First International Conference on Damage Tolerance of Aircraft Structures
R. Benedictus, J. Schijve, R.C. Alderliesten, J.J. Homan (Eds.)

ENSURING STRUCTURAL DAMAGE TOLERANCE OF RUSSIAN AIRCRAFT

Prof. G.I.Nesterenko *, B.G.Nesterenko **

* Central Aerohydrodynamic Institute (TsAGI),
Ul. Zhukovskogo 1, Zhukovsky, Moscow reg, 140180, Russia
email: prof.nesterenko@mail.ru

** Institute of Mechanical Engineering,
Russian Academy of Sciences (IMASH RAN),
Maly Kharitonovsky, 3, 101990 Moscow, Russia,
email: boris.nesterenko@mail.ru

Abstract. *This paper considers most common problems related with structural integrity of civil aircraft in Russia taking into account the development of regulatory requirements, prevention of multiple site fatigue damages, improvements of crack resistance of structural materials, optimizations of aircraft type structures, development of methods for residual strength analyses of stiffened structures as well as for crack growth rates under random service loading spectra, experimental results for crack resistance degradation, methods to prevent structural failure for long operated aircraft due to corrosion.*

1 INTRODUCTION

The problem to ensure simultaneous reliability, high durability, minimum weights and economic efficiency of transport airplanes is the principal one in contemporary aircraft industry. More than 50 years of experience in design, development and operation of aviation transport in the USSR and Russia has shown that in order to get such aircraft characteristics it is required to design the structure basing on three concepts. Regular longitudinal joints of wing panels and longitudinal lap joints of fuselage skin should be designed according to safe life concept. The rest of the primary airframe components should satisfy both fail-safe and damage tolerance concepts. By now based on numerous specimen and full-scale structures tests as well as on aircraft service experience, the comprehensive results in fatigue, fail safety and damage tolerance of aircraft structures were obtained. This paper contains principal generalized results of test-analytical study of aircraft structural damage tolerance performed in TsAGI in collaboration with Antonov, Ilyushin, Tupolev and Yakovlev companies.

2 DEVELOPMENT OF REGULATORY REQUIREMENTS

The only concept of Airworthiness Regulations of USSR to ensure safe long-term aircraft operation in 1950-70s was safe life concept. In 1976 in addition to safe life concept another one called “operational survivability” was introduced. It included fail-safe and damage tolerance concepts. In 1994 Aviation Regulations for transport aircraft AP25.571 have been introduced where the above concept of operational survivability (further referred to as “damage tolerance”) was assigned as a principal one. In accordance with Airworthiness

Standards and Aviation Regulations some recommendations have been developed for structural engineers in ensuring damage tolerance [1, 2, 3] and fatigue strength [4, 5] of aircraft structures.

Principal recommended criteria to ensure structural damage tolerance at the design stage of aircraft are presented in Figs. 1-3 [1,3]. The structure having regulated damages shown in Figure 1 should sustain strength under limit load, i.e. it should satisfy fail-safe requirements.

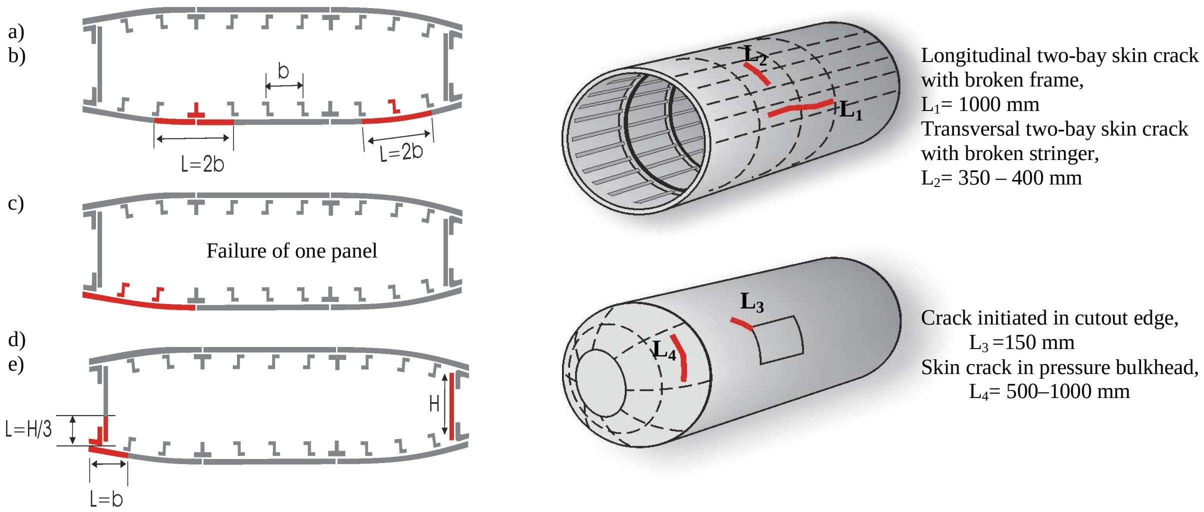

Figure 1: Wing regulated damages: a) simultaneous cracks in two panels; b) two-bay skin crack with broken stiffener and fuselage; d) broken spar cap, crack of 1/3 web height, one bay skin crack; e) spar web broken. Fuselage regulated damages

The requirements to crack growth shown in Figure 2 are related to damage tolerance. Importance was given to ensure structural damage tolerance in case of multiple site and widespread fatigue damages. [1].

