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## Effect of size on fatigue strength of steel components

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## THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Stress Analysis and Strength of Components Committee which first met in 1964 and now has the following membership:

|                     |                                              |
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| Chairman            |                                              |
| Dr T.G.F. Gray      | — University of Strathclyde                  |
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| Mr D. Duval         | — Foster Wheeler Power Products Ltd          |
| Dr R.B. Heywood     | — A. Macklow-Smith Ltd                       |
| Dr L.C. Laming      | — Imperial College of Science and Technology |
| Dr G.G. Leckie      | — National Engineering Laboratory            |
| Prof. C.E. Turner   | — Imperial College of Science of Technology  |
| Mr J.V. Vint        | — NEI Parsons Ltd.                           |

The construction and subsequent development of the Data Item was undertaken by

|                |             |
|----------------|-------------|
| Mr D.F. Hunter | — Engineer. |
|----------------|-------------|

The person with overall responsibility for the work in this subject area is Mr M.E. Grayley, Head of the Strength Analysis Group.

## EFFECT OF SIZE ON FATIGUE STRENGTH OF STEEL COMPONENTS

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## EFFECT OF SIZE ON FATIGUE STRENGTH OF STEEL COMPONENTS

### 1. INTRODUCTION

This Item presents data on the effect of relative scale and the influence of thickness on fatigue strength. Three main situations concerning size effect are covered; (a) plain components without stress gradients, (b) components having stress concentrations or stress gradients and (c) welded joints. These three categories present differing sets of circumstances that affect fatigue strength. In the absence of a stress gradient there is unlikely to be a discernible trend resulting from size effect, and other factors, such as heat treatment and surface finish, are likely to be more significant. In all types of component, size effect is most significant in cases where the failure crack initiates and grows in a region of stress gradient. Provided that all the relevant data are available, application of linear elastic fracture mechanics techniques should take full account of the influence of size (that is, relative scale) on the growth of an existing crack\*.

### 2. NOTATION

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

|            |                                                                                                                                                                         |                                     |                                         |
|------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|-----------------------------------------|
| $a$        | crack length (for crack free to extend at one end only)                                                                                                                 | m                                   | in                                      |
| $a_0, a_f$ | initial and final crack lengths, respectively                                                                                                                           | m                                   | in                                      |
| $C$        | coefficient in simple crack growth rate law defined by $da/dN = C(\Delta K)^n$                                                                                          | $m\left(\frac{m^{3/2}}{N}\right)^n$ | $in\left(\frac{in^{3/2}}{lbf}\right)^n$ |
| $d$        | notch root diameter                                                                                                                                                     | m                                   | in                                      |
| $D$        | diameter                                                                                                                                                                | m                                   | in                                      |
| $f_p$      | proof stress of material                                                                                                                                                | N/m <sup>2</sup>                    | lbf/in <sup>2</sup>                     |
| $f_t$      | tensile strength of material                                                                                                                                            | N/m <sup>2</sup>                    | lbf/in <sup>2</sup>                     |
| $K_f$      | fatigue strength reduction factor, ratio of fatigue limit of plain specimen to that of notched specimen, where fatigue limit is based upon minimum cross-sectional area |                                     |                                         |
| $K_t$      | elastic stress concentration factor                                                                                                                                     |                                     |                                         |
| $\Delta K$ | stress intensity factor range (equal to $\Delta S(\pi a)^{1/2}\alpha$ )                                                                                                 | N/m <sup>3/2</sup>                  | lbf/in <sup>3/2</sup>                   |
| $L$        | total weld attachment length (see Figure 5)                                                                                                                             | m                                   | in                                      |
| $m$        | exponent indicating sensitivity to size, see Equation (4.2)                                                                                                             |                                     |                                         |
| $N$        | number of load cycles                                                                                                                                                   |                                     |                                         |

\* See Data Item No. 80036 "Use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components" and also the example calculations in other Data Items providing crack propagation rate data (see latest edition of "Validated Engineering Data Index").

|                    |                                                                                                 |                  |                     |
|--------------------|-------------------------------------------------------------------------------------------------|------------------|---------------------|
| $N_0$              | endurance of a joint having thickness $t_0$                                                     |                  |                     |
| $n$                | characteristic of slope of crack growth rate curve                                              |                  |                     |
| $P$                | applied load                                                                                    | N                | lbf                 |
| $S$                | nominal stress in absence of crack                                                              | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $\Delta S$         | nominal stress range in absence of crack                                                        | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $S_{am}(N)$        | fatigue strength of welded joint at given mean stress for endurance $N$                         | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $S_{am}(N_0)$      | fatigue strength of welded joint at given mean stress for endurance $N_0$                       | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $S_{a0}(\infty)_D$ | fatigue limit of specimen of diameter $D$ when $S_m = 0$                                        | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $S_m$              | mean stress                                                                                     | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $t$                | thickness                                                                                       | m                | in                  |
| $t_0$              | reference plate thickness                                                                       | m                | in                  |
| $w$                | weld leg length                                                                                 | m                | in                  |
| $\alpha$           | geometrical factor in stress intensity factor<br>(equal to $\Delta K/(\Delta S(\pi a)^{1/2})$ ) |                  |                     |

## Suffixes

1, 2 refers to diameters ( $D_1 \leq D_2$ )

### 3. PLAIN COMPONENTS WITHOUT STRESS GRADIENTS

#### 3.1 Sheet Having Uniform Thickness

Very few data are available concerning systematic tests on geometrically similar sheets or plates of differing thicknesses. Test data, for mild steel sheet, presented in Derivation 3, show no size effect for thicknesses up to 25.4 mm (1.0 in).

