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Stress intensity factors in lugs (through-thickness cracks)

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The Item was accepted for inclusion in the Stress and Strength Series by the Stress Analysis and Strength of Components Committee. This Committee first met in 1964 and now has the following constitution:

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STRESS INTENSITY FACTORS IN LUGS (THROUGH-THICKNESS CRACKS)

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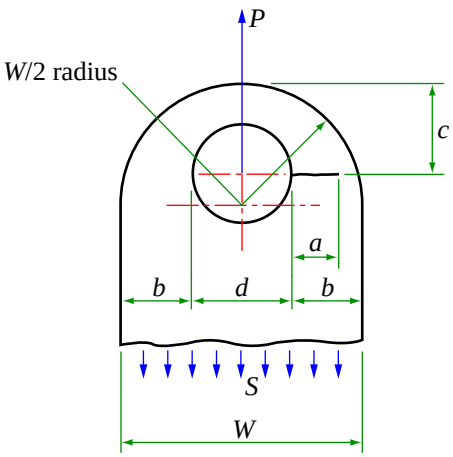
STRESS INTENSITY FACTORS IN LUGS (THROUGH-THICKNESS CRACKS)

1. NOTATION

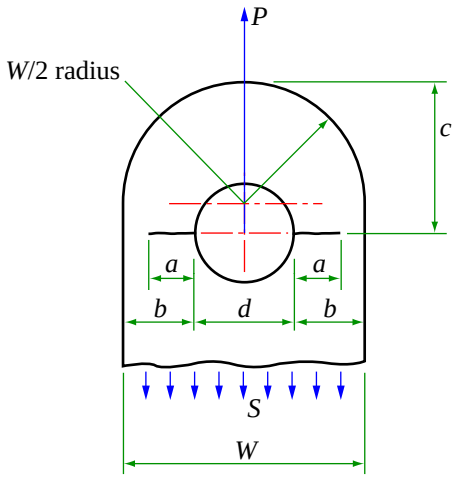
a	actual crack length as defined in Sketches 1.1 and 1.2	m	in
b	width of net section on one side of lug, thus $b = (W-d)/2$ (note that b is defined this way even when $c/W < 1/2$ as depicted in Sketch 1.1)	m	in
c	distance from centre of hole to lug end (see Sketches 1.1 and 1.2)	m	in
d	diameter of hole in lug	m	in
K_I	mode I stress intensity factor* defined by $K_I = S(\pi a)^{1/2}\alpha$	$N/m^{3/2}$	$lbf/in^{3/2}$
P	load on lug	N	lbf
S	stress based on gross cross-sectional area, $S = P/(Wt)$	N/m^2	lbf/in^2
t	thickness of lug	m	in
W	width of lug	m	in
α	geometrical factor* in K_I		

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

* See ESDU 80036 "Introduction to the use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components" for a definition of mode I cracks and notes on α.



Sketch 1.1 Single crack



Sketch 1.2 Double cracks

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2. NOTES

The general expression for stress intensity factor is

$$K_I = S(\pi a)^{1/2}\alpha \tag{2.1}$$

in which α accounts for the crack configuration and surrounding boundaries. This Item provides values of α for round-ended lugs loaded axially by a single central clearance-fit pin and containing cracks of uniform depth through the full thickness of the lug. For ease of use this Item uses the true crack length a (rather than, for example, $d+2a$) in Equation (2.1)*. Values of α are presented in Tables 5.1 and 5.2 and graphically in Figures 1 to 6.

Data are provided for both a single crack on one side of the lug hole on the transverse diameter (see Sketch 1.1) and for two equal length cracks on the opposite sides of the hole, both on the transverse diameter (see Sketch 1.2). The data have been obtained via finite element calculations (Derivation 2) in which the load supplied by the pin was taken to be sinusoidally distributed over the loaded half of the hole perimeter. This condition is similar to that obtained with pin-to-hole clearances in the region of 0.2 per cent of d for uncracked lugs (see ESDU 81006†).

Values of α provided for $a/b = 0$ have been derived as follows. The local circumferential stress acting at the side of the lug hole has been obtained from stress concentration data, see ESDU 81006. It is then assumed that K_I is identical to the K_I for an edge crack in a wide bar subject to a uniform stress field of this magnitude. The value of α is then calculated to satisfy Equation (2.1) which is based on S, the gross stress in the lug‡.

2.1 Effect of Pin-to-Hole Clearance

ESDU 81006 provides information on the effect of pin-to-hole clearance on the stress at the side of the hole. Thus, for small values of a/b, those data may be used to obtain an indication of the effect of pin-to-hole clearance on α. (Note that at large values of pin-to-hole clearance the maximum stress provided by ESDU 81006 is away from the transverse diameter. Thus estimates of K_I based on ESDU 81006 for such fits are unlikely to be compatible with the data for finite values of a/b provided in this Item for cracks on the transverse diameter.)

