Review of scientific and engineering activities performed in Russia on aeronautical fatigue and structural integrity during 20115-2017.

Content:

1. INTRODUCTION

The paper gives an overview of the activities in Russian Federation, including the research and tests related with current aviation programs. Data given in the paper is based on the work of academic organizations:

- Federal State Unitary Enterprise «Central Aerohydrodynamic Institute n.a. Professor N.E. Zhukovsky»,
- Federal State Unitary Enterprise «Central Institute of aviation engines n.a. P.I. Baranov»,
- Federal State budget-funded Scientific enterprise «Mechanical Engineering Research Institute n.a. A.A. Baranov of the Russian Academy of Sciences»;

organizations of aviation industry that are enterprises of the public joint stock company «United Aircraft Corporation»:

- Federal State budget-funded Scientific enterprise «Mechanical Engineering Research Institute n.a. A.A. Blagonravov of the Russian Academy of Sciences»;

This paper gives the overview of the most valuable research in the field of the structural fatigue and integrity of operated aircraft and perspective ones.

The major part of the research on aviation structure fatigue and damage tolerance characteristics is performed traditionally in Central Aerohydrodynamic institute in close collaboration with design offices of United Aircraft Companies , such as “IRKUT”, “Sukhoi Civil Aircraft”, “Tupolev”, “Ilushin” and others depending on their current aviation program status.

Current aviation program activities are related with MC-21 program by “IRKUT Corporation” aimed for certification of the new structure and “Sukhoi Civil Aircraft” aimed for the future modifications of SSJ-100 airplane

Along with the aviation program National Research Center “Institute of Zhukovsky” and Central Aerohydrodynamic Institute (TsAGI) jointly coordinate the fundamental research with the universities and research centers of the Russian Academy of Science.

The paper was prepared as a survey report for International Congress on aeronautical fatigue and structural integrity to be held in Japan (Nagoya) 5-9 June, 2017.

2. AIRWORTHINESS REGULATIONS

2.1. Overview

Airworthiness regulations that are in power in Russian Federation are quite similar to FARs. Most of the regulative rules are the same as FARs, nevertheless the sufficient work had been performed both analytical and experimental to introduce the rules for civil aircraft.

The full-scale tests became mandatory for estimation of a service life of airplanes of all categories since the early 50-ties, every airplane type should be operated only after such fatigue tests.

The principle of a safe-life was the only principle to ensure the structural safety under long-term operation. In 1961 «Norms of durability» of Russian civilian airliners have included the special section 4.9 "Safety Requirements conditioned by fatigue life".

The accident of the An-10A passenger plane in 1972 showed the need to solve the problems of airframes safe operation at principally new level. In 1976 the cardinal revision of Civil Airworthiness Requirements was carried out, where the possibility is foreseen to set the assigned service life based on either the allowable operating time conditioned by structure safe-life up to fatigue damage appearance; or the allowable operating time taking into account the fail-safe, damage tolerance.

In the 1994 the national Russian Aviation Regulations were harmonized with worldwide regulatory requirements FAR 25.571 and JAR 25.571. There are the following important requirements in the AP 25.571 harmonized national aviation norms (1994). First, the need is specified to consider not only the fatigue but also the possible corrosion and occasional damages. Secondly, the use of safe-life is allowed only when the applicant shows that the use of damage tolerance for a specific structure is impracticable.

2.2. Changes to regulations

In 2015 the AC-AR 25.571-1A Advisory Circular i.e."Estimation of damage tolerance and structural fatigue strength" was developed (Fig. 1).

This Circular considers the FAA и JAA requirements to validate experimentally that the wide spread damage (WFD) will not take place during the aircraft assigned service life. In order to meet the requirement to avoid the WFD in operated structures it is to estimate the Limit of Validity (LOV) for each of the aircraft fleet. The LOV is a airframe operation limit, which is expressed in flights or flight hours and beyond which the WFD extra-risk appearance exists. When the LOV is reached the airframe is to be updated or replaced. To estimate the LOV the full-scale fatigue tests are required to be carried out in scope of two or more aircraft designed service lives.

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РЕКОМЕНДАТЕЛЬНЫЙ ЦИРКУЛЯР

Оценка допустимости повреждений и усталостной прочности конструкции

РЦ-АП25.571-1А

Figure 1 Advisory Circular i.e."Estimation of damage tolerance and structural fatigue strength"

I should be noted that the national Civil Airworthiness Requirements paid great importance to laboratory fatigue tests of full-scaled airframes. The obligatory requirement for full-scale fatigue tests was included in all Strength standards editions. All the existing types of national aircraft have their structure full-scale fatigue tested with high margin of durability in relation to design goal.

The AC-AR 25.571-1A gives the methods to define the compliance with fatigue and damage tolerance requirements for polymeric composite structures. AC is based on national and foreign experience in metallic composite structures design.

The principle difference between the national Airworthiness standards and the foreign ones is a step-by-step augmentation of the set service life of the certain type of aircraft (and helicopters) within designed service lives and extra-designed ones and the individual service extension of each board of this aircraft fleet. The generic opinion letters for fleet operation and the individual ones for each aircraft are issued per each 4-5 years and 1-2 years correspondently. The System assumes the common responsibility of the Manufacturer (Developer) and the Operator.

The stepping is caused by the difficulties to predict for the long operational time, the possible modifications of structure, the presence of a large number of independent operators, the different levels of maintenance, the possible various failures.

3. THEORETICAL BASIS RESEARCH

in the field of fatigue and fracture mechanics for current and potential application in design of airplanes, their maintenance and repairs.

Currently the set of joint research activities is developed between TsAGI and Mechanical Engineering Research Institute n.a. A.A. Blagonravov of the Russian Academy of Sciences. Given below is the example of principal research to be incorporated in practice of TsAGI for fracture analysis of the aviation structures.

3.1. A COMPUTATIONAL TOOL FOR ESTIMATING STRESS FIELDS ALONG A SURFACE CRACK FRONT

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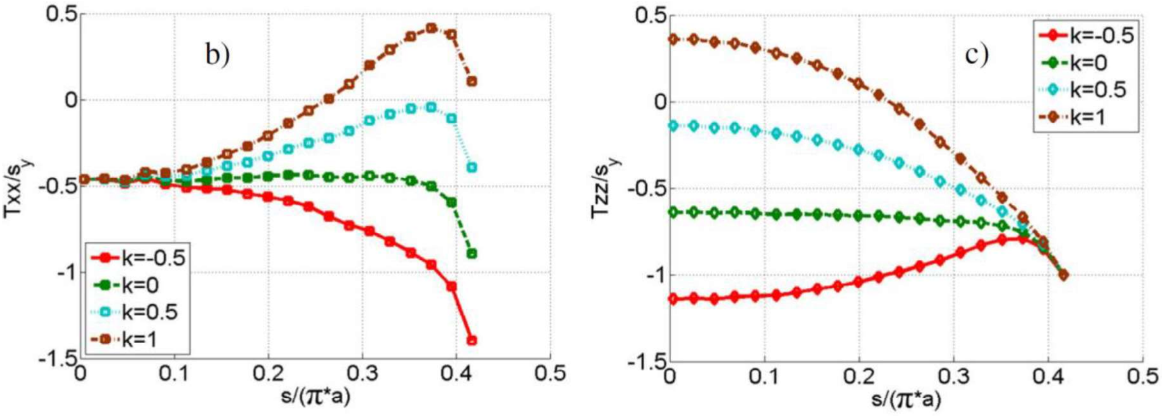
Research proposes a combined experimental and computational method for determination of the singular and non-singular stress terms along the front of the 3D surface crack is proposed. It is suggested to evaluate the terms by means of comprehensive comparison between deformation responses on the structure surface in the vicinity of the crack obtained experimentally and from numerical solutions of the corresponding boundary problem of solid mechanics. As the deformation response, a local displacement field caused by the formation of a small hole at the tip of the crack recorded by digital speckle pattern interferometry may be considered. The proposed approach allows defining such real parameters of the structure as the active load conditions in the crack region and crack sizes. These parameters are used to solve the direct problem and to determine the stress intensity factor KI and Txx-, Tzz-stresses along the surface crack front by means of an improved technique of their calculation. The approach accuracy and stability at different conditions have been proved by means of numerical simulation that examined half-space with planar semi-elliptical surface crack under biaxial loading, thus the potential applicability of the proposed method is demonstrated. The biaxiality effect on KI and Txx, Tzz is discussed.

Numerical modelling. Generation of the original data for the displacement fields is performed by numerical simulation of instant formation of the blind hole in the vicinity of the surface crack. The finite element (FE) model of the elastic half-space under biaxial loading is built in ANSYS software environment in the form of a brick body of finite dimensions, including the surface crack and volume of the blind hole. The special multipurpose macros was created to build the planar crack with arbitrarily 3D orientation and front geometry along which a grid of singular elements is constructed in FEmodel. The crack is represented as a slot that has a wedge-shaped notch tip (along the front) with a very small angle. A 3D 20-node structural solid element (SOLID 95) is used for numerical modelling. The proposed approach of extrapolation with circumference averaging provides more stable values that are less dependent on the choice of measurement point location. Moreover, this method takes into account the stress fields all around the crack tip, so the calculated values of the SIFs and the T-stresses are integral values.

The biaxiali ty effect on the stress Intensity factor and T-stresses.

The biaxial ratio is varied as k =- 0.5, 0, 0.5, 1. Calculation of the SIF and the T-stresses are carried out using the circumference averaging technique. The singular and non-singular term distributions along half of crack front for different biaxial ratios are presented in figure below. As expected, the value of K_I is almost constant along the crack front (slightly decreases towards the body surface), and it does not depend on sx acting along the crack surface. The T_{xx}-stress is negative in the mid-plane of the crack front and does not depend on the biaxial ratio k. The T_{xx}-stress decreases for decreasing k in other parts of the crack front. Generally, a sign of T_{xx} is a function of the k-value and coordinate s. In contrast to the Txx-stress, the Tzz-stress always is negative and constant at the vicinity of the body surface. The value of Tzz tends to increase in the other part of the front when k increases. These results are expected, because the Txx-stress direction in the mid-plane of the front is orthogonal to the direction of the sX, while in the crack front on the surface, these directions coincided. In the case of the value Tzz, the situation is reversed.

