

FATIGUE OF ALUMINIUM ALLOY JOINTS WITH VARIOUS FASTENER SYSTEMS. HIGH LOAD TRANSFER

1. INTRODUCTION

This Item presents data on the fatigue endurance, secondary bending and load transfer of high load transfer joints. Bending as a consequence of joint geometry is termed secondary bending (this term is defined in Section 3) and is shown to be a factor that has great influence on the fatigue lives of high load transfer joints. In most situations secondary bending will reduce the fatigue endurance of a joint and this reduction can be significant when high values of secondary bending ratio apply. Two further factors for which data are presented are fastener fit and hole preparation. Both of these can have significant effects on the fatigue endurance of high load transfer joints.

Endurance curves of the total peak stress plotted against endurance (in FALSTAFF* flights) are provided. These allow estimation of fatigue endurance for high load transfer joints. The total peak stress is the sum of the peak stress due to the axial load and the peak stress due to the secondary bending in the joint. The peak axial stress is taken as the net peak stress in the fighter aircraft loading sequence, FALSTAFF. The stress due to secondary bending is taken to be the product of the peak axial stress and the average secondary bending ratio.

The data in this Item are derived from tests using proprietary fasteners. These fasteners were fitted according to standard practice. In all the tests failure occurred in the joint itself; there were no fastener failures.

Data are presented for five joint types in all of which secondary bending occurred under load. For two of these joint types there is a double shear equivalent joint for which data are also presented. These equivalent joints are subject to negligible secondary bending and they therefore provide a basis upon which the influence of secondary bending can be assessed. The data show that while cold expansion of the holes and the use of interference fit fasteners can give large increases in fatigue endurance, these increases can be completely negated by high secondary bending.

* Fighter Aircraft Loading STAndard For Fatigue evaluation, see Data Item No. 97018, "Standard fatigue loading sequences".

2. NOTATION

Both SI and British units are quoted.

c	clearance, $d_h - d_f$	m	in
d_f, d_h	fastener and hole diameter, respectively	m	in
ϵ_a, ϵ_b	axial and bending strain, respectively (see Sketch 7.6a)		
f_p	0.2 per cent proof stress of material	N/m ²	lbf/in ²
f_t	tensile strength of material	N/m ²	lbf/in ²
i	interference, $d_f - d_h$	m	in
r_{sb}	secondary bending ratio, $r_{sb} = \frac{\epsilon_b}{\epsilon_a}$		
S_{max}	peak (level 32) stress in FALSTAFF sequence based on net cross-sectional area	N/m ²	lbf/in ²
S_T	total peak stress	N/m ²	lbf/in ²
	$S_T = (1 + r_{sb}) S_{max}$		

3. HIGH LOAD TRANSFER JOINTS

It is convenient to define bolted structural joints as being of low, medium or high load transfer depending upon the fraction of the load that is transferred between members at the first row of fasteners. Low load transfer joints are usually defined as those that transfer less than 10 per cent of their load between members. The fatigue strength of low load transfer joints is the subject of Data Item No. 89046^{*}. Medium load transfer joints transfer between 10 and 30 per cent of their load between members. The fatigue strength of medium load transfer joints is the subject of Data Item No. 90009[†]. Usually, if a joint transfers more than 30 per cent of its load between members, it is considered to be a high load transfer joint. Many joints in aircraft wings are either medium or high load transfer joints.

This Item presents the results of strain measurement and fatigue tests on a variety of high load transfer joints. These joints are illustrated in Sketches 7.1 to 7.5. Apart from the double shear equivalent joints, all the joints experience secondary bending under the application of an axial load. Under axial loading, a bending moment is established in the region of the fasteners due to the asymmetric distribution of the load and this is termed secondary bending. The secondary bending ratio, r_{sb} , is defined as the ratio of the measured bending strain to the measured direct strain. The secondary bending ratios in these tests were in the range 0 to 1.55. The methods by which the secondary bending ratio and load transfer were measured are illustrated in Sketch 7.6. The values of the secondary bending ratio and load transfer are presented as functions of the applied load. The secondary bending ratio for a particular joint also varies with fastener type, size and fit, and other factors. The double shear equivalent joints, by virtue of their symmetry, have been assumed to have negligible secondary bending. For this reason no measurements of their secondary bending ratios were made.

* Data Item No. 89046 "Fatigue of aluminium alloy joints with various fastener systems. Low load transfer".