The lifetime of aircraft structures in most cases is limited both by the fatigue of longitudinal joints in wing lower surface panels and by longitudinal joints in fuselage skin. Hardly detectable multiple site cracks are formed in these joints. Hence, the lifetime of these longitudinal joints and consequently the service of the aircraft are defined by safe life concept. No multiple site fatigue damage (MSD) should initiate in the pointed joints during the aircraft design goal. In order to define the lifetime of pressurized fuselages a lot of test data on fatigue of longitudinal lap joints in pressurized fuselage skins had been generalized (Fig. 3)

These data were obtained from full-scale tests of airplanes. In such cases MSD had been initiated in the skin longitudinal joints of several fuselages. Different airplane types are pointed in Fig. 3 by different experimental points. Arrows indicate that no MSD had been detected at the given number of cycles. The data for Boeing, McDonnell Douglas and Airbus planes are based on the analysis of Refs. [6] – [10]. Fuselage skins of Russian airplanes are of aluminium alloy D16ATV, and other mentioned are of 2024-T3 alloy. Fatigue parameters of these two alloys are quite similar. Fig. 3 also gives experimental fatigue curve of standard flat specimens of D16chTV alloy tested under tensile loads with aspect ratio of R=0.

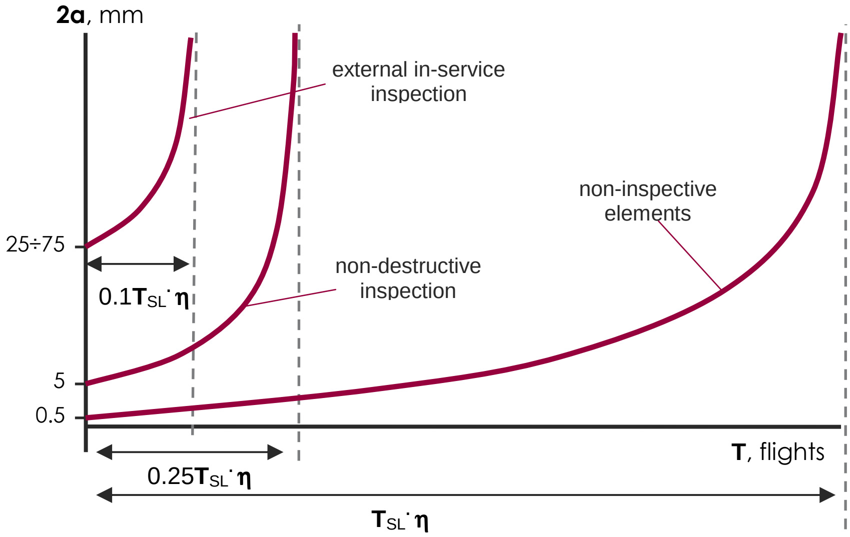

Figure 2 Requirements to crack growth

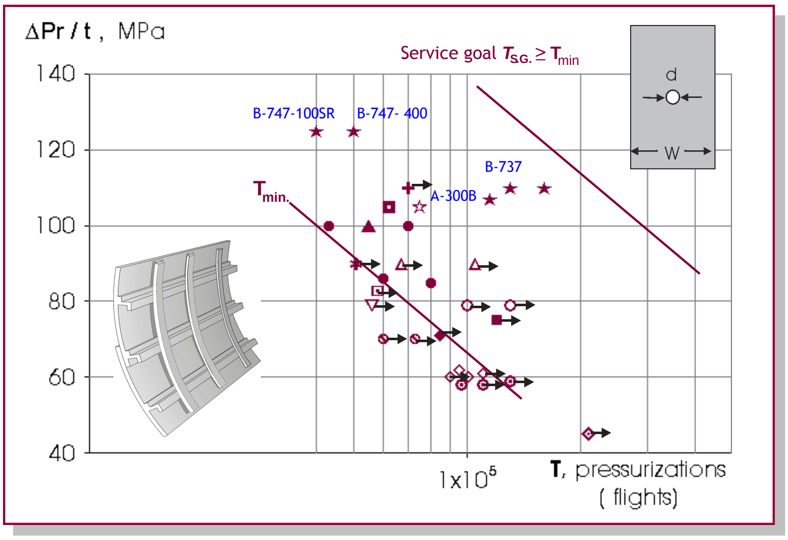

Figure 3 Fatigue of longitudinal skin joints of the pressurized fuselages. Full-scale structure tests

In Airworthiness Standards of the USSR civil aviation a lot of attention was paid to the test results of full-scale laboratory fatigue and damage tolerance tests. All of the Russian airplane types were full-scale fatigue tested with safety factor of 3 relatively to design goal. By several full-scale structures of every airplane type had been tested including those taken from operation. The nondestructive inspection methods were approved while tests for principal structural elements. After test completion the structure was disassembled to inspect it and detect small fatigue cracks. Analytical methods for calculating structural fatigue and damage tolerance have been corrected basing on test results.

3 IMPROVEMENT OF ALUMINIUM ALLOY CRACK RESISTANCE

One of the effective ways to ensure airplane long operation is the improvement of crack resistance and fatigue characteristics of aluminum alloys, which are principal structural materials for airspace vehicles. That could be done by adding some chemical elements (e.g. zirconium *Zr*, lithium *Li*), by decreasing impurities such as iron (*Fe*), silicon (Si) and by improvements of alloy manufacturing technologies. As the result, the following semi-products of Al-alloys were developed: extruded *Al-Cu* panels with zirconium additive; aluminum-lithium 1424TG1 sheets of *Al-Mg-Li-Zr-Sc* system, 1441RT1 sheets of *Al-Cu-Mg-Li* system; 1163ATV (similar to 2524-T3) sheets; 1163T7 (similar to 2324-T39) plates. Fig. 4 presents the comparison of fatigue crack growth in the improved alloy sheets applied for fuselage skin. The tests have been conducted at stress levels σ_{max}=133 MPa and σ_{min} =3 MPa. The tests demonstrated that crack growth in *Al-Cu* alloys of 2524-T3 and 1163RDTV type are close to *Al-Li* alloy 1441RT1. Fig. 5 gives comparison of crack growth in plates and extruded panels applied in lower wing skin. The tests were conducted on the specimens loaded by the truncated TWIST spectrum. Crack growths in the plates of 2324-T39 and 1163T7 are close to each other. Crack growths in the extruded panels of 1161T containing zirconium additives are much higher than those in the plates.

