

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

1. INTRODUCTION AND SUMMARY

This Data Item is concerned with the fatigue strength of medium load transfer bolted joints. Data are presented for the effects of various fastener types and hole preparations on the fatigue strength of such joints. Different combinations of these can result in large variations in the fatigue strength of a bolted joint.

The factors that are shown in this Data Item to produce significant changes in fatigue endurance are:

- (1) the bolt head design,
 - (2) the amount of interference or clearance of the fastener in the hole,
 - (3) the bolt diameter
- and (4) the plate thickness

Other factors that also produce identifiable changes in fatigue endurance are fastener material, cold working of the hole bore, and joint material. A factor that is believed to be significantly detrimental to fatigue strength is secondary bending (this term is explained in Section 3). However, no firm data are available on the amount of bending in the joints. The relative effects of the various factors on fatigue endurance are shown to vary with fastener type and with the load applied to the joint.

The data in this Item are derived from tests involving proprietary fasteners. In the tests the fasteners were fitted according to recommended standard practice. In all the tests failures occurred in the joint material; there were no fastener failures. When extrapolating from the data in this Item, caution should be exercised. Large changes in geometry or scale, from the cases presented in this Item, can produce considerably different values of fatigue endurance. Care should be taken when examining the results of individual tests. The trends indicated by the results from the comparable tests should be taken into account.

If a particular treatment or fastening system is to be of use in enhancing fatigue life it must give consistent and predictable benefits. Comparative test data are available on three commonly used fasteners, namely Huck-EXL, Hi-tigue and Hi-lok. The Huck-EXL fastener system had the highest endurances in certain situations but also had some of the lowest. This lack of predictability detracts from its suitability as a fatigue life enhancing device. The Hi-tigue fastening system had consistently high endurance values in the situations examined. The Hi-lok (CX + interference) fastening system also has consistently good endurance values. Thus, in medium load transfer joints, interference fits and hole cold working can be beneficial. Also, where possible, protruding head bolts should be used for their fatigue life enhancement benefits. They are of most benefit in highly stressed joints. The aluminium-zinc alloys tested generally gave higher endurance values than the aluminium-copper alloys but it should be noted that there were only a limited number of tests. If a joint is to be subject to high stress levels, large bolt sizes may help extend its fatigue life but in lightly stressed joints, large bolts may reduce the fatigue life. Similar benefits may be obtained from reduced plate thickness, although it is not usually possible to alter this dimension. In medium load transfer joints fatigue failure will usually originate from the area around the fasteners. However, the origin of fatigue failure may move from the area around the fasteners to another site on the joint, particularly in well clamped joints with high interference fits and/or with cold worked holes.

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
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	interference, $d_f - d_h$	m	in
S_{1g}	mean stress, in undisturbed flight at 1g under cruise conditions, based on net cross-sectional area	N/m ²	lbf/in ²

3. MEDIUM LOAD TRANSFER JOINTS

It is convenient to define bolted structural joints as being of low, medium or high load transfer. Which of these a particular joint is depends on 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 endurance 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. 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. Most chordwise and spanwise joints in aircraft wings are either medium or high load transfer joints.

Sketch 8.1 shows the joint used in Derivation 3 to examine medium load transfer joints. Under the application of an axial load to this type of joint, the different stiffnesses of the joined members along adjacent parts of their length cause unequal load distribution between them. This results in load transfer from one member to another via the fastener. As a result of the unequal load distribution, a bending moment is established in the members in the region of the fastener. This is termed secondary bending and the secondary bending ratio is defined as the ratio of the measured bending strain to the measured direct strain. All the joints of the type shown in Sketch 8.1 investigated had an estimated secondary bending ratio in the range 0.1 to 0.7. The exact value of the secondary bending ratio for a particular joint geometry depends on applied load, fastener fit and size and various other factors. All the data presented in this Item are based on axial stresses. The exact values of local bending strains were not measured and they are not readily calculable.

