Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 37 (1982)

Artikel: Reinforcement for concrete structures subject to fatigue
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DOI: https://doi.org/10.5169/seals-28916

Reinforcement for Concrete Structures Subject to Fatigue

Armature des structures en béton soumises à la fatigue

Bewehrungsstähle unter Ermüdungsbeanspruchung

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SUMMARY
Studies of the effects of differences in materials and exposure conditions on the fatigue endurance of reinforcing steels have been undertaken. Cold-working of steel reinforcing appears to be detrimental to its fatigue properties. Both in air and sea water, galvanizing of hot-rolled and cold-worked steel reinforcing is beneficial. Nickel cladding does not appear to significantly influence the corrosion fatigue properties of reinforcement.

RESUME
Des études ont été entreprises dans le but de mettre en évidence les effets de différences dans les matériaux et les conditions d'exposition, sur la résistance à la fatigue des barres d'armature. L'écrouissage à froid des aciers d'armature semble désavantageux pour leurs propriétés à la fatigue. La galvanisation d'aciers d'armature laminés à chaud et étirés à froid est bénéfique aussi bien à l'air que dans l'eau de mer. Un traitement de surface au nickel ne semble pas avoir d'influence significative sur la résistance à la fatigue en atmosphère corrosive.

ZUSAMMENFASSUNG
Der Einfluss verschiedener Materialeigenschaften und verschiedener Umgebungsbedingungen auf die Ermüdungseigenschaften von Bewehrungsstählen wurde untersucht. Die Kaltverformung scheint sich bei Bewehrungsstählen negativ auf ihre Ermüdungseigenschaften auszuwirken. Sowohl unter atmosphärischen Bedingungen als auch im Meerwasser wirkt sich eine Galvanisierung der warmgewalzten und kalt verarbeiteten Stähle günstig auf die Ermüdungseigenschaften aus. Ein Nickelüberzug scheint die korrosionsbedingten Ermüdungseigenschaften nicht entscheidend zu beeinflussen.

1. INTRODUCTION

During the last few years there has been an intensification of interest in the fatigue behaviour of steel reinforcement in concrete structures. Although fatigue has not proved to be a problem to date, loading cycles and corrosive conditions are becoming increasingly severe so that the margin of reserve strength is progressively being reduced. Changes in codes, such as the decrease in the amount of stirrup reinforcement for static load by the Swiss Railroads has further stimulated interest (1). Fatigue endurance of reinforcement can be influenced by type of steel, geometry and size of bars, nature of the loading cycle, welding and presence of corrosive liquids. A recent review paper, chiefly related to highway bridges has been presented by Tilly (2).

Data available on the life of offshore structural concrete has been presented by Browne and Domone (3). They state that in composite reinforced or prestressed concrete sections, the levels of stress in the steel are a greater percentage of the ultimate stress than for concrete and it is therefore generally sufficient to consider the fatigue properties of the steel as controlling the fatigue performances of the structural element. Gerwick and Venuti (4) suggest that as opposed to bridges, typical concrete sea structures are more influenced by low-cycle high amplitude fatigue than by high cycle cumulative usage. They state that when concrete is cracked and then is cycled repeatedly into the "crack re-opening" tensile range, the steel is subjected to significantly increased stress ranges. As a result bond is progressively lost particularly along smooth bars, strand and wire. Adequate fatigue capacity of the steel must therefore be assured in design for such conditions.

The present work was undertaken to study the effects of differences in materials and exposure conditions on the fatigue endurance of reinforcing steels with the hope of improving their performance where this may become necessary.

2. EXPERIMENTAL INVESTIGATION

2.1 Reinforcement

Three types of uncoated reinforcement were used in this study, two being manufactured in Australia, and the third in the United States:-

(i) mild steel hot-rolled deformed 24 mm bar of 230 MPa Grade to AS 1302,
(ii) cold-worked 24 mm bar of 410 MPa Grade manufactured by twisting, without tensioning, the 230 MPa Grade bar according to the same standard,
(iii) alloy-steel hot-rolled deformed No.8 bar of 414 MPa Grade to ASTM-A615.

