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Methodology and practices to provide the Russian civil and transport aircraft structures service life

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Abstract: The paper presents the system to provide the Russian civil aircraft structural life time conditioned by strength. There are given as follows: the system operation layout, the methods to assure the safety, the evolution of the USSR Russia norms, conditioned by structural fatigue and damage tolerance, the service lives of attested ageing transport aircraft, the design operational lives of new certifies aircraft, the studies of strength, fatigue and crack growth resistance of enhanced Al-alloys, structural damage tolerance analytical methods, the fatigue and damage tolerance certification tests of full-scale structures and assurance of aircraft airworthiness conditioned by strength.

SYSTEM TO PROVIDE AND SUPPORT THE SERVICE SAFETY OF RUSSIAN CIVIL AIRCRAFT

The assurance and maintenance of service safety of civil aircraft structures conditioned by fatigue strength is a challenge to be solved by following the developed and operative system that is reflected in Russian Transport Aircraft Aviation Regulations.

This system is based on a number of major principles following which the safety is taken into consideration at design, manufacturing and is supported during the entire aircraft service life. It is not possible to obtain a high safety level without regular control of the factually changing environment due to the change of operation conditions and aircraft loading, the creation of information on the factual health both of the individual aircraft and the fleet as a whole. Table I. demonstrates a scheme of system functioning.

Table I. Tasks on airplane creation and exploitation.

Requirements specification and maintenance	Draft project	Working plan
• Performance requirements on life time; • Weight limits; • Selection of material and technology; • Loading; • Determination of allowable stresses for regular zones; • Selection of method to assure the life time.	• Calculation of loads repetition with resilience considered; • Controllability requirements specifications; • Tryout of regular structure main components; • Tryout of main load-bearing irregularities.	• Clarification of loading; • Tryout of durability and damage tolerance of panels, units and tested sections; • Calculation of durability per detail; • Determining the regulations and means of operational control.
Airplane testing	**Operation within the designed life time**	**Operation beyond the designed life time**
• Checking up the damage tolerance and durability sufficiency; • Checking up the structure production technique; • Tryout of regulations to assure the safety of structure in exploitation.	• Checking up the conditions; • Checking up the structural integrity; • Generalization of operational experience; • Testing the aircraft with long flying time; • Development of supplementary activities to assure the life time; • Step-by-step life time extension.	• Assuring the safety of structure with corrosional and multisite fatigue damages while taking into account the degradation of materials; • Assuring the structural durability in zone of repair; • Development and fault detection of long-term exploited aircraft structures; • Individual life time extension.

According to this system the step-by-step implementation of extending the specified lives of attested aircraft fleet. At that the life time is specified at each step. The step duration is 5 – 10 thousand hours. When the specified life time is expired the aircraft operation is given up and the further service conditions are investigated, i.e. the conditions of the next step of specified life time.

The individual extension of each aircraft life time is made for aging (long exploited) airplanes.

METHODS TO PROVIDE THE SAFETY

The assurance of Russian aircraft safe exploitation is based on three principles: safe life, fail-safe and damage tolerance. (Figure1).

