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Long Endurance Fatigue of Steel Reinforcement

Résistance à la fatigue à long terme des aciers d'armature

Langzeitfestigkeit von Bewehrungsstählen unter Ermüdungsbeanspruchung

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SUMMARY
The fatigue performances of steel reinforcing bars have been studied for both axial loading in air and 4-point bending in concrete. The effects of type of reinforcement, bar diameter, butt-welding and random loading have been evaluated. It has been shown that the performances can be described by a power law expression. There is no evidence of the commonly assumed endurance limit at 2 million cycles, and fractures can occur at longer endurances and lower stresses.

RESUME
Les caractéristiques de résistance à la fatigue des aciers d'armature ont été étudiées à la fois sous charge axiale à l'air libre et sous flexion pour des barres enrobées dans des poutres en béton. On a évalué les effets du type d'armature, du diamètre des barres, du soudage en bout et des charges aléatoires. On a pu définir ces caractéristiques par une fonction exponentielle. Il n'existe pas de preuve de la résistance à la fatigue qui est généralement supposée exister à 2 millions de cycles, et des fractures qui peuvent se produire pour des endurances plus élevées et des contraintes plus basses.

ZUSAMMENFASSUNG
Das Ermüdungsverhalten von Bewehrungsstählen ist für axiale Belastungen in nicht einbetoniertem Zustand und in Biegeträgern untersucht worden. Die Einflüsse von Bewehrungsart, Stabdurchmesser, geschweissten Stössen und Zufallsbelastungen wurden berücksichtigt. Es wird nachgewiesen, dass das Ermüdungsverhalten durch eine Exponentialfunktion beschrieben werden kann. Die generell angenommene, ab 2 Millionen Lastwechseln auftretende Dauerfestigkeit wurde nicht bestätigt. Ermüdungsbrüche können bei grösseren Lastwechselzahlen und kleineren Spannungen auftreten.

1. INTRODUCTION

The behaviour of steel reinforcement bars subjected to mechanical fatigue loading has been comparatively well researched in the past and the state-of-the-art has been reviewed [1]. The effects of features such as type of test, type of bar, mean stress, corrosion and welding have been studied and the resulting trends in behaviour are fairly well understood in a qualitative sense. In recent years the volume of research has expanded due to the need for more information for new and revised design codes. There has also been an increased awareness of fatigue through service experience with welded steel structures both land-based and off-shore. The material science research has not however been matched by an equivalent volume of work related to loading of structures. In consequence, much of the available data are for conditions convenient to study in the laboratory but not fully simulative of service behaviour. This is illustrated in fig 1 for a typical

