

STRENGTH OF LUGS

1. STRENGTH AND PERMANENT DEFORMATION ANALYSIS

1.1 INTRODUCTION

This Data Item provides data to determine the minimum load to cause failure by rupture or unacceptable permanent deformation of parallel sided and tapered lugs under in-plane axial, transverse or oblique loading. Methods of allowing for the effects of pin bending on lugs in a double shear joint are also included. The data are provided in the form of figures and a Fortran computer program. They are applicable to round- or square-ended lugs made of metallic extrusion, bar, forging plate or sheet but caution should be used in applying them to hand forgings.

The data given in this Item are based on the analysis presented in Derivations 1 and 2. They have been compared with theoretical and test data given in Derivations 1, 2 and 3 and Reference 7, the sources on which the principal design codes used for lugs in many countries are based. These comparisons are given in Reference 12. **The comparisons show that the data represent mean load values, with the extreme values for tests on axially loaded lugs being within ± 10 per cent of those given.**

The Data Item is presented in two parts. The first part provides the rupture and permanent deformation analysis of lugs. However, only examples can be given for the factor K_{lux} used in determining the axial tensile rupture load. ESDUpac A9108 provides a Fortran computer program that may be used to calculate this factor appropriate to any metallic material and use of this program is described in the second part of this Item.

1.2 NOTATION

Both SI and British Units are quoted but any coherent system of units may be used.

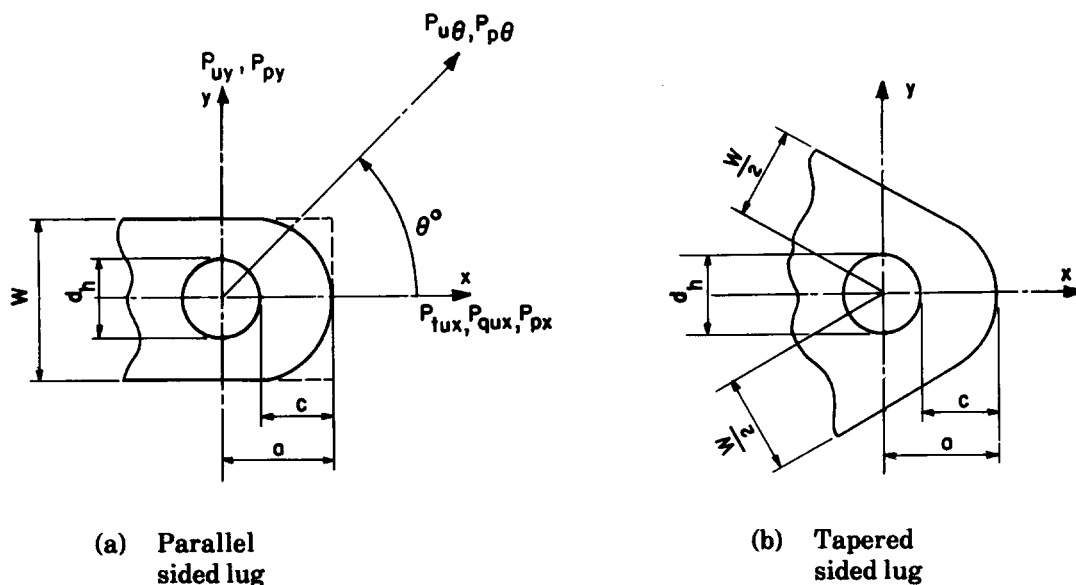
A_E	effective area of lug under transverse load $A_E = 6 / [(3/A_1) + (1/A_2) + (1/A_3) + (1/A_4)]$	m ²	in ²
A_1, A_2, A_3, A_4	critical loaded areas of lug under transverse load (see Sketch 1.4)	m ²	in ²
a	distance from centre of pin hole to lug end (see Sketch 1.1)	m	in
b	equivalent moment arm on pin (see Sketch 1.5)	m	in
b_{10}	1.0 per cent proof bearing stress causing a permanent deformation of $0.01d_h$ in lug at lug-to-pin interface	N/m ²	lbf/in ²
c	distance from edge of hole to lug end (see Sketch 1.1)	m	in
d	diameter of pin or hole in lug	m	in
E	modulus of elasticity of lug material	N/m ²	lbf/in ²
f	direct or bending stress in lug or pin material	N/m ²	lbf/in ²
f_{so}	allowable basic shear stress of pin material	N/m ²	lbf/in ²

