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Endurance of steel lugs with clearance-fit pins (Tensile mean stress)

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ENDURANCE OF STEEL LUGS WITH CLEARANCE-FIT PINS (TENSILE MEAN STRESS)

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ENDURANCE OF STEEL LUGS WITH CLEARANCE-FIT PINS (TENSILE MEAN STRESS)

1. NOTATION

a	distance between centre of hole and end of lug	m	in
d	pin diameter of test lug	m	in
d_d	pin diameter of lug under design	m	in
e	diametral clearance as a percentage of d		
f_p	0.2 per cent proof stress of lug material	N/m^2	lbf/in^2
f_t	tensile strength of lug material	N/m^2	lbf/in^2
K_e	elastic stress concentration factor, based upon net cross-sectional area, including corrections for pin-to-hole clearance and lug thickness (see Section 3)		
N	endurance		
S_a	applied alternating stress, based upon net cross-sectional area (half stress range)	N/m^2	lbf/in^2
S_m	applied mean stress, based upon net cross-sectional area	N/m^2	lbf/in^2
S_{max}	peak stress in loading cycle $(S_m + S_a)$	N/m^2	lbf/in^2
t	thickness of lug	m	in
W	width of lug	m	in
γ	d_d/d (see Section 3.1.1)		
θ	angle between transverse diameter of lug bore and points of maximum stress on lug bore to which K_e relates (see Sketch 1.1 and Section 3)	deg	deg

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

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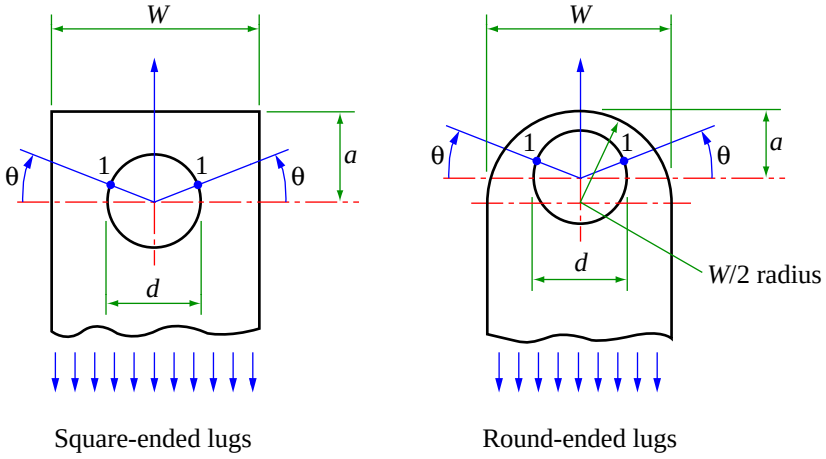

Sketch 1.1

2. DATA PROVIDED AND RANGE OF APPLICATION

This Item presents the analysis of approximately 440 tests on steel lugs subjected to constant amplitude axial and in-plane tensile loading applied by a single central clearance-fit pin. The available data have been analysed and are presented as one of the four material groups shown in Table 2.1. Further details of the material and test specifications are provided in Table 5.1.

TABLE 2.1

Material description	*Specifications*
Ferritic stainless steel	Firth Vickers FV 520 B (Company specification)
2½% Ni-Cr-Mo	*BS: S96, BS: S98, and †DTD 331, DTD 473
1% Cr-0.55% Mo	AS 111624 (SAAB-Scania company specification)
18% Ni Maraging steel	Grade 200, DTD 5212

* Aerospace series of British Standards specifications.

† UK Ministry of Defence specifications.

Data are provided on the effect of pin fit and lug size and on some types of treatment and/or lubrication of lug bore.

All the data provided relate to plain, unbushed, lugs. An estimate of the fatigue strength of lugs containing thin bushes can be formed from the data. Lug stresses resulting from an interference-fit bush exist and will act so as to increase the endurance above the estimated value (see last paragraph of Section 3.1.2). The value of K_e should be estimated for the lug bore (that is, the bore into which the bush is inserted). Account of size effect (see Section 3.1.1) should be based upon the pin diameter. This assumes a relatively rigid pin and flexible bush.

