2. Fatigue of Steel Structures

Fatigue failure may occur when a cyclic tensile stress is applied to a component or structure. Failure is progressive, each stress cycle causing incremental growth of the fatigue crack. Fatigue crack surfaces are often characterised by regular steps, each step being due to the crack growth during one cycle.

Fatigue life is expressed as the number of cycles N, endured by the component at a particular cyclic stress range. It is influenced by what is used to define the end of life. In the case of small polished samples, the end of fatigue life is the point at which cracks are observed. In a real structure or component, it can be when the loss of cross section causes ductile overload or it may be when brittle failure occurs, or when leaks occur.

Fatigue strength S, is the cyclic stress range that leads to failure at a particular number of cycles. The relationship between fatigue strength and life is expressed on an S-N or Whöler curve, a plot of cyclic stress range against number of cycles to failure. These curves are usually Log-Log plots that approximate straight lines.

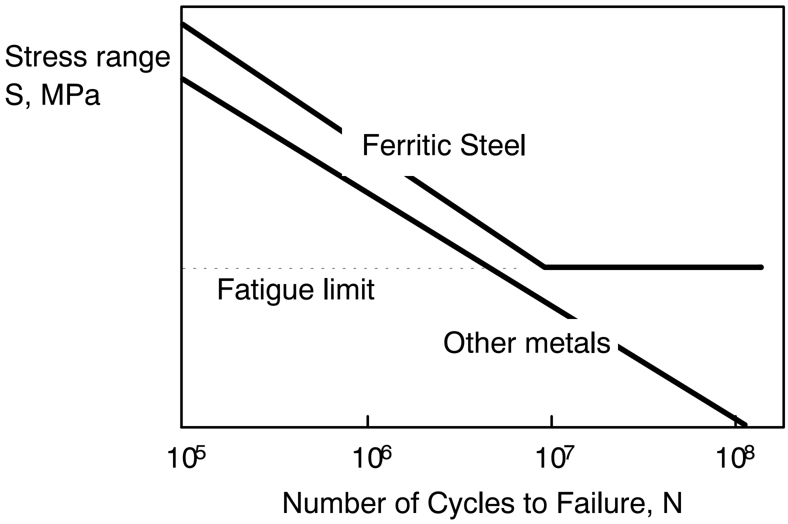

Figure 23 S-N Curves for Ferritic Steel Showing Fatigue Limit

2.1. Fatigue of Polished Samples

Most fatigue testing has been done on small, circular section polished samples, which are considered defect-free. One fallacy is that these tests are studying initiation of fatigue failure, as failure is only judged to have occurred when a crack is observed. In fact all materials contain flaws, even though they maybe on a sub-microscopic scale. Low stresses do not initiate flaws, whether cyclic or not. Fatigue stresses can only cause the propagation of existing flaws. Careful examination of polished samples shows microscopic flaws increase in size, under the influence of cyclic stress even at low stress ranges. Crack growth may stop when the crack tip reaches a metallurgical obstruction, such as a grain boundary or second phase particle. Higher stresses can cause the crack tips to overcome these obstacles.

Polished specimen tests are therefore influenced by material-dependent properties, such as grain size and second-phase particle distribution. They have been used to provide data for comparing materials, which is misleading when considering life of real structures. The use of yield or tensile strength factors to design against fatigue failure grew out of these tests. It will be shown that this concept is misleading and possibly dangerous.

Tests on smooth samples of ferritic steels exhibit a fatigue limit of roughly half the yield strength as is shown in Figure 23. Below this stress, fatigue failure was not observed. Similar tests of other materials exhibit no fatigue limit; and at low levels of cyclic stress, failure will eventually occur at a large number of cycles. The fatigue limit for steels now believed to be dependent on a number of factors. Firstly the limit disappears in corrosive conditions, and even brief exposure to corrosive conditions can cause its removal. Secondly, the fatigue limit is dependent on the size of the initial flaw that propagates to failure. Thirdly, failure at stress ranges below the limit has been observed beyond 10^8 cycles.

