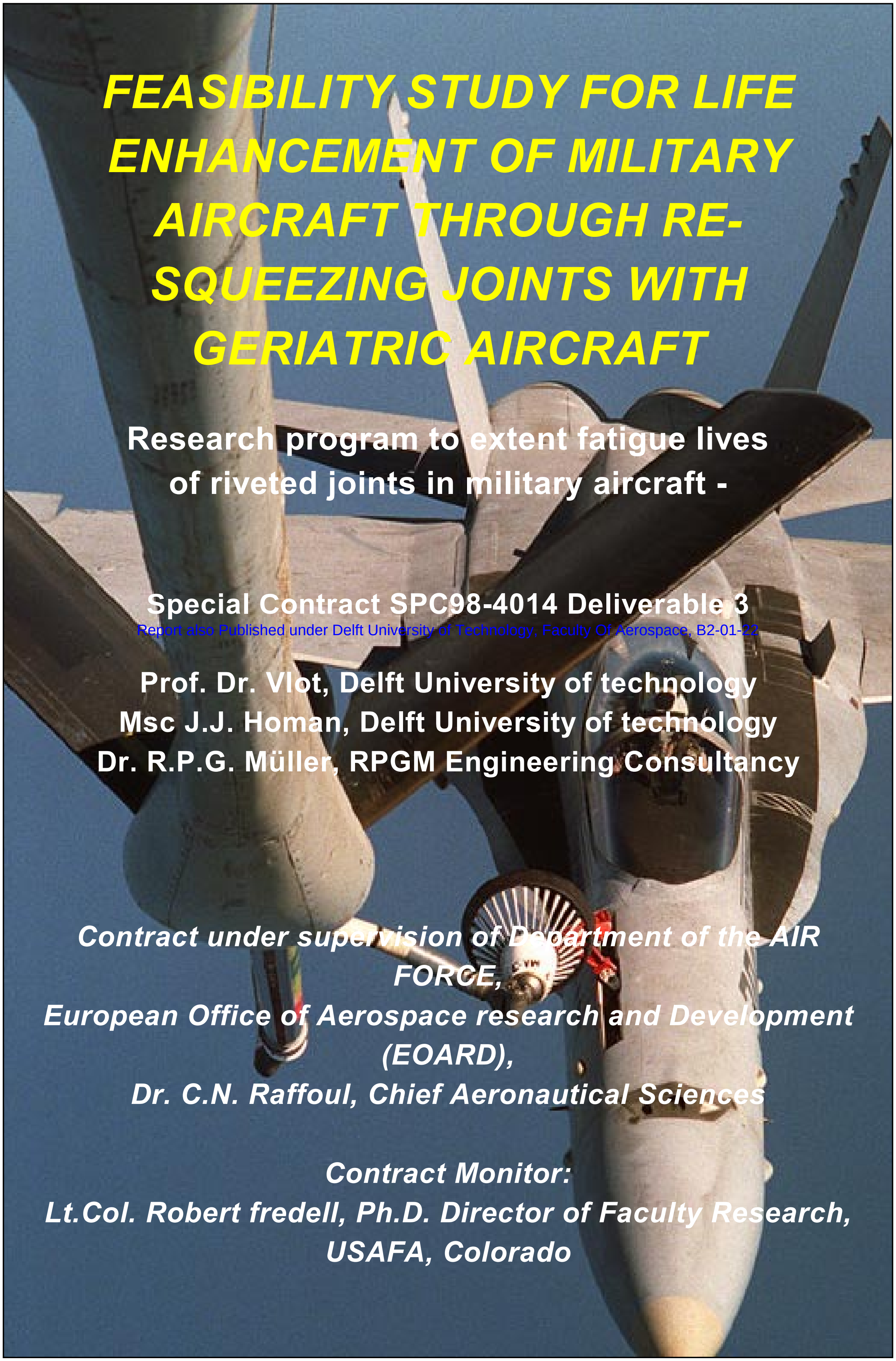

FEASIBILITY STUDY FOR LIFE ENHANCEMENT OF MILITARY AIRCRAFT THROUGH RE-SQUEEZING JOINTS WITH GERIATRIC AIRCRAFT

Research program to extent fatigue lives of riveted joints in military aircraft -