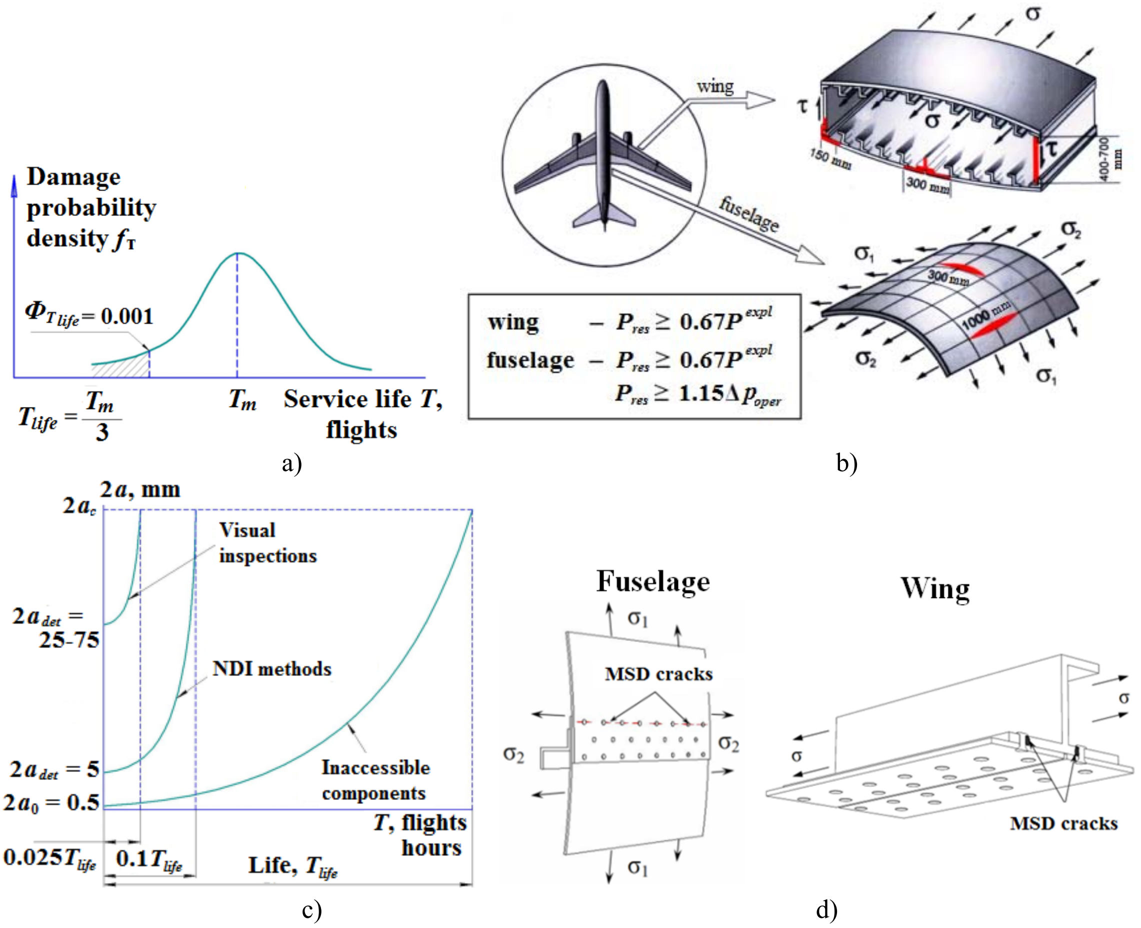


Figure1. Fatigue and durability criteria, a) safe life, b) fail safe, c) damage tolerance, d) prevention of MSD.

Safe-life is the property of structure and the method to provide its safety conditioned by strength. This method requires no special inspections in operation through specifying the allowable operating time in terms of hours or flights, during which the possibility of structural strength degradation is less than the rated designed level.

This principle is applied to the wing panels' longitudinal joints, the fuselage skin lap joints where the multiple site damage cracks (MSD) may be.

Fail-safe is the property of structure and the method to provide its safety conditioned by strength through creating such a structure, the residual strength which of after the serious obvious damage (the failure of one of the primary components, the two-bay crack in skin with failed stiffener and so on) due to the fatigue, corrosion technological and random damages will not degrade without repair below the allowable level during the repetitive, mainly, visual inspections period, during which the damage will be a fortiori found out while maintaining the aircraft.

Damage tolerance is the property of structure and the method to provide its safety conditioned by strength by assigning the period of the first structure inspection and the following ones by NDT methods to find out the possible fatigue damage and to repair the structure or replacement of the damaged component before such a state of structure when its residual strength degrade below the out-of-tolerance level, i.e. the residual strength becomes below the allowable level prescribed by Regulations.

EVOLUTION OF USSR AIRCRAFT AIRWORTHINESS REGULATIONS AND RUSSIAN AR IAC AVIATION REGULATIONS ON TRANSPORT AIRCRAFT STRUCTURAL FATIGUE AND DAMAGE TOLERANCE

The approaches of Europe, USA and the USSR to assure the aircraft structures service safety were greatly influenced by the accidents of two "Comet" English civil jet aircraft. These accidents were caused by the fatigue damages of pressurized fuselage.

In the 50-th the national approach was influenced by the European requirements in connection with this the "safe-life" principle was the only one to assure the safety during the long-term exploitation in the first versions of the USSR airworthiness standards for civil airplanes. The main drawbacks of this approach were that there remained always a doubt in safe-life prediction reliability to be kept during the decades of those service conditions which were approved under such a prediction. Due to this the margins system expanded, the number of tested full-scaled structures increased, including those ones with exploitation period. E.g., from 4 to 6 full-scale airframes of such aircraft as Tu-104, Il-18 and An-24 were tested. The approved in our country principle of step-by step extension of specified service lives within assigned designed values turned out to be highly effective. When stating the next specified service life the durability prediction and loading revaluation takes place for the next step.