#### 3.2 Cylindrical Specimens Under Reversed Direct Stress

Size effect is slight in plain specimens under reversed direct stress. This can be seen from Figure 1 which shows no discernible trend of fatigue limit with specimen diameter. Other factors, such as surface finish, frequency of loading and specimen temperature, are more significant than size. Surface finish effects may be due to (a) surface roughness\* and (b) special treatments such as peening, rolling or plating.

\* See Data Item No. 74027 "The effect of surface roughness on the fatigue limit of steels (at zero mean stress)".

## 4. COMPONENTS HAVING STRESS GRADIENTS

It has been found that size effect is significant in components containing stress gradients. The fatigue strength is greatly affected by the form and degree of the stress gradient. The nature of size effect is such that for geometrically similar components the fatigue strength of the largest component is the lowest.

### 4.1 Plain Cylindrical Specimens Under Reversed Bending Stress

A plain cylindrical specimen under bending loading will experience a stress gradient the magnitude of which, for a given maximum surface stress, is inversely proportional to specimen diameter. Therefore, fatigue strength in bending is likely to be size dependent, with small specimens having less material working at high stress, and so having greater fatigue strengths. Thus, fatigue strength decreases with increasing specimen diameter. At large diameters, where the stress gradient is small, the fatigue strength tends to approach a value equivalent to that derived from reversed direct stress loading. Size effect under reversed bending is illustrated in Figure 2 which shows fatigue limit ratio plotted against specimen diameter. It must be noted that the data on Figure 2 do not show any tendency to level off at the large diameter end of the figure, because this effect occurs well above the limit of 50 mm (2.0 in) diameter of the data. Although Figure 2 demonstrates that some size effect is likely, because of the scatter of results it is not necessarily true that a specific set of data will show a size effect. Many factors affect this scatter, one being that production techniques necessary for larger components sometimes give poorer surface finish, thereby lowering their fatigue strengths further. A linear regression analysis of the results yields the following relationship for diameters up to 50 mm (2.0 in).

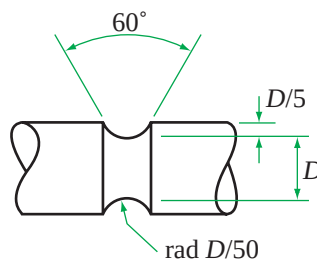
$$S_{a0}(\infty)_{D_2} = S_{a0}(\infty)_{D_1} \left( \frac{D_2}{D_1} \right)^{-0.05} \quad (4.1)$$

### 4.2 Cylindrical Specimens Containing Transverse Holes Under Direct Stress

Results of tests on geometrically similar cylindrical specimens containing transverse holes are shown in Figure 3. These confirm the trend that larger specimens have lower fatigue strengths and higher fatigue strength reduction factors. At very large specimen diameters  $K_f$  approaches  $K_t$ . A similar trend may be expected for other components containing stress concentrations. From Figure 3 the size,  $D$ , at which  $K_f = K_t$  is very large, illustrating the fact that it is the notch radius, in this case  $d/2$ , that controls the high stress region in which a fatigue crack initiates, and not  $D$ .

### 4.3 Cylindrical Specimens Containing Notches

Data are available (from Derivation 10) on size effect on the fatigue of notched medium carbon and low alloy steel specimens having the form shown in Sketch 4.1 subjected to reversed bending.



Sketch 4.1

Results from reversed bending tests have been shown to be difficult to assess since stress gradients through the specimens will be dependent upon both the diameter and the notch effect. However, the results of fatigue endurance versus specimen working diameter over the range of diameters tested from 5 mm to 40 mm indicate a relationship for the combined effect of stress gradients caused by bending and by the notch of the following form

$$S_{a0}(\infty)_{D_2} = S_{a0}(\infty)_{D_1} \left( \frac{D_2}{D_1} \right)^{-m} \quad (4.2)$$

Values of  $m$  and material properties for the three steels for which test data are available are given in Table 4.1.

**TABLE 4.1**

| <i>Material</i> | $f_p$<br>MN/m <sup>2</sup><br>(10 <sup>3</sup> lbf/in <sup>2</sup> ) | $f_t$<br>MN/m <sup>2</sup><br>(10 <sup>3</sup> lbf/in <sup>2</sup> ) | <i>Heat treatment</i>                               | $m$  | $K_t$ |
|-----------------|----------------------------------------------------------------------|----------------------------------------------------------------------|-----------------------------------------------------|------|-------|
| 35              | 235 – 275<br>(34 – 40)                                               | 520 – 569<br>(75 – 83)                                               | Annealed before machining                           | 0.08 | 3.75  |
| 40Kh            | 299<br>(43)                                                          | 736<br>(107)                                                         | Annealed at 840°C after turning but before grinding | 0.10 | 3.75  |
| 38Kh2N2MA       | 353 – 383<br>(51 – 56)                                               | 716 – 755<br>(104 – 110)                                             | Annealed before machining                           | 0.09 | 3.75  |

## 5. WELDED JOINTS

An over-estimate of fatigue strength will be made if results obtained from specimens of restricted size are assumed to be representative of much larger and thicker section components without making an allowance for the effect of size.

