ENGINEERING APPLICATION OF FRACTURE MECHANICS TO AIRCRAFT STRUCTURE DAMAGE TOLERANCE ESTIMATION

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ABSTRACT

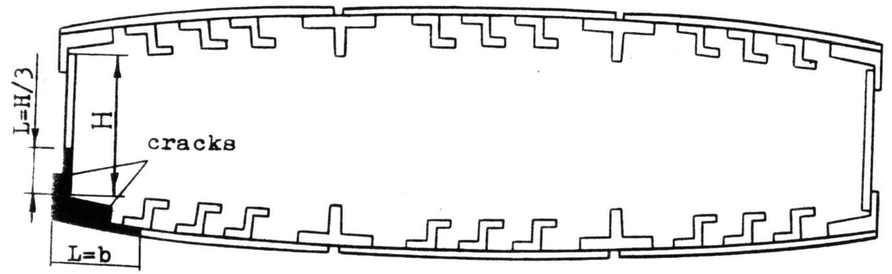
The results of airframe structure damage tolerance calculations and tests carried out at TsAGI are briefly reported. The present paper gives: damage tolerance criteria; results of crack resistance testing of wing/body skin materials of aging aircraft; ways of analyzing aircraft structure residual strength and predicting fatigue crack propagation rates, based on linear elastic fracture mechanics; methods to provide airframe damage tolerance in design and operation; damage tolerance acceptance test procedure.

KEYWORDS

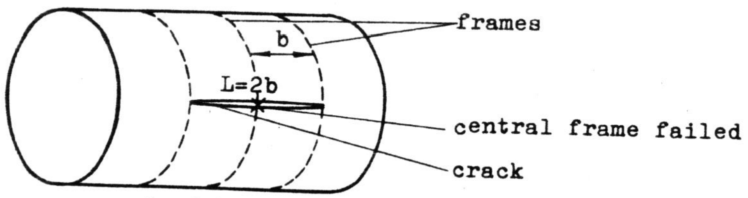
Damage tolerance, fatigue, crack resistance, residual strength, fatigue crack propagation rate, inspectability, flaw detection.

Damage tolerance is meant as the property of a structure to retain its safety level for a specified service life after partial or complete fracture of primary components due to fatigue, corrosion and/or accidental operational damages or in-process/in-repair defects. On the basis of the experience available, TsAGI has developed a system to provide aircraft structure damage tolerance in design and operation. According to this system, for each type of aircraft the following is to be identified: damage tolerance criteria; material crack resistance; stress-strain state and stress intensity factors for primary airframe components; operational stress spectra; residual strength; fatigue crack propagation rate; design features to provide damage tolerance; inspectability; the programs of damage tolerance acceptance testing of full-scale structures; inspection schedule. The operational experience is to be surveyed.

The main damage tolerance criteria include: standardized damages; required (specified) residual strength; required crack propagation rate (Nesterenko and Selikhov, 1982). The standardized damages (Fig. 1) are defined by analyzing



wing box



pressurized body section

Fig. 1. Examples of standardized damages to airframe

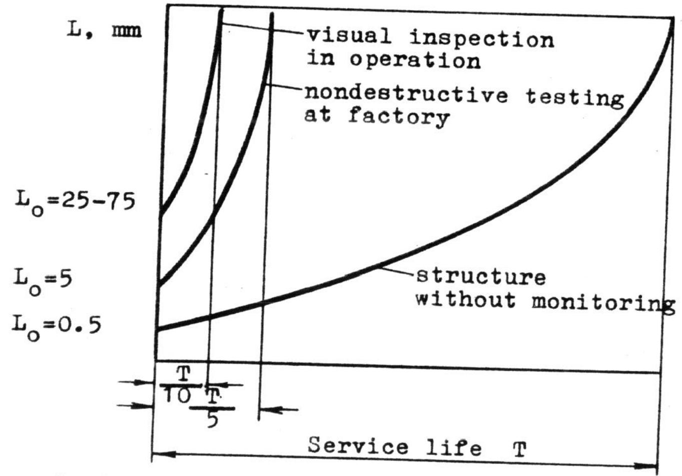


Fig. 2. Crack growth rate requirements

statistics on cracks and cover practically all the damages revealed in airframes.

The structure with standardized damages must sustain loads of no less than 67% of the ultimate load. The standardized damages must be detected during the frequent outer inspections. With standardized damages present in a structure with an adequate residual strength, the crack growth duration requirements are imposed for decreasing the probability of failure (Fig. 2). The required crack growth duration corresponds to the occasional inspection interval.

The static and cyclic crack resistances are determined for airframe materials. The fatigue kinetics diagrams representing the fatigue crack growth rate as a function of the stress intensity factor range are obtained from experimental data for the crack growth rates of 10**(-7) to 1 mm/cycle. For skin materials the experimental data on the fracture toughness as a function of the specimen width (over the 200 to 2000 mm range) are necessary. The test data have been a reliable basis for development of (I) the technique for predicting the fracture toughness of wide specimens after testing narrow specimens for the residual strength (Dotsenko, 1984) and (II) the technique taking into account the effect of specimen displacements in a crack zone on the static crack resistance (Dotsenko, 1987). The experimental investigations into the crack resistance of specimens cut out of wing and body skins of aircraft operated for 15--30 years (Nesterenko, 1983) have been accomplished. The experiments have shown that the fracture toughness of materials of these aging airplanes is 20--50% less, and the crack growth duration is 4--7 times less in comparison with new materials of the same grades made in recent years. The reduced crack resistance of old materials can be due to both imperfection of the corresponding production processes and the influence of a long-duration usage. According to damage tolerance criteria (Figs 1, 2) the required crack resistances have been determined for aluminum alloys to be used in the skin of the passenger transport (Nesterenko, 1984): fracture toughness >155 MPa$\sqrt{m}$, the required values of the fatigue crack growth rate of 0.75-1.5 mum/cycle at the stress intensity factor range of 31MPa$\sqrt{m}$.