2.2. Fatigue Tests of Real Structures

Over the past forty years, extensive fatigue testing has been undertaken on large test pieces representing structural connections. At first, this testing was undertaken on welded structural elements, but more recently, it has been extended to bolted structures. Much of this testing was coordinated by Maddox and Gurney at The Welding Institute, and they formulated a set of guidelines based upon their extensive data. This was published as a proposed set of rules in 1976 [Reference 1]. This data is presented in the form of an S-N plot in Figure 23, and by Equation 1 for which the constants are given in Table 2.

The factors that determine fatigue life of real structures are as follows:

- The applied cyclic stress ranges, their frequencies and directions in relation to the crack. Original tests considered principal (normal) stresses.
- The mean tensile stress
- The geometry of the structure or component
- The depth of the notch that initiates failure, and the size of the pre-existing flaw at this location
- The tip radius of this flaw
- The size of the fatigue crack when fatigue life is considered to be complete
- Environmental factors - temperature and corrosion.

Real structures were found to have widely scattered fatigue lives. Life was dependent more on the notch effect of structural shape changes (such as attachments or holes) and on welds, than on material type. As an example of the wide scatter of the data, samples with a Class-C detail subjected to a 150 MPa stress range would have a mean life of 2.6 million cycles. However, the test results will be scattered over a range of 1 million to 6.7 million cycles, which is plus and minus two standard deviations from the mean.

$$\log_{10} N = \log_{10} a - d\sigma + m \log_{10} S \quad \text{Equation 1}$$

Their concept was to rate structural detail types for fatigue performance and then use one of a set of generalised S-N curves for predicting life of each standard detail category. In their original work, details were categorised with letters A, B, C, D, E, F, F2, G and W. A S-N curve with its equation was presented for each detail category. Each category was carefully described.

Table 2 Constants in Equation 1 for Various Detail Classes

Class	a	m	Standard Deviation σ Log σ
B	2.343×10^{15}	-4.0	0.1822
C	1.082×10^{14}	-3.5	0.2041
D	3.988×10^{12}	-3.0	0.2095
E	3.289×10^{12}	-3.0	0.2509
F	1.726×10^{12}	-3.0	0.2183
F2	1.231×10^{12}	-3.0	0.2279
G	0.566×10^{12}	-3.0	0.1793
W	0.368×10^{12}	-3.0	0.1846

The highest fatigue performance is achieved with unwelded plain material with all surfaces machined and polished. Reference 1 describes this as a Class-A detail, but as this surface finish is unrepresentative of real structures, no data was presented. As the detail complexity increases from B to W, the fatigue life is reduced. As an example of the effect of structural shape, a Category-B joint was found to have a mean fatigue life of 23 million cycles when subjected to a cyclic stress of 100 MPa. With the same stress range, a Category-W detail has a mean life of only 370 thousand cycles.

The original data, augmented by more recent results, have since been used as the basis for the current British Standard BS 7608 [Reference 2]. Two new detail categories are added, ‘T’ for the node joints in tubular structures and ‘S’ for shear studs embedded in concrete. The original experimental data is still used. For safe design of structures, the S-N curves are those based on the mean life minus two standard deviations. This will give a 96% confidence of survival. If it is desired to monitor the growth rate of an identified fatigue crack, the line for the mean life can be used.

The same approach has become the foundation of most modern codes for designing to avoid fatigue failure issued since, such as those used by AS 3990 and AS 4100 [References 3 and 4].