In the 70-th the national safety assurance system was considerably revised. The accident of the Ukrainian passenger airplane AN-10A in 1972 had the most serious influence. The accident was caused by widespread fatigue damages (WFD) wing lower surface skin and stringers in panel joints along the aircraft axis. As a result of analyzing the reasons of this accident in 1976 along with "safe-life" the new concept was fairly introduced, called the "operational durability". In the national practice the operational durability concept is exercised broadly and includes both the damage tolerance and the fail-safe principles. The fail-safe principle characteristics are verified by check of the structure residual strength required at presence of the so-called regulated damages (Figure1) like two-bay crack in skin, the completely fractured spar boom, stringer, frame with adjacent skin parts, walls and so on. The operational durability concept is interpreted as fail-safe principle for the great category of structural components where the multipath load transfer and the redundancy of connections (high-lift devices hinge fitting units, engine and empennage fastener assemblies, double lugs) are provided.

In the 90-th the AP 25.571 national Regulations were harmonized with FAR 25.571 and JAR 25.571 foreign ones. The operational durability concept is the basic in harmonized domestic Regulations. The safe life principle is possible to be practiced only when the Applicant proves that the operational durability concept is impossible to be implemented for a concrete structure.

It is to be noted that the concept of limit of validity (LOV) was approved in 2011. In the domestic the analog requirement was stated in the 70-th. In conformity with this requirement the ultimate assigned life time was limited by condition to prevent the MSD and WFD damages appearance.

Evolution of USSR NLGS airworthiness requirements and of Russian AP 25.571 on fatigue and damage tolerance of transport aircraft structures is considered. The evolution of USSR and Russia Regulations in terms of aircraft structures safety assurance is given in Table II.

Table II Evolution of USSR NLGS airworthiness requirements and of Russia AP 25.571 on fatigue and damage tolerance of transport aircraft structures (latest version).

Regulations	Conformity assurance methods (MOS)	Approval date	Main principles of assuring the life-time
NLGS -1		1967	Safe-life
NLGS -2		1974	Safe-life
NLGS-2 Amendment 2 to Part 4		1976	Safe-life or service damage tolerance (damage tolerance and fail-safe)
НЛГС-3		1984	Safe-life or service damage tolerance (damage tolerance and fail-safe)
Aviation Regulations AP 25.571		1994	Safe-life, service damage tolerance (damage tolerance and fail-safe)
	MOS 25.571	1996	Safe-life, service damage tolerance (damage tolerance and fail-safe), WFD
AP 25.571		2004	Safe-life, service damage tolerance (damage tolerance and fail-safe), WFD
AP 25.571		2009	Safe-life, service damage tolerance (damage tolerance and fail-safe), WFD

LIFE-TIMES OF RUSSIAN AGING TRANSPORT AIRCRAFT

Currently the Russian civil aircraft fleet consists mainly of those aircraft types the exploitation which of started in the 60-th (Table III). During this period the major part of them has not only reached the designed goal but significantly is beyond it.

It is aware that the all outdated aircraft were designed by the safe life principle. In conformity with the USSR Fatigue Regulations the full-scale airframe fatigue tests were performed for each aircraft in a scope which is necessary to corroborate the designed life time. In 1976 the national Fatigue Regulations were supplemented with the “service durability” requirement. Due to it the additional full-scale tests of aging aircraft structures were performed (Table III) where the fatigue cracks growth rates and the residual strength of airframe structure at presence of cracks and failures were investigated. The durability tests were carried out both for the new aircraft and those ones which are characterized by rather long operating time and the service life period in exploitation. This made it possible to take into account the environment effect and other factors related with calendar service life period which influenced on the fatigue and crack growth resistance characteristics of structural materials. The approved inspection regulations were revised based on the results of fault detecting the structures in operation. This was made by specially developed and validated statistic methods.

Table III. Russian aging aircraft service lives (attested before 1994).

Airplane model	Designed life-time, DSG flights	Allowable operational flying time, ESG flights
Tupolev		
Tu-134	20 000	32 000
Tu-154	15 000	22 000
Ilyushin		
Il-18	10 000	25 000
Il -62	7 500	9 000
Il -76	10 000	10 000
Yakovlev		
Yak-40	25 000	32 000
Antonov		
An-12	8 000	18 000
An-24	20 000	47 000

The aging aircraft operational safety depends greatly upon the structure corrosion health. The current Regulations on structure fatigue strength bind to consider the structure corrosion health and to prevent the catastrophic fracture due to corrosion.

