JOURNAL OF AIRCRAFT
Vol. 43, No. 3, May–June 2006

Stress and Fatigue Analysis of Modified Wing–Fuselage Connector for Agricultural Aircraft

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This paper presents numerical stress and fatigue analyses of a main wing–fuselage connector for agricultural aircraft. A nonlinear finite-element method was utilized to determine the stress states of both standard and modified connectors under operating conditions. High-stress zones were found at the region of the standard wing lug, where the failure occurred. Obtained results were next put into total fatigue life (*S–N*) and crack initiation (ε–*N*) analyses performed for load time history equivalent to 10 min operating flight. In these analyses, the number of flight hours to the first fatigue crack and also to total damage of the wing lug were estimated. Moreover, the influence of many factors such as overload, corrosion, heat treatment, and surface treatment on the fatigue lives of the standard and modified connectors were analyzed.

I. Introduction

THE wing–fuselage connector is one of the most critical parts of aircraft. This connector joins the wing spar and the bulkhead of a fuselage (Fig. 1). It transmits aerodynamic, inertial, and gravitional forces from the wing to the fuselage. Its life often limits service life of the entire airframe due to large operational stresses. Agricultural operations often expose structural components to warm, humid, and polluted air. Work in an environment of atomized chemicals has a negative influence on fatigue durability of airframe components of agriculture aircraft. Corrosion can affect aircraft structural integrity because fatigue cracks can nucleate from corrosion pits and grow at an accelerated rate in the corrosive environment. It has been pointed out that fatigue combined with corrosion is one of the primary causes of aircraft fleet aging[1,2] encouraging studies related to this issue. Descriptions and results of investigations concerned with stress, fatigue, and failure analysis of aircraft components are presented in Ref. 3–14.

The problem of premature fracture failure of the wing–fuselage connector occurred in certain type of agricultural aircraft after about 5000–6000 h of operation. Failure of the connector occurred because of the growth to critical size of an undetected fatigue crack in the lower lug of the wing–fuselage connector. In two cases the failure of the connector was the reason for the crash. After these accidents, the producer of aircraft give an order for detailed inspection of connectors in all planes that had more than 3000 flight hours operation. In a few cases both corrosion pits and small cracks were detected in the lugs of aircraft that had a total time of 4000–5000 h of operation. In most cases these problems were reported to the producer. In consequence these connectors were quickly replaced. However, in one case, a certain user of this plane, after inspection and detection of the first short crack in the lower wing lug, introduced certain modifications of the connector without knowledge of the producer. The lug's hole with embedded small corner crack was first reamed. Next, the lacking volume of lug material was filled by an additional intermediate sleeve. However, the local aviation supervising office had not given permission for performing flights on this modified aircraft. After that, the modified connector was dismantled and sent to the producer for a laboratory fatigue test. The results of this investigation were most interesting. The fatigue life of the modified connector was four times higher than that of the serial connector designed by professional aircraft engineers.

Attention in this paper is mainly devoted to explaining the considerable increase in the fatigue life of the modified connector and also the reasons for the premature failure of the original component.

II. Finite-Element Model of the Modified Connector

Using the Patran 2000r2 program,[15] the geometry and mesh for all components of the model were created. The model consist of the following parts: 1) Lug connected to the wing spar—critical component 1; 2) Double lugs connected to bulkhead of the fuselage, 2; 3) Expanding pin, 3; 4) Screw with conical head, 4; 5) Conical sleeve and nut, 5; and 6) Intermediate sleeve, 6 (thickness 3.5 mm)—additional element in modified lug. This component does not occur in the original serial connector designed by the producer of the aircraft.

The finite-element (FE) model of the modified connector consists of 13,500 first-order HEX-8 elements.[15] All components of the connector before assembly are shown in Fig 2.

The main components of the connector are made out of nickel–chrome high-tensile steel, 30 HGSA (0.32 C; 0.9 Mn; 1.1 Si; 0.9 Cr; 0.3 Ni according to Polish Standard PN 89/M-84030/04) with the following properties after heat treatment: 1) Ultimate tensile strength (UTS) 1200 MPa, 2) Yield stress 1050 MPa, 3) Young's modulus 210 GPa, and 4) Poisson ratio 0.3.