Finite element analyses have shown that in the limiting case of a line loading across the thickness of the lug at point 1, shown on Sketch 1.1, K_I on the transverse diameter is about 10 per cent greater than the value obtained using the data given in this Item. Also, finite element calculations for theoretically perfect-fit pins gave values of K_I below those obtained using the data in this Item by about 3 per cent at $a/b \to 0$ and by about 15 per cent at $a/b = 0.5$. In theoretically perfect-fit pins the pressure distribution around the hole was radically affected by the presence of a crack. For example in lugs with $d/W = 0.6$ loaded by pins having the same modulus of elasticity as the lug, the pressure adjacent to a single crack equalled the average bearing pressure of P/dt when $a/b = 0.2$ and at $a/b = 0.6$ the pressure increased to about twice the average bearing pressure. This situation is only likely to develop at a very long crack in a lug carrying a close-fitting pin.

* ESDU 80036 Section 3 provides notes on methods of defining crack length and the consequential effects on the values of α.

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

‡ Note that for an edge notch in a wide bar under uniform stress α is 1.12. Also ESDU 81006 provides stress concentration factors on a net cross section basis. Thus to obtain α for a short crack in a lug for Equation (2.1), the stress concentration factor given by ESDU 81006 must be divided by $(1 - d/W)$ and the quotient multiplied by 1.12.

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2.2 Use of the Data in Fatigue Calculations

Where a crack is generated by fatigue loading the existence of a through-the-thickness crack on one side of the hole is almost always accompanied by a shorter crack on the other side of the hole. In such circumstances the value of K_I lies between the values obtained for single and double cracks both having the same value of a. As $a/b \to 0$ the solutions for double and single cracks tend to the same value of α, so the difference between the solutions for K_I may not in practice be significant. For example, for double cracks with $a/b = 0.1$ the difference between the two values of α only varies between 1.5 and 6.5 per cent, depending upon the values of d/W and c/W.

Tables 5.1 and 5.2 are provided for determining α for use in computerised calculations. The values presented are chosen such that linear interpolation for α across either d/W, c/W or a/b produces negligible errors. For rapid computation it is recommended that linear interpolation should be employed to obtain values of α for a range of a/b for the desired c/W and d/W. These values can then be used with a curve-fitting technique to evaluate the coefficients of a suitable polynomial, usually of 4th or 5th degree, for α in terms of a/b. Alternatively a slower linear interpolation procedure can be employed throughout.

The figures are carpet plots. Each curve is displaced horizontally from the ordinate by a scalar factor equal to its a/b or d/W value. This allows easy interpolation via the horizontal scale. For example Figure 1 shows a dashed line on which is marked the $d/W = 0.42$ and $a/b = 0.07$ point. To obtain this point the ends of the dashed line are fixed as being 0.02 horizontally along the $a/b = 0$ and 0.1 lines from the 0.4 curve and the required point is then 0.07 horizontally along the dashed line from the $a/b = 0$ line.

ESDU 80036 contains a description of the concept of stress intensity factors together with descriptions of its application to fatigue and residual strength calculations.

3. DERIVATION

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

1.	KIRKBY, W.T. ROOKE, D.P.	A fracture mechanics study of the residual strength of pin-lug specimens. *Fracture mechanics in engineering practice*, pp. 339-360, Applied Scientific Publications, London, 1977.
2.	WHITEHEAD, R.A. ABBEY, A.J. GLEN-BOTT, M.G.	Analytical determination of stress intensity factors for attachment lugs. British Aerospace, Aircraft Group, Report No. SON(P)199, November 1978.
3.	HSU, T.M.	Analysis of cracks at attachment lugs. American Institute of Aeronautics and Astronautics, Paper No. 80-0753, 1980.

4. EXAMPLE

For the purposes of drawing-up an inspection schedule it is required to calculate the load cycles associated with the growth of a fatigue crack in a steel lug until yielding of the net remaining section is approached. The lug is to be subjected to a periodic load of ± 140 kN. Inspection techniques are such that the largest crack that will escape detection is 1 mm long. The lug is manufactured from an austenitic corrosion resistant steel that has an 0.2 per cent proof stress of 292 MN/m^2 and the crack propagation properties given by Figure 1b of ESDU 84003. The dimensions of the lug are $d = 30$ mm, $W = 70$ mm, $c = 33$ mm and $t = 20$ mm.

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