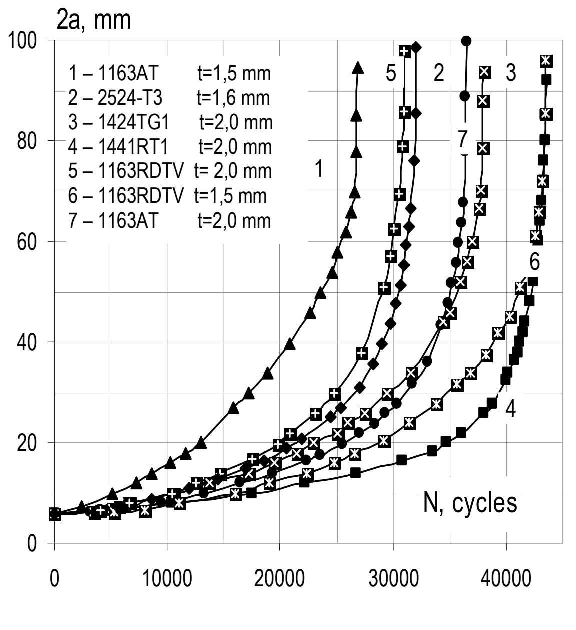

Figure 4 Fatigue crack growth duration in fuselage skins, σ_{max}= 133MPa, σ_{min} =3 Mpa

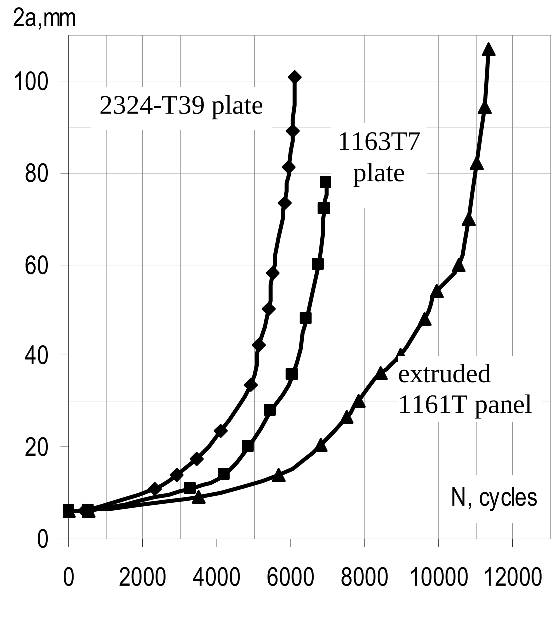

Figure 5 Fatigue crack growth duration in various Al-alloys under TWIST spectrum

4 DEVELOPMENT OF OPTIMUM STRUCTURES

Two traditional ways of structure design had been formed in Russia – using riveted structures (Fig. 6, Il-96-300 wing), the other developed integrally stiffened structures of extruded panels (Fig. 6, An-124 wing). Those who preferred the first way of design considered that riveted structures would have better fail-safe and damage tolerance parameters due to separated primary elements, and integrally stiffened structures would have worth corrosion resistance. Sticklers of integral design suppose that the advantage of integral structures over riveted ones is that they have less stress concentrators and thus fatigue crack origins. Damage tolerance comparison of integrally stiffened and riveted structures [11] has shown that crack resistance of these two structural types made of advanced Al-Cu alloys are close to each other. It is confirmed, for instance by experimental data on residual strength of D16chT panels with two-bay skin crack and the broken stringer (Fig. 7). Forty years of service experience for the airplanes with wing made of integral extruded panels confirms the possibility to ensure corrosion protection of such structures.

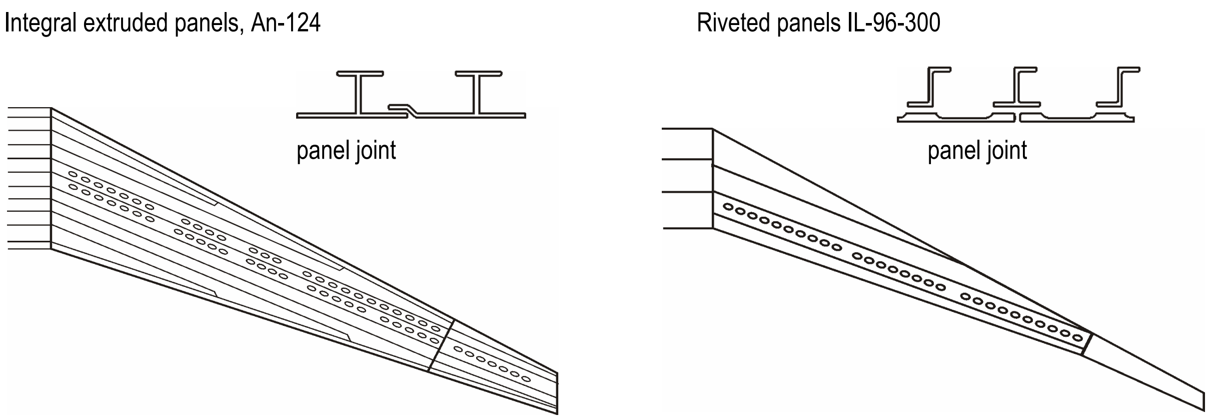

Figure 6 Two structural options: a) An-124 wing, integral panels b) Il-96-300 wing, riveted panels

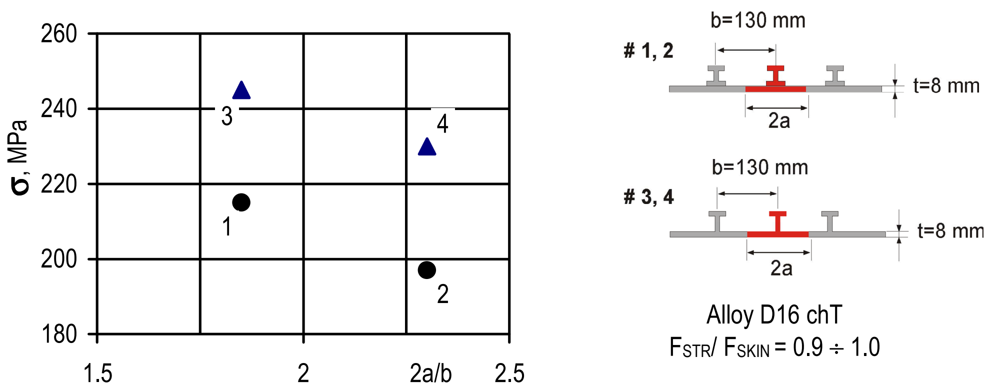

Figure 7 Comparison of residual strength in D16chT riveted and integrally stiffened panels