To model interaction between adjacent surfaces of solids, three-dimensional contact interface elements with friction coefficient of 0.05 were used.[15] This value of the coefficient represents interaction of the components when they are lubricated.

The assembled model of the connector with additional sleeve is presented in the sectional view in Fig. 3. In this figure are additionally shown the boundary conditions and load used in computations. The fuselage lug was fully restrained in the cutoff plane, whereas a force of 126 kN was applied to the cut off section of the wing lug as indicated at the right side of the figure.

The finite-element program MSC–Advanced FEA[15] was used for stress analysis of the connector. In calculations reported here, the nonlinear (incremental) Newton–Raphson method with initial step of 0.1 was applied. In all presented results, megapascal (MPa) units were used to describe the stress fields.

III. Results of the Stress Analysis

Figure 4 shows the von Mises (a) and circumferential (b) stress distributions in the serial lug. The zone of maximum von Mises stress (1144 MPa) was located in the left top part of the hole. The area of maximum circumferential stress (Fig. 4b) was situated at the top part of the hole, where the tensile stress is equal to 739 MPa.

Received 21 October 2004; revision received 17 August 2005; accepted for publication 19 August 2005.

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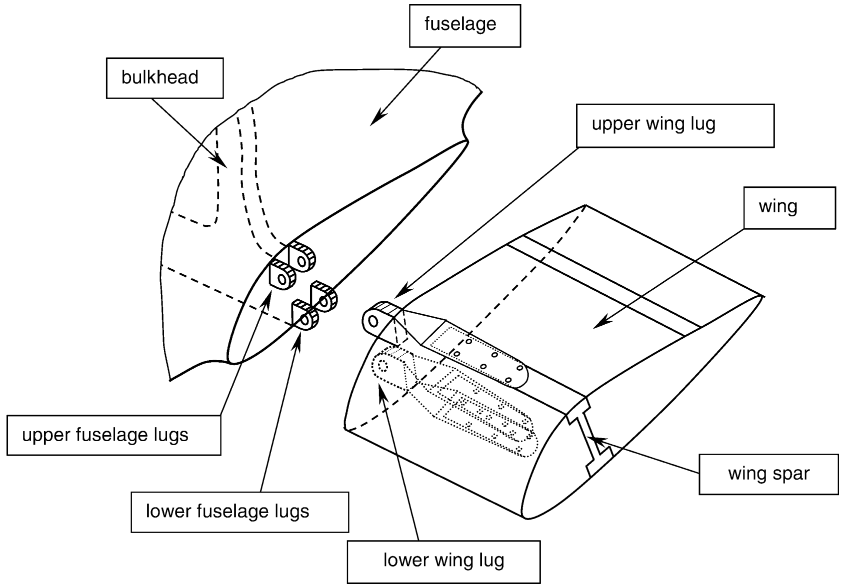


Fig. 1 Components of typical wing–fuselage connector of aircraft.

