RIGA TECHNICAL UNIVERSITY
Transport and Mechanical Engineering Faculty
Institute of Aeronautics

Vladislav TURKO
Doctoral Study Program's „Transport" doctoral candidate

The aircraft vehicle's fatigue cracks early detection and inspection methods outlook during bench tests

The author's Abstract of Doctoral Thesis

Scientific Advisor
Dr. Habil. Sc. Ing, professor
M.BANOVS

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Riga Technical University, Latvia.

Professor, Dr.Habil.Sc.Ing. Vasily Shapkin,
Director General of State Scientific & Research Institute of Civil Aviation, Russia.

Assoc.professor, Dr. Sc. Ing. Vyacheslavs Zhilinskis
Baltic International Academy, Latvia.

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I confirm that I have developed this Doctoral Paper, which is presentet on consideration in Riga Technical University to take doctor's degree in science engineering. This Doctoral Paper is not presented in any other university fot taking a science degree.

Vladislav Turko …………………………….(Paraksts)

Date: ………………………

Doctoral Thesis is written in English. It contains introduction, 5 chapters, conclusion, bibliography, 9 attachments, 55 illustrations, 45 tables, total 138 pages. 82 titles are in bibliography.

CONTENT

GENERAL ESSAY of WORK

The Urgency of the Problem

The real situation of Civil Aviation is characterized by increasing in the sizes, complication and rise in price of aircraft vehicles and working service expenses. It is clear the tendency on increase to their loading and passenger capacity. Such tendency with need leads to

- increasing of the work life time of commercial use of aircrafts – withdrawal from the principle of designing on *Limited Service Life* (LSL) to the principle of operation on a technical condition and after that to the principle of safe destruction of the Structural Significant Items (Fail-Safe Conception);

- searches of possibility of application of *nondestructive testing* (NDT) methods in an “online” mode directly in Operation and during the Bench Tests.

Obviously, the carrying out of full-scale natural objects’ testing is very expensive, but allows to investigate various scenarios of loading and behavior of a Design and to examine various options of NDT application.

Especially important item of the Research is EARLY detection of damages’ formation, with the subsequent her CONTROLLED evolution. It allows to change, if necessary, the scenario of a Design’s investigation during the Bench Test. It is known that at Bench Tests the first and most important item of the Research is to identify weak places, it’s location on the Design. It is obvious that on the large-size Design there are may be several of weak places. The nature and the process of these places’ formation and how it influence to the reliability of total Design is not investigated to the full extent now. Also how to adapt the known NDT methods for checking these places is not sufficient evaluted.

Periodic visual surveys, different installations of sensors of NDT checking without knowledge of the basic phenomenological principles of the Design’s degradation leads to arising time, material and human resource expenditures.

The Goal of the Research

Research objective is to take a look more closely at nature of *fatigue damages’ accumulation* (FDA) and to develop a methodology of their early detection and monitoring on large(full)-size Designs on the basis of the proposed the *Hypothesis of Local Zones* (HLZ) with dependent FDA.

Research Tasks

To achieve this goal it is necessary to solve the following problems:

1) to develop mathematical and phenomenological models of FDA to largesize Designs, namely:

- phenomenological models of zone's local FDA;
- mathematical model of the origin and size of a Local Zone;
- mathematical model of reliability of the Local Zone including the definition of criterion of her destruction (refusal), characteristics of fatigue strength (probability *distribution functions* (DF) of fatigue durability, limits of fatigue endurance, a mode of S-N fatigue curve, a sensitivity threshold on cycles);

2) to check the made hypotheses and models on experimental data:

- to make experiment on samples with several concentrators, as on model-analogue of FDA on a body of Design;
- to process the experimental data obtained by other authors;
- to use the data obtained at Bench Tests of real aviation Designs;

3) to prove methods of NDT the most adapted for application at Bench Tests of large-size Designs:

- to develop sequence of actions (algorithm) of application of the chosen NDT at Bench Tests for early detection of initial damages and/or its propagation;
- to put forward recommendations about application of received results at Bench Tests of full-size aviation Designs.

Research Methods

The following methods were applied to the solution of this objectives:

- mathematical, including probabilistic, modeling of processes of FDA on large-size Designs;
- fatigue tests of samples with a various size and disposal of concentrators;
- the statistical analysis of results of specimen's fatigue tests, including correlation analyses, the analysis with application of the Order Statistics theory,
- experimental check of various methods of NDT on various Designs of aviation appointment and technical systems.

The Novelty of Research Results

The novelty of the proposed Research consists in approaching to investigate FDA on specimens with various system of concentrators as the model-analogue of uniform (solid) body. So:

1) the Hypothesis of Local Zones with dependent FDA is formulated and confirmed. Thus

- emergence of the first fatigue crack not only provokes formation of other cracks in her direction and localize her seat (so-called "airplane model of extension of damages"), but also leading to emergence of the multiple cracks which aren't merging with each other ("helicopter model of development of damages");

- so identified cracking of Design allows to mark the areas of high attention for her control destruction;

- stochastic dependance of FDA allows to manage the sufficient monitoring during Bench Tests and to develop the methodoly of the early detection of fatigue cracks.

2) Large-size Design, as a pool of several Local Zones, can be considered as grouping of weak places. Some Designs can be considered as one lonely Local Zone.

3) The integrated four parametric model of Fatigue Strength of the Local Zone (fatigue durability, fatigue endurance limit, S-N fatigue curve and a sensitivity threshold on cycles) is based on *two parametric double expotential distribution function with logarithmic durability* (DEDF). Advantage of application of DEDF to the description of fatigue durability is the best description of the left tail of the distribution known as "a sensitivity threshold on cycles" in the field of small probabilities.

4) The most effective NDT for early detection of cracks is the method of the acoustic emission, allowing to manage "on-line" monitoring with control of FDA in chosen Local Zone. The acoustic emission method can be applied to monitoring of tests of various Structural Significant Items, including composite ones, under various natures of loading (dynamic, static, thermal, etc.).

Practical Relevance of the Research

Basic provisions of the proposed Research were applied in the analysis of Life Time Service of the stabilizer of the Mi-8 helicopter, structural significant elements of the Tu-154 plane’s main landing gear, at an evaluation of Safe Life Time and cracking process of tail and keel beams of the Mi-26T helicopter, in the process of updating of fatigue tests’ programs and investigations structural items of the Mi-26, Mi-38 and Ka-62 helicopters in the SIA

„Aviatest”. The methodology of NDT monitoring during the fatigue tests of the helicopters nature fatigue Bench Tests was proposed.

It is shown that if several zones of the accelerated FDA is identified, it is desirable to supervise the consecutive destruction of these zones by other methods (a tenzoreview, thermovision etc). At achievement of the critical level of cracking it is necessary to repair total area of damaged Local Zone completely.

The proposed mathematical model of reliability of the Local Zone as weak place of Design, specifies the Design’s Safe Operation Life evalution.

The main principles of the methodology for management of monitoring of a technical condition of large-size Designs are developed.

The Thesis submitted for Discussion

The following theses are submitted for discussion:

- the Hypothesis of Local Zones (HZL) with dependent accumulation of fatigue damages;

- mathematical models of accumulation of fatigue damages on large-sizes Designs and determination of the sizes of Local Zones;

- probabilistic models of characteristics of the Fatigue Strengh of Local Zones: double exponential distribution function (DEDF) of a logarithmic durability until failure (or Largest Extreme Value (LEV)) and the piecewise and linear description of S-N fatigue curve in double logarithmic coordinates, the method of estimation of Limited Service Life Time of a Local Zone as weak place;

- the methodology of management for monitoring of large-sizes Designs (on example of tail and keel beams of the helicopter Mi-26) for the purpose of early detection of fatigue damages.

The Approval of Research Results

The main results of scientific work have been presented in the following ***international scientific conferences*** (2009-2013):

1) The International Conference “Non-Destructive Testing and Diagnostics-2006”, 28-29 May 2006, Vilnius, ULTRASOUND Kaunas University of Technology - *“Undercarriage fatigue test control by acoustic emission method”*.

2) The 15th International Conference „Mechanika 2010”, 8-9 April, 2010, Kaunas University of Technology, Lithuania. - *„Acoustic emision diagnostic of fatigue crack development during undercarriage bench testing”.*

3) The 6th International Conference „Mechatronic System and Materials. MSM 2010”, 5-8 July, 2010, Opole, Poland. Opole University of Technology. - *„Acoustic emission checking of welded rail joints”.*

4) International Conference „The Space & Global Security of Humanity (SGS 2010)”, 5-9 July, 2010. Transport and Telecommunication Institute, Riga, Latvia - *„Estimation of mechanical properties of the anisotropic reinforced plastics with application of the method of acoustic emission”.*

5) The 18. zinātniski praktiskās un mācību metodiskās konferences „The Step into the Future”. 10 – 11. december, 2010., Transporta un Sakaru Institūts, Rīga, -*„Features of behavior of acoustic emission signāls at dinamic tests of pre-stressed concrete elements of railways*”.

6) The 14th International Conference “Transport Means”, 21-22 October,2010, Kaunas University of Technology, Lithuania. – “*Some features of behavior of Acoustic Emission signals at dynamic bench tests of prestressed concrete sleepers”*

7) 13th International Conference „Maritime Transport and Infrastructure”. 28-29 April 2011., Riga, Latvia. – „*Noguruma plaisu rašanās likumsakarību pētīšana daudzkoncentratoru paraugos”.*

8) The 16th International Conference „Mechanika 2011”, Kaunas University of Technology, Lithuania, 7-8 April, 2011 - *“Investigation of mechanical properties of composite materials using the method of acoustic emission”.*

9) The 7th International Conference „Mechatronic System and Materials MSM 2010”, Kaunas, Lithuania. 7-9 July, 2011. - *„The Mathematical Model of the Dependent Fatique Damage Zone”.*

10) The Eight International Conference „Advances and Trends in Engineering Materials and their Applications”. AES-ATEMA 11-15 July 2011. Riga, Latvia - *„Investigation of micromehanics of plasto-elastic behavior of anisotropic composite materials under static loading by the acoustic method”.*

11) The International Conference „Appplied Mechanics and Mechanical Engineering. ICAMME 2011”, 28-30 November, 2011, Venice, Italy.- *„The fatigue damage accumulation on systems of concentrators”.*

12) The International Conference „Appplied Mechanics and Mechanical Engineering”. ICAMME 2011, 28-30 November, 2011, Venice, Italy. - *„Diagnostic of fatigue damge of gas turbine engine blades by acoustic emission method”.*

13) The XYII International Conference “Mechanics of Composite Materials”. May 28-June 1, 2012. Institute of Polimer Mechanics University of Latvia. Jurmala , Latvija.- *Research into the Micromechanics of the Plastic-Elastic Behaviour of Anisotropic Composite Materials under Static Loading by the Acoustic Emission Method”*

14) The 14th International Conference "Maritime Transport And Infrastructure- 2012”, Latvian Maritime Academy 23-24 April, Riga, Latvija – “*New approach to use the acoustic emission monitoring for the defects detection of composit material's design elements"*.