5 DEVELOPMENT OF RESIDUAL STRENGTH ANALYSIS METHOD

Currently residual strength analyses are performed using criteria of linear fracture mechanics. Most methods of residual strength calculation for stiffened structures do not consider the stable crack growth at applied static load, e.g. crack growth in the skin. Disregard of this crack growth leads to decreased accuracy. In some cases disregard of stable crack growth leads to uncertainties in defining critical element in terms of residual strength, would it be skin or stringer. TsAGI has developed a method to estimate residual strength of stiffened structure with two-bay skin crack under the broken stringer using skin material R-curves [12]. This method is approved by comparing analytical and test values of residual strength of integral and riveted wing and fuselage panels, and Tu-334 riveted wing. The accuracy is about 95–98.5%. The essence of this method is demonstrated by residual strength analysis of fuselage panel having two-bay skin crack under broken stringer (Fig. 8) [12]. The panel is tested under tensile stresses. The scatter between calculation and experiment is about 1%.

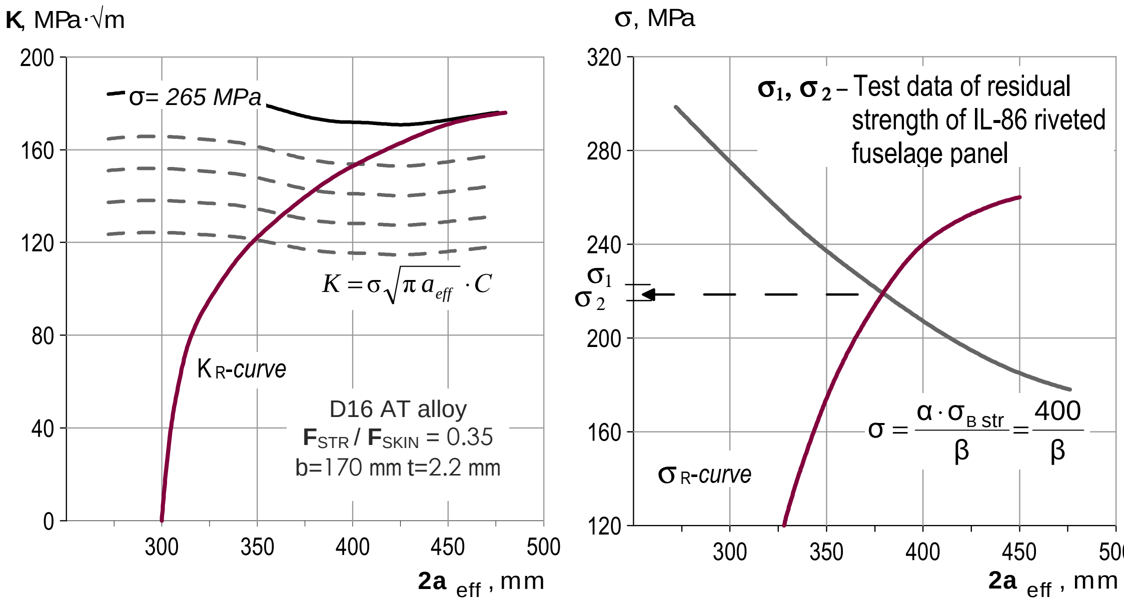

Figure 8 Residual strength analysis for fuselage panel using R-curve method

6 IMPROVEMENTS OF CRACK GROWTH ANALYSIS METHODS

To determine accurately structural damage tolerance, the complete information on airplane load spectra is required. Interaction of loads with different amplitudes should be taken into account while crack growth analysis. TsAGI performed test-analytical study of fatigue crack growth characteristics in the specimens of various aluminum alloys. The specimens were tested in the electrohydraulic machines at different constant and random operational load spectra typical for the lower wing surfaces of passenger aircraft, namely block spectra, truncated TWIST, TsAGI spectrum (Russian transport), Boeing spectrum [13]. Fig. 9 presents block one. Average stresses of these spectra in the cruise were 85 MPa. Besides, some high-strength alloy 7055-T7751 specimens have been tested under random load spectrum typical for upper wing skins of Boeing airplanes (Fig.12) [14]. Principal results of the study are given below. Relation between fatigue crack growth and load spectra have been determined by tests of 1973T2 extruded panel (Al-Zn alloy with Zr additive) specimens. The tests had demonstrated that most severe fatigue damage results from truncated TWIST spectrum. Fatigue damages from TsAGI and Boeing spectra are close to each other (Fig. 10). Fatigue crack growths were compared for constant and random load spectra of 1163T plate (Al-Cu system) specimens. To improve crack growth analysis method in case of random load spectra a number of test-analytical studies of crack growth under standard Boeing spectra typical for lower and upper wing skins [14] were carried out. Specimens of the wing lower and upper skin were made of 2324-T39 and of 7055-T7751 alloy consequently. The retardation and acceleration effects were taken into account while crack growth calculation by using modified Willenborg model. Calculations are compared with test results, Fig. 12.

