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Strength of lugs under axial load



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STRENGTH OF LUGS UNDER AXIAL LOAD

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STRENGTH OF LUGS UNDER AXIAL LOAD

1. STRENGTH AND PERMANENT DEFORMATION ANALYSIS

1.1 INTRODUCTION

This Data Item provides data for use in determining the minimum load to cause failure by either rupture or maximum permissible permanent deformation of parallel-sided and tapered lugs under in-plane axial 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 and castings due to uncertain grain flow.

The data given in this Item are based on the analysis presented in Derivations 1 and 4. They have been compared with theoretical and test data given in Derivations 1 and 3 and Reference 8, the sources on which the principal design codes used for lugs in many countries are based. These comparisons are given in Reference 14. **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.**

There may be considered to be two important factors that affect the accuracy of the results obtained using this Data Item. Those are:

- the reliability of the methodology itself, and
- the reliability of the data, specifically the material properties, used when employing the methodology.

The figure of ± 10 per cent quoted above for the accuracy of the methodology presented is dependent upon appropriate and applicable material properties being used, in particular values of f_{bru} that have been obtained in accordance with Reference 15 and with appropriate pin orientation with respect to the lug grain orientation.

The Data Item is presented in two parts. The first part provides details of the rupture and maximum permissible permanent deformation analysis of lugs. In Figure 1, the factor K_{tux} , which is used in determining the axial tensile rupture load, is plotted for a few specific materials. ESDUpac A9108 provides a Fortran computer program that may be used to calculate this factor for lugs fabricated from 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	distance from centre of pin hole to lug end (see Sketch 1.1)	m	in
b	equivalent moment arm on pin (see Sketch 1.3)	m	in
b_{10}	1.0 per cent proof bearing stress, that is the stress ($P/d_h t$) corresponding to a permanent distortion of the hole of 1.0 per cent of its original diameter.	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

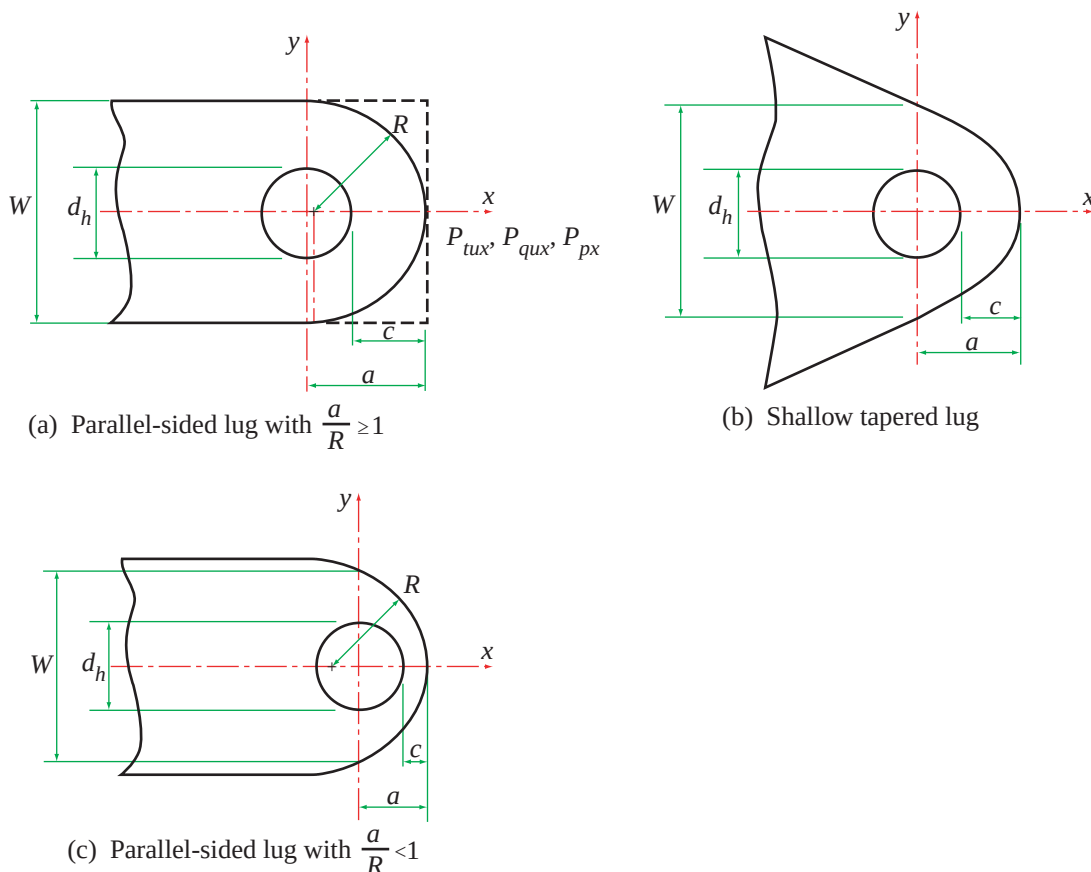
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E	modulus of elasticity of lug material	N/m ²	lbf/in ²
f	direct or bending stress in lug or pin material	N/m ²	lbf/in ²
$f_{bru, d}$	allowable, dry-pin, ultimate bearing stress of lug material (see Section 1.3.2.2)	N/m ²	lbf/in ²
$f_{bru, w}$	allowable, wet-pin, ultimate bearing stress of lug material ($f_{bru, w} = 0.9 \times f_{bru, d}$) (see Section 1.3.2.2)	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 1.3)	m	in
K	factor for lug load (see Equations (1.1) to (1.3))		
K_r	shear-bearing reduction factor for lugs with low $f_{bru, w}$ properties (see Section 1.3.2.2 and Figure 2b)		
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
R	radius of end of lug (see Sketch 1.1)	m	in
R.F.	reserve factor		
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 (see Equation (1.7))		
τ	mean shear stress in pin (shear load divided by area of pin cross-section)	N/m ²	lbf/in ²

