

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

1. INTRODUCTION

This Data Item presents the results of over 900 fatigue tests designed to show the influence of various hole preparations and fastener types on the fatigue strength of low load transfer bolted joints. For a given loading careful choice of these can lead to significant increases in joint fatigue endurance.

The major factors shown to affect fatigue endurance are

- (a) the interference fit of the fastener in the hole,
- (b) interfay treatment
- and (c) fastener head design.

Other factors that can influence fatigue strength but that were not specifically investigated are

- (i) the degree of cold expansion of the material surrounding the hole
- and (ii) the fastener pre-tension.

In the majority of the available tests proprietary fasteners were used and these were fitted in accordance with usual practice. In all of the tests fatigue failures occurred in the joint material; none of the fasteners failed in fatigue.

2. NOTATION

Both SI and British units are quoted.

c	$d_h - d_f$ clearance	m	in
d_f, d_h	fastener and hole diameters respectively	m	in
e_i, e_c	percentage interference or clearance respectively between hole and fastener $e_i = (i/d_h) \times 100$ $e_c = (c/d_h) \times 100$		
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	$d_f - d_h$ interference	m	in
N	endurance in cycles		
N_f	endurance in flights		
S_a	alternating stress based on gross cross-sectional area	N/m ²	lbf/in ²

S_{1g}	stress level in 1g level flight based on gross cross-sectional area	N/m^2	lbf/in^2
S_m	mean stress based on gross cross-sectional area	N/m^2	lbf/in^2
S_{max}	peak stress in tests based on gross cross-sectional area	N/m^2	lbf/in^2

3. DEFINITION OF LOW LOAD TRANSFER JOINTS

Structural joints in which members are fastened together can usually be classified as being of low, medium or high load transfer, depending on the fraction of the load transferred from one member to another at the fastener under consideration. Low load transfer joints are defined as those that have a load transfer between the members of less than 10 per cent of the total axial load. Medium load transfer joints have a load transfer of between 10 and 30 per cent and high load transfer joints have a load transfer of greater than 30 per cent. An example of low load transfer joints on an aircraft wing is the skin-to-stiffener connection. Medium and high load transfer are mainly confined to the spanwise and chordwise joints.

Sketch 8.1 shows a type of test specimen used to examine the fatigue strength of low load transfer joints in aircraft structures. Under the application of an axial load to such a test specimen, the different stiffnesses of the joined members along adjacent parts of their length cause unequal load distribution between them and therefore some load passes from one member to the other via the fasteners. Additionally, the unequal load distribution causes the specimens to bend and this is termed secondary bending. It is defined (see Derivation 1) as the ratio of the measured bending strain to the measured direct strain in one of the members in the region of a fastener. For the low load transfer joint data presented in this Data Item, where the secondary bending ratio was measured it was found to be in the range 0.1 to 0.25 as determined from strain gauge measurements. The resulting detail stress distribution within the joints in the region around the fastener holes where fatigue cracks are initiated and grow is not amenable to calculation. Therefore, the data are presented and analysed in terms of the stress resulting only from the direct load divided by the gross cross-sectional area of the specimen (see Table 8.1).

Secondary bending does not refer to moments applied directly to the joint. If a joint is subject to an applied (primary) moment in addition to an axial load and consequent secondary bending, then the applied (primary) and the developed secondary moments can either add to or subtract from one another at the fastener location, according to joint geometry and applied moment direction. Consequently, the fatigue strength of a joint loaded in such a way can be significantly different from that of an axially loaded joint. The information given in this Data Item only refers to joints under axial loading.

4. DETAILS OF THE TESTS AND TEST SPECIMENS

The specimen used to represent low load transfer joints is illustrated in Sketch 8.1 and the accompanying table (Table 8.1) provides the dimensions of the four different geometries for which test results are available. Table 8.2 details the joint materials and Section 4.1 describes the fastener systems.