Thus, the main peculiarity of assuring the operational safety of aging aircraft consists in that that they are exploited beyond the designed life time as it complies with the current Regulations based on service durability concept, that were not taking into consideration when designing, i.e. some excessive strength that exists in each type of structure is used.

The next peculiarity of assuring the operational safety of aging aircraft is not only a requirement to register the typical fleet operation Certification but also the individual one for each aircraft of this fleet accompanied with mandatory inspection of this board before the life time extension.

The next important component in maintenance of aging aircraft airworthiness is step-by step life time extension, which is used for aircraft that are in operation both before the designed life time and beyond it.

One of the main peculiarities of supporting the aging aircraft airworthiness is the possibility to fly at presence of fatigue cracks. At this, the aircraft designer evaluates the crack growth duration up to ultimate value under which the residual strength remains higher than the maximal standardized load.

DESIGNED LIFE TIMES OF NEW CERTIFIED AIRCRAFT

The designed life times of Russian new attested aircraft are given in Table IV. The life times of foreign analog aircraft are given for comparing. The structures of Russian new attested aircraft were designed in conformity with the harmonized AP 25.571 Regulations that consider the service durability requirement.

Table IV. Designed service lives of new attested Russian and certified foreign airplanes.

Russian Airplanes Foreign analogs	Designed service life	
	Flights	Hours
SSJ-100	54 000	70 000
Embraer 195	50 000	70 000
Bombardier CRJ-1000	60 000	
An-148A	60 000	80 000
TU-204SM	45 000	60 000
A320	48 000	
Boeing 757	50 000	
Il-96-300	12 000	60 000
A340-600	16 600	
Boeing 777-200 (short lines)	44 000	66 000
Boeing 777-200 (long lines)	11 000	88 000
Il-76D	10 000	30 000
Lockheed C-141 Starlifter	-	45 000
Il-76MD-90A	8 000	30 000
McDonnell Douglas C-17A Globemaster	-	30 000
An-124-100	10 000	50 000
Lockheed C-5B Galaxy	6 500	45 000

As it follows based on given data (Table IV), the life times of Russian new attested aircraft are comparable with life times of foreign counterparts. The enhanced life times of these aircraft are obtained due to the application of improved structural materials made of Al-alloys, the upgrade of design and structures production engineering.

The structures airworthiness maintenance is implemented by the step-by-step technique and when necessary by the revision of previously stated conditions of life time use up period.

The required level of airworthiness during the long-term exploitation specifies the necessity to state the conditions of life time use up period for each aircraft individually.

RESEARCH OF STRENGTH, FATIGUE AND CRACK GROWTH RESISTANCE OF ENHANCED AL-ALLOYS

Currently the aviation alloys still remain the principle structural material for transport aircraft. To provide the high weight efficiency in combination with high life time and high operational durability characteristics of aircraft structures the Al-alloy are needed to have the following characteristics complex: high resistance against variable loads, low fatigue cracks growth rate, specified residual strength.

Table V presents the mentioned above characteristics of enhanced Russian and foreign Al-alloys that are recently created and used in existing and being designed aircraft. Only those characteristics of materials that are testes in TsAGI by one and the same technique are shown. The materials under consideration were developed in All-Russia Scientific Research Institute of Aviation Materials (VIAM) and at ALCOA Company (USA). These characteristics were determined in compliance with the Russian standards (strength) and the ASTM ones fatigue cracks growth rate, R-curves). The material characteristics were obtained in the course of testing the specimens by electro-hydraulic machines of MTS, Instron and Schenk firms.

Table V. Enhanced Al-alloys properties.