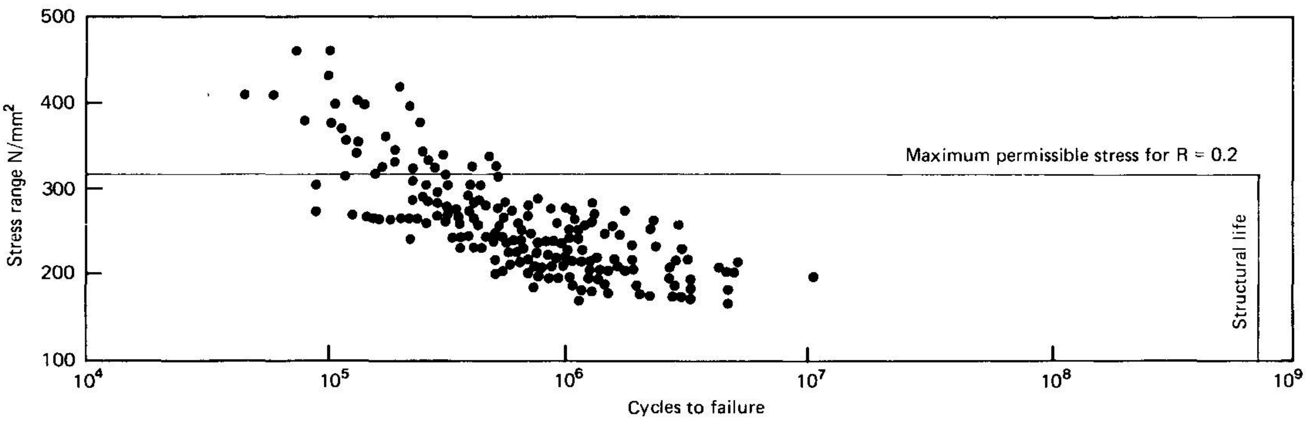

Fig.1 Published data in relation to permissible stress and structural life

set of published data; the design limits are shown as boundaries of stress range and number of cycles as used in the design of highway bridges. Much of the data are at unduly high stresses so that they tend to be limited to 10^7 cycles whereas designs are assessed for up to 7.10^8 cycles and it is clear that more work is required for conditions relevant to service. In addition, there is a general lack of quantitative information about the features that influence fatigue. For example, it is generally accepted that performance decreases with increase in bar size but there are insufficient data to enable this dependency to be expressed numerically. Different investigations have produced differing quantitative results due mainly to the fact that fatigue performance is strongly dependent on aspects generally beyond the investigator's control. There can be relatively wide experimental scatter for tests on a single supply of material and additional differences between bars from different casts or produced by different rolls. In the case of bar size for example it is not sufficient to compare the performances of a single supply of bars of each diameter but it is preferable to test from several sources. In assessing performance it is necessary for designers to know the minimum properties of available reinforcement when used under service conditions rather than mean properties.

In order to improve the knowledge of behaviour in service, an investigation has been undertaken in which reinforcement from different suppliers has been tested under conditions relevant to concrete highway bridges. The tests have been mainly on 16 mm diameter bars manufactured by different methods and with different types of rib. The loading has been axial in air and flexural in concrete to provide a definitive relationship between the two types of test. Endurances were up to 10^8 cycles. The tests were mainly with constant-amplitude cycles but a small number were conducted with variable-amplitude loading. Data were also obtained for butt welded 16 mm bars and larger diameter, 32 and 40 mm, bars.

2. AXIAL TESTS IN AIR

2.1 Test method

Axial testing is favoured by many investigators because it can be conducted at relatively high frequencies so that it is inexpensive in terms of machine occupancy. It has a major drawback in that it is difficult to grip the bars so that it is necessary to take special precautions to ensure that fractures occur in the central section of the gauge length [1]. The technique used in the present investigation involved casting the ends of bars into pots containing low melting point alloys and is described in ref [2]. The tests were conducted at frequencies of up to 150 Hz. Normal care was taken to ensure that loading was axial. The loading was wholly tensile and the ratio (R) of minimum to maximum cyclic stress was 0.2.

2.2 Performance of 16 mm bars

The fatigue data for 16 mm diameter bars are shown in fig 2. Six types of bar

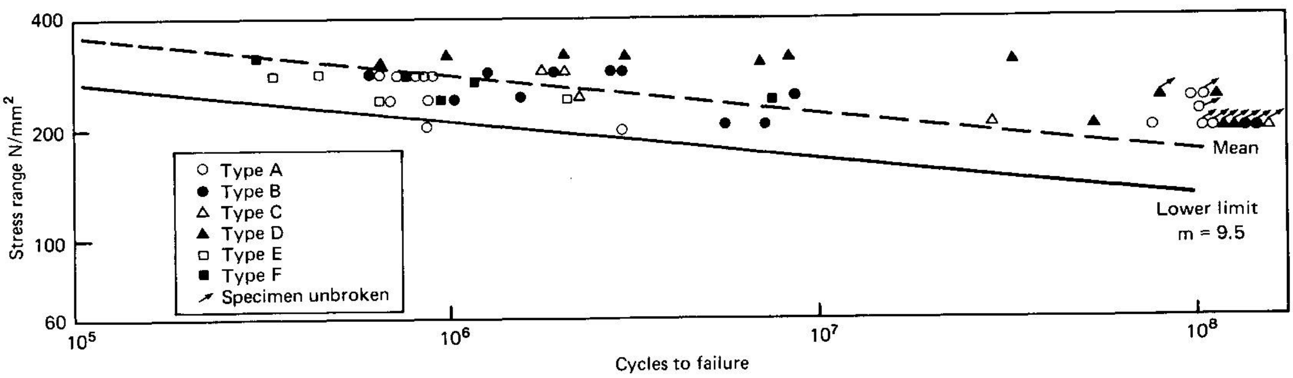

Fig.2 Performance of 16mm bars tested axially

were tested, details of chemical compositions and the specifications are given in ref [2]. Type A was the cold-worked material Torbar. Type B was cold-worked square-twisted. Types C, D and E were hot-rolled deformed material, the latter having been obtained in a severely rusted condition. Type F was re-rolled scrap material of high carbon content.