In order to allow comparison among the various fastener and hole preparation systems, a set of datum joints has been selected. Details of the datum joints including the hole preparation and fastener type and fit, are given in Table 8.3. Table 8.4 provides an index to Tables 8.5 to 8.9 and to the figures, listing the loadings and the variables investigated for each joint material.

The majority of the tests were conducted under the FALSTAFF loading sequence. Wherever this sequence was used the stresses stated relate to the level 32 value, which is the peak stress in the loading sequence. The FALSTAFF sequence is detailed fully in Data Item No. 97018* and in Reference 3. The TWIST and MiniTWIST loading sequences were used in a few cases and the stresses given for these sequences relate to the 1g level flight value. Details of these sequences are also given in Data Item No. 97018 and in Derivation 1. All the tests were made under axially applied loading.

4.1 Description of Fastener Systems

The fasteners used are described below and are illustrated in Sketches 8.2a to 8.2e. The interference or clearance values for particular tests are given in the tables. Unless otherwise stated the fastener heads were flush. Both countersinks were on one side of the specimen and were of included angle 100° and 1.52 mm (0.060 in) deep. Where protruding head fasteners were fitted, plain holes without countersinks were used.

4.1.1 Hi-lok (Sketch 8.2a)

4.1.1.1 Hi-lok (Clearance)

In this system the Hi-lok fasteners are assembled into a clearance fit drilled and reamed hole. Each fastener consists of two parts, a close tolerance threaded pin, which contains a hexagonal recess in the threaded end, and a threaded collar. The collar includes a hexagonal driving portion that shears off at a groove at a predetermined torque, thus providing consistent preload. In a number of tests a more conventional nut was used. This is because conventional nuts permit the widespread industrial practice of retorquing during assembly.

4.1.1.2 Hi-lok (CX cold expanded + interference)

In this system the fasteners are identical to those of Section 4.1.1.1 above. The hole is reamed and is then cold expanded using the FTI[†] CX split sleeve process. In this process, a mandrel carrying the split sleeve is inserted into the hole. The mandrel is then pulled through the sleeve thereby expanding the hole. The sleeve is discarded. The hole is reamed to size, countersinks are drilled if required, and deburred.

4.1.2 Hi-tigue (interference) (Sketch 8.2b)

The pin is designed to be an interference fit in the prepared (reamed) and countersunk hole. The threaded end of the pin shank carries a small raised bead. On insertion the bead allows the pin to be driven easily into the reamed hole expanding and burnishing the hole as it travels down it, and achieving the desired interference fit. The nut is then assembled and torque tightened. The value used for 6.35mm (0.25in) diameter fasteners was between 10.2 and 11.3 N m (90 to 100 lbf in).

4.1.3 Huck EXL (cold expanded + interference) (Sketch 8.2c)

This is a cold expanded hole plus interference fit fastener system in which the fastener is not threaded but has a series of parallel circumferential grooves at the end of the shank. The shank also has an extension that carries a raised spherical portion that is designed to cold expand and burnish the bore of the prepared and countersunk hole as it is drawn through. When the pin is in position a collar is placed over the end. The collar is swaged into the locking grooves on the shank whilst the extension is gripped and pulled by a special tool until it separates from the installed pin beyond the collar.

In place of the shank extension a separate mandrel may be used to cold expand the hole. The bolt is then

* Data Item No. 97018 "Standard fatigue loading sequences".

† FTI is Fatigue Technology Incorporated.

inserted in a separate assembly operation. This method of cold expanding the hole was used in Derivation 2.

4.1.4 Taper-lok (interference) (Sketch 8.2d)

This consists of a tapered shank bolt with a threaded end and a washer and nut assembly. The hole is tapered to match the bolt and requires careful preparation using special tools and gauges. The interference achieved is directly proportional to the protrusion of the bolt from the hole before it is pulled into the hole. This is measured using a special gauge and the hole bore is controlled in manufacture to ensure that the required protrusion limits are met. The bolt is then pulled into the tapered hole until the head is fully seated using a prescribed torque applied to the nut to avoid over tightening and consequent head distortion.