† Data Item No. 90009 "Fatigue of aluminium alloy joints with various fastener systems. Medium load transfer".

The C-type joint (Sketch 7.1) is a single lap joint with three fastener rows and is subject to high secondary bending. The double shear equivalent of the C-type is the C1-type (Sketch 7.1) which has two splice plates joining the two main plates. Owing to its symmetry its secondary bending ratio should be negligible. The 1½ Dogbone joint (Sketch 7.2) is intended to simulate the load transfer and secondary bending characteristics of runouts of stiffeners attached to the skins of aircraft wings. Load transfer in the 1½ Dogbone joint is dependent to a large extent on the fastener system fitted. It also has a low compression limit load of approximately 10 kN (2200 lbf) beyond which buckling is likely to occur. In the 1½ Dogbone double shear equivalent (Sketch 7.2) a third plate is used to give symmetry and thus minimise secondary bending. The Q-joint (Sketch 7.3) is based on a single lap joint but the addition of a third plate reduces bending by increasing lateral stiffness. Also, the double shear connection at the controlling section helps ensure that fatigue failure occurs at the test section. The X-joint (Sketch 7.4) comprises a system of three doubler plates in single shear arranged to provide load transfer and different secondary bending characteristics from the C-type joint. The U-joint (Sketch 7.5) is a derivative of the X-joint. It is essentially a single column X-joint with a U-channel splice plate instead of the flat plate used in the X-joint. The U-joint represents a skin joint at a relatively stiff structural member.

4. TEST DETAILS

4.1 Testing Procedure and Specimen Preparation

All the endurance tests were carried out with the FALSTAFF loading sequence (References 5 and 6). The quoted values of peak stress are the maximum values of stress in the FALSTAFF sequence (level 32). The stresses are based on the net cross-sectional area of the particular joint at the first row of fasteners.

The measurements of secondary bending ratio and load transfer were made under static loading. The joints were subjected to a large number of loading cycles before the measurements were taken, to ensure that the strain response to load had stabilised. These measurements were made using strain gauges as shown in Sketch 7.6.

In the majority of the tests, 6.35 mm (0.25 in) diameter fasteners were used. In the controlling section of the Q-joint (see Sketch 7.3) a 4.76 mm (0.1875 in) diameter fastener was used as the datum. However, in the tests on the Q-joint with the Hi-lok fastener systems, fasteners of both 6.35 mm (0.25 in) and 4.76 mm (0.1875 in) diameter were fitted in the controlling section of the joint. The results from these particular tests are separated in the presentation here according to the size of the Hi-lok fastener fitted in the controlling section.

All the joints except the C and C1 types were manufactured from 7050-T76. The C and C1 types were manufactured from 7050-T7651. Data are given for these materials in Table 7.1. The general procedure for producing the fastener holes was: pilot drill, ream, cold expand, ream, deburr, measure the hole diameter, and countersink. The cold expansion and second reaming operations were only employed for those fastener systems with cold expanded holes (see Sections 4.3 and 4.4). The joint plates were treated with epoxy primer and all the joints except the C and C1 types were assembled with interlay sealant PR1431G. No sealant was used in the assembly of the C and C1 type joints.

4.2 Introduction to Fastener Systems

The two fastener types for which data are presented are Hi-lok and Hi-tigue and these are illustrated in Sketch 7.7. These fasteners are used in four fastener systems which are described in this section. The values of interference or clearance are given in Table 7.2. The countersinks were of included angle 100° and depth 1.52 mm (0.060 in).

4.3 Hi-lok (Sketch 7.7a)

4.3.1 Hi-lok (clearance)

The Hi-lok fastener consists of two parts, a close tolerance pin with a threaded end, and a threaded collar. This collar contains a hexagonal driving portion which shears off at a groove at a consistent preload. In some tests conventional nuts were used because these allow for the standard industrial practice of retorquing during assembly. In this system the Hi-lok fasteners are fitted in a clearance fit drilled and reamed hole.

4.3.2 Hi-lok (CX + interference)

The Hi-lok fasteners are identical to those described in Section 4.3.1 but the hole preparation and fastener fit are different. The hole is reamed and then cold expanded using the FTI CX (cold expansion) split sleeve process^{*}. In this process a split sleeve is inserted into the hole and an oversize mandrel is pulled through it. This cold-expands the material around the hole to give a permanent set and introduces a compressive stress in the material around the hole. The sleeve is discarded and the hole is reamed to size. Countersinks are drilled if required and the hole is deburred.