Special Contract SPC98-4014 Deliverable 3

Report also Published under Delft University of Technology, Faculty Of Aerospace, B2-01-22

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Contract under supervision of Department of the AIR FORCE,
European Office of Aerospace research and Development (EOARD),
Dr. C.N. Raffoul, Chief Aeronautical Sciences

Contract Monitor:
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FEASIBILITY STUDY FOR LIFE ENHANCEMENT OF MILITARY AIRCRAFT THROUGH RE-SQUEEZING JOINTS WITH GERIATRIC AIRCRAFT

Research program to extent fatigue lives
of riveted joints in military aircraft without the need of re-skinning

special contract SPC98-4014[κ] Deliverable 3

Report also Published under Delft University Of technology No: B2-01-22

By Dr. R.P.G. Müller, RPGM Engineering Consultancy
Prof. Dr. Ad vlot, Delft University of Technology
Ir. J.J. Homan, Delft University of Technology

Contract under supervision of Department of the AIR FORCE,

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Contract Monitor:

Lt Col Robert S. Fredell, Ph.D. Director Faculty Research, EOARD,

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Deliverable SPC98-4014, deliverable 3 encloses:

- Introduction
- Theoretical analysis of rivet squeeze force in relation to re-squeezing
- Fatigue test program with re-squeezed riveted
- Fatigue test results with re-squeezed riveted joints
- Discussion for feasibility of re-squeezing joints with existing military aircraft
- Recommendations for design development for re-squeezed riveted joints

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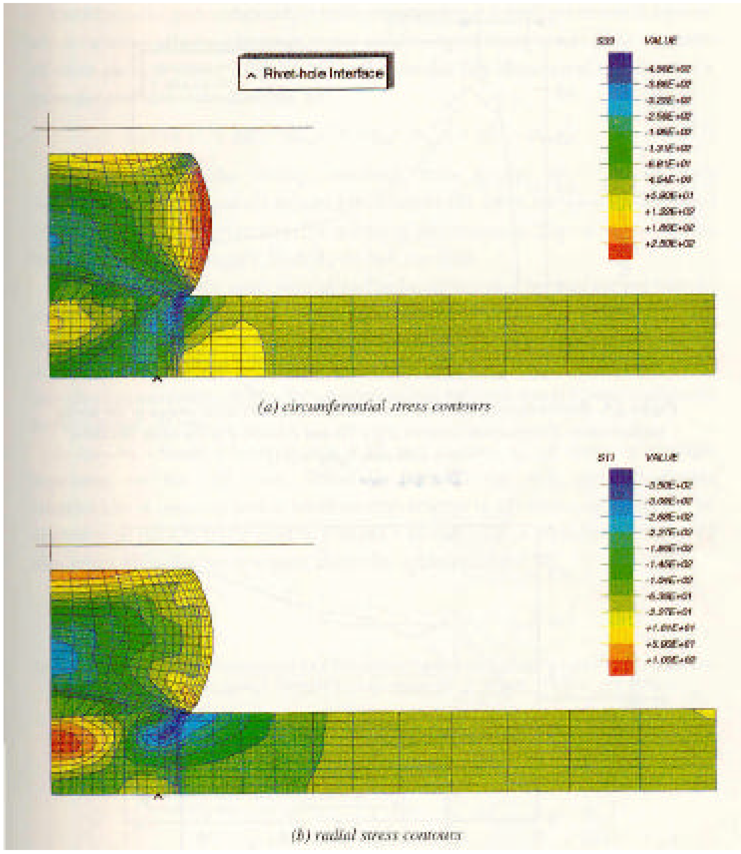
Introduction