The results are shown in fig 2. With the exception of Type D, the fatigue performances of the different types of bars were similar. There was considerable experimental scatter, particularly for the two types of cold-worked material, types A and B, and this may have obscured small differences between them. Type D was superior to the others. The performance of the rusted bars was a little low but the difference was insufficient to attach any significance. Although it was not possible to obtain comparable bars as-manufactured, it is evident that the rusting had less effect than is normally expected.

There is no evidence of the fatigue limit which is usually considered to develop at about 2 x 10^6 cycles. Five fractures occurred at beyond 10^7 cycles, the longest being at 97 x 10^6 cycles. Tests which survived 10^8 cycles were stopped unbroken but were treated as broken in analysis of the data. Tests which failed at the grips or were stopped short of 10^8 cycles for other reasons have been excluded.

With the exception of Type D, the bars were treated as a single group and the relationship between stress range (σ_r) and cycles to failure (N) was assumed to be of the form $N \sigma_r^m = K$. A regression analysis of Log N on Log σ_r (treating N as the dependent variable) was obtained and the mean line and lower 95 per cent confidence limits are shown in fig 2.

2.3 Performance of 32 and 40 mm bars

Tests were conducted on two sizes of larger diameter bars (32 and 40 mm) for types A and G material. The latter was hot-rolled deformed material of 40 mm diameter having a specification similar to type C but supplied by a different manufacturer. It had a fatigue performance generally lower than others in the group. The performance of 32 mm bars of type A material was significantly better than the rest of the group. Many of the tests were stopped at 10^7 cycles because of the expense of running long endurances at the high loads demanded by the bigger diameter bars. Consequently the results are less balanced than for 16 mm bars and the longest number of cycles to failure was only 9×10^6 cycles. Data from comparable tests conducted by BSC [3] are also included in the appraisal and it is evident that performances are within the extremes bounded by the TRRL tests on types A and G, see fig 3.

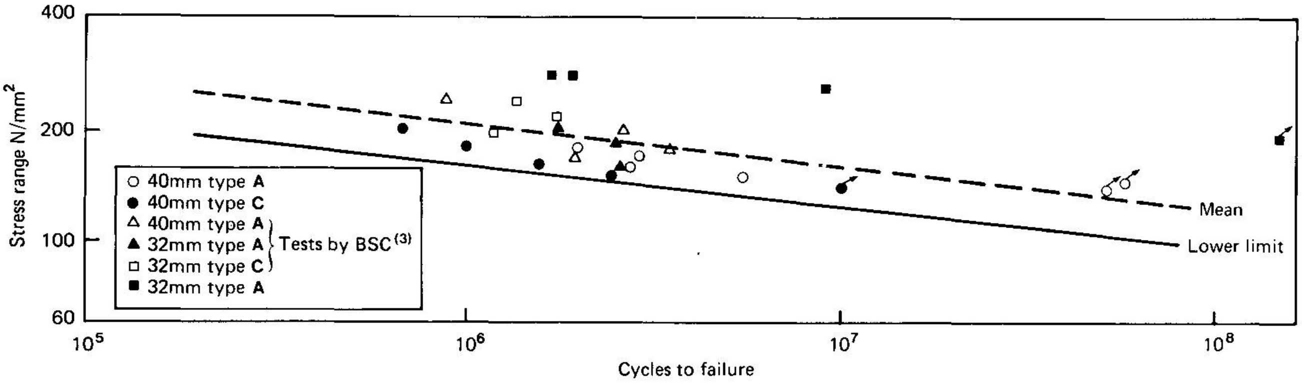

Fig.3 Performance of 32 and 40mm bars tested axially

The two sizes have been grouped together because there is insufficient evidence to treat them separately, see fig 3. The performance is significantly lower than for the 16 mm bars; the lowest stress to cause fracture was 150 N/mm^2 compared with 200 N/mm^2 for 16 mm bars.

2.4 Variable amplitude loading

Using a resonant machine (an Amsler Vibrophore) narrow-band random loading having an approximated Rayleigh spectrum was applied at 150 Hz. Type A continuous reinforcement bars of 16 mm and 32 mm diameter and 16 mm diameter bars with manual metal arc-welded joints (as described in ref [2]) were tested. The spectra are characterised by the RMS values of stress but it is emphasised that this is for convenience; for comparison with constant-amplitude data the effective stress should involve a higher exponent than 2. The results of the tests are shown in fig 4.