4.1.5 Huck crimp (clearance) (Sketch 8.2e)

This consists of a standard threaded bolt and a special design free-running twelve point nut. The nut is torqued up and then locked by a special tool which crimps (permanently deforms) part of the nut body onto the bolt thread. After crimping the deformation is checked using a special gauge.

5. PRESENTATION OF ENDURANCE DATA

Constant amplitude data are presented as $S-N$ curves in Figures 1a, 1b, 1c, and 1d for joints in 7010-T7651 for endurances of between 2×10^3 and 10^7 cycles. Figures 2 and 3 present $S-N$ curves for 7050-T76 and 2024-T3 respectively subject to FALSTAFF loading for between 4×10^2 and 10^5 flights. The majority of the data are presented in Tables 8.5 to 8.9 inclusive. Since tests were only conducted at 2 or 3 stress levels, the tables present the endurances, in flights, as bar charts on a logarithmic grid. Where tests have been conducted with one variable altered from the datum value the bar chart also shows the datum joint endurances as dashed bars. Notes in the following sections detail the changes from the datum joints investigated and comment on their influence on endurance. Each set of tests carries a reference number. Where individual tests are referred to in the text this reference number is composed of the number of the table in which it appears plus its number in that table.

6. DISCUSSION OF THE DATA

The primary factors influencing the endurance of any given low load transfer joints are the type and magnitude of the applied fatigue loading and the amount of load transferred through the fasteners. As has been previously noted the secondary bending ratio has been kept below 0.25 (Derivations 1 and 2). Thus, for a given loading, the factors influencing fatigue strength, and that are normally open to selection, are hole preparation, fastener type and fit and the interfay treatment. These factors are discussed in the following sections.

Note that the peak stress levels for the tests were in the region of the material proof stresses and will therefore modify the stresses within the joint.

6.1 Constant Amplitude Loading (Figures 1a, 1b, 1c and 1d)

Figures 1a and 1b present curves of alternating stress, S_a , against endurance, N , for datum joints at the mean stress levels of 56 and 93 MN/m² (8120 and 13 500 lbf/in²) respectively. Figure 1c summarises Figures 1a and 1b by presenting only the curves from those figures. Figure 1d represents the data of Figure 1c in terms of S_{max} . This is to allow comparison with data for variable amplitude loading which are also presented in terms of S_{max} . For both mean stress levels Figure 1d shows that at the higher values of S_{max} the clearance fit fastener system gives much shorter endurance than those achieved by cold expansion and/or interference fit fasteners. However, the fatigue limits for a given mean stress level are relatively close. For example at $S_m = 56$ MN/m² the fatigue limit for the Hi-lok (clearance) and the Huck EXL fasteners are 85 and 88 MN/m² (12 300 and 12 800 lbf/in²) respectively. Thus, the benefits of cold expansion and/or interference fit shown at higher values of S_{max} are not maintained near the fatigue limit.

The three datum interference fit fasteners all give similar endurance at high values of S_{max} . For all values of S_{max} the Hi-tigue fastener gives longer endurance than the other systems but not by an appreciable margin.

6.2 FALSTAFF Loading for a Range of Values of S_{max} (Figures 2 and 3)

Figure 2 for joints in 7050-T76 shows that the systems using Hi-lok fasteners exhibit similar behaviour under FALSTAFF loading to that under constant amplitude loading. That is, significant benefit is achieved from cold expansion and interference over clearance at higher values of S_{max} but no significant benefit at S_{max} values near to the fatigue limit. The data for Lockbolts (SALP*) are for two values of interference fit and show that the higher value gives a marginal improvement in endurance over the lower value.

Figure 3 for joints in 2024-T3 shows marginal improvement in endurance from increased interference. The curves are close at both ends and are broadly in agreement with the conclusions noted for Figure 1d for constant amplitude loading.

