

Considerations for Design of Concrete Structures Subjected to Fatigue Loading

Reported by ACI Committee 215

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This report presents information that is intended to aid the practicing engineer confronted with consideration of repeated loading on concrete structures. Investigations of the fatigue properties of component materials+oncrete, reinforcing bars, welded reinforcing mats, and prestressing tendons-are reviewed. Application of this information to predicting the fatigue life of beams and pavements is discussed. A significant change in Section 3.1.2 of the 1992 revisions is the increase in the allowable stress range for prestressing steel from $0.04 f_{pu}$ to $0.06 f_{pu}$.

Keywords: beams (supports); compressive strength; concrete pavements: cracking (fracturing); dynamic loads; fatigue (materials); impact; loads (Forces); microcracking; plain concrete; prestressed concrete; prestressing steel; reinforcedconcrete: reinforcingsteels; specifications; static loads: strains; stresses; structural design; tensile strength; welded wire fabric; welding; yield strength.

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CHAPTER 1-INTRODUCTION

In recent years, considerable interest has developed in the fatigue strength of concrete members. There are several reasons for this interest. First, the widespread adoption of ultimate strength design procedures and the use of higher strength materials require that structural concrete members perform satisfactorily under high stress levels. Hence there is concern about the effects of repeated loads on, for example, crane beams and bridge slabs.

Second, new or different uses are being made of concrete members or systems, such as prestressed concrete railroad ties and continuously reinforced concrete pavements. These uses of concrete demand a high performance product with an assured fatigue strength.

Third, there is new recognition of the effects of repeated loading on a member, even if repeated loading does not cause a fatigue failure. Repeated loading may lead to inclined cracking in prestressed beams at lower than expected loads, or repeated loading may cause cracking in component materials of a member that alters the static load carrying characteristics.

1.1-Objective and scope

This report is intended to provide information that will serve as a guide for design for concrete structures subjected to fatigue loading.

However, this report does not contain the type of detailed design procedures sometimes found in guides.

Chapter 2 presents information on the fatigue strength of concrete and reinforcing materials. This information has been obtained from reviews of experimental investigations reported in technical literature or from unpublished data made available to the committee. The principal aim has been to summarize information on factors influencing fatigue strength that are of concern to practicing engineers.

Chapter 3 considers the application of information on concrete and reinforcing materials to beams and pavements. Provisions suitable for inclusion in a design specification are recommended.

An Appendix to this report contains extracts from current specifications that are concerned with fatigue.

1.2-Definitions

It is important to carefully distinguish between static, dynamic, fatigue, and impact loadings. Truly static loading, or sustained loading, remains constant with time. Nevertheless, a load which increases slowly is often called static loading; the maximum load capacity under such conditions is referred to as static strength.

Dynamic loading varies with time in any arbitrary manner. Fatigue and impact loadings are special cases of dynamic loading. A fatigue loading consists of a sequence of load repetitions that may cause a fatigue failure in about 100 or more cycles.

Very high level repeated loadings due to earthquakes or other catastrophic events may cause failures in less than 100 cycles. These failures are sometimes referred to as low-cycle

fatigue; however, this report does not specifically deal with these types of loadings.

1.3-Standards cited in this report

The standards and specifications referred to in this document are listed below with their serial designation, including year of adoption or revision. These standards are the latest effort at the time this document was revised. Since some of the standards are revised frequently, although generally only in minor details, the user of this document may wish to check directly with the committee if it is correct to refer to the latest revision.

ACI 301-89	Specifications for Structural Concrete for Buildings
ACI 318-89	Building Code Requirements for Reinforced Concrete
ASTM A 416-90	Standard Specification for Uncoated Seven Wire Stress Relieved Steel Strand for Prestressed Concrete
ASTM A 421-90	Standard Specification for Uncoated Stress Relieved Steel Wire for Prestressed Concrete
ASTM A 615-90	Standard Specification for Deformed and Plain Billet Steel Bars for Concrete Reinforcement
ASTM 722-90	Standard Specification for Uncoated High Strength Steel Bar for Prestressing Concrete
AWS D1.4-79	Structural Welding Code-Reinforcing Steel

CHAPTER 2-FATIGUE PROPERTIES OF COMPONENT MATERIALS

The fatigue properties of concrete, reinforcing bars, and prestressing tendons are described in this section. Much of this information is presented in the form of diagrams and algebraic relationships that can be utilized for design. However, it is emphasized that this information is based on the results of tests conducted on different types of specimens subjected to various loading conditions. Therefore, caution should be exercised in applying the information presented in this report.