If the lug is to carry a ball race the lug bore should be used as a basis for both K_e and size effect. This will be satisfactory if the outer casing is sufficiently rigid to act as the pin does in the tests analysed in this Item. In the case of a ball race and all non-interference-fit bushes care must be taken to ensure that the method of containment does not introduce additional stress concentrations at critical locations on the lug.

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3. PRESENTATION OF DATA

The data are presented in Figures 1 to 4 and 7 to 11 and 13 and 14 in terms of $K_e S_a / f_t$ against N with values of $K_e S_m / f_t$ being indicated by symbol type. Each figure relates to one of the material groups described in Table 2.1. The effects of various bore treatments and pin-to-hole clearances are shown in separate figures. Throughout this Item the nominal pin diameter, d, has been chosen to indicate the absolute size of the lug.

The value of K_e used has, in each case, been estimated using ESDU 81006*. In addition to the lug geometry, expressed as d/W and a/W, ESDU 81006 includes corrections for the lug thickness, expressed as t/d, and the pin-to-hole clearance, e. In most of the data analysed values of e were directly calculable. In a few cases the pin-to-hole fit was described as "push-fit" or "exact fit". For these e was taken to be 0.2 or, where the methods of measurement of pin and bore were stated, the value of e implied by the practical limits of the measuring devices was calculated and used. Errors arising in K_e from these assumptions are unlikely to be greater than about ± 3 per cent. In all instances the point of maximum stress to which K_e relates is in the lug bore at the points 1 shown on Sketch 1.1. The value of θ lies between 0 and 35 degrees depending upon pin-fit (see ESDU 81006).

In some of the data analysed the value of $K_e S_{max}$ exceeded the tensile proof stress, f_p. In these cases $K_e S_{max}$ was assumed to be limited to f_p and the value of $K_e S_m$ was reduced to $f_p - K_e S_a$ so that the most highly stressed regions (points 1) cycled between f_p and $f_p - 2K_e S_a$.

3.1 Ferritic Stainless Steel FV 520B

This is the largest body of data and it is presented on Figures 1 to 9. The composition and properties of FV 520B, which has a martensitic microstructure, are shown in Table 5.1. All the lugs were of identical proportions with d of either 12.7 or 50.8 mm (excepting that the thickness, t, for the larger lugs was only twice that of the smaller). Because of this and because corrections to K_e for t/d ratio were negligible the values of K_e for similar values of e were identical. The dimensions are given in Table 5.1. The lugs were cut from fully heat treated bars, the faces being ground and all sharp edges removed. Tests on the lugs with $d = 12.7$ mm were conducted at 140, 170 or 220 Hz and tests on lugs with $d = 50.8$ mm were conducted at 12 to 16 Hz.

3.1.1 Lugs with *e* = 0.02

Figure 1 provides data on lugs with d of 12.7 or 50.8 mm. All the lug bores were carefully honed or ground to give $e = 0.02 \pm 0.01$ and K_e was 2.37 in every case.

The three solid curves on Figure 1 indicate the effect of mean stress for the $d = 12.7$ mm lugs. The curves merge to a single line in the region $2 \times 10^5 < N < 10^6$. The primary effect of mean stress is to alter the endurance limit significantly. This is consistent with the increased dependence of crack propagation rate on mean stress as the threshold stress intensity factor is approached (see Section 4.2.1 of ESDU 80036†).

* ESDU 81006 "Stress concentration factors. Axially loaded lugs with clearance-fit pins".
† ESDU 80036 "Use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components".