15) The 3 rd International Conferences „Mechanical And Aerospace Engineering” (ICMAE 2012), July 7-8, 2012, Paris, France. – „*The Characteristic Features of Composite Materials Specimen’s Static Fracture Investigated by the Acoustic Emission Method”*.

16) The 3 rd International Conferences „MechanicaL And Aerospace Engineering” (ICMAE 2012), July 7-8, 2012, Paris, France. – „*Hypothesis of Local Zones with Dependent Fatigue Damages Accumulation”*.

The Research Results (papers) what nave been ***published in scientific and technical editions***, including the electronic and entering into the information bases:

1.TURKO Vl., „The simplest model of the scale effect based on the hypothesis of the local volumes**.**” *Strenght of Materials, 1986, vol 18, N4, p.455-460,* ISSN 0039-2326, 0039-2326/1804-1455, Public Publishing Corporation. USA.

2. URBAH A., BANOV M., DOROSHKO S., TURKO V., Non-destructive inspectionof aircraft landing gear during residual strenght testing. In *Ultragarsas (Ultrasound)-40 metu, vol.64, No1, 2009., p43-45.* Kaunas, Lietuva, ISSN 1392-2114

3. TURKO Vl., „Estimation of fatigue durability dispersion in operation by results of tests and loading measurements”, In *RTU Zinātniskie raksti. „Mašīnzinātne un transports*”. VI sērija, 34.sējums, P.17-23, RTU Izdevniecība, Rīga, 2010.g., ISSN 1407-8015.

4. URBAHS A., BANOVS M., DOROŠKO S., TURKO Vl.,FESCHUK Y., 2010, „Acoustic emission checking of welded rail joints”. In *6th International Conference MECHATRONIC SYSTEM and MATERIALS MSM 2010, 5-8 July, 2010,* (HTML-file #105), *Opole, Poland.* Opole University of Technology, 2010. [Electronic CD] The Archive of Mechanical Engineering ISSN 0004-0738

5. URBAHS A., BANOVS M., TURKO Vl., BRATARCHUCK S., HODOS N., FESHCHUK Y., 2010, „Features of behavior of acoustic emission signāls at dinamic tests of pre-stressed concrete elements of railways”. In *„Research and Techology-Step into the*

Future". Vol.5, No2, 2010, 18. zinātniski praktiskās un mācību metodiskās konferences "Zinātne un tehnoloģija – Solis nākotnē" 2010., 10.– 11. decembrī, Rīga, P.106. Transporta un Sakaru Institūts, Rīga, 2010. ISSN 1691-2853, ISSN 1691-2861.

6. URBAHS, A., BANOV, M., TURKO, V., BRATARCHUSK, S., KHODOS, N. Some features of behavior of Acoustic Emission signals at dynamic bench tests of prestressed concrete sleepers (2010) *Transport Means* - Proceedings of the International Conference, pp. 45-48.

http://www.scopus.com/inward/record.url?eid=2-s2.0-79952648219&partnerID=40&md5=726267b6a03bb4de474bebd15fd8fb77

7. URBAHS A., BANOVS M., TURKO Vl., SOLOGUBOVS Y., "Noguruma plaisu rašanās likumsakarību pētīšana daudzkoncentratoru paraugos". In *Maritime Transport and Infrastructure. 13th International Conference. 28-29 aprīlis 2011.g., Rīga, Latvija.* P.170-173. Latvijas Jūra Akadēmija, Rīga,2011.g. ISSN 1691-3817.

8. TURKO Vl., „The Mathematical Model of the Dependent Fatique Damage Zone". In *7th International Conference Mechatronic System and Materials MSM 2010, 7-9 July, 2011, Kaunas, Lithuania.* Kaunas University of Technology, 2011. ISSN 1822-8283

9. URBAHS A., BANOVS M., TURKO Vl., FESHCHUCK Y., HODOS N., 2011, „Investigation of micromehanics of plasto-elastic behavior of anisotropic composite materiāls under static loading by the acoustic method" . *AES-ATEMA 2011 Eight International Conference Advances and Trends in Engineering Materials and their Applications. 11-15 July 2011, Riga, Latvia.* ISSN 1915-5409

10. URBAHS A., BANOVS M., TURKO Vl., „The fatigue damage accumulation on systems of concentrators". *International Conference on Appplied Mechanics and Mechanical Engineering. ICAMME 2011, 28-30 November, 2011, Venice, Italy.*

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11. URBAHS A., BANOVS M., TURKO Vl., FESHCHUCK Y., „Diagnostic of fatigue damge of gas turbine engine blades by acoustic emission method". *International Conference on Appplied Mechanics and Mechanical Engineering. ICAMME 2011, 28-30 November, 2011, Venice, Italy.*

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12. URBAHS A., BANOVS M., TURKO Vl., „The fatigue damage accumulation on systems of concentrators". In *World Academy of Science, Engineering and Technology. Issue 59.*November 2011, Venice, Italy. p.p.934-939, pISSN 2010-376X, eISSN 2010-3778.

13. URBACH, A., BANOV, M., TURKO, V. Hypothesis of local zones with dependent fatigue damages accumulation (2012) *Applied Mechanics and Materials*, 232, pp. 19-23.

http://www.scopus.com/inward/record.url?eid=2-s2.0-84871572669&partnerID=40&md5=657a147df5523fe413e020cb1aae3c6b

14. A.URBAHS, M.BANOVS, V.TURKO,, Y.FESHCHUCK, *New approach to use the acoustic emission monitoring for the defects detection of composit material's design elements"* Latvian Maritime Academy 14th International Conference "MARITIME TRANSPORT AND INFRASTRUCTURE- 2012", 23-24 April, Riga, Latvija .ISSN 1691-3817

15. URBACH A., BANOV M., TURKO V., 2012, Hypothesis of Local Zones with Dependent Fatigue Damages Accumulation. In *3 rd International Conferences of MechanicaL And Aerospace Engineering,(ICMAE 2012),* July 7-8, 2012, Paris, France.

16. URBACH A., BANOV M., TURKO V., Y.FESHCHUK, 2012, The Characteristic Features of Composite Materials Specimen's Static Fracture Investigated by the Acoustic Emission Method. In *3rd International Conferences of MechanicaL And Aerospace Engineering,(ICMAE 2012),* July 7-8, 2012, Paris, France.

17. TURKO Vl. 2013, The Uniform Statistical Model of Fatigue Strength. In *RTU Zinātniskie raksti. „Mašīnzinātne un transports*". RTU Izdevniecība, Rīga, ISSN 1407-8015.(is accepted to publication).

The Structure of the Doctoral Thesis.

The Doctoral Thesis contains the Announcement, the Introduction, five Chapters, the Conclusion, 9 appendices, 55 figures, 45 tables, 138 pages, 82 links of the bibliography.

The Sections of the Thesis consists of:

- introduction. The objectives of Research, Research methods, novelty of the Research results, the practical relevance of Research, Theses submitted for discussion are presented in this Section;

- chapter 1. The review and the short analysis of a problem of early detection of fatigue cracks in largesize Designs describe the nowadays problem status and view to future. It is shown that methodology of largesize Designs management of crack's monitoring differs than usual one;

- chapter 2. Three original models of accumulation of fatigue damages in largesize Designs are given with short characteristics of their reliability. The Hypothesis of Local Zones with dependent accumulation fatigue damages in these zones is formulated;

- chapter 3. Results of fatigue tests on specimens with numerous concentrators are given. Application of statistical methods of the Order Statistics' analysis and interclass coefficients of correlation has prove the existence of stochastic relationships (both positive and negative are shown). The mathematical model of determination of the sizes of Local Zone and model validation by results of specimen's tests are given. Assumptions of a Hypothesis of Local Zones with dependent accumulation of fatigue damages are confirmed. Consequences of the existence of stochastic relationships for determination of reliability of local zones are given for largesize Designs;

- chapter 4. Four parametrical mathematical model of Fatigue Strength of the Local Zone, uniting parameters of the distribution functions of durability, limits of endurance, S-N fatigue curve and sensivity threshold on cycles are given. It is proved that distribution function of fatigue durability for great values of durability (operational conditions) looks like double-expotential distribution of durability of a logarithm of number of cycles (DEDF), or Largest extreme Values (LEV). Parameters of piecewise and linear S-N fatigue curve are determined in this area by parameters of increasing in dispersion and coefficient of a variation of a logarithm of number of cycles versus decreasing in applied loading. The example of modified evaluation of Limit Safe Life Time of a keel beam of the Mi-26 helicopter by results of Bench Tests is given;

- chapter 5. The short characteristic of NDT is provided. It is shown that the best inspection methods of "on-line" damageability of Local Zones are the method of acoustic emission and thermovision. Examples of existence of a Hypothesis of Local Zones and a consequence of its application are shown at Bench Tests and Operation. The methodology of managament of monitoring of control of Local Zones is given at Bench Tests of the Mi-26 helicopter.

- conclusion. The results confirms theses of Doctoral Work., Items nominated to discuss in the future, are given;

- attachments. Results of the made experiments and others tests, intermediate deductions of mathematical models and other calculations are listed.

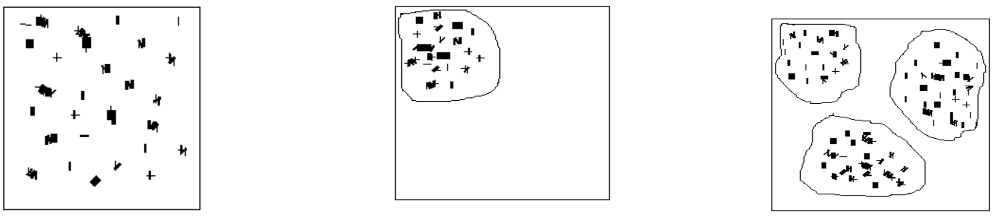
SCOPE OF RESEARCH

Introduction. The short characteristic of Doctoral Thesis is presented.

Chapter 1 The current state of a problem shows the lack of methodology of approach to Bench Tests and Operation of largesize Designs. The evaluation of the Design's technical condition during her NDT monitoring, the principles of weak places' identifying are differs that of usual. The significant increasing of time, material and human resources at investigation of largesize Designs need to evaluate the process and conditions of Design's degradation.

Chapter 2. Model of the accumulation of damages to largesizes Designs. Hypothesis of Local Zones

In chapter 2 three models of FDA on a uniform area which lead to destructions of various nature are proposed.



a) в) c)

Fig. 2.1 Distribution of Fatigue Damages on a surface section: a) - evenly on entire surface; b) - it is concentrated in one lonely area; c) - it is concentrated on several separate areas

Known system models for static and fatigue destructions (the Weibull's hypothesis of a „weak link", Daniels model of „a classical bunch" and etc), and also the parametrical models that describing FDA as processes of various modes, consider only QUANTITY of the saved-up damages, but don't consider their DISTRIBUTION on making structural elements of the Design. If it didn't bring great error by consideration of small-size elements and details, but at the description of big large-size Designs it can already lead to great error (for example, influence of the large-scale factor, floating of "a weak place", redistribution of stress at partial damage). Uniform distribution of damages on entire surface (fig. 2.1 a) as Poisson's simplest flow (evenly on space) represents the most dangerous case, when there is no accurately give up the seat of weak place. It is impossible to manage effective damage monitoring as monitoring of total surface of a Design for this purpose is required. Usually such Designs is operated by the principle of the Limited Safe Life. Usually such principle is applied to Strucrural Significant Items for which application of any monitoring of NDT checking is complicated.