2.1-Plain concrete*

2.1.1 General-Plain concrete, when subjected to repeated loads, may exhibit excessive cracking and may eventually fail after a sufficient number of load repetitions, even if the maximum load is less than the static strength of a similar specimen. The fatigue strength of concrete is defined as a fraction of the static strength that it can support repeatedly for a given number of cycles. Fatigue strength is influenced by range of loading, rate of loading, eccentricity of loading, load history, material properties, and environmental conditions.

* Dr. Surendra P. Shah was the chairman of the subcommittee that prepared this section of the report.

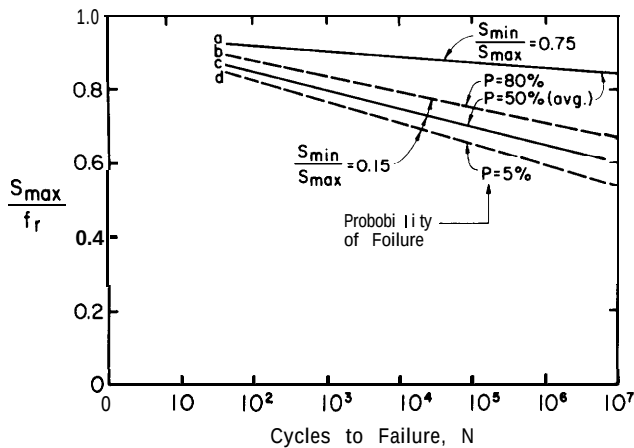


Fig. 1-Fatigue strength of plain concrete beams

Fatigue is a process of progressive permanent internal structural change in a material subjected to repetitive stresses. These changes may be damaging and result in progressive growth of cracks and complete fracture if the stress repetitions are sufficiently large.^{1,2} Fatigue fracture of concrete is characterized by considerably larger strains and microcracking as compared to fracture of concrete under static loading.^{3,4} Fatigue strength of concrete for a life of ten million cycles-for compression, tension, or flexure-is roughly about 55 percent of static strength.

2.1.2 Range of stress-The effect of range of stress may be illustrated by the stress-fatigue life curves, commonly referred to as *S-N* curves, shown in Fig. 1. These curves were developed from tests on 6 x 6 in. (152 x 152 mm) plain concrete beams⁵ loaded at the third points of a 60 in. (1.52 m) span. The tests were conducted at the rate of 450 cycles per min. This concrete mix with a water-cement ratio of 0.52 by weight provided an average compressive strength of 5000 psi (34.5 MPa) in 28 days. The age of the specimens at the time of testing ranged from 150 to 300 days.

In Fig. 1, the ordinate is the ratio of the maximum stress, S_{max} , to the static strength. In this case, S_{max} is the computed flexural tensile stress, and the static strength is the modulus of rupture stress, f_r . The abscissa is the number of cycles to failure, plotted on a logarithmic scale.

Curves *a* and *c* indicate that the fatigue strength of concrete decreases with increasing number of cycles. It may be observed that the *S-N* curves for concrete are approximately linear between 10^2 and 10^7 cycles. This indicates that concrete does not exhibit an endurance limit up to 10 million cycles. In other words, there is no limiting value of stress below which the fatigue life will be infinite.

The influence of load range can be seen from comparison of Curves *a* and *c* in Fig. 1. The curves were obtained from tests with loads ranging between a maximum and a minimum which was equal to 75 and 15 percent of the maximum, respectively. It is evident that a decrease of the range between maximum and minimum load results in increased fatigue strength for a given number of cycles. When the minimum and maximum loads are equal, the strength of the specimen

corresponds to the static strength of concrete determined under otherwise similar conditions.