Tests were also undertaken on hot dipped galvanized bars of the first two types and nickel-clad bars of the third type.

3. TEST SPECIMENS, CONDITIONS AND LOAD CALCULATIONS

The specimens tested were concrete beams having the dimensions and reinforcement layouts given in Fig. 1, and concrete mix design of 1:2.7:1.2:0.4, Cement: Coarse Aggregate: Fine Aggregate: Water by weight, giving a 45 MPa design strength. All hot-rolled bars were placed with their longitudinal lugs in the vertical plane. No preferential orientation could be given to the twisted, cold-worked bars.

After being cast in steel forms and cured for 24 hours under polythene sheeting, the beams were stripped and allowed to cure at 25°C and 100 per cent relative humidity until loading commenced. Beam age at test varied from 15 to 40 days.

Beams were simply supported over a span of 1800 mm and centrally loaded (Fig. 2). Three conditions of test were used, viz, in air, in natural sea water and in 3 per cent NaCl solution, all with sinusoidal cyclic loading at a frequency of 6.7 Hz. Not each bar type was necessarily subjected to all three conditions. Throughout the period of test water was continuously aerated and circulated around individual beams up to their mid-height (Fig. 2); when tests ran for longer periods than one week the water was replaced each week.

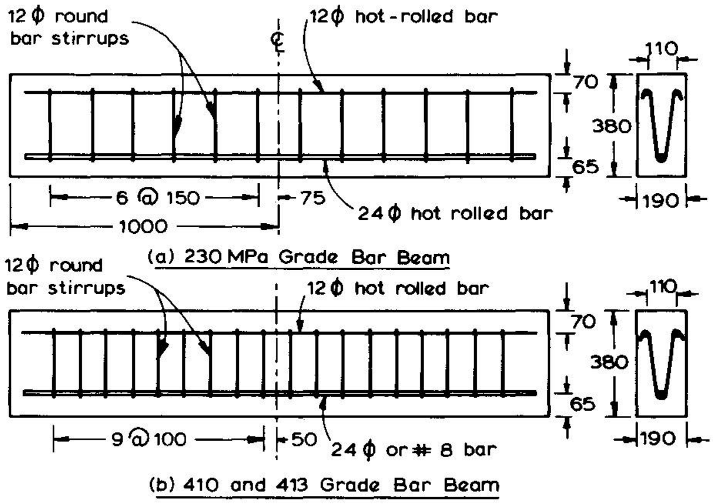


Fig. 1 Beam dimensions & reinforcement

On loading of the beam, cracks in the concrete which were not preformed, generally developed at three locations. The first crack was within 50 mm of the beam centre-line. Two others, approximately 200 mm on either side of the first either developed during initial loading or shortly after cycling commenced. Fatigue failure of the reinforcement did not always occur at the first-formed crack. Both because the tip of the flexural cracks in any beam ended close to the intersection of the centre-line and the neutral axis, and the effect of aggregate interlock forces is reduced during fatigue loading, no reinforcement-stress adjustment was made for the displacement of the cracks from the precise centre-line of the beam.