When evaluation of durability of such Designs, logarithmic normal distribution (NDF), resulted as summation of a large number of microdamages, is usually applied:

$$F(\lg N) = \Phi\left(\frac{\lg(N - N_0) - a}{b}\right) \qquad (2.1)$$

where N – number of cycles of loading,

N_0 – a sensitivity threshold on cycles,

a, b – respectively location and scale parameters of distribution function.

Otherwise, FGA is also the elementary Poisson flow, but in some limited area (Fig. 2.1 b). In this case it is easy to manage monitoring of a technical condition as "the weak place" is clearly defined. The initial main fatigue crack brings to origin before density of damages reach the critical value. Control of FDA, if this place is readily available, can be carried out almost continuously. Limitation of zone’sizes and her certain location allows to carry out repair work in due time. If uncontrollable destruction of a zone (for example, in the form of rapid formation of a magistral fatigue crack), leads to destruction of total Design, the durability of such system is well described by model of "a weak link" known as Weibull's distribution or Smallest Extreme Value (SEV):

$$F(N) = 1 - \exp[-\left(\frac{N - a}{b}\right)^m] \qquad (2.2)$$

where N – number of cycles of loading,

a, b, m – respectively location, scale and mode parameters of the DF.

If monitoring of a zone allows to carry out her repair, such nature of destruction is most suitable for Operation on a technical condition. This model is usually characteristic for airplane Designs, as control of the only " weak place" as the center of the subsequent one main crack, allows not only to apply known NDT, but also to carry out repair work in time.

For large-size Designs intermediate nature of FDA (see Fig.2.1 c) is often observed.

Intermediate nature of FDA allows to apply to Design not only the principles of operation on a technical condition, but also Fail Safe Concept. Localization of damaged area gives the chance to define "weak places" with her following monitoring. In case of the main crack's formation in a Local Zone, special danger is constituted by merge of other cracks in magistral not only in that Zone but from nearby ones. It is possible to assume that formation of the main crack in Local Zone is the indicator of possible subsequent destruction of total Design. Then for transition to the Fail Safe Concept it is necessary to identify a location of these "weak places by results of Operation, and/or Bench Tests very precisely.

Destruction of a Local Zone (in the form of emergence some main fatigue cracks) usually doesn't lead to immediate destruction of total Design. It is possible to assume that distribution of durability of a Local Zone is well described by distribution function of "maxima" with logarithmic durability (double exponential distribution with logarithmic life time (DEDF) or Largest Extreme Value (LEV) as

$$F\ \ (\tau) = \exp[-\exp(-\frac{\tau - a}{b})] \qquad (2.3)$$

where τ=lgN – logarithm of loading cycles' number,

a, b – respectively location and scale parameters of distribution function.

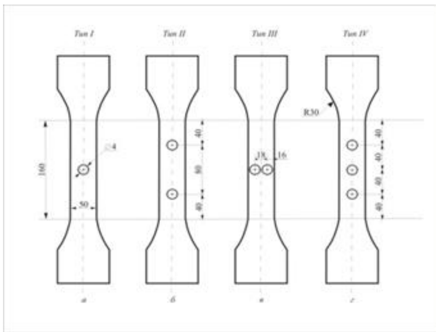
In uniform Design the formation of such zones is possible only due to dependent FDA in this Zone, i.e. emergence of damages or provokes new cracks or, on the contrary, localizes cracking area. These relationships has to extend on some distance, weakening in process of her increase. The given reasons lead to hypothesize the Local Zones' existence with dependent accumulation of fatigue damages.

Basic principles of a Hypothesis of Local Zones:

- the large-size Design can be presented as pool of several Local Zones;
- in Local Zones FDA proceeds stochastic dependent, but independently from each other in other Zones;
- reliability (durability) of a Local Zone is depend on nature of stochastic relationships mode: positive relationship provokes emergence of new cracks in sequence, as continuation of the first and localizes a place of future destruction. Whereas negative relationship accelerates its numeral cracking at late emergence of cracks in this Zone;
- the Local Zone determinates the reliability (fatigue durability) of whole Design as weak place;
-the Local Zone can envelope the total Design.

Chapter 3 Research of dependence of accumulation of fatigue damages on different systems of concentrators.

In Chapter 3 experimental check of the Hypothesis of Local Zones is given. Inspection of the offered Hypothesis was made on specimens (aluminum alloy D16T) with several concentrators. The concentrators of hole-kind were located along and across to the applied load.



a). b). c). d).

Fig. 3.1 Specimen’s configuration of "V"-type

When preparing the specimens, choosing the type, the order of application of concentrators and installation specimens on the Test Bench, the principle of total randomization was applied throughout the experiment. Concentrators were deposited at such distance one from other and from the sealaing area of specimens (the beginning of radius of curvature’s transition from working part of the specimen), that is allowed to apply the assumption of non-perturbed stress fields around other concentrators or influence of the Test Bench grips. The fatigue test load: maximum stress cycle (net) - 120 MPa, the minimum stress cycle (net) to 12 MPa, loading frequency 8.3 Hz were conducted before the emergence of the crack in the concentrator (only from the ONE side edge of the each hole). For an objective determination of the emergence moments of cracking, wire system was used: gauges of wire with a diameter of 0.01 mm, were pasted around the hole. Gauges were triggered when the fatigue crack reaches length of about 0.5 mm from the edge of the hole. In tests of specimens with multiple concentrators in order to get cracks in each of the concentrator, the first and following cracks were stayed by plastic deformation of area before the mouth of the crack. It have been made due to forcing poisson of 4 mm diameter. Poisson was pressed into the body of the specimen by force of 24 kN according to the procedure offered by Dc.h.Sc.I., prof. V. Pavelko and I.Savinaev[1]. Let’s concentrator located in the middle of the working part of the specimen determinates by the

[1] *Author’s USSR sertificate № 456003, 1975.*

term „inner” and concentrators located closer to the grips of the Test Bench - the term „outer". Over the durability τ of concentrator let’s will take logarithm of the number N of cycles until wire gauge indicates the crack at this hole. Let’s *distributuin function* (DF) of the durability take in the form (3.1) without the threshold of sensitivity of the cycles N_0. The results of fatigue tests of specimens of the „V”-type „a” (single inner hole) are shown in Figure 3.2.

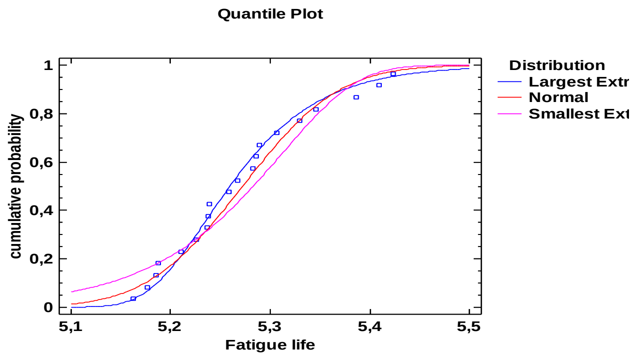


Fig. 3.2 Durability CDF for single „inner” concentrator. The DEDF(LEV) (2.3) has the best fitting with experimental data

On the Fig. 3.2 the three kinds of *cumulative distribution function* (CDF) out of Chapter 2 are shown. It is proved that the CDF (2.3) is the best match the experimental Data. But in the following statistical investigations the NDF (2.1) will be used for more convenience.

This result is the base, so the test was carried out without the influence of other concentrators.

$$\hat{a}_{in\,/\,a} = 5{,}27230;\ b^2_{in\,/\,a} = 0{,}00582;\ b_{in\,/\,a} = 0{,}07278;\ \ v_{in\,/\,a} = b_{in\,/\,a} / \hat{a}_{in\,/\,a} = 1{,}38\% \qquad (3.1)$$

Legend indices: in – „inher” and •/a - the type”a” specimen on Figure 3.1.

The results of fatigue tests of specimens of „V”-type „b” for the external (outer) holes are shown in Fig. 3.3.

Assuming stochastic independence of the emergemces of fatigue cracks in the holes, the test results of external holes’ lifetimes can be combined into a single sample with the following parameters of the CDF:

$$a_{ot\,/\,b} = 5{,}18012;\ \ b^2_{ot\,/\,b} = 0{,}01081;\ \ \ b_{ot\,/\,b} = 0{,}10397;\ \ \ v_{ot\,/\,b} = 2{,}0\% \qquad (3.2.)$$

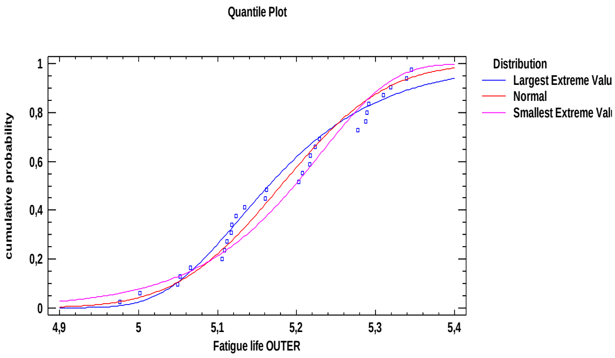


Fig. 3.3 Durability CDF for „outer” (lonely) concentrators. The NDF (2.1) is more suitable describe the fatigue life in this case.

The distribution functions of Order Statistics for a system of two stochastical independent holes with NDF (3.1) have the form:

The First Order Statistics CDF:

$$F_{(1)}(\tau_{(ot)}) = 1 - \left[1 - \Phi\left(\frac{\tau - a_{ot}}{b_{ot}}\right)\right]^2 \quad (3.3)$$

The Second Order StatisticsCDF:

$$F_{(2)}(\tau_{(ot)}) = \Phi^2\left(\frac{\tau - a_{ot}}{b_{ot}}\right) \quad (3.4)$$

It is known that the mathematical expectation M{•}and variance D{•} of the distribution function of the First and Second Order Statistics, as well as the correlation coefficient $\rho_{0\,(1,2)}$ are associated with the parameters of the initial NDF by the following expressions:

$$a_{o(1,2)} = a_o \pm 0{,}5642\, b_o \quad ; \quad b^2_{o(1,2)} = 0{,}6816\, b^2_o; \qquad \rho_{0(1,2)} = 0{,}467 \quad (3.5)$$

Table 3.1

Comparison of the theoretical values of Order Statistics CDF with the experimental data („outer” concentrators).