6.3 Comparison of Fastener Systems. Datum Joints under FALSTAFF loading (Tables 8.5, 8.13, 8.17 and 8.19)

Tables 8.5, 8.13, 8.17 and 8.19 provide data for the datum joints of Table 8.3 in 7010-T7651, 2024-T351, 7475-T7351 and 2014-T651 respectively. In all cases the clearance fit assemblies had significantly lower endurance than the cold expansion and/or interference fit assemblies. For any of the alloys at the lower stress level of $S_{max} = 164$ MN/m² (23 800 lbf/in²) the differences among the three cold expansion and/or interference fit fastener systems were not significant. Similar results are apparent at the higher peak stress of 206 MN/m² (29 900 lbf/in²) except for the 2024-T351 plate data recorded in Table 8.13. Here the Hi-lok (cold expansion + interference) systems have distinctly lower endurance than the Hi-tigue or Huck EXL systems tested. Note that the data are for only two stress levels and that at even lower stress levels the differences between cold expanded and/or interference fit and clearance fit systems may be less (see Section 6.2).

* SALP Shear, pull type, lockbolt, protruding head.

6.4 Effect of Initial Corner Cracks. Datum Joints under FALSTAFF loading (Tables 8.11, 8.15, 8.18 and 8.20)

Specimens containing a small corner crack in a plane transverse to the applied loading were tested. These were designed to investigate the case of a repaired fastener assembly where the hole bore is drilled out, but not sufficiently to eliminate an existing crack. Alocromed non-countersunk members were manufactured with corner fatigue cracks of lengths between 0.75 and 1.25 mm (0.030 and 0.049 in) when measured along the surface of the plates from the hole bore. The actual shape of the initial crack front was found to be either elliptic or to be composed of two different sized overlapping ellipses. The major axes of the ellipses were always down the hole bore. The joints were assembled with the crack at the joint interface.

The tables show the endurances obtained and compare them with the endurances for uncracked joints. Note that the scatter for pre-cracked joints is generally larger than that for uncracked joints. The following table summarises the relative fatigue endurances for the four materials and the four datum fasteners found from Tables 8.11, 8.15, 8.18 and 8.20. The table indicates the logarithmic mean endurance of pre-cracked joints in relation to that of uncracked joints.

<i>Material</i>	<i>Hi-lok (clearance)</i>	<i>Hi-lok (CX cold expanded + interference)</i>	<i>Hi-tigue (interference)</i>	<i>Huck EXL (cold expanded + interference)</i>
7010-T7651	lower	marginally higher	marginally higher	similar
2024-T3	marginally lower	marginally higher	similar	marginally lower
7475-T351	lower	similar	lower	lower
2014-T651	lower	similar	lower	lower

In all cases the Hi-lok (clearance) fasteners in pre-cracked specimens gave lower endurances than were achieved in uncracked specimens. Reductions in logarithmic mean values to between 0.25 and 0.65 of the uncracked endurances are shown. Conversely, the Hi-lok (CX cold expanded + interference) fasteners in pre-cracked specimens gave similar or marginally higher endurances than in uncracked specimens.

In noting the generally good endurances achieved by joints made with the Hi-lok (CX cold expanded + interference) fasteners it should be remembered that their measured interference fit is only $0.13 \leq e_i \leq 0.39$ and that the holes are cold expanded to between 4.0 and 5.6 per cent. The holes for Hi-tigue fasteners are not cold expanded and those for Huck EXL fasteners are cold expanded to between 0.4 and 4.4 per cent. The data therefore indicate that the benefits resulting from cold expanding initially cracked holes are superior to the benefits resulting from using interference fit fasteners.

6.5 Comparison of Countersunk and Protruding Head Fasteners, under FALSTAFF Loading (Tables 8.5 and 8.7)

Table 8.7 shows that, for all four of the datum fastener systems, protruding head fasteners gave marginally longer endurances than otherwise identical countersunk fasteners (Table 8.5). This applies at both the peak stress levels at which tests were conducted.

