BENDING FATIGUE OF HIGH-YIELD REINFORCING BARS IN CONCRETE

by

D S Moss

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ABSTRACT

Continuous and butt-welded specimens of three types of high-yield reinforcing bars have been fatigue tested in bending, in concrete, at a frequency of 3 Hz and to endurances up to $100 \times 10^6$ cycles. The test results have been compared with those from axial tests, in air, on the same types of bar.

The performance of continuous bars tested in bending was higher than that of similar bars tested axially in air, but it is unlikely that the same relationship would exist in all structures. It is suggested, therefore, that the fatigue properties of reinforcement be assessed for design purposes by axial tests in air.

The relationship between $\sigma_r$, stress range and $N$, cycles to failure, has been assumed to be of the form $N = \frac{1}{m} \log \sigma_r$, where $m$ is the inverse slope of the log $\sigma_r$ - log $N$ curve and $K$ is a constant. A modified form of the expression is proposed and values of $K$ are given, which are appropriate to bars up to 16 mm diameter.

It is suggested that all continuous high-yield reinforcement might be included in a single design classification and that the modified relationship be used for all sizes, provided that values of $K$ appropriate to bar diameter were used.

The performance of welded bars was reduced by the presence of a weld, but by a smaller amount than in axial tests. The Class C design curve of BS 5400 gave a better estimate of the performance of 16 mm diameter bars than Class D, to which welded reinforcement is assigned, but adoption of the higher classification is not recommended.

Fractographic examination indicated that, when tested in concrete, the rib pattern on continuous bars was influential in the positioning of the crack initiation site.

1. INTRODUCTION

In the TRRL programme of research into the fatigue behaviour of reinforcement, the primary objective has been to produce data, which can be used to predict the long-term performance of high-yield reinforcing bars in bridges. A bridge deck may experience up to $700 \times 10^6$ stress cycles in the course of its assessed life of 120 years and in order to represent a reasonable fraction of that life, tests to endurances of up to $100 \times 10^6$ cycles were necessary.

The investigation has been carried out in two stages. In the first, different types of high-yield reinforcement were tested under pulsating axial tension, in air. This part of the programme has been completed and reported. Axial tests, of this type, are the most convenient to carry out as only small specimens are required and the testing frequency is limited only by the capability of the available testing machine. Data can be collected comparatively quickly by this method, which is, therefore, the one most likely to be preferred for the routine assessment of fatigue properties. In axial testing, however, the conditions of test are not representative of the service environment of reinforcing bars and to relate axial test data to service performance, it is necessary to carry out a comparable series of tests on similar bars embedded in concrete beams.
In the tests, comprising the second stage of the investigation, the service environment was simulated by using the specimen bars as the main reinforcement of concrete beams, which were tested in bending. Three types of bar were studied and each type was tested in both the continuous state and as bars, which had been cut at the centre and rejoined by a manual metal arc butt-weld. The types selected had been tested axially in both the continuous and welded condition.

The introduction of concrete into the fatigue test programme made it necessary to limit the testing frequency to about 3 Hz to avoid any difficulties that might arise from the effects of hysteresis in the material particularly in the vicinity of cracks. At such a low frequency tests to long endurances took a very long time to complete; for example a test to $100 \times 10^6$ cycles required over one year. It was essential, therefore, that a number of tests should proceed simultaneously to enable data to be acquired at a reasonable rate. The test programme was preceded by the design and development of a special purpose testing machine (see Appendix), which was sufficiently inexpensive to allow ten to be constructed.

2. SPECIMENS

2.1 General

The tests were conducted on concrete beams made to the design shown in Figure 1. The specimen bars were used as the tensile reinforcement in the beams and were either in a continuous length, as manufactured, or had been cut and rejoined by a manual metal arc butt-weld at the centre.

2.2 Reinforcement

The physical properties of the high-yield reinforcing bars have been fully described in reference 1, in which the types used in the beams were identified as follows:

- Type A. Cold-worked, deformed.
- Type B. Cold-worked, chamfered square-twisted.
- Type C. Hot rolled.