The number of military ageing aircraft flying has been increased significantly over the last decades. Economic restrictions force the military to use their fleet much longer than initially designed for. Aircraft development from design to development equals minimally 10 years. Aircraft design life is varying up to 20 years. However, in the year 2000 more than 5700 commercial aircraft were over twenty years old. In 1993, 51% of the USAF fleet was over 15 years in age and 44% was over twenty years in age. As a consequence, fatigue and corrosion problems became an important topic for the maintenance of these aircraft. A well-known, though dramatic accident was the explosive decompression of the Aloha Airlines Boeing back in 1988, were major part of the crown was separated from the fuselage due to fatigue problems at the joints leading to multiple site damage. Since that moment abundant financing was initiated for investigation programs for fatigue of riveted joints. An extremely important aspect of rivet joint manufacturing is the squeeze force. Squeeze force can increase the fatigue life within industry standards (by controlling the rivet head dimensions) up to a factor 10.

This deliverable is performed in cooperation with Delft University of Technology. This deliverable is part of a frame work to investigate the feasibility for improving the utilization life of geriatric aircraft with respect to riveted joints. As part of the Air force investigation program a new philosophy has been investigated. Instead of rivet removal and oversize rivet installation or more labor and cost extensive re-skinning programs a re-squeezing approach of solid rivets has been followed. Lt.Col. Robert Fredell from the United States Air Force initiated this deliverable supported by Dr. Charbel Raffoul and funded the theoretical and experimental research. The theoretical analysis has been performed by Müller and the experiments have been performed by the Delft University of Technology, Faculty Aerospace engineering, Structures and Materials Laboratory. This laboratory has the sophisticated equipment and the experience in order to identify the opportunity for life improvement. From Delft Mr. Homan, Msc. initiated the test program under the supervision of Prof. Dr. Ad Vlot, head of Materials Laboratory. The results of the re-squeezing deliverable are presented in this report SP-98-4014, deliverable 3.

Theoretical analysis of rivet squeeze force in relation to re-squeezing

Rivet squeezing is a process which uses the plastic capability of metals to adhere sheets together. The process is based on having individual sheets allowing an overlap, which is drilled and riveted together. Rivet installation was performed with hand held rivet guns. The rivet gun was opposed against the preformed rivet head and the bucking bar the deform the rivet without having the sheets to oppose the squeeze force was placed on the other side of the skin. This requires a skilled team to drive the rivets. Riveting was never performed under close controlled squeeze force conditions. From the thesis of Müller it could be derived that a clear relation between driven head and fatigue life could be established. However, the scatter in fatigue for hand driven rivets was too large to make advantage of this driven head relation ship. It was when the driven heads of the rivets were controlled by rivet squeezing when a controlled relation ship with fatigue life was established. Force controlled riveting as a production process excludes the many scatter parameters in fatigue lives to which the residual stress in the sheet and the rivet due to squeezing are reproducible. Theoretical analysis showed the rivet upsetting to result in rivet head expansion as well in rivet shank expansion. It is the axial sheet compression in combination radial rivet hole expansion which results in favorable residual stress system to better withstand repetitive fatigue loads. The hole edge develops with larger squeeze force compressive residual stresses, reducing the mean stress but more important the stress amplitude. The Finite element calculations prepared demonstrate that with increased squeeze force the residual stresses even can become negative in circumferential direction around the hole. Also demonstrated with experiments it has been demonstrated that an optimum squeeze force exists based on the deformations in the sheet leading to nuisance stresses and unfavorable tensile stresses removed from the hole edge as a result of stress equilibrium with the compressive stresses at the hole edge. In figure 1 a finite element result is presented for reference.



(a) circumferential stress contours

(b) radial stress contours

Figure 1, Finite element representation of contours of residual stress distribution in rivet and sheet after squeezing.