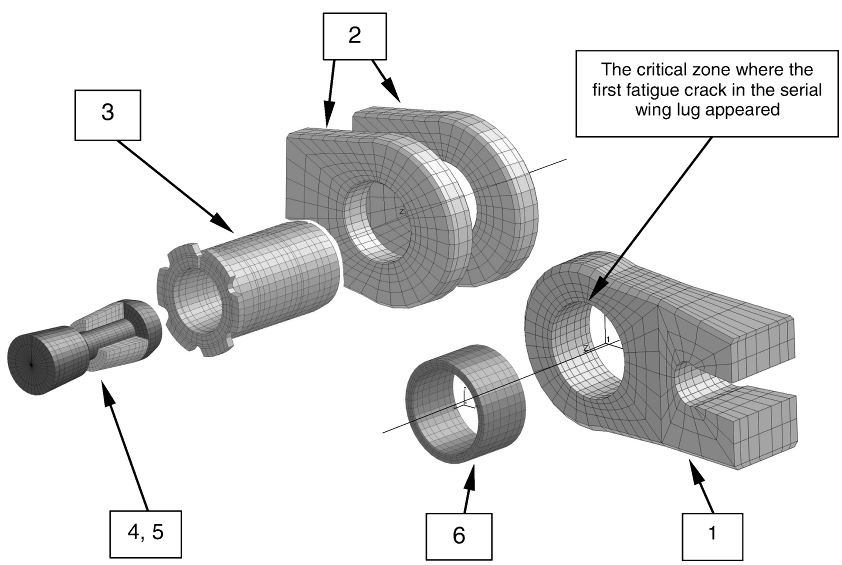


Fig. 2 Components of the connector before assembly.

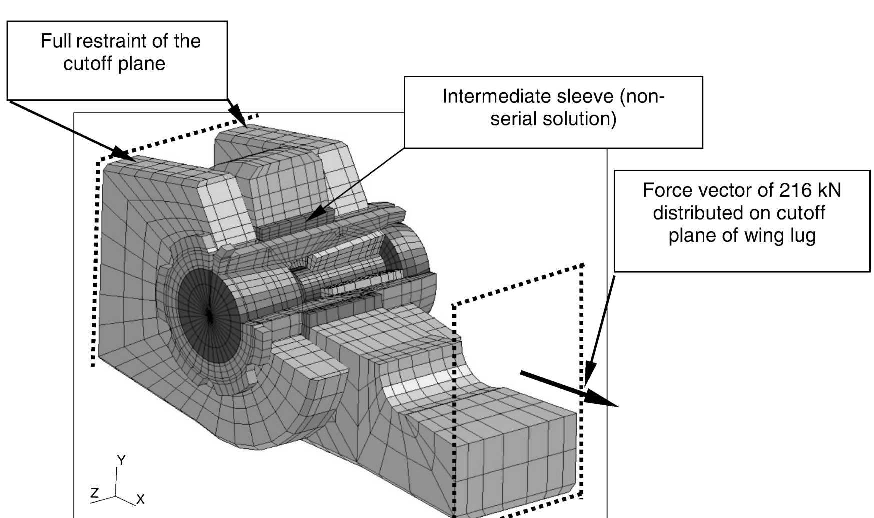
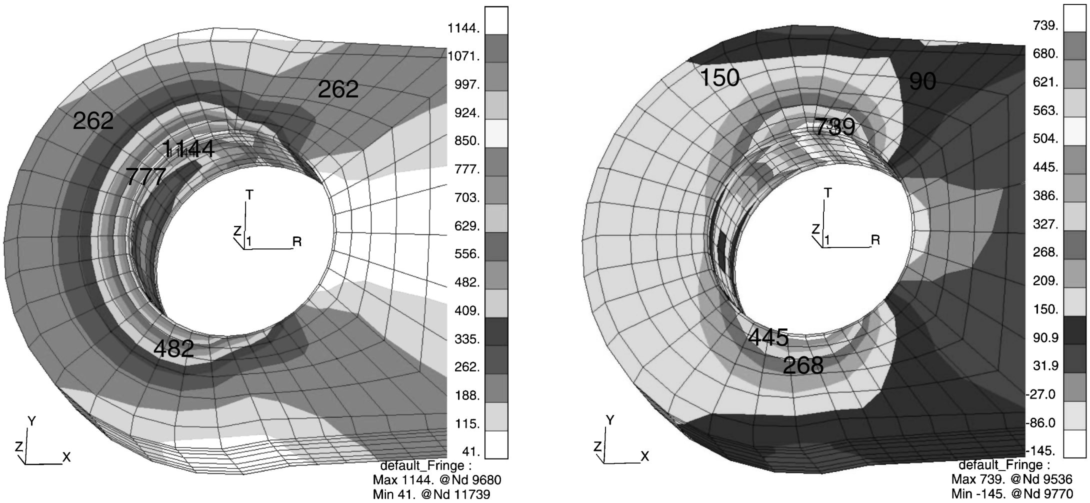


Fig. 3 Load and boundary conditions for FE model of connector.



a) b)

Fig. 4 a) Von Mises and b) circumferential stress distribution in the serial lug.

