mechanisms of deformation of these materials, which are dependent on the type of reinforcement, matrix properties, loading conditions, directions of loads with respect to reinforcement and some others. These mechanisms and their interactions determine the stress-strain behavior of materials that influence the damage evolution and fracture properties of composite materials. To describe the damage accumulation process, the system of general failure model assumptions is formulated that include the choice of first ply failure criterion, constitutive relations for damaged materials with the use of corresponding damage parameters, the dependence of first ply failure criterion and elastic properties on the damage rate parameters and others. Some particular models are considered taking into account different types of nonlinearities, Lomakin et al. (1981, 2007, 2014, 2015 and 2017). This approach is verified using complex loading experiments. The theoretical dependencies obtained on the base of proposed models are compared with the results of experimental studies and good correspondence of them is shown. The proposed approach to the formulations of constitutive models from simple to more complex ones allows to describe adequately the behavior of composite materials under different loading conditions with the necessary precision

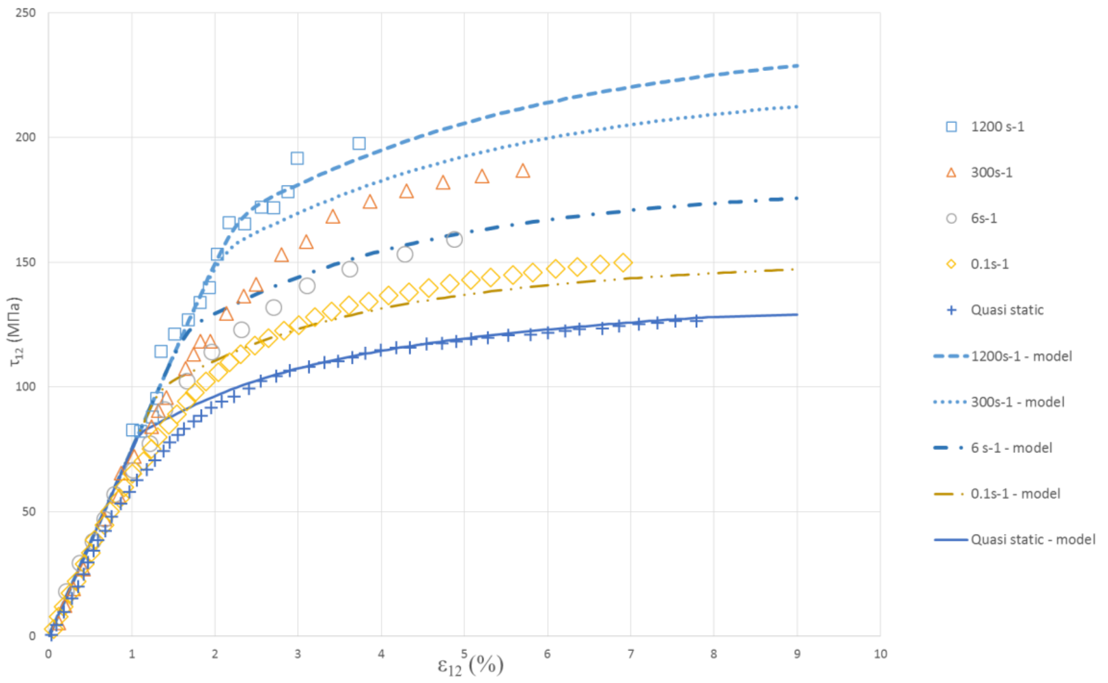


Figure 4.5.1 Experimental and predicted inplane shear loading diagrams

The use of proposed anisotropic elastic model of materials susceptible to stress state and exhibited nonlinear shear properties shows a good correlation between experimental data and theoretical predictions. All loading diagrams are close to ones recorded during the tests. Development and implementation of proposed model, including damage consideration, represent the effective tool for engineering applications.

## 4.6. Failure analysis of laminated composites based on degradation parameters

B. N. Fedulov . A. N. Fedorenko . M. M. Kantor . E. V. Lomakin
) Lomonosov Moscow State University, Moscow, Russia,

This work was devoted to develop approach to the formulation of models characterizing nonlinear deformation and damage of composite materials and includes the consideration as the simplest model as more complex ones. In this research a number of assumptions to build up a theory for failure prediction in laminated composites are presented, which are generalized enough to serve as the basis for explanation of current models and for further development of modelling theory. The presented approach is a phenomenological one and introduces degradation parameters explicitly influencing on the stiffness characteristics of composite materials. It describes common assumptions for material degradation theory and the main part of the research focuses on development of simplified constitutive relations suitable for practical application in testing and Then research was followed by formulated approach to capture and take into account the complex effects such as initial nonlinear shear deformation behavior of laminated composites and the influence of high strain rate on strength properties. The results obtained show a good correlation between the results obtained with proposed modelling method and analyzed experimental data.

As example of failure modelling approach based on assumptions formulated above is presented. For the sake of clarity, authors have chosen the simplest variants of necessary input relations and failure criteria. A classic case of orthotropic elasticity is chosen for elastic constitutive relations.  At the next step damage parameters allowing consistent modification of initial elastic relations are chosen. Considering the simplest way of introducing damage characteristics, only two parameters, $\psi 1$ and $\psi 2$, are chosen, where first parameter corresponds to fiber failure and the second one to matrix failure.

$$\begin{cases} \psi_1 = 0\, fiber\, failure,\ \psi_1 = 1\, initial\ value \\ \psi_2 = 0\, matrix\, failure,\ \psi_2 = 1\, initial\, value \end{cases}$$

The modified constitutive relations with damage parameters for third assumption can be formulated as follows

$$\begin{aligned} E_{11}^c &= \psi_1 E_{11} \\ E_{22}^c &= \psi_2 E_{22} \\ E_{33}^c &= \psi_2 E_{33} \\ G_{12}^c &= \psi_2 G_{12} \\ G_{13}^c &= \psi_2 G_{13} \\ G_{23}^c &= \psi_2 G_{23} \\ \upsilon_{12}^c &= \psi_1 \psi_2 \upsilon_{12} \\ \upsilon_{13}^c &= \psi_1 \psi_2 \upsilon_{13} \\ \upsilon_{23}^c &= \psi_1 \psi_2 \upsilon_{23} \end{aligned}$$

Eventually, the constitutive relations for damaged material can be written in the following form

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{Bmatrix} = \begin{bmatrix} 1/E_{11} & -\nu_{21}/E_{22} & -\nu_{31}/E_{33} & 0 & 0 & 0 \\ -\nu_{12}/E_{11} & 1/E_{22} & -\nu_{32}/E_{33} & 0 & 0 & 0 \\ -\nu_{13}/E_{11} & -\nu_{23}/E_{22} & 1/E_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{23} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix}$$

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{Bmatrix} = \begin{bmatrix} \frac{1}{\psi_1 E_{11}} & -\frac{\psi_2 \nu_{21}}{E_{22}} & -\frac{\psi_2 \nu_{31}}{E_{33}} & 0 & 0 & 0 \\ -\frac{\psi_2 \nu_{12}}{E_{11}} & \frac{1}{\psi_2 E_{22}} & -\frac{\psi_2 \nu_{32}}{E_{33}} & 0 & 0 & 0 \\ -\frac{\psi_2 \nu_{13}}{E_{11}} & -\frac{\psi_2 \nu_{23}}{E_{22}} & \frac{1}{\psi_2 E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\psi_2 G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\psi_2 G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\psi_2 G_{23}} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix}$$

At the next step, the influence of $\psi 1$ and $\psi 2$ parameters on the failure criterion is determined. In order tomodel load drop in corresponding test curve, the dependencies for Yc($\psi 1$), Yt($\psi 2$) and S($\psi 2$) can be used, however, to avoid the necessity of complex analysis of experiential data we assume that material has no load drop stage in loading diagrams. A comparison between test and simulation results obtained using the criterion presented in this paper is shown in figures below.

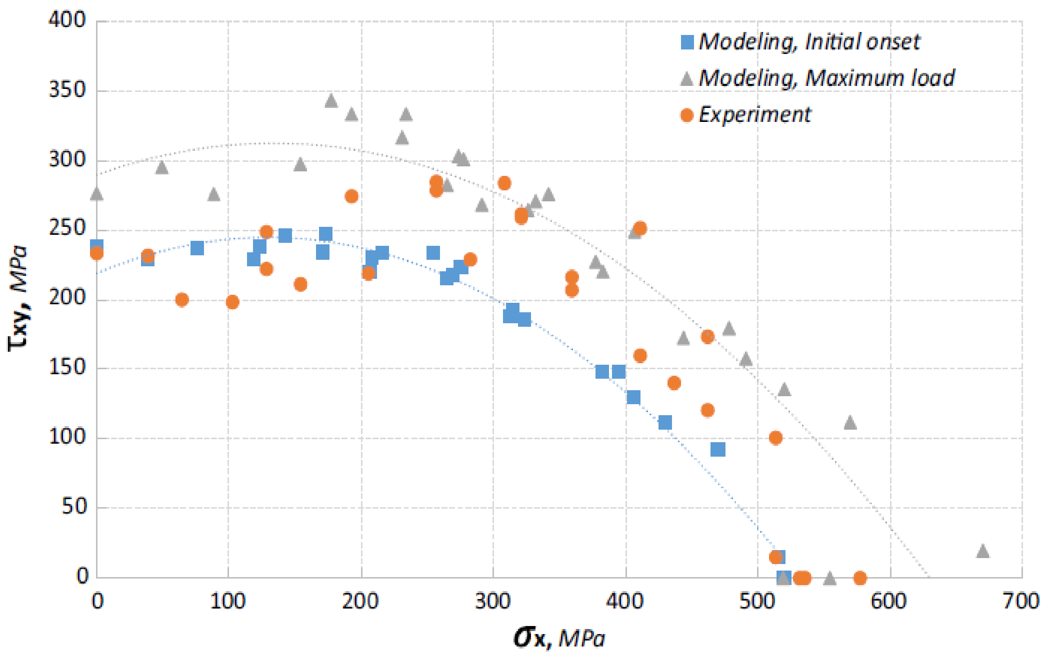


Figure 4.6.1 Biaxial failure envelope for [90/± 30/90] E-glass/LY556 epoxy laminate under combined $\sigma_x$ and $\tau_{xy}$ stresses

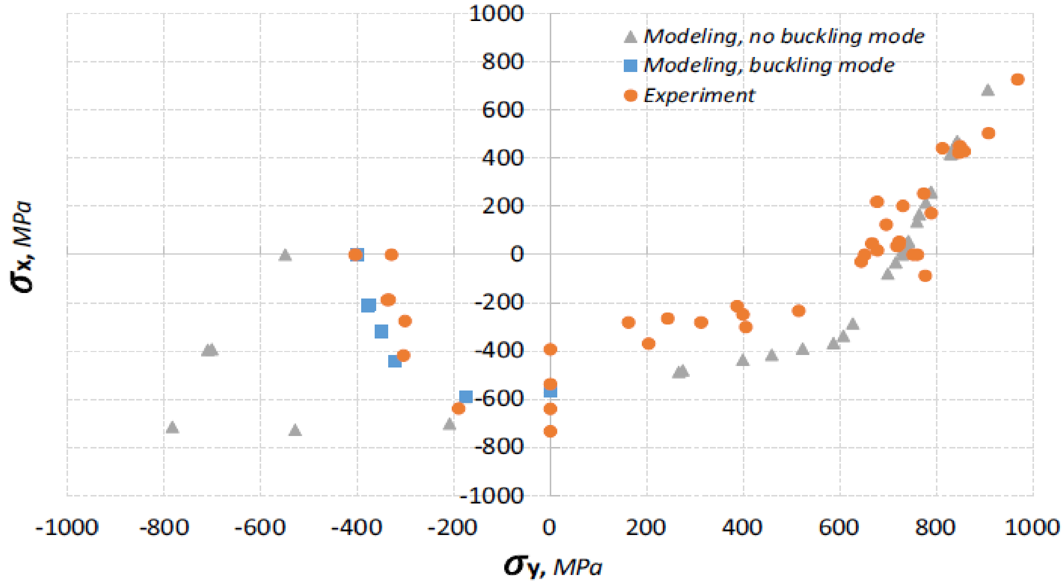


Figure 4.6.2 Biaxial failure envelope (0/ ± 45/90) AS4/3501–6 epoxy laminate under combined $\sigma_x$ and $\tau_{xy}$ stresses

Modification of initial elastic condition might be necessary for some particular engineering problems, especially if stiffness plays an important role for designed structure. An example of test with compression loading of composite specimen with circular hole was analysed. Specimens of composite T300/976 graphite/epoxy resin have sufficient thickness to prevent buckling and have only ±45 grade layers. For this loading conditions and this particular layup, the shear stress– strain curve exhibits essential nonlinearity from the initial stage of loading. Next figure shows results of modelling with the use of two types elastic shear stiffness. It is possible to see that limit values of load applied to the specimen in both cases are very close to each other and to experimental one. Nevertheless, nonlinear shear elastic model gives much preferable predicted loading diagram at all stages of loading.