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

4. TEST DETAILS

The joint type used in the tests is shown in Sketch 8.1. Two sets of tests involved changes in the dimensions of the joint. Tests were conducted with the thickness reduced from 6 mm (0.24 in) to 4 mm (0.16 in) and this was the only change in the dimensions for this set of tests. Tests were also conducted with larger diameter bolts. These required increases in several dimensions and these are detailed in Table 8.1.

Datum joints have been established for the purposes of comparing the data from the various tests. There are four datum joints which differ only in that each has a different fastener system. The datum joints have 6 mm (0.24 in) thick aluminium alloy DTD 5120 plates with anodised and epoxy primer painted surfaces. Their geometry is shown in Sketch 8.1 and their dimensions are set out in Table 8.1. The interlay is Thiokol PR 1422 A4. The fasteners are 6.35 mm (0.25 in) diameter titanium alloy (Ti-6Al-4V) bolts with countersunk heads. The datum joints were tested at two FALSTAFF* peak stress levels. This established two datum values of endurance for each fastener system. These datum values provide a basis for comparison of the effects of various treatments on the endurances of joints fitted with a particular fastener system.

Most of the testing was carried out using the FALSTAFF loading sequence. A few tests were performed using the TWIST† loading sequence. With FALSTAFF, the quoted values of peak stress refer to the highest value of stress applied (the level 32 value). These stresses are for the net cross-sectional area of the continuous element (see Sketch 8.1) at the bolted section. The stress values quoted for the tests using TWIST are the S_{1g} values of applied stress.

Tests were also carried out with specimens containing initial cracks in the hole bore. These tests were intended to simulate the situation where a crack has developed in the hole bore and repair is attempted by boring out the hole and then refastening but insufficient material is removed and part of the defect remains. The test plate was prepared by drilling a 3 mm (0.12 in) pilot hole with a 1 mm (0.04 in) notch cut at the corner of the hole in the plane normal to the applied axial loading. A crack was grown from the notch by constant amplitude fatigue loading until it was between 2.18 mm (0.09 in) and 2.68 mm (0.11 in) in length. The pilot hole was opened up to the specified size required by the individual fastener system. This left a crack that was between 0.5 mm (0.02 in) and 1.0 mm (0.04 in) in length. The joint was then assembled and subjected to FALSTAFF loading until failure.

* Fighter Aircraft Loading STandard For Fatigue evaluation (see Data Item No. 97018 and References 5 and 6).

† Transport aircraft WIng loading STandard (see Data Item No. 97018 and Reference 4).

5. DESCRIPTION OF FASTENER SYSTEMS

5.1 Introduction to Fastener Systems

The fastener systems for which data are presented are described in this section and further details are illustrated in Sketch 8.2. The values of interference or clearance are given in Table 8.2. The countersinks were of included angle 100° and were 1.52 mm (0.06 in) deep. Where protruding head fasteners were used plain holes without countersinks were used. Four fastener systems were tested. They were Hi-lok (clearance), Hi-lok (CX + interference), Hi-tigue (interference) and Huck-EXL (cold expanded + interference) and these are described in the following sections.

5.2 Hi-lok (Sketch 8.2a)

5.2.1 Hi-lok (Clearance)

The Hi-lok fastener consists of two parts, a close tolerance pin with a threaded end, and a threaded collar. The collar contains a hexagonal driving portion which shears off at a groove at a consistent preload. In these tests conventional nuts were used as 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.

5.2.2 Hi-lok (CX + interference)

The Hi-lok fasteners are identical to those described in Section 5.2.1 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 mandrel is pulled through the split sleeve which lines the hole. The hole is cold expanded and cold worked in this operation. The sleeve is discarded and the hole is reamed to size. Countersinks are drilled if required and the hole is deburred.

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

This fastener consists of a threaded pin and a nut. The threaded end of the pin carries a small raised bead. This bead expands and burnishes the hole as the pin is inserted into the hole. When the pin is fully inserted, the nut is fitted and torque tightened.