CDF parameters of Order Statistics		Math. expection $a_{0(1,2)}$	Varianse $b^2_{0(1,2)}$	Correlation coefficient $\rho_{0(1,2)}$
Theoretical value	1-st	5,12146	0,00737	0,467
	2-nd	5,23878	0,00737	
Experimental Data	1-st	5,12165	0,00899	0,466
	2-nd	5,23860	0,00610	

Comparison of experimental values for the variance, average and the correlation coefficient of the First and the Second Order Statistics with the theoretical values showed that the hypothesis of independence of observations is not rejected[2]. Satisfactory fitting between the experimental and theoretical data is clearly seen in Figure 3.4.

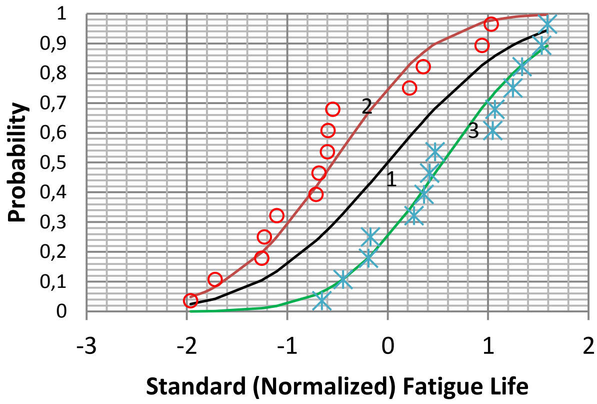


Fig. 3.4 The First and Second Order Statistics CDF for „outer” concentrators: 1) initial Standard NDF; 2) the 1st Order Statistics Standard CDF and normalized experimental fatigue life points of 1st crack detection); 3) the 2nd Order Statistics Standard CDF and normalized experimental fatigue life points of 2nd crack detection

Comparing the average durability (3.1) and (3.2) we get an unexpected result of a statistically significant reduction in durability of „outer” concentrators (a_{ot} = 5,18012) compare with „inner” ones (a_{in} = 5,27230). We can suppose that in all other conditions being equal, weakness part of structure must be placed in an area close to a load transition from one to another System „spacimen-bench grips” parts or on the border area of inhomogeneity of any kind.

After a similar analysis for the of test specimens „V”-type „c” (two „inner” concentrators, the following data were obtained: comparison of these results with data (3.1) showed that both samples are homogeneous and can be combined into one with NDF parameters (Figure 3.5)

$$a_{in} = 5,27219; \quad b^2_{in} = 0,00703; \quad b_{in} = 0,08387; \quad v_{in} = 1,59\% \qquad (3.6)$$

[2] *On default all statistical hypotheses the tests was made at a significance level α=0.05 (an error of the first kind).*

But a comparative analysis of the Order Statistics CDF parameters showed a statistically significant relationship between the moments of the stochastic emergemces of cracks in the system of two internal holes.

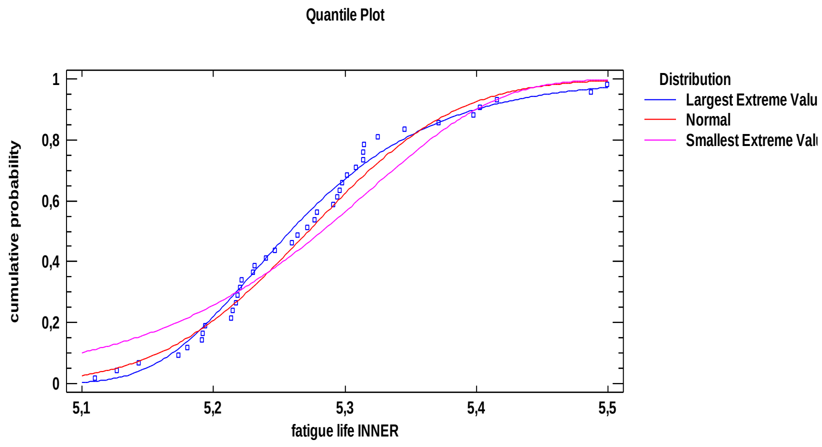


Fig. 3.5 Durability CDF for twin „inner” concentrators. The LEV is more suitable to fit the experimental data

Table 3.2

Comparison of the theoretical values of Order Statistics DF with the experimental data (internal holes)

CDF parameters of Order Statistics		Mathematical expection $a_{0(1,2)}$	Variance $b^2_{0(1,2)}$	Correlation coefficient $\rho_{0(1,2)}$
Theoretical Value	1st	5,22487	0,00479	0,467
	2nd	5,31951	0,00479	
Experimental Data	1st	5,24662	0,00840	0,955
	2nd	5,39766	0,00626	

The deviations of the experimental data from the theoretical values of Order Statistics parameters are seen clearly on Fig. 3.6. Thus the put forward hypothesis by the independent appearance of fatigue cracks on a system of holes is rejected.

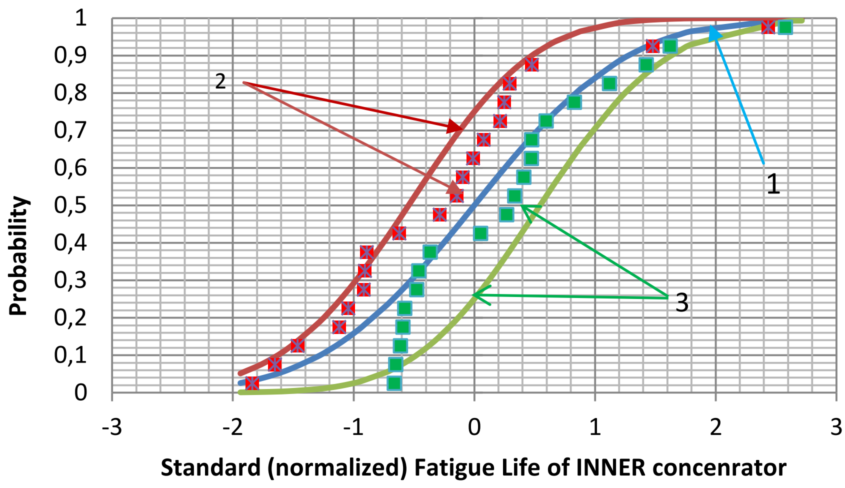


Fig.3.6 Theoretical CDF of the 1st and 2nd Order Statistics for Standard Fatigue Life CDF. The normalized fatigue life experimental data for the 1st and 2nd cracks on two inner concentrators: 1) initial Standard NDF; 2) the 1st Order Statistics Standard CDF and normalized experimental fatigue life till 1st crack detection), 3) the 2nd Order Statistics Standard CDF and normalized experimental fatigue life points of 2nd crack detection

Now let's analyze the results of tests of specimens „V"-type „d" (Fig. 3.1 d) with three holes located along the specimen (along the direction of acting applied load) - one internal and two external. The test results for specimens of the „V"- type „d" of internal holes

$$\hat{a}_{in/d} = 5{,}30935; \quad \hat{b}^2_{in/d} = 0{,}00625; \quad \hat{b}_{in/d} = 0{,}07908; \quad \hat{v}_{in/d} = 1{,}49\% \qquad (3.7)$$

when compared with the results of tests of specimens of „V"- type „a" and „c" (3.1) showed that the null hypothesis of equality of internal holes durability is rejected in favor of the greater durability of alternative internal holes on specimens „V"-type „d".

Durability of an external holes, compared with (3.2) is the same:

$$\hat{a}_{ot/d} = 5{,}17258; \quad \hat{b}^2_{ot/d} = 0{,}00916; \quad \hat{b}_{ot/d} = 0{,}0840; \hat{v}_{ot/d} = 1{,}62\% \qquad (3.8)$$

But a comparison of the First Order Statistic CDF parameters for external holes of three concentrators specimens:

$$\hat{a}_{ot/d} = 5{,}11363; \quad \hat{b}^2_{ot/d} = 0{,}00367; \quad \hat{b}_{ot/d} = 0{,}06062; \quad \hat{v}_{ot/d} = 1{,}19\%; \qquad (3.9)$$

with similar data for specimens of the „V”-type „b” (Table 3.2) showed a statistically significant discrepancy between the theoretical values and experimental data in favor of the hypothesis of the existence of stochastic relationships in the system of holes on specimens „V”-type „d”. Considering the system of holes on specimens „V”-type „d” as the combination of two systems: one internal hole and a system with two external holes, we obtain

$$F_{(1)}(\tau) = 1 - [1 - \Phi\{\frac{\tau - a_{in}}{b_{in}}\}][1 - \Phi\{\frac{\tau - a_{ot}}{b_{ot}}\}]^2$$
$$F_{(2)}(\tau) = \Phi^2\{\frac{\tau - a_{in}}{b_{in}}\} + 2\Phi\{\frac{\tau - a_{ot}}{b_{ot}}\}\Phi\{\frac{\tau - a_{in}}{b_{in}}\}[1 - \Phi\{\frac{\tau - a_{ot}}{b_{ot}}\}] \tag{3.10}$$
$$F_{(3)}(\tau) = \Phi\{\frac{\tau - a_{in}}{b_{in}}\}\Phi^2\{\frac{\tau - a_{ot}}{b_{ot}}\}$$

where the input parameters are defined (3.2) and (3.3)

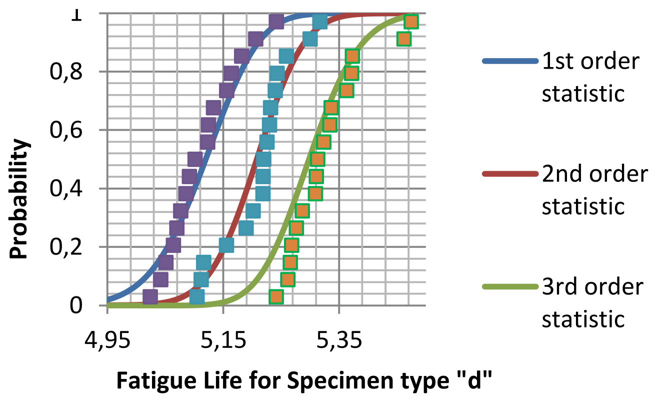


Figure 3.7 Durability CDF of Order Statistics for concentrators Vd- type specimens, experimental points and theoretical graphs

For simplicity and without loss of generality, we find expressions for the normal two-dimensional DF with different correlation matrix.

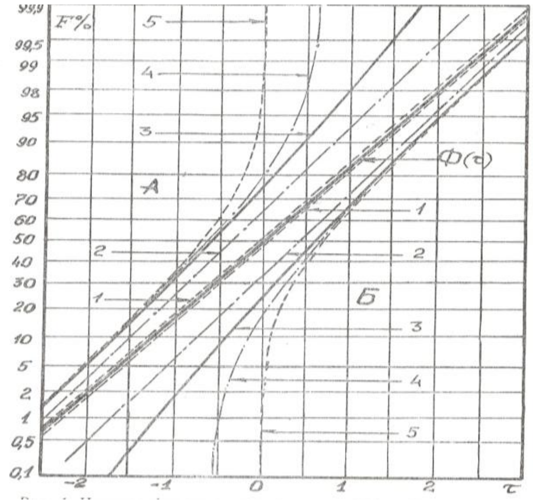


Fig. 3.8 The distribution functions of order statistics for the bivariate normal distribution

1) ρ = +1,0; 2) ρ = +0,7; 3) ρ = -0,7; 4) ρ = -1,0.