Conclusions. The proposed method is based on comprehensive comparison between deformation responses (for measurement points on the surface of the engineering components), which can be obtained experimentally, and numerical solution of the corresponding boundary problem of solid mechanics. As a result, loading conditions and distribution of the singular (KI, KII) and non-singular (Txx, Tzz) terms along the surface crack front can be estimated. A new approach for calculation of the SIF and components of the T-stress is proposed. This approach is based on circumference averaging extrapolation technique. The calculated values of K and T-stress are averaged for every radius of circumference with data points surrounding the crack front and are extrapolated to the crack front tip. The proposed approach provides more stable predicted values that are less dependent on the choice of measurement point locations. The effect of biaxial loading on components of the non-singular T-stress as well as the stress intensity factor is analysed for the elastic half-space with a semielliptical surface crack. In contrast to the stress intensity factor, components of the T-stress along the surface crack front are strongly dependent on the biaxial ratio.



Distribution of the stress intensity factor KI (a), Txx-stress (b) and Tzz-stress (c) along the surface crack front.

3.2. ELASTIC–PLASTIC CONSTRAINT PARAMETER A FOR TEST SPECIMENS WITH THICKNESS VARIATION

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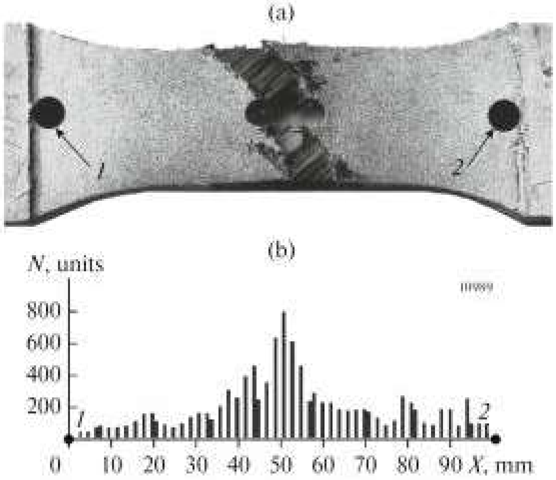
Three-dimensional elastic–plastic problems for a power-law hardening material are solved using the finite element method. Distributions of the J-integral in terms of the normalized elastic–plastic stress intensity factor and constraint parameter A along the crack front for varying the strain hardening exponent, specimen thickness and crack length are determined for edge cracked plate, centre cracked plate, three-point bend and compact tension specimens. The second parameter A in three-term elastic–plastic asymptotic expansion of the crack tip stress field is a measure of stress field deviation from the Hutchinson-Rice-Rosengren field and can be considered as a constraint parameter in elastic–plastic fracture. The loading levels cover conditions from small-scale to largescale yielding. Results of finite element analyses show that the constraint parameter A significantly decreases when specimen thickness changes from 0.1 to 0.5 of the specimen width. Then, it has more or less stable value. Among four specimens, the highest constraint is demonstrated by the compact tension specimen that has the constraint parameter A lower than its small-scale yielding value.



Destruction of the sample in the hole area (a) and sample-length location graph (b) for sources of AE signals detected for the critical tensile load of P = 173 kN; (a1), (a2) positions of AETs for linear location.

3.3. ACOUSTIC-EMISSION EVALUATION OF THE PROCESS OF DESTRUCTION OF A COMPOSITE MATERIAL UNDER TENSILE, COMPRESSION, AND CYCLIC LOADS

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Destruction of the structure of polymer composite materials (PCMs) has been studied by acoustic-emission evaluation method under tensile, compression, and alternating-sign cyclic loads. A program of cluster classification of registered data arrays has been developed and used to reveal specific AE signals that are typical of studied load types. Detection of such signals in the course of deformation of the test samples indicates that irreversible structural changes occur in the composite, it is losing its carrying capacity, or a predestruction state that is critical for PCM has been reached.

3.4. J-A ELASTIC-PLASTIC CRACK TIP FIELD AND THE TWO-PARAMETER FRACTURE CRITERION

(same authors)

The research deals with a review of theoretical and numerical aspects of the two-parameter J-A approach in elastic-plastic fracture mechanics. This approach is based on the three-term asymptotic expansion for the stress field near the tip of mode I crack in an elastic-plastic solid. The parameter A is introduced in fracture criterion as a constraint parameter. The unified JC-A master curve is constructed for different geometry and thickness of specimens. Constraint parameter A and J value for various configurations of specimens and the hardening exponent is computed by means of three-dimensional elastic-plastic stress analyses employing finite element method.

Theoretical and numerical aspects of basic parameters J and A including in the three-term asymptotic expansion of the crack-tip stress field are discussed. The effect of specimen geometry and type of loading on the J-integral and the constraint parameter A is demonstrated. The two-parameter elastic-plastic fracture criterion JC-A is described for structural integrity assessment. Conservativity of elastic approach in elastic-plastic fracture mechanics from a viewpoint of the two-parameter J-A fracture criterion has been analysed.

4. AIRFRAMES VARIABLE LOADING RESEARCH

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State Research Center Federal State Unitary Enterprise «Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky"»

The variable loads that are applied to the structure are the physical nature of its fatigue. The typification of load test programs of flight ground and air phases is carried out to perform the full-scaled structures fatigue testing

In order to reproduce the factual civil and transport aircraft wing loading the ISKRA-100 typified quasirandom sequence of stresses in the lower wing surface program was developed under the lead of Yu. A. Svirsky in TsAGI (Fig. 2).

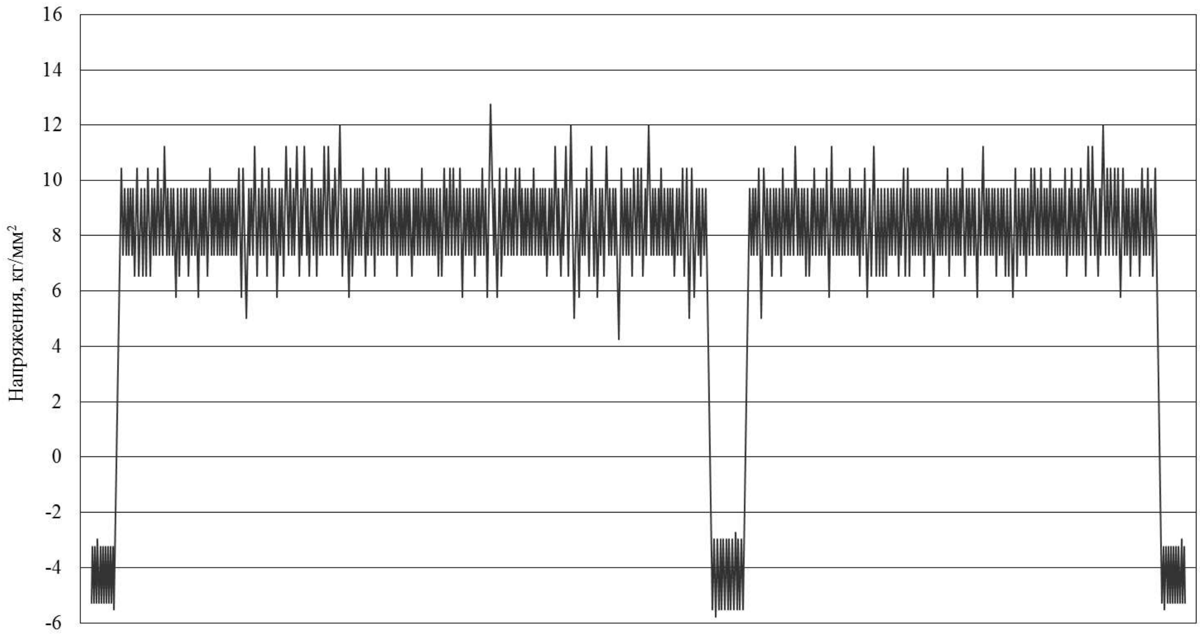


Fig. 2. Stresses cyclogram of the 6-th and 7-th flights (iFhGi) of ISKRA-100 program

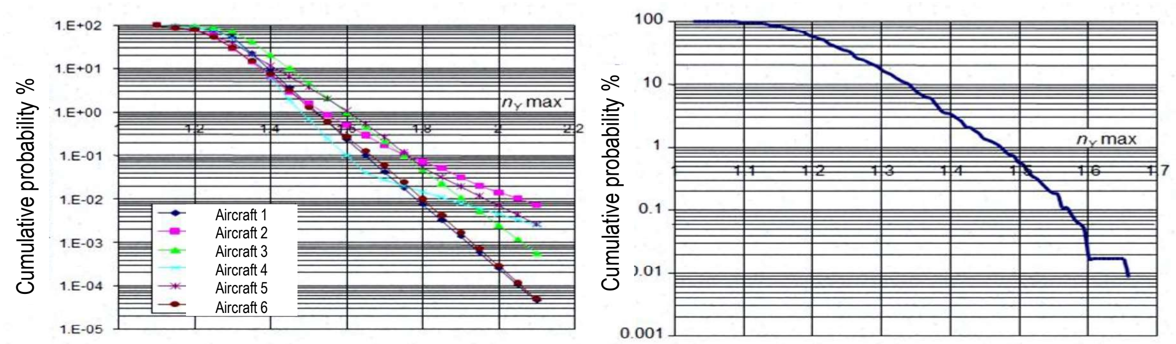
The ISKRA-100 program structure is similar to that of the TWIST program one and the Boeing-767 fatigue tests loading program one. Currently, the service life full-scale tests of SSJ-

100 and MC-21 Russian civil aircraft are carried out based on quasirandom programs, which are updated versions of ISKRA-100 and TWIST programs.