5.4 Huck-EXL (cold expanded + interference) (Sketch 8.2c)

This 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. This raised portion is designed to cold expand, cold work and burnish the bore of the hole as it is drawn through. When the pin is in position a collar is placed over the end and swaged onto the locking grooves while the extension is pulled by a special tool until it separates from the installed pin beyond the collar. The makers also supply the Huck-EXL system as a bolt without the shank extension but with a separate mandrel. The mandrel is used to expand the hole and the bolt is then fitted in a separate operation. This latter method was used in the tests in Derivation 3.

* This process was originally known as the Boeing split-sleeve process. It is now marketed by Fatigue Technology Incorporated.

6. ENDURANCE DATA

6.1 Guide to Data Presented

Endurance data are presented for the datum joints and for joints with a range of parameters or treatments which differ from those of the datum joints. The datum joints are described in Section 4. There are two datum values of endurance for each fastener system. These are the log mean endurance values of the datum joints at the two stress levels at which tests were conducted. For joints with the same fastener systems, comparisons of endurance may be made using values of relative endurance. The relative endurance value of a joint is the ratio of its endurance (in FALSTAFF flights) to the datum endurance (also in FALSTAFF flights) of the same joint type, fitted with the same fastener system, at the same test stress level. Relative endurances give comparative measures of how effective the various treatments and preparations are at increasing fatigue endurance.

Table 8.1 provides data on the dimensions of the test joints. The hole preparations and interference/clearance values are set out in Table 8.2. The identification numbers of the fastener systems are listed in Table 8.3. Data on the plate materials are given in Table 8.4. Tables 8.5 to 8.9 contain the log mean endurance and log mean relative endurance values for the four fastener systems. The relative endurance values are shown in Figures 1 to 8 while the endurance values are shown in Figures 9 to 15. In Figures 1 to 8 the bars indicate the log mean relative endurance values. The relative endurance values for individual tests are shown by dashes along the associated line that joins the maximum and minimum values of relative endurance. Figures 9 to 15 present the endurance values as dashes along a line that joins the maximum and minimum values of endurance.

6.2 Fastener Type and Fit

All the fastener systems that use an interference fit, namely Hi-lok (CX + interference), Hi-tigue and Huck-EXL, have consistently higher endurances than the clearance fit system: Hi-lok (clearance). Hi-tigue and Huck-EXL have higher interference values and generally longer endurances than Hi-lok (CX + interference). It is clear that interference fits can be particularly successful at increasing fatigue life in medium load transfer bolted joints. However, it is important to note that the endurance values of Hi-lok (CX + interference) and Huck-EXL are not as consistently high as the values of Hi-tigue. The hole is cold worked in the Hi-lok (CX + interference) and Huck-EXL systems but not in the Hi-tigue system. In one instance Hi-tigue fasteners were fitted in cold worked holes. The resulting log mean relative endurances are 0.58 (at the 375 MN/m^2 ($54\,400 \text{ lbf/in}^2$) stress level) and 0.37 (at the 300 MN/m^2 ($43\,500 \text{ lbf/in}^2$) stress level). This demonstrates that cold working the hole may reduce the effectiveness of an interference fit.

6.3 Fastener Bolt Head Type

With the single exception of the Hi-tigue system at the 300 MN/m^2 ($43\,500 \text{ lbf/in}^2$) stress level, all the relative endurance values for systems fitted with protruding, as opposed to countersunk heads, are greater than or equal to one. Therefore, in almost every case tested, protruding head bolts performed better than countersunk head bolts. At the higher stress level of 375 MN/m^2 ($54\,400 \text{ lbf/in}^2$) all the protruding head fasteners show significant increases in endurance over their datum values. The log mean relative endurance values at this stress level range from 1.5 to 2.5. The increases in endurance over the datum values are smaller at the lower stress level of 300 MN/m^2 ($43\,500 \text{ lbf/in}^2$) and the log mean relative endurance values range from 0.53 to 1.8. The increased endurances can be attributed to the better clamping achieved with protruding head bolts.