6.6 Comparison of Influence of Three Interfay Treatments under FALSTAFF Loading (Tables 8.5 and 8.10)

Table 8.10 compares endurances of the 7010-T7651 datum joint, which uses the Thiokol PR 1422 A interfay (see Table 8.3), with endurances of otherwise identical joints assembled using JC5 and Celloseal QH interfays. The datum joint endurances from Table 8.5 are repeated in Table 8.10 as dashed values against both the JC5 and QH interfay sets of data. The endurances obtained using JC5 and Celloseal QH were similar for all four datum fastener systems and at both stress levels. Both of these interfays gave increases in endurance over the Thiokol PR 1422 A by factors of between 1.25 and 3 based on logarithmic mean values.

6.7 Comparison of Different Types of Hi-lok Fasteners and Bolts (Table 8.14)

The first six sets of data in Table 8.14 show the effect of varying Hi-lok fastener type or diameter. The factors investigated are as follows.

Test	Fastener diameter	Hi-lok fastener type
1	5 mm (0.197 in)	As datum
2 3 4 5	6 mm (0.236 in)	Type LN 29767 Tension Protruding head Type MST M11
6	8 mm (0.315 in)	As datum

All the fits were in the range $i = 13$ to $51 \mu\text{m}$ (0.0005 to 0.002 in). The resulting endurances at the lower peak stress level of 280 MN/m^2 (40 600 lbf/in²) were all similar.

The two tests on bolts, numbers 7 and 8, were on joints having cold expanded holes. These show that the clearance fit bolt has a lower endurance than that of the comparable interference fit, when the holes are cold expanded. Note that the peak stress levels of the test are in the region of the material proof stress and will therefore modify the stresses within the joint.

6.8 Influence of Joint Plate Thickness under FALSTAFF Loading (Table 8.6)

Table 8.6 compares the results for joints between 4 mm (0.157 in) thick plates with otherwise identical joints between 6 mm (0.236 in) thick plates subject to the same peak stress levels. The thinner plates have the longer endurances in all but the Huck EXL fasteners, which show the same endurances for both plate thicknesses. For the Hi-lok and Hi-tigue fasteners the logarithmic mean endurances for the 4 mm plate exceed those for the 6 mm plates by factors of between 1.2 and 2.7.

6.9 Comparison of Steel Hi-tigue Fasteners and Large Diameter Fasteners with Datum Fasteners (Tables 8.8 and 8.9)

Table 8.8 compares the endurances of joints having steel Hi-tigue fasteners with otherwise identical titanium alloy fasteners of number 3 in Table 8.5. At the higher peak stress of 206 MN/m^2 (29 900 lbf/in²) the endurance of the joints with steel fasteners is marginally longer than that of those having titanium fasteners. At the lower stress level of 164 MN/m^2 (23 800 lbf/in²) the endurances of joints with either type of fastener are similar.

Table 8.9 compares the endurances of joints with 9.5 mm (0.374 in) diameter fasteners with joints having the datum 6.35 mm (0.250 in) diameter fasteners of Table 8.5. Joints with the interference fit larger diameter fasteners have only slightly longer endurances than those with the smaller diameter fasteners. Joints with the Hi-lok (clearance) fasteners show no significant differences in endurance between the two diameters.

6.10 Joints Subjected to TWIST or MiniTWIST Loading Sequences (Tables 8.16 and 8.22)

Table 8.16 shows the results for the four datum joints subject to two values of S_{1g} under the full TWIST loading sequence. At the higher stress level of 160 MN/m^2 ($23\,200 \text{ lbf/in}^2$) the endurances are comparable for all four datum joints. At the lower stress level of 140 MN/m^2 ($20\,000 \text{ lbf/in}^2$) the clearance fit Hi-lok fastener system has the shortest endurance. The logarithmic mean endurance recorded for the Hi-lok (CX cold expanded + interference) fasteners is twice that for the clearance fit fastener. For the Hi-tigue and Huck EXL (cold expanded + interference) the logarithmic mean endurances are respectively 4 and 10 times that for the clearance fit Hi-lok fastener.