3. BENDING TESTS IN CONCRETE

Bending tests on concrete beams are generally considered to be more relevant to service conditions than axial tests in air but take longer to conduct. A variety of types of beam have been used by different investigators but the most common arrangement is to have 4-point loading with a single bar as the main tensile reinforcement. This has been adopted for the present investigation.

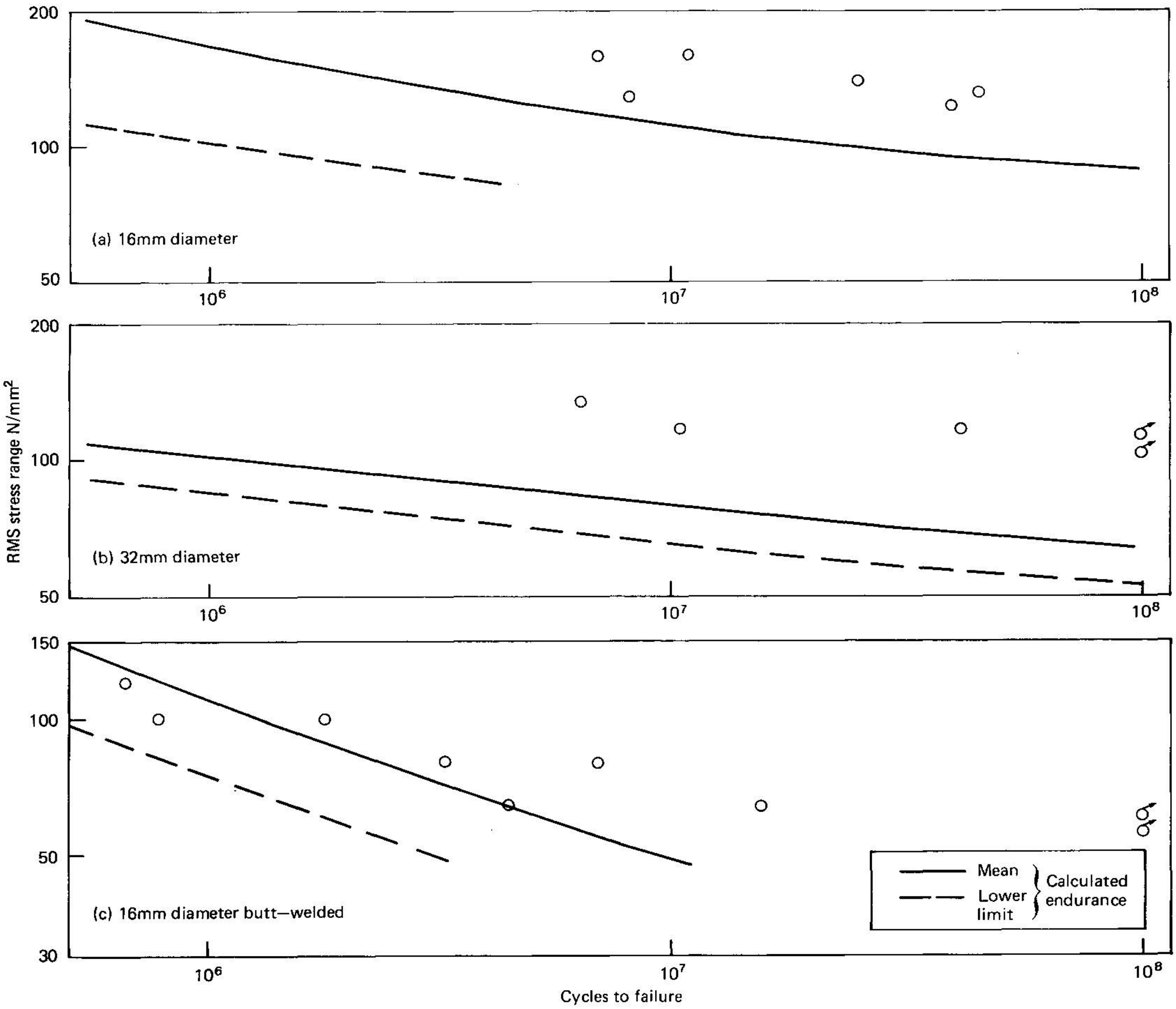

Fig.4 Variable - amplitude Rayleigh loading

The tests were conducted on 3.4 m concrete beams of rectangular cross section with 16 mm diameter reinforcement. It was considered essential to test at a frequency no greater than 3 Hz to avoid hysteretic heating at cracks in the concrete and at this frequency tests to 10^8 cycles last for 386 days. Ten special machines were constructed therefore because it is impractical to use commercial machines for such times.