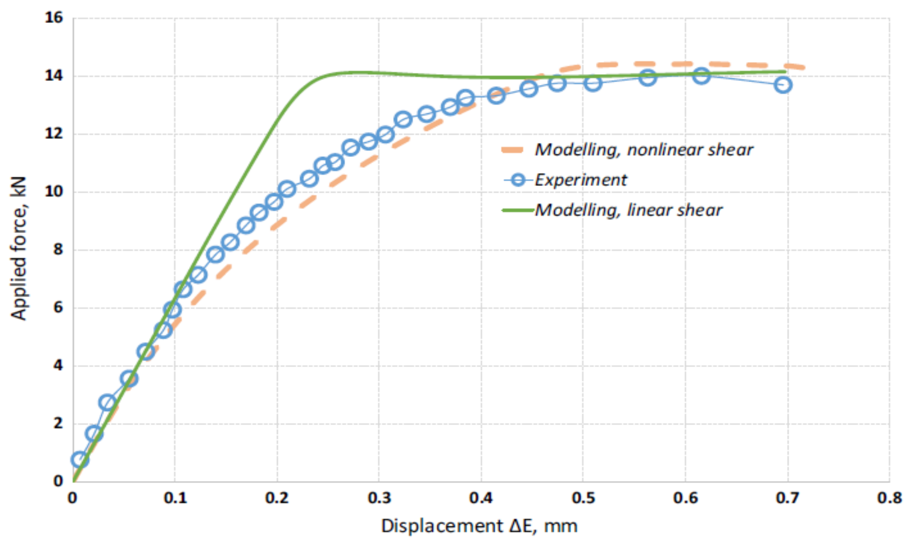


Figure 4.6.3 Experimental and predicted loading diagrams with linear and nonlinear shear stiffness

# 5. Determination of typical damages of composite airframes

## 5.1. Research of surface dents relaxation in composite structures

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*2. GosNIIGA, Moscow, Russia*

For determination of the visual inspectability threshold of dents\impact damages, which appear due to random impact on airframes, it is necessary to define not only the initial dent size, that characterizes the damage immediately after the impact but also the size, which corresponds to that moment of time when the visual inspection of structure is being conducted. The time interval between these two events could be sufficient so that the dent size can rela. It means that it will decrease under the effect of operational and climatic factors.

To determine the regularities of such kind of relaxation, a number of experimental studies was carried out where the surface dents relaxation level of the composite reinforced panels under effect of time and various factors had been defined in tests. The research results were compared with earlier activities performed in Europe.

Along with the standard conditions, the relaxation phenomenon was studied also at specimens exposed to drying and water saturation. It was demonstrated that among all the factors that could lead to dent reduction including the operational, structural, and technological ones, the thermal- humid effect on structure is the most crucial.

Based on the regularities obtained for primary composite airframes the general principles were formulated to set the strength criteria conditioned by damage tolerance.

## 5.2. Specifications for ultrasonic inspection of impact damages in composite structures

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The impact damages are one of the main operational damages types of composite structures that had been analyzed in this research. There is a number of problems arise when revealing such damages in operation or testing. One of them is related with probabilistic nature of such damages.

This fact imply some limitations to the composite structure requirements, namely – impact and other haphazard damages, which were not revealed during the elementary maintenance, must not develop in the course of standard operation of aircraft.

Another problem is related with the fact that the damage sizes found out during the routine inspection may ten times surpass their visible size identified during the standard inspection.

The acoustic methods are the most widely used for FRP’s structures:

- low frequency acoustic (resonance, impedance, and free oscillation methods)
- ultrasonic (shadowgraph and pulse-echo technique, acoustic-emissive method)

The paper gives the analysis of certain factors which influence the impact damages detectability and accuracy to estimate their borders when using the pulse-echo technique:

- composite components geometrical peculiarities;
- heterogeneity of material acoustic properties;
- impact damages peculiarities

## 5.3. Simulation of impact damages at fatigue full-scale tests of composite structure

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The requirement to verify experimentally the life of the structure with impact damages is one of the key problems when ensuring the service life of airframes produced with application of FRPs. This lead to requirements and the necessity to simulate full scale impact damage tests that should be representative for standard operation, and to study the propagation of those damages both under operational cyclic loading and the ultimate one.

Related experimental studies were carried out in TsAGI using impact testing machine by INSTRON. Vertical copper damaging was introduced to specimens. The specimens were the typical upper and lower panel structures of wing box and vertical tail. Those structures are considered as the close prototypes for airframe structural elements.

The impact damage of 90-140 J resulted in occurrence of damage dent on the panel surface and through thickness cracking of panel.

The method of videogrammetry evaluated the dent shape and the ultrasonic method measured the cracking area size.

The fatigue and residual strength tests of structures were carried out after the damages were inflicted. The impact damages were not found out both under the cyclic loading and the static one when loading up to operational load.

## 6. Fatigue and durability tests of composite structures

### 6.1. General approach to provide the equivalence of loading of FRP structures while full-scale fatigues tests

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The research deals with the basic principles and approaches that are currently recommended by Russian Aviation authorities to ensure the equivalence of loading program of metal-composite structures of transport and passenger airplanes while full-scale tests for service life definition at standard operation conditions. The formulated statements were developed with consideration of the analysis of experience and practice of airplane development and operation that have airframe or structural elements made of polymer composite materials.

The measure of compliance and correlation of laboratory test loading with operational loads is the parameter of “equivalence" which is a ratio of fatigue life values for typical structure concentrators. These values should be obtained for loading cases at two programs to be compared.

Experience in development of the metal airplane structures showed the acceptance to use strip specimens with the open hole to define the parameter of equivalence. For composite structural components there exists no generally accepted procedure to find out the loading programs equivalency due to these structures specifics:

- Insufficient state of knowledge of composite structures;
- the presence, especially in layered CFRP, which are used currently, of fracture modes of various nature;
- the CFRP characteristics dependence on the great number of various factors, including the manufacturing technology;
- high slope of S-N curve

So currently the following was recommended in the research:

1. The test should be performed on two identical full-scale structures from serial production to represent the manufacturing technology. The first structure is used to confirm the and prove the metal components strength. The second one is used to prove the composite components strength.
2. The quasi-random loading program spectrum for full-scale tests should be generated by use of known principles and procedures accepted for integrally metal structures
3. To prove the composite components fatigue life characteristics the full-scale tests of the second structure should be performed with use of the additional loading enhancement factor.

It is to be noted that, though the Russian regulations contains some differences comparing to other regulations (i.e. the logarithm normal probability distribution law of durability at the probability of not destruction of structure which is equal to 0.999 with the reliability level that is equal to 0.9 instead of Weibull distribution law B-basis stating the probability of not destruction of 0.9 at reliability level of 0.95), the experience showed that for contemporary materials the load increase factor has the level that is in agreement to the world practice.

It should be noted that the procedure presented in the research does not allow to prove the required strength of delaminated composite components.

Therefore, at structural design stage it is necessary to decrease the actual stress levels to prevent development of delamination below the durability limits.

It is necessary to show that in case of delamination presence, in spite of reason that caused it, there will be no development during operation up to the sizes that are critical and that will lead to decrease of strength below operational levels.

## 6.2. Fatigue and residual strength tests of composite spar box of civil aircraft

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*"Aerocomposit", Moscow, Russia,*

The research is aimed to study the delamination aspects of reinforced advanced composites typical for the application in aircraft load bearing elements and primary structure elements. During the recent decades from all variety of polymer composites in spite of variety of fracture forms the most critical subject of researches is the study of delamination of composite laminates.

However, most of the research results available for the analyses, there is still no answer to the key problems that should be solved in order to provide the structural integrity and safe operation in terms of fatigue strength of composite structure elements. Most actual are the following:

- Strength of metal - composite details joints depends on a great number of parameters;
- Hardly visible impact damages of composite details can develop at the subsequent cyclic loading by compression and, as a result, lead to significant decrease in strength at compression;
- Cyclic load in standard operation can lead to decrease in bearing capacity of composite structure.

It caused the need to carry out the fatigue and residual strength tests of the full-scale wing box in order to validate experimentally the basic manufacturing technologies, the assembly technologies and the quality control system for civil airplane composite structural part.

In scope of the research performed the two identical wing boxes were the main test subject. These full scale boxes simulated the typical root part of outer wing panel of civil airplane.

The tests were performed on special test rig that is shown in the picture below. The variable loading that was applied to the structure simulated the typical flight loading and was representative for middle range civil airplane operation at standard conditions.

The tests were carried out n the specimens with detected technological defects in order to estimate the degree of possible fault while manufacturing process.

In addition the impact damages of three categories were introduced to the structure to the upper and lower panels. There were three types of damages introduced:

- visually non-detectable
- barely visible damages
- visually detectable.

As a result of impacts onto the surface, the small dents and delamination zones were formed.

Figure 6.2 Fatigue tests and residual strength test of composite wing box structures

***Tests of spar box #1***

During the fatigue tests of spar box #1 loaded with representative flight cycles the damages appeared in the form of the stringers beams delamination with simultaneous delamination of their edges and delamination of hatches frames.

After the repairmen and typical maintenance procedures of the structure with above mentioned damages, the spar box was tested up to 120000 flight cycles; after that the residual strength tests of spar box were performed. When the load equal to 120% of operational load of rated "A" case was applied to the structure, the complete destruction of the top panel and the destruction of the front and rear spars caps occurred.

***Tests of spar box #2***

The tests of spar box #2 were carried out accordingly to the same procedure as for the spar box #1.

At approximately 55 000 flight cycles the destruction of the top panel occurred in the same zone as the destruction of the top panel of spar box #1 when the latter was subjected to residual strength testing.

Tests results demonstrated a number of essential features of composite structures of this class, including:

- impact damages of both the top panels and the lower ones practically do not grow or develop at cyclic loading and also are not a cause of the destruction at residual strength tests;
- the cyclic loading in compression area of the upper panel of wing box causes the decomposition of stringer caps simultaneously with the delamination of their edges, the delamination of panel edge in radius blend;
- in tension area on the low panel the cyclic loading causes the delamination of hatches/manholes edges and the delamination of the stringer vertical stem;
- -damage of the structure by cyclic loading leads to significant decrease in spar box bearing capacity as a result of the lower breaking compression stresses in comparison to the breaking compression stresses of intact structure;
- both the fatigue characteristics and the residual strength properties have some high scattering.

## 6.3. Fatigue tests of MC-21-300 composite empennage

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1. TsAGI, Zhukovsky, Russia
2. "Irkut corporation" Moscow, Russia

Fatigue tests of the typical aempinage structure of MC-21-300 airplane and vertical surfaces were carried out in order to verify the service life characteristics of the structure manufactured by serial production technologies.

These tests had not been completed up to now. Major results and conclusion regarding structure itself as well as manufacturing technologies will be available later.

