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Foundation of damage tolerance principles in-service for the RRJ-95 aircraft structural components

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Abstract

Fatigue cracks initiated from holes in several zones and structural components of the RRJ-95 aircraft frames were investigated. Using the method of quantitative fractography the crack growth duration in the brackets of the in-service airframe and in the wing panels during full-scale bench tests was estimated the spacing of meso-beach-marks (MBM) and fatigue striations. The applied program of bench test consisted of blocks of variable loads that were equivalent to the wing loading in flight and reproducing schematized flight-cycle. It was shown that the duration of fatigue crack propagation in several structural components of the RRJ-95 aircraft frames was approximately the same as for the crack nucleation duration. The total lifetime is sufficiently long for cracks in the structural components to be detected and reliably monitored with a large operating time interval between adjacent inspections.

Foundation of damage tolerance principles in-service for the RRJ-95 aircraft structural components

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Abstract. Fatigue cracks initiated from holes in several zones and structural components of the RRJ-95 aircraft frames were investigated. Using the method of quantitative fractography the crack growth duration in the brackets of the in-service airframe and in the wing panels during full-scale bench tests was estimated the spacing of meso-beach-marks (MBM) and fatigue striations. Applied program of bench test consisted of blocks of variable loads that were equivalent to the wing loading in flight and reproducing schematized flight-cycle. It was shown that the duration of fatigue crack propagation in several structural components of the RRJ-95 aircraft frames was approximately the same as for the crack nucleation duration. The total lifetime is sufficiently long for cracks in the structural components to be detected and reliably monitored with a large operating time interval between adjacent inspections.

Keywords : aircraft components, in-service fatigue, variable amplitude loading, quantitative fractography, crack growth duration, number of flights

NOMENCLATURE

a crack length

h spacing of the meso-beach-marks

δ fatigue striation spacing

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n_{f} the number of loading blocks

N_{f} the numbers of unit loading cycles

P_{Y} applied load to wing panel in bench tests along OY axis

P_{Z} applied load to wing panel in bench tests along OZ axis

1. Introduction

The process of fatigue damage accumulation in different zones of aircraft leads to the initiation of fatigue cracks due to various reasons and their following propagation with different intensity [1-3]. The process is realized under in-service conditions and at different combinations of variable amplitude loading various [4-9]. It follows that the fundamental principle of in-service aircraft is the knowledge about that the total process of damage accumulation should be divided on two separate stages, i.e. crack nucleation and propagation stages. It is worth noting that due to the cracks grow for a rather long period of lifetime, the initiated cracks can be monitored by the non-destructive test methods [10].

Therefore, the basic principle of aircraft operation is the Damage tolerance approach [11-15]. Damage tolerance is a property of a structure relating to its ability to sustain defects safely until a repair can be effected. This approach is commonly used in aerospace engineering, mechanical engineering, and civil engineering to manage the extension of cracks in structure through the application of the principles of fracture mechanics. In engineering, a structure is considered to be damage tolerant if a maintenance program has been implemented that will result in the detection and repair of accidental damage, corrosion and fatigue cracking before such damage reduces the residual strength of the structure below an acceptable limit. To implement this principle of operation, the introduction of periodic inspection of the crack propagation zones with reasonable frequency is required. The introduction of monitoring is based on an understanding of the intensity with which the crack growth process will be implemented. Therefore, on the one hand, information on the development of in-service cracks is necessary, and, on the other hand, full-scale fatigue testing is required to correlate the expected and realized in-service loading mode of load-bearing structural components.

The loads acting on the structural components of the aircraft wings and airframe have a pronounced non-stationary character, and depending on the flight conditions, wind gusts can occur that affect significantly the material behaviour in the process of crack initiation and growth. For example, on the one hand, during overloading the process of damage accumulation is more intensive, but, on the other hand, following deceleration of damage accumulation can arise [1-3]. Therefore, a correlation of data on the realized in-service failure with data of full-scale tests under variable amplitude loading conditions allows introducing the reasonable estimation of inspection frequencies for flight safety.