g	gap between inner and outer lugs in double shear joint (see Sketch 1.5)	m	in
K	factor for lug load (see Equations (1.1) to (1.6))		
K'_e	elastic stress concentration factor for axially loaded lug with clearance fit pin, where e denotes percentage clearance between pin and hole diameters (see Section 2.3.1)		
M	bending moment on pin	N m	lbf in
P	load on lug or pin	N	lbf
t	thickness of lug	m	in
t_i, t_o	thickness of inner and outer lugs respectively in a double shear joint	m	in
t_n	0. n per cent proof (permanent deformation) stress of lug material	N/m ²	lbf/in ²
W	nominal width of lug (see Sketch 1.1)	m	in
x, y	coordinate system for lug (see Sketch 1.1)		
γ	peaking factor for pin bending in double shear joints		
θ	angle of oblique load on lug measured from x -direction (see Sketch 1.1)	degrees	degrees
τ	mean shear stress in pin (shear load divided by area of pin cross-section)	N/m ²	lbf/in ²

Suffixes

br	denotes bearing
c	denotes material cross-grain property (in plane of lug)
E	denotes effective area or effective moment arm
h	denotes hole
l	denotes material longitudinal (with-grain) property
M	denotes maximum allowable stress with respect to grain direction, in plane of lug (chosen from longitudinal, long transverse and short transverse values)
m	denotes minimum allowable stress with respect to grain direction, in plane of lug (chosen from longitudinal, long transverse and short transverse values)
min	denotes minimum value of load (see Section 1.3.2.3)
θ	denotes load applied at angle θ to x -direction
p	denotes permanent deformation condition

pin	denotes stress, load, moment or dimension related to pin
q	denotes shear-bearing
t	denotes tensile
u	denotes ultimate (rupture) condition
x, y	denotes stress, load or factor in axial or transverse lug directions respectively (see Sketch 1.1)
γ	denotes load peaking effect (see Section 1.3.6.2)



Sketch 1.1 General lug geometry and loading

1.3 NOTES

1.3.1 General

This Item provides data that enable the loads that cause failure by rupture and unacceptable permanent deformation to be determined for lugs under in-plane axial (x -direction), transverse (y -direction) and oblique (angled) loading. A check is also provided to determine whether or not the load that causes failure by unacceptable bearing permanent deformation is less than the rupture or overall permanent deformation loads. Additional data show whether or not pin bending will affect the lugs in a double shear joint. The term rupture is taken here to denote complete failure in the lug by fracture of the lug material in tension or shear. The forms of rupture are shown in Sketches 1.2 and 1.3. The term permanent deformation denotes that the lug material is strained beyond the elastic range (that is beyond the yield point) of the material resulting in an irrecoverable permanent set. The use of a chosen allowable proof stress enables the loads that produce an unacceptable permanent deformation to be determined.

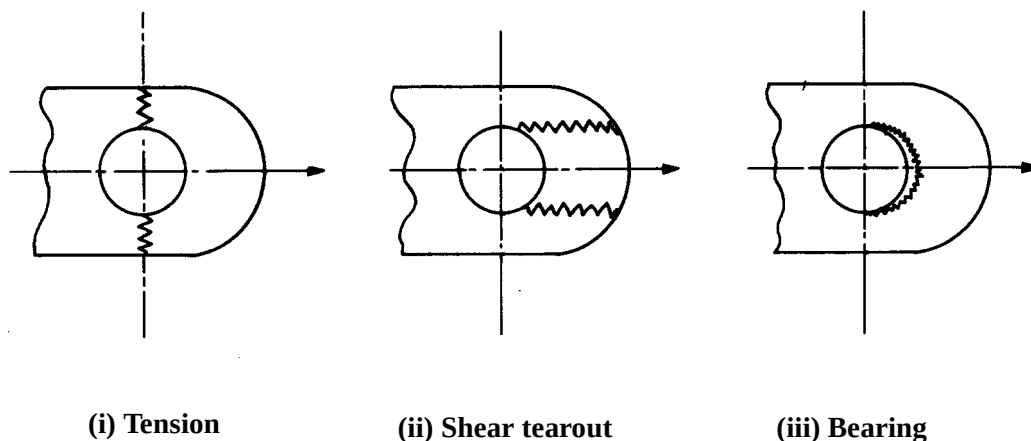
Data are provided for parallel and tapered sided lugs with round or square ends of the forms shown in Sketches 1.1 and 1.4. The mode of lug failure can vary with the type of loading. Sections 1.3.2 to 1.3.4 detail the modes of failure to be considered for each type of loading, axial, transverse and oblique respectively. They are followed by sections on the bearing permanent deformation of the pin in the lug and the effects of pin bending.