In the tests, cracking occurred in the first cycle of load and grew till about 0.25×10^6 cycles when it stabilised. Because the rig is deflection controlled, adjustments were made during this period to ensure that the cyclic loads were maintained. After this stabilising period, the stiffness of the beams remained effectively constant till immediately before fracture and it was not necessary to make any further adjustments to the control.

The test programme was limited to bars of types A, B and D. The experimental scatter of the fatigue data was similar to that of the axial tests in air, see fig 5. There was little difference between the performance of Types A and B. Type D was a little stronger but only two of the tests led to fracture and the better performance is less clearly defined than for axial tests. As in the axial tests, there is no evidence of a fatigue limit. Two tests fractured at endurances

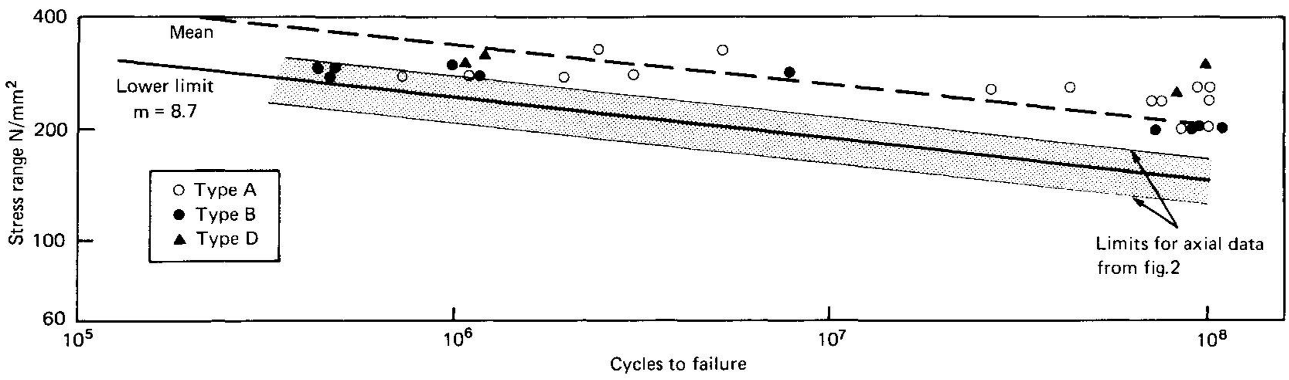

Fig.5 Performance of 16mm bars tested in bending

greater than 10^7 cycles; these were at a stress range of 260 N/mm^2. There were no other fractures at this stress or below.

The data for the three types of reinforcement bar were treated as a single group and a regression analysis of log N on Log σ_r was performed. The mean line and lower 95 per cent confidence limits are shown in fig 5.

4. COMPARISON BETWEEN AXIAL AND BENDING TESTS

There has been surprisingly little work to determine the effect of embedment in concrete. The type of test has been a matter of choice for different laboratories and investigators tend to be content with a given method once a technique has been developed. In consequence although it is generally held that the fatigue strength is greater when tested in concrete, there is no consensus on the qualitative relationship between the performances of axial tests in air and bending tests in concrete.

4.1 Continuous bars

Data obtained for the bending tests on continuous bars are shown in relation to the lower limit for axial tests in fig 5. It is evident that the axial tests exhibited lower fatigue performances; values of the lowest stresses to cause fracture were 200 N/mm^2 compared with 260 N/mm^2 for bending.

A representative selection of fracture surfaces were examined metallographically with special attention to the initiation sites. It was found that fractures of the axial tests originated from imperfections in the surfaces of the bars whereas those of the bending tests originated from positions close to the ribs. It is generally held that fracture of axial tests occurs from a worst flaw whereas the range of initiation sites in bending tests is restricted to the surface of the bar closest to the tensile flange in the vicinity of cracks in the concrete. Under these circumstances it is consistent that the axial tests exhibit a lower fatigue performance. The calculation of stresses is dissimilar in the two tests and may also be a factor in the differing performances. In the axial tests there is no problem but in bending tests it is necessary to make assumptions about structural behaviour. This merits investigation in its own right but broadly the approach is to treat the reinforced beams as in design calculations so that the fatigue performance can be interpreted in relation to structures without extra analysis.