The bars were all 16 mm diameter and were part of the same batches of material, from which the axial test specimens were selected. Type C material was not included in the second part of the investigation because it was no longer in production and only a small sample, sufficient for axial testing, was obtained. Before they were incorporated into the concrete beams, the bars were lightly wire brushed to remove any loose rust or scale and were also degreased, if any oily contamination of the surface was evident.

2.3 Concrete

The beams were manufactured under external contract, using the mix given in Table 1. The beams were made with more care than is usually associated with the commercial production of such units, but they were not all manufactured at the same time and some variation in strength was observed. A total of 118 beams were produced, for which the mean value of the cube strength at 28 days was $57.6 \text{ N/mm}^2$ and the standard deviation $3.95 \text{ N/mm}^2$. 2
TABLE 1
Concrete mix

<table>
<thead>
<tr>
<th>Component</th>
<th>kg/m³</th>
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<tbody>
<tr>
<td>Rapid hardening Portland cement</td>
<td>399</td>
</tr>
<tr>
<td>Zone 2 Tallington sand</td>
<td>719</td>
</tr>
<tr>
<td>10 mm Hoveringham aggregate</td>
<td>1223</td>
</tr>
<tr>
<td>Water/cement ratio 0.47:1</td>
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</tbody>
</table>

The beams were not moved for a period of 28 days after casting and in practice, the shortest period between casting and the commencement of test was approximately 15 weeks.

2.4 Welding

The specimen bars were butt-welded by the manual metal arc process, using the procedures and materials described in reference 1. The welding was carried out by the same contractor, who had prepared the axial test specimens and the bars were used in the 'as welded condition', as in the axial tests.

3. TESTING

3.1 Test procedure

The beams were subjected to repeated bending at a frequency of 3 Hz. under constant load amplitude, using the testing machine described in the Appendix. The loads were calculated by the modular ratio method, using the values of short term elastic modulus for concrete given in CP 110·Part 1:1972\(^2\) and BS 5400·Part 4:1978\(^3\). At each stress range, the loads were arranged to produce in the reinforcement a constant stress ratio of 0.2, the same value as used in the axial tests. (The stress ratio is min. stress ÷ max stress.)

4. RESULTS AND DISCUSSION

4.1 General

In all tests the first cycles of loading caused cracking of the concrete in the tensile zone of the beams. The combined effect of the development of the cracks and creep of the concrete caused the beam to relax in the early stages of test. The testing machine produced a cyclic displacement and it was necessary, therefore, to adjust the mean displacement during this period, in order to maintain the upper and lower limits of loading at the desired values. The beams all required approximately 0.25 x 10⁶ cycles of loading before reaching a stable condition, after which only minor adjustments were required, to compensate for wear in the machine bearings.

4.2 Continuous bars

The test results from beams containing continuous bars are shown in Figure 2. The experimental scatter was comparable with that encountered in the axial tests and any minor differences which may exist between the
performances of the different types were obscured. There was some evidence of the superiority demonstrated in the axial tests by the Type D material, but it was less conclusive than in the tests reported in reference 1.

In the analysis of the test results it was assumed that the relationship between \( \sigma_f \), stress range and \( N \), cycles to failure, was of the form given in BS 5400: Part 10: 1980\textsuperscript{4}, ie \( N_{\sigma_f}^{-m} = K \), where \( m \) is the inverse slope of the log \( \sigma_f \) - log \( N \) curve. \( K \) is a constant, which is defined as either \( K_0 \) for the mean line of the relationship, or \( K_2 \) for the mean - 2 standard deviations line. In the absence of any clear distinction between the performances of the different types of bar, the test results were treated as if belonging to a single group.

The analysis gave the result \( N_{\sigma_f}^{8.7} = K \), where \( K_0 = 0.11 \times 10^{29} \) and \( K_2 = 0.59 \times 10^{27} \). The curves are shown in Figure 2, in which they are compared with those obtained by similar analysis of the axial test results.