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The single chain-dotted curve for lugs with $d = 50.8$ mm falls just below that for lugs with $d = 12.7$ mm in the region $3.5 \times 10^5 < N < 10^6$. Also, the endurance limit falls well below that of the lugs with $d = 12.7$ mm for the same $K_e S_m / f_t$ range. This shows a strong size effect in which the fatigue limit increases with decreasing lug size or, conversely, reduces with increasing lug size. The effect of size must therefore be taken into account when applying the data to lugs of different sizes from those of the tests. For size differences based on d of less than about ± 50 per cent the fatigue limit value $(K_e S_a / f_t)$ can be corrected by a factor of $\gamma^{-1/2}$. Beyond these limits this method is likely to underestimate the increase in fatigue limit with size reductions and overestimate the reductions in fatigue limit for size increases. The observed size effect may be attributed to both local stress gradient effects and to fretting. The factor thought to be the major cause of size effect is the variation in fretting action with size. Section 4.2.3 of ESDU 90031* discusses test results on simple specimens which show that the amplitude of movement between rubbing areas affects the fatigue strength. Up to a certain amplitude of movement the fretting reduces the fatigue strength but beyond that amplitude fretting does not further reduce the fatigue strength. It is likely that a similar but more complex fretting phenomenon occurs in lugs and that there is, for given lug proportions and loading condition, a limit to the reduction in fatigue strength with increasing size.

3.1.2 Effect of increased clearance

Figures 2 and 3 show the results of increasing e for lugs with $d = 12.7$ or 50.8 mm respectively. The lugs were identical to those having the same value of d on Figure 1 in all respects other than pin fit. Within the range of data available (up to $e = 0.8$ per cent) increasing e results in an increased fatigue strength. This is because the effect of increased clearance is to move the region of maximum fretting away from the point of maximum stress in the lug bore. It should be noted that an increase in fatigue strength is only possible if the applied load is always maintained as tensile. It is not normal practice to employ large clearance-fits in lugs in which the load may be reversed, even if this is only a relatively rare event. Because of the lack of data below $N = 10^4$ ycles it is not clear whether or not any improvement results from increased clearance at low endurances. The increase may therefore only be in the fatigue limit. Figure 5 has been derived from a detailed analysis of the fatigue limits (that is, using the exact values of $K_e S_m / f_t$ for each data point). This indicates that increasing e beyond about 0.8 is unlikely to bring significant further increase in the fatigue limit. It also shows that the fatigue limit of lugs can be doubled simply by increasing the clearance into the region $0.5 < e < 1.0$.

Note that the curve of Figure 5 should not be extrapolated below $e = 0$. This is because the stress field caused by interference-fits is radically different from that in lugs with clearance-fit pins. It produces, under load, a reduced local alternating stress at the expense of a higher mean stress, which combination leads to an improvement in fatigue strength over lugs with $e = 0$. Thus, lugs with $e = 0$ are associated with the lowest fatigue strength.

3.1.3 Effect of side relief

Figure 4 shows the effect of retaining a close fitting pin $(e = 0.02)$ but removing material from the pin and/or lug in the region of maximum lug stress, as shown in the sketches on Figure 4. All the results on Figure 4 relate to conditions of high mean stress $(K_e S_m / f_t = 0.67)$ on lugs with $d = 50.8$ mm which were identical to the $d = 50.8$ mm lugs of Figure 1 (excepting that the pins were not allowed to rotate so as to preserve the positions of the relieved areas). Both the fatigue strength and the fatigue limit increase with the pin relief angle. At a relief angle of 20 degrees only very slight improvement occurs. Definite improvement occurs at 30 degrees and substantial improvements in the fatigue limit occur at 35 to 40 degrees. This behaviour is to be expected since ESDU 81006 states that the point of maximum stress can be up to 35 degrees from the hole transverse axis. Thus, only if the relief angle is above about 35 degrees and the pin-to-lug contact point is away from the region of maximum stress will significant improvements in the fatigue strength be realised. Figure 6 is derived from Figure 4 and shows the effect of pin relief angle

* ESDU 90031 "Fretting fatigue".

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on fatigue limit. Once the relief angle is sufficient to remove the pin-to-lug contact point from the region of maximum stress the fatigue strength will cease to increase with increasing relief angle. In consequence the curve of Figure 6 should not be extrapolated.

The use of side relief to increase the fatigue strength is only possible if the pin is maintained in correct alignment with the axial load and if the reduced pin bearing area is satisfactory under the extreme load.