The next figures show the structure in the test rig in TsAGI fatigue laboratory.

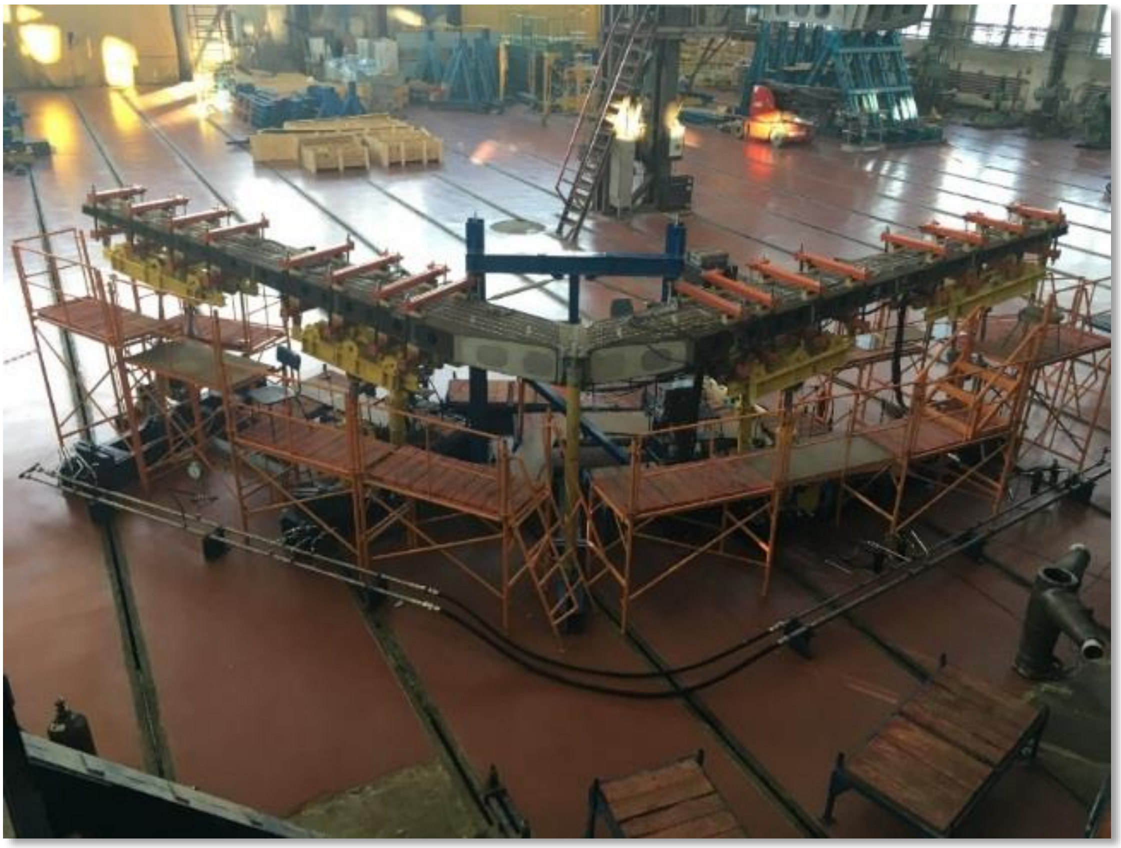

Figure 6.3.1 Composite structures of MC-21-300 empennage surfaces at fatigue tests

Figure 6.3.2 MC-21-300 airplane vertical fin composite structure at fatigue tests

## 7. Development and implementation of technique to design airframes with principle load-bearing components made of FRP to effectively satisfy static and fatigue strength and damage tolerance criteria

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The current and advanced transport aircraft e.g., MC-21, Boeing B-787, and Airbus A350 are characterized by application of innovative design and technology solutions, automatic control and software complex, high velocities regimes upranging that ensures the operation efficiency and safety, which are conditioned by strength. One of the main features of being developed and perspective structures is the mass application of polymer composite materials in production of principle primary components. The effective implementation of new material requires to maintain the balance between two multidirectional problems. On the one hand, it is necessary to carry out the deep revision and modernization of all existing approaches to create the aircraft equipment to start with the design methods and principles up to the methods to prove the durability, the certification and the working off of the life. On the other hand, the decisions used should not lead to decrease in aircraft equipment safety that can be confirmed, finally, by aircraft fleet successful operation only.

The problem to develop the design solutions of new generation first of all requires the solution of the problem to reduce the cycle of creation and development of novel AC, which of the design is effective and safe in terms of strength and durability. One of the ways to find a solution is to increase the scope of problems, which are to be solved by calculation methods that allows among others, to reduce the risks of early destructions at certification tests and to improve the reliability of results obtained in the course of laboratory and experimental researches. The solution of this problem is ensured by the development of recommendations for rated estimation of PCM structures durability, which is effectuated at design step. Based on these recommendations, the industry standards to design the PCM structural components are to be developed. the development of new and already existing rated estimations methods will allow to expand the scope of the carried-out calculations as well as to increase the technological developments readiness level. Considering the severe reliability and reliability requirements for results obtained by calculation methods they are to be developed based on statistically significant amount of test-bench and full-scale test results as well as to ensure the possibility to calculate those conditions where the AC operates both in terms of the loading, and the climatic environment.

The probable variations of mass and inertial, elasticity and strength (static and fatigue) properties of AC structural comosite components due to effect of operational factors (climatic effects, mechanical damages, and structural modifications of highly loaded components etc.) need the arrangements to estimate and ensure the A/C safety during the long-term operation in terms of static strength, life, flutter and static aeroelasticity. To prove and maintain the high flight and operational characteristics of A/C and in some cases to enhance their efficiency, requires to develop the specific procedures and the regulatory-technical documentation, which ensure the estimation of the main structural parameters, analysis and criteria of safety in terms of strength while taking into consideration the operational factors. The problem to obtain the not available currently data on structures and joints strength characteristics degradation under operation is highly actual for A/C, which have aggregates made of advanced aviation composites because to disregard the degradation, especially under certification static tests, during which dozens loadings, which are close or equal to design ones, can result into premature failure of structure, which actually meets all the strength requirements necessary. It will lead to considerable additional material and time expenditures, which are possible to be avoided by eligible planning of tests.

One of the problems to ensure the safe operation of airplanes with extensive application of composites in airframe is to justify the adequate level of the allowed damages and to ensure the operational durability. Unlike the metal structures, for which the durability, as a rule, is understood as a controlled fatigue cracks growth up to some limit state the, the composite structure durability is defined by possibility of airplane safe operation at presence of defects and damages obtained in course of manufacturing and during operation. On the one hand, it predetermines the need to introduce the special control methods to reveal the damages immanently inherent in composites: the hidden layering caused by accidental impact effects, the internal lack of adhesion due to basic materials defects and variability of process parameters, not pro-glues, etc. On the other hand, it is not possible to assume that the increasing volume of the necessary control leads to increase in labor intensiveness of maintenance of composite structures vs. the metal ones, as it actually reduces their competitiveness and levels the objective advantages of polymer composites. The combined approach allowing to coordinate two specified requirements is needed to eliminate this contradiction. The approach comprises the program of mandatory inspections of A/C PCM structures, which is based exclusively on inspections, during which the need of deeper inspections is to be defined by external symptoms, including use of tools. Due to it the approach to ensure the composite A/C operational durability, notwithstanding the fundamental differences of mechanisms of initiation and behavior of defects in composite and metal structures, depends completely on visual inspectability. Therefore, the experimental assessment of a threshold of defects detectability for wing and empennage PCM components, taking into account all the influencing parameters, including the type of material, the distance to a surface, the position of sample in relation to the observer, the damage size, the state and the color of surface, the site of inspection, the illumination is a highly relevant task.

At design of composite structure, it is necessary to consider that PCM have a number of basic features caused by their heterogeneous structure and also an essential distinction of fibers and cohesive agent strength properties. These features are not basic for low loaded structures, however for the high-loaded structures, such a wing box or fuselage panels, they can become the key factor to define the weight efficiency of structure. The key parameters almost do not vary: it is deemed that the structure is defined in general. At the same time the accuracy of the carried-out calculations becomes very important. The mathematical models are adjusted by the modal tests results. The adjustment of computation model is a long and labor-consuming procedure. At the same time, the forms, the frequencies and the natural oscillations decrements obtained by calculation and experiment are compared and at this the comparison of oscillations forms is carried out subjectively based by quality factors. In case of results divergence, the adjustment of mathematical model is carried out. The mathematical models adjustment ways are carried out proceeding from the previous experience, for example, they adjust the distribution of elasticity and mass characteristics, they change the joints pliability or apply the both options, and it means the variation of hundreds of model parameters. Thus, the relevant task is a formation of recommendations and the regulated procedures to adjust the mathematical models.

The application of novel computational and experimental methods to define the modal characteristics will allow to use directly the results of modal tests in calculations of flutter, the mathematical model obtained in such a way will be maximally approached to a real object.

The major task is not only to create and verify the new computational and experimental methods and techniques to assess the structural integrity, but also their implementation in process of design and operation of civil aircraft of new generation. This demands the development of normative and technical documents of various levels (manuals for designers, enterprise standards, recommendation, etc.) to design the composite structures developed using the estimation procedure for strength and durability parameters of aeronautical structures created within the project.

Thus, the development and the verification of the applied tools, which are necessary to ensure the effective design of aeronautical structures with main primary perspective materials components being manufactured via advanced technologies by strength and durability criteria represent a relevant complex scientific and technical problem, with the solution which of the further progress in the specified area and retaining the  Russian Federation leadership in highly competitive international market of aircraft industry are related.

In 2018, to solve the problems stated above, the "Development and Implementation of Technology to Design the Aeronautical Structures with Principle Primary Elements from Polymeric Composite Materials, which are Effective by Criteria of Strength and Durability " project started, which was financed by the Ministry of Education and Science of the Russian Federation (Agreement # RFMEFI62518X0044) and "Irkut" Corporation" PJSC, the industrial partner. Project duration is 3 years, within which based on experimental data obtained during the implementation of certified "pyramid" of computational and experimental studies of the MC-21 plane, it is planned to validate the models and the calculation methods of structural components strength, which are carried out at design stage and justification of airplane structural integrity, taking into account all the failure modes, which determine the structural integrity, effect of multi-axial loading and delamination at static and fatigue loading as well as the analysis of equivalents.

# 8. Research of fatigue and damage tolerance of metallic airframe structure

## 8.1. Experimental and computational study of pressurized fuselage skin buckling on longitudinal crack growth under intact and failed frame and in frame bay

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The excessive pressure influences the longitudinal fatigue cracks growth in skin of pressurized passenger and transport planes. The skin buckling that occurs under excessive pressure leads to increase in cracks growth rate. The research was devoted to the modeling of crack growth at conditions of the skin buckling in case of excessive pressure with the aim to avoid considerable mistakes when calculating the crack growth.

Currently various authors developed the models that consider the buckling influence. The study presented gives the verification of the most known buckling models .

### *One-bay longitudinal crack growth*

Five buckling models were verified, including Swift; Broek (Jeong and Tong); Chen and Schijve; Bakuckas; Rose, Young and Starnes.

The verification is carried out by use of experimental data on growth duration of one-bay longitudinal crack in fuselage skin of YAK-42 airplane. Also the comparison of experimental crack growth duration vs. the computed one, without considering the buckling, is carried out. Figure 8.1 demonstrates the comparison of computed and experimental durations of one-bay crack in fuselage skin of YAK-42 plane.