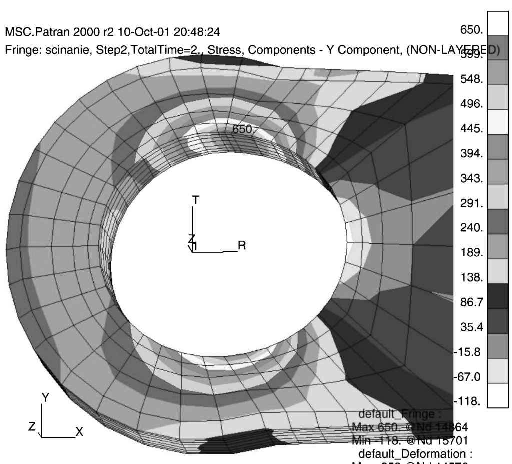


Fig. 5 Circumferential stress distribution for the modified lug.

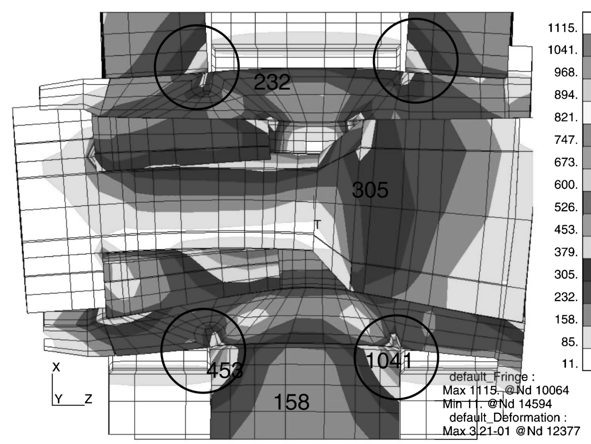


Fig. 6 Von Mises stress distribution in axle section of connector. Stress field is displayed on the deformed model with displacement visualization of 20:1.

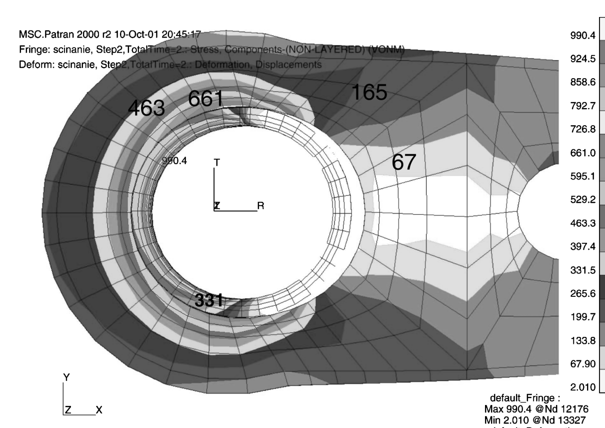


Fig. 7 Von Mises stress distribution for the modified lug with inserted intermediate sleeve.

The second result (Fig. 4b) is particularly interesting from the point of view of fatigue strength because just the tensile circumferential stresses contribute most to the appearance of fatigue cracks and hence to damaging the connector.

By comparison of Figs. 4b and 5 it is easily seen that after the intermediate sleeve is introduced the critical cross-sectional area of the modified lug was decreased and the maximum circumferential stress was reduced from 739 to 650 MPa.

Figure 6 shows the von Mises stress distribution in the horizontal cross section of the serial connector. As seen from this figure, the sleeve-screw team is bent. The bending effect causes additional stress concentrations on the edges of the wing lug (marked by circles).

Figure 7 shows the von Mises stress distribution for the lug and the sleeve in assembly. The stress field is displayed on the deformed model with displacement visualization of 10:1. As seen from this figure, only the left part of the intermediate sleeve transmits load from the lug to the expanding pin. By use of the intermediate sleeve, the zone of high gradient stress was moved from the critical area of the lug onto the sleeve. This is a very beneficial result because the intermediate sleeve is not load-carrying component of the connector.