The results of fatigue tests usually exhibit substantially larger scatter than static tests. This inherent statistical nature of fatigue test results can best be accounted for by applying probabilistic procedures: for a given maximum load, minimum load, and number of cycles, the probability of failure can be estimated from the test results. By repeating this for several numbers of cycles, a relationship between probability of failure and number of cycles until failure at a given level of maximum load can be obtained. From such relationships, *S-N* curves for various probabilities of failure can be plotted. Curves *a* and *c* in Fig. 1 are averages representing 50 percent probability of failure. Curve *d* represents 5 percent probability of failure, while Curve *b* corresponds to an 80 percent chance of failure.

The usual fatigue curve is that shown for a probability of failure of 50 percent. However, design may be based on a lower probability of failure.

Design for fatigue may be facilitated by use of a modified Goodman diagram, as illustrated in Fig. 2. This diagram is based on the observation that the fatigue strength of plain concrete is essentially the same whether the mode of loading is tension, compression, or flexure. The diagram also incorporates the influence of range of loading. For a zero minimum stress level, the maximum stress level the concrete can support for one million cycles without failure is taken conservatively as 50 percent of the static strength. As the minimum stress level is increased, the stress range that the concrete can support decreases. The linear decrease of stress range with increasing minimum stress has been observed, at least approximately, by many investigators.

From Fig. 2, the maximum stress in tension, compression, or flexure that concrete can withstand for one million repetitions and for a given minimum stress can be determined. For example, consider a structural element to be designed for one million repetitions. If the minimum stress is 15 percent of the static ultimate strength, then the maximum load that will cause fatigue failure is about 57 percent of static ultimate load.