Table 8.22 presents results for joints with protruding head fasteners subject to MiniTWIST III loading sequences. There are no data available with which to compare their endurances.

7. DERIVATION AND REFERENCES

7.1 Derivation

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

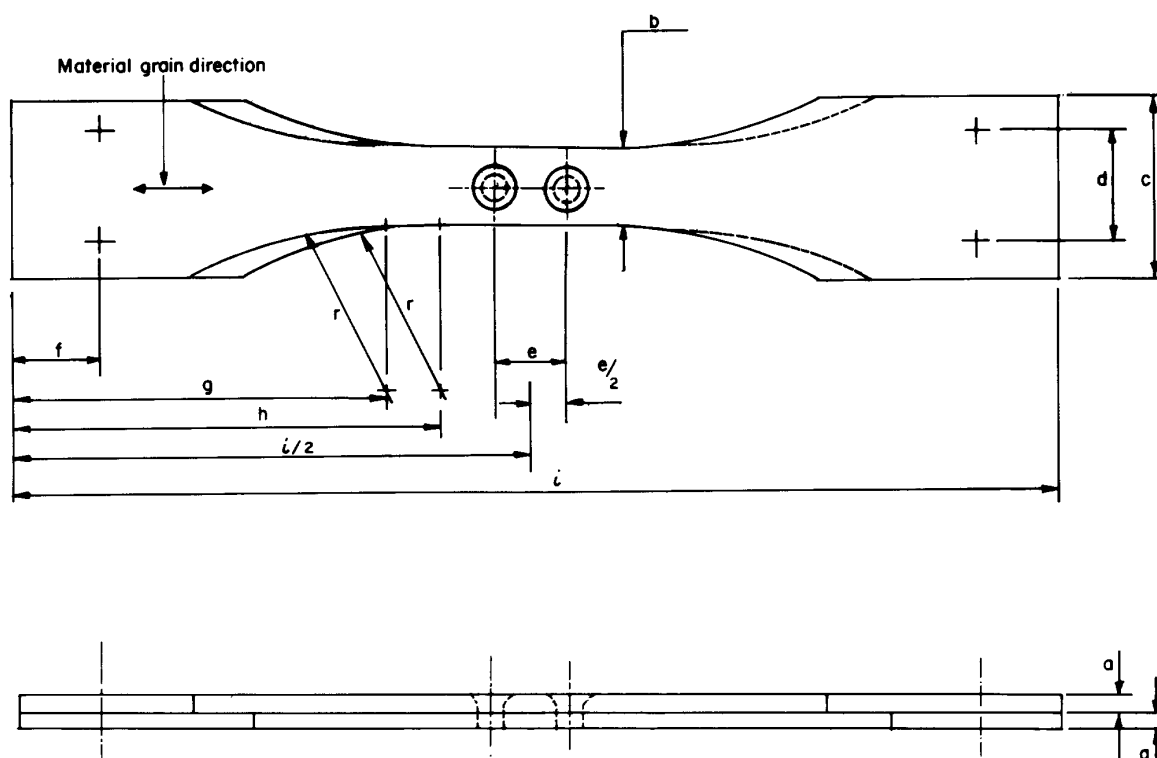
1. van der LINDEN, H.H. Fatigue rated fastener systems. AGARD Report No. 721, 1985.
2. SIMPSON, A. The evaluation of fatigue resistant fasteners. British Aerospace Report No. BAe-MSM-R-Gen-0519, 1987.