The von Mises stress values as a function of the radial node position of the lug, presented in Fig. 8, show that on the cross section of the wing lug a non even stress distribution occurred. For the internal zone of the serial lug the stress range is 100–570 MPa (curve C–D). The bending effect of the expanding pin caused the stress on the edge of the lug to increase to 1025 MPa (point B).

Maximum von Mises stress on the edge of the modified lug (Fig. 9) decreased about 25% (from 1025 MPa (see Fig. 8) to 750 MPa).

IV. Numerical Fatigue Analysis

To estimate the total fatigue durability of the connector, the program MSC Fatigue 9.0 was used. This program enables one to perform two main kinds of analyses, total fatigue life (S–N) and crack

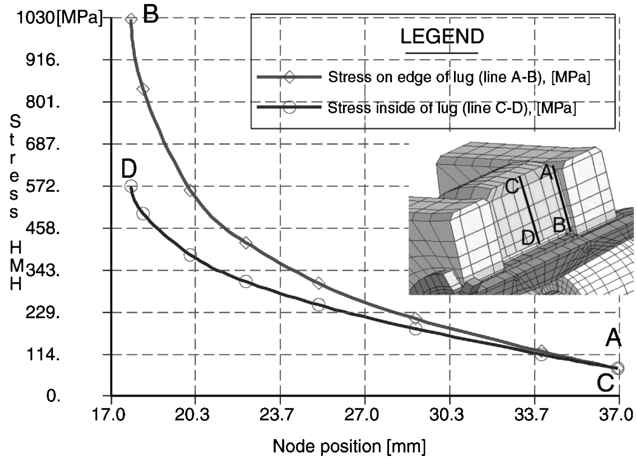


Fig. 8 Von Mises stress on the edge (curve A–B) and in the internal zone of the standard wing lug (curve C–D).

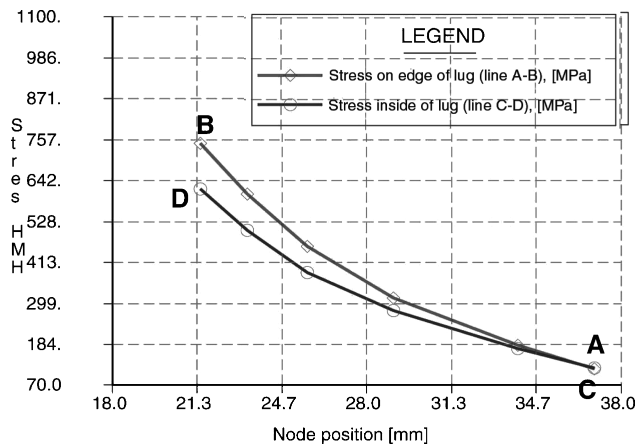


Fig. 9 Von Mises stress on the edge (curve A–B) and in the internal zone of the modified wing lug (curve C–D).

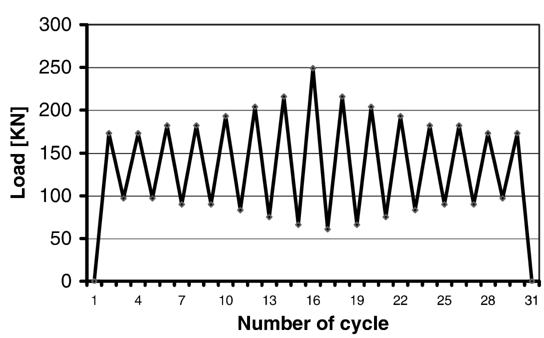


Fig. 10 Simplified load spectrum of connector for 10-min operating flight of agricultural airplane.

initiation (ε–N), for nonlimited geometry defined by user.[16] During the analysis, the program MSC Fatigue uses the procedures of rain flow counting and linear damage summation[16] to transpose the nonsymmetric time history with different levels of loads on the results of experimental standard tests performed for constant amplitude of load.

The load time history for the wing–fuselage connector, presented in Fig. 10, was defined on the basis of the simplified spectrum, which is equivalent to 10 min operating flight, typical for agricultural aircraft. This history consists of take-off, a few working maneuvers over the field area, and landing. In the S–N analysis presented here, the correction of mean stress according to Goodman theory was also applied.