When ρ = +1,0 bivariate normal distribution degenerates into a one-dimensional (3.1.) With the same CDF of Order Statistics (3.7.) and (3.8).

If ρ = -1,0 CDF take a form

$F_{(1)}(\tau) = 2\Phi(\tau)$ if $\tau \leq 0$

$F_{(1)}(\tau) = 1{,}0$ if $\tau > 0$ (3.11)

$F_{(2)}(\tau) = 0$ if $\tau \leq 0$

$F_{(2)}(\tau) = 2\Phi(\tau) - 1$ if $\tau > 0$

For different values of the correlation coefficients CDF of Order Statistics are given on Figs. 3.8. The crack emergence on the first hole SLOW DOWN cracking (negative correlation) to follow the hole thus forming some zone of ACCELERATED accumulation of fatigue cracks (positive correlation), see Figure 3.7 and a zone of slowing down.

The test of null hypothesis of no stochastic relationships on hole concentrators system for the calculated value of intraclass correlation coefficient (ICC), where the number of classes (number of holes on one specimen) is k = 3.

$$\bar{r} = \frac{1}{k-1}\left(k\frac{\overline{b_{\bar{\tau}}^{2}}}{\overline{b^{2}}} - 1\right) \qquad (3.12)$$

где $\hat{r}$ - sample value of ICC,

k – the number of class, in our case– quantity of holes, equal to 3,

$\bar{\tau}_k$ – mean class life time (durability),

$\hat{b}^2$ -whole sample variance relative total mean $\bar{\tau}$ of hole's life time,

$\hat{b}^2_{\bar{\tau}}$ – the sample variance of class means $\bar{\tau}_k$.

Have:

$$\hat{b}^2 = 0{,}01140; \qquad \hat{b}^2_{\bar{\tau}} = 0{,}00125; \qquad \hat{r} = = - 0{,}336 \tag{3.13}$$ [3]

The critical value of intraclass correlation coefficient is α = -0,10. Then calculated test value of intraclass correlation coefficient lies outside the set of acceptance of the null hypothesis of his vanishing.

The following conclusions based on experimental data are obtained:

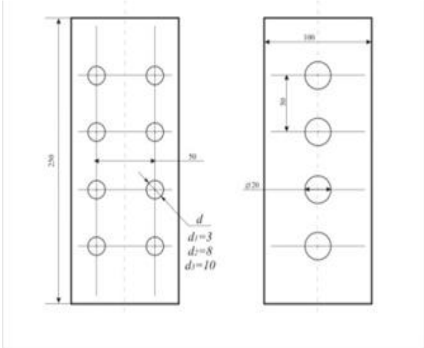
- to evaluate the stochastic correlation the intraclass correlation coefficient was used. It allow to assess the level of stochastic correlation of observations in the group, regardless of the time and order of occurrence;

- the dependence of FDA in the hole system along the working part of the specimen, or along the direction of the applied load, has negative correlation. The presence of negative correlation between durability of concentrators indicates the localization FDA near one of the holes;

- the dependence of FDA in the holes, located across the width of the working part of the specimen, has the character of a positive correlation. The positive correlation between durability of holes means that the destruction of one (the first) of the holes accelerates the destruction of others. Consistent subsequent destruction of holes can be considered as the first crack propagation. Correlation analysis based on the intraclass correlation coefficient is carried out for specimens with the „W"- type[4].

[3] I*t should be noted that the intraclass correlation coefficient is asymmetric with respect to zero. At the same absolute value of the negative correlation coefficient expressing a stronger dependence on the comparison with positive values. Field existence intraclass correlation coefficient is within 1 / (k-1) ≤ r ≤ 1*

[4] *Prof., Dc.Hab.Ing.S., V.P.Pavelko had obtaind this experimental data.*



a). b).

Fig.3.9 Specimens of aluminum alloy with holes systems

Table 3.3

The dependence of the intraclass correlation coefficient on the size of the circular holes.

The hole diameter, mm	Sample ICC, rˆ	Sample Size	Sample Criterial Statistic, Tˆ	Critical Value of Criterial Statistics
3	0,91	40	9,48	2,02
8	0,76	32	5,50	2,04
10	0,63	40	4,60	2,02
20	0,28	16	1,10	2,13

Where intraclass correlation coefficient r was defined by (3.12), and T is the criterion statistics :

$$T = (z – z_0)\sqrt{(2n-3)/2}$$

$$z = ½ \ln(1+\hat{r})/(1- \hat{r})$$

A tendency to decrease stochastic correlation with an increase in the diameters the holes is shown also under the increase a distance between the holes centers .

Table 3.4

Dependence intraclass correlation coefficient from a distance between the centers of holes

Distance between hole centers, mm	Quantity of hub in class, *k*	ICC, r̂	Samp le size	Criterial Statistics T	Critical Value of Criterial Statistics
50	2	-0,80	24	4,99	2.07
100	3	-0,45	48	1,89	2,01
150	4	-0.29	32	1,13	2,04

A mathematical model was developed to describe the changes ICC with increasing distance. With some simple assumptions for a single dimension, an expression of changes ICC, depending on the distance:

$$R(l) = exp\left\{-\int_0^l \mu(x)dx\right\} = e^{-\varphi(l)} \quad (3.14)$$

where $\varphi(l) = Cl^m$ – C и m – model parameters.

Table 3.5.

Test Data to determinate of Local Zone Sizes

	Across the Load direction				Along the Load Direction		
diameter (*l, mm)*	3	8	10	20	50	100	150
Ln(l))	1,10	2,08	2,30	3,0	3,91	4,61	5,01
R(l)	0,91	0,76	0,62	0,28	-0,80	-0,45	-0,29
Ln(-Ln(R))	-2,36	-1,29	-0,74	0,24	-1,50	-0,23	0,21

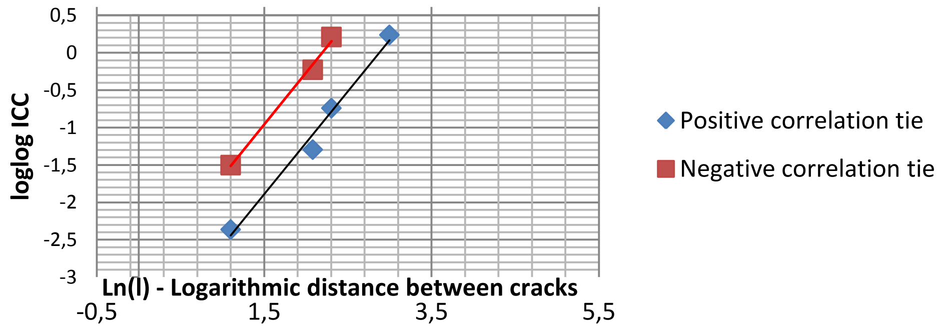


Fig.3.10 The intraclass correlation coefficient versus to the distance between the places of fatigue cracks origins.

The model parameters value are $\hat{C} = 0,0192$ $\acute{m} = 1,3716$

So, for positive correlation relationship:

$\hat{C} = 0,0192;$ $\acute{m} = 1,3716;$

for negative correlation relationship:

$\hat{C} = 0,00047;$ $\acute{m} = 1,590;$

or (see Fig.3.11)

$l_{0hor.} = 14,9$ mm; $l_{0vert} = 106,0$ mm.

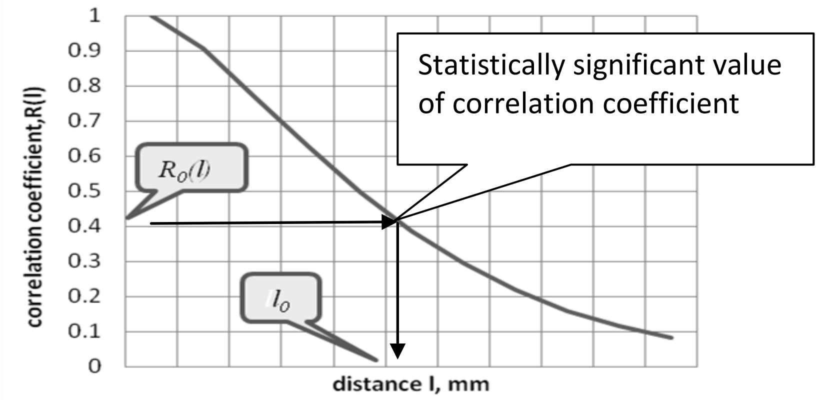


Fig.3.11 The Local Zone size detection

This proves the existence of Local Zones with FDA.

Let see the Fig. 3.12

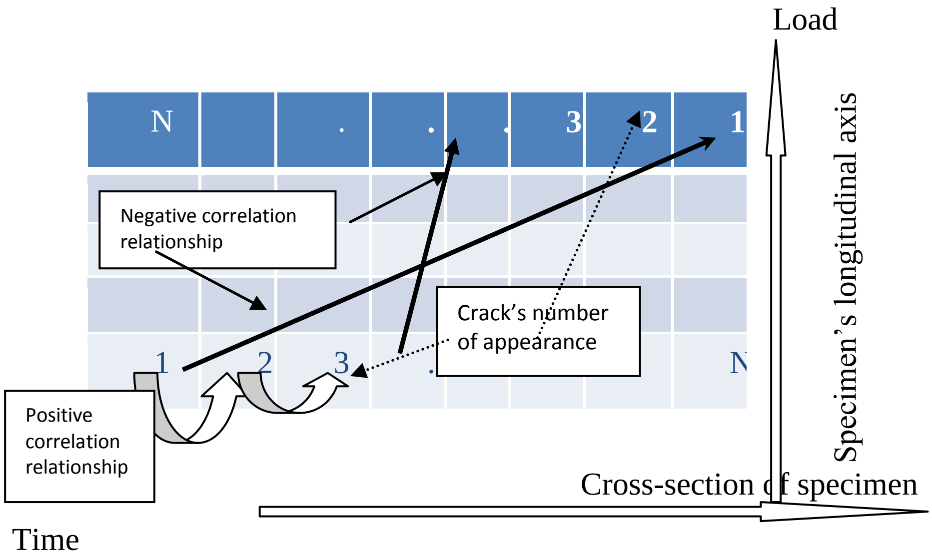


Fig.3.12 The Stochastic Ties in Local Zone

Suppose that in a certain part of a homogeneous Structure first in time damage occurs. If there is a positive correlation across the vector of load application, the likelihood of further damage near the first appears. In the event of a second, nearby damage is emergenced - most likely the third also occurs, etc. This process can be considered as the formation of the main trunk crack, and the process does not have to be consecutive. Damages flow generates the local area of future fractures and determines (in section accumulation of damage) the nature and speed of its spread. Obviously, the early appearance of damages leads to the rapid formation of the main crack and the following destruction of the total Structure. This stage of propagation is characterized by the FDA to a high level of loading of the Structure. If the first damage in this section occurs later, and the subsequent damage to this section will occur somewhat later. It is reducing the probability of occurrence of the main crack. Positive cross-correlation relationship supposes that before there the fatigue crack will have been originated, the early the subsequent crack will be found out in direction perpendicular to the applied force. Such sequence of fatigue cracks' emergences assumes a mode as a propagation of the first crack, converting it *to the only main spread out one*. So therefore this merging crack's sequence will determinate the durability of whole zone.