The inverse slopes of the log \( \sigma_f \)-log \( N \) relationships were similar (ie 9.5 for the axial tests and 8.7 for the bending tests) and it is suggested that the simplified value of 9 would be suitable for both types of test and would also suit the system already used in BS 5400. The simplification would have little practical effect on the relationship and would give the constants the values \( K_0 = 0.59 \times 10^{29} \) and \( K_2 = 2.9 \times 10^{27} \) for continuous high-yield bars up to 16 mm diameter.

In Figure 3 are shown the results of axial and bending tests, which have been carried out on bars 32 mm and 40 mm diameter, at different laboratories. The lower limit curves shown in the figure were derived by rotating to a slope of \( m = 9 \), the log \( \sigma_f \)-log \( N \) curves given by regression analysis. The fit of the modified curves with the experimental data is such that it would not be unreasonable to use \( m = 9 \) in the \( \sigma_f \)-\( N \) relationship for large diameter bars, although the fatigue strength is lower than that of the 16 mm size.

It is suggested, therefore, that a single classification, Class R, might include all continuous high-yield reinforcement and that the relationship \( N_{\sigma_f}^{9} = K \) be used to describe the performances of all sizes. Provision could be made for the different fatigue strengths of different sizes of reinforcement, by the use of values of \( K \) appropriate to the bar diameter.

The regression analyses showed that the performance of 16 mm diameter bars tested in bending, in concrete, was about 20 per cent higher, in terms of stress range, than that of similar bars tested axially in air and Figure 3 shows that a similar relationship is obtained from tests on larger bars. It is suggested, however, that the fatigue performance used for design purposes should be that obtained from axial tests, although this might be a conservative approach, because it is unlikely that the relationship between the axial and bending performances will be the same in all structures as in the tests. It is possible that a combination of particular features of the structure and concrete, which is defective for one reason or another, could result in the fatigue strength of the reinforcement being no higher than that of bars loaded axially in air.

A difference between the results from the two types of test was not unexpected, as the specimens experienced different conditions. In axial tests the section is stressed uniformly and the fatigue crack initiates at the worst defect, but in flexural tests there is a stress gradient across the section and a similar defect is less effective if it lies in that part of the section experiencing the lower stress range.
It was observed that the specimen bar always failed at the position of a crack in the concrete, which had formed at the beginning of the test and it was concluded that the sections of concrete between the cracks supported some load, thereby reducing the stress range experienced by the embedded lengths of bar. It follows that a defect in the bar must be in close proximity to a crack in the concrete, to be effective.

A representative selection of specimens were removed from the beams after test and the fracture surfaces examined by scanning electron microscopy, to identify the factors influencing crack initiation. The examination showed that the feature having the strongest influence on the position of the crack initiation site was the surface geometry of the bar, ie the pattern of raised ribs. This conclusion differed from that reached after a similar study of fractures occurring in axial tests, where it was found that the rib pattern had very little effect and the fatigue cracks initiated at very much smaller surface defects.

In the tests on beams containing welded bars, it was noted that the concrete always cracked at the weld position. It is possible that the weld reinforcement, which causes an abrupt change to the surface profile of the bar, has the effect of producing a notch in the concrete, inducing the beam to crack at that position, when loaded. In beams containing continuous bars, the ribs may be large enough to have a similar effect locally, which would ensure that the bar is subjected to the maximum stress range at a rib.

The examination confirmed that crack initiation occurred in the side of the section experiencing the higher stress range.

In addition to the fractographic study, bars which had survived fatigue testing were removed from the beams and examined for cracks, by the magnetic particle method. The bars were examined initially in the unloaded condition and then at progressively higher tensile loads until a stress of approximately 85 per cent of yield was attained. No cracks were found.