The data on axially loaded lugs may be applied to any metallic material but they have been obtained by a combination of theoretical and empirical methods for steel and aluminium alloy lugs made from bar, forging, extrusion, plate or sheet. The data given for transversely loaded lugs are limited to steel and aluminium alloy lugs. Caution should be used in applying the data to hand forgings. The analyses have been developed for lugs for which $1 \leq d_h/t \leq 5.5$ and $1.3 \leq a/d_h \leq 2.0$ but may be used outside of those limits within the geometrical range covered by Figures 1 to 6. However, when $d_h/t < 1.0$ it is recommended that $t = d_h$ be taken throughout the calculations (but not in the calculation for pin bending) and when $d_h/t > 8.0$ it is advisable to check the stability of the lug.

1.3.2 Axial Loading

For a lug under axial load three modes of lug failure are considered:

- (i) tension
- (ii) shear tearout
- or (iii) bearing.



Sketch 1.2 Modes of lug failure under axial load

Failure of the lug under axial load is determined by considering the tensile rupture mode (i) separately (Section 1.3.2.1) and the shear rupture and bearing permanent deformation modes (ii) and (iii) as a combined mode, described in this Item as shear-bearing (Section 1.3.2.2). The assessment of overall lug permanent deformation is then related to the minimum of these two failure loads (Section 1.3.2.3). The bearing load to cause unacceptable permanent deformation (yield) in the lug at the pin-to-hole interface is given as a separate check (Section 1.3.5) as this may be a separate requirement, particularly for lugs subject to compression.

The tensile rupture mode has been treated separately because Derivation 1 shows that tensile rupture may be represented by a factor, K_{tux} , which for a given material varies with the value of the elastic stress concentration factor, K'_e . It has also been determined in Derivation 1 that the shear rupture and bearing permanent deformation (between the hole and the end of the lug), are interrelated and can therefore be represented by a single factor, K_{qux} . In this mode the dominance of either the shear or bearing effect depends principally on the a/d_h ratio, and to a lesser degree, the ratio d_h/t . For values of $a/d_h > 2.0$ shear rupture can be accompanied by significant bearing permanent deformation.

Because the tensile rupture factor K_{tux} is material and geometry dependent a Fortran computer program to calculate values of K_{tux} has been written. This is given in ESDUpac A9108 and is explained in the second part of this Item. Examples of K_{tux} for particular materials, obtained from the computer program, are given in Figures 1a and 1b.

1.3.2.1 Lug failure due to tensile rupture

The load to cause lug failure by tensile rupture is given by the expression:

$$P_{tux} = K_{tux} f_{tux} (W - d_h) t, \quad (1.1)$$

where f_{tux} is the allowable tensile ultimate stress in the axial, x-direction, appropriate to the direction of grain flow in the lug.

The value of the axial tensile rupture factor, K_{tux} , for a particular lug is dependent on the lug material properties and its geometry (see Section 2.3). ESDUpac A9108 provides a Fortran computer program for calculating K_{tux} from K'_e and the material properties. Values of K'_e may be obtained from Data Item No. 81006*. The program is provided on the Compact Disc and on disk in the Sub-series Software Volume. Instructions for running the program are given in the second part of this Item. Example values of K_{tux} for various material specifications over a range of K'_e and, as an alternative, over a range of materials and lug geometries, are given in Figures 1a and 1b respectively. The properties for the materials considered in Figures 1a and 1b are given in Table 1.1. The example data in Figure 1b have been obtained from the computer program using values of the stress concentration factor, K'_e obtained from Data Item No. 81006, appropriate to particular values of W/d_h and a/W for a lug/pin fit of 0.2 per cent clearance.