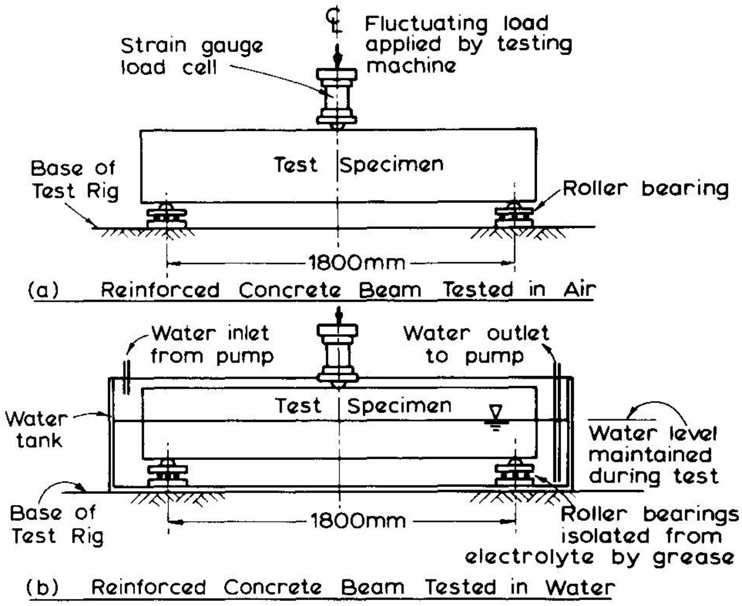


Fig. 2 Test layout of fatigue specimens

Yield stress values for the unencased bars were obtained from standard tensile tests. In the case of the hot-rolled steel, yield was defined by the yield-point, whereas for the cold-worked bars the 0.2 per cent proof stress was used. For a reinforced concrete beam loaded in flexure an elastic crack section analysis may be used to relate the applied central point load to the stress in the tensile reinforcement. Such an analysis was applied to each test beam using the following:-

(i) the average measured yield or proof load of the particular steel,
(ii) an assumed modular ratio between the steel and concrete equal to $42.0/\sqrt{f_c}$ (f_c being the compressive strength at the time of test expressed in MPa).

From this analysis, test-rig loads were calculated for a required stress range. The lowest stress to which the reinforcement was subject by the applied fluctuating load was set as 5.7 per cent of the reinforcement yield stress.

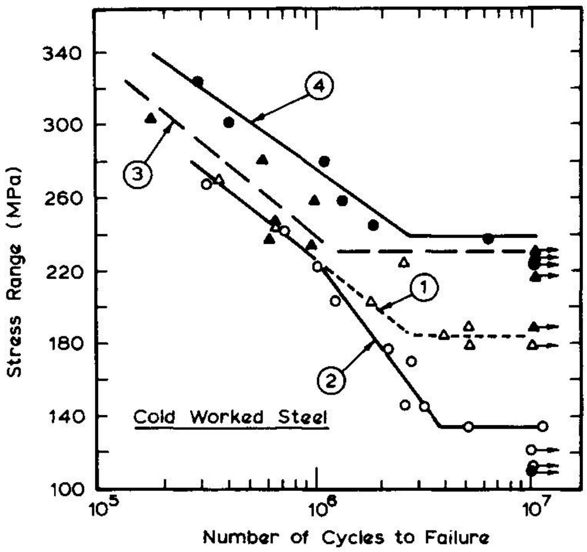
4. EXPERIMENTAL RESULTS

The experimental results are summarised in Figs. 3,4 and 5; detailed results are available in Research Reports on PROJECT ZE-302 of ILZRO (5).

Figure 3 represents the results obtained for beams manufactured with Australian cold-worked steel reinforcement. All four curves show properties similar to those discussed by Helgason et al (6). Each consists of a finite life region followed by a long life region. In the case of the uncoated reinforcement in concrete tested in sea water the finite life region appears to have two different slopes, one of which is the same as that for the air tested beams, while above 10^6 cycles the slope increases. Galvanizing leads to improved performance in both the finite and long life sections of the curves.