1.2.1 Suffixes

br	denotes bearing
c	denotes material long transverse property (in plane of lug)
E	denotes effective area or effective moment arm

h	denotes hole
l	denotes material longitudinal 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)
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	co-ordinate system for lug (see Sketch 1.1)
γ	denotes load peaking effect (see Section 1.3.4.3)



Sketch 1.1 General lug geometry and loading

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1.3 NOTES

1.3.1 General

This Item provides data that enable the loads that cause failure by rupture and maximum permissible permanent deformation to be determined for lugs under in-plane axial (x-direction) loading. A check is also provided to determine whether or not the load that causes failure by maximum permissible 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 of the lug by fracture of the lug material in tension or shear. The forms of rupture are shown in Sketch 1.2. 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 a maximum permissible permanent deformation to be determined.

Data are provided for parallel-sided and tapered lugs with round or square ends of the forms shown in Sketch 1.1. Section 1.3.2 gives details of the modes of failure considered. Sections 1.3.3 and 1.3.4 deal with bearing permanent deformation of the pin in the lug and the effects of pin bending respectively.

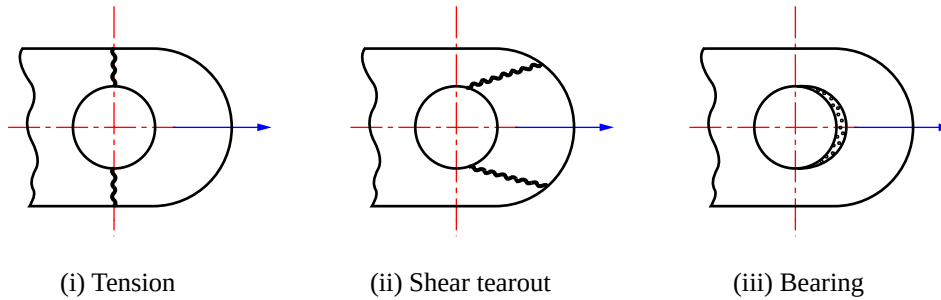
The data may be applied to lugs fabricated from any metallic material but they have been obtained by a combination of theoretical and empirical methods for steel and aluminium alloy lugs made from bar, forging, extrusion, plate or sheet. Caution should be used in applying the data to hand forgings and castings due to uncertain grain flow and also to lugs made from extrusion with short transverse grain orientation not parallel to the pin axis. The following points should be borne in mind when using the data presented in this Item.

- The analyses have been developed for lugs for which
 - $1.0 \leq d_h/t \leq 5.0$ and
 - $1.3 \leq a/d_h \leq 2.0$
 but may be used outside of these limits within the geometrical ranges covered by Figures 1a to 4.
- When $t > d_h$, it is normal practice to use a value of t equal to d_h throughout the calculations (except in the calculation for pin bending).
- Whilst noting the limit of $d_h/t \leq 5.0$ above, it is advisable to check the stability of the lug should it be the case that $d_h/t > 8.0$.
- **As stated in the introduction, reliable results will only be obtained if appropriate and applicable material properties are used, in particular values of f_{bru} that have been obtained in accordance with Reference 15 and with appropriate pin orientation with respect to the lug grain orientation.**

1.3.2 Modes of Failure

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

- (i) tension
 - (ii) shear tearout
- and (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 maximum permissible permanent deformation in the lug at the pin-to-hole interface is given as a separate check (Section 1.3.3) as this may be a separate requirement, particularly for lugs subject to compressive load.