Fatigue test program with re-squeezed riveted joints

A careful selection has been made for a joint configuration. In figure 2 the geometrical dimensions from the joints are given. The skin material equals 2024 T3 alloy with thickness 1.2 mm (0.0472"). The rivets are non-ice box rivets and of type NAS1097AD5-5, being 2117-T4 alloy. This rivets is non-heat treated and sequentially quenched prior to rivet installation. The rivet therefore does not have a shelf-life or changed mechanical properties with time other than strain hardening due to squeezing. The diameter *D* of the rivet equals 4.0 mm (5/32"). The length of the rivet equals equals 7.9 mm (5/16"). Rivet pitch *S* and row pitch *P* are defined at 20 mm (0.787") and the free edge distance *e* equals 10 mm (0.394"), being respectively 5*D and 2.5*D. The total specimen width *W* equals 125 mm (4.9"). The specimen length is chosen such as to avoid clamp effects in the overlap area.

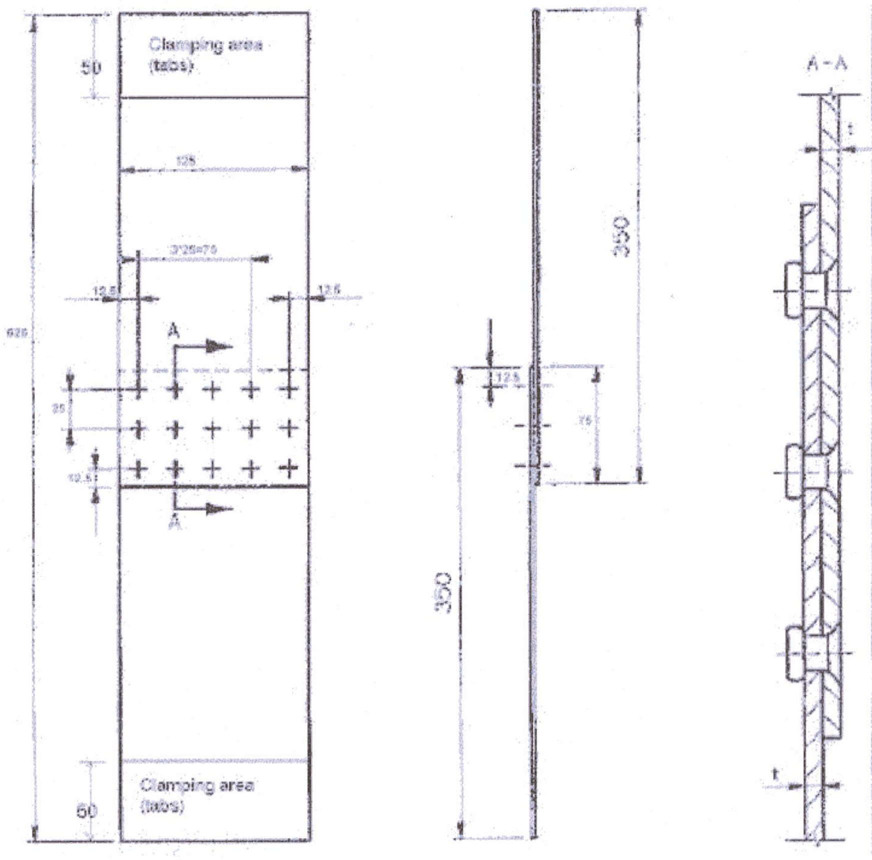


Figure 2 Joint configuration

The test plan comprises of a for fold step procedure

1. First squeeze force cycle. The squeeze force is applied in a single hit squeeze step.
2. Fatigue testing of joint to specified percentage of the fatigue life. The joints are loaded in the 60kN MTS fatigue test machine. Tested will be in lab air at ambient temperatures. A Constant amplitude load will be applied at 10 Hz and a stress ratio of R=0.05.
3. Second squeeze force cycle. The joint will be removed from the test frame and re-squeezed to a new increased force.
4. Fatigue testing of the joint to failure

The squeezing has been done a three different squeeze force levels:

A. Lower bound of industry standard (8.2 kN gives driven head ratio of approximately 1.25),

B. intermediate squeeze force level according to industry standard (12.5 kN with driven head ratio of approximately 1.5).