4.2 Welded bars

Comparison of the performance of axial and bending fatigue is made for bars having manual metal arc butt-welded connections. It is evident that the axial tests have lower fatigue performances, see fig 6. Values of the lowest stresses to cause

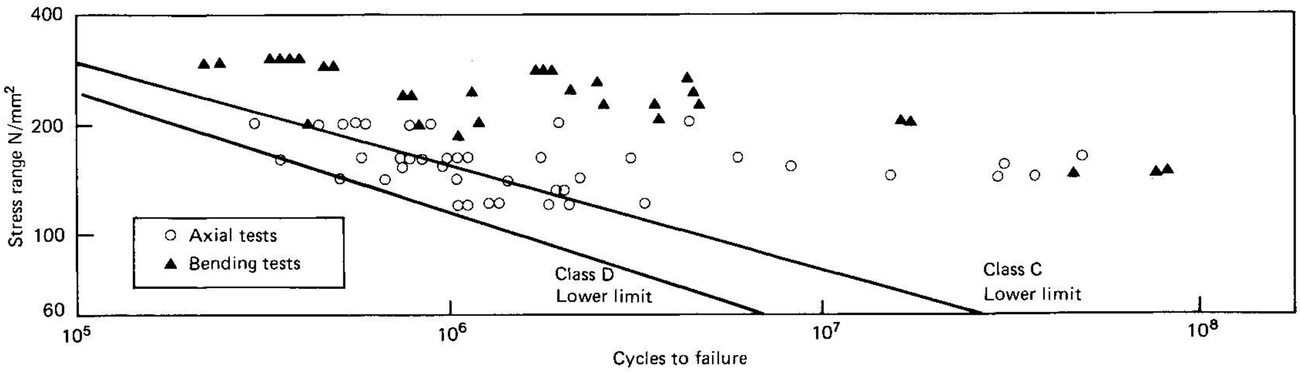

Fig.6 Performance of butt-welded bars

fracture are 120 N/mm^2 for axial tests and 140 N/mm^2 for bending. In the case of welded bars it is appropriate to relate performance to the joint classifications given in the design standard for bridges, BS5400 (ref [4]). For these data, the lower limits to performance can be represented by the Class D relationship for axial loading (see ref [2]) and the class C relationship for bending see fig 6.

Fractographic examinations of specimens from the respective tests indicated that the welds in the bending specimens were to a somewhat higher quality. In order to test whether this was a factor in the improved performance, four concrete beams were broken up and the welded bars removed. They were tested axially and the data were compared with the other axial data; it was found that the data were a little low in relation to mean performance and very low in relation to the beam tests so it can be concluded that the reason for the improved behaviour in bending is associated with the nature of the test rather than differing qualities of welding.

5. ANALYSIS OF THE FATIGUE PERFORMANCES

Analysis of the constant-amplitude data reported in this paper presents special problems because the tests are biased to long endurances where the behaviour is more sensitive to stress. The scatter in endurances is therefore wider than is normally found for higher stresses. Although there is a general trend for the stress exponents to increase at long endurances, there is no evidence to support interpretation in terms of an endurance limit and the associated abrupt change in slope of the σ_r-N curve. Moreover analysis involving an endurance limit requires identification of the discontinuity point and definition of the confidence limits but there is no consensus on the approach to either of these tasks.

In related work on welded plate connections it was shown that it is safer and more consistent with fatigue theory to represent constant-amplitude data with a power law expression having different exponents above and below 10^7 cycles, as in the design standard BS5400 [4]. Regression analyses of the data for 16 mm continuous bars gave exponents close to 9 (figs 2 and 5) and it is reasonable to incorporate this value in a general expression which may be denoted class R:

$$\sigma_r^9 \, N = K \tag{1}$$

The term K defines the relative positions of the fatigue curves. Values of K for the lower limits based on the data for 16 mm bars and derived for 32 and 40 mm are as shown overleaf. These lower limits are shown in relation to data for type A bars produced by other investigators in fig 7 and can be seen to give a realistic lower bound.