4.4 Hi-tigue (Sketch 7.7b)

4.4.1 Hi-tigue (interference)

This fastener consists of a threaded pin and a nut. The threaded end of the pin carries a small raised bead which expands and burnishes the hole as the pin is inserted. Tolerances and dimensions are such that when the pin is fully inserted it has a high interference fit. The nut is then fitted and torque applied.

4.4.2 Hi-tigue (CX + interference)

The Hi-tigue fasteners are identical to those described in Section 4.4.1. The fastener fit is also the same but the hole is cold-expanded using the FTI CX split sleeve process (see Section 4.3.2) prior to fastener installation.

5. ENDURANCE DATA

5.1 Guide to Data Presented

Tables 7.3 to 7.6 provide a summary of the data for the joints. The values of secondary bending ratio given in these tables are average values and the endurance values quoted are log mean values of from three to five individual test results. The individual test results are shown in Figures 1 to 4. Tables 7.7 to 7.15 present the values of secondary bending and load transfer as functions of applied load. From the limited data available on the secondary bending ratio of the X-joint, an average value of 0.8 was taken for the purposes of plotting the endurance curves (Reference 7).

5.2 Influence of Fastener Systems on Endurance

Figure 1 presents graphically the endurances of the joints fitted with the different fastener systems. The log mean endurances are detailed in Tables 7.3 to 7.6. It is clear from these data that the Hi-tigue fastener systems tend to produce endurance values that are significantly longer than those obtained with the Hi-lok fastener systems. This can be attributed to the high interference fits of both Hi-tigue systems.

^{*} This process was originally known as the Boeing split sleeve process. It is now marketed by Fatigue Technology Inc.

Results suggest that cold-expansion of the holes in high load transfer joints may also extend the fatigue life. This is shown by the longer endurance values of those joints fitted with the Hi-tigue (CX + interference) system compared with the endurance values of the same joints fitted with the Hi-tigue (interference) system. The combination of an interference fit in a cold-expanded hole may also give significant increases in endurance compared to those obtained with a clearance fit in a plain hole. This can be seen by comparing the endurance values of joints fitted with the Hi-lok (CX + interference) system with those of the same joints fitted with the Hi-lok (clearance) system.

In high load transfer joints with high secondary bending ratios, the increases in endurance obtained by the use of interference fits and/or cold-expanded holes are likely to be significantly less than the increases that would be obtained if a lower secondary bending ratio applied. This is shown by comparing the data for the C-type joint with that of the C1-type joint and the data for the 1½ Dogbone with that of the 1½ Dogbone double-shear equivalent. Also, if the introduction of an interference fit with or without a cold-expanded hole causes an increase in the secondary bending ratio of the joint, the increase in endurance obtained may be less than would be obtained had there been no increase in secondary bending. This is shown by the endurance data for the 1½ Dogbone and the 1½ Dogbone double shear joints fitted with the Hi-lok (clearance) and the Hi-lok (CX + interference) systems.

5.3 Endurance Curves

It is not possible to quantify the exact effects of secondary bending on the fatigue endurance of joints. However, the endurance curves presented in Figures 2 to 5 indicate the trends of these effects. The curves plot total peak stress, S_T , against endurance (in FALSTAFF flights). The endurance curves are for joints with average secondary bending ratios in the range 0 to 1.55. For the purpose of calculating the total peak stress, S_T , the average value of secondary bending ratio is used. These curves should be used for estimating the endurance of joints similar in size and form to those investigated in this Item. The use of these curves to estimate the endurance of joints that differ significantly from the joints presented here should be undertaken with caution. Changes in the geometry or scale of joints are likely to produce, of themselves, significant changes in endurance. It is important to note that in order to use these curves to estimate the endurance of a particular joint, a value for the secondary bending ratio of the joint must be used.

There are three curves presented. The first (Figure 2) is based solely on the data for joints with the Hi-lok (clearance) system fitted. The second curve (Figure 3) is based on the data that are for joints with the Hi-lok (CX + interference) system. The third endurance curve (Figure 4) is based on the data for the joints fitted with either of the Hi-tigue fastener systems. Figure 5 presents these three endurance curves together.

6. DERIVATION AND REFERENCES

6.1 Derivation

This section lists selected sources that assisted in the preparation of this Data Item.