7.2 References

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

3. – Description of a fighter aircraft loading standard for fatigue evaluation, FALSTAFF. Joint report of F+W (Switzerland), LBF (Germany), NLR (The Netherlands) and IABG (Germany). March 1976.
4. READ, J.M.
HARTLEY, P.J. The evaluation of fatigue resistant fasteners. British Aerospace Report No. SOR(P) 131, 1982.
5. BIRKS, A. Development of mechanical fastening systems for aluminium alloy aerospace structures. *Aluminium Industry*, Volume 1, pp. 7-14, September 1982.
6. BIRKS, A. Development of mechanical fastening systems for aluminium alloy aerospace structures. *Aluminium Industry*, Volume 1, No. 2, pp. 21-25, November 1982.
7. COOK, R. Standard fatigue test specimens for fastener evaluation. AGARD-AG-304, 1987.
8. VAN DIJK, G.M.
de JONGE, J.B. Introduction to a fighter aircraft loading standard for fatigue evaluation. NLR-MP-75017U.
9. de JONGE, J.B. A standardised load sequence for flight simulation tests on transport aircraft wing structures. NLR-TR-73029U.

8. TABLES



Sketch 8.1 Test specimen design for low load transfer joints

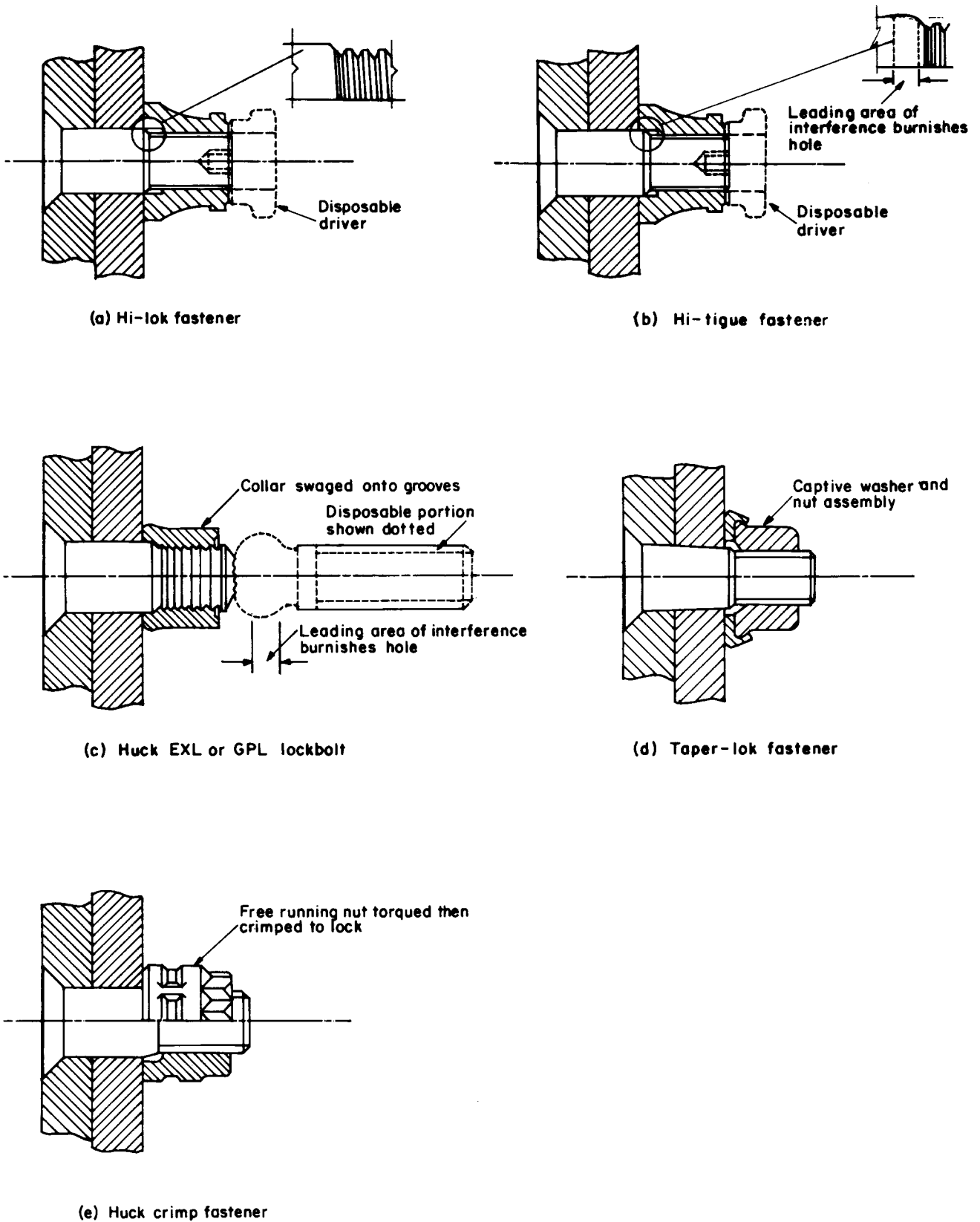
TABLE 8.1 SPECIMEN DIMENSIONS

Dimension (see Sketch 8.1)	Specimen type									
	A ^(a)		B		C ^(a)		D ^(b)		E ^(b)	
	mm	in	mm	in	mm	in	mm	in	mm	in
<i>a</i>	6	0.236	6.0	0.236	4	0.157	5.0	0.197	5.0	0.197
<i>b</i>	25	0.984	37.1	1.461	25	0.984	38.1	1.500	38.1	1.500
<i>c</i>	55	2.165	81.6	3.213	55	2.165	88.9	3.500	88.9	3.500
<i>d</i>	30	1.181	30	1.181	30	1.181	—	—	—	—
<i>e</i>	25	0.984	25	0.984	25	0.984	25.4	1.000	25.4	1.000
<i>f</i>	40	1.575	59.3	2.335	40	1.575	114.3	4.500	30	1.181
<i>g</i>	110	4.331	163	6.417	110	4.331	176.4	6.945	149.9	5.902