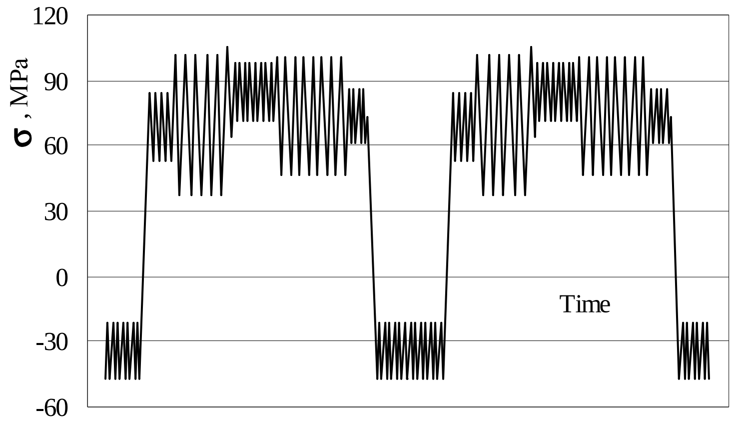

Figure 9 Block loading cyclorama for wing lower surface

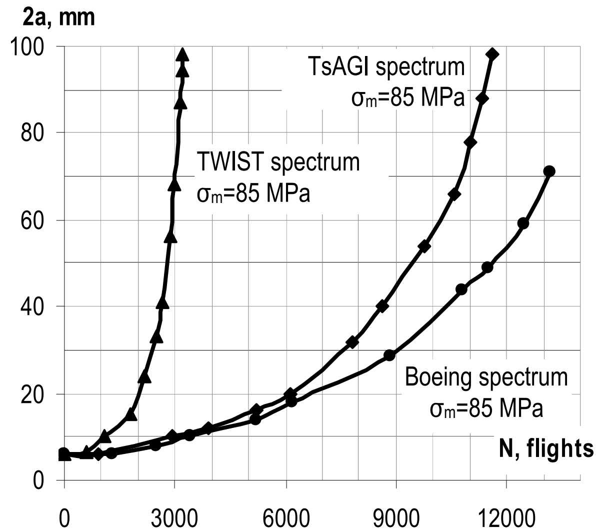

Figure 10 Crack growth in 1973T2 alloy @ TWIST, TsAGI and Boeing loading spectra

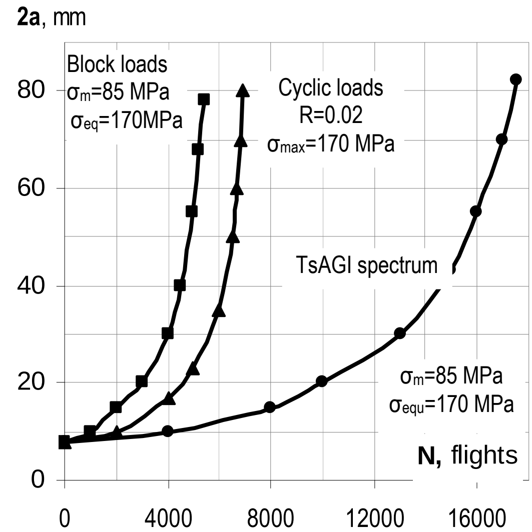

Figure 11 Crack growth durations in 1163T alloy under random regular and irregular loads

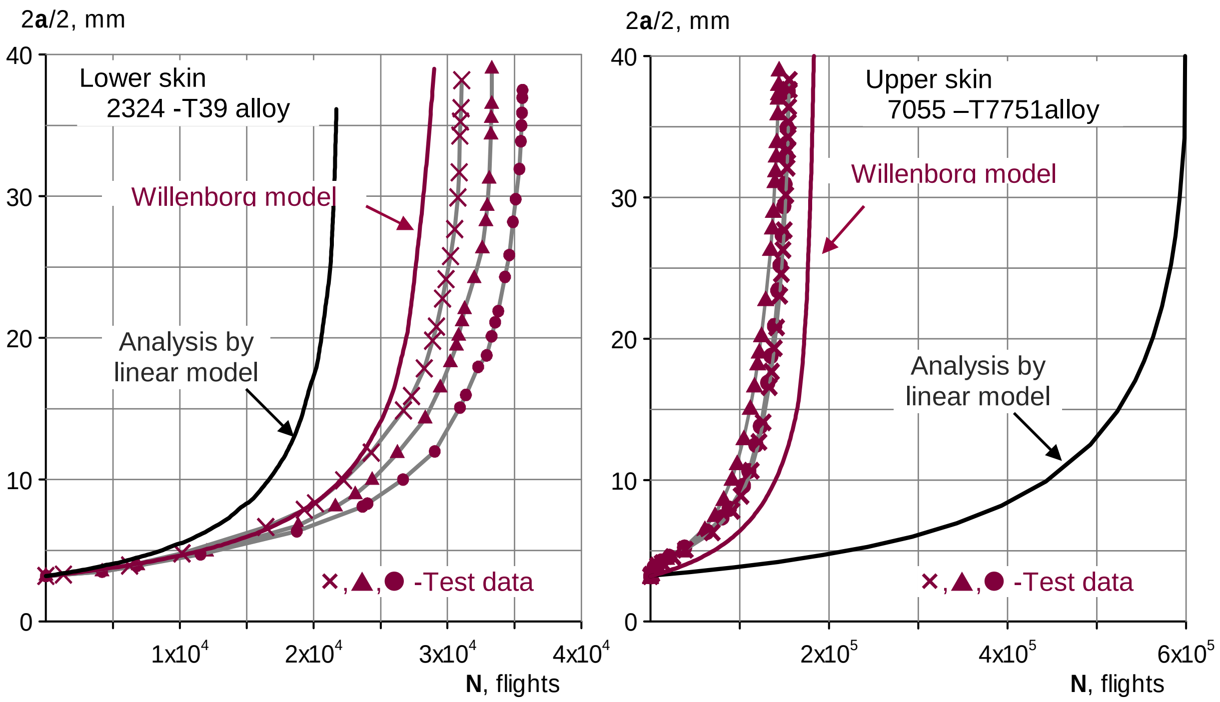

Figure 12 Analytical and test results on crack growth in wing at typical load spectra of wide body airplane

Crack growth in the wing lower surface calculated by the linear method (regardless load interaction) are smaller than experimental ones. Such results approve the necessity to correct analysis method in every case with regard to specifics of load spectra and material properties.