1.3.2.2 Lug failure due to shear-bearing rupture

The load to cause failure due to shear-bearing is given by the expression:

$$P_{qux} = K_{qux} f_{tum} d_h t, \quad (1.2)$$

where f_{tum} is the minimum tensile strength, with respect to the grain direction, in the plane of the lug.

Values of the shear-bearing factor, K_{qux} , are plotted against a/d_h for various values of d_h/t in Figure 2. If the pin is a loose fit in the lug d_{pin} should be used in Equation (1.2) in place of d_h .

1.3.2.3 Lug failure load due to overall permanent deformation

A lug permanent deformation of greater than $0.02d_h$ is considered unacceptable. The load to cause this level

* Data Item No. 81006 "Stress concentration factors. Axially loaded lugs with clearance-fit pins".

of permanent deformation is given by the expression:

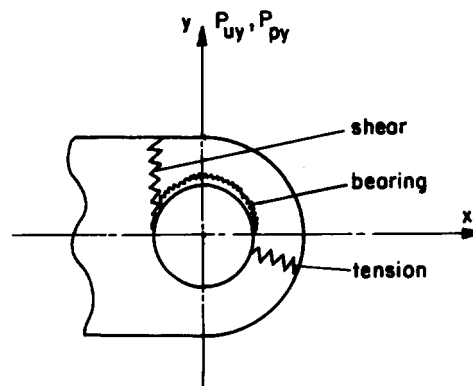
$$P_{px} = K_{px} \left(\frac{f_{tpm}}{f_{tum}} \right) P_{uxmin} , \quad (1.3)$$

where P_{uxmin} is the lower of P_{tux} and P_{qux} . The stress f_{tpm} is a minimum proof stress, with respect to the grain direction, in the plane of the lug.

Values of the axial permanent deformation factor, K_{px} , are plotted against $P_{uxmin}/d_h t f_{tum}$ in Figure 3. The tests on which Figure 3 is based relate to a permanent deformation of $0.02d_h$ with $f_{tpm} = t_2$. Note that certain materials with proof stresses that are high compared to their ultimate strength may produce less deformation than $0.02d_h$ by the time rupture has occurred.

1.3.3 Transverse Loading

In Derivation 2 it is shown that failure of a lug under transverse (y-direction) load is likely to occur as a rupture due to shear and bearing effects in the section of the lug receiving the pin load or a rupture due to tension around the end of the lug (see Sketch 1.3). These effects are combined in a single empirical expression for the rupture load. The load to cause unacceptable permanent deformation ($0.02d_h$) under transverse load is also given by a single expression.



Sketch 1.3 Modes of lug failure under transverse loading

1.3.3.1 Lug failure due to rupture

The load to cause rupture under transverse load is given by the expression:

$$P_{uy} = K_{uy} f_{tum} d_h t . \quad (1.4)$$

Values of the transverse rupture factor, K_{uy} , are plotted against $A_E/d_h t$ in Figure 4 in which curve (a) is for steel lugs and curve (b) is for aluminium alloy lugs. The effective area is given by