<i>h</i>	140	5.512	207.7	8.177	140	5.512	206.9	8.146	180.4	7.102
<i>i</i>	340	13.386	504.5	19.862	340	13.386	550.9	21.689	436.9	17.200
<i>r</i>	75	2.953	—	—	75	2.953	101.6	4.00	101.6	4.000
Fastener diameters used	6.35	0.250	9.50	0.374	6.35	0.250	6.35 6.00 5.00	0.250 0.2360 0.197	6.35	0.250
Gross cross-sectional area ^(c) mm ²	300		445.2		200		381		381	

(a) Specimen types A and C are identical excepting for dimension *a*.

(b) The test section dimensions for specimens D and E are identical.

(c) Section AA in Sketch 8.1.



Sketch 8.2 Fastener assemblies

TABLE 8.2 JOINT MATERIALS DATA

Specification	Designation *	Composition	Heat treatment	f_t	f_p
				MN/m ² (lbf/in ²)	MN/m ² (lbf/in ²)
DTD 5120	7010-T7651	6.2Zn - 2.4Mg - 1.7Cu - 0.13Zr	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.	520 [†] (75 400)	450 [†] (65 300)
L 93	2014-T651	4.4Cu - 0.5Mg - 0.8Si - 0.8Mn	Solution treated and artificially aged, stress relieved by stretching to between 1½ and 3 per cent permanent set.	450 (65 300)	410 (59 500)
—	2024-T351	4.4Cu - 1.5Mg - 0.6Mn	Solution treated and cold worked, stress relieved by stretching after solution treatment.	430 (62 400)	310 (45 000)
—	2024-T3		Solution treated and cold worked.	471 (68 300)	352 (51 000)
—	2024-T3 Clad sheet			425 (61 600)	275 (39 900)
—	7050-T76	6.2Zn - 2.3Cr - 2.2 Mg - 0.12 Zr	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)
—	7475-T7351	5.7Zn - 2.2 Mg - 1.6 Cu - 0.22 Cr	Solution treated and stabilised to provide highest resistance to stress-corrosion cracking and stress relieved by stretching to between 1½ and 3 per cent permanent set.	510 (74 000)	444 (64 400)

* International alloy designations and chemical composition limits.

† Specification values in longitudinal direction.