C. Also a high squeeze force has been applied above industry standard (17.5 kN with driven head ratio of approximately 1.6).

Six different configurations have been evaluated in this program to validate the influence of re-squeezing, see table 1.

Configuration	**1st squeeze force cycle [kN]**	**Fatigue cycles [cycles]**	**[%N1]**	**2nd squeeze force cycle (re-squeeze) [kN]**
1	8.2	Failure	100	-
2	8.2	250,000	50	12.5
3	8.2	400,000	80	12.5
4	8.2	150,000	36	13.25
Configuration	**1st squeeze force cycle [kN]**	**Fatigue cycles [cycles]**	**[%N5]**	**2nd squeeze force cycle (re-squeeze) [kN]**
5	17.5	Failure	100	-
6	8.2	200,000	50	17.5

Table 1 Test configuration

Note:

%N1 equals fatigue life as percentage of cycles to failure from configuration 1

%N5 equals fatigue life as percentage of cycles to failure from configuration 5

With every configuration three specimens are prepared for statistical reference. The joints per configuration are manufactured in one batch. The joint load levels are chosen to have a peak stress equal to 80 MPa (11.6 Ksi). The joint is not supported with anti-buckling guides. The lower stress at 5% (R=0.05) from the maximum stress does not exert compression forces in the joint. The riveted joint is across its entire width free to deform as the eccentricity induces secondary bending. No edge clamps have been used to suppress preferred crack initiation in the sheet at the edge rivet. This preferred crack initiation at the rivet close to the free edge is induced by lateral compression of the sheet edges under tension loading (Poisson's ratio). No interfaying sealant is applied at the mating surfaces of the overlap. The specimen rotating hinge connection with the test frame contributes to homogeneous loading of the joint to prevent preferred edge rivet cracking due to in-plane bending moment.

Fatigue test results with re-squeezed riveted joints

The fatigue test results are given in table 2

Configuration	**1st squeeze force cycle [kN]**	**Fatigue cycles [cycles]**	**[%N1]**	**2nd squeeze force cycle (re-squeeze) [kN]**	**Average fatigue life after 2nd squeeze force cycle Specimen**	**[cycles]**
1	8.2	Failure	100	-	RE01	563,744
					RE02	522,543
					RE03	353,972
					RE04	749,046
					RE09	297,000
					RE10	206,871
					average	**410,698**
2	8.2	250,000	50	12.5	RE05	499,070
					RE07	916,579
					RE08	494,833
					average	**609,439**
3	8.2	400,000	80	12.5	RE06	546,300
					average	**546,300**
4	8.2	150,000	36	13.25	RE11	393,136
					RE12	556,517
					average	**467,747**
Configuration	**1st squeeze force cycle [kN]**	**Fatigue cycles [cycles]**	**[%N5]**	**2nd squeeze force cycle (re-squeeze) [kN]**	**Average fatigue life after 2nd squeeze force cycle**	**[cycles]**
5	17.5	Failure	100	-	RE15	> 1,573,517
					RE16	> 1,612,596
					average	**> 1,592,937**
6	8.2	200,000	50	17.5	RE13	1,978,551
					RE14	> 1,455,453
					average	**> 1,696,900**

Table 2, fatigue test results

Specimens from configuration 1 and 5 are not re-squeezed in a second step. These specimens from configuration 1 and 5 were loaded to failure in the original configuration.

In figure 3 the results are graphically depicted. In the graph the total number of fatigue cycles are shown. For the re-squeezed specimens this implies that the cycles prior to resqueezing is superimposed to the number of cycles ran after re-squeezing. Counting the total number of cycles enables direct comparison with the baseline specimens.