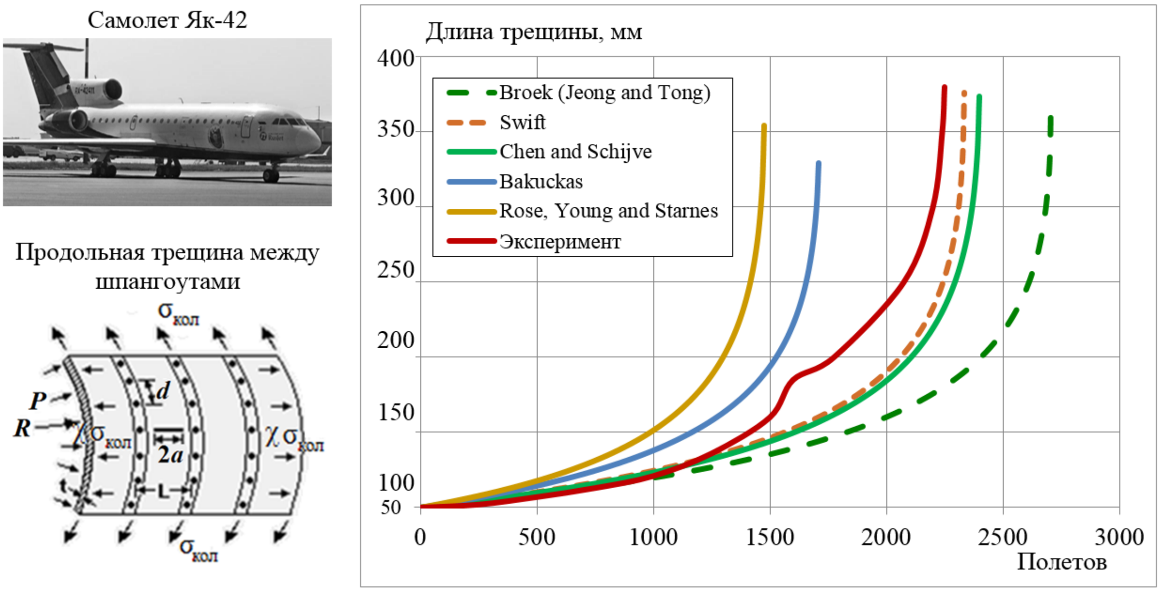


Figure 8.1.1 Comparison of computed and experimental results of longitudinal crack growth between ribs obtained using the various buckling models (Yak-40 airplane)

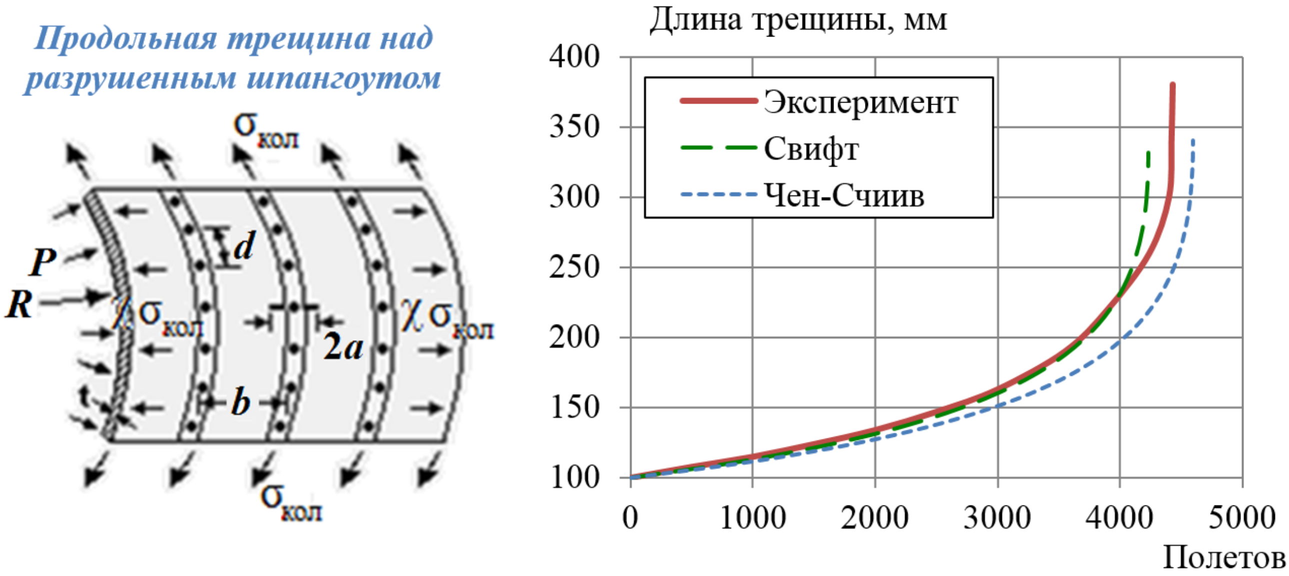


Figure 8.1.2 Comparison of computed and experimental results of growth of two –bay longitudinal crack in case of broken frame

## 8.2. Combined static & fatigue tests of the full-scale structure of a transport aircraft

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This applied experimental research work is a non-traditional approach in strength tests of the full-scale structure of a transport aircraft, which consists of combining static and fatigue tests on one object. The test object included a full span wing with installed pylons, the middle part of the fuselage and the main landing gear. The tests were carried out on the bench that allowed reproducing both static cases of loading and variable loads of flight cycles. To confirm the static strength, the structure of wing half span was loaded with limit loads and simultaneous strain measurement. The data of strain gauges verified the finite element model (FEM), on the basis of which the prediction of the stress-strain state of the structure was made with the ultimate loads. To confirm the strength capacity of the upper wing panels under the stability conditions, tests of full-size wing panels were carried out. After loading with the limit load, fatigue tests were carried out which are required to confirm the service life.

The research is related with development of the modification of IL-76 transport aircraft. It became necessary to experimentally confirm the static strength of the wing structure, as well as fatigue life of the wing, engine mount and main landing gear of the modified Il-76MD-90A aircraft. To carry out the necessary tests, non-conventional approach was applied, which consisted in combining static and fatigue tests one full scale structure of airplane.

The test object could be found in the section of industrial fatigue activities of Ilushin company. The test analyses

- a full span wing, on which pylons for PS-90A-76 engine with dummy power engines are installed, flaps rails with dummy carriages;
- the middle part of the fuselage with installed fairing along the left side;
- the main landing gear with dummy wheels.

The wing of the aircraft is swept, wing box type, trapezoidal shape with a change form along the trailing edge. On the axis of symmetry of the aircraft, the wing is conventionally divided into right and left half span of wing. The wing has two technological joints at a distance of 2,4 m from the axis of the aircraft, which divide the wing on the center section and the two out parts of the wing. The wing connected with the fuselage on the power frames. The basis of the structure of the wing box - prefabricated-monolithic structures. The wing box is divided by ribs into 12 fuel tanks, two drain tanks and two dry sections. Tanks are completely sealed. The joint of the out part of wing with the center section is by a set of fittings connecting the upper and lower panels. On the lower surface of the wing, there are attachment points for engine pylons. On the pylons are mounted dummy engine for the application loads. For the application the forces to the rails of the flaps, dummy carriages are mounted on them.

The structural tests were carried out in two stages. At the first stage, the wing was loaded with the limit load of loading case “A” with simultaneous strain measurement, and at the second stage the cyclic loading with flight cycles “At the height” and “At the ground” was performed. At the first stage, the right wing half span was loaded up to limit load, left half span to maximum loads which simulated during fatigue tests.

At the second stage fatigue test were carried out. When testing for fatigue, the wing, the rails of the flaps, the engine suspension, the middle part of the fuselage, and the main landing gear were cyclically loaded. Simultaneously with the cyclic loading, an overpressure was simulated in the cabin. The loading was carried out by blocks of variable loads consisting of 7 flight cycles “At the height” and one flight cycle “At the ground”.

The flight cycle “At the height” is divided into two types: B1 — in which, at the “Pre-preparation” stage, two cycles of the engine thrust are reproduced alternately on the external and internal engine, and B2 - in which there is no engine thrust. In one block of loads from the 7 flight cycles “At the height”, variant B1 is repeated 1 time and variant B2 - 6 times. In flight cycles “At the height” (B1 and B2), the “Reverse engine” mode was reproduced only on external power plants. In flight “At the ground” - the “Engine reverse” mode was reproduced both on external and internal engines. In the flight cycle “At the ground” at the air stage there is no simulation of overpressure of the fuselage.

The test complex  setup for testing provides to perform both static strength tests and fatigue tests. It consists of a setup of multichannel loading, a compressor station, an oil pump station, an information-measuring system, a non-destructive testing instrument and a programmer. At static strength tests the loading up to limit loads is provided. At fatigue tests simultaneous cyclic loading of the wing, rails of flap, engine suspension, the middle part of the fuselage, the main landing gears is provided. To balance the active loads, which simulate the aerodynamic and inertial loads that occur in flight, special loading channels prevent the aircraft from moving as a whole body. In addition pressurization is available to overpressure the cabin. The set-up for multi-channel loading includes digital servo cylinders and load-tree systems to load the wing, flaps, engine mount, main landing gears. For simultaneous loading of the airframe 93 servo cylinders are applied.

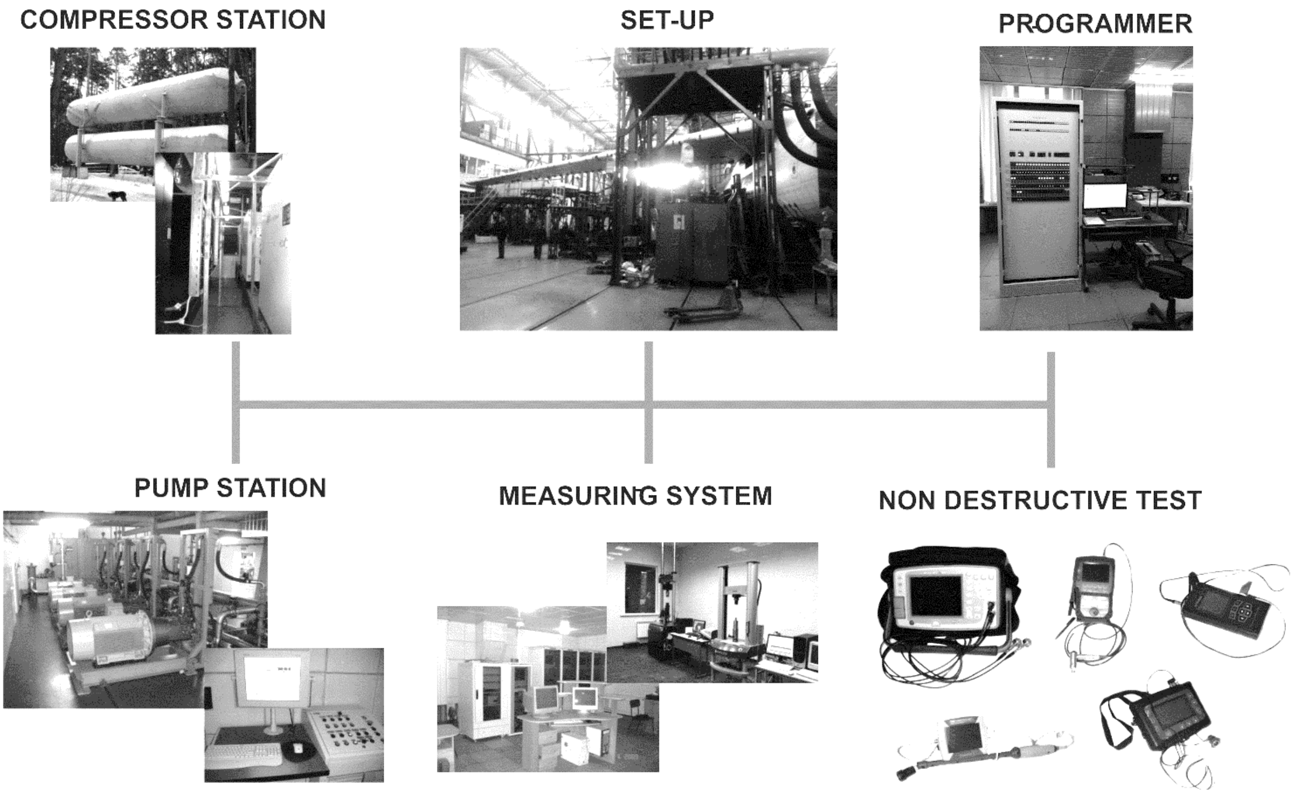


Figure 8.2.1   The complex for testing

The experimental research was supported with REM analysis of the wing structure. As a result of the finite element calculation of the stress-strain state of the wing loaded with the loading case “A”, the distributions of normal stresses along the stringers in the upper panels and lower panels were obtained. The compressive stress in the upper panels, obtained by FEM, reaches -288,5 MPa, and slightly exceeds the stress obtained by measure, -275,7 MPa. The deviation does not exceed 4,5%. The greatest tensile stress in the lower panels obtained by FEM reaches 233,4 Mpa, vs. 247,5 MPa from strain measurement that is within 6% difference. This validates the FEA model to predict the stress state of the wing structure.