If in this area early appeared damage provokes the appearance of damages, the existing stochastic negative relationship delays the appearance of new damages in other sections by locating future focus of the first damage (of course within the coverage dependence, discussed earlier). This case leads to the formation of several zones, while at high loading of - a multifocal destruction of the section. When damages occur later, the negative stochastic relationship provokes an outbreak earlier fractures in the other sections. Therefore, the later occurrence of damage characterizes the subsequent rapid flow of damage at an accelerated pace and scattered throughout the area under consideration.

Vice versa, negative cross-correlation relationship, operating along the applied load, results in that early fatigue crack will have been originated, the later the subsequent crack will be found out in direction along to the applied force. So also that later there is a fatigue crack in the looked after zone, the early next one has to arise up, or it will be as a mode of *their joint together origination*. It is interesting note that negative relationship spreads to considerably greater distance, than positive.

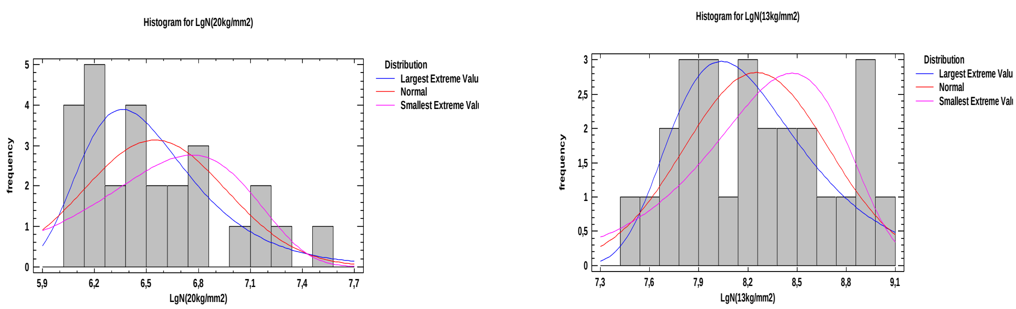
Let's consider physical nature of cracking at presence of negative relationship: than later it will be found out the first damage, the early the next ones will be originated, that results in speed-up and frequently out-of-control destruction after the protracted period of zero-defects operation.

There is a paradoxical situation where the earlier of the crack can provide control over its propagation, while the later of the crack is a signal to the accelerated cracking of the total Design (named "fatigue overheating"). The above supports the Hypothesis of Local Zones FDA.

Chapter 4. Model of durability of a Local Zone

In chapter 4 there are four parametric model of the Fatigue Strength of the Local Zone, which allows to describe the S-N fatigue curve, the fatigue durability CDF, the CDF of fatigue endurance and sensitivity threshold on cycles. This model, based on DEDF of fatigue durability, unites listed above Fatigue Strength Characteristic by four parameters only. The comparison of the three most often used kinds of CDF mentioned in Chapter 2, shows the preference the DEDF (LEV) for the fatigue characteristics' description.

The analisys of the most presentative samples of fatigue test data more then 2 000 specimens under different level of loading shows and proves the advantage of DEDF (LEV) versus other CDF. In Fig. 4.1 the experimental probability density DF and her description of three main kind DF (NDF, SEV, LEV) for the sample of test specimen loaded at stress level 20 kg/mm^2 and under stress 13,5 kg/mm^2 are presented[5].



a) b)

Fig.4.1 The comparison of the main probability density distribution function of Life Time (Durability) of Specimens: a) - 20 kg/mm^2; b) - 13 kg/mm^2

Table 4.1

Goodness-of-Fit by Tests Kolmogorov-Smirnov Test for LgN

Sample volume 600 specimens				Sample volume 50 specimens			
Stress level 20kg/mm^2	*Largest Extreme Value*	*Normal*	*Smallest Extreme Value*	*Stress level 13/mm2*	*Largest Extreme Value*	*Normal*	*Smallest Extreme Value*
DPLUS	0,145635	**0,131531**	0,147069	DPLUS	**0,0818195**	0,103213	0,11574
DMINUS	0,082505	0,118338	0,178423	DMINUS	0,0734303	0,084682	0,08521
DN	0,145635	0,131531	0,178423	DN	0,0818195	0,103213	0,11574
P-Value	0,615832	**0,738575**	0,359496	P-Value	**0,994983**	0,944609	0,87704

[5] *The calculations had been made by use the Statistical Program "Statgraphics Centurion XYI.Version 16.1.17 (evaluation mode).*

were DPLUS – maximal positive experimental point deviation from theoretical value;

DMINUS – maximum negative experimental point deviation from theoretical value;

DN – maximum experimental point deviation;

P-value –the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true.

So we can see: the less stress level the more adjustment of DEDF to evaluate the probability density DF. So the assumption of the DEDF best fitting for low-stressed (high reliability) Design is verified.

Of even greater importance is the fact that the goodness of fit is more significant for the left tie of DF in area of low failure probabilities, known as a sensitivity threshold of cycles.

Table 4.2

Lower Tail Area (p if $X \leq x$) for LgN

Sample volume 600 specimens				Sample volume 50 specimens			
20kg/mm² X (Lg N)	*Largest Extreme Value*	*Normal*	*Smallest Extreme Value*	*13kg/mm²* X (LgN)	*Largest Extreme Value*	*Normal*	*Smallest Extreme Value*
5,23856	8,63762E-18	0,000739	0,028759	6,60117	7,34736E-19	9,46868E-5	0,0103042
5,89337	0,00985306	0,055975	0,124801	7,42632	0,00742421	0,0309904	0,0749089
6,54819	0,580863	0,5	0,456088	8,25147	0,562294	0,5	0,44308
7,20301	0,93812	0,944025	0,93808	9,07661	0,93463	0,96901	0,987725
7,85783	0,992517	0,999261	0,999997	9,90176	0,992093	0,999905	1,0

Here it clearly seen the good fit of DEDF left tail as „a sensitivity threshold of cycles”, the occurence of which markedly affect to evaluation of Safe (Limited) Service Life.

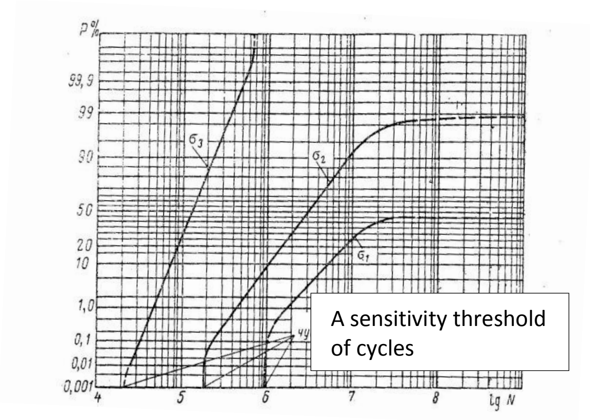


Fig.4.2 The existence of a sensitivity threshold of cycles N_0 during fatigue tests of aviation elements (stress: $\sigma_1 < \sigma_2 < \sigma_3$)

So, it is possible to take assumption of adequate description of the fatigue durability by DEDF (LEV) in Operation loads area.

Indeed, see the Table 4.3.

Table 4.3

Calculation and comparison the values of probabilities for NDF, Weibull (SEV) and DEDF

Quantile level p	0.001	0.01	0.1	0.2
Quantile NDF	-3,090	-2,326	-1,281	-0,841
Quantile Weibull (SEV)	-4,935	-3,136	-1,304	-0,719
Quantile DEDF (LEV)	-1,057	-0,741	-0,200	0,079

where quantile NDF = $\Phi^{-1}(p)$;

quantile SEV = $(\log(-\log(1-p)) - \Gamma'(1))\sqrt{6}/\pi$;

quantile LEV = $(-\log(-\log(p)) - \Gamma'(1))\sqrt{6}/\pi$;

So, if the Design (or her fatigue prone Local Zone) is under NDT monitoring, or have Safe Fail frame, the best approach is to use the DEDF (LEV) for the evaluation of Safe Life Time.

For an assessment of reliability of a Local Zone one of important points is to define and formalize the moment of refusal of the Local Zone (decision making condition or the Failure Criterion).

It is proposed the following Failure Criterions of Local Zone refusal:

- critical value of density of the found damages in some area (cracks in stringers, a covering and other Structural Significant elements in a certain Zone;

- critical number of the destroyed Structural Significant elements in a certain Zone;

- critical number of fatigue cracks in a covering, extending in the direction of action of positive correlation relationship (Chapter 3) – especially aspiring subsequently merging to one main crack;

- the accelerated growth of one of the main crack in a covering;

- increase in number of the subsequent repairs of Structural Significant elements by the criteria stated above, that brings to increase idle times of object of tests.

Assume that CDF of fatigue life at low stress levels relates to the same family CDF and owned family of double exponential CDF (DEDF or LEV) and it’s change depending only on the magnitude of the stress as on the change of parameters:

$$F(\tau \mid \sigma) = \exp\left[-\exp\left(-\frac{\tau - a(\sigma)}{b(\sigma)}\right)\right] \quad (4.1)$$

Mathematical expectance:

M{σ}= *a(σ)-b(σ)Г′*(1), *Г′*(1) = -0,5772...Eiler constant, (4.2)

Variance: D{σ}= $\pi^2 b^2(\sigma)/6$ (4.3)

note

$$\varphi(\tau, \sigma) = \frac{\tau - a(\sigma)}{b(\sigma)} \quad (4.4)$$

The function (4.1) will have the properties of the distribution function if the condition will be executed

if σ = 0	φ(τ,σ) → -∞
if σ → ∞	φ(τ,σ) → ∞

It is easy to see that this condition is satisfied than the proportionality of the function (4.2) is the logarithm of the stress σ. Note s = lgσ.

$$\varphi(\tau,\sigma) \propto s$$

It is known that when the stress increases and the coefficient of variation of the dispersion decreases. The coefficient of variation υ (τ, σ) for the CDF (4.1) with the known expressions (4.2) and (4.3)

$$v(\tau, \sigma) = \frac{\pi / \sqrt{6}}{\frac{a(\sigma)}{b(\sigma)} + \Gamma^{'}(1)} \quad (4.5)$$

Suppose

$$b(\sigma) = C/s^m \quad (4.6)$$

$$\frac{a(\sigma)}{b(\sigma)} = \gamma \cdot s^m + \theta \quad (4.7)$$

Substitute (4.2) in (4.3), take into account (4.5) and note following

$$\gamma C = \tau_0; \qquad \left[\theta - \Gamma^{'}(1)\right] C = P; \qquad M\{\tau\} = \tau_{cp} \quad (4.8)$$

get the S-N fatigue Curve for mean life time:

$$(\tau_{cp} - \tau_0)s^m = P \tag{4.9}$$

Substitute (4.4) and (4.5) in (4.1) and twice take the logarithm, get the S-N curve for quantil p-level.

$$(\tau_{cp} - \tau_0)s^m = C(-f(p) + \theta) \tag{4.10}$$

where

$f(p) = \ln(-\ln p)$, p – given quantil of CDF.