The validated refinement of conditions to outlive the aircraft prescribed service life is based on the information on the airframe critical areas variable loading. The flight parameters information that is recorded by the crash data recorder is to be processed correspondently.

The flight parameters recording based on airborne recorders is used to define the individual loading of individual groups and single aircraft.

Based on the post flight processing of data obtained from flight regimes recorders of magnetic type (FRRMT) Orlova T.I. and Tsymbalyuk V.I. have found out the static regularities for vertical g-factor in aircraft center mass (Fig.3), the static regularities for fatigue damageability (Fig.4), and the $\boldsymbol{\eta_3}$ reliability factors fir individual loading scattering for metal and composite materials (Fig. 5).

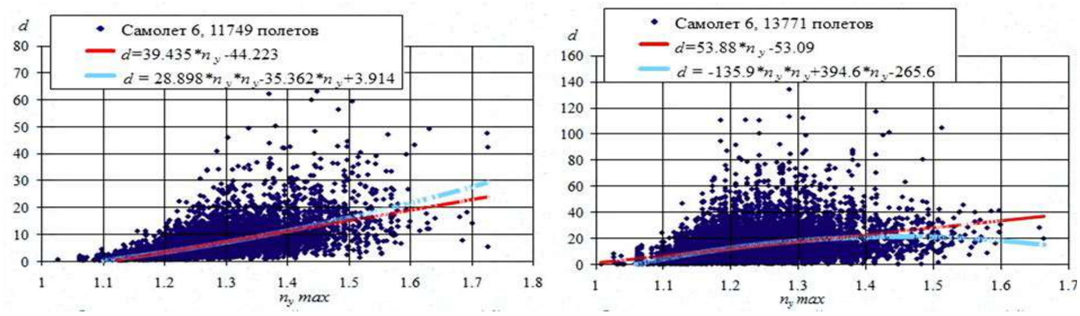


Cumulative probability of vertical load factor maximums per air phase of flight

Cumulative probability of vertical load factor maximums per ground phase of flight

The logarithm of maximum load factor per flight does not fit the normal distribution law

Figure 3 Statistical regularities for maximum overload factor in airplane center of mass

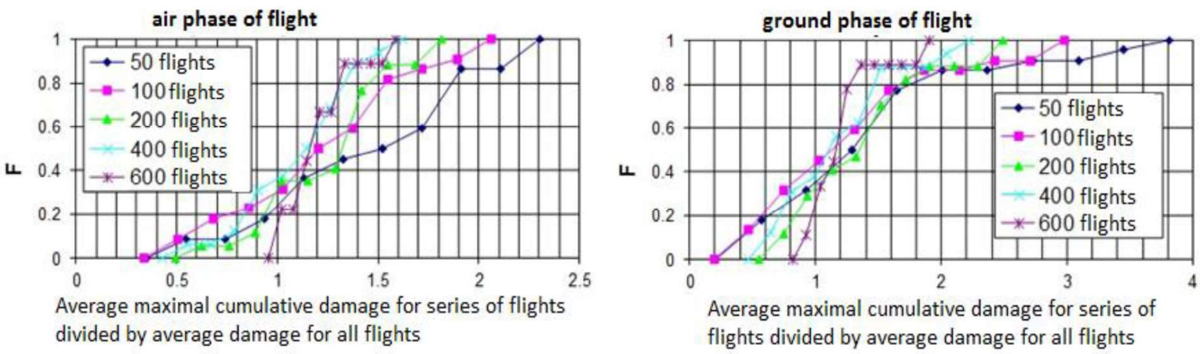


Assumed fatigue damage due to vertical load factor vs. maximal values of vertical load factor, air phase

Assumed fatigue damage due to vertical load factor vs. maximal values of vertical load factor, ground phase

Similarity of exceeding loads (they are parallel in different flights) was not proved. It that were true, maximal fatigue damage should be greater than mean damage in hundreds times, while this relation does not exceed 10, and is close to 3- 5 for maximum load factor

Figure 4 Statistical regularities for fatigue damage



Data were collected on 27 airplanes of 4 companies, total 15000 flights

	Air stages					Ground stages				
Number of flights	50	100	200	400	≥600	50	100	200	400	≥600
η3, metal	2.7	2.5	2.2	2.1	2	4.2	3.4	2.9	2.6	2.3
η3, composite	14	9	7	5	4	14	9	7	5	4

η3, recommended factor of reliability on individual loading scattering (Methods of compliance 25.571)

Implementation of monitoring will allow to increase the service life of fleet in two times

Figure 5 Accumulated fatigue damages during aircraft operation

5. STUDY OF POLYMERIC COMPOSITE MATERIALS FRACTURE BEHAVIOR

In Russia and in TsAGI the comprehensive composite material and structures strength researches were carried out recently as the MC-21 aircraft with polymeric composite material (PCM) wing was created. A number of important results in this area are given hereunder.

5.1. RESULTS OF RESEARCH BASED ON THE DEVELOPMENT OF EQUIVALENTS DETERMINATION PROCEDURE FOR THE PRIMARY LOAD-CARRYING ELEMENTS OF AIRCRAFT POLYMERIC COMPOSITE MATERIALS

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State Research Center Federal State Unitary Enterprise "Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky", 2016

The possibilities to use the following methods to estimate the PCM components damage tolerance are developed and justified:

- fatigue curve approximation in fatigue damage range up to 10^7 cycles;

- taking into consideration the cycles with different asymmetries;

- fatigue damages summing up.

Based on the investigations been performed the Conclusion was made for compression zone concentrator typified as a strip with free hole:

- the tests procedure is developed that allows to obtain the experimental data with durability scattering not more than **SlgN = 0,3**. Taking into account the fatigue curve slope obtained when working off three service lives of PCM structure the stress uprating coefficient (art 7.11. CDT 25.571) is from 1.09 to 1.15 i.e. it does nor surpass the value been adopted for full-scale tests;

- it was obtained that the application of the damages summation linear hypothesis and the suggested form of extreme amplitudes diagram allows to obtain the acceptable results to justify the PCM members strength under condition that the calculation is carried out for loading levels under which the durability exceeds the 50 000 cycles level. At this, for all the tested loading programs which meet this criterion the sum of fatigue damages is in range as follows:

A = 0,57÷1,08.

5.2. VALIDATION OF METHODS TO DETERMINE THE PARAMETERS OF CRACK RESISTANCE UNDER STATIC AND FATIGUE LOADING BY USE OF MODEL I AND II FOR POLYMERIC COMPOSITE MATERIALS

KOROLEVA YU. V., LOUKYANCHUK A.A., PANKOV A.V., SVIRSKY YU. A., TOKAR V.L. // State Research Center Federal State Unitary Enterprise "Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky", 2016

The fracture toughness vs. the material thickness (Fig. 7) and the fracture kinetic diagram are obtained in paper (Fig. 8).

