National Cooperative Highway Research Program

RESEARCH RESULTS DIGEST

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These Digests are issued in the interest of providing an early awareness of the research results emanating from projects in the NCHRP. By making these results known as they are developed and prior to publication of the project report in the regular NCHRP series, it is hoped that the potential users of the research findings will be encouraged toward their early implementation in operating practices. Persons wanting to pursue the project subject matter in greater depth may obtain, on a loan basis, an uncorrected draft copy of the agency's report by request to the NCHRP Program Director, Highway Research Board, 2101 Constitution Ave., N.W., Washington, D.C. 20418

Fatigue Strength of High-Yield Reinforcing Bars

An NCHRP staff digest of the essential findings from the interim report on NCHRP Project 4-7, "Fatigue Strength of High-Yield Reinforcing Bars," by John M. Hanson, Norman F. Somes, Thorsteinn Helgason, W. G. Corley, and Eivind Hognestad, of the Portland Cement Association.

THE PROBLEM AND ITS SOLUTION

The AASHO Road Test indicated that the fatigue strength of reinforcing bars is one of the key elements determining the life of reinforced concrete bridge members. The increased use of high-strength reinforcing bars increased the possibility that the fatigue strength of the reinforcement could limit the life of the structure if test data to support realistic design criteria did not become available. Previous fatigue tests on low- and intermediate-strength reinforcing bars indicated that stress range, minimum stress, details, and bends are among the variables that can affect fatigue strength. Therefore, research was needed to extend the knowledge of fatigue behavior of reinforcing bars to grades with yield strengths in excess of 50,000 psi for realistic working stress levels to permit the achievement of the ultimate goal of developing design criteria for high-yield-strength reinforcing bars.

The Portland Cement Association, in response to the design criteria goal, directed its research efforts to obtaining fatigue strength test data on ASTM A 432 steel bars (60,000-psi yield strength) by the design and execution of a statistically valid experiment that evaluated the effects of stress range, minimum stress (including reversal), bar diameter, type of specimen, and grade of steel. Three minimum stress levels were selected for investigation--6 ksi compression, 6 ksi tension, and 18 ksi tension. Five bar sizes--5, 6, 8, 10, and 11--were investigated. The influence of type of specimen was investigated by testing T or rectangular beams with a test bar at each of three different nominal depths. Grades 40, 60, and 75 reinforcing bars were tested; however, the primary emphasis was placed on grade 60 reinforcement, which was used in 194 of the total of 236 tests. To minimize unwanted variables, all the test bars were

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obtained from the same mill of a leading manufacturer of reinforcing bars in the United States. The order of testing was completely randomized and replicate specimens were included as a measure of experimental variability.

The main part of the experimental investigation consisted of 236 fatigue tests carried out on concrete beams, each containing a single, straight deformed bar as the main reinforcing element. These 236 tests were divided according to a statistical plan into 31 groups, each including at least 7 tests. While all other variables within a group were nominally held constant, stress range in the test bars was adjusted to obtain fatigue failures between approximately 50,000 and 5 million cycles of loading.

The findings reported herein result from a large-scale experimental program, plus consideration of the results of previous research related to this topic. Hence, it is believed that they are reliable; however, it became apparent in evaluating the literature that a parameter of major significance--surface characteristics of deformed reinforcing bars--had not been examined. In the interest of producing the most complete research findings possible on the fatigue strength of grade 60 reinforcing bars, continuation of the research has been arranged and the PCA will investigate the effects of surface characteristics. The results of the continuation work, expected to be available in about 18 months, will be incorporated into these interim findings and the complete project results considered for publication in the NCHRP Report series.

FINDINGS

1. Reinforcing bars have a practical fatigue limit. In the experimental portion of this investigation, the transition from the finite life region to the long-life region of the stress range-fatigue life relationship occurred at about 1 million cycles.

2. Stress range was the predominant variable affecting the fatigue strength of the test bars in the finite life region. It accounted for about 75% of the variation in life.

3. Variations due to minimum stress level, grade of bar, and bar size were statistically significant. These variations, together with that due to stress range, account for more than 90% of the variation in the test data.

4. The type of specimen measured by the depth of the bar below the neutral axis of the beam did not have a statistically significant influence on the test data.