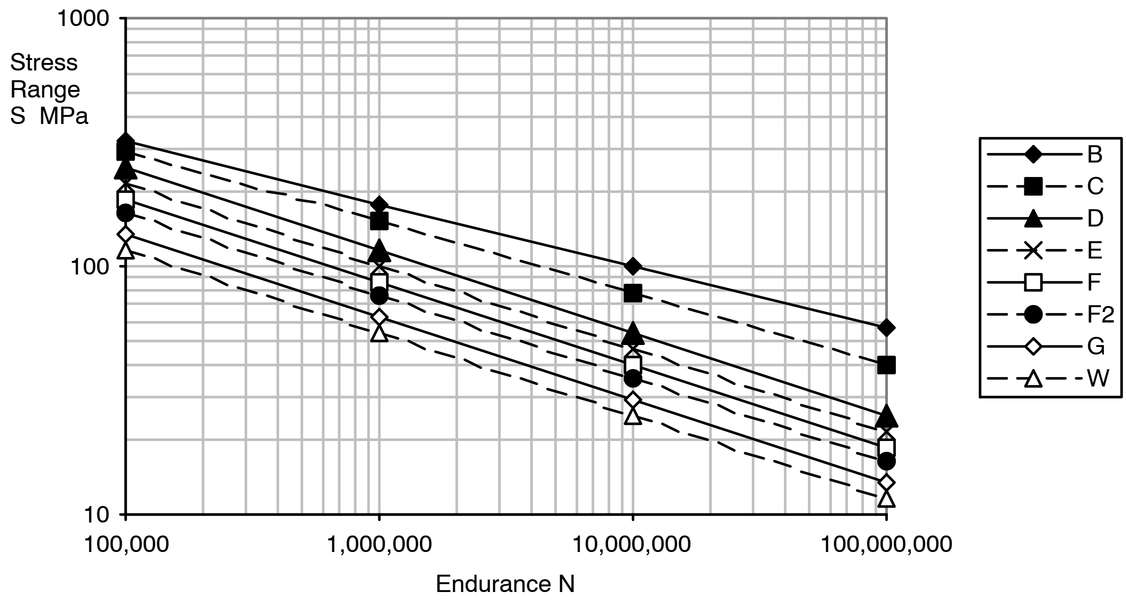

Figure 24 S-N Curves Derived from Experimental Data Minus 2 Standard Deviations (95% confidence of survival)

2.3. Fatigue Design using AS 4100

AS 4100 follows a similar concept to BS 7608, but with some significant differences. The approach is simpler, but does not account for some factors detailed in BS 7608. The S-N curves used in AS 4100 are almost identical to those in Eurocode 3, which is issued as DIN 4133 in Germany.

The main difference to the British approach is that a number is used to identify the detail categories, rather than a letter. The number, S_{CAT}, is the stress range (MPa) that gives a life of two million cycles. Therefore, Detail Category 125, when exposed to a stress range of 125 MPa has an allowable fatigue life of two million cycles. One other important difference is that the lines have two slopes. Up to 5 million cycles, the slope ('m' in Equation 1) is –3, from then on the slope is –5. A fatigue limit (called a cut-off limit in the standard) of 10^8 cycles is assumed. Instead of the 11 detail classes in BS 7608, AS 4100 has 15 Detail Categories. The third difference is that instead of presenting experimental data, the curves are agreed by a panel of experts with access to the original data. They thus represent what is considered reasonable practice.

2.3.1. Method of Determination of Fatigue Life

Each detail of the structure should be considered. Its category should be determined from the table in AS 4100. These detail categories are briefly described below, but a fuller description is given in AS 4100. If it is not possible to categorise a detail, it can be considered Category 36.

The acting stress range, S_{ACT}, is determined at each detail of interest. Stress range is the difference between the maximum and minimum stress, or it is twice the amplitude as shown on Figure 34. It is beyond the scope of this publication to consider how stresses are calculated. The reader is referred to AS 4100 or other relevant standards for further details. The structure should be designed first for static loading and then checked for fatigue performance. The cyclic stresses to be considered are principal (normal) stresses, and should account for the combined effect of bending or shear. If the S_{ACT} is less than the cut-off limit shown in Figure 25, fatigue can be ignored. The design categories take account of local stress concentration developed by the detail itself, so the stresses considered should be nominal stresses adjacent to the detail under consideration. The presence of the detail is ignored when calculating this stress. However where joints are situated next to regions of stress concentration because of other effects, such as gross shape changes, these stress concentrations have been taken into account.