The results of the S–N analysis for the serial lug is presented in Fig. 11. The practical sense of this result is the minimum estimated

Table 1 Results of ε–N and S–N analysis for standard and modified lugs

Type of analysis	Standard lug	Modified lug
Result of ε–N analysis (time to crack initiation, flight hours)	4,003	9,120
Result of S–N analysis (total time to damage of structure, flight hours)	5,012	21,380

Table 2 Influence of surface treatment and work in corrosive environment on the time to first crack initiation of the standard and modified wing lugs

Surface treatment and environment of work	Flight hours	
	Standard lug	Modified lug
Nitroided	25300	55987
Shot-penned	8122	20713
Polished	6248	15147
Ground	4003	9120
Well machined	2365	4946
Average machined	1703	3426
Poorly machined	1251	2435
Forged	245	415
Cast	199	331
Water corrosion	168	279
Seawater corrosion	88	139

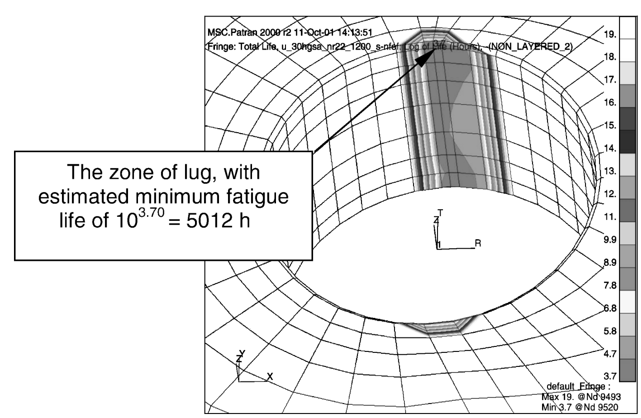


Fig. 11 Results of the S–N analysis (zones of the FE model with determination of total fatigue life).

life of $10^{3.70}$ h (5012 flight hours). The critical fatigue zone estimated here overlaps the area where the maximum value of circumferential stress occurred (Fig. 5). Introducing the intermediate sleeve into the lug was a very beneficial solution because after modification, the total fatigue life of the component increased about four times (see Table 1).

The ε–N analysis, implemented into the MSC Fatigue program, known as "crack initiation,"[16] gives much more information than the S–N analysis. The influence of many factors, such as surface treatment, heat treatment, corrosion, and overload, on the time to crack initiation can be estimated using ε–N analysis. In the ε–N calculation reported here, correction of mean stress according to Smith, Watson, and Topper and the Neuber elastic–plastic correction of strain were used.[16]

Table 1 presents summarized results of the ε–N and S–N analyses performed for the standard and modified connectors. Results of the ε–N analysis were obtained for the ground surface treatment of the lug. This results show that after modification of the serial connector, the time for crack initiation increased from 4003 to 9120 h, whereas the expected time to damage of the structure increased from 5012 to 21,380 h.

Results of ε–N analysis for different surface treatments of the lug and for its work in a corrosive environment are presented in Table 2.

Table 3 Critical time of crack initiation for wing lugs manufactured out of different sorts of steel

Type of lug	30 HGSA, UTS = 1100 [MPa]	30 HGSA, UTS = 1200 [MPa]	SAE 4130	SAE 4340
Standard lug	2,896	4,003	5,299	9,327
Modified lug	6,186	9,120	11,843	58,200

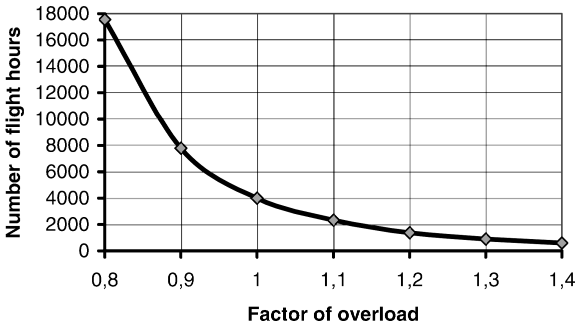


Fig. 12 Influence of overloading of connector on time to crack initiation of lug.