Airplane	Material	σ_b, MPa	$\sigma_{0.2}$, MPa	δ_5, %	*Fe*, %	*Si*, %	*Zr*, %	N_{133}, cycle	*m*	$(da/dN)_{31}$, mm/kcycle	K_{app}, MPa√m	K_c, MPa√m
Wing upper surface												
B777, A380	7055-T7751 plate	620	595	7	0.13	0.12	0.11	300 000	5.9	3.1	90	
	V96ts-3pchT12 plate	635	595	10	0.12	0.03	0.12	320 000	7.4	4.1	70	
IL-96-300	V95ochT2 plate	540	460	10	0.12	0.07	—	170 000	4.7	2.4	160	198
AN-124	1973T2 plate	531	484	14	0.15	0.1	0.12	110 000	4.5	2.6	111	
Wing lower surface												
TU-204	1163T plate	460	340	20	0.07	0.04	—	205 000	4.8	2.6	158	212
IL-96-300	1163T7 plate	500	390	14	0.12	0.06	—	200 000	5.0	2.6	163	
AN-124	1161T extruded panel	474	324	16	0.10	0.03	0.11	220 000	5.3	1.4	155	
A380	2324-T39 plate	500	460	12	0.08	0.04	—	275 000	5.9	2.5	148	
A340	C433-T351 plate	456	320	15	—	—	—	260 000	5.3	1.1		
Fuselage												
IL-96-300	1163ATV sheet	442	315	24	0.12	0.05	—	90 000	4	1.8	156	239
TU-204	1163RDTV sheet	456	350	23	0.14	0.03	—	115 000	4.0	1.7	171	245
A380	2524-T3 sheet	450	363	20	0.07	0.03	—	95 000	3.4	1.8	181	264
	1441RT1 sheet	443	364	13	0.05	0.03	—	100 000	4.34	3	115	141
	6013-T6 HDT sheet	365	333	—	—	—	—	85 000	3.6	1.9	175	252

STRENGTH

The strength characteristics are determined as follows: σ_b strength limit, $\sigma_{0.2}$ yield strength and $\sigma_{0.2}$ relative extension.

The strength and the yield strength values of 7055-T7751 and V96ts-3pchT12 alloys that have *Zr* additives are significantly higher than the corresponding characteristics of Al alloys, which are widely used for wing upper surface.

The $\sigma_{0.2}$ relative extensions of Al-alloys that are used for the wing lower skin and fuselage significantly exceed those of alloys which are used for the wing upper surface.

FATIGUE

The fatigue tests used the flat specimens in the form of strip with a hole in its center. The stress concentration coefficient was equal to $K_t = 3.1$. The specimens were tested under zero-to-tension stresses (the asymmetry ratio was $R = 0$) and 3 – 5 Hz loading frequency in 80 – 220 MPa maximal stresses range.

Table V shows the values of *m* degree index in fatigue curve equations of tested alloys.

$$\sigma^m N = 10^C, \tag{1}$$

where *m* and *C* are constants.

Table V shows also the N_{133} damage tolerance values that are the average values of alloys durability under maximal stresses gross $\sigma_{max}^{gross} = 133$ MPa and $R = 0$ asymmetry ratio.

The zero-to-tension stresses with $\sigma_{max}^{gross} = 133$ MPa constitute the basic test type, which is widely used in Russia to compare the properties of aviation Al-alloys materials.

In logarithmic reference system the straight lines indicate the σ – *N* dependence in tested durabilities range for specimens made of sheets that are used for fuselage skin, wing extruded panels.
The *m* exponents for damage curves are as follows:

- 4.5…7.4 for wing skin alloys;
- 3.4…4.3 for fuselage skin alloys.

FATIGUE CRACKS GROWTH RATE

The flat specimens with central hole were tested. The specimen width was 100 – 200 mm. The initial through cracks of $2a_0 = 6.4$ mm length were created in the centers of specimens by electroerosion method. The tests were carried out without recovery of specimens buckling in zone of crack. The cracks growth rate was determined visually by the optic microscope.

Table V shows the cracks growth rate as $(da/dN)_{31}$ mm per kilocycle where *a* – is half the length of crack. The $(da/dN)_{31}$ values are equal to the cracks growth rate under the $\Delta K = 31$ MPa√m stresses intensity coefficient amplitude. The $\Delta K = 31$ MPa√m amplitude is used in Russia to compare the cracks growth rates in different aviation materials of Al-alloys.

Based on the experimental data that are given in Table V it follows: the *da*/*dN* cracks growth rates in wing and fuselage skin materials under the $\Delta K = 31$ MPa√m stresses intensity coefficient amplitude are in e 1.1 – 4.1 $\frac{mm}{kilocycle}$.

RESIDUAL STRENGTH

The flat specimens with central hole were tested. The *W* specimen width was 1200 mm. The initial through cracks of $2a_0 = 0.33W$ mm length were created in the center of specimens. The tests were carried out with recovery of specimens buckling due to use of special device. The R-curves were plotted based on tests results. These curves were used to calculate the K_{app} and K_c values.

The main results of residual strength are as follows (Table V):

- The critical stresses intensity coefficients values for plastic materials of the wing lower surface and the fuselage are twice higher vs. the high-strength materials of the wing upper surface;
- The K_c plastic materials values for the wing lower surface and the fuselage are approximately 40 – 60 % higher than K_{app} ones.

It is to be noted that the development of structural Al-alloys materials is differentially performed for the wing upper surface skin, the wing lower surface skin, for the fuselage upper part and the lower one.