6.4 Fastener Diameter

At the higher stress level, the Hi-lok (clearance), the Hi-lok (CX + interference) and the Huck-EXL systems have increased endurance with the larger diameter fastener. With the 9.53 mm (0.375 in) diameter fasteners the log mean relative endurance of these three fastener systems at the high stress level range from 1.3 to 2.3. The Hi-tigue fastener system has a log mean relative endurance of 0.5 at this stress level. Thus, in highly stressed medium load transfer joints, large fasteners may give benefits in terms of fatigue strength.

At the lower stress level the log mean endurance values of all the systems were lower than their respective datum values. In Table 8.1 the dimensions of the joint used for the tests with the large diameter bolts are given. It should be noted that the thickness of the joint members is unchanged and thus the thickness is low in comparison with the other dimensions. With the large diameter fasteners and relatively thin plate the load transfer pattern is probably significantly altered. This has considerable influence on the endurance values of the joints.

6.5 Plate Thickness

As peak stress levels of 350 MN/m² (50 800 lbf/in²) and 280 MN/m² (40 600 lbf/in²) were used in these tests, accurate comparisons can not be made with the data from the tests with the thicker plate material as the majority of these tests were carried out at the 375 MN/m² (54 400 lbf/in²) and 300 MN/m² (43 500 lbf/in²) stress levels. Of the four fastener systems, Hi-tigue gives the highest endurance at both stress levels. The endurance values of Hi-lok (CX + interference) and Huck-EXL are relatively low at both stress levels. Reducing plate thickness is similar to increasing bolt diameter and should result in better clamping and stiffer joints. Also, and perhaps more importantly in terms of fatigue life, reduced plate thickness gives reduced bending in the joint.

6.6 Fastener Material

Endurance values are presented for joints with Hi-lok (Clearance), Hi-lok (CX + interference) and Huck-EXL fastener systems with steel instead of titanium fasteners. The only case where there is not an increase in endurance over the relevant datum value occurs for Hi-lok (CX + interference) at the lower stress level. The increases in endurance are most pronounced at the higher stress level where the log mean relative endurance values range from 1.2 to 2.0. At the lower stress level the values range from 0.8 to 1.8. The Hi-lok (clearance) system is the least affected by the use of a steel bolt. Therefore, it seems that the beneficial effects of the steel bolts are the result of the high circumferential tensile stresses introduced in the material around the hole with an interference fit*. These stresses are higher than those produced by titanium bolts because of the higher elastic modulus of steel. With steel bolts more clamping may be achieved, with the consequent benefit of less slip.

6.7 Plate Material

Data are presented for four plate materials. These materials are DTD 5120, BS L 93, 7475-T7351 and 2024-T351. Basic material data are set out in Table 8.4 for these alloys. For each fastener system the relative endurance of the joints manufactured from each material are presented together. For the most part the endurance of the various fastener systems do not show great material dependence and remain reasonably constant. Of the four materials, DTD 5120 (the datum material) gives the highest endurance values. Not all the tests were carried out at the same stress levels. The stress levels used in each test are given in Tables 8.5 to 8.8.

* See Data Item No. 84025 "Endurance of aluminium alloy lugs with steel interference-fit pins or bushes".

Endurance data for pre-cracked specimens are also presented for these four alloys. There is a greater amount of scatter in these data than in the data for the uncracked specimens. Some of the endurance values of the pre-cracked specimens are quite close to the corresponding values of the uncracked specimens. This is particularly evident for the specimens fitted with the Huck-EXL and, to a lesser extent, the Hi-lok (CX + interference) fastener systems. The pre-cracked DTD 5120 specimens, fitted with the Huck-EXL fastener system, have longer mean endurance values than the corresponding uncracked specimens at both test stress levels. It may be possible, with cold working of cracked specimens, to achieve endurances approaching those of equivalent uncracked specimens.