Development and improvement of quantitative fractography technique [1, 7, 16] allows to systematize fracture surface relief parameters responsible for the different loading regimes of structures under variable amplitude loading conditions for the flight. Therefore, it makes possible to generalize the established regularities of fatigue crack developed in the load-bearing structures of one of the most in-service active RRJ-95 (Russian Regional Jet 95) aircraft.

During the operation of the RRJ-95 aircraft (No. 89051) the failure of the bracket across four lug sections was found in the mount fitting of the top rudder drive. The operating time from the new was 3785 hours or 2345 flights. To identify the factors influencing the process of crack generation and to substantiate the inspection frequency for brackets in operation, the estimation of crack growth duration was required.

At the same time, full-scale bench tests of the RRJ-95 aircraft (No. 95075) wing structure were carried out according to the schematized program of the flight loading cycle in order to determine the crack propagation duration in different zones of the structure.

The test program included cycles with variable amplitude and maximum stress that simulate the loads during aircraft taxiing, take-off, climb, cruising regime, descent, and landing. The schematized loading program

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could not reproduce the entire spectrum of in-flight loads but reflected the estimated damage accumulation per flight with an average duration of 1.5 hours.

The cracks revealed in the structural components had a considerable length, indicating their long-term nature of propagation. However, by using the results of quantitative fractography, it was necessary to clarify the nature and duration of the crack growth, as well as to specify the sequence of crack development over different sections of the above-mentioned objects.

The results of studies are summarized below with an estimate of the fatigue crack growth duration in accordance with the methodology for systematizing fracture relief parameters reflecting the crack propagation per flight or unit loading cycle.

2. Research methodology

2.1 Bracket material of the RRJ-95 aircraft (No. 89051) and its fracture zone

The bracket was failed over four lug sections at the holes with a diameter of 8 mm for a bolt (Fig. 1). Mechanical and corrosion damages in the zones of bracket fracture were not observed. The bracket surfaces were typical for shot peening.

The origins of fatigue cracks were located at the inner edges of holes without chamfer (see Fig. 1b). The lug fracture surfaces were numbered in accordance with the sequence of studies.

Material researches had shown that the structural material is aluminium alloy 1933T3 (Al-Zn-Mg-Cu) with a standard chemical composition (Table 1) and the microstructure (Fig. 2a) recommended for the manufacturing bracket with the ultimate tensile stress of 500 MPa.

2.2 Components of the RRJ-95 aircraft (No. 95075) wing airframe

In the process of bench testing of the RRJ-95 aircraft (No. 95075) wing airframe, after operating of 19950 laboratory flights, a crack was found that spread to the face plane of the stiffened panel from under the middle bracket of the engine pylon mount, Fig. 3. When 20019 laboratory flights were generated, the crack appeared from under the plane of the middle bracket of engine pylon mount in the aft direction.

The tests were continued, and during the inspection for likely defects of the lower stiffened panel after the operating time of 20487 laboratory flights, a crack was found that appeared from under the root bracket of the engine pylon mount. This crack developed from the hole with a diameter of 12 mm for the bolt connecting the bracket with the stiffened panel. The crack length was 96 mm in the forward direction and 21 mm in the aft direction.

When disassembling the middle bracket, it was found that the crack developed to the face plane of the stiffened panel from the hole with a diameter of 14 mm for the bolt connecting the bracket with the stiffened panel. The crack length was 23 mm in the flight direction and 74 mm in the opposite flight direction.

Material researches had shown that the structural material is aluminium alloy 1163 (Al-Cu-Mg) with standard chemical composition (Table 1) and the microstructure (Fig. 2b) recommended for the manufacturing bracket with the ultimate tensile stress of 460 MPa.

Fracture surfaces of all structures were analysed by the well-known method [2] on the scanning electron microscope Carl Zeiss EVO40.