To determine the strength capacity of compressed upper wing panels, three span panels were tested for stability. Testing of three-span panels made it possible to most fully realize the working conditions of the panel in the structure, since such tests take into account the initial deflection of the panel, the mutual influence of spans, moments at the junction of the panel with ribs, ribs stiffness, fastener strength. For testing, panels with a length of 3 distance between the ribs and the width of 5 stringers were selected. Two panels were connected to the box to provide real conditions of support on the ribs.

The panels included in the box, were tested in turn. The panel was mounted on the support plates with end planes in such a way that the center of gravity of the panel section coincided with the central power line of the testing machine. Monitoring over the possible eccentricity, in case of uneven loading across the width was carried out using strain gauges mounted on the panel. The tests were carried out on a Riehle-300 testing machine. While loading, according to the indications of strain gauges mounted on the panel, loads and stresses were determined, corresponding to the local loss of stability of the panel elements and the overall loss of stability of the panel as a whole. In the test, measurements were made by laser displacement sensors. Tests of two panels were carried out before the general loss of stability.The loss of the carrying capacity of the panels resulted from the general loss of stability of the three-span panel and its fracture in the middle span (Figure 8.2.2). The fracture of the panels was accompanied by the fracture of the stringers and the rupture of the rivets.

Figure 8.2.2   The panel after general loss of stability

Critical stresses for monolithic panels are also obtained by calculation. The form of the total loss of stability obtained by calculation is shown below. Comparison of the critical stresses obtained by calculation and testing has shown their good agreement.

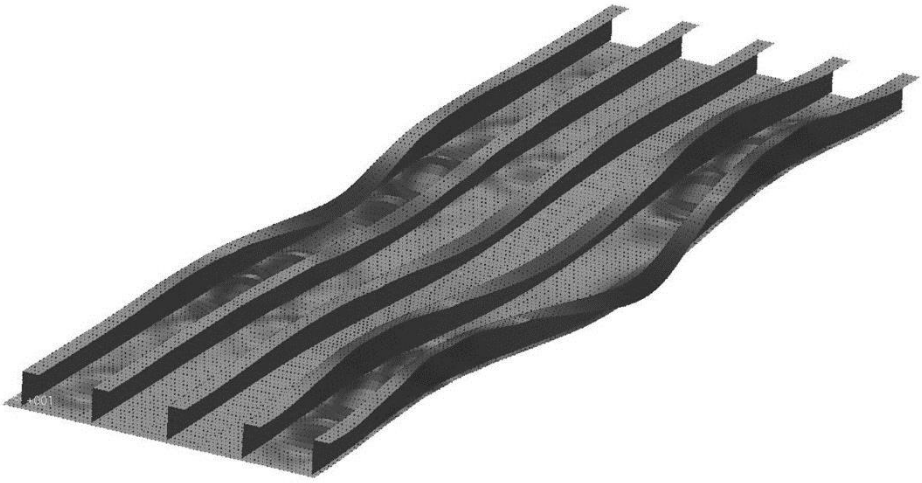

Figure 8.2.3 . Buckling of for monolithic panels obtained by calculation

Applying non-traditional approach in strength tests of the full-scale structure of a transport aircraft, which consists of combining static and fatigue tests on one object allowed to significantly reduce the duration of the test and the cost of their conduct. This became possible due to the fact that one object was used for testing and the tests were carried out on a single universal set-up. The reliability of the tests was achieved by the accompanying stress researches by experimental and computational methods and testing of full-scale panels.

### 8.3. Damage tolerance tests of civil airplane fuselage section made of aluminium alloy

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The research was devoted for the damage tolerance studies of fuselage structure. The laboratory tests of fuselage section were carried out to prove experimentally the fuselage life characteristics. The geometry, the materials and the design of section test zone correspond to the standard geometry and materials. The right side of fuselage section has the emergency exit door, the rear cargo door and standard windows as shown in the Figure 8.3.1.

The first stage of the test program of section included the research of fatigue cracks growth in the window edges, in the emergency exit and in the cargo reinforced cutout hatch. Before introduction of the artificial initial damages in the form of cracks with considered length of L = 7 mm in window frame, L = 30 mm in emergency door and L = 30 mm in cargo door edge the strain gauge measurements were carried out to specify the calculated values of stress-strain state in the section. The experimental study of damages development duration in windows frames, emergency exit door and cargo hatch was carried out when working off of 10,000 flight cycles. As a result of the conducted researches, the experimental data on fatigue cracks development were obtained.

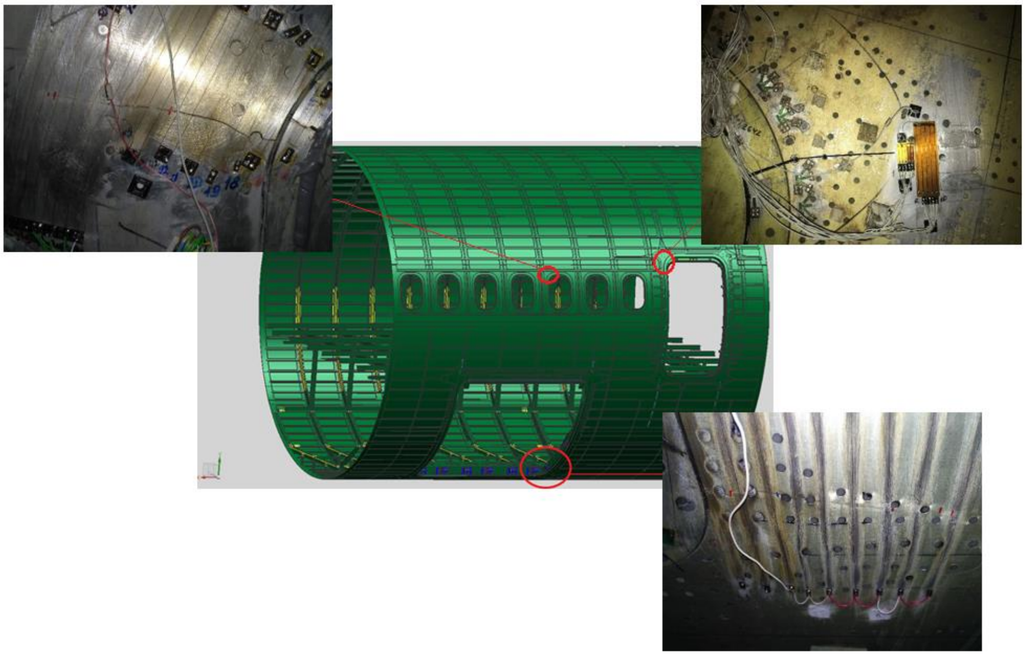

Figure 8.2.1 Fuselage full-scale section of MC-21 -300 airplane used for damage tolerance tests followed by residual strength tests

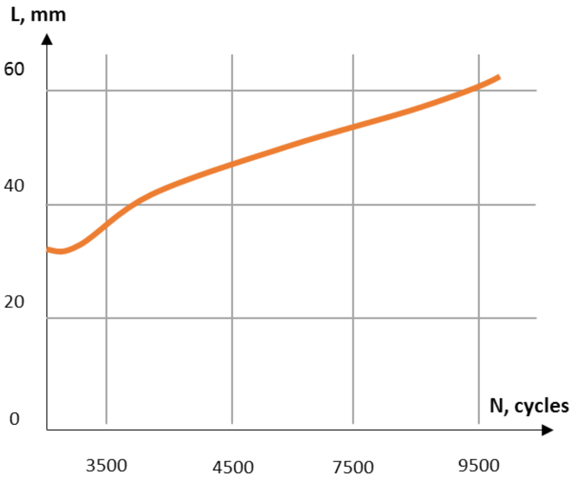


Figure 8.2.2 Crack growth in cargo door edge obtained from test

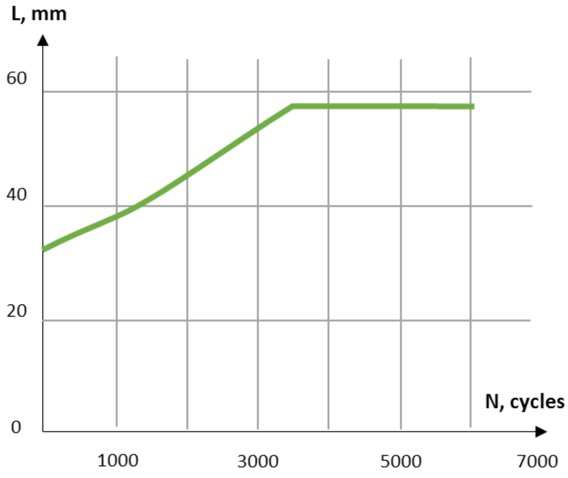


Figure 8.2.3 Crack growth in emergence door frame obtained experimentally

## 9. Methods to provide safe operation of aircraft structures with high-time service

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The work was carried out to formulate general approach on how to provide safe operation of aging aircraft structures including those with long-term operation. Methods to detect and eliminate the structural corrosion damages were considered basing on operation experience and statistical data on distribution of typical defects in civil aircraft structures. Authors outline the approaches to prevent the failure of aircraft structures due to widespread fatigue damage with provided statistics on the multiple site fatigue damages in panel joint of the upper wing surface of Il-62M civil airplane that were identified while full-scale tests of aircraft and obtained from operation. In addition, the results of experimental research on degradation of strength, fatigue, and crack growth resistance of long-term-operated airframes are given.


Figure 9.1 Compared operation time of Russian airplanes to their design goals. Dotted lines correspond to individually extended service life fleet leaders

It has been found by the studies of FSUE “GosNII GA” that corrosive damages could be in range of 35–92% of all fuselage damages depending on the aircraft type. The largest number of corrosive damages was recorded in the underfloor space of the fuselage. The proportion of corrosive damage in the wing structural elements could be up to 50% of the total number of damages and defects. Results of the analysis of corrosion damages of Il-86 wide body civil aircraft wing and fuselage skins carried out at TsAGI are shown in figure 9.2. followed by corrosion depth data. Further the analysis of IL-62 structural integrity was continued by MSD growth analysis basing on previous test data and experiments on skin joints. The figures below shows the growth of MSD in the joint of the upper surface wing panels of IL-62M aircraft. Based on the analysis of these data, a modification program was developed to reinforce the joint connection profile by installation of the reinforcing plate. Additional tests were performed (Figure 9.5) on longitudinal joint specimens Generalizing results obtained in various experiments, it was stated that the growth duration of multiple site fatigue cracks is approximately 35% of the total durability of the specimen before failure. Net stress level at failure is in the range of 0.47 ÷ 0.54 of the material yield strength $\sigma_{0.2}$. On the basis of these studies, recommendations have been developed for ensuring the design goal of the fuselage of the aircraft while design stage, to prevent formation of multiple site fatigue cracks.