AIRCRAFT STRUCTURES DAMAGE TOLERANCE CALCULATION TECHNIQUE

The required life time, the operation safety and the cost-effectiveness of current aircraft structures are assured based on the operational damage tolerance concepts, the principle characteristics which of are the fatigue cracks growth rate and the residual strength.

FATIGUE CRACKS GROWTH RATE

Currently, TsAGI has comprehensively researched based on the linear fracture mechanics methods the fatigue cracks growth rate mechanisms.

To calculate the cracks growth rate under regular loads the Paris equations and the Forman ones and their modifications are mainly used. At the complex spectrum with variable amplitudes the linear models, the Willer models, the Willenborg models and the Elber crack closing model.

Figure 2 presents the results of cracks growth rate calculation in transport aircraft wing lower surface. The calculation is performed at TsAGI.

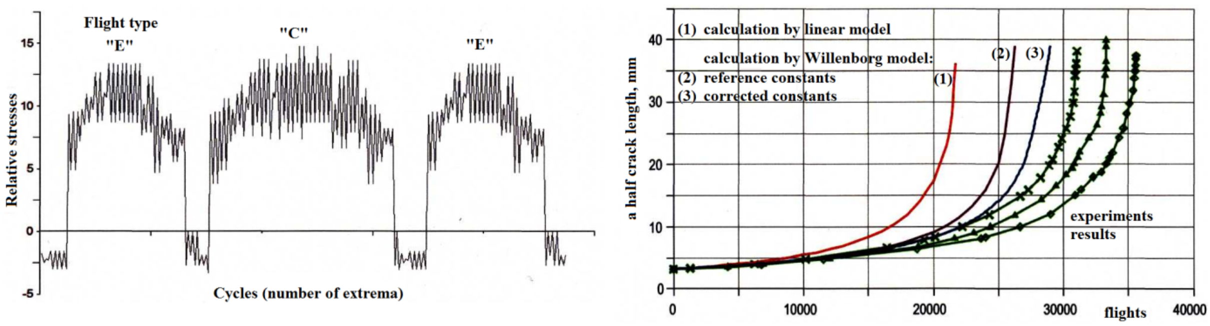


Figure 2. Calculation of fatigue cracks growth rate in aircraft structures.

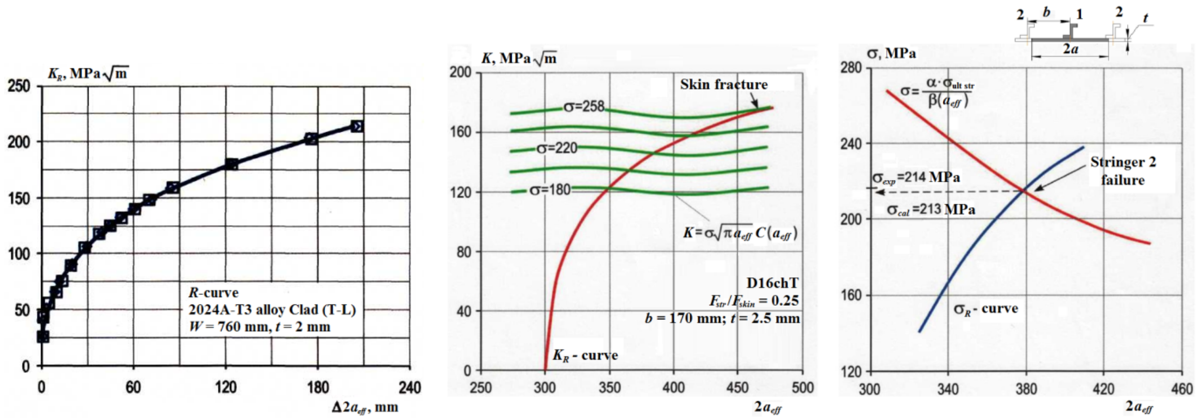
The typified quasi-random program of wing lower surface loading is developed.

The program that models computationally the crack growth was developed for calculating the crack growth rate and duration. The calculations based on Willenborg model were carried out. The computed results were compares with the experimental ones that determined the cracks growth rate in wing lower surface specimens.

RESIDUAL STRENGTH

The corresponding calculation methods to determine the residual strength of stiffened structures with crack in skin was developed at TsAGI. Under the static loading the structure with crack in plastic skin (materials of D16T, 2024-T3 types) the sustain crack extension takes place. The R-curve is a quantitative description of such an extension. This curve presents the K_R stresses intensity coefficient dependence on the $\Delta 2a_{eff}$ effective crack length extension. At TsAGI the R-curves for main Al-alloy materials of wing and fuselage skin were determined experimentally.