In assessing service lives, there is currently some debate about how to represent very long endurance data, beyond 10^7 cycles, and methods most commonly used are:

Type of loading	$K \times 10^{27}$	
	16 mm diameter	32 and 40 mm diameter
axial	0.75	0.11
bending	3.09	0.31

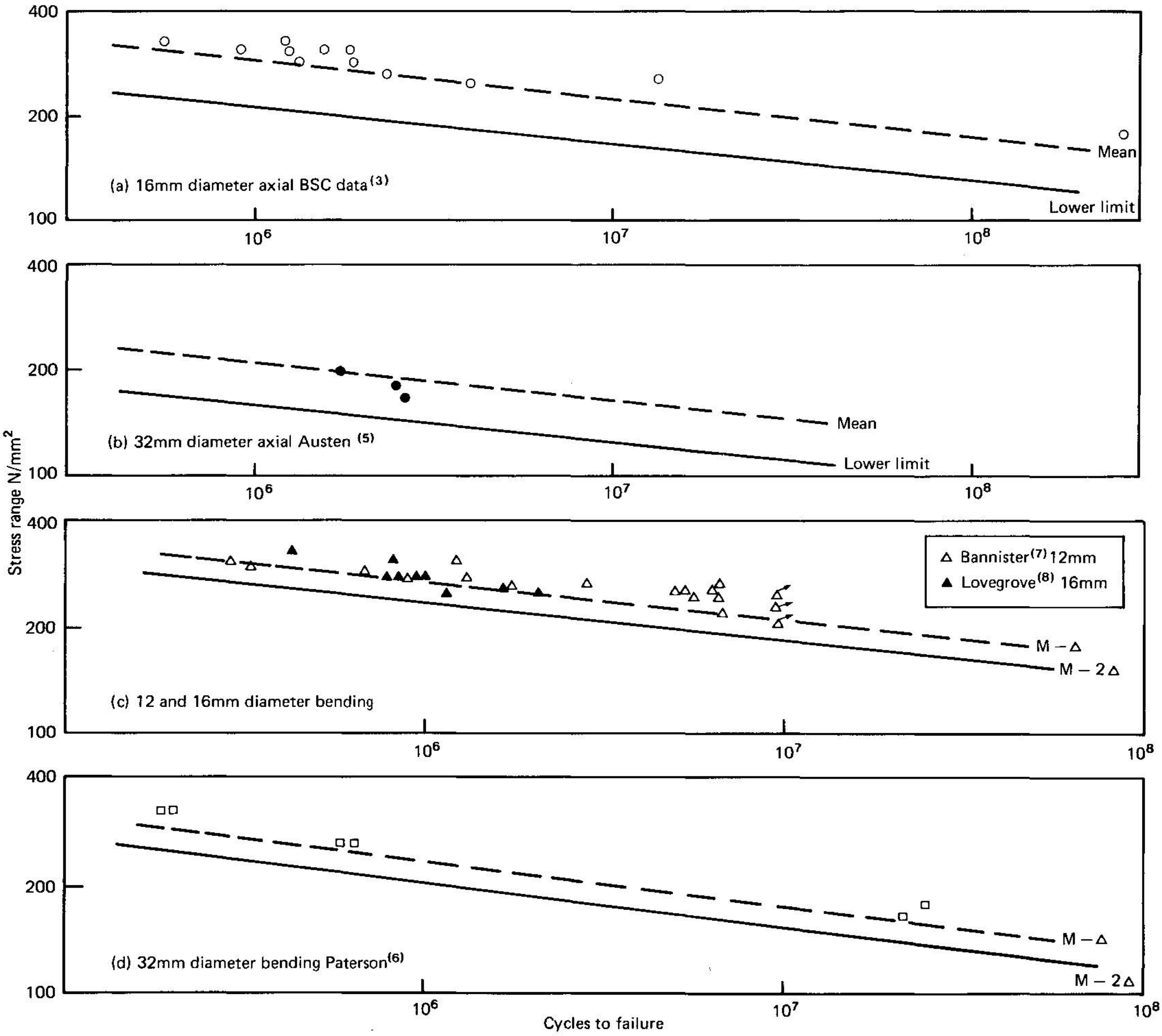

Fig.7 Comparison of performance curves with data from other laboratories : tests on type A bars

(i) $\sigma_r{}^m N = K$ to 2×10^6 cycles with an endurance limit at this point. It is assumed that no damage is caused by lower stresses and this is an optimistic or upper bound representation;

(ii) $\sigma_r{}^m N = K$ to 10^7 cycles with the stress exponent raised to $(m + 2)$ at $N > 10^7$. It has been shown that for welded joints this gives a reasonable allowance for the contribution of low stresses which become damaging after some crack propagation has occurred;

(iii) $\sigma_r{}^m N = K$ for all endurances. This is a pessimistic or lower-bound representation.