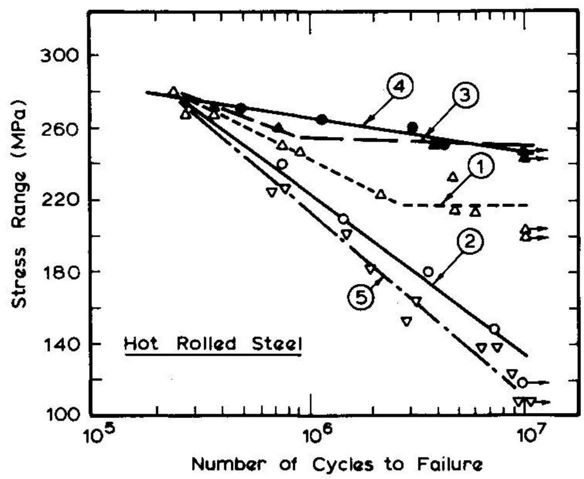
Figure 4 represents the results obtained for beams manufactured with Australian hot-rolled steel reinforcement. Only two of the five curves have a long life region viz, the air tested beams with the uncoated and galvanized reinforcement. All the beams tested in aggressive waters showed no long life region before 10^7 cycles of loading had been performed. The significant decrease in fatigue endurance of beams containing the uncoated reinforcement when tested in aggressive waters, and the considerable improvement under these conditions due to the galvanizing can be observed.

The data for beams using bars manufactured to ASTM-A615 are given in Fig. 5. The results available up to date indicate that, for both the uncoated bars and the nickel clad bars, a long life region exists between 140 and 160 MPa stress range. Failure before 10^7 cycles had not occurred in the case of the two beams, one containing an uncoated bar and one a nickel clad bar at 156 MPa and 146 MPa respectively. Close examination of the removed bars indicated that a crack had initiated before 10^7 cycles in the nickel coated bar subjected to cycling at 146 MPa, but it had not progressed so as to cause failure before the test had stopped. The nickel cladding of the reinforcement does not significantly changes the beam behaviour either in the finite or long life regions of the curves.



		Coating	Environment
△	1	None	Air
○	2	None	Sea Water
▲	3	Galvanized	Air
●	4	Galvanized	Sea Water

Fig. 3 S-N curves for beams



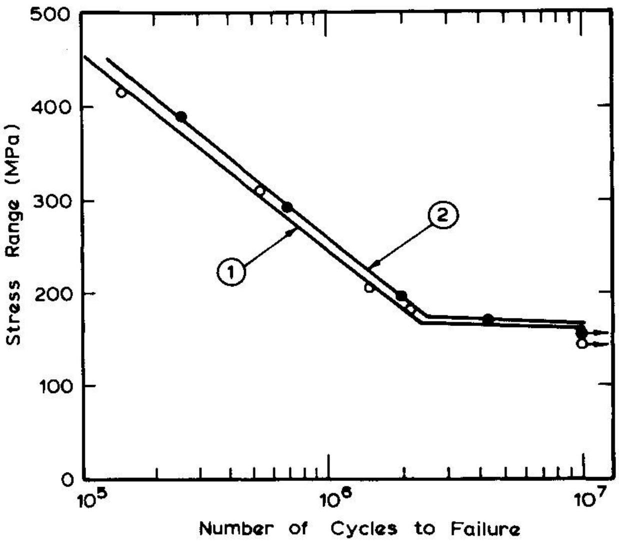
		Coating	Environment
△	1	None	Air
○	2	None	Sea Water
▲	3	Galvanized	Air
●	4	Galvanized	Sea Water
▽	5	None	NaCl Solution

Fig. 4 S-N curves for beams

5. DISCUSSION OF RESULTS AND CONCLUSIONS

5.1 Uncoated bar

For detailed discussion of the results observed on the uncoated Australian bars, reference can be made to an earlier paper by Roper and Hetherington (7). In brief it is concluded that several factors related to the cold twisting process itself, or resultant changes in the structure of the steel may contribute to the lower fatigue limit and reduced fatigue endurance of the twisted bar beams when tested in air:



		Coating	Environment
o	1	None	Sea Water
•	2	Nickel Clad	Sea Water

Fig. 5 S-N curves for beams

(i) Changes in bar geometry which result in a reduction in the lug base radius from that existing in the untwisted bar, tending to reduce both the fatigue strength and the fatigue limit of the cold-worked bar.