As seen from this table, polishing and the shot penning can increase the fatigue life by over 50–100%. Moreover, the corrosive environment (i.e., chemical agents atomized by the agricultural aircraft and mixed with rainwater) has a huge influence on the decrease of life.

Sometimes, in the manufacturing process, certain parameters such as temperature or speed of cooling for the heat treatment of the component are not observed. In these cases, materials with different mechanical properties can be obtained and, in consequence, fatigue life is often lower. For example, if the UTS (ultimate tensile strength) of the 30 HGSA steel is only 1100 MPa (this is 100 MPa less than the value of UTS recommended by the designer of this aircraft), the fatigue life can decrease about 25%. Results of crack initiation analysis ε–N for 30 HGSA steel with the lower value of yield point and for similar steels classified according to SAE standards are presented in Table 3.

The specific type of duty of agriculture aircraft is often overloaded. This causes a magnified spectrum of load. In this study, the influence of under- and over loading on the fatigue durability of the standard connector was also investigated.

Figure 12 shows results of ε–N analysis performed for the standard wing lug for different factors of overload. As seen from this plot, the wing–fuselage connector is very sensitive to exceeding the maximum take–off weight. Only 10% overload decreases the fatigue by about 40%. The high level of operational stress in the standard lug (close to the yield point of the material) is why the decrease in fatigue life at overload is so significant.

V. Experimental Investigations

In a few cases both corrosion pits and the small cracks were detected in lugs of aircraft that had a total time of 4000–5000 h of operation. In consequence these connectors were replaced. These cracked connectors were next subjected to experimental investigations. In these investigations the cracked lugs were subjected to the cyclic loading presented in Fig. 10. This kind of load was realized with a simple rig consisting of one actuator operated by on electronic control system.

The connector failure location is presented in Fig. 13. The connector presented on this figure was sent to experimental test after 4367 flight hours of aircraft operation, after the first crack detection. The size of this corner crack was about 2×3 mm. The lug fractured in test after 1130 h.

As seen from Fig. 13, the wing lug was fractured in two zones. The crack was initiated in the bottom zone of lug (region I), where the typical fatigue breach marks are observed (Fig. 14). After fatigue damage of the bottom lug area there occurred plastic bending and the rupture of the top lug zone (region II).

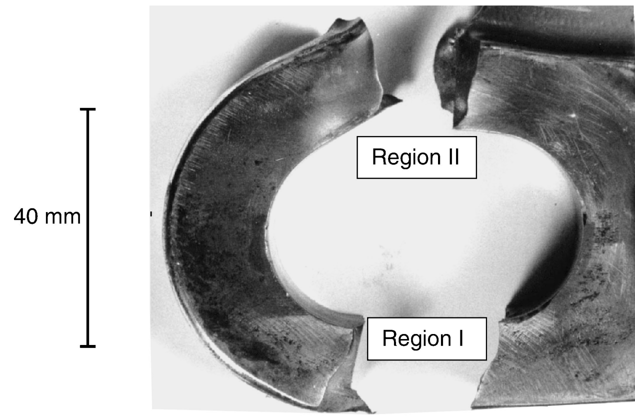


Fig. 13 View of lower wing lug after damage.