$$A_E = 6 / [(3/A_1) + (1/A_2) + (1/A_3) + (1/A_4)] . \quad (1.5)$$

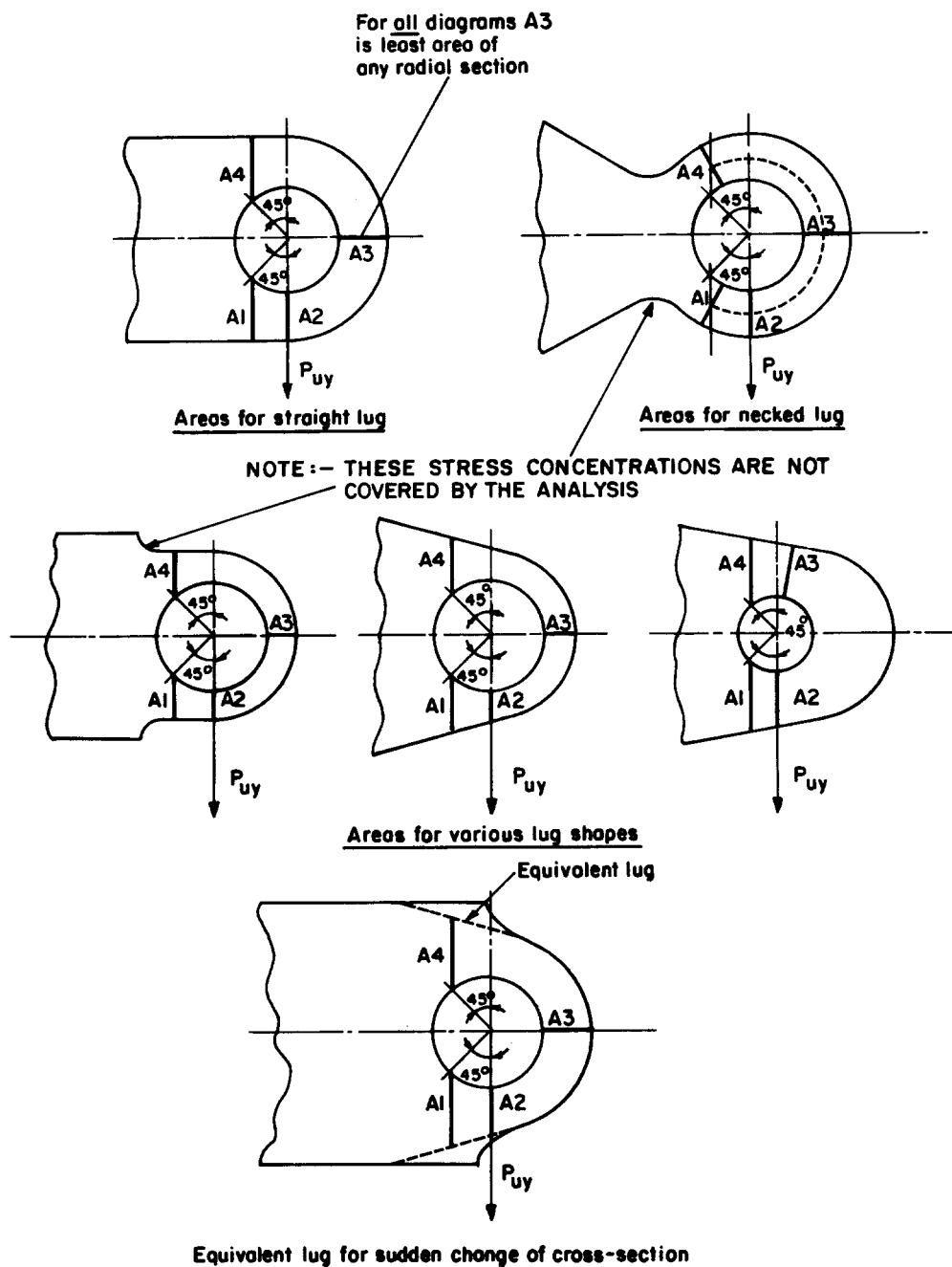
Guidance on how to obtain values of the areas A_1 , A_2 , A_3 and A_4 for lugs of various forms is given in Sketch 1.4.

1.3.3.2 Lug failure load due to overall permanent deformation

The load to cause unacceptable permanent deformation of the lug under transverse load is given by

$$P_{py} = K_{py} f_{tpm} d_h t, \quad (1.6)$$

where f_{tpm} is a minimum proof stress, with respect to the grain direction, in the plane of the lug. Values of the transverse permanent deformation factor, K_{py} , are plotted against $A_E/d_h t$ in Figure 5.



Sketch 1.4 Definition of areas used in calculation of equivalent area for lugs under transverse load

1.3.4 Oblique Loading

The failure load of a lug under oblique loading at angle θ to the x -direction may be estimated from the rupture loads of the lug under axial loading and transverse loading by using the following interaction formula.

$$P_{u\theta} = \frac{1}{\left[\left(\frac{\cos \theta}{P_{uxmin}} \right)^{1.6} + \left(\frac{\sin \theta}{P_{uy}} \right)^{1.6} \right]^{0.625}}, \quad (1.7)$$

where P_{uxmin} is the minimum of P_{tux} and P_{qux} , obtained as detailed in Sections 1.3.2.1 and 1.3.2.2, and P_{uy} is obtained as indicated in Section 1.3.3.1.