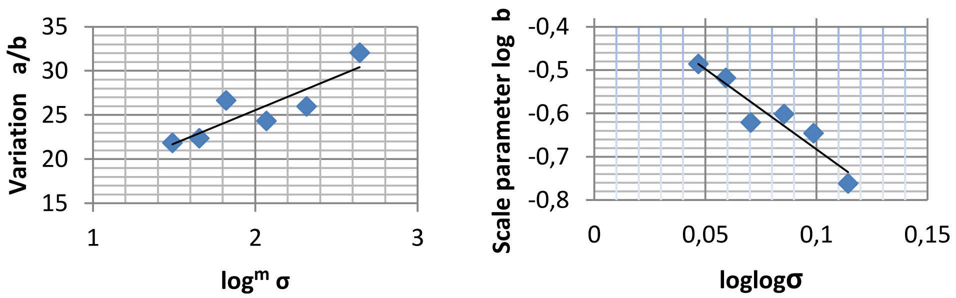
Note

$$A\{\tau\} = \theta \cdot C/(\tau-\tau_0); \qquad B\{\tau\} = C/(\tau-\tau_0); \tag{4.11}$$

get

$$F(\sigma \mid \tau) = \exp\left[-\exp\left(-\frac{s^m - A\{\tau\}}{B\{\tau\}}\right)\right] \tag{4.12}$$

It can be seen that the Local Zone's limits of endurance DF is also DEDF (LEV). Estimation of the parameters of the proposed model was carried out on the above mentioned test results of more than 2000 specimens made by M.N.Stepnov



a) b)

Fig. 4.3 The increase in the dispersion of fatigue life, depending on the reduction of Load to Structures: a) reciprocal variation coefficient versus power "m" logarithmic stress, b): scale parameter b versus double logarithmic stress.

The parameters (4.6) evalution:

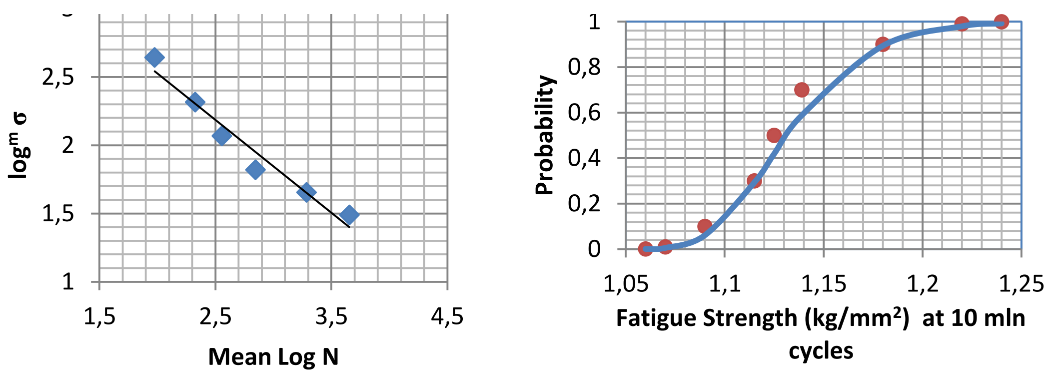
m = 3,6936, log C = - 0,313207, C = 0,4862

the same for (4.7)

$$a/b = 10{,}43 + 7{,}55847 \cdot s^m$$

where

γ·= 7,55847, θ = 10,43



a) b)

Fig. 4.4 The S-N Curve (a) and Fatigue Strength (Limit of Endurance) DF (b) at 10 ml loading cycles base

On the basis of the adopted model and the assumption of the DEDF for long life time durability and the fatigue life of a piecewise linear S-N fatigue curve is proposed.

Table 4.1

Piecewise and linear display of S-N fatigue curve.

Range of durability,cycles	Value of m parameter[6]	The distribution function of the durability
up 1 ml	4	Weibull (SEV) (2.1)
from 1 ml up 10 ml	6	logarithmic-normal (2.2)
from 10 ml up 100 ml	8	logarithmic-normal (2.2)
from 100 ml up 1 000 ml	10	DEDF (LEV) (2.3)
from 1 000 ml	12	DEDF (LEV) (2.3)

[6] *The given "m" parameter of S-N fatigue curve and point of her changing are used under the evaluation the Safe Life of the some aviation strength elements under design and test practise.*

The “m” parameter of S-N fatigue curve is changing due to shift of the mechanism of FDA under the load level changing. In points of sucn transition the break of S-N curve is observed on frequent occasions.

By way as example the modified estimation of the Local Zone durability (Limit Service Life) based on the results of fatigue tests and her extrapolation to working load condition is given for tail and keel beem of helicopter Mi-26.

Shortly, it is known, that Limit Safe Life is determinate by

$$R = \frac{N_{\min\, work}}{\eta_N}$$

where R – Limit Safe Life;

$N_{\min\, work}$ – minimal load cycles number after her extrapolation (within S-N fatigue curve) to working condition area after test results; in our case $N_{\min\, work}$ = 175 400 flight hours,

$\eta_N = \exp(2{,}303\beta \ln \nu)$ - cycles safety factor; (4.13)

$\beta = \mathrm{var}\{\tau_{work}\} M\{\tau_{work}\} \frac{\sqrt{6}}{\pi}$ - the scale parameter in working condition (4.3);

$\mathrm{var}\{\tau_{work}\} M\{\tau_{work}\} = \sigma(\tau_{work})$ - mean square deviation of LgN in Service condition;

$$P_{norm} \prod_{i=0}^{n-1} \left(\frac{\nu}{n-1} + 1\right) = 1 \qquad (4.14)$$

ν – is determinate by (4.14);

P_{norm} – the normative probability of the that class of Design’s fracture, if P_{norm} =0,001, ν =999;

n – the quantity of Desigh tested (n = 2).

In aviation practice for fatigue prone elements σ_{lgN}/m = 0,025 so if m=12 σ_{lgN}= 0,30 and β=0,234.

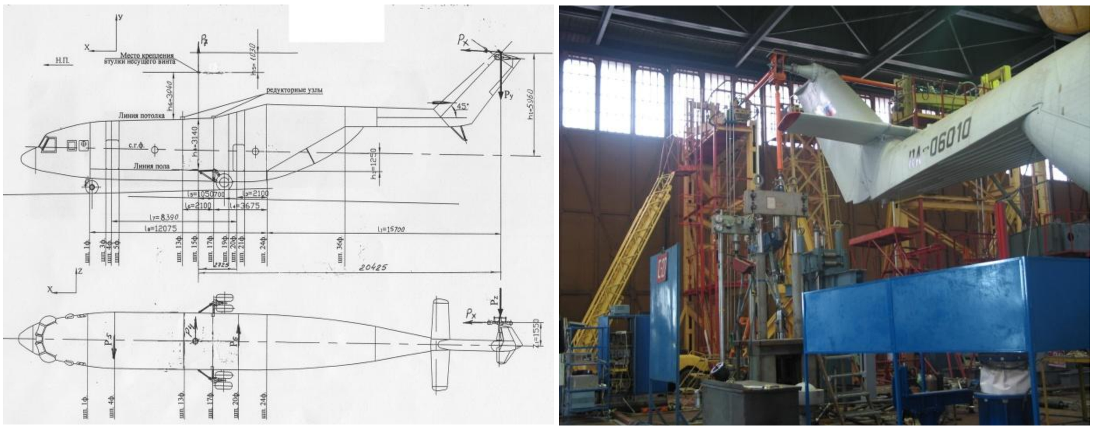
Than η_N = 41,35, $N_{\min\, work}$=175 400 flight hours, so the Safe Life Limit R = 4200+1000 (real work time in operation) or no more than 5 200 flight hours[7].

[7] *This Calculation is given as an example and is used for evaluation’s procedure example only.*

Chapter 5 Monitoring of a local zones technical condition on largesizes Designs

In the chapter 5 overview of nowadays non-destructive testing, the most suitable for monitoring of Local Zones are presented. The acoustic emission was chosen as the most serviseable method during the fatigue Bench Tests. To prove this application of acoustic emission method for testing of various aircraft strength elements the various tests and experiments were realized during the fatigue tests in SIA “Aviatest”. That allows predicting the beginning of fatigue failure even before emergence of fatigue cracks. This property does AE-method as almost irreplaceable means when monitoring during the Bench Tests and definitions of a location of Local Zones, as "special attention" areas. One more advantage of AE-method is possibility of formalization of experimental data in directly digital form whereas installations of thermo vision ("thermal imagers") have not of such opportunity.

On pictures some proves of the assumption of the Hypoteses of Local Zones are shown.

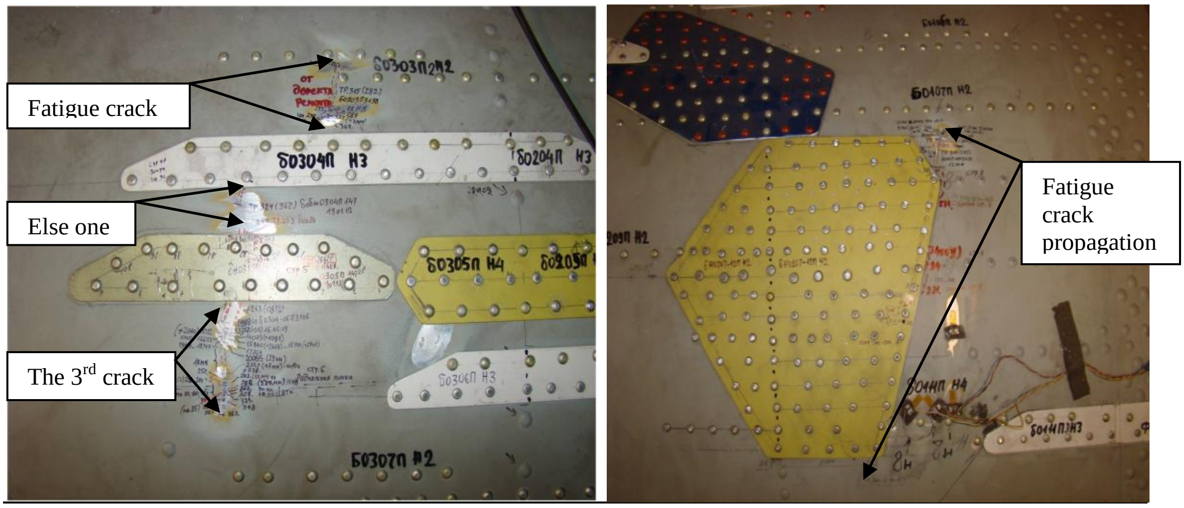


a) b)

Fig.5.1 Loading scheme of Mi-26 helicopter on the branch (a) and it’s general view (b)

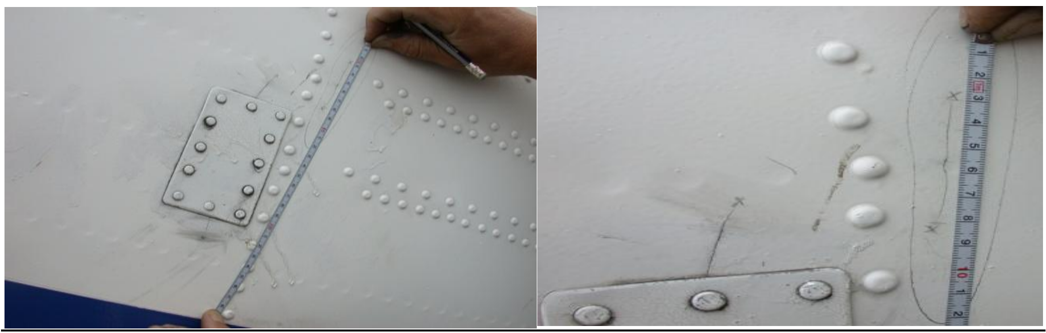
a) b)

Fig.5.2 The Local Zone on the Keel Beam of helicopter Mil-26: a) general view, b) keel beam as one unit local zone.