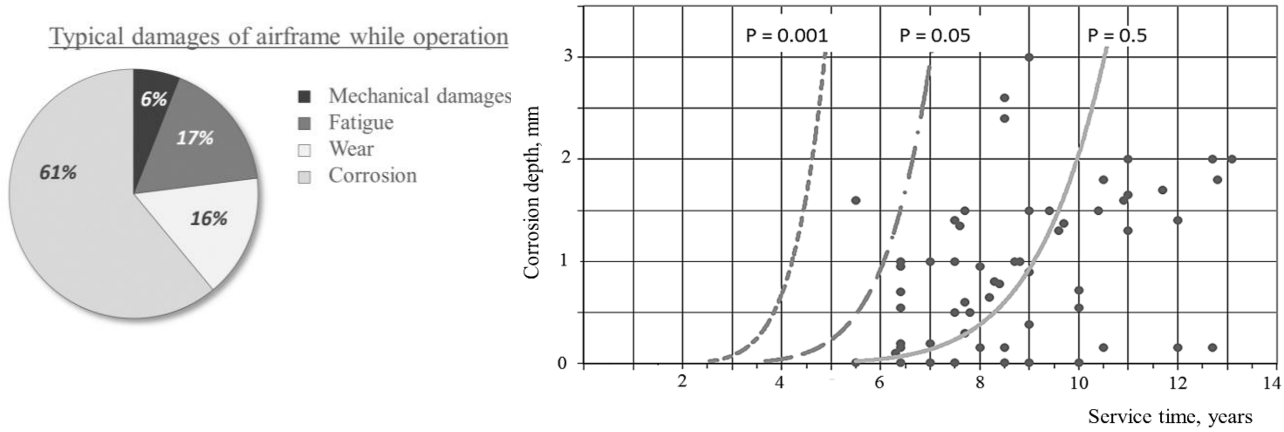



Figure 9.2. Operational damages of IL86 airframe and propagation of layer corrosion in aluminum wing lower surface panels at operation conditions

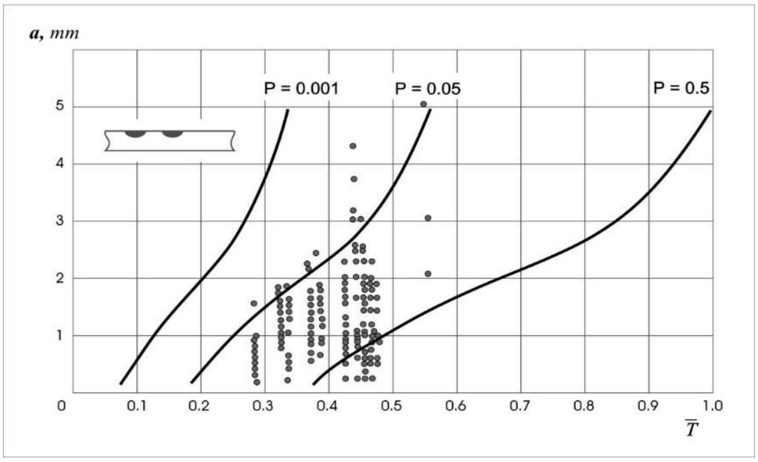
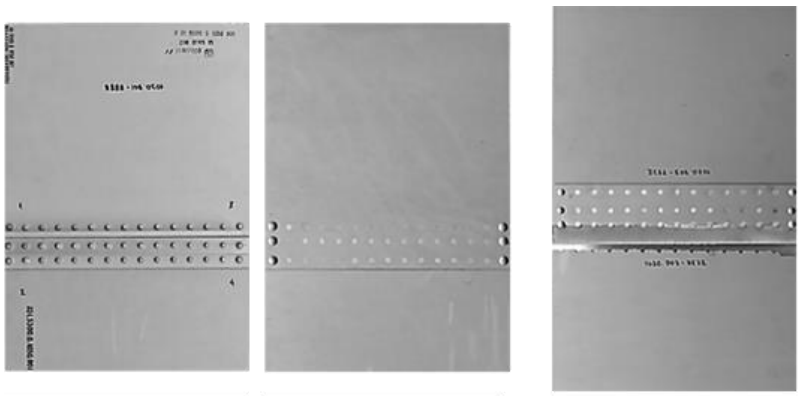



Figure 9.3 The relative growth of MSD cracks in IL-62 wing panel joint, upper surface, found in operation



a) Test specimen, «internal side»
b) Test specimen, «outer side»
c) Specimen after failure

Figure 9.4 Specimen of longitudinal fuselage skin joint made of 1163RDTV alloy

# 10. Industrial research - ILUSHIN Company

## 10.1. IL-76MD-90A fatigue related activities

The “Ilushin Company” currently perform a program on modification of Il-76 aircraft with extensive development of IL-76MD-90A that is an upgrade of the Il-76MD aircraft. It will satisfy reviewed requirements to satisfy potential customers. The airplane is designed for production at aircraft factories in the Russian Federation.

As a main modification the aircraft will have PS-90A-76 engines. The manufacture of the main airframe units and details and the final assembly of the aircraft are carried out at Aviastar-SP CJSC (Ulyanovsk).


Figure 10.1.1 IL-76MD-90A airplane

Taking into account the need to improve the technical level, fatigue and damage tolerance characteristics at efficient weight ratio as well as renewed production technology of aircraft wing production (developed Aviastar-SP), the following changes were made to the design of the base aircraft:

1. A wing with a newly designed wing box is introduced:
   - external wing geometry has a slight change
   - design and power scheme of the wing remained unchanged compared with the IL-76MF wing, with the exception to removed middle spar of the wing making it similar to wing configuration of IL- 96-300 aircraft
   - structural materials correspond to the wing of the IL 96 300 aircraft.

- type of fastener has been changed to connect stringers to the box skin, UZ rivets (OST 1340.44-80) are used; the rest of fasteners is fully consistent with the wing of IL-96-300.
- wing mechanization, spoilers, brakes, ailerons and their attachments remained the same as on IL-76MD / MF except minor changes in the geometry of individual elements

2. The PS-90A-76 engines are installed on pylons similar IL-76MF aircraft.
3. The fuselage design is strengthened in the zone of the joint with the wing to ensure a maximum take-off weight of 210 tons.
4. Main landing gear is reinforced.
5. Other changes as upgraded autopilot and AC systems were introduced.

The list of modification related activities related to fatigue strength and damage tolerance are aimed to ensure the strength of the structure of IL-76MD-90A aircraft in accordance with established regulatory requirements.

1. The analyses of expected operational conditions of IL 76MD 90A aircraft.
2. The analyses of typical flight tasks, the choice of the typical flight for analyses and certification, the calculation of loads and stress levels of IL-76MD-90A load bearing elements according to the flight profile
3. Compilation of a list of list of the primary structure elements of the airframe, landing gear and aerodynamic control systems
4. Analytical and experimental study and validation tests on fatigue and damage tolerance of regular and irregular zones of the airframe structure.
5. Development of “ General Test Program” to conduct joint static and fatigue tests
6. Analysis of the results of full-scale fatigue tests of the airframe and landing gear
7. Validation and official approval of design goal with conditional requirements statement
8. Validation and official approval of allowed flights number (service goal), service life with conditional requirements statement
9. Preparation and approval of the Conclusion on the compliance of the aircraft with the regulatory requirements of AR RF for the strength of the structure during long-term operation within the assigned flight numbers and service life.

Presented below is the list of planned tests in scope of highlighted activities.

Table 10.1 The list of bench tests necessary to establish the compliance with the regulatory requirements to structural strength of IL-76MD-90A aircraft

| Type of test | Tested object | Test program | Status |
|---|---|---|---|
| Fatigue tests of aircraft structure elements in lab | Airframe with installed :<br>– landing gear supports<br>– takeoff and landing mechanization<br>– and control systems<br>– engine mountings and pylons<br>– other structural elements | The test program is established in accordance with the program of validation of the design goal. Minimum three design goals should be reached.<br>@ILUSHIN test facilities,<br>Figure 10.1.2 | In progress |
| Static\combined tests | Wing with elements with takeoff and landing mechanization<br>Installed on a central fuselage section with main landing gear | – Wing with new designed structure is tested<br>– The wing joint to the fuselage<br>– The main landing gear supports and their attachment points.<br>@ Tsagi static test lab facilities ,<br>Figure 10.1.3 | In progress |
| Static tests of 3-bay specimens of the wing upper panel | Test specimens (2 pieces), including 4 panels of the upper surface of the wing. | Compression loading for stability (buckling) analysis<br>Figure 10.1.4<br>@ Tsagi fatigue lab facilities<br>Figure 10.1.4 | Completed |
| Fatigue tests of wing panels | Tests of "3-stringer" panel specimens representing wing structure<br>3 specimens of the wing lower surface 3 | The number of loading cycles is set in accordance with the program of aircraft design goal validation<br>@ Tsagi fatigue lab facilities ,<br>Figure 10.1.5 | Completed |


Figure 10.1.2 IL-76MD Fatigue tests of aircraft structure elements in lab

Figure 10.1.3 Static test of wing - central fuselage section with main landing gear in TsAGI lab

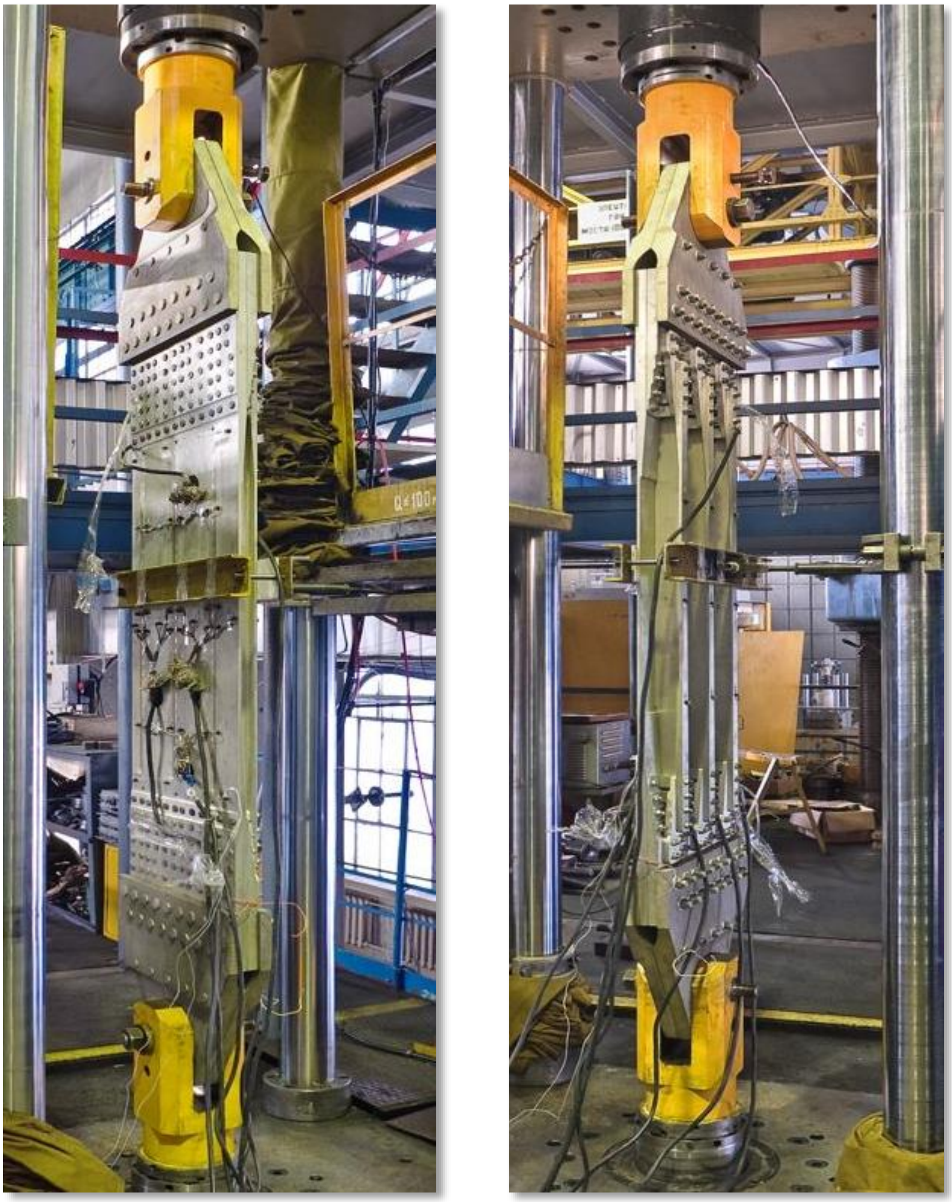


Figure 10.1.4 Fatigue tests of "3-stringer" panel specimens representing wing structure of IL-76MD-90A aircraft

## 10.2. IL-112 B fatigue related activities

Light Il-112V military transport aircraft according to the classification of the Special Requirements of the Durability Standards of Military Planes of 1978 belongs to class B type 13 airplanes (transport planes).