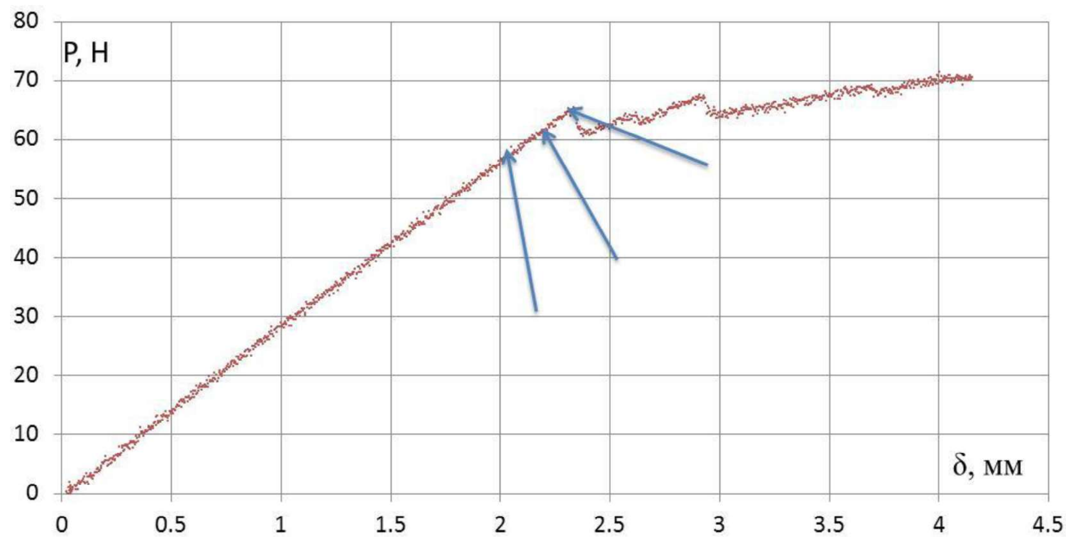

Fig. 7. Fracture toughness

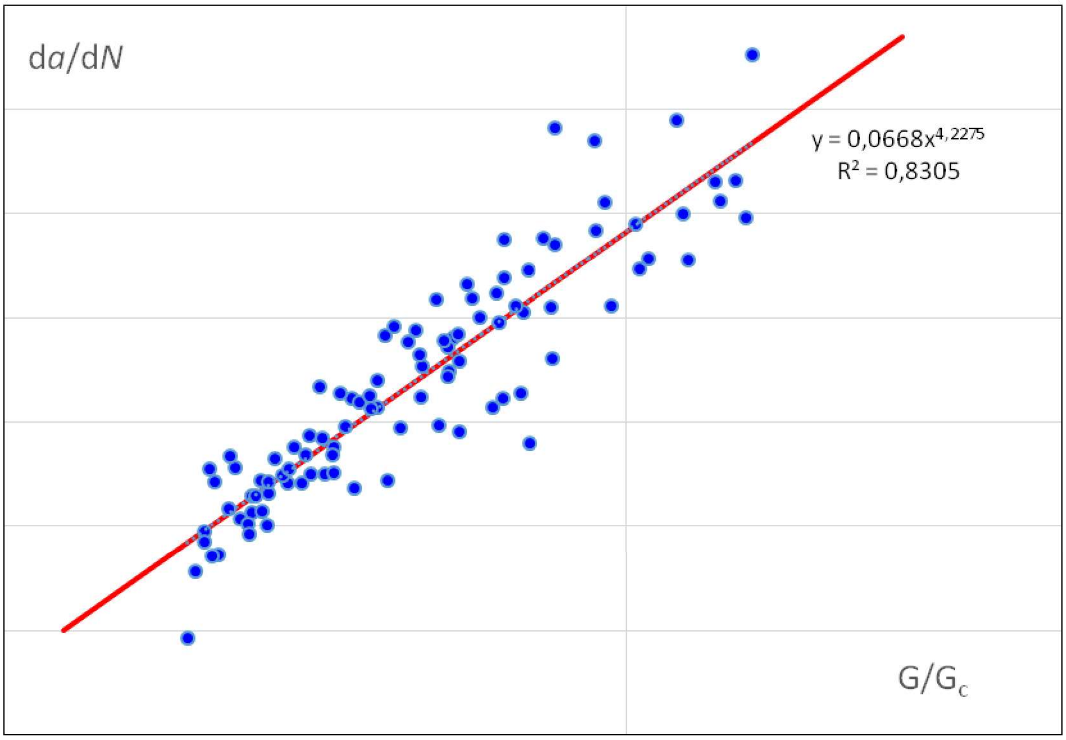

Fig. 8. Fracture kinetic diagram

The following results are obtained of the studied carried out:

1. The list is compiled of parameters needed to justify experimentally and analytically the service life characteristics of airframe delaminated components;

2. The standards are developed the tests techniques are refined to define the interlaminar fracture strength parameters under static and fatigue loading by modes I (uneven delamination) and II (shear);

3. The fracture toughness values as well as the parameters of fatigue curves and fracture kinetic diagrams for PCM by modes I and II are obtained experimentally;

4. Taking into consideration the fracture strength parameters values obtained in order to justify the PCM principle structures components strength conditioned by delamination permissibility, it is necessary to carry out the full-scale tests by quasirandom loading program, which is used for metallic part of structure with making the artificial delamination in the mostly loaded areas.

5.3. STATISTIC PROCESSING PROCEDURE FOR TEST DATA TO ESTIMATE THE IMPACT DAMAGE DETECTABLITY IN COMPOSITE STRUCTURES IN CE\ASE OF VISUAL INSPECTIONS

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1 - State Research Center Federal State Unitary Enterprise "Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky"; 2 - Federal State Unitary Enterprise "State Civil Aviation Research Institute"

The authors have developed the experimental data statistic processing procedure to obtain the defect detection probability vs. its size under different conditions of inspection, as well as the estimations of the composite material structures minimal damage size that is reliably detectable by visual inspection.

The procedure is based on the binominal distribution of impact damages detection probability.

By use of a number of experimental data been obtained under different conditions and scopes of testing it is showed that the Weibull function is the most acceptable in terms of deviation square minimum.

Fig. 9 shows graphically (by spots) the experimental estimations of probability of detection vs. the dent depth.

Fig. 10 shows the approximation by different functions of experimental data been obtained by detailed (a) and general (b) visual inspections.

Fig. 11 shows the reliably detectable damage size (RDDS) estimation vs. the number of inspections when simulating the experiment by Monte-Carlo method.

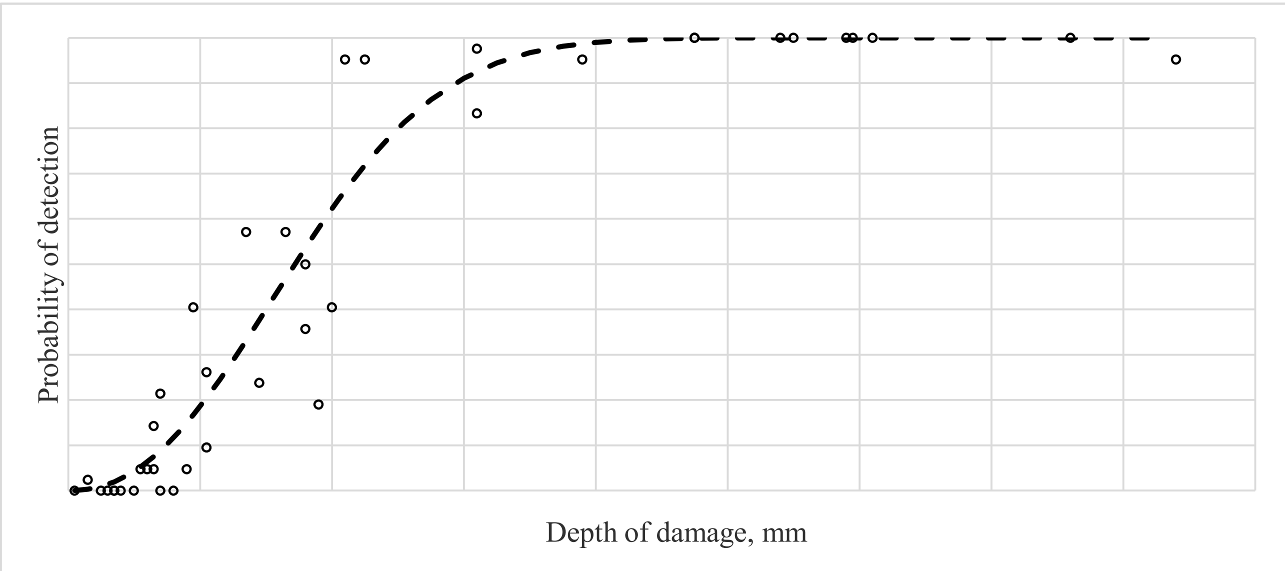

Fig. 9. Probability of detection vs. dent depth

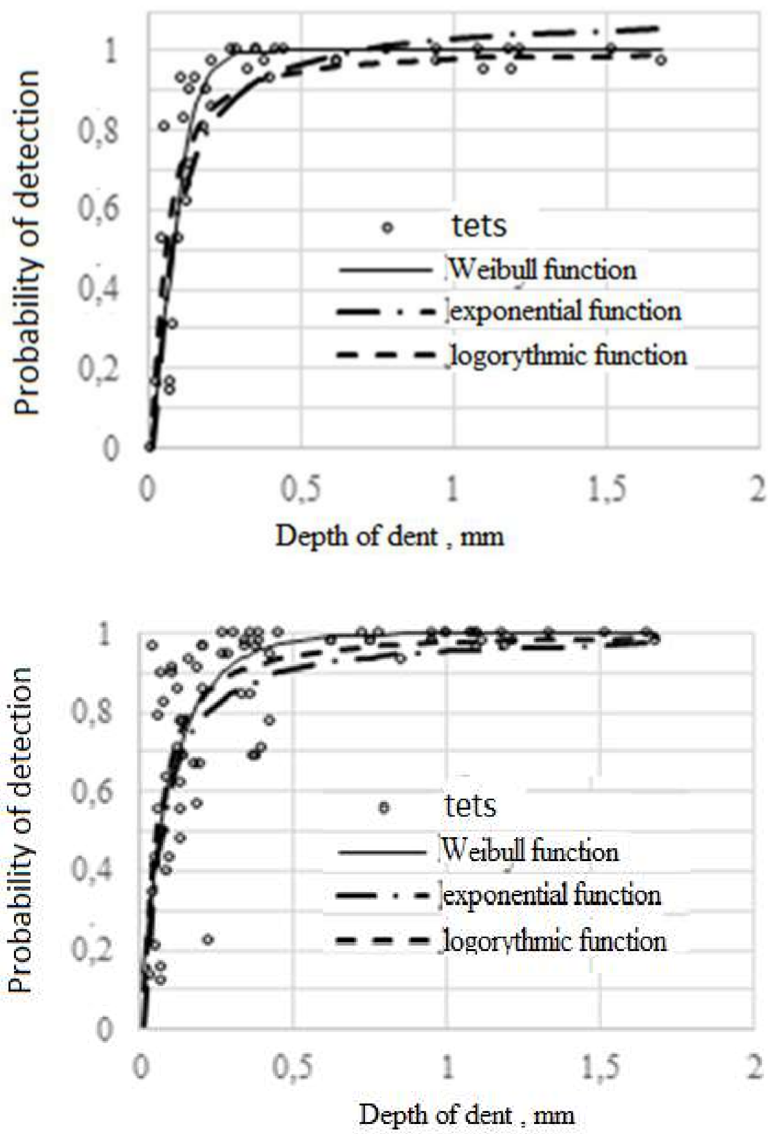

Fig. 10. Approximation by different functions of experimental data been obtained by detailed (a) and general (b) visual inspections

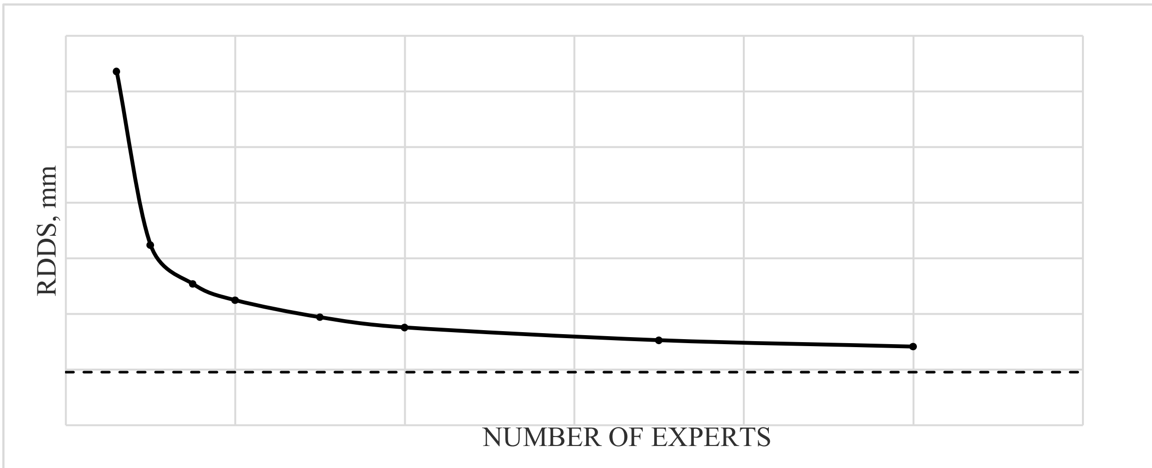

Fig. 11. RDDS estimation vs. the number of inspections

5.4. EXPERIMENTAL STUDY OF RELIABILITY TO DETECT THE SURFACE DEFECTS OF COMPOSITE STRUCTURE WHEN CARRYING OUT VISUAL INSPECTION

SENIK V.YA.[1], DUBINSKY S.V.,[1] GVOZDEV S.A. [1], KHLEBNIKOVA I.G. [1], FEIGUENBAUM YU.M.[2], METELKIN E.S.[2], MIKOLAYCHUK YU.A.[2]

1 - State Research Center Federal State Unitary Enterprise "Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky"; 2 - Federal State Unitary Enterprise "State Civil Aviation Research Institute"

In the work the experimental assessment of probabilities of detection of the impact damages (dents) of different sizes is obtained.