4.3 Welded bars

In each beam the concrete cracked at the weld position, in the early stages of test and fatigue failure of the bar occurred at the weld.

The test results for welded bars are shown in Figure 4, in which they are compared with the results from axial tests on similar bars. Also shown in the figure are the design curves for Classes C and D from BS 5400: Part 10.

Butt-welded reinforcement is classified as a Class D detail in the British Standard and the axial test results were in agreement with this assessment up to endurances of about \(2 \times 10^6\) cycles. The results indicated a lowest fracture stress range of about 120 N/mm\(^2\), and in consequence, the D classification gave increasingly conservative estimates of the performance of 16 mm diameter bars at higher endurances.

The bars tested in bending gave a substantially better performance, showing a reduction in fatigue strength (compared with continuous bars) of about 20 per cent at \(10^7\) cycles, compared with about 40 per cent in the axial tests. It was not possible to investigate fully the lowest stress range to cause failure, but the test results indicated that a value of about 130 N/mm\(^2\) might be expected.
The performance of the welded bars tested in bending could be more accurately described by the Class C relationship from BS 5400, but it is prudent to retain the present D classification, because the improvement in performance resulting from the embedment of the reinforcement in concrete, might not have the same value in all structures. In addition, the fatigue properties of site executed welds are unlikely to be as good as those of the specimens, which were made under ideal conditions.

Fractographic examination of the welded specimens showed that the fatigue cracks had initiated at the junction of the weld reinforcement with the surface of the bar, as in the axial tests and that this generally occurred on the side of the bar experiencing the higher stress range.

The examination suggested that the quality of welding in the bending test specimens was higher than in those tested axially and to test the possibility that this might have influenced the fatigue test results, axial tests were carried out on bars removed from four untested beams. The results agreed with those from previous axial tests and it was concluded that the improved performance of the bars tested in bending was related to the method of test and not to the standard of welding.

5. CONCLUSIONS

5.1 Continuous bars

Three types of high-yield reinforcing bars have been used as the tensile reinforcement of concrete beams and fatigue tested, in bending, to endurances between $0.1 \times 10^6$ and $100 \times 10^6$ cycles. The same types of reinforcement have been tested previously under pulsating axial tension in air and the results of the two types of test have been compared.

The relationship between $\sigma_f$ and $N$ was assumed to be of the form $N_{\sigma_f}^m = K$, as given in BS 5400: Part 10 and values for $m$ and $K$ have been derived. It is proposed that the value of $m$ might be simplified to 9, for design purposes and this value has been used to derive alternative values of $K$, appropriate for use with 16 mm diameter bars.

It is suggested that all high-yield reinforcement might be included in a single classification and that the expression $N_{\sigma_f}^9 = K$ be applied to all sizes, provided that values of $K$ appropriate to the bar diameter were used.

In terms of stress range, the fatigue strength of 16 mm diameter bars tested in bending, in concrete, was approximately 20 per cent higher than that of similar bars tested axially in air. However, it is suggested that the fatigue properties of reinforcement should be assessed, for design purposes, from axial tests, as the beneficial effect of embedment in concrete may vary in different structures.

Fatigue failure of the reinforcement occurred at the position of a crack in the concrete and fractographic examination of the specimens indicated that the crack initiation site (in the steel) was associated with the pattern of raised ribs on the surface of the bar.
5.2 Welded bars

The fatigue strength of reinforcement was reduced by the presence of a weld, but by a smaller amount than in axial tests. The performance of 16 mm diameter bars could be better represented by the Class C relationship from BS 5400, than by Class D, to which welded reinforcement is assigned at present. It is not recommended, however, that the higher classification be adopted because embedment of the welded bar in concrete may not always effect the same improvement to the fatigue properties. In addition, if welding is carried out on site, the fatigue properties of the joints are likely to be more variable than those of the test specimens.

The concrete cracked at the weld position and fatigue failure of the bar occurred at the weld. The fatigue cracks initiated at sites similar to those found in axial tests, i.e. at the junction of the weld reinforcement with the surface of the bar.