6.8 Interfay Material

The interfay for the datum joints is Thiokol PR 1422 A4. Data are presented for two alternative interfays, JC5 and Celloseal QH. The endurances with all the fastener systems are only marginally affected by the interfay type. The JC5 and QH interfays perform slightly better than the Thiokol at the higher stress level but the differences in the values are minimal. It appears that, for medium load transfer joints at the stress levels examined, the choice of interfay among these three is of low relative importance.

6.9 TWIST Loading Sequence

Tests were carried out using the TWIST loading sequence. The specimens for these tests were the standard medium load transfer joint (as shown in Sketch 8.1) manufactured from 2024-T351. Huck-EXL has the lowest endurance values at both stress levels. Hi-lok (clearance) has the second highest endurance at both stress levels. Hi-lok (CX + interference) has the highest endurance at the lower stress level while Hi-tigue has the highest endurance at the higher stress level. It should be noted that, at both stress levels, the peak stress in the TWIST sequence is significantly higher than the proof stress of 2024-T351. At these peak stresses it is likely that any beneficial stresses, due to an interference fit for example, will be relieved by yielding.

7. DERIVATION AND REFERENCES

7.1 Derivation

This section lists selected sources that have 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.

7.2 References

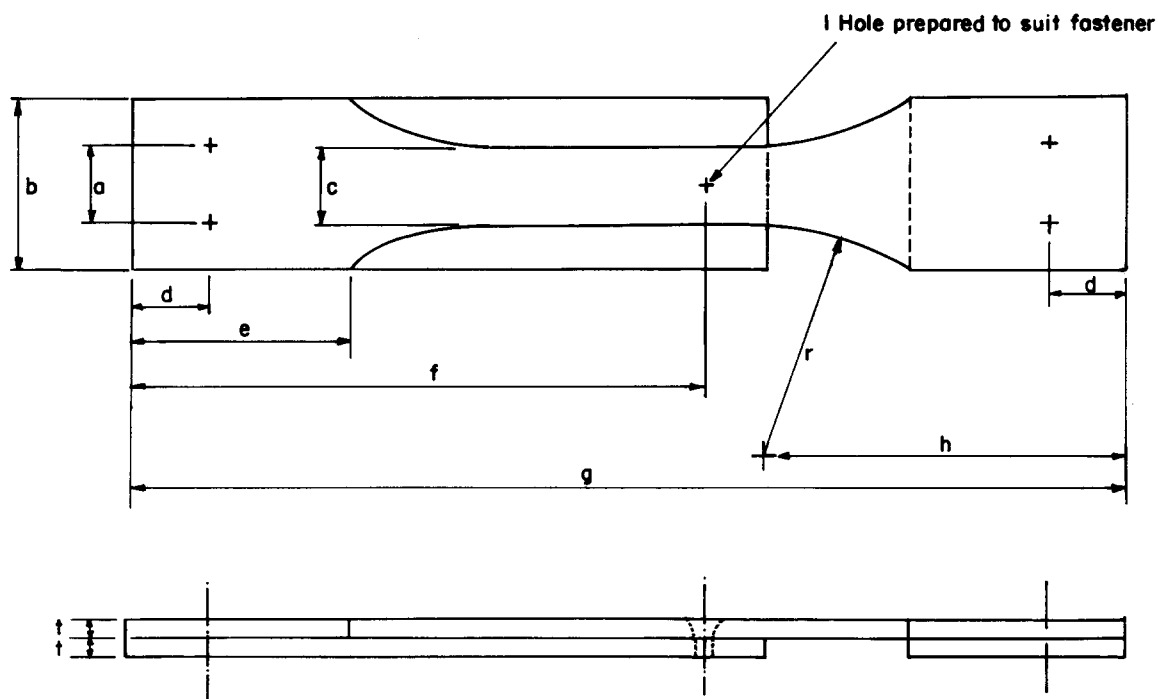
The references given are recommended sources of information supplementary to that in this Item.