The load, $P_{p\theta}$, to cause permanent deformation of the lug under an oblique load can be obtained from the same interaction equation by replacing P_{uxmin} by P_{px} and P_{uy} by P_{py} .

1.3.5 Failure Due to Bearing Permanent Deformation

The load to cause failure due to unacceptable bearing permanent deformation at the lug-to-pin interface is given by the expression:

$$P_{pbr} = b_{10} d_h t, \quad (1.8)$$

where b_{10} is the 1.0 per cent proof bearing stress appropriate to the direction of load. This is the bearing stress that will cause a permanent deformation of $0.01d_h$ in the lug at the lug-to-pin interface. Values of b_{10} and guidance on how to obtain such values can be obtained from Reference 13.

1.3.6 Pin Bending in a Double Shear Joint

1.3.6.1 Analysis assuming uniform loading between pin and lug

The lug strength analyses given in Sections 1.3.2 to 1.3.4 assume that the pin through the lug joint is sufficiently strong to transfer the load between the inner lug and the outer lugs that the lug stresses are uniform across the thickness of the lug sections. For double shear joints as shown in Sketch 1.5 this is taken to be so if the bending moment under the application of the minimum rupture load does not exceed the permissible bending moment for the pin, where the applied moment is

$$M = P_{pin} b/2 \quad (1.9)$$

in which P_{pin} is taken as the minimum allowable rupture load for the centre lug or twice that for the outer lugs. Guidance on the maximum permissible bending moment on a circular pin can be obtained from Data Item No. Struct. 01.06.01*.

If the load is assumed to be uniformly distributed across the lug-to-pin interface, as shown in Sketch 1.4a, the equivalent moment arm is

$$b = t_o/2 + t_i/4 + g. \quad (1.10)$$

* Data Item No. Struct. 01.06.01 "Form factors for circular sections under combined bending and axial load".

1.3.6.2 Analysis assuming load peaking between pin and lug

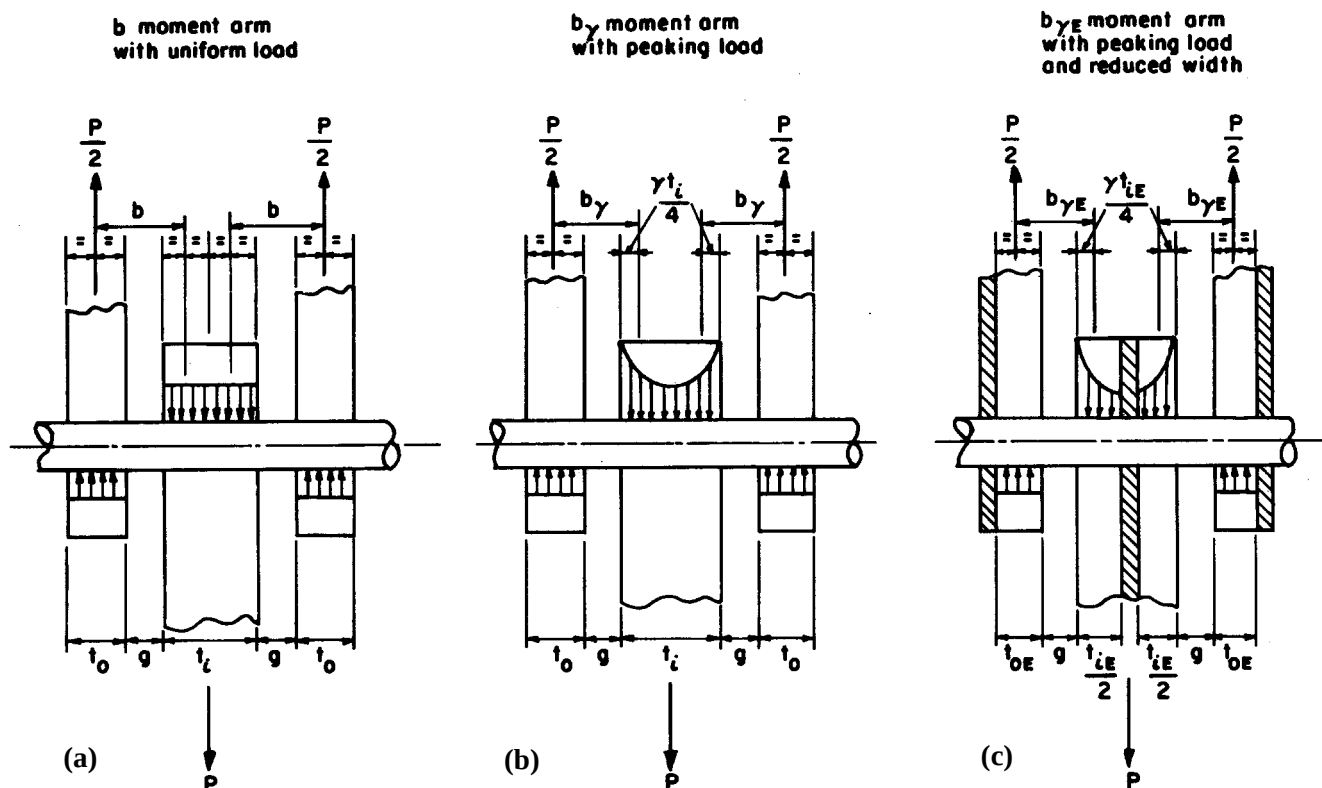
If the pin is found to be inadequate on the basis of the criterion of Equation (1.10), it is acceptable to take into account the tendency of the bearing stresses due to pin loading to peak near the shear faces of the inner lug so reducing the moment on the pin, see Sketch 1.5(b). If that assumption is made the equivalent moment arm is obtained from the expression