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 is also shown in Derivation 1 that 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 ratio a/d_h and, to a lesser extent, the ratio d_h/t . For values of $a/d_h > 2.0$ shear rupture can be accompanied by significant bearing permanent deformation.

Experimental data (Derivation 4) indicate that the shear-bearing rupture data in Derivation 1 for axially loaded lugs are, in some cases, unconservative by an amount greater than the value of 10 per cent quoted in Section 1.1; greater unconservatism is found for lugs with $f_{bru, w}/1.44f_{tum} < 1.0$. Therefore Figure 2b has been introduced to specify reduction factors K_r which give acceptable agreement between calculation and test results. The K_{qux} values obtained from Figures 2a and 2b reliably and accurately cover the lowest K_{qux} values obtained from tests over a range of values of W/d_h for a given combination of values of a/d_h and d_h/t . The failure mode for thin lugs, that is those with $d_h/t > 5$, changes from bearing at the hole to localised buckling at the edge of the hole and therefore a separate local buckling analysis must be carried out for thin lugs.

1.3.2.1 Failure due to tensile rupture

The load to cause lug failure by tensile rupture is given by the expression (see Derivation 1)

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

where f_{tux} is the allowable ultimate tensile stress in the axial (x-) direction. Note that when using Equation (1.1), a value of f_{tux} appropriate to the material grain direction in the lug should be employed. If there is a large variation in the value of f_{tux} with grain direction, it is suggested that the minimum value of f_{tux} in the plane of the lug be used.

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 ESDU 81006*.

* ESDU 81006, "Stress concentration factors. Axially loaded lugs with clearance-fit pins".

Instructions for running the program are given in Section 2 of this Item. Values of K_{tux} for various material specifications over a range of values of K'_e and over a range of materials and lug geometries are given in Figures 1a and 1b respectively. The properties of 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 ESDU 81006 and appropriate to particular values of W/d_h and W/a for a pin-to-hole clearance of 0.2 per cent.

1.3.2.2 Failure due to shear-bearing rupture

The load to cause failure due to shear-bearing is given by the expression (see Derivation 1)

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

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

Values of K_{qux}/K_r are plotted against a/d_h for $d_h/t \leq 5.0$ in Figure 2a. The shear-bearing reduction factor, K_r , for lugs with low $f_{bru, w}$ is plotted against $f_{bru, w}/f_{tum}$ in Figure 2b. Note that K_r is independent of the value of d_h/t .

Reference 17 contains dry-pin values of allowable ultimate bearing stress, $f_{bru, d}$, for various aerospace specification metallic materials, for $a/d_h = 1.5$ and 2.0. These values were obtained from tests using the test method specified in Reference 15. It is also recommended that wet-pin (that is, lubricated, even by touching with the fingers) values of allowable ultimate bearing stress, $f_{bru, w}$, should be taken as 90 per cent of the dry-pin values of the allowable ultimate bearing stress, $f_{bru, d}$.

In this Item wet-pin values of the allowable ultimate bearing stress, $f_{bru, w}$, with $a/d_h = 1.5$ must be used.

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 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 of permanent deformation is given by the expression (see Derivation 1)

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

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, of the lug material 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 lugs fabricated from certain materials with proof stresses that are high compared to their ultimate strength may exhibit less deformation than $0.02d_h$ by the time rupture has occurred.

1.3.3 Failure Due to Bearing Permanent Deformation

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

$$P_{pbr} = b_{10} d_h t, \quad (1.4)$$

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 16.

1.3.4 Pin Bending in a Double Shear Joint

1.3.4.1 Pin Shear

The pin should be checked to ascertain whether or not it can sustain the applied ultimate load. This is done by comparing the pin shear stress with the allowable shear stress, f_{so} , of the pin material where the average shear stress in the pin (in double shear) is determined using the expression

$$\tau_{pin} = \frac{2 \times P_{pin}}{\pi \times d_{pin}^2}.$$

1.3.4.2 Pin bending analysis assuming uniform loading between pin and lug

The lug strength analyses given in Section 1.3.2 assume that the pin used to transfer the load between the inner lug and the outer lugs is sufficiently stiff that the lug stresses are uniform across the thickness of the lug sections. For double shear joints as shown in Sketch 1.3 this is taken to be so if the bending moment under the application of the ultimate applied load does not exceed the permissible bending moment for the pin, where the applied moment is (see Derivation 1)

$$M = P_{pin} \frac{b}{2}, \quad (1.5)$$

in which P_{pin} is taken as the ultimate applied load for the central lug or twice that for the outer lugs. Guidance on the maximum permissible bending moment on a circular pin can be obtained from ESDU Struct 01.06.01*.