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SCHIJVE, J. A standardised load sequence for flight simulation tests on transport aircraft wing structures. NLR TR 73029 U, 1973.
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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. COOK, R. Standard fatigue test specimens for fastener evaluation. AGARDograph No. 309, 1987.
8. HODGSON, W.S. Fatigue resistance fastener research programme, stage 4 – Effect of joint parameters. British Aerospace Warton, No. SOR(P)183, May 1988.

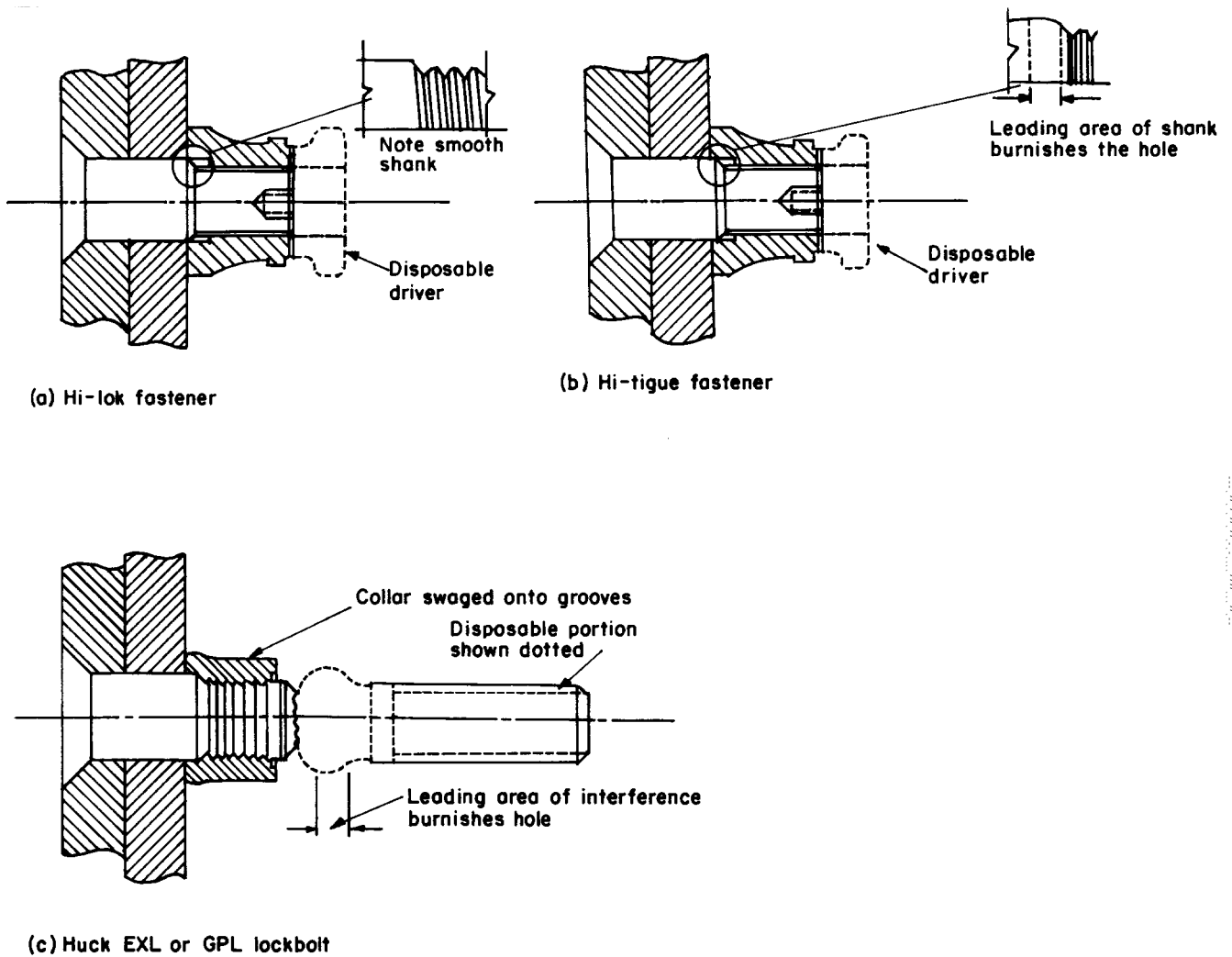
8. TABLES

TABLE 8.1 SPECIMEN DIMENSIONS

Dimension (See Sketch 8.1)	Joint type					
	Datum joints		Joints with 4 mm thick plate		Joints with 9.53 mm diameter fasteners	
	mm	in	mm	in	mm	in
<i>a</i>	25	0.984	25	0.984	40	1.57
<i>b</i>	55	2.17	55	2.17	84	3.31
<i>c</i>	25	0.984	25	0.984	38	1.50
<i>d</i>	25	0.984	25	0.984	30	1.18
<i>e</i>	70	2.76	70	2.76	75	2.95
<i>f</i>	185	7.28	185	7.28	190	7.48
<i>g</i>	320	12.6	320	12.6	343	13.5
<i>h</i>	115	4.53	115	4.53	129	5.08
<i>r</i>	75	2.95	75	2.95	75	2.95
<i>t</i>	6	0.24	4	0.157	6	0.24



Sketch 8.1 MEDIUM LOAD TRANSFER JOINT



Sketch 8.2 FASTENER SYSTEMS



TABLE 8.2 HOLE PREPARATIONS FOR EACH FASTENER SYSTEM

<i>Fastener system</i>	<i>Hole preparation</i>	<i>Cold expansion of hole, per cent</i>	<i>Fastener diameter</i>	<i>Hole final diameter</i>	<i>Specified fit</i>	<i>Tightening torque</i>