The list of key activities in scope of structural fatigue strength and damage tolerance that should be must be performed to ensure the strength of the IL-112B aircraft according to the established regulatory requirements is given below

Figure 10.2.1 IL-112 V light transport airplane

1. Calculation of the repetition of loads according to the flight profiles under conditions of typical mission.
2. The calculation of the loading of the aggregates and elements of IL-112V aircraft in typical operating conditions.
3. Estimated acoustic load rating of the airframe.
4. Compilation of a list of the primary structure elements of the airframe, landing gear and aerodynamic control systems
5. Analytical and experimental study and validation tests on fatigue and damage tolerance of regular and irregular zones of the airframe structure.
6. Refinement of the load of the units and the frequency of load basing on the results of flight tests.
7. Justification and validation of the design goal up to the moment of retirement of the airframe and landing gear. Conditions for validation.
8. Preparation and approval of the Conclusion on the compliance of IL-112V aircraft with the regulatory requirements for the strength of the structure during long-term operation within the assigned service goal and service life.
9. Refinement of typical operating conditions, loads to elements and assemblies, repeatability of overloads based on data from operation

Table 10.2 The list of tests necessary to establish the compliance with the regulatory requirements to structural strength of IL-112V aircraft

| Type of test | Tested object | Test program | Status |
|---|---|---|---|
| Static and Fatigue tests of aircraft structure and its elements | Airframe №0102 with installed :<br>– landing gear supports<br>– takeoff and landing mechanization<br>– fuselage mechanisms<br>– empennage elements<br>– engine mountings and pylons<br>– other structural elements | Test program for main airframe elements plus fuselage pressurization according to certification program<br>The number of load cases for each unit is determined by the results of the strength analysis.<br>The number of loading cycles of the specified units is set in accordance with the test programs. | Preparation<br>Installation of AC<br>To start in 2020 |
| Fatigue tests , damage tolerance tests, residual strength tests | Airframe №0104 with installed :<br>– landing gear supports<br>– takeoff and landing mechanization<br>– empennage elements<br>– engine mountings and pylons<br>– other structural elements | The number of loading cycles will be specified according to test program<br>To be accomplished by structure teardown and disassembly for damage analysis fractography analysis. | To start in 2020 |
| Tests of flap mechanisms for operation & functionality Fatigue tests of flap structure | Mechanisms of flap release with elements of their transmission, electric and hydraulic systems of the aircraft, necessary for the functioning of the mechanisms and check for failure situations | The number of loading cycles is established according to test program of flap and the program of simulation of the failure situations.<br>Figure 10.2.1 | In progress |
| Tests of nose landing gear | Landing gear rack support | For each support:<br>about 100 drops at operational and maximum absorption to confirm the specified working capacity of the amortization system;<br>about 100 drops at various drops to confirm the specified fatigue life of the amortization system; | In progress |
| Fatigue tests of nose landing gear | Landing gear with structural elements , rack support, weal turn system, etc | The number of loading cycles is set in accordance with the program and the agreed reliability coefficient equal to 4 | Installation<br>Assembly in progress |
| Operational and fatigue tests of main landing gear | Landing gear rack with the hatch doors, locks at release\retract positions, the load carrying elements of the release\retract system | The number of loading cycles is set in accordance with the program and the agreed reliability coefficient equal to 4 | Installation<br>Assembly in progress |
| Fatigue tests of wing panels and fuselage structure | Wing panels specimens<br>Fuselage longitudinal panel joint:<br>– panel transverse joint;<br>– panel with riveted stringer;<br>– bulkhead;<br>– typical frame. | Amount of specimens will be specified according to program and additional req. due to new design | To be started in 2020 |


Figure 10.2.2 Test of IL-112 flap mechanisms for operation & functionality

### 10.3. IL-114 -300 fatigue related activities

The passenger aircraft IL 114-300 is a turboprop two TV7-117CT-01 engines. This airplane is a modification upgrade of IL-114 serial aircraft and is designed to carry passengers, cargo at regional airlines. It could be operated with class A, B , C, D runway with soil strength of 7.5 kg / cm$^2$.

Figure 10.3.1 IL-114 -300 passanger airplane

The basic airplane IL -114 is certified by the IAC Aviation Register type for compliance with the airworthiness requirements of the NLGS-3 and is mastered in production and is mass-produced in the Republic of Uzbekistan.

As part of the modernization program, the following changes were made to the design of IL-114 aircraft, affecting the strength characteristics of the structure:

1. Transition to the TV7-117CT-01 engine with an AB-112-114 propeller with an increased value of the rods.
2. Improvements of the fuselage structure:
   - changes in the layout of the passenger cabin and in the interior of the passenger cabin;
   - changes in the mechanization of the fuselage;
   - local improvements of the fuselage for the installation of new equipment;
   - changes in the design of standard frames (to ensure the residual strength of the fuselage with a regulated longitudinal crack, in accordance with the requirements of paragraph 25.571 AR-25).

3. Wing structure modifications:

- Changes in the geometry design of the wing in the fuselage connection area (a change in the V-shape of the wing);
- Changes in the design of the engine nacelle;
- Changes in the mounting structure of the main landing gear;
- Changes in the flap control system.

The list of planned activities in the nearest time related with research and validation of fatigue strength and damage tolerance to be performed in order to ensure the strength of the IL-114-300 airframe in accordance with established regulatory requirements is the following:

1. Calculation of the repetition of loads on the considered flight profiles.
2. Calculation of the loading of the Il-114-300 aircraft structural elements and details at standard operating conditions.
3. Compilation of a list of the primary structure elements of the airframe, landing gear and aerodynamic control systems
4. Analytical and experimental study and validation tests on fatigue and damage tolerance of regular and irregular zones of the airframe structure.
5. Refinement of structural elements loading and frequency of loads basing to the results of flight tests.
6. Justification and validation of the design goal and conditions for this validation.
7. Preparation and approval of the Conclusion on the compliance of the IL-114-300 aircraft with the regulatory requirements for the strength of the structure during long-term operation within the assigned service goal and service life.

Table 10.3 The list of tests necessary to establish the compliance with the regulatory requirements to structural strength of IL-114-300 aircraft

| **Type of test** | **Tested object** | **Test program** | **Status** |
|---|---|---|---|
| Fatigue, damage tolerance and residual strength tests of aircraft structure elements in lab | Wing and fuselage panels :<br>– Regular zones<br>– Joints<br>– Additional elements if req. | The test program is established in accordance with the program of validation of the design goal..<br>To be accomplished by teardown, disassembly, inspection and fracto-graphy analysis | To start in 2020-2021 |
| Fuselage pressurization | Fuselage panels with modified frame design | The test program is established in accordance with the program of validation of the design goal.<br>@ Tsagi fatigue lab, | To start in 2020-2021 |
| Full-scale airframe fatigue tests | Airframe of IL114-300 with installed :<br>– landing gear supports<br>– takeoff and landing mechanization<br>– fuselage mechanisms<br>– engine mountings and pylons<br>other structural elements if req | The number of loading cycles is set in accordance with the program of aircraft design goal validation<br>@ Tsagi fatigue lab facilities ,<br>Figure 10.1.5 | To start in 2020-2021 |

# 11. Industrial research - Sukhoi Company

## 11.1. SSJ (RRJ-95) fatigue related activities

Currently the amount of research activities related to fatigue issues of Sukhoi Super Jet aircraft are in progress. They are a part of structural integrity program aimed to provide required airframe fatigue and damage tolerance characteristics.

Some of the test under continuation and activities planned for the nearest future are outlined below.

Table 10.1 List of tests to provide and validate structural strength of SSJ-100 aircraft

| Type of test | Tested object | Test program | Status<br><br>(as available by summer 2018) |
|---|---|---|---|
| Full scale test of structure on fatigue and damage tolerance<br><br>AC **95006** | Wing and fuselage structure, incl:<br>– wing;<br>– fuselage;<br>– stabilizer, RV;<br>– empennage, fin ;<br>– engine pylons;<br>– engine mountings to pylons;<br>– flaps;<br>– slats;<br>– ailerons;<br>– spoilers * and brake flaps<br><br>AC systems , considering deformations<br>– AC hydraulic system<br>– Electric systems<br>– ECS<br>– Fuel system | The test program is established in accordance with the program of validation of the design goal..<br><br>To be accomplished by teardown, disassembly, inspection and fractography analysis | N=<br><br>37000 flights<br><br>37000 pressurizations<br><br>+ 18560 isolated tests of nose landing gear<br><br>+100000 isolated tests of main landing gear |
| Fuselage tests<br><br>**Barrel 1** | **Barrel 1:**<br><br>Full-scale fuselage section with cockpit, front door, cargo compartment front hatch | The test program according to program of validation of the design goal.<br><br>Evaluation of durability\fatigue, duration of crack propagation and patterns, residual strength.<br><br>@ Tsagi fatigue lab, | N=<br><br>76705 flights<br><br>76705 pressurizations<br><br>+ 100458 cycles for nose landing gear |

| | | | |
|---|---|---|---|
| Fuselage tests<br><br>**Barrel 2** | **Barrel 2:**<br><br>Full-scale fuselage section with typical frames, door, cargo door, pressure bulkhead | The test program according to program of validation of the design goal.<br>Evaluation of durability\fatigue, duration of crack propagation and patterns, residual strength. | N=<br><br>40426 flights<br><br>70000 pressurizations |
| Test rig **S0157** fatigue**-** | Pressure bulkhead | Evaluation of fatigue, damage tolerance, crack propagation and patterns, residual strength. | 103550 pressurizations |
| Full scale test of structure on fatigue and damage tolerance<br><br>AC **95075** | Wing and fuselage structure, incl:<br>– wing;<br>– fuselage;<br>– stabilizer,<br>– empennage fin ;<br>– engine pylons;<br>– flaps;<br>– slats; | | N=<br><br>30350 flights<br><br>29000 pressurizations |


Figure 11.1.1 Tests of SSJ structure and elements

## 12. Aircraft engine fatigue related activities

Traditionally the sufficient amount of scientific work related with fatigue issues og aviation engines structures and their operation was conducted in Centarl Institute of Aviation motors named after P.I. Baranov, Moscow, Russia.

Major part of the research is related with low cycle fatigue. Nevertheless the problems solved are of high importance to provide the overall safety of aircraft structure.

### 12.1. Strength tests of ceramic heat-protective coatings for hot parts of GTE

Bychkov N.G., Nozhnitsky Yu.A., Avrutsky V.V., Pershin A.V., Khamidullin A.Sh.
*P.I. Baranov Central Institute of Aviation Motors (CIAM)*

Ceramic heat-protective coatings (HRC) along with the system of convection-film cooling are the important elements of the system protecting parts of the engine hot section from high temperatures. The cyclic life of parts and the safety of operation of an aircraft engine sufficiently depend on the strength characteristics affecting the performance of coatings.