7 DEGRADATION OF CRACK RESISTANCE PROPERTIES

One of the key problems in current day aviation is to ensure safe operation of aging (or long operated) aircraft. Many Russian airplanes have worked out by now their design goals, and because it is not possible to substitute old airplanes by new ones, the service lives of aircraft structure is prolonged sometimes up to 1.5 – 2.5 times above their initial design goals. The safety of aging fleet is ensured due to many actions: test-analytical study of damage tolerance, fatigue and damage tolerance tests of structures after aircraft long operation; development of additional regulations for non-destructive inspection; individual service life prolongation for each copy of the aircraft. While solving the problem of aging fleet safe operation, three principal scientific tasks should be worked out: damage tolerance of structures having multiple site fatigue damages; degradation of crack resistance and fatigue strength of the structures during long-term aircraft operation; initiation and duration of corrosive damage growth.

The investigation of widespread fatigue damage (WFD) problem, being the result of multiple site fatigue damage (MSD) and multi element damage (MED) was started in the USSR in 1972 after An-10A passenger airplane accident due to WFD in the central part of wing [15]. Now it is inadmissible in Russian to operate airplane with potential presence of

MSD in the structure. The structures of new airplanes are designed so that no WFD initiation will occur during operation within design goal.

To solve the problems of degradation of static and fatigue strength characteristics TsAGI conducted a set of test investigations to analyze the effect of long-term operation of the airplane on skin material properties for Al-alloy wing and fuselage [16]. Tests were carried out on the specimens cut out of various airplanes by Antonov, Ilyushin, Myasishev, Tupolev, Boeing, MacDonnell-Douglas, Lockheed and Airbus. Parallel to that the mechanical properties of the same alloy semi-products taken from storage have been determined according to standards on common specimens. Fatigue strength was estimated on a strip-with-a-hole specimens, static and cyclic crack resistance was defined on flat 160-1200 mm wide specimens with center crack. All these tests were conducted in TsAGI laboratory. Chemical analysis of the tested materials was performed in All-Russian Institute of Aviation Materials (VIAM) and All-Russian Institute of Light Alloys (VILS).

The comparison of structural materials from long operated aircraft and the sheets of the same brand taken from the stock showed significant deterioration of crack resistance in wing and fuselage skin materials after airplane long operation. Residual strength of different semi-products has decreased in 1.15 – 1.4 times, crack growth rate increased in 1.5 – 4 times [16].

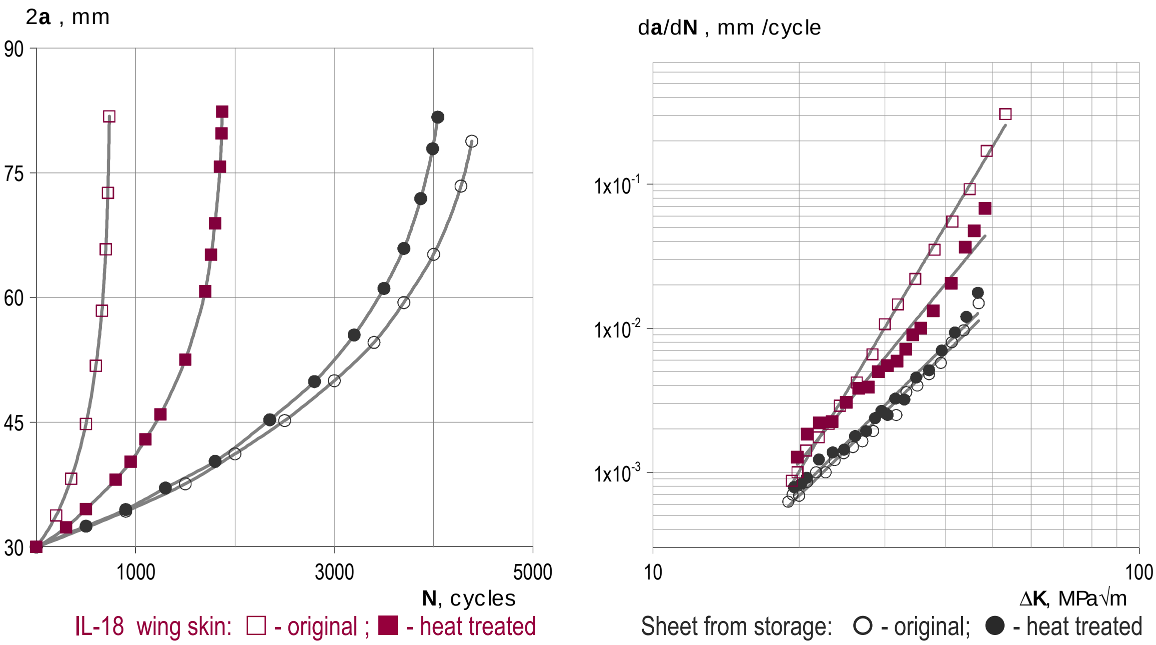

Figure 13 Effect of heat treatment (annealing) on crack growth in operated and from storage wing skin sheets

Degradation effect for Al-alloys was proved using heat treatment method while comparing fatigue crack growth rates in materials taken from stock and from long operation (Fig. 13). Heat treatment constituted of specimen heating up to 400°C followed by cooling down to 20°C. Heat treatment affected those specimens cut out of wing and fuselage skins of long-operated aircraft and sheets taken from the stock.

Crack resistance decrease of Al-alloys after long-term operation of the airplane may result from combined effect of several factors: presence of internal material defects, increased content of silicon and iron, structural element fabrication technology, external loads, temperature recurrence.

8 RESIDUAL STRENGTH OF STRUCTURES WITH WFD

Widespread fatigue damages occur in structural sections including where a lot of elements have almost identical fatigue life. Table 1 gives residual strength data on full-scale structures with WFD. The apparent fracture stresses in the net section, $\sigma^{app}_{fr\ net}$, were defined with regard to reduction of cross section area in load-bearing elements due to holes and initial cracks. The initial cross section size was correlated to the size of area with WFD. While calculating critical fracture stresses $\sigma^{c}_{fr\ net}$, attention was paid to section weakening due to crack increase while its stable growth. The values of these stresses were compared to the yield strength σ_{02}. The fracture stress intensity factors K_{fr} were calculated according to common methods. The apparent fracture toughness K_{app} was determined on sheets with buckling in crack zone.