1. BIRKS, A. Development of mechanical fastening systems for aluminium alloy aerospace structures. *Aluminium Industry* – Vol. 1, No. 1, September 1982.
2. van der LINDEN, H.H. Fatigue rated fastener systems. AGARD Report No. 721, 1985.
3. SIMPSON, A. The evaluation of fatigue resistant fasteners, stage 4 – The effects of joint parameters. British Aerospace Report No. BAe-MSM-R-GEN-0519, 1987.
4. COOK, R. Standard fatigue test specimens for fastener evaluation. AGARD-ograph No. 309, 1987.

6.2 References

The references given are recommended sources of information supplementary to that in this Item.

5. van DIJK, G.M.
de JONGE, J.B. Introduction to a fighter aircraft loading standard for fatigue evaluation, "FALSTAFF". NLR MP 75017 U, 1975.
6. – Description of a fighter aircraft loading standard for fatigue evaluation, FALSTAFF. F+W (Switzerland), LBF (Germany), NLR (The Netherlands) and IABG (Germany), March 1976.
7. PALMBERG, B. Fatigue life and fastener flexibility of single shear joints with countersunk fasteners. FFA TN 1986-01, 1986.

7. TABLES

TABLE 7.1 JOINT MATERIALS DATA

<i>Designation</i> [*]	<i>Composition</i>	<i>Heat treatment</i>	<i>f_t</i>	<i>f_p</i>
			MN/m ² (lbf/in ²)	MN/m ² (lbf/in ²)
7050-T76	6.2Zn - 2.3Cr - 2.2Mg - 0.12Zr	Solution treated and artificially aged to provide highest available strength with high resistance to exfoliation corrosion and some improvement in resistance to stress-corrosion cracking.	566 (82 100)	532 (77 200)
7050-T7651		Solution treated and stress relieved by stretching to produce a permanent set of between 1½ and 3 per cent and artificially aged to give improved resistance to exfoliation and stress-corrosion cracking.	570 (82 700)	533 (77 300)

* International alloy designations and chemical composition limits administered by Aluminum Association Inc., USA.



TABLE 7.2 DETAILS OF FASTENER SYSTEMS

<i>Fastener system</i>	<i>Nominal fastener diameter</i>	<i>Range of measured fastener diameters</i>	<i>Specified fit</i>	<i>Range of measured fits</i>	<i>Fastener system identification numbers</i>
Hi-lok (clearance)	6.35 mm (0.25 in)	6.310 – 6.330 mm (0.248 – 0.2492 in)	$c = 10 - 30 \mu\text{m}$ ($3.9 \times 10^{-4} - 12 \times 10^{-4}$ in)	$c = 38$ to $i = 9 \mu\text{m}$ (15×10^{-4} to 3.5×10^{-4} in)	HL 19 PB-8-7 with HL-70-8 collar [*]
Hi-lok (CX + interference)	6.35 mm (0.25 in)	6.324 – 6.330 mm (0.2490 – 0.2492 in)	$i = 15 - 35 \mu\text{m}$ ($5.9 \times 10^{-4} - 14 \times 10^{-4}$ in)	$c = 9$ to $i = 18 \mu\text{m}$ (3.5×10^{-4} to 7.1×10^{-4} in)	HL 1 9PB-8-7 with HL-70-8 collar [*]
Hi-tigue (interference)	6.35 mm (0.25 in)	6.325 mm [†] (0.2490 in)	$i = 60 - 80 \mu\text{m}$ ($24 \times 10^{-4} - 31 \times 10^{-4}$ in)	$c = 67$ to $i = 100 \mu\text{m}$ (26×10^{-4} to 39×10^{-4} in)	HLT 319-8-7 with H 541 L-4F nut [‡]
Hi-tigue (CX + interference)	6.35 mm (0.25 in)	6.325 mm [†] (0.2490 in)	$i = 60 - 80 \mu\text{m}$ ($24 \times 10^{-4} - 31 \times 10^{-4}$ in)	$c = 68$ to $i = 105 \mu\text{m}$ (27×10^{-4} to 41×10^{-4} in)	HLT 319-8-7 with H 541 L-4F nut [‡]

^{*} The 4.76 mm (0.187 in) Hi-lok fasteners used in the controlling section of some of the Q-joints are designated HL 19 PB-6-9 and were used with an HL 70-6 collar.

[†] The Hi-tigue fasteners were from a single batch.