3. RESEARCH RESULTS

3.1 Mount fitting of the top rudder drive

Fracture origins No. 1 and No. 2 are located at the distance of about 1 mm from the edge of the bolt hole, while fracture origins No. 3 and No. 4 are located on the edges of the holes (Fig. 4). At an insignificant distance from the fracture origins in lug sections No. 1 and No. 2 the products of fretting process are observed on fracture surfaces. The products are formed as a result of contact interaction of the propagating crack edges. Therefore, the crack opening along the lug sections was insignificant, and the crack growth rate was low and corresponded to the first stage of the kinetic diagram – Paris curve. According to the existing concepts of the fatigue crack kinetics, at this stage the crack growth rate is less than 40 nm/cycle.

Therefore, the load sequence and interaction under variable amplitude loading conditions has a significant effect on the crack retardation [17]. It belongs to the short crack development process, that is the longest part of the total lifetime of structural component spent for nucleation and the stage of initial fracture. As in the considered case the fracture relief elements were not formed with any regularities, the duration of fracture process development discussed below excludes the stage of short-crack propagation corresponding to the initial crack length of 1 mm.

On fracture surface No. 1, the meso-beach-marks (MBM) were formed along the entire direction of crack growth from the hole towards the opposite surface of the lug, while in all other sections the blocks of fatigue striations were revealed (Fig. 5).

Therefore, the spacing of the MBM "h " on fracture surface No. 1 and the fatigue striation spacing "δ" on the fracture surfaces No. 2-4 were measured, respectively (Fig. 6).

After comparing the step of the loading blocks per flight identified by the MBM spacing (fracture surface No. 1) with the fatigue striation spacing discovered in other sections of the lugs it was established that fracture surface No. 1 was formed first, but not through total section, when cracks in the remaining sections began to propagate. However, an insignificant portion of the fast bracket fracture in all lug sections indicates that, as the crack propagated, the load was redistributed and the bracket was finally fractured at a low-stress level. It is worth noting that when the crack length reaches about 8 mm in lug section No. 3, the crack growth rate is decreased abruptly as compared to the lug section No. 4. Such behavior of the material may be resulted from a change in the loading intensity of the bracket because of to the redistribution of loads due to the fact that the crack in lug section No. 4 began to propagate later than in lug section No. 3. This fact is confirmed by the performed estimation of the crack increment per a unit loading cycle or block as a function of the crack length for both fracture surfaces No. 3 and No. 4 (see Fig. 6).

The assessment of the crack growth duration showed that the number of blocks "n_{f}" during fracture of section No. 1 was about 4000, and through sections No. 2-4 the numbers of unit cycles "N_{f}" were 50000, 97000 and 29000, respectively (Fig. 7).

3.2 Structural components of the aircraft wing

The studied fragments of four cracks were numbered by No. 1 (crack length of 21 mm), No. 2 (crack length of 96 mm), No. 3 (crack length of 23 mm) and No. 4 (crack length of 74 mm) (Fig. 8). On three fragments of fracture surfaces (No. 2, 3, and 4), the fracture origins are located on the inner surface of the holes at a distance of about 1 mm from their edges; on the fragment of fracture surface No. 1, the origin is located at the edge of the hole.

Origins of cracks No. 3 and 4 have pronounced features of the effect of contact loads on the hole surface that led to the formation of intense fretting products and a partial mechanical damaging of the crack initiation zones. The cracks were initiated by the fretting corrosion process. The occurrence of cracks in both holes was caused by the high-stress concentration, which was associated with a high level of contact loads (for cracks No. 1 and 2) and with a fretting corrosion process over the hole surface (for cracks No. 3 and 4).

Crack propagation had a fatigue nature and belonged to the high-cycle fatigue regime. A characteristic feature of crack propagation across all four fracture surfaces was the formation of MBM and fatigue striations with different spacing at different stages of growth (Fig. 9). The revealed features of fracture relief formation were used to estimate the duration of crack growth in terms of the number of blocks "n_{f}" for each cracks studied (Fig. 10).