$$b_{\gamma} = (t_o/2) + \gamma (t_i/4) + g. \quad (1.11)$$

Values of γ are plotted against $P_{pin}/(d_{pin}t_{lum})$ for various values of c/t in Figure 6. Although load peaking is assumed to have occurred, the overall stress distribution in the lug is still considered to be uniform over the thickness of the lug.

1.3.6.3 Analysis including excess strength of lug

If the pin is still found to be inadequate when load peaking is considered it is possible to take into account any excess strength that the lug has over the required design load (reserve factor). In that event it may be assumed that a proportion of the thickness of the lug in the joint is inactive (see Sketch 1.5(c)) so that the effective lug thicknesses are t_{oE} and t_{iE} . The minimum lug rupture load is recalculated using the new effective thicknesses. The pin bending calculation is then performed again, including the effect of peaking, with the revised loading and moment arm using Equation (1.11). This process can be repeated with an increased inactive portion if the pin is still unable to transfer the load and the lug still has excess strength.



Sketch 1.5

1.4 DERIVATION AND REFERENCES

1.4.1 Derivation

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

1. COZZONE, F.P.
MELCON, M.A.
HOBLIT, F.M. Analysis of lugs and shear pins made of aluminium or steel alloys. *Product Engineering*, pp. 113-117, May 1950.
2. MELCON, M.A.
HOBLIT, F.M. Developments in the analysis of lugs and shear pins. *Product Engineering*, pp. 160-170, June 1953.
3. ELANGO VAN, P.T. A method to calculate the allowable tension fracture load of a lug. Report No. SM-123, Fokker B.V., Amsterdam, January 1982.