5. Number 6 test bars exhibited the highest fatigue strength, whereas number 10 bars had the lowest fatigue strength. The irregular variation in fatigue strength with bar size was attributed to variables introduced in the manufacturing process.

6. Stress ranges producing a maximum stress exceeding the actual yield stress were slightly detrimental for the grade 40 bars and slightly beneficial for the grade 60 bars.

7. At high stress ranges, the fatigue life of test bars that had previously sustained 5 million cycles of a low stress range was as great as the fatigue life of bars not previously subjected to cycling.

8. All the fatigue fractures originated at the base of a lug, except for

five tests where the fracture originated at the base of the manufacturer's mark. The geometry both at the base of the lug and at the base of the manufacturer's bar mark was sharp.

9. The experimental data obtained in this investigation showed a few failures at lower stress ranges than most previously reported data. The relatively low fatigue strength of the test bars was believed to be due to variables introduced in the manufacturing process, mainly to the sharp geometry at the base of the lugs and the base of the manufacturer's bar marks.

10. Design provisions should be based on stress range and minimum stress level. They should not be based on bar grade or size.

11. The stress range in straight deformed reinforcing bars should not be permitted to exceed the value given by Eq. 1 unless a higher value is substantiated by tests. At a minimum stress level of 0.2 of the yield strength of grade 60 bars, the fatigue strength at 1 million cycles computed from Eq. 1 is 21 ksi. This value of fatigue strength should be considered as the fatigue limit for these conditions.

Suggested Specification

The following is suggested wording for a design specification for fatigue of reinforcing bars:

> The stress range in a deformed hot-rolled reinforcing bar, under repeated application of service loads, shall not exceed
>
> $$S_r = [\ 40 - 19\ (\log N - 5)\ ]\ (1.13 - 0.67\ \frac{S_{min}}{f_y}) \qquad (1)$$
>
> where
>
> S_r = stress range, ksi;
>
> N = design fatigue life (number of load applications);
>
> S_{min} = minimum stress level, ksi; and
>
> f_y = specified yield strength of bar, ksi.
>
> The value of S_r at N = 1 million cycles may be used for all greater values of N.
>
> Greater stress ranges are permitted if determined by fatigue tests on similar bars.

APPLICATIONS

Findings of this study should be of interest to structural engineers involved in the design of reinforced concrete members subjected to fatigue loading, researchers working in the subject area, and members of specification writing bodies providing specifications for fatigue design of reinforcing bars.

The findings are interim and cannot stand alone, but must be combined with finding from continuation work under way in order to be useful. The interim results (1) are defined explicitly but cannot be directly applied to practice because they are incomplete; (2) are presented in suggested specifications--the working tool with which the practicing engineer is familiar--although the specification is not proved reliable for all patterns of bars; and (3) have not been evaluated sufficiently to make some reasonable determination of the probability of their success when applied to practice.

The findings of the report were obtained from tests on bars made by a single U.S. manufacturer. The primary observation of the review of literature was that the variation in fatigue strength of bars made by different manufacturers is substantial. Therefore, mathematical models developed from statistical analyses of the test data cannot be regarded as having general validity. It is of importance to note, however, that the limits on experimental test data from this investigation, when compared with previously published data, show that the lower limit to the data from this experiment also fits the lower limit of previously published test data on North American-manufactured reinforcing bars. The important conclusion is that recommendations based largely on the data from this experiment could be expected to be conservative for most North American-made bars. It also is important to note that limiting the stress range to 20 ksi for fatigue--as included in the old Bureau of Public Roads criteria--is a highly suitable lower limit.

To remove the uncertainty regarding the influence of surface characteristics on fatigue strength, further research will be conducted on samples of bars selected from several different manufacturers throughout North America. Emphasis will be placed on development of a technique suitable for inclusion in a specification for measuring critical bar geometry. The additional research also will be concerned with clarifying the influence at minimum stress levels. The continuation work should commence during March 1971 and will continue for some 18 months. It is anticipated that the findings of the continuation work, combined with the interim findings, will provide the complete evidence necessary to support a design criterion for fatigue behavior of grade 60 reinforcing bars.

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