A small amount of reliable data on the strength properties of individual layers of thermal protective coatings (HRC) makes it difficult to predict their operational characteristics (effectiveness of thermal protection, durability, etc.). Due to the difficulties in testing thin coatings with the "engine" thickness of the layers and in simulation of the operational loading conditions and temperatures, determination of the coatings properties are based on various simplified test methods.

The Federal State Unitary Enterprise "CIAM" had developed a set of methods to determine experimentally the strength properties of individual layers of HRC having real thickness and deposited by serial manufacturing technology. Experimental methods are based on tests of the simplest types of specimens under operational temperatures and loading conditions (Figure 11.1.1).

*Specimens for cohesive strength tests of HRC* | *Specimens for adhesive strength tests of HRC*

Figure 11.1.1 Specimens to determine the strength properties of HRC layers


Figure 11.1.2 Sublayer and ceramic layer of HRC after tests

The methods proposed for the analyses of the individual HRC layers cohesive and adhesive strength at operating temperatures and loading conditions allow to optimize the coating characteristics (its composition, structure, etc.) at the early stages of HRC development for application in hot engine parts and details that operate under various conditions of thermal loads.

The detailed paper is planned for poster presentation.

## 12.2. Study on the effects of vibration loads on thermal fatigue durability of materials

Bychkov N.G., Nozhnitsky Yu.A., Avrutsky V.V., Pershin A.V., Khamidullin A.Sh.
*P.I. Baranov Central Institute of Aviation Motors*

Details of the hot path of gas turbine engines (GTE) in operation are experiencing low and high frequency loads, with the powerful heat fluxes leading to the appearance of significant thermal stresses on the blades and disks of turbines. CIAM's methods for studying thermal fatigue of materials and thermocyclic durability of full-scale parts of GTE (including those with ceramic coatings) with their high-frequency heating with a given irregularity [1] are widely used in the industry. However, the effect of additional vibration loads imposed on part\detail while operation on thermal fatigue of high-temperature alloys remains unexplored.

To carry out such research the CIAM has developed the unique P926 test rig (Figure 1) allowing simultaneous independent axial loading of a standard cylindrical specimen with thermal stresses and fatigue loads of various levels. The specimen is rigidly fixed between the membranes and is heated by electric current. The vibration-loading unit contains piezo elements and a variable mass disk. Figure 2 presents the results of a study on the influence of vibration loads on the thermal fatigue durability of ZhS6U alloy at maximum cycle temperature of 1000 °C. In case of two-frequency non-isothermal loading of the specimen, the summarized damage at the time of fracture was significantly lower than 1 and valued to 0.53.

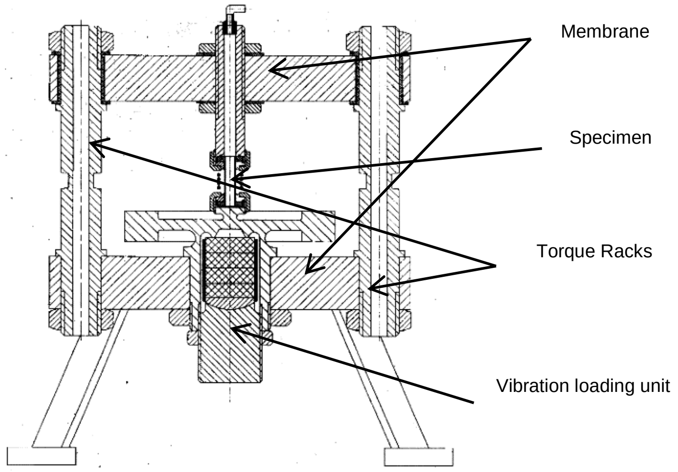



Figure 11.2.1 P926 test rig allowing independent axial cyclic loading at various levels in combination with thermal stresses

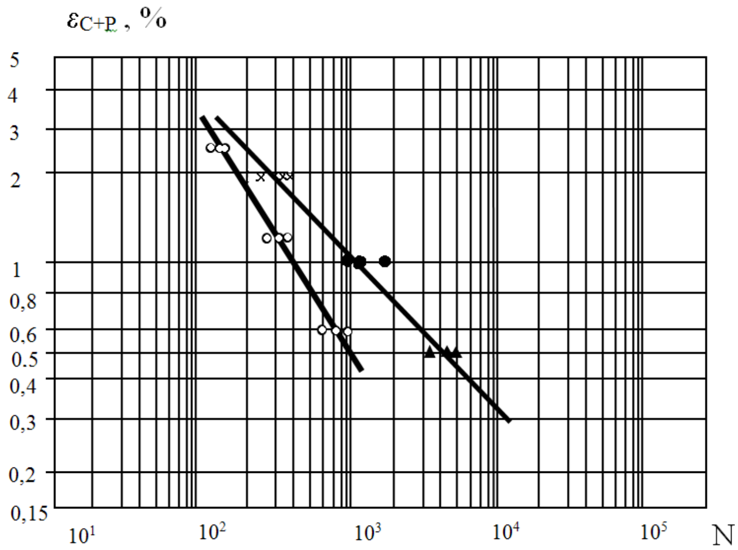



Figure 11.2.2 Influence of vibration loads on the thermal fatigue durability of ZhS6U alloy: × - 2 % ; ● - 1%, ▲ - 0,5 %; ○ – with imposed vibration.

Due to revealed significant effect of fatigue loads on thermal fatigue durability, it is necessary to conduct a set of similar studies for currently used and perspective materials under simultaneous thermal cycling and vibration loading in order to perform a reliable prediction of the service life of hot GTE unit.

## 13. New ICAF participant from Russian Federation

This year representatives from “UEC-Aviadvigatel” JSC design and production company for the development of gas turbine engines for aviation, as well as industrial gas turbines and power plants based on aviation technologies. “UEC-Aviadvigatel” JSC is fully certified and licensed company for development, production, testing and repair of aviation engines and equipment.

Aviadvigatel Business Activities

- development of aviation jet engines;
- development, serial production, turnkey installation, adjustment & start-up, overhaul, warranty and line maintenance of GT gensets rated from 2.5 to 25 MW;
- development, supervision of serial production and operation of IGTs for pipeline gas compressor packages rated from 4 to 34 MW;
- manufacturing of modules, parts, components for aero engines and IGTs developed by UEC-Aviadvigatel and other companies;
- designer’s supervision of serial production of aero engines and IGTs developed by UEC-Aviadvigatel;
- life extension of UEC-Aviadvigatel’s products in service;
- overhaul of UEC-Aviadvigatel’s products;
- maintenance of aero and industrial engines, as well as gensets made by UEC-Aviadvigatel;
- engineering services in mechanics, vibration, combustion, aerodynamics, computer-aided design, development of gas turbine engine components and modules, test stands and test rigs for their testing.

UEC-Aviadvigatel design bureau is a lead designer of the family of the 5th generation engines for MC-21 type short- and medium-haul aircraft and IGTs. Development of the baseline PD-14 engine is one of the priorities of the State Program of the Russian Federation «Development of Aerospace Industry in 2013-2025».

## 13.1. Aviation Aircraft with the PS-90A Engines

Passenger aircraft:

- Tu-204-100 with the PS-90A engines

  Operators: SLO Rossiya Government Squadron, Red Wings, Air Koryo, Cubana Airlines

- Tu-204-300 with the PS-90A engines

  Operators: SLO Rossiya Government Squadron, Air Koryo
  Operators: Business-Aero

- Tu-204SM with the PS-90A2 engines
- Tu-214 with the PS-90A engines

  Operators: SLO Rossiya Government Squadron

- IL-96-300 with the PS-90A engines

  Operators: SLO Rossiya Government Squadron, Cubana Airlines

Special Purpose Aviation

- IL-96-300PU

  Special aircraft for transportation of the RF President, Prime Minister and top officials

- Tu-214PU

  Special aircraft for RF President, Prime Minister and top officials

- Tu-214SR

  Airborne relay aircraft intended to provide communication with top state officials including the regions where receipt/ transmit is impeded

- Tu-214ON

  Special aircraft for inspection flights within the Open Sky Agreement

Cargo Aviation

- IL-76TD-90 with the PS-90A-76 engines

  Operators: Volga-Dnepr, Silk Way Airlines

- IL-76MF-EI with the PS-90A-76 engines

  Operators: Jordan Inter Air Cargo

- IL-96-400T with the PS-90A1

### 13.2. Structural Testing Equipment

Static test stand: certification static testing of the PD-14 engine casings and mounts to evaluate strength, stiffness, steadiness and load carrying capacity of engine casing structural components under loads corresponding to various flight and landing cases, as well as engine casings and mounts cyclic life. The test stand is certified by VNIIMS (Certificate #208/33-13). The stand measurement system is certified by the Federal Agency for Technical Control and Metrology (Certificate of measuring instruments type approval RU.E.28.004.A № 52157).

Optical system of displacement measurement with markers AICON MoveInspect HR: measurement of displacement of an object at the static test.

### 13.3. Sample testing lab\ Aerospace Materials Structural Testing Lab

- 6 x LFM test machines, Walter+Bai AG
- 2 x LFV test machines, Walter+Bai AG
- 3 x Testronic test machines, Rumul
- 14 x ATS Series 2330 test machines, Applied Test Systems
- 1 x INSTRON test machine

The lab is certified by the Federal Agency of Technical Control and Metrology, Interstate Aviation Committee (Certificate # IL-098).


Figure 12.2.1 Materials test facilities at JSC “UEC Aviadvigatel

- Measurement of residual stress at nickel, titanium, iron samples subject to qualification

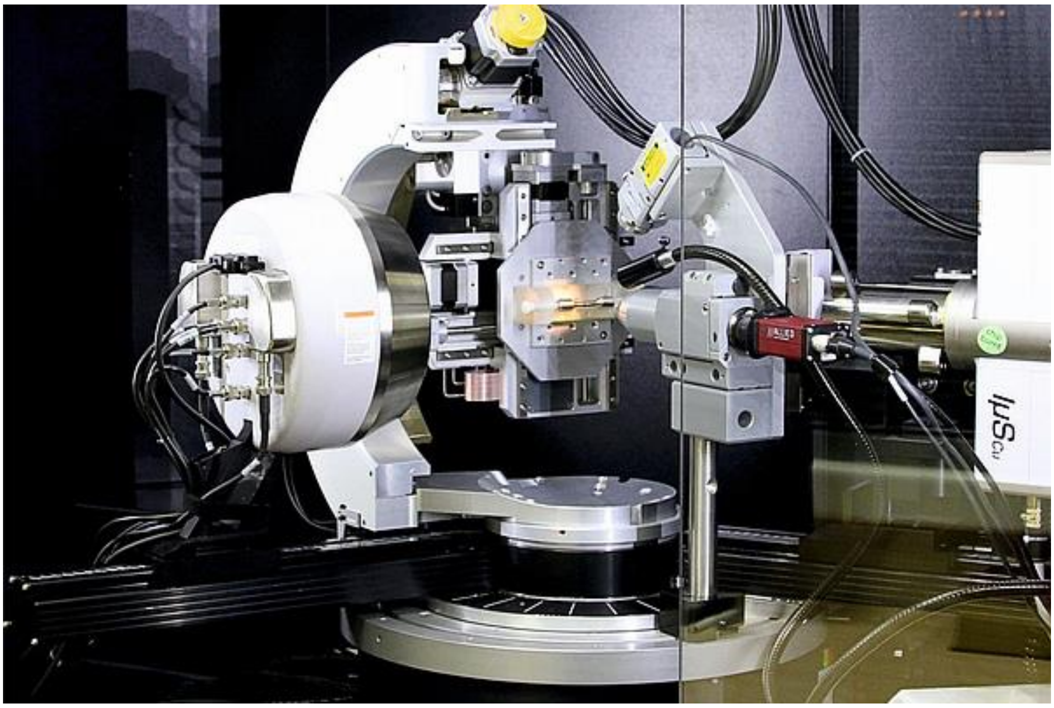


Figure 12.2.2 Bruker D8 Advance X-Ray Diffraction Meter

## 14. Acknowledgements

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