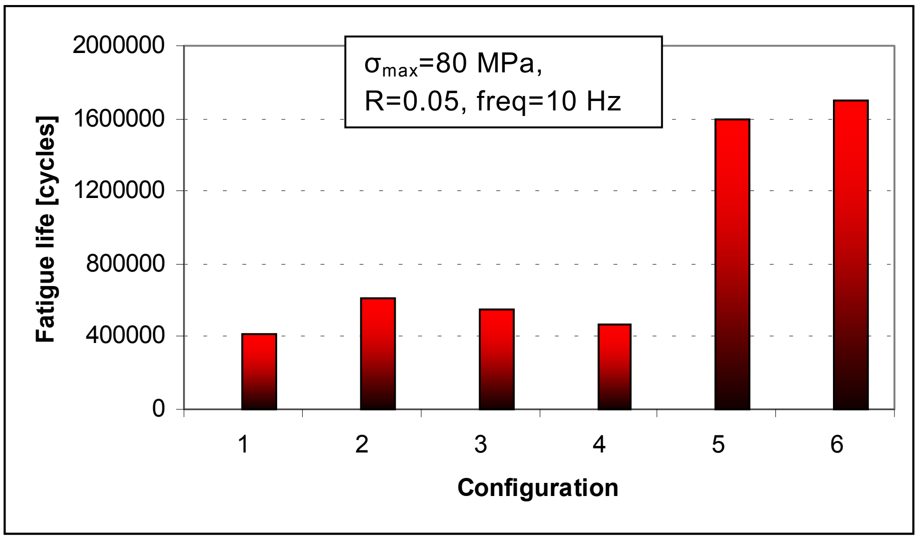
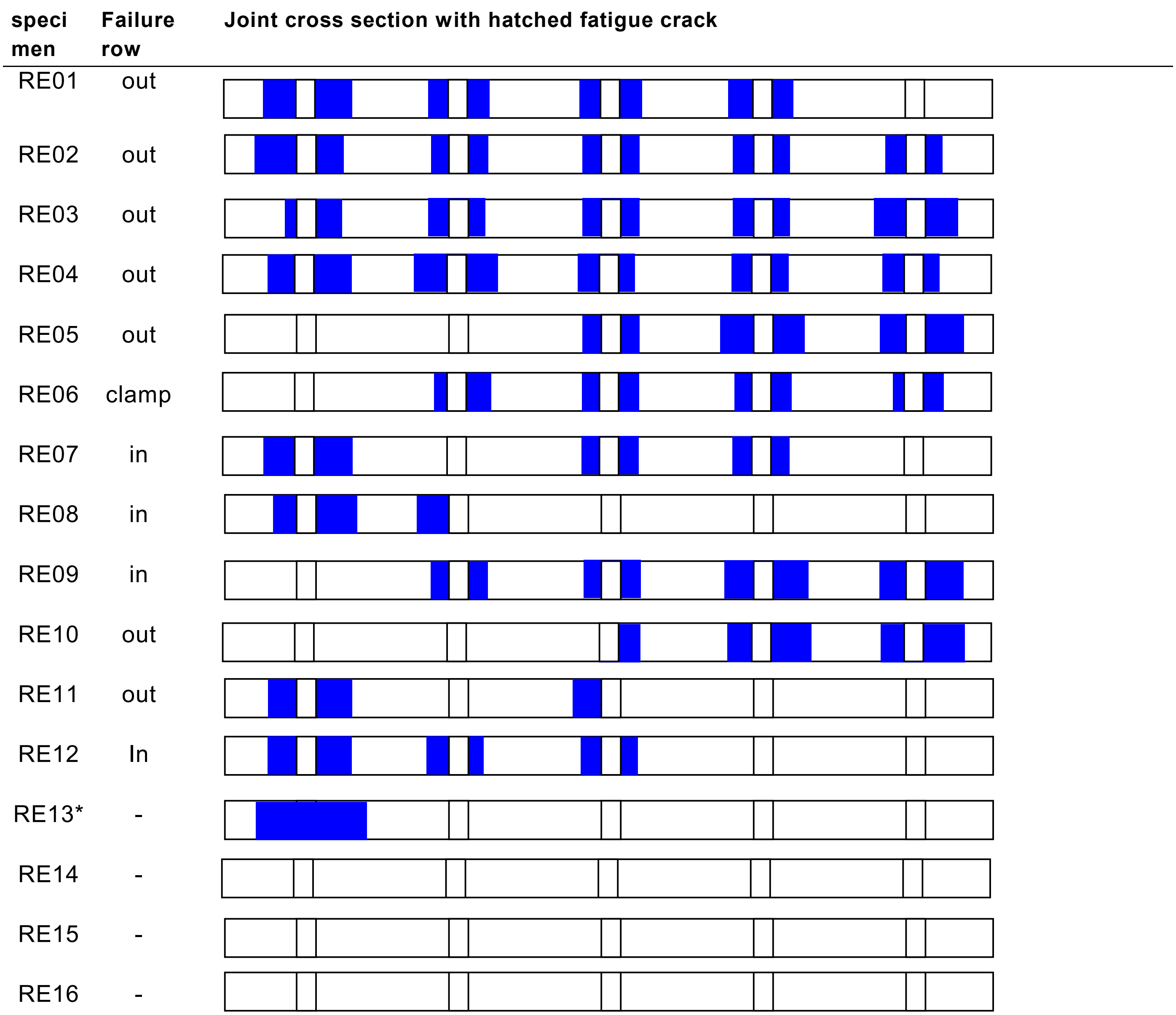