From the results of evaluating the crack growth duration, it follows that the formation of cracks in the stiffened panel in the area of the bolt hole for the root bracket of the engine pylon is primary in regard to

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cracks formed in the zone of the bolt hole for the middle bracket of the engine pylon.

The obtained estimates of the crack growth duration in all studied lug sections are demonstrated in Table 2.

Therefore, it can be concluded that loading blocks (almost half of 20487 blocks) were associated with the successive nucleation of fatigue cracks in different areas of the structure and their propagation for at least 10000 blocks.

4. Discussion

The results of studies on the regularities governing the propagation of fatigue cracks in the structural components of RRJ-type aircraft wing indicate that cracks propagated for a long period under variable amplitude loading conditions. This fact allows to organize effective monitoring for timely in-service crack detection.

At the same time, the question of how to reproduce the duration of fatigue crack growth in the RRJ-95 aircraft (No. 89051) bracket remains unresolved, since both MBM blocks (see crack growth in section No. 1) and fatigue striations (other sections) were identified simultaneously. The analysed regularity of the fatigue striation formation with different spacing under variable amplitude loading conditions did not allow to demonstrate convincingly the block of variable loads responsible for the flight of the aircraft. Thus, the number of flights in the indicated bracket was estimated based on the data of the aircraft wing bench tests using the blocks that reproduced the schematized flight loading cycle.

The program of bench tests consisted of sequence of loading blocks. Each block was equivalent to the set of variable loads acting on the aircraft wing for the full flight-cycle and simulated the entire sequence of the aircraft flight regimes and operation on the ground – taxiing, warming, etc. It was taken into account that the loading of the aircraft wing resulted in the realization of a biaxial stress state. In this regard, in-phase loading was carried out along two axes (Fig. 11). The preliminary results of the strain gauge measurement for stress-state estimation in stiffened panels of the RRJ-95 aircraft wing had shown that for all the stages of flight the in-phase biaxial loading takes place. Therefore, the bench-test program consisted of only the in-phase loading.

The resulting crack growth duration was about 50% of the wing operating time on the device at the moment of test termination. As shown by the results of the fractographic analysis, the origins of the cracks are located near the hole edges at a distance of about 1 mm similarly in the bracket of the RRJ-95 aircraft (No. 95075) wing airframe and in the wing of the aircraft (Fig. 12). This fact allows to suppose that the stress concentration is close in the compared cases.

The tensile strength of both aluminium alloys is as close as the chemical composition and microstructure of the deformable heat-treated alloy.

All of the above-mentioned facts allow to assume that at the durability near the low-cycle fatigue regime, the ratio between the crack growth period and durability under comparable conditions is also similar, i.e. about 50%.

The validity of such an analysis is consistent with the results of the RRJ-95 aircraft (No. 4862) wing previous tests, in which fragments of the lower panel were fractured during the operating time of 28180 laboratory flights. The development of the crack was accompanied by the MBM formation (Fig. 13a), and an assessment of the crack growth duration in the blocks of test flights showed that it was approximately 16000 blocks (Fig. 13b). The obtained assessment indicates the fact that the crack growth duration is about 16000/28180=57%.

Therefore, it can be assumed that for the fractured bracket of the RRJ-95 aircraft (No. 89051) the duration of crack growth at the operating time of 2345 flights is about $2345 \times 0.5 = 1172$ flights.

As a result of the study, it was found that the longest period of crack growth was in section No. 3 for about 97000 unit loading cycles. This duration is slightly less than that corresponding to the full period of crack growth because the first section was No. 1, in which the crack began to propagate. However, it could not

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reach the maximum length, because due to the operating other sections, the load was redistributed from section No. 1 to the remaining sections of the bracket lug.

It is worth noting that with the performed assessment of the block duration per flight, the error will not exceed 15%.

So, if we use the duration of 1172 flights and the number of striations equal to 97000, it appears that for one flight the bracket was loaded approximately 97000/1172 = 83 times. The obtained result of estimating the duration and the number of unit loading cycles per flight does not contradict the fractographic data (see, for example, Fig. 5b). On the fracture surfaces of the bracket in different sections, the extended areas with fatigue striations were revealed, which do not have clearly defined block boundaries due to the fact that the number of single cycles in the blocks reached many numbers. Moreover, the fatigue striation spacing varies irregularly due to the random loading of the bracket.