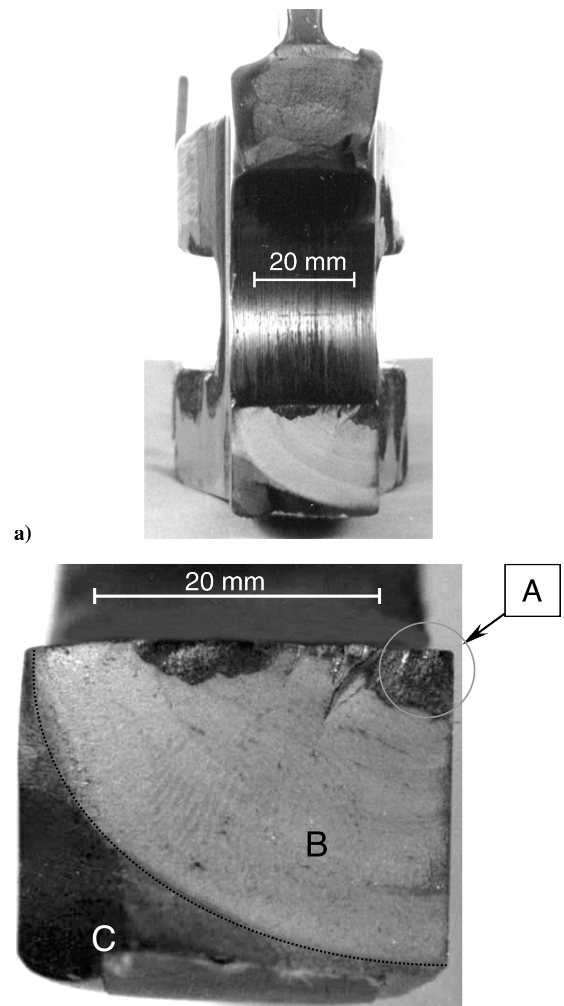


Fig. 14 a) Cracked lug surfaces and b) magnified view of lower fracture surface.

Figure 14a presents the cracked lug surfaces with top and bottom fracture areas distinguished. Figure 14b is a magnified view of the lower fracture surface. The curvature of the breach marks indicated that incremental crack growth had taken place from the corner of the lug fracture region (zone A in Fig. 14b). Careful observation showed that the crack origin surface was covered by corrosion products; thus the crack initiation process was accelerated by corrosion. The fractured surface showed a clear difference in color in three different regions. The crack origin zone, the fatigue fracture area with

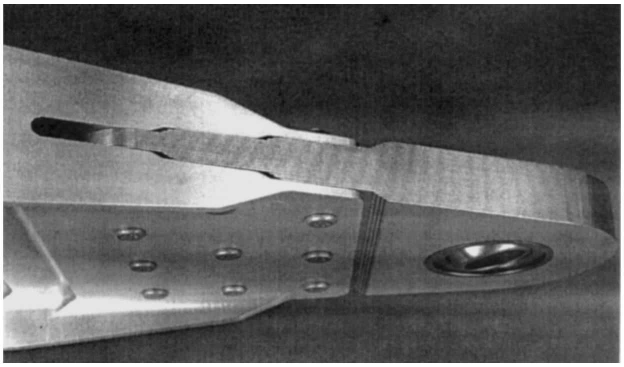


Fig. 15 Wing-lug designed with fatigue resistance philosophy.

presence of breach marks, and the ruptured zone are marked A, B, and C, respectively. The region that finally ruptured is dark gray (C).

A laboratory fatigue test performed for the modified connector with intermediate sleeve was finished before damage of the structure (at about 20,000 h) because of long time and high costs of investigation. The results of experimental tests clearly showed that after the additional sleeve was introduced the fatigue life was at least 4 times greater than the life of the standard connector.

An example of a fatigue-resistant wing lug used in a different aircraft is presented in Fig. 15 (see Ref. 17). In this solution a special sleeve to reduce the excessive stress concentration in the critical lug area was introduced.

VI. Conclusions

This paper explains reasons for considerable increase in the fatigue life of individually modified wing–fuselage connectors for agricultural aircraft. Using complex FE analysis, the stress contours for both serial and modified connectors were first generated. It was evident that the excessive stress in the critical lug area was the main reason for premature fatigue failure of the standard wing lug. Results of S–N and ε–N numerical calculations and experimental investigations clearly show that introducing the additional sleeve was a very beneficial solution. The high stresses were reduced and in consequence the fatigue life of the modified connector was much higher. Results of visual inspection showed that the corrosive environment of work, typical for agriculture aircraft, also has a negative influence on the cracking process. The main conclusion can be formulated based on the results of investigation carried out through the work: the wing–fuselage connector should be redesigned for better fatigue durability.

Acknowledgment

The author would like to thank Henryck Kopecki of the Rzeszow University of Technology for his assistance in this study.

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