Figure 3 cites as an example the R-curve of fuselage skin material, the calculation of the residual strength of fuselage with crack in skin under the failed stringer and the calculation vs. experiment.



a) b)

Figure 3. Calculation of stiffened structures residual strength, a) Fuselage skin material R-curve, b) Il-86 aircraft fuselage computed residual strength vs. the experimental one.

FATIGUE AND DAMAGE TOLERANCE CERTIFICATION TESTS OF AIRCRAFT FULL-SCALE STRUCTURES

The Russian Airworthiness Regulations paid great attention and go on to highlight the availability of full-scale structures laboratory fatigue tests. Both the moments of fatigue cracks emergency and their growth durations and character were also determined in the course of these tests. There exists no one type of Russian aircraft the full-scale structure which of was not tested by fatigue condition with large damage tolerance margin as compared with designed life time. This ratio factor is not less than 3. The crack growth duration due to artificially cut notches is tested at the finish of these testes. The life time tests are completed with the residual strength tests of structures with regulated failures in the form of two-bay cracks in skin, the damage of individual components and so on. At this the corresponding methods of protection against the damage are used.

Late 40-th for the first time the full-scale aircraft structures fatigue tests were performed in the USSR (TsAGI). Since early 50-th such tests became mandatory in order to assess the life-time of aircraft of all categories.

In the 50-th to provide the tests safety the pressurized fuselages were located in the hydraulic channel that was created in TsAGI. The pressurized fuselages of the Tu-104 (1955-1957) civil jet airplane, the Il-18 (1958-1963) civil turbo-prop airplane. Later since the 60-th the methods to provide the safety of full-scale aircraft structures fatigue tests were optimized without use of hydraulic channels

Figures 4-6 cite as examples of residual strength tests of some structures. Figure 7 shows the example of fuselage skin lap joints specimens' fractures due to MSD cracks.

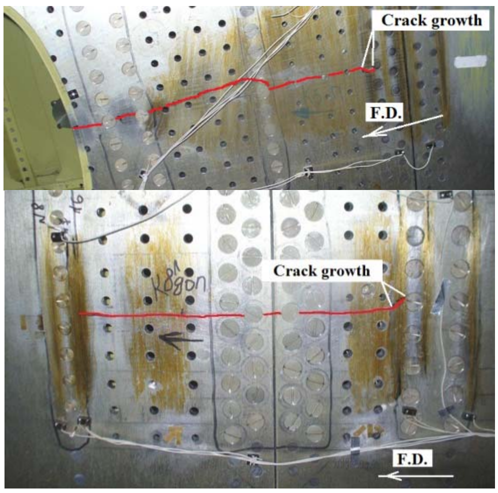


Figure 4. Durability tests of wide-body aircraft wing.

Figure 5. Durability tests of pressurized fuselage.

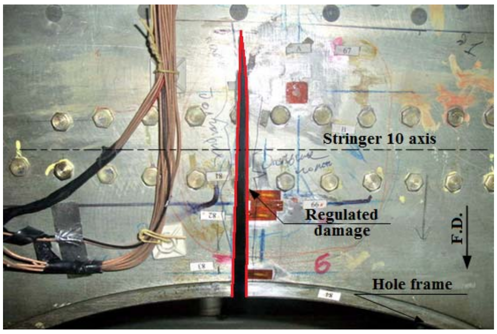


Figure 6. Durability tests of medium-range aircraft wing.

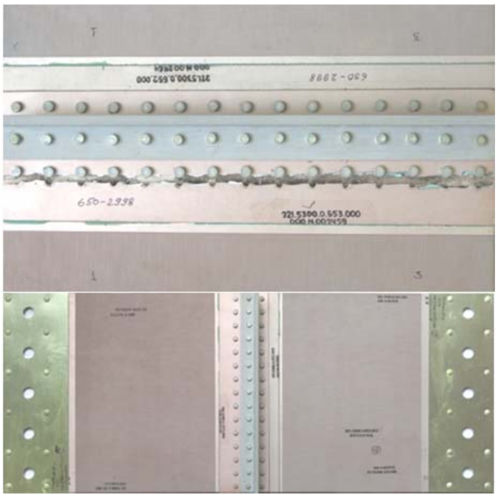


Figure 7. Research of MSD cracks in longitudinal joints specimens of pressurized fuselage skin.