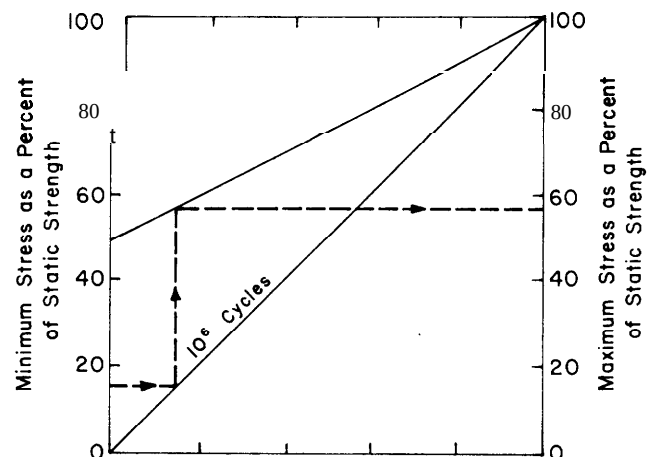


Fig. 2-Fatigue strength of plain concrete tension, compression or flexure

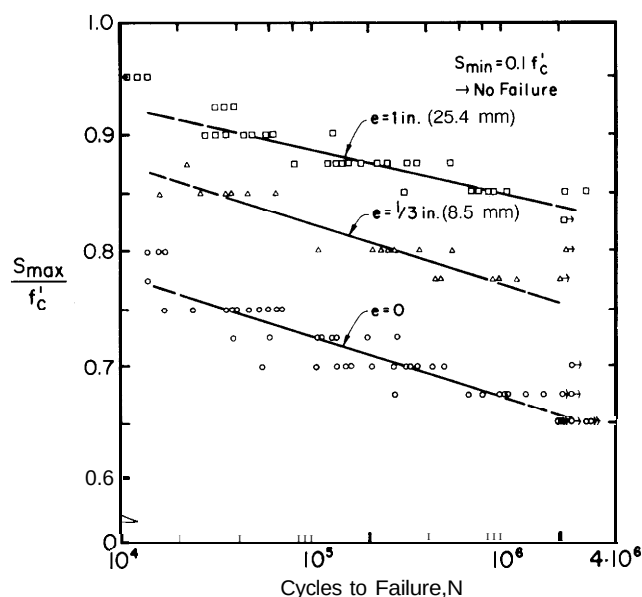


Fig. 3-Influence of stress gradient

2.1.3 Load history-Most laboratory fatigue data are idealized, since in these tests the loads alternated between constant minimum and maximum values. Concrete in structural members may be subjected to randomly varying loads. Currently, no data are available⁶ showing the effect of random loading on fatigue behavior of concrete. Effects of different values of maximum stress can be approximately, although not always conservatively, estimated from constant stress fatigue tests by using the Miner hypothesis.⁷ According to this rule, failure occurs if $\sum(n_r/N_r) = 1$, where n_r is the number of cycles applied at a particular stress condition, and N_r is the number of cycles which will cause fatigue failure at that same stress condition.

The effect of rest periods and sustained loading on the fatigue behavior of concrete is not sufficiently explored. Laboratory tests have shown that rest periods and sustained loading between repeated load cycles tends to increase the fatigue strength of concrete.⁵ In these tests, the specimens were subjected to relatively low levels of sustained stress. If the sustained stress level is above about 75 percent of the static strength, then sustained loading may have detrimental effects on fatigue life.³ This contradictory effect of creep loading may be explained from test results which show that low levels of sustained stress increase the static strength, whereas high levels of sustained stress resulted in increased microcracking and failure in some cases.

2.1.4 Rate of loading-Several investigations indicate that variations of the frequency of loading between 70 and 900 cycles per minute have little effect on fatigue strength provided the maximum stress level is less than about 75 percent of the static strength.⁸ For higher stress levels, a significant influence of rate of loading has been observed.⁹ Under such conditions, creep effects become more important, leading to a reduction in fatigue strength with decreasing rate of loading.

2.1.5 Material properties-The fatigue strength for a life of 10 million cycles of load and a probability of failure of 50 percent, regardless of whether the specimen is loaded in compression, tension, or flexure, is approximately 55 percent of the static ultimate strength. Furthermore, the fatigue strength of mortar and concrete are about the same when expressed as a percentage of their corresponding ultimate static

Many variables such as cement content, water-cement ratio, curing conditions, age at loading, amount of entrained air, and type of aggregates that affect static ultimate strength also influence fatigue strength in a similar proportionate manner.¹¹

2.1.6 Stress gradient-Stress gradient has been shown to influence the fatigue strength of concrete. Results of test¹² on 4 x 6 x 12 in. (102 x 152 x 305 mm) concrete prisms under repeated compressive stresses and three different strain gradients are shown in Fig. 3. The prisms had a compressive strength of about 6000 psi (41.4 MPa). They were tested at a rate of 500 cpm at ages varying between 47 and 77 days.

For one case, marked $e = 0$, the load was applied concentrically, producing uniform strain throughout the cross section. To simulate the compression zone of a beam, load was applied eccentrically in the other two cases, marked $e = 1/3$ in. (8.5 mm) and $e = 1$ in. (25.4 mm). The loads were applied such that during the first cycle of fatigue loading the maximum strain at the extreme fiber was the same for all three sets of specimens. For the two eccentrically loaded cases, the minimum strain was zero and half the maximum strain, respectively. The stress level, S , was defined as the ratio of the extreme fiber stress to the static compressive strength f'_c . The extreme fiber stress in eccentrically loaded specimens was determined from static stress strain relationships and the maximum strain at the extreme fiber as observed during the first cycle of fatigue loading.

From the mean S - N curves shown in Fig. 3, it can be seen that the fatigue strength of eccentric specimens is 15 to 18 percent higher than that for uniformly stressed specimens for a fatigue life of 40,000 to 1,000,000 cycles. These results are in accord with the results of static tests where it was shown that the strain gradient retards internal microcrack growth.¹³ For the purpose of design of flexural members limited by concrete fatigue in compression, it is safe to assume that fatigue strength of concrete with a stress gradient is the same as that of uniformly stressed specimens.