6. FUTURE WORK

It is possible that in the design life of a bridge there would be sufficient time for corrosion to become the dominant influence on the fatigue behaviour of the reinforcement. To study the effect of corrosion, reinforced concrete beams, of the type described, have been fatigue-loaded for a small fraction of their estimated lives to establish the pattern of cracking in the concrete. The beams are now being exposed to an aggressive environment and will be returned to TRRL for the resumption of fatigue testing, after different periods of exposure.

In order to verify the application of the Palmgren-Miner rule (for the summation of fatigue damage occurring under variable amplitude loading) to reinforcement encased in concrete, it will be necessary to apply variable amplitude loading to the same design of specimen in order that the tests will be directly comparable with the constant amplitude tests described in this report.

7. ACKNOWLEDGEMENTS

The work described in this report was carried out in the Bridges Division (Division Head: Dr G P Tilly) of the Structures Department of TRRL. The author acknowledges the contributions made by Mr E N Gregory (Welding Institute), Mr D S Bagley (Fulmer Research Institute) and Dowmac Concrete Ltd.

8. REFERENCES


Fig. 1 Beam specimen
Fig. 3 Fatigue of 32mm and 40mm diameter bars
Fig. 6 Method of controlling testing machine mean and cyclic displacement
Displacement transducer
Load dividing beam
Cantilever

Load cell unloaded

Measured movement
Load
Deflection

Load cell loaded

Fig. 7 Load cell
9. APPENDIX
Testing machine

It was considered necessary to limit the testing frequency to approximately 3 Hz to avoid hysteretic heating effects in the concrete, but at this frequency a test to $10^8$ cycles lasts for 386 days. If data were to be collected at a reasonable rate, such long durations made it necessary to conduct several tests simultaneously. Under these circumstances the use of commercial hydraulic testing machines was economically impractical and the machine shown in Figure 5 and Plate 1 was therefore developed. The construction of the machine was made as simple as possible to minimise cost, which allowed ten units to be constructed. Standard rolled steel sections were used throughout, joints were made by bolting and machining operations were kept to a minimum. Commercially produced parts, such as bearings, pulley wheels and the 750W driving motor, were selected from readily available standard stock items.

The machine employed a toggle mechanism, which derived oscillatory motion from an eccentric and produced a cyclic displacement at the point of application of the load. The mechanical linkage is shown diagrammatically in Figure 6 in which the full lines show the limits of movement of the toggle, when the machine has been adjusted to produce a small displacement $\delta_1$. The connecting rod linking the toggle with the eccentric was made in such a way that its length could be varied. In Figure 6 it is shown how an increase in length, of the amount indicated, causes the toggle to oscillate between the limits shown dotted and produce the larger displacement $\delta_2$. It was possible to make fine adjustments in this way, but it was necessary to stop the machine in order to do so. Provision had been made for attaching the connecting rod to the toggle in five different positions, for the purpose of making coarse adjustments to the cyclic displacement, but in the course of the fatigue tests it was not found necessary to make use of this feature.

The vertical position of the lower pivot of the toggle was made adjustable, allowing the mean displacement to be varied. In Figure 6 the pivot has been moved from $O_1$ to $O_2$ to give displacements $\delta_1$ and $\delta_2$ the same datum. The mean displacement could be adjusted whilst the machine was running.

The loading applied to the specimen was measured by a load cell, the construction and operation of which are shown in Figure 7. The device made use of the hollow section load dividing beam, inside which an unstressed cantilever was fixed to one end. When loaded, the relative movement between the free end of the cantilever and the end of the beam, magnified the deflection of the beam. The movement was measured by an electrical displacement transducer and monitored by means of peak reading voltmeters. The device was calibrated against a conventional load cell.

Bearings were provided at the specimen beam supports and loading points. Three of the bearings also permitted longitudinal movement of the beam, with the object of reducing any secondary stresses in the specimen.
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