The experiments are carried out of three-stringer solidly reinforced specimens of 3mm thickness skin.

90 specimens were manufactures totally..

The damages were made by the striking spherical end with 25 mm diameter.

Two groups of experts inspected the specimens. One group was not experienced in inspecting visually the aircraft (not qualified experts). The second group was composed of experts experienced in visual inspections if metallic airframes. The inspections were carried out in three steps: at 5m distance, 3m distance, and o.7m distance (detailed inspection simulation).

In Fig. 12 the averaged dependences of dents detection probability obtained in work on their depth are presented.

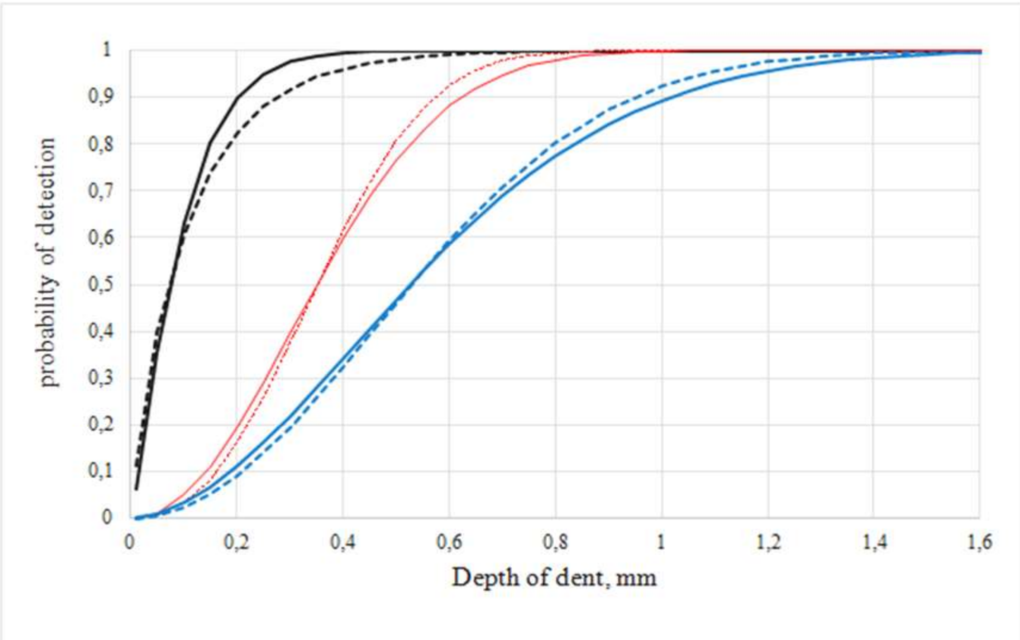

Fig. 12. The averaged dependences of dents detection probability on their depth obtained during inspecting the grey specimens at different distances.

The defect is considered as a reliably detectable when the detection probability which of at a single check is ≥90% at 95% reliability.

When detailed visual inspecting the minimal values of reliably detectable dent size are in range from 0.25 mm to 0.85 mm.

To compare the experimental results obtained and the foreign authors data the foreign works experience in estimating the damages visual detection probability was summarized based on Boeing and Airbus PCM structures in EASA and SAA.

It is noted that the tests environment and the reliably detectable impact damages size values obtained, in general have a good agreement with the analogue foreign researches data.

5.5. COMPOSITES PROGRESSIVE DELAMINATION IN BOLTED JOINTS

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1- State Research Center Federal State Unitary Enterprise "Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky", 2 - Federal State Unitary Enterprise "Siberian Aeronautical Research Institute n. a. S.A Chaplygin"

The PCM bolted joints specimens strength was experimentally tested. Based on the progressive failure pattern the computational estimation of ultimate load and failure type of two shear bolted joints in layered composites was made.

The progressive failure pattern use efficiency to predict the ultimate load and the failure type of shear bolted joint is proved by comparison of numerical study results and the experimental data.

The calculation used the 3-D FE Model of bolted joint contact interaction with taking into account the friction factor. The model was created based on the FE ANSYS complex. The CM layers are simulated by the homogeneous material with monolayer mechanical characteristics.

The research presented applies the Hashin criterion to analyze the failures.

The paper presents the junction strength estimation results for a number of specimens groups by use of Hanshin criterion and maximal stresses one. It is demonstrated the progressive failure model application is possible when using the both criteria. Nevertheless the Hanshin criterion gives mainly the conservative estimation.

The possibility to predict the type of specimen failure (fracture, fissure, bearing stress) is a relative particularity of bolted joint strength estimation by the progressive failure pattern.

5.6. ANALYSIS OF RANDOM OPERATIONAL EFFECTS ON THE TRANSPORT AIRCRAFT WING STRUCTURE

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1- State Research Center Federal State Unitary Enterprise "Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky", 2 - Federal State Unitary Enterprise "Siberian Aeronautical Research Institute n. a. S.A Chaplygin"

The analysis of the extensive database (about 2 500 cases) of the impact damages registered in the course of transport aircraft terrestrial service during 2000-2015 is carried out.

Damages are classified by the types, the airframe elements, and the damages reasons. The wing structure critical zones, which are most strongly subjected to casual interactions are found out; the most typical scenarios of their realization are defined for each zone. The statistical regularities of impact effects, which are characterized by their probability and intensity are defined.

6. AGEING AIRFRAMES SERVICE SAFETY ENSURING

NRC, TsAGI, GosNII GA, PJSC "Ilyushin", PJSC" Tupolev, "Antonov" Company

Up to our days many types of aircraft have run their design course and service life. As far as such ageing aircraft (long-term operation) are practically impossible be replaced by new types, the aviation authorities are forced to extend the service life and the operation time of ageing aircraft extra designed values. About 80% of national civil aircraft which of the operational endurance surpasses the designed values by 1.5-2.0 and more is still in operation. These aircraft were produced in the 60-70-th of the last century. Their designed operation life was supposed to be 15-20 years, but up to nowadays the operation life of aircraft such as Il-18 and An-12 is 50-60 years.

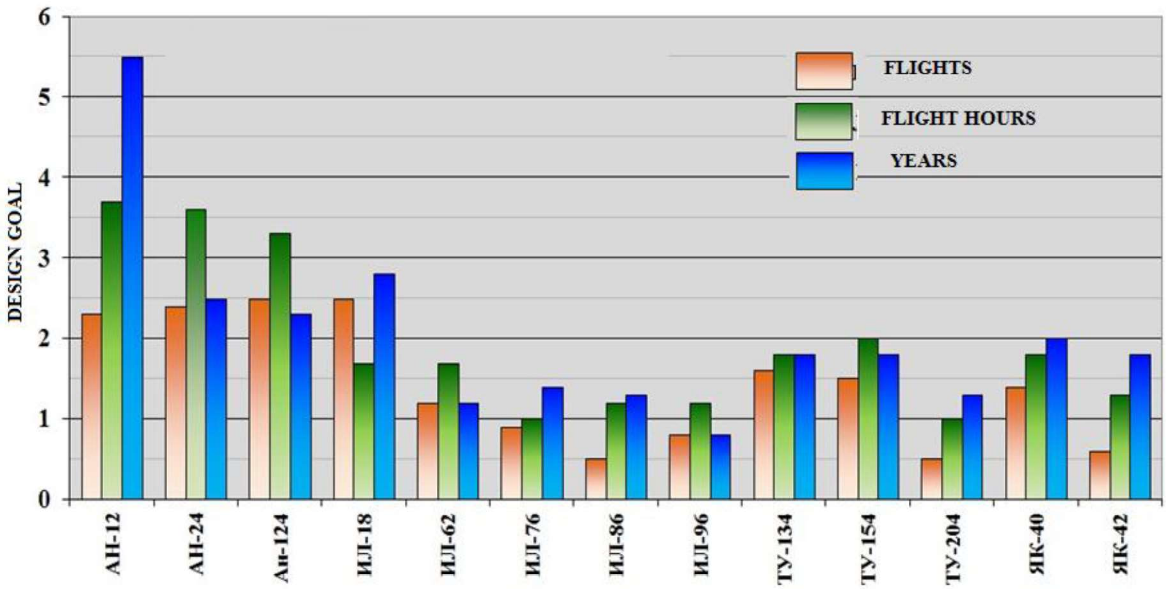

Figure 13 Relationship of the allowed operating time and the designed values (flights, flight hours, years) of the main types of national transport aircraft

According to the procedure been approved in Russia the aircraft service life and cycle life are extended step by step for fleet and for each board individually.