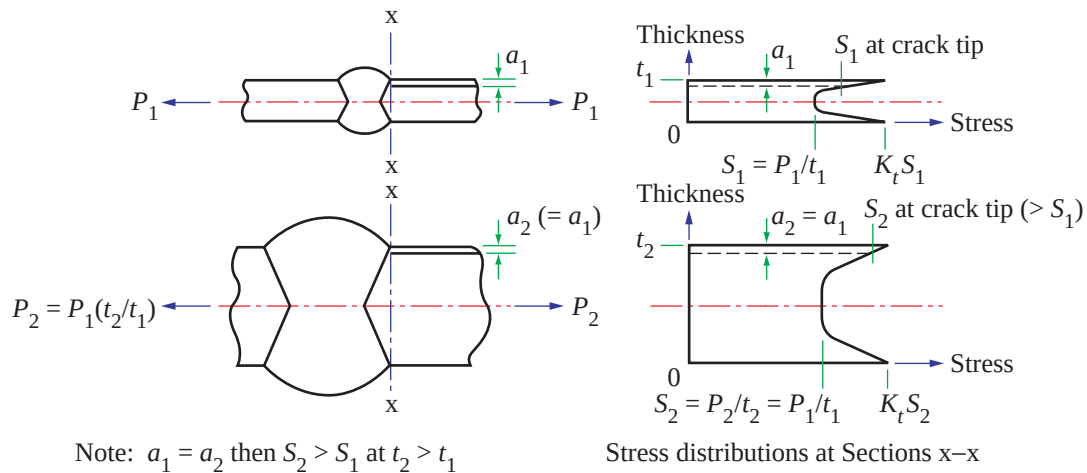
It is difficult to obtain unambiguous experimental evidence of the influence of plate thickness on the fatigue strength of welded joints. This is because in increasing the plate thickness a number of other secondary variables are often altered. For example, a higher level of residual stresses is associated with a larger plate thickness and this, in turn, increases the likelihood of fabrication cracks.

The inherent characteristics associated with a weld and the heat affected zone, such as intrusions at the weld toe, act as regions in which fatigue cracking is initiated, and, in consequence, virtually all of the fatigue life is occupied by the propagation of cracks. Because of this, fracture mechanics can be used to estimate the fatigue endurance of a welded joint. However, as Section 5.3 notes, much of the basic information required for such an estimate is difficult to obtain. More information on fatigue in welded structures is available from Data Item No. 86013\*.

### 5.1 Geometrically Similar Welded Joints

Load-carrying welded joints of the same type in various plate thicknesses are typically geometrically similar. An example of two geometrically similar butt welded joints is shown in Sketch 5.1.

\* Data Item No. 86013 "Guide to the use of Data Items on the fatigue strength of welded joints in steels".



**Sketch 5.1 Stresses in geometrically similar joints, containing a crack of the same depth**

If the loads are appropriately scaled, the stress concentration fields will exhibit the same maximum level, that is  $K_t S$ , but a steeper stress gradient will occur in the thinner joint. If the initial crack length (assumed to be a weld toe defect) is of the same absolute size in each joint, the initial crack in the thicker plate will experience a larger value of the crack stress intensity factor range  $\Delta K$ , and therefore faster crack growth. In the thicker plate the crack will also reach a larger absolute size while still remaining in the zone of influence of the stress concentration. It is assumed that the final crack length that is either acceptable or causes failure is the same fraction of the thickness,  $t$ , in each case. However, when calculating the total life of a component containing a small initial crack, the final crack length has little influence on the total life. This is because the vast majority of life is accrued at small crack lengths, while the larger crack lengths grow very rapidly and contribute little to the total life. Thus, the crack in the thicker plate experiences a shorter overall life since the increased plate thickness does not compensate for the increased crack growth rate.

## 5.2 Experimental Data

Figure 4 shows the effect of size, as represented by plate thickness,  $t$ , on the relative fatigue strength for a variety of welded joints. The curves have been normalised to a reference thickness,  $t_0$ , of 22 mm (0.87 in)\*. Separate curves are provided for bending and axial loading. The curves are each derived from the results of fatigue tests on complete joints and all relate to an endurance of  $2 \times 10^6$  cycles. The curves terminate at the limits of the experimental data. Extrapolation beyond the ends of the lines is not recommended.

The curve of Figure 4 for joints subject to bending is considerably steeper than the curve for axial loading. This is probably a result of the stress gradient effects described in Section 4.

\* Data on the fatigue strength of various types of welded joint may be located by reference to the latest edition of the "Validated Engineering Data Index".