Hi-lok (clearance)	Drill and ream	—	6.35 mm (0.25 in)	6.35 – 6.37 mm (0.2500 – 0.2509 in)	c (mm) 0 – 0.02 c (in) 0 – 0.0009 e_c 0 – 0.36	6.8 – 9.0 N m (60 – 80 lbf in)
			9.53 mm (0.375 in)	9.53 – 9.55 mm (0.3750 – 0.3759 in)	c (mm) 0 – 0.02 c (in) 0 – 0.0009 e_c 0 – 0.24	23 – 27 N m (200 – 240 lbf in)
Hi-lok (CX + interference)	Drill and ream, CX cold expand and ream	3.0 – 6.0	6.35 mm (0.25 in)	6.30 – 6.32 mm (0.248 – 0.249 in)	i (mm) 0.05 – 0.03 i (in) 0.002 – 0.001 e_i 0.80 – 0.40	6.8 – 9.0 N m (60 – 80 lbf in)
			9.53 mm (0.375 in)	9.47 – 9.50 mm (0.373 – 0.374 in)	i (mm) 0.06 – 0.03 i (in) 0.002 – 0.001 e_i 0.54 – 0.27	23 – 27 N m (200 – 240 lbf in)
Hi-tigue (interference)	Drill and ream	—	6.35 mm (0.25 in)	6.21 – 6.25 mm (0.2445 – 0.2460 in)	i (mm) 0.14 – 0.10 i (in) 0.0055 – 0.004 e_i 2.2 – 1.6	10 – 11 N m (90 – 100 lbf in)
			9.53 mm (0.375 in)	9.32 – 9.37 mm (0.367 – 0.369 in)	i (mm) 0.21 – 0.16 i (in) 0.008 – 0.006 e_i 2.1 – 1.6	36 – 40 N m (320 – 350 lbf in)
Huck-EXL (cold expanded + interference)	Drill and ream, cold expand	0 – 4.6	6.35 mm (0.25 in)	6.20 – 6.32 mm (0.244 – 0.249 in)	i (mm) 0.15 – 0.03 i (in) 0.006 – 0.001 e_i 2.4 – 0.40	—
			9.53 mm (0.375 in)	9.32 – 9.45 mm (0.367 – 0.372 in)	i (mm) 0.21 – 0.08 i (in) 0.008 – 0.003 e_i 2.1 – 0.80	—

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