If the load is assumed to be uniformly distributed across the lug-to-pin interface, as shown in Sketch 1.3(a), the equivalent moment arm is

$$b = \frac{t_o}{2} + \frac{t_i}{4} + g. \quad (1.6)$$

1.3.4.3 Pin bending analysis assuming load peaking between pin and lug

If the pin is found to be inadequate on the basis of Equation (1.6), 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 thus reducing the moment on the pin, see Sketch 1.3(b). If that assumption is made the equivalent moment arm is obtained from the expression

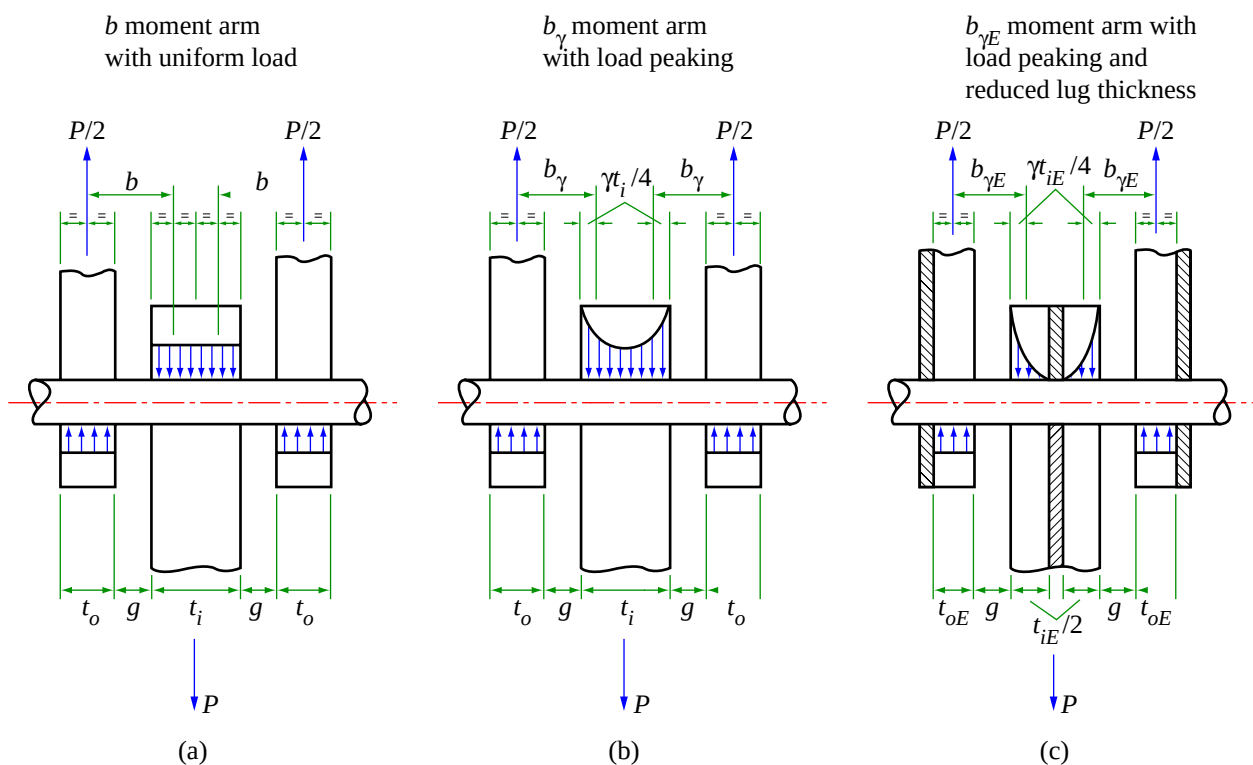
$$b_\gamma = \frac{t_o}{2} + \gamma \frac{t_i}{4} + g. \quad (1.7)$$

Values of γ are plotted against $P_{pin}/d_{pin}t_{lum}$ for various values of c/t in Figure 4. 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.

* ESDU Struct 01.06.01, "Form factors for circular sections under combined bending and axial load".

1.3.4.4 Pin bending 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. In that event it may be assumed that a proportion of the thickness of the lug in the joint is inactive (see Sketch 1.3(c)) so that the effective lug thicknesses are t_{oE} and t_{iE} . The minimum lug rupture load is recalculated using the ratios of the effective thickness to the actual thickness of the lugs (t_{iE}/t_i and t_{oE}/t_o). The pin bending calculation is then performed again, including the effect of peaking, with the revised loading and moment arm obtained from Equation (1.7). 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. The analyses of Sections 1.3.2 and 1.3.3 should also be performed again using the effective lug thicknesses.



Sketch 1.3 Pin loading in a double shear joint