3.1.4 Lugs with treated bores (untreated pins)

Figures 7, 8 and 9 provide data on the effects of cadmium plating, surface hardening or overstraining the lug bores. Figure 7 indicates that cadmium plating may offer a slight improvement in the fatigue strength of FV 520B but this is supported by only twelve data points. Hardening the lug bores and inducing residual compressive stresses by the 'Sulfinuz'* treatment gives a definite improvement at all stress levels as shown by Figures 8 and 9. This therefore has the benefit over the use of extra clearance or side relief in that it yields significant improvements in the region $2.5 \times 10^5 < N < 10^6$. Figures 8 and 9 show that overstraining so as to produce residual compressive stress around the lug bore gives similar improvements to the 'Sulfinuzing'. The overstraining was achieved by pressing an oversize steel ball through the lug hole. The permanent strain induced was between 0.004 and 0.005 and was such that the residual compressive hoop stress approached the yield stress.

A few results on Figure 8 relate to lugs with overstrained bores with clearances of $e = 0.4$. Although they indicate good fatigue strength they are too few to support useful conclusions.

3.2 2½% Ni-Cr-Mo Steel

Data on this steel are presented in Figures 10, 11, and 12. Figure 10 provides data on untreated lugs and pins. Curves are drawn for three values of $K_e S_m / f_t$ through the points for lugs with $e = 0.06$ to 0.22 and $d = 12.7$ mm. The two data points for $d = 31.75$ mm fall well below the other data. The value of e is unknown for these. Their position is consistent with the effects of size observed in Section 3.1.1.

3.2.1 Effect of cadmium plating and zinc plating

Figure 11 shows the effect on dry assemblies of zinc plating both the pins and lugs and the effect of cadmium plating either the lug or the pin or both. In all cases the effect is to increase the endurance with maximum benefit when both the lug and pin are plated. These data are predominantly at one value of alternating stress, $K_e S_a / f_t = 0.25$, so that no direct indication is available on the effect of plating on the fatigue limit. The data for cadmium plated lugs and/or pins are also shown on Figure 12.

3.2.2 Effect of greases and anti-fretting compounds

Figure 12 shows the effect of various greases and anti-fretting compounds on endurance. All the data relate to lugs with e in the range 0.08 to 0.24 and to the single fatigue loading of $K_e S_a / f_t = 0.25$ at $K_e S_m / f_t = 0.63$. Figure 12 reproduces the data on Figure 11 at this stress level so that a full comparison can be made. A statistical analysis of the data labelled "various greases" on Figure 12 has shown them all to be of one population within which differences are not significant. The data suggest that cadmium plating is the dominant factor and that greases have only a very small beneficial effect on endurance. The results indicate that anti-scuffing compound gives a similar improvement to that obtained from cadmium plating both the pin and lug.

* 'Sulfinuz' treatment is a salt bath process, operated at about 570°C, which increases the amounts of nitrogen, sulphur and in some cases carbon, in the surface layers of ferrous materials and some alloys. The process increases the surface hardness (for FV 520B from 350 Vickers pyramid number untreated to 390 treated) and induces compressive residual stresses.

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3.3 1% Cr-0.55% Mo Steel

Data on this steel are presented in Figure 13. The value of e for these tests was not reported and has been assumed to be 0.2. Only a few results are available for each mean stress level, consequently only a single line is drawn through all the data points.

The data are significantly higher than those for the other materials (Figures 1, 10 and 14). This is due in part to the fact that Figure 13 relates to smaller lugs with pins of 5 mm diameter (see comments on size effect in Section 3.1.1).

3.4 Maraging Steels (18% Ni)

Data on maraging steels are presented in Figure 14. The data relate to untreated dry assembled lugs with $d = 12.7$ or 15.9 mm and e in the range 0.06 to 0.22. With the relatively small size differences no indication of size effect is possible. Three curves are provided for three different mean stress values, none of which shows a fatigue limit. All testing of unfailed specimens was terminated at about 10^8 cycles. Failures at the very low stress of $K_e S_a / f_t = 0.025$ are recorded at 2×10^7 and 9.5×10^7 cycles. Thus, the curves indicate a downward trend even as N approaches 10^8 cycles and no fatigue limit is apparent. This is consistent with the data for maraging steels presented in Figure 8 of ESDU 71027.*

4. DERIVATION

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

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* ESDU 71027 “Endurance of high strength steels (in bending)”.

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