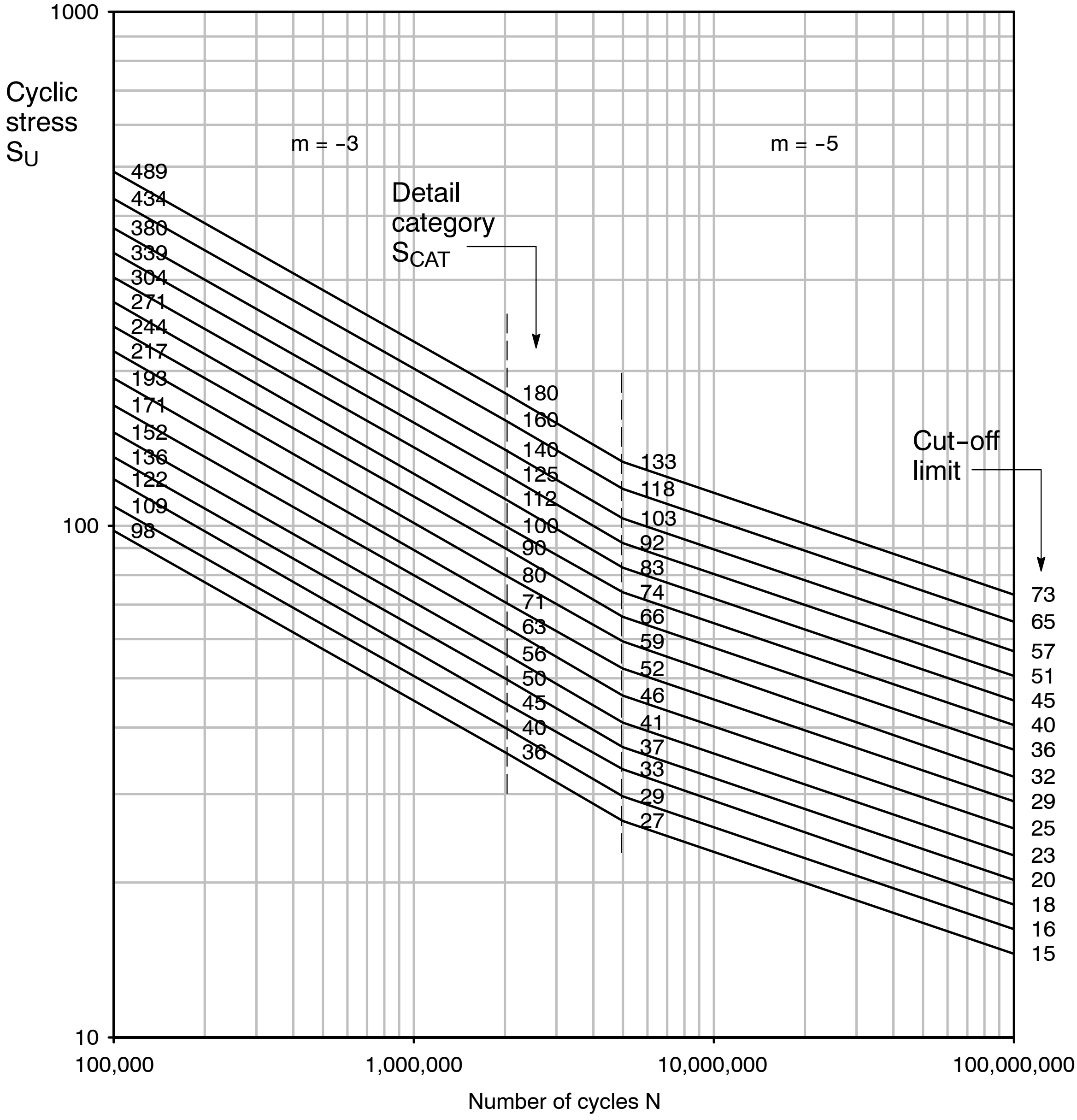

Figure 25 S-N Curves for Normal Stress (AS 4100)

Next, the number of cycles of the stress range, N, over the life of the structure is determined at the detail of interest using some rational counting method. Many specific codes (such as those for cranes and bridges) specify how cycles should be counted.

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Successful Welding of Steel Structures

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