2.1.7 Mechanism of fatigue fracture-Considerable research is being done to study the nature of fatigue failure in concrete^{1-4,14-17} Researchers have measured surface strains, changes in pulse velocity, internal microcracking and surface cracking to understand the phenomenon of fracture. It has been observed that fatigue failure is due to progressive internal microcracking. As a result, large increase in both the longitudinal and transverse strains and decrease in pulse velocity have been reported preceding fatigue failure. External surface cracking has been observed on test specimens long before actual failure.

Progressive damage under fatigue loading is also indicated by reduction of the slope of the compressive stress-strain curve with an increasing number of cycles. In addition to in-

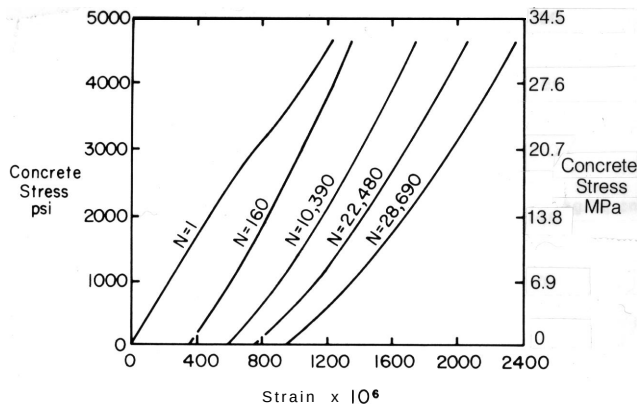


Fig. 4-Effect of repeated load on concrete strain

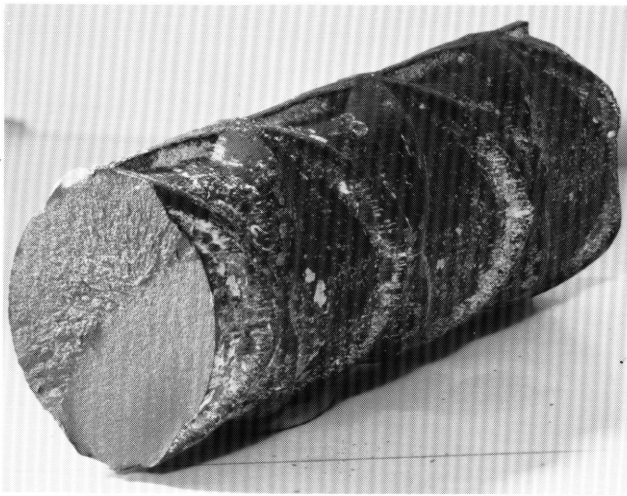


Fig. 5-Fatigue fracture of a reinforcing bar

ternal microcracking, fatigue loading is also likely to cause changes in the pore structure of the hardened cement paste. Creep effects must also be considered. They become more significant as the rate of loading decreases.

2.1.8 Concrete strain-Similar to the behavior of concrete under sustained loads, the strain of concrete during repeated loading increases substantially beyond the value observed after the first load application,² as shown in Fig. 4. The strain at fatigue failure is likely to be higher if the maximum stress is lower.

2.2-Reinforcing bars*

2.2.1 General-Fatigue of steel reinforcing bars has not been a significant factor in their application as reinforcement in concrete structures. However, the trend in concrete structures toward use of ultimate strength design procedures and higher yield strength reinforcement makes fatigue of reinforcing bars of more concern to designers. It is noteworthy, though, that the lowest stress range known to have caused a fatigue failure of a straight hot-rolled deformed bar embedded in a concrete beam is 21 ksi (145 MPa). This failure occurred after 1,250,000 cycles of loading on a beam containing a #11, Grade 60 test bar, when the minimum stress level was 17.5 ksi (121 MPa).²⁶

A typical fatigue fracture of a reinforcing bar is shown in Fig. 5. This is also a #11, Grade 60 bar which at one time was embedded in a concrete beam that was subjected to repeated loads until the bar failed. In this figure, the orientation of the bar is the same as it was in the beam; the bottom of the bar was adjacent to the extreme tensile fibers in the beam. The smoother zone, with the dull, rubbed appearance, is the fatigue crack. The remaining zone of more jagged surface texture is the part that finally fractured in tension