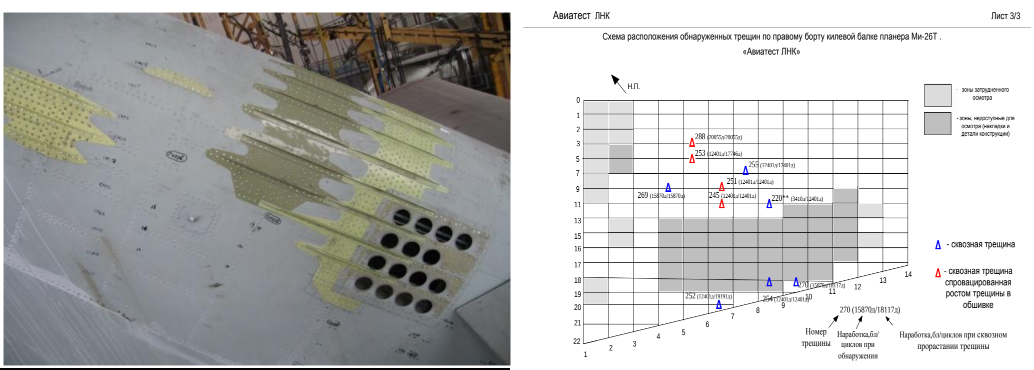
a) b)

Fig. 5.3 Examples of cracking the local area: a) - of fatigue cracks potentially form a single trunk (positive correlation), b)- the occurrence of fatigue cracks under repair pad (positive and negative correlations)



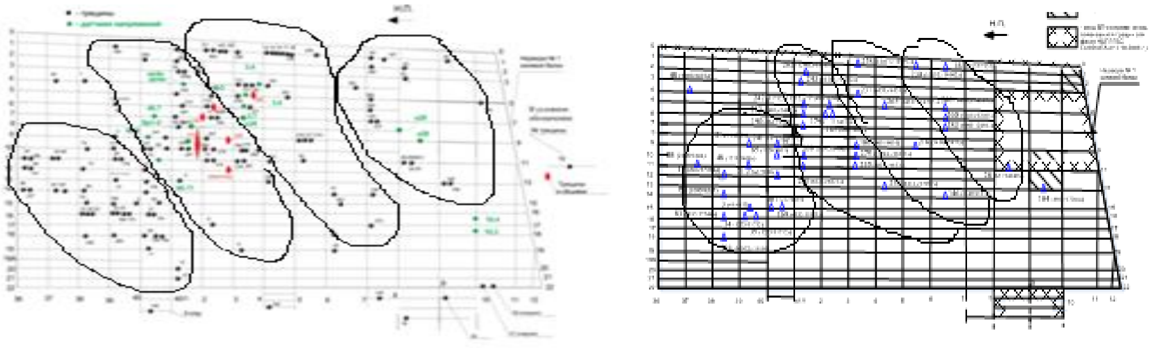
a) b)

Fig.5.4 The propagation of fatigue crack in Operation: a) under repair pads; b) formation of cracks in one Local Zone



a) b)

Fig.5.5 Fatigue cracks on keel beam, after several repairs a) - natural view, b) –scheme view



a b

Fig.5.6 Fatigue on Tail Beam of Mil-26 helicopter: a) – general scheme of all cracks on the right board (inside view), b) – scheme of dangerous fatigue cracks

For Tail beam of the helicopter Mil-26 (Fig.5.6) four mail Local Zones are checking by Kruskall- Wallis criterion:

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1) = 15{,}05 \qquad (5.1)$$

where

N = Σk_I = 7+5+12+18 = 42,

к = 4 number of local zones,

$R_i = \sum_1^k R_i^j$ – summing of ranks for $к_i$- zone

n_i – data quantity in i- zona.

show the nonuniform state of Data between Local Zones or its differs each of other.

Similar for Keel Beam (Fig.5.5):

Comparison of two samples by Mann-Whitney's criteria shows the following:

total ranks of samples:

U4 = mn+1/2m (m+1) – R4 = 15+6-9 = 12

U5 = mn +1/2n (n+1) – R5 = 15+15-27 = 3

Comparing the received value of statistics to critical U_{cr} = 2 at a significance level α = 0,05 it is possible to draw a conclusion that both selections are uniform. So the keel beam itself can be considered as lonely whole Local Zone.

Above mentioned allows to formulated the main methodology and management principles of the technical condition monitoring of full-size Designs.

Stage 1 Preliminary studying of a stress condition of a Design. Complexity consists in initial uncertainty of an installation site of sensors of NDT: acoustic issue, strain gages, wires of thermal imagers. Therefore one of the first stages it is considered to be a preliminary estimate of a stress distribution of Design by computational methods and, if there is an opportunity, a strain-gaging at static loading without entering damages into observed Design.

Stage 2 Correction of installation places of sensors and frequency of inspection. After installation in the chosen places of a Design of NDT sensors functioning in a "online" mode, there is an information acquisition about parameters of AE- signals, change of nature of deformations on strain gages and places of emergence of fatigue cracks and damages. At insufficient number of sensors the "fan"-mode of information acquisition is organized. The following correction and data processing, including correlation analyses of the moments of fatigue cracks emergences, AE-signals and if necessary of other methods of stochastic processes data processing are follows.

Stage 3 *Monitoring of a Technical Condition of Local Zones and Research of Speed of Accumulation of Fatigue Damages. Then the attention is directed on survivability of this (these) of zone (zones): strain gages are re-stuck on a way of possible distribution of a crack (in principle carry out a role of sensors of cracks), functioning of AE-sensors passes in from a mode of quality standard of recorded of AE-signals to the quantitative – the purpose of both methods to prevent premature destruction of a Local Zone and to receive characteristics of her survivability.*

At this investigation phase the size of Local Zones, its interposition on Design of test, nature of dependence of fatigue cracks emergence, preliminary analyses of durability, survivability and other characteristics of reliability of the Local Zone that may define reliability of total Design, is defined. Visual control of Local Zones ("special attention" zones) is exercised with the increased frequency and with adapting, if necessary, other methods of NDT: thermo vision, ultrasonic, eddy-current.

Stage 4. Decision on scenarios of continuation of tests. By results of processing of data on intensity of fatigue cracks emergence in a Local Zones, the analysis of measurements of deformations from strain gages, periodic visual and NDT check-up, character of AE-signals there is accepted and defined the decision on a continuation of tests. Usually it is necessary:

- to carry out the repair of the damaged Local Zone and to continue tests according to the same load program;

- to carry out the repair of the damaged Zone, to estimate her durability (Safe Life) and to change conditions of loading;

- to carry out repair of the out of interest Local Zones and change to research of survivability of a Design.

These repairs need to be done for TOTAL ZONE, instead of separate cracks and damages.

Stage 5 Development of Recommendations based on Results of Tests.

CONCLUSION.

1. The Hypothesis of Local Zones with fatigue damages dependent accumulation is developed and experimentally confirmed.

Main assumption of the Hypothesis of Local Zones:

- the full (large) Design can be presented as association of several Local Zones;
- in Local Zones accumulation of fatigue damages happens stochastic dependent, and beyond her borders – independent;
- with increase in distance from initial damage, stochastic relationship between the moments of emergence of damages decreases;
- some Design units may be represented as one Local Zone;
- characteristics of durability, survivability of large-size Design are defined by characteristics of Local Zones.

2. There are developed and confirmed by experimnental data

- phenomenological models of zone's local accumulation of fatigue damages;
- mathematical model of the origin and size of a Local Zone;
- mathematical model of reliability of the Local Zone, that determinates the Reliability of total Design;
-the actually method of the fatigue prone Design's Safe Life evaluation is modified.

3 The experimental data on specimens as on model-analog of accumulation of fatigue damages for uniform body of Design have been:

- made for the specimens with several sorted configuration of hole-type concentrators (under totally randomization of the test procedures);
- processed under the fatigue test results of other authors;

The experimental Data of real fatigue prone aviation Design's Test have been proceeded.

4) It is shown that the fittest methods of NDT, which are the most adapted for application at bench tests of large-size Designs, are the acoustic emission and thermovision method. The methodology (algorithm) of application of the chosen methods of NDT at bench tests for early detection of initial damages and different scenario of Design's (or her Local Zones) reliability is developed.

5) The most signified summary for next investigation:

-in Local Zones stochastic relationships (both positive and negative) localize a disposition of initial damages which can be considered subsequently as one damage. Negative relationship leads to formation of other Local Zones. The later the initial fatigue damage is arising; the early fatigue damages are arising in other Local Zones. That leads to "fatigue overheats" of Design as accelerated flow of damages. Early emergence fatigue damages allow managing the NDT and other monitoring of technical condition of Local Zone and employ the principle of Safe (fail controlled) Failure;

-the durability of a Local Zone is defined by function of distribution of "maxima": double exponential distribution with logarithm of life time (cycles);

- the main characteristics of Fatigue Strength of a Local Zone (parameters of fatigue durability distribution function, fatigue limits of endurance distribution function, S-N fatigue curve and threshold on cycles may be described by only four parameters;

- the acoustic emission-method allows determinatig the origin of degradation process even BEFORE the emergence of visible damages at variable kinds of loading (static, dinamic, thermo etc.). In this case the Local Zone can serve as the indicator of fatigue damage accumulation for all total Design, that allows to develop the principles of Safe (controlled) Destruction of the Design.

6) The Hypothesis of Local Zones together with application of suitable method of NDT (acoustic emission) allows the monitoring of a large-(full)-size Designs with minimization of temporary, material and human expenses and provides most to an early damages' detection at Bech Tests and Operation condition.

7) The Hypothesis of Local Zones points out the possibility to manage the Design's monitoring for the early cracks' detection and change the operating principle of Technical condition to a safe destruction (Fail Safe Concept).