The main requirement when extending the service life individually is both the airframe detailed inspection by the special program, and the analysis of this aircraft sample loading during the previous operation.

The aircraft are in exploitation by the durability principle (fail-safe and damage tolerance)

The main problems that are to be solved when assuring the ageing aircraft structures safe life are as follows:

- Corrosion;
- Materials properties degradation (changes);
- Widespread Fatigue Damaged (multi site damages (MSD) and multi element damages (MED).

7. FULL-SCALE AIRFRAMES FATIGUE AND DURABILITY TESTS IN TSAGI IN 2015-2017 PERIOD

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1-State Research Center Federal State Unitary Enterprise "Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky"; 2 -SCAC, Sukhoi Civil Aircraft Company 3- PJSC " Ilyushin Aviation Complex"; 4 - JSC A.S. Yakovlev Design Bureau; 5- LLC "Scientific-production concern " Sukhoi Attack aircraft" ; 6 -Public JSC "Irkut" Scientific production Corporation ; 7 - AeroComposite JSC

To carry out the service life tests of full-scale airframes TsAGI has implemented the computer-controlled multichannel electro-hydraulic servo-systems, the computerized informational and measuring systems and the nondestructive method of structures control. .

Use of multi-channel loading systems allows carrying out the comprehensive bed tests of airframe assembled, including the wing, flaps, and slats, the fuselage, horizontal tail surfaces and vertical tailplane with elevators and rudders, main gear leg and nose gear, engines mounts. Such tests allow reproducing more completely the external loadings that take place in standard aircraft operation.

The fatigue tests are performed until the operating time that corresponds not less than to three designed service lives.

The transport and civil aircraft are tested by loading programs of random alteration of variable loads of TWIST type.

The durability tests are performed to estimate the duration of damage growth in structure and the damaged structure residual strength. As a rule, the structure is tested after the fatigue testing.

When testing the structure by non-destructive methods the use as follows: visual optic techniques, instrumental methods (eddy-current tests, ultrasonic defectoscopy, acoustic emission method, X-rays, and so on); continuous monitoring by thin-foil sensor or wire one, which are bonded onto structure surface in enhanced concentration areas of.

The test-bed complex of TsAGI allows performing in laboratory the durability and fatigue tests up to five full-scale structures simultaneously.

7.1. STRUCTURAL FATIGUE TESTS OF MODIFICATION OF CIVIL AIRCRAFT SUKHOI SUPERJET- 100LR

The tests are aimed at experimental verification of designed service life in 54 000 flights.

Figure 14 The service life test rig to trial the Sukhoi Superjet 100LR modification.

7.2. STRUCTURAL FATIGUE TESTS OF MODIFICATION OF ILUSHIN IL-76

Figure 15 Test rig to trial the Il-76-MD-90A transport aircraft updated version

The possibility to combine and carry out the static strength test and the fatigue test of the same airframe is the principle peculiarity of this tests.

7.3. STRUCTURAL FATIGUE TESTS OF MC-21 FULL SCALE COMPONENTS

To select the design engineering solutions and to ensure the structure designed service life of 60 000 flights for the MC-21 civil aircraft pressurized fuselage the fatigue and durability tests are carried out of test section and pressurized fuselage curved panel.

Figure 16 Full scale test of wing and fuselage structure of MC-21.

7.4. STRUCTURAL FATIGUE TESTS OF MC-21 FULL SCALE WINGBOX

The fatigue and durability tests were performed of composite wing box prototype in order to perfect experimentally in production the basic technologies of manufacturing, assemblage and quality control of MC-21aicraft composite wing. Fig. 17 shows the facility to test the MC-21 aircraft test composite wing box.

Fig. 17. Fatigue testing the MC-21 medium-haul civil aircraft test composite wing box at NIO-18 TsAGI

7.5. STRUCTURAL FATIGUE TESTS OF COMBAT AIRPLANE YAK-130

The fatigue tests of theYak-30 trainer aircraft design are carried out by random range of variable loads. The aim was to verify the service life in 10 000 flight hours, 20 000 flights.

Figure 18. Fatigue testing the Yak-40 airframe

7.6. STRUCTURAL FATIGUE TESTS OF COMBAT SU-25

To provide the Su-25 airframe extra-designed service life the fatigue tests were carried out after the aircraft long-term operation. Figure 19 shows the test bench for testing this aircraft

Figure 19 Fatigue testing the Su-25 airframe

The detailed results of the above mentioned service life tests of full-scale aircraft structures are given in the oral report of Sherban' K.S., head of service life tests laboratory, NIO-18, TsAGI, Doctor of Engineering.

8. DEVELOPMENT OF METHODS FOR FULL-SCALED METALLIC-COMPOSITE AIRFRAMES SERVICE LIFE TESTS

KONOVALOV V.V.[1], SHERBAN K.S.[1], KOULIKOV S.V.[2], STRIZHIUS V.E.[2]

1- State Research Center Federal State Unitary Enterprise "Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky" 2 - AeroComposite JSC

The composite materials peculiarities lead to the fact that experimental verification of metal-composite structures service life characteristics are to be based on relevant requirements both for the composite structures, and the metal ones. Such testing is to show that catastrophic failure of airframe due to fatigue, environment effect, production defects or accidental operational damages shan't take place within aircraft service life.

The paper has analyzed the main features of failure mechanism under the cyclic loading the metal and composite structures. The theoretical principles based on these features are developed of variable loading range formation during the certification service life tests of metallic-composite structures.

It is demonstrated that the loading program is required to provide the service life justification reliability when certifying the aircraft composite structure part and to assure the full-scale tests performance within appropriate time-frame. The basic correlations are obtained that specify the augmentation coefficients of loading program.

Approaches to form the quasi-random loading block program for service life tests of the full-scale airframe taking into account the failure mechanism feature of metal-aircraft structures

Two main approaches to carry out the certification tests of aircraft metal-composite structures are analyzed and the recommendations for their practical use are developed.

9. FATIGUE CRACKS GROWTH DURATION ESTIMATION BY FRACTOGRAPHY IN MAIN PRIMARY AL-ALLOY COMPONENTS DURING AIRCRAFT FULL LEVEL SERVICE LIFE TESTS

STOYDA YU.M. //

State Research Center Federal State Unitary Enterprise "Central Aerohydrodynamic Institute n. a. Professor N.E. Zhukovsky"

The fractography is widely used in TsAGI to obtain the fatigue cracks growth curves in structure zones, which are inaccessible for nondestructive control, including the estimation of small cracks growth.

The accuracy enhancement and the time-saving are obtained by introducing the encoded sequence of marker loads into the loading program.

The examples are given below the way to estimate the fatigue cracks growth duration by fractography in a number of aircraft primary structural members that were tested in TsAGI.. Figure below shows the fatigue crack growth curve in Yak-130 airframe rib strut.

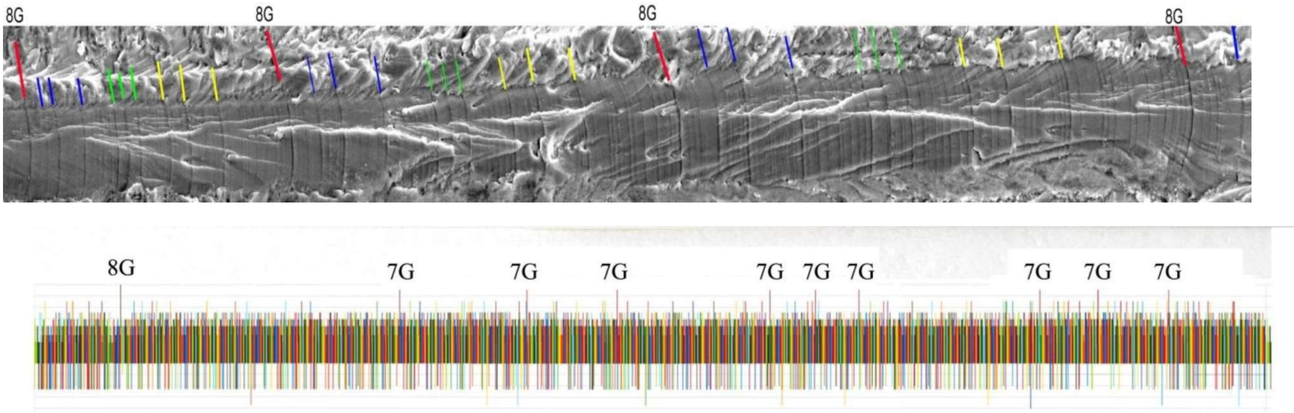


Figure 20 Comparison of the micro-picture of fracture with the maximal g-loads range in a single regular block of flights (1 block = 856 flights)

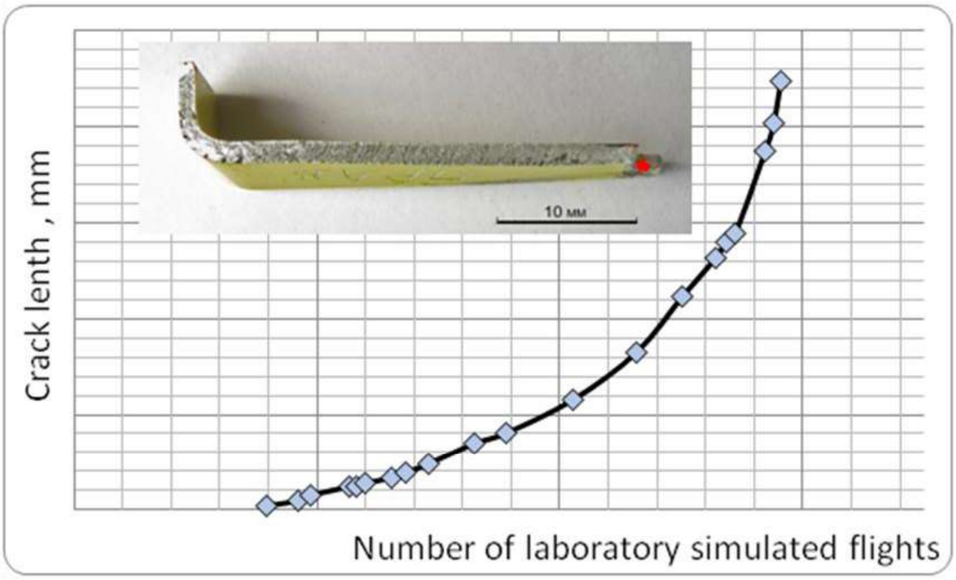


Figure 21. The fatigue crack growth curve in rib right strut under laboratory service life testing the Yak-130 airframe