For welded joints which typically have values of the stress exponent (m) of 3, estimation of behaviour under variable-amplitude loading using the Palmgren-Miner concept is strongly dependent on the method used to represent constant-amplitude data at long endurances. This can be demonstrated for welded bars using the lower confidence limit of Class D. Endurances calculated for a theoretical Rayleigh distribution of loading and an RMS stress range of 30 N/mm^2 are 149 x 10^6 cycles for method (i), 17.7 x 10^6 cycles for method (ii) and 15.3 x 10^6 cycles for method (iii). It is evident that at this stress, method (i), the upper bound, gives a significantly longer endurance. At lower stresses differences between (ii) and (iii) increase.

For continuous bars having a stress exponent of 9, behaviour is relatively insensitive but it is appropriate to use method (ii) in order to have a uniform approach to all cases.

For the variable amplitude Rayleigh loading, endurances have been estimated by method (ii) using measured stress spectra (as distinct to the theoretical spectra) and the generalised relationships between σ_r and N. The estimated behaviour is conservative in relation to the test data particularly at the long endurances and confirms that the calculation procedure gives very safe values of endurance, see fig 4.

The common practice of interpreting constant-amplitude data as having a fatigue limit at 2 x 10^6 cycles is not only an upper bound representation but is unsupported by available long-endurance data. This can be illustrated for some of the data cited in this paper. If, instead of continuing till about 10^8 cycles, the tests were stopped unbroken at 10^7 cycles and an apparent endurance limit derived at 2 x 10^6 cycles, there are several cases where an unsafe situation would arise:

- In fig 7(a), for 16 mm bars tested axially, the apparent lower endurance stress is 240 N/mm^2. However, one out of the two tests unbroken at 10^7 cycles eventually failed; at 175 N/mm^2 and 260 x 10^6 cycles.
- In fig 6, for welded 16 mm bars tested in bending, the apparent endurance stress is 160 N/mm^2 whereas two out of five tests unbroken at 10^7 cycles failed; at 140 N/mm^2 and 75 x 10^6 cycles.
- In fig 7(d), for 32 mm bars tested in bending, the apparent endurance stress is 215 N/mm^2 whereas two tests unbroken at 10^7 cycles failed; at 170 and 180 N/mm^2 in about 20 x 10^6 cycles.

For the worst case, failure occurred at a stress which was about 30 per cent below the apparent endurance stress for tests not considered beyond 10^7 cycles.

6. CONCLUSIONS

The long endurance fatigue behaviour of six types of high strength reinforcement bars has been studied and quantitative relationships involving the main variables have been evaluated. The performances have been expressed by a power law as is commonly used for fatigue of welded plating ie $\sigma_r{}^m N = K$.

(1) The performance of different types of high strength bars are generally similar;

(2) For 16 mm bars, regression analyses have been made of the data and the value of stress exponent has been shown to be close to 9. This holds for both axial tests in air and 4-point bending in concrete;

(3) The performance of bars tested in bending is better than for axial loading. The fatigue relationships are of the same form but have different values of K; the stresses to produce a given endurance are about 20 per cent higher for bending;

(4) Fractographic examinations indicate that fatigue under axial loading tends to initiate at surface defects rather than in the vicinity of the ribs. This contrasts with the behaviour under bending fatigue which exhibited fractures having initiation associated with the ribs;

(5) The performance of larger bars, 32 and 40 mm diameter, is weaker than the 16 mm bars; the stresses to produce a given endurance are about 30 per cent lower;

(6) Butt welded bars have fatigue performances that are substantially weaker than

continuous bars. A lower limit to the fatigue performance can be represented by an expression having a different stress exponent; for axial loading this is given by Class D (m = 3) from the Design Standard BS5400 and for bending it is given by Class C (m = 3.5);

(7) The performances under variable-amplitude loading of both continuous and welded bars, can safely be calculated using the approach recommended for welded joints in BS5400 ie the stress exponent for the constant-amplitude σ_r-N relationship changed from m to m+2 at beyond 10^7 cycles and damage is summed using the Palmgren-Miner concept;

(8) Representation of the constant-amplitude performance by using data for endurances of up to 10^7 cycles and assuming that there is a fatigue limit at about 2 x 10^6 cycles ignores the possibility that tests at lower stresses can eventually fail if continued to 10^8 cycles or so. There have been comparatively few examples of data at long endurances but such as are available do not support the concept of a fatigue limit.

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 The data for narrow band random loading, given in fig 4, were produced by Arthur Greenan of National Engineering Laboratory under contract to TRRL.