ASSURANCE OF RUSSIAN CIVIL AIRCRAFT AIRWORTHINESS CONDITIONED BY STRENGTH

The national and foreign legislative regulative base that has absorbed the knowledge and experience of forming the airworthiness of advanced aeronautical states forms a fundament for the events to assure and support the civil aircraft airworthiness.

The properties of the conventional structure that assure the civil aircraft airworthiness conditioned by strength are formed at the design, tests, certification and permit-to operation and series production exploitation phases.

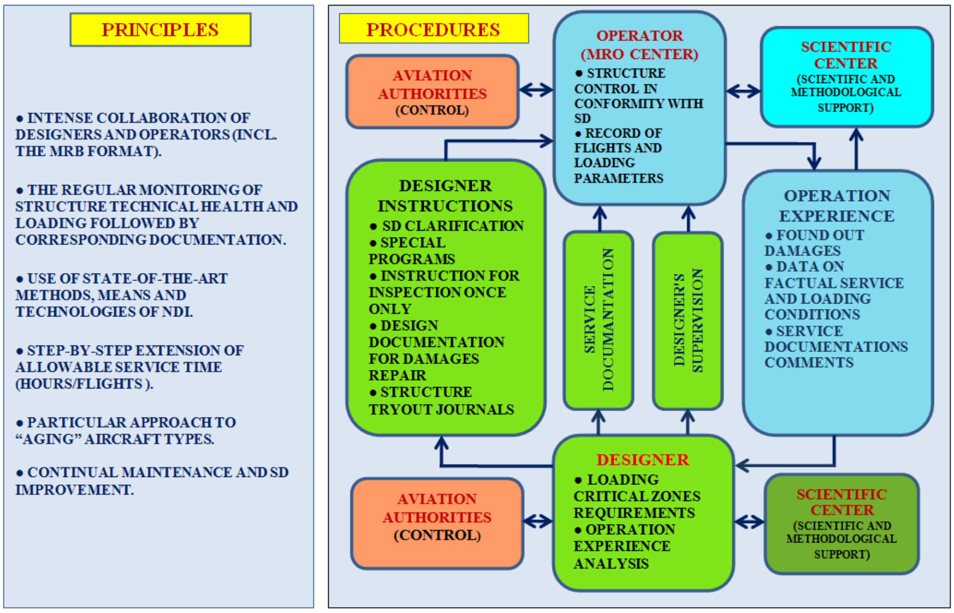
Table VI shows the layout to support the Russian civil aircraft structures airworthiness conditioned by fatigue and damage tolerance.

The airworthiness support includes as follows:

a. For developer and aviation authorities:
   - Revision of Level of validity/Airworthiness limitations Section, that is a part of aircraft type certification documentation;
   - Revision of the Maintenance Guidance and Maintenance Regulations based on Aircraft type and the identified particularities foe individual items;

b. For operator:
   - Executing the requirements of the current Level of validity/Airworthiness limitations Section, that is a part of aircraft type certification documentation;
   - Executing the requirements of the current Maintenance Guidance and Maintenance Regulations.

Table VI. Support of airworthiness of Russian civil aircraft structures conditioned by fatigue and damage tolerance.



Russian and International practice has demonstrated that the inadmissible lowering of airworthiness level may be prevented only due to explicitly formulated monitoring procedure. Within Russian practice the monitoring procedure is implemented in a form of step-by-step specified operational lives extension. It is to be noted that the Russian procedure differs from those foreign ones by form only that are to assure the possibility of designed life time tryout conditions change, when required.

CONCLUSION

The national system of assuring the passenger and transport aircraft structures life time is successfully validated and corroborates its high efficiency.

During the past 43 years no one incident of civil passenger and transport aircraft took place due to fatigue damage of structure.

ACKNOWLEDGEMENT

The procedure presented to assure the life time of civil and transport aircraft in the USSR and in the Russian Federation was developed at TsAGI that is a highly-reputed research institute in aeronautical industry. This comprehensive approach to assure the aircraft structures damage tolerance and durability at all phases of design, testing and operation is implemented when creating the transport aircraft at O.K. Antonov design bureau,

S.V. Ilyushin design bureau, A.N. Tupolev design bureau, P.O. Sukhoi design bureau and A. S. Yakovlev design bureau. The support of core principles of the procedure considered was made in close collaboration of design bureaus and research institutes such as TsAGI, GosNIIGA, SibNIA, VIAM and other major enterprises of aeronautical industry. The abstract of the methodology presented is made based on papers [1-14].

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