The stress intensity factors may in many simple cases be got from the reference books containing the particular solutions in the form of equations, tables, and plots. When the stress intensity factor cannot be determined by the known solutions, then the numerical methods (Pereslavtsev, 1979), a specialized hybrid finite element method (Dement'yev, 1987), a method based on displacement fields and the crack opening displacement (Gorodnichenko and Dement'yev, 1988), an analytical method using strain gauging at the crack tip (Dement'yev, 1986) may be used for evaluating this factor.

The airplane load spectra to be implemented in tests could be compiled on the basis of standard airborne recorder data and strain gauging data from special-purpose flight experiments.

The technique of calculating the airframe residual strength has been developed by generalizing and analyzing the experimental data on the residual strength of full-scale airplane structures and large-size stiffened panels. The technique based on the linear elastic fracture mechanics makes it possible to calculate the residual strength of an airframe with standardized damages. The effects of material ductility, compliance of fasteners, bending, biaxiality and other factors encountered in full-scale structures, are included into correction factors. These factors were introduced into equations for stress intensity factors (Nesterenko, 1977). Beyond the applicability of the linear fracture mechanics, the structure residual strength calculations use the material yield stress in the failure criterion. For evaluating the residual strength of thin-walled stiffened structures, the nomograms (Nesterenko, 1983) were developed to allow determining the stress intensity factors for the skin and stresses in stiffeners. The equations for computing the residual strength of a wing and a pressurized body have been obtained (Nesterenko et al. 1982); the methods of analyzing the residual strength of a structure with a multi-site damage have been developed (Nesterenko, 1974). The error of the results is on the order of 10%.

The method of computing the fatigue crack propagation rate was developed by generalizing the experimental data on crack propagation in full-size structures, panels and samples. Using the linear elastic fracture mechanics as the basis, the crack propagation rate calculations (Vorob'yov and Nesterenko, 1984) assisting the airframe inspection scheduling are performed. To generate a kinetic fracture curve and calculate the rate of crack propagation under regular loads, the well-known equations presented by Paris, Walker--Erdogan, Forman, Yaryoma S.Ya.--Mikitishin S.I., Collipriest--Jaske may be employed. The crack propagation rate at random loads is calculated using a linear model, models developed by Wheeler, Willenborg, Elber, and their derivatives (Kozlov and Konovalov, 1990; Vorob'yov and Nesterenko, 1984). It was found that the ratio of the crack propagation rates predicted (by these models) to the test data falls into the range of 0.1 to 4.0. As a rule, the linear model gives conservative results. The analysis showed that the present equations, models and an engineering approach make it possible to obtain the fatigue crack propagation rate to a reasonable accuracy. There are no universal equations or models to calculate the rate of crack propagation in different materials subjected to various random load spectra.

At the design stage, the required damage tolerance is achieved first of all using materials with improved crack resistance (Nesterenko and Selikhov, 1982). In stiffened structures, ductile materials are used in skins, and high-strength materials in stringers. To improve the damage tolerance, design features are elaborated as well. For example, structures should be separated into components; crack stoppers in the form of grids should be bonded to skins of pressurized bodies.

Inspectability of a structure is taken to mean that cracks allowed by residual strength requirements can be easily detected using the specified inspection methods, with the frequency, time consumption, and reliability of inspection being also specified.

The size of reliably detectable cracks should be determined for the following types of inspection: visual inspection of a structure as a whole; detailed visual inspection; selective inspection using nondestructive techniques (eddy-current, ultrasonic, X-ray methods, etc.). The visual inspection method is favourable in operation. Therefore an airframe should be designed so that any probable initial crack in its internal components appear on an outer surface and be detected before the crack size exceeds critical values.

Aircraft structure damage tolerance should be demonstrated by the damage tolerance acceptance tests on the full-scale airframe (Belyi et al., 1991). Meeting the damage tolerance criteria is checked, nondestructive inspection methods are fitted, techniques for calculation of the fatigue crack propagation rates and the residual strength are corrected during these tests. The damage tolerance certification tests on full-scale structures were carried out practically for all types of domestic operating aircraft.

Providing structure damage tolerance is based on a reliable flaw detection. It is carried out in compliance with the corresponding inspection programs at repair plants and at the scheduled maintenance during operation. The objective of the control is to reveal cracks in significant structural items, caused by fatigue, corrosion and accidental damages. The list of the significant load-carrying components is compiled (Nesterenko, 1992) from the comprehensive survey of analytical results, full-scale fatigue test results, operational experience, the estimates given by strength experts and designers.

The system for providing structure damage tolerance includes a continuous acquisition and processing of data on the cracks revealed in the operated structures. Statistical analysis methods are developed that make it possible to calculate the fatigue crack propagation rate from the operational data (Senik, 1975). The use of these methods allows us to correct the fatigue crack propagation rates forecasted on the basis of linear fracture mechanics methods. The predicted values of the fatigue crack propagation rate may also be refined by the results of the fractographic analysis of crack surfaces. In practice, if a crack is revealed in a load-carrying component of the operating structure, a piece with a crack is cut out and analyzed by fractography. The developed methods of the crack surface fractography by the electronic microscope make it possible to plot, in some cases, a curve of the crack growth under the operating conditions. The available data on crack propagation under the operating conditions make it possible to upgrade the procedures for computing the rates of crack propagation under random loads, including the effects of the corrosive environment.

The present methodology of providing aircraft structure damage tolerance can, with the corresponding modifications, be applied to structures in other engineering systems and constructions.

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