A comparison of the operating time according to the schematized flight cycle and the bracket in-service duration indicates that the loading on the device does not fully reproduce the structural component loading intensity for the flight.

Nevertheless, the duration of the crack propagation in the structural components of the RRJ-type aircraft wing is significant, which allows cracks to be reliably detected with an organized inspection frequency exceeding 500 flights. The start of monitoring can be arranged after the operating time of 1000 flights. By reducing the stress concentration on the holes in which cracks occurred, it is possible to significantly increase the duration up to the moment of crack initiation.

5. Conclusion

Loading in operation and at the device of structural components of the RRJ-type aircraft wing with variable stress amplitudes leads to a long period of fatigue crack propagation in them, which is approximately 50% of the total lifetime of the structure. It allows to organize reliable monitoring of crack propagation with a large operating time interval between adjacent inspections. The duration of the fatigue crack advance per flight can be approximately 80 variable loading cycles.

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Figure Captions

Fig. 1. The fractured bracket (inside the circle) on the RRJ-95 aircraft (No. 89051) (a) and fracture surfaces by the four lug sections (b).

Fig. 2. Microstructure of investigated aluminum alloys: 1933T3 (a) and 1163 (b).

Fig. 3. The crack (inside the circle) propagated to the face plane of the stiffened panel from under the middle bracket of the engine pylon mount in the RRJ-95 aircraft (No. 95075) and the scheme of the airframe with the area of bracket position (view A).

Fig. 4. Initial fracture zones in bracket lug sections No. 1 (a), 2 (b), 3 (c), and 4 (d) of the engine pylon mount in the RRJ-95 aircraft (No. 95075) with origins indicated by the arrows.

Fig. 5. The blocks of MBM (a) and fatigue striations (b) on the fracture surfaces No. 1 and No. 4 of the RRJ-95 aircraft (No. 89051) lug, respectively.

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Fig. 6. The plot of the MBM spacing "h " (lug section No. 1) and the fatigue striation spacing "δ" (lug sections No. 2-4) versus the crack length "a " of the RRJ-95 aircraft (No. 89051).

Fig. 7. The plot of crack growth duration in terms of the number of blocks "n_f" (lug section No. 1) and the number of unit cycles "N_f" (lug sections No. 2-4) versus the crack length "a " of the RRJ-95 aircraft (No. 89051).

Fig. 8. The fracture surfaces No. 1-4 in the RRJ-95 aircraft (No. 95075) wing panel.

Fig. 9. The fatigue MBM blocks on the fracture surfaces No. 2 (a) and No. 3 (b) at different crack length for the RRJ-95 aircraft (No. 95075).

Fig. 10. The plot of the MBM spacing "h " and the number of blocks "n_f" versus the crack length "a " for fracture surfaces No. 2 (a) and No. 4(b) of the RRJ-95 aircraft (No. 95075).

Fig. 11. The program of bench-test loading along the OY (a) and OZ (b) axes for the lower panel of the RRJ-95 aircraft (No. 4862) wing reproducing single schematized flight loading cycle.

Fig. 12. Fracture surfaces in the lower panel of the RRJ-95 aircraft (No. 4862) wing.

Fig. 13. The MBM reflecting the block loading of the lower panel of the RRJ-95 aircraft (No. 4862) wing in accordance with the schematized flight cycle (a), and the plot of the MBM spacing "h " and the number of blocks "n_f" versus the crack length "a " in the panel (b).

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Highlights.

1. The fatigue cracks in structural components of the RRJ-95 aircraft frames were analysed.
2. The data on crack growth duration in terms of the number of cycles and blocks are shown.
3. The portions of total lifetime spent for both crack nucleation and propagation are close.
4. The recommendation on the extension of the structural component lifetime was made.

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