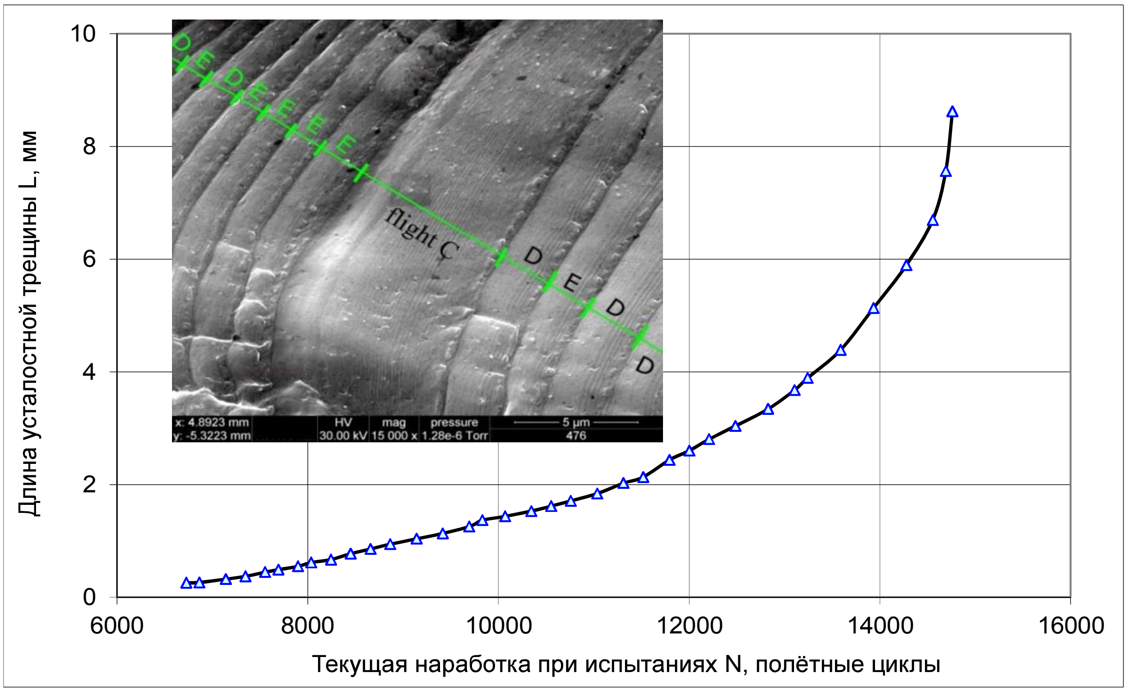
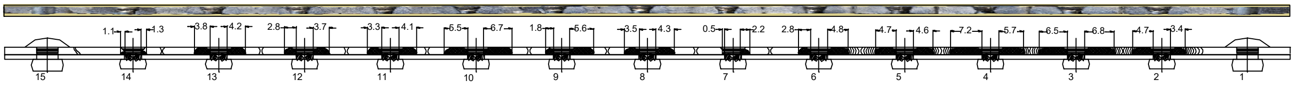


Figure 22 The fatigue crack growth curve in rib #33 under laboratory service life testing the RRJ 95B airframe



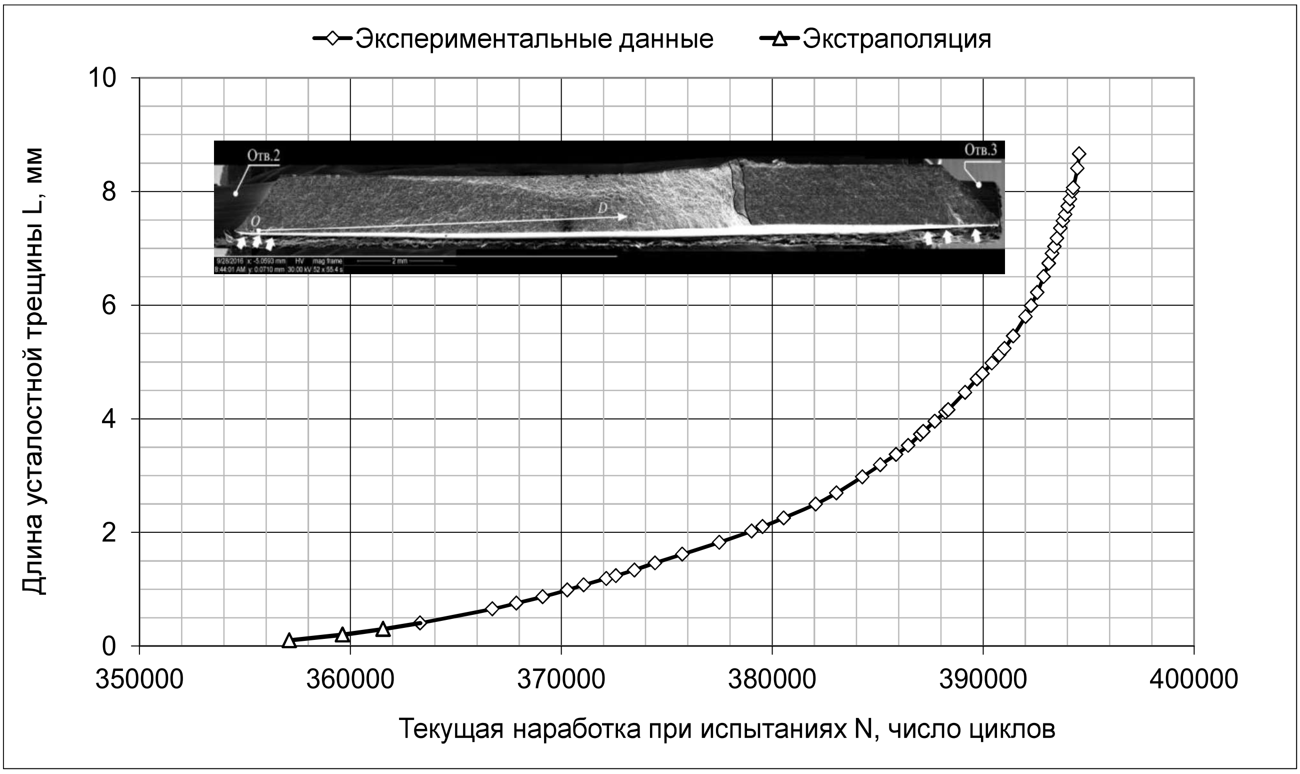


Figure . 23 MC-21 fuselage skin longitudinal joints, damaged by multisite cracks and the growth curve of one of these multi site cracks.

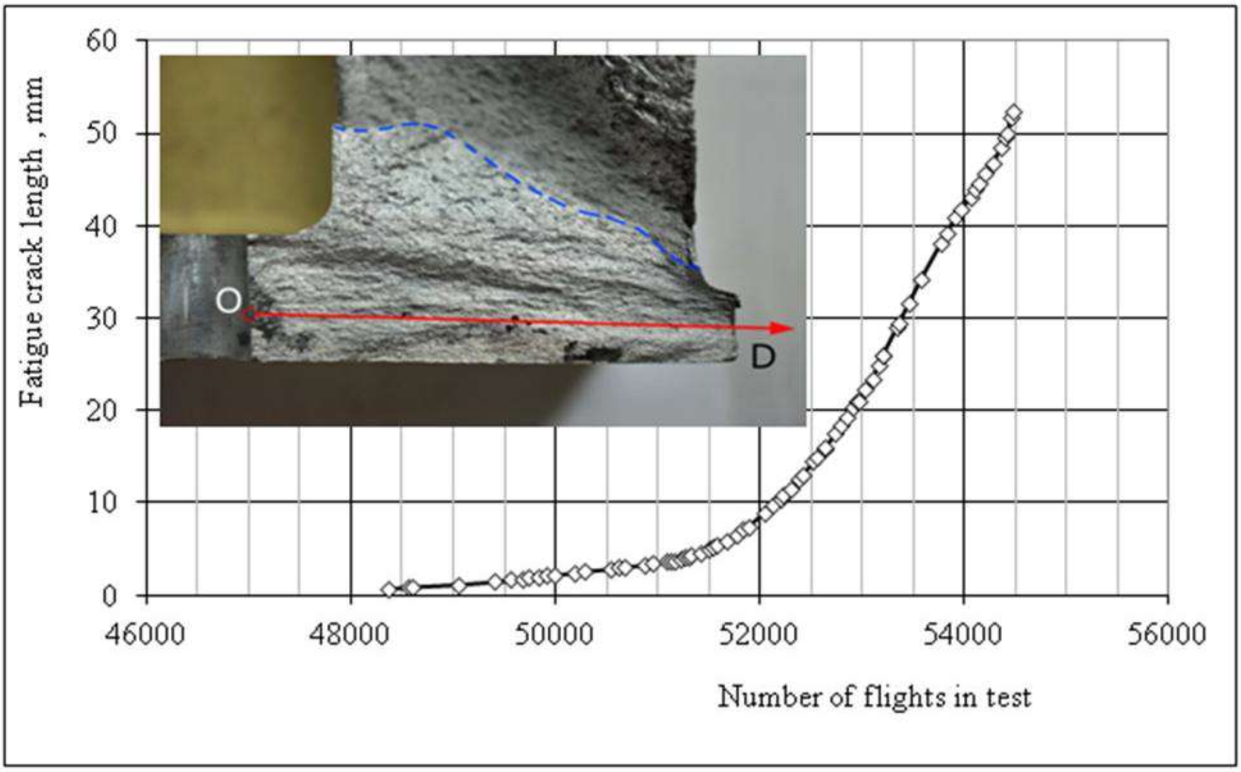


Figure 24 The fatigue crack growth curve in rib #50 under laboratory service life testing the Il-96-300 airframe