Figure 3 fatigue test results of fatigue life of re-squeezed riveted joint compared to reference joints

Configuration identification with figure 3,

1. *low squeeze force and no re-squeezing*
2. *re-squeeze after 250 kc at intermediate squeeze force*
3. *re-squeeze after 400 kc at intermediate squeeze force*
4. *re-squeeze after 150 kc at intermediate squeeze force*
5. *high squeeze and no re-squeeze force*
6. *re-squeeze after 250kc at high squeeze force*

Specimen fractographic analysis showed that specimens squeezed at a higher squeeze force had a failure shift from the countersunk top row to the inner bottom row. Specimen RE13 re-squeezed at high squeeze force showed failure removed from the hole edge. This failure location is in concurrence with the stress calculations with squeezed riveted joints. The critically loaded location is removed from the hole edge. Also the peak stress is reduced allowing longer fatigue life. The fatigue crack locations for the failed specimens can be determined from figure 4. Most specimens have fatigue cracks in the sheet at multiple rivet locations, implying equally loaded joint and equal fatigue performance of the installed rivets.



*failed outside hole edge
in = inner row non visible and out is outer row with countersunk row

Figure 4, failure locations with observed from fractographic analysis

Conclusions

1. By increasing the squeeze force from the lower industry standard to a optimum squeeze force the fatigue life can be improved with this configuration to more than a factor of 5.
2. Re-squeezing of riveted joints at an arbitrary moment in the fatigue life, read operational aircraft life, is feasible. Up to 80% of the fatigue life re-squeezing can be performed without adversely affecting the joint performance.
3. Re-squeezing from a low industry standard to a intermediate industry standard only has a limited improvement of the fatigue life to a maximum of factor 5. The scatter existing with fatigue life of rivets in geriatric aircraft is too large to have a clear benefit. Rivets should be squeezed at elevated squeeze force magnitudes.
4. Scatter in rivet quality will result to preferred sheet cracking. Re-squeezing rivets will prevent premature cracking.
5. Re-squeezing of riveted joints with initially lower industry standard squeezed rivets results to a more than factor 5 improvement of the fatigue life, as tested with this configuration
6. After 50% of the operational life is spent re-squeezing at optimum squeeze forces (higher bound and above compared to industry standard) does improve the fatigue life with more than a factor of 5. Based on the results from the tested configurations 1 through 4 (see also conclusion 2.) after 80% fatigue life finished this similar improvement factor of 5 for this configuration is anticipated.