(ii) The proportion of the fatigue life occupied by crack initiation is reduced by the cold-working since voids are already developed, which without cold-working would require a significant proportion of the fatigue life to form. Imperfections are, by the twisting process, placed in a preferred orientation that is no longer parallel to the axis of the bar, thus possessing a greater potential to act as crack-initiation sites.

(iii) Notch formation is developed in the steel at the degree of twisting applied, and this lowers the stress range below which a crack will propagate in the bar; thus fatigue limit is lowered.

The cold-worked series in sea water shows a linear finite life, followed by a long life region, The hot-rolled series show no long life region up to 10^7 cycles. Despite this fact, when slopes of the finite life portions of the curves for the cold-worked and hot-rolled series are compared, it is noted that the cold-worked series has a statistically significant higher slope than that of the hot-rolled series. For both series of bars, the reduction in fatigue endurance in the corrosive environments when compared to in-air tests of concrete beams, is attributable to two effects of the electrolyte:

(i) Crack initiation time is reduced as corrosion pits readily become initiation sites for fatigue cracks. Pit development is time dependent rather than frequency dependent; the longer the corrosion fatigue life, the greater the reduction in fatigue endurance.

(ii) The effect of the corrosive medium is to increase the fatigue crack growth rate.

The presence of a long life region in the case of the cold-worked series, and its absence prior to 10^7 cycles, in the hot-rolled series is noteworthy. This difference can be attirbuted to the cold-working of the reinforcement. Apart from changes in the geometry already discussed, the difference can be explained by considering the combined effect of corrosion attack with the movement of dislocations and the resultant formation of fresh unoxidised metal surface, raising the potential for corrosion to occur in the case of the hot-rolled steels. For cold-worked steels reduced dislocation movement and reduced plastic deformation resulting in less development of fresh metal for attack may decrease the potential for crack initiation and growth. The similarity of results in sea water and chloride solution suggests that the rate of attack of chlorides on the steel is not appreciably modified by other salts in the sea water.

5.2 Galvanized bar

The effects of galvanizing are to improve the fatigue properties of concrete beams in all cases. For beams tested in air, the existence in the case of galvanized reinforcement of long life regions at higher stress ranges is of import, but most significant are the improvements in fatigue properties when beams are tested in the presence of sea water. In the case of the high-strength cold-worked bars, the best performance of beams tested under all conditions are displayed by those containing galvanized bars when tested in sea water. This indicates that the improvement is not solely due to any heat-treatment effects brought about during hot-dipping, but that the zinc is acting as an anode to protect the steel at the crack. The efficiency of this mechanism is increased in the presence of the sea water acting as an efficient electrolyte even within the crack. Its action depends on sacrificial wastage of zinc in the cracked region, and must therefore be considered time dependent. Data for galvanized hot rolled bar have been more difficult to obtain. Beams containing this material when tested in sea water have failed due to the fatigue of the concrete at the central load point. The reason for this is that the sea water environment decreases the fatigue endurance of concrete whereas the galvanizing tends to increase the fatigue strength of the steel. Because of the relatively high stresses coupled with the high number of cycles, failure of the concrete per se has occurred in several specimens. As yet no beams of this type have endured 10^7 load cycles chiefly because of the concrete failures. The fact that concrete fatigue is the limiting factor, points to the advantage of galvanizing in this test series.

5.3 Nickel clad bar

The nickel cladding does not appear to contribute any significant beneficial effect under the conditions of test, either in the finite life region or the long life region. Detailed explanations of the relatively minor differences noted between the unclad and nickel clad bar types will require further work, however it appears that there is no evidence as yet to suggest that nickel cladding is as effective as galvanizing in improving the fatigue endurance of reinforcing steels in concrete when tested in sea water. On the other hand no evidence is yet available that the presence of nickel accelerates the progression of a developing crack to any significant extent.

5.4 Closure

This work on bar types for fatigue is part of an ongoing study at the University of Sydney being sponsored by the International Lead Zinc Research Organisation.

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