[‡] The Hi-tigue fasteners used in the controlling section of the Q-joint are designated HLT 319-8-9 and were used with an H 541 L-4F nut.

TABLE 7.3 SUMMARY OF DATA FOR C-TYPE AND C1-TYPE JOINTS

Joint type	Fastener type	Fastener fit	Hole treatment	Average secondary bending ratio	Peak FALSTAFF stress, S_{max}	Log mean endurance (FALSTAFF flights)
C-type	Hi-lok	Clearance	Ream	1.32	204 MN/m ² (29 400 lbf/in ²)	9860
					272 MN/m ² (39 500 lbf/in ²)	3050
		Interference	Ream + cold-expand	1.55	204 MN/m ² (29 400 lbf/in ²)	10 410
					272 MN/m ² (39 500 lbf/in ²)	3840
C1-type	Hi-lok	Clearance	Ream	0	204 MN/m ² (29 400 lbf/in ²)	106 490*
					272 MN/m ² (39 500 lbf/in ²)	25 940
					340 MN/m ² (49 300 lbf/in ²)	9613
		Interference	Ream + cold-expand	0	272 MN/m ² (39 500 lbf/in ²)	65 450
					340 MN/m ² (49 300 lbf/in ²)	28 430

* One of the specimens was unbroken.

TABLE 7.4 SUMMARY OF DATA FOR 1½ DOGBONE AND 1½ DOGBONE DOUBLE SHEAR JOINTS

Joint type	Fastener type	Fastener fit	Hole treatment	Average secondary bending ratio	Peak FALSTAFF stress, S_{max}	Log mean endurance (FALSTAFF flights)
1½ Dogbone	Hi-lok	Clearance	Ream	0.035	268 MN/m ² (38 900 lbf/in ²)	44 839
					335 MN/m ² (48 600 lbf/in ²)	16 635
		Interference	Ream + cold-expand	0.14	268 MN/m ² (38 900 lbf/in ²)	39 722
					335 MN/m ² (48 600 lbf/in ²)	16 045
	Hi-tigue	Interference	Ream	0.37	268 MN/m ² (38 900 lbf/in ²)	33 542
					335 MN/m ² (48 600 lbf/in ²)	12 899
		Interference	Ream + cold-expand	0.42	268 MN/m ² (38 900 lbf/in ²)	39 280
					335 MN/m ² (48 600 lbf/in ²)	16 358
1½ Dogbone double shear equivalent	Hi-lok	Clearance	Ream	0	268 MN/m ² (38 900 lbf/in ²)	33 880
					335 MN/m ² (48 600 lbf/in ²)	15 440
		Interference	Ream + cold-expand	0	268 MN/m ² (38 900 lbf/in ²)	87 266*
					335 MN/m ² (48 600 lbf/in ²)	83 688

* One of the specimens was unbroken.

TABLE 7.5 SUMMARY OF DATA FOR Q-TYPE JOINTS

Joint type	Fastener type	Fastener fit	Hole treatment	Average secondary bending ratio	Peak FALSTAFF stress, S_{max}	Log mean endurance (FALSTAFF flights)
Q-type	Hi-lok (4.76 mm (0.1875 in) diameter Hi-lok in controlling section)	Clearance	Ream	0.35	280 MN/m ² (40 600 lbf/in ²)	13 280
					350 MN/m ² (50 800 lbf/in ²)	3639
		Interference	Ream + cold-expand	0.36	280 MN/m ² (40 600 lbf/in ²)	13 337
					350 MN/m ² (50 800 lbf/in ²)	3905
	Hi-lok (6.35 mm (0.25 in) diameter Hi-lok in controlling section)	Clearance	Ream	0.37*	280 MN/m ² (40 600 lbf/in ²)	11 571
					350 MN/m ² (50 800 lbf/in ²)	6063
		Interference	Ream + cold-expand	0.39	280 MN/m ² (40 600 lbf/in ²)	11 195
					350 MN/m ² (50 800 lbf/in ²)	5147
	Hi-tigue	Interference	Ream	0.25	280 MN/m ² (40 600 lbf/in ²)	32 572
					350 MN/m ² (50 800 lbf/in ²)	14 448
		Interference	Ream + cold-expand	0.28	280 MN/m ² (40 600 lbf/in ²)	56 504
					350 MN/m ² (50 800 lbf/in ²)	18 364

* This is an estimated value as measurements were not made for this case.