Discussion for feasibility of re-squeezing joints with geriatric aircraft

As discussed in the introduction no uniform squeeze force has been applied with manufacturing joints in the past decades. This for reasons hand riveting does not allow this kind of control or squeeze machines used since the nineties have the rivet squeeze force as a derivative from the driven head dimension. This resulted to extensive variation in driven head ratios as long the driven head was within the production standards, which allows extreme change in fatigue life. For some configurations this could imply fatigue life variation with a factor of 10 by comparing low and high squeeze force levels. The aircraft manufactured without the current awareness of the influence of squeeze force are being repaired by

various techniques, like oversized rivet installation up to even re-skinning. Re-squeezing here is understood as life enhancement technique.

Re-squeezing of rivets has been demonstrated to improve the fatigue life of the joint with a factor of 5, despite the joint has serviced for already 50% of its anticipated fatigue life. The initial results demonstrate that re-squeezing can be performed at arbitrary stages of the fatigue life. Mid-life update of aircraft having rivet quality at mean industry standard by re-squeezing seems a valid approach to enhance the fatigue life and reduce the scatter in joint failure tremendously. No corrosion aspects are included with this initial research program. However, the changed failure mechanism with fatigue crack locations emanating away from the hole edge is promising to reduce the effect of corrosion on joint performance.

The (macroscopic) crack free life of riveted joints in monolithic aluminum is considered to be 90% of the joint life. The cracked life therefore of the joint starting with macroscopic crack growth (POD >90%) to final failure is 10% of the joint life. With using this re-squeezing approach it should be determined whether during the entire crack free life this approach can be used. The hour accumulation of the fleet gives sufficient range that aircraft with similar duty cycle (pressure cabin inflation is driving the loads for the cabin, but for wings it can be different) and less load cycles can be selected. With knowing the crack free life of the oldest and most heavily (mechanically and durability wise) loaded aircraft, and using a scatter factor a selection of aircraft can be made with operational lives profiting from this approach. Knowing the relation between squeeze force and joint life a good indication can be acquired by checking the driven head dimensions being the derivative of the squeeze force. Based on this approach the driven heads of early failed joints should be investigated. With the driven heads being on the lower bound of the industry standard for rivet head dimensions the approach as discussed here becomes feasible.

It is understood that this technology can not be used to theoretically infinite aircraft skin life as the test results imply with fatigue lives above 1.5 million cycles (40 commercially aircraft utilization lives). Important aspects like durability and modifications are not included in this initial test program. However, this technology will work to postpone re-skinning of the joint as a direct cost pay-off and indirect cost pay off is the lesser scatter with optimized inspection intervals for the aircraft joints.

Recommendations for design development for re-squeezed riveted joints

For reasons this program can reduce the life cycle cost of the aircraft and with that the cost of ownership a follow-up program is proposed. Aspects like corrosion and re-squeezing with small visible cracks present.

Re-squeezing with small cracks present in the joint will not be an approved airworthiness approach, but will indicate the applicability and safety margins of this approach when performing on a wide scale to aircraft with the opportunity of sometimes missing small cracks. It has to be evaluated if indeed re-squeezing will also favorably affect the fatigue life of a cracked rivet hole as suggested due to plastic deformation at the crack tip due to re-squeezing as was already determined by Schijve being the consequence of the pressure proof test with pressure cabins of serviced Comet Aircraft.

The current experimental program has been performed with non-ice box rivets. No heat treating is required to have the yield stress reduced to have improved formability with lesser load. However, with many aircraft ice-box rivets have been used (2024 alloy). It should be investigated if these rivets can be re-squeezed and have similar beneficial fatigue live enhancements possible as with the here used “soft” rivets. Research performed at Delft University already demonstrated that hard rivets (2024 alloy) can be squeezed without heat treating by using specially shaped bucking bars with cups to prevent excessive expansion.