1.4.2 References

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

4. VOLKERSON, O.
GOSCHLER, R. The strengths of lugs or eyebolts. *Luftwissen*, Vol. 8, No. 5, pp. 151-156, May 1941.
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6. DIXON, J.R.
SCOTT, H.M. Effect of non-axial loading on stress distribution in plates loaded through pin joints. National Engineering Laboratory, Report No. 108, August 1963.
7. LAYTON, A.W.J. Static strength tests at room temperature of lugs from bar material. U.K. Min. Defence S. and T. Memo. No. 2/64, March 1964.
8. CALLINAN, R.J. Stress analysis of a lug loaded by a pin. Aeronautical Research Laboratories, Struct. Note 439, AR-000-842, Melbourne, Australia, July 1977.
9. SCOTT, R.G.
STOVE, J.C. The effects of design variables on the critical stresses in eye bars under load: an evaluation by photoelastic modelling. Lawrence Livermore National Laboratory, California, Joint Conference on Experimental Mechanics, Hawaii, 1982.
10. KATHERISON, K.
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BRUSSAT, T.R. Advanced life analysis methods. Volume II - crack growth analysis methods for attachment lugs. AFWAL-TR-84-3080, September 1984.
11. EKVALL, J.C. Static strength analysis of pin-loaded lugs. Institute of Aeronautics and Astronautics, *Journal of Aircraft*, Vol. 23, No. 5, pp. 438-443, May 1986.
12. PENNING, R.L. Comparison of design codes with theoretical and test data on lugs. ESDU Memorandum No. 81.
13. ESDU Metallic materials data handbook. DEF STAN 00-932. Volume 1. Published by ESDU International, London, 1991.

1.5 EXAMPLE

1.5.1 Problem

It is required to find the load, applied at an angle of 30° , that will cause rupture in the critical inner lug in a balanced joint and the load that will cause a permanent deformation of no more than 0.02 times the hole diameter. It is also required to ensure that the pin strength is adequate.

The lug material is aluminium alloy to British Standard Aerospace Series specification L168 which has the following properties in the plane of the lug.

$$\text{Modulus of elasticity,} \quad E = 72\,000 \text{ N/mm}^2.$$

$$\text{Ultimate tensile strength, longitudinal,} \quad f_{tul} = 465 \text{ N/mm}^2.$$

$$\text{Ultimate tensile strength, cross-grain,} \quad f_{tuc} = 394 \text{ N/mm}^2.$$

$$\text{0.2 per cent proof stress, cross-grain,} \quad f_{tpc} = 360 \text{ N/mm}^2.$$

$$\text{1.0 per cent proof bearing stress,} \quad b_{10} = 517 \text{ N/mm}^2.$$

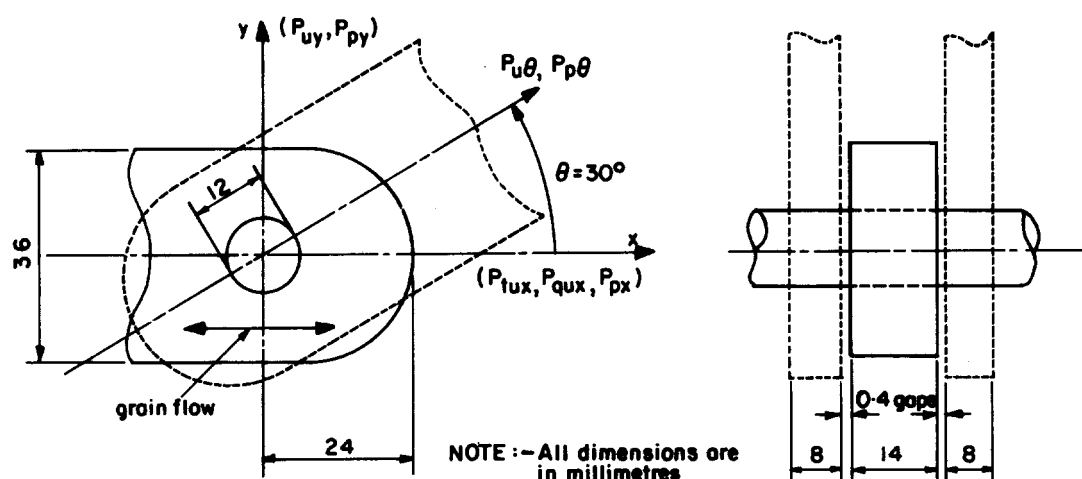
The material grain is aligned in the axial (x -direction) (see Sketch 1.6).

The pin material is steel to British Standard Aerospace Series specification S99 which has the following properties.

$$\text{Allowable shear stress,} \quad f_{so} = 780 \text{ N/mm}^2.$$

$$\text{0.2 per cent proof stress,} \quad t_2 = 1080 \text{ N/mm}^2.$$

The geometry of the lug and joint is shown in Sketch 1.6 together with the loading alignment.



Sketch 1.6