Damaged principal structural element	Material	$\frac{\sigma^{app}_{fr\ net}}{\sigma_{0.2}}$	$\frac{\sigma^{C}_{fr\ net}}{\sigma_{0.2}}$	$\frac{K_{fr}}{K_{app}}$	$\frac{K_{fr}}{K_{IC}}$
Skin& stringers near stringer splice in wing lower surface	D16ATNV D16T	0.8	1.0	0.5	
Skin, stringers & spar of lower wing surface around stiffening lap edges	D16ATNV D16T	0.9	1.0	0.6	
Skin and stringers of lower wing surface around stiffening lap edges	D16ATV D16T	0.9	1.0	0.5	
Skin & stringers of monolithic stiffened panel of wing lower surface near fuel holes in stringer	D16T	0.7	0.83	1.0	
Spars & shapes of upper wing surface	D16T	0.3	0.47	0.5	
Splice shapes of upper wing surface	D16T	0.7	1.0	0.75	
Stringer & lap for circumferential skin splice of pressurized fuselage	D16ATV D16T	0.75	0.88	1.0	
Pressurized fuselage skin near three-row longitudinal riveted splice	D16ATV	0.57	1.0	0.5	
Pressurized fuselage skin near two-row longitudinal riveted splice	D16ATV	0.63	1.05	0.9	
Pressurized fuselage skin near two-row longitudinal riveted splice	D16ATV	0.48	0.85	0.7	
Pressurized fuselage skin between two frames and between two stringers (19 through-thickness notches) (experiment)	D16ATV	0.9	0.9	1.0	
Pressurized fuselage skin between two frames and between two stringers (19 through-thickness notches) (experiment)	D16ATV	0.85	0.85	1.0	
Strip joining the cylindrical pressurized fuselage with spherical pressure bulkhead	D16ATV	0.16	0.17	0.45	
Skin and stringer of lower wing surface around stiffening lap edges	V95AT1V V95T1	0.45	0.46	1.0	
Lap joining the skins of lower wing surface	V95T1V	0.4	.41	0.4	1.0
Wing pivot assembly	V93T1	0.4	0.40	~	1.0

Table 1. Residual strength of full-scale aircraft structures with widespread fatigue damages

Structural residual strength criteria are those fracture parameters whose relative values are equal to 1.0. During residual strength tests of two pressurized fuselages with skin notches simulating MSD no notch growth was observed.

9 CORROSION FAILURE PREVENTION

Aluminum alloys should obtain good corrosion resistance. No crack should originate in material during long-term airplane operation caused by stress corrosion and inter-crystalline corrosion. To prevent delaminating corrosion the appropriate methods of corrosion protection are applied (painting, cladding etc.).

In TsAGI practice residual strength of structures with corrosion damages is calculated by considering corrosion damage as some equivalent fatigue crack. It is recommended in case of corrosion damage to ensure standardized residual strength of the structure with regulated damages (Fig. 1). Time interval before initiation of corrosion damage and its growth in operational conditions are also could be calculated. Analytical method that had been developed is given in Ref. [17]. This method utilizes the approaches from mathematical statistics and in-service data about corrosion damage size and aircraft number of flights till the moment of damage detection. Fig. 14 presents an example of such analysis. Using the approaches and methods described above on ensuring required damage tolerance characteristics of the structure, some current Russian transport airplanes have reached the operation time of about 45 years