The fatigue cracks growth duration values given above are used when determining the fatigue cracks growth regularities, the beginnings and periodicity of inspecting the main primary elements of aircraft structures in operation

10. CENTRAL INSTITUTE OF AVIATION MOTORS. CERTIFICATION TESTS LABORATOTY

10.1. STUDY OF LOW-CYCLE AND MULTICYCLE FATIGUE RESISTANCE AND CRACK RESISTANCE FOR SPECIAL QUALIFICATION OF MATERIALS FOR PRIMARY DETAILS OF AVIATION GAS-TURBINE ENGINE

N.P. VILTER, M.E. VOLKOV, E.R. GOLUBOVSKY,

CIAM , Moscow RF

For the period of 2015 -2017 “Central Institute Of Aviation Motors” performed a number of certification tests. In CIAM, tests for the special qualification of materials for the primary and critical parts of aviation gas turbine engines were carried out in CIAM laboratory , including cross-testing in joint SAFRAN research. Tests were performed according to ASTM standards and local Russian standards.

For the period of 2015 – 2016 more than 6,000 specimens were tested for short-term strength to obtain the deformation curves, low-cycle fatigue for severe and soft loading. Characteristics of crack growth rate, multi-cycle fatigue, long-term strength and creep were defined. The test temperature was up to 1100 ° C

Figure 25 Certification test laboratory in CIAM

10.2. ***ESTIMATION OF CHARACTERISTICS OF RATES AND INTERVALS OF STABLE GROWTH IN OF NICKEL DEFORMABLE ALLOYS AND GRANULAR ALLOYS***

M.E. VOLKOV, E.R. GOLUBOVSKY, A.S. PEREVOZOV , N.M. EMAUSSKY

Journal "Deformation and material ftracture" 2015 , № 6 pages 43- 48"

The results of tests for the fatigue crack growth rate in the temperature range of 20-650 ° C of compact CT specimens made of nickel deformable alloys (EI698VD, EC151ID) and granular alloys (EP741NP, EP962P) for aviation GTE disks are presented. Parameters (C and n) of the Paris equation for the second stage of the kinetic diagram of fatigue crack growth are obtained. It is shown that the parameters of the Paris equation (C and n) of the investigated alloys are related by one linear dependence in the coordinates "logC-n". The average values of these parameters and the boundaries of the steady growth of the fatigue crack (ΔKmin-ΔKmax) for each alloy are determined

10.3. FATIGUE OF MONOCRYSTALS OF NICKEL ALLOY "ВЖМ-5" AT HIGH TEMPERATURES

E.R. GOLUBOVSKY, M.A. ARTAMONOV, M.E. VOLKOV, N.M. EMAUSSKY, S.A. SHIBAYEV

Journal "Technology of light alloys" 2016 , №3, pages 83- 88"

Experimental data obtained by results of tests at temperatures of 850 and 1050 C with low cycle (LCF) and high cycle (MCF) fatigue of single-crystalline specimens of heat-resistant Nickel alloy "ВЖМ-5" alloyed with rhenium, for monocrystalline blades of aviation gat –turbine engine. LCF tests were carried out under axial loading with stress ratio values Rε =0; -1. MCF tests with axial loading were conducted with the asymmetry of a cycle R ε = 0,1. The numerical model and the curves of LCF and MCF were obtained. It was shown that the hypothesis of existence of a general fatigue curve for a single crystal alloy VIM-5 is not valid. The results of fractographic analysis of the fracture properties of single-crystalline specimens after the test are presented.

11. FATIGUE AND DAMAGE TOLERANCE ENGINEERING PROJECT PERFORMED AT MOSCOW BOEING DESIGN CENTER

- ***Engineering project on Boeing A/C durability and damage tolerance analyses performed at MBDC // Dadunashvili S., Nikitin E., Nikitin A.***

The Moscow Boeing Design Center (BDC) jointly with Russian and Ukrainian engineering companies including Progresstech; NIK Research and Engineering Co.; aerospace companies Ilyushin; Sukhoi Aviation Corp. and Khrunichev State Research and Production Space Center performs the engineering projects in support of the 767-200SF, 747-400BCF, 737-900ER, 777-300ER/200LR, 747-400 Dreamlifter, 747-8 Freighter and Intercontinental, 787-8/-9/-10 Dreamliner including fatigue and damage tolerance calculations for the programs mentioned. For the past 15 years, BDC structural engineers have performed durability and damage tolerance analyses on almost every new Boeing commercial airplane and new 777X.

Components designed and analyzed at BDC include fuselage pressure bulkheads, frames, skin/stringer assemblies, lugs and fittings, intercostals and other reinforcing elements, complex door surround structure, and major fuselage joints, as well as wing fixed and moveable leading and training edge structure and control surfaces. This includes DaDT of parts and assemblies covered by new regulatory requirements concerning damage tolerance of repairs.

- ***Wing Side-of-body Composite Joint Interlaminar Fatigue Analysis***

  // Dr. Andreas Panayi; Prof. Sergo Dadunashvili; ATF Kirill Zhidyaev

Research for the checks put in place by the Boeing 787 Wing Side-of-Body (SoB) Interlaminar Finite Element Methods (iFEM) team in a joint effort of the Everett, Washington and MBDC to obtain composite fatigue margins for the SoB joint - one of the most critical joints on the airplane as it reacts large body and wing spanwise loads. It comprises the upper and lower joints with both metallic and composite parts. The objective of the analysis is to ensure the structural integrity of the composite components at the joint under cycling compressive and tensile loading, satisfying the requirement criterion of "No detectable growth of damage from an embedded defect at the critical loading location under cyclic loading". Typical interlaminar fatigue checks for the SoB joint include:

- Check 1: Fatigue for stringer pull-off strength at the composite stringer noodle.
- Check 2: Fatigue for skin/stringer disbond at the skin/stringer termination and edge-of-flange using the virtual crack closure technique (VCCT).
- Check 3: Fatigue for stringer web end trim strain concentration.

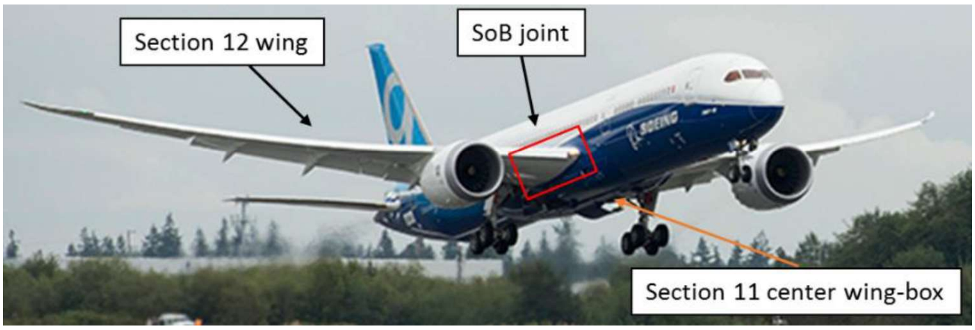


Figure 26 The 787 Wing Side-of-Body Joint

Analyses were performed at design ultimate load for worst up-bend and down-bend load cases, accounting for thermal loading. The resulting loads are scaled by the ratio of the maximum operating load divided by the maximum ultimate load to compare to the fatigue allowables, running loads based for Check 1, energy release rate-based for Check 2, and strain-based for Check 3, in order to write the fatigue margins

Considering the noodle pull-off fatigue damage (Check 1):

As the load comes into the joint and the elastic centroid shifts at the transition cross-section of composite-only to composite-metallic parts, some local bending is introduced which in turn gives rise to secondary out-of-plane loads

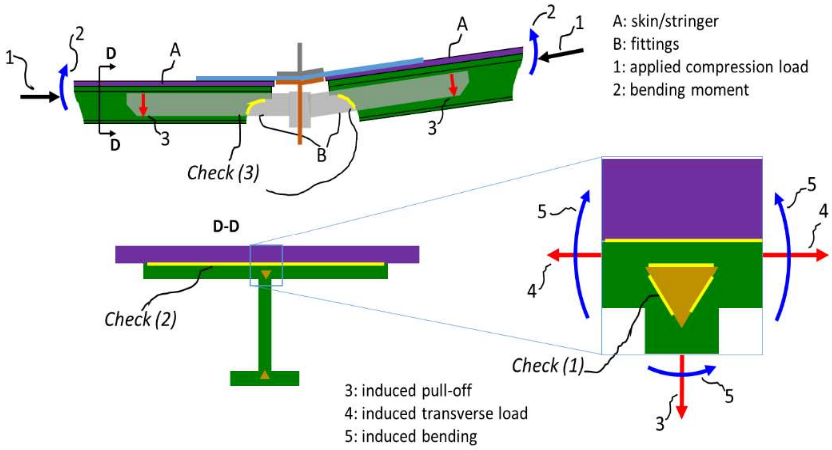


Figure 27 Fatigue Checks and Induced Loads

These out-of-plane loads can be detrimental to the fatigue life if they are sufficiently high. All the secondary loads surrounding the noodle are extracted from the submodels, and accounting for their interactions as well as environmental factors, are compared against the fatigue allowable to obtain the noodle damage fatigue margins. In a similar way, the skin/stringer bondline (Check 2) and stringer trim strain concentrations (Check 3) are assessed for adequate fatigue life. These checks have been applied on all of the 787 derivatives and are currently utilized to substantiate similar 777X composite structure