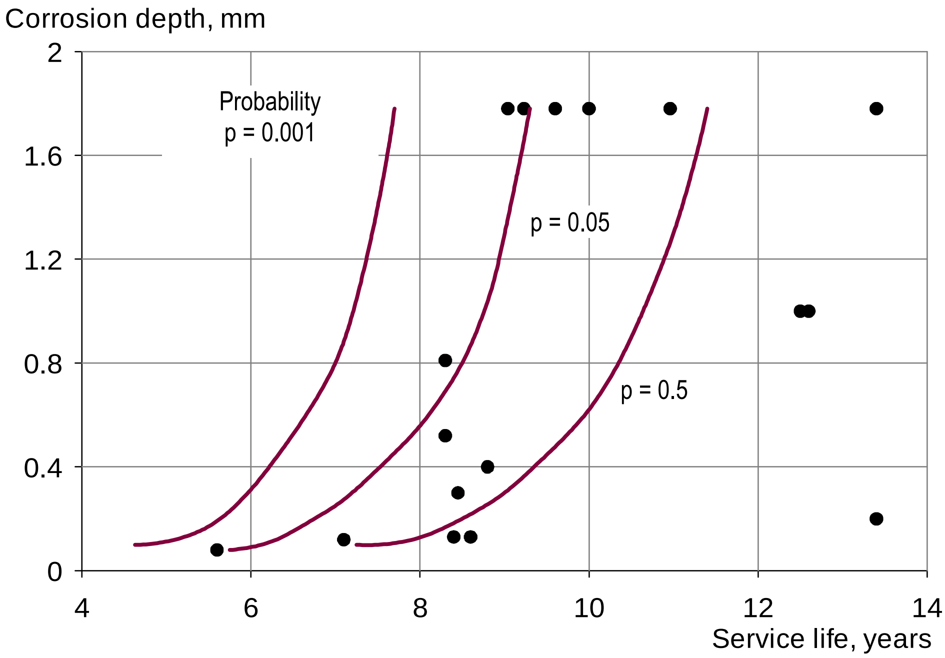

Figure 14 Analysis of corrosion depth growth in fuselage made of D16ATV

9 CONCLUSION

- Accumulated experience of aircraft operation helps to improve regulatory requirements, standardized regulations and recommendations to ensure structural safety in terms of strength during airplane long-term operation. It is recommended in contemporary Russian airplane structures to ensure simultaneously safe life, fail-safe and damage tolerance concepts. Operation of structures with MSD is not acceptable.
- To provide high damage tolerance characteristics and economic efficiency of airplane operation simultaneously *Al*-alloys are permanently under development. Improvements of their fatigue strength and crack resistance results from decreased iron and silicon additions, development of advanced alloys (with additions of Zr, Lt etc.) and from the development of production technology of alloys.
- Two panel types are applied in the wing structures of transports, i.e. integrally stiffened panels and riveted ones. Damage tolerance parameters of these two panel types made of *Al-Cu* alloys are close to each other.
- To estimate residual strength of stiffened structures some method has been developed for residual strength calculation using skin material R-curves. When initial data are reliable the accuracy of calculations may be 95– 98.5%.
- The experimental study was performed for regularities in fatigue crack growth in *Al*-alloys applied for wing and fuselage skins of Russian, Boeing and Airbus airplanes. The experiments have been conducted under various loading spectra: symmetric, block, irregular spectra TWIST, Boeing, TsAGI.
- Accuracy in crack growth analysis in the skins of upper and lower wing surfaces has been investigated. The specimens were tested under Boeing random spectrum. Crack growth rate was calculated according to linear model and by modified Willenborg model taking into account crack growth retardation and acceleration effects. The difference is shown between the accuracies of crack growth rates in the wing lower and upper skins.
- The effect of aircraft long-term operation on the material properties in *Al*-alloy wing and fuselage skins was estimated by experiments. The specimens were cut out of wings and fuselages from Antonov, Ilyushin, Myasishev, Tupolev, Boeing, McDonnell-Douglas and Lockheed airplanes. The experiments have demonstrated some degradation in material crack resistance after long-term operation of some structures. Degradation effect is proved by specific heat treatment of the tested specimens.
- To find out onset of initiation and growth rates for corrosion damage of aircraft structures TsAGI has developed and now utilizes some special analysis method based on in-service data about corrosion damage size.
- During last 35 years there were no accidents of Russian transport airplane caused by fatigue cracks in the structures.

REFERENCES

[1]. G.I.Nesterenko. Damage tolerance of aircraft structures.// Inter-High-School Collection of Scientific Proceedings. Issue 2. Kiev Institute of Civil Aviation Engineers, 1976, p. 60-70 (in Russian).
[2]. G.I.Nesterenko, A.F.Selikhov. Applying damage tolerance concept while developing wide body airplanes.// Strength of aircraft structures, Moscow, Mashinostroyeniye, 1982, p. 151-189 (in Russian).
[3]. G.I.Nesterenko. Service life and damage tolerance of aircraft structures.// Journal ”Problemy mashinostroyeniya i nadezhnosti mashin”, Russian Academy of Sciences, Moscow, “Nauka”, 2005, №1, p. 106-118(in Russian).
[4]. A.F.Selikhov. Principal tasks and typical features of ensuring strength in wide body passenger airplanes.// Strength of aircraft structures, Moscow, Mashinostroyeniye, 1982, p. 7-45 (in Russian).
[5]. A.Z.Vorob’ev, V.G.Leybov, B.I.Ol’kin, V.N.Stebenev. Ensuring enhanced service life of wide body airplanes.// Strength of aircraft structures, Moscow, Mashinostroyeniye, 1982, p. 122-151(in Russian).
[6]. T. Swift. The application of fracture mechanics in the development of the DC-10 fuselage. //AGARD-AG-176. v. 5, pp. 227-287.
[7]. Ulf G. Goranson. Damage tolerance. Facts and fiction. //14th Plantema Memorial Lecture Presented at the 17 th Symposium of ICAF. Stockholm, Sweden, June 9.1993. 58 p.
[8]. R.F. Fowlen, R. Kevin and Roy T. Watanabe. Development of jet transport airframe test spectra. //Boeing Commercial Airplanes. Seattle. Washington. USA. May 1989. 16 p.
[9]. Gokgol. Crack free and cracked life of the pressurized cabin of the A300B. Calculation, test and design measurements to improve damage tolerance. //Aeronautical Journal. 1979. v.83. 817. pp. 1-15.
[10]. M.M. Spenser. The 747 fatigue and fail-safe test program. //The American Society of Civil Engineers. National Structural Engineering Meeting. San Francisco. California. 9-13/IV. 1973.
[11]. G.I. Nesterenko. Damage tolerance of integrally stiffened and riveted stiffened structures. //Proceedings of the 20th Symposium of the International Committee on Aeronautical Fatigue. Volume 11. Bellevue. Washington. USA. 14-16 July 1999. pp. 873-894.
[12]. B.G. Nesterenko. Analysis of the Stiffened Structure Residual Strength Using R-curve of the Skin Material. //Proceedings of the 22th Symposium of the International Committee on Aeronautical Fatigue. ICAF 2003. Volume 11. Lucerne. Switzerland, 7-9 May 2003. pp. 749-762.
[13]. V.N.Basov, G.I.Nesterenko Fatigue strength of Al-alloys under irregular loading.// Trudy TsAGI, Issue 2669, Moscow 2005, p. 119-125(in Russian).
[14]. B.G.Nesterenko. Test-analytic estimation of fatigue crack growth in structural materials // Trudy TsAGI, Issue 2664. Moscow 2004, p. 259-263(in Russian).
[15]. G.I. Nesterenko, B.G. Nesterenko. Residual strength analysis of the stiffened structures with WFD, MSD and single crack. //Proceedings of the 6th Joint FAA/DoD/NASA Conference on Aging Aircraft. San Francisco, CA, USA. September 16-19. 2002. CD-ROM Proceedings.
[16]. G.I.Nesterenko, V.N.Basov, B.G.Nesterenko, V.G.Petrusenko. Aircraft long-term operation effect on their structural material properties.// ”Problemy mashinostroyeniya i nadezhnosti mashin”, Russian Academy of Sciences, Moscow, “Nauka”, 2006, №4, p. 41-50(in Russian).
[17]. V.Ya.Senik Analysis of fatigue crack growth parameters in aircraft structural elements based on in-service data. // Trudy TsAGI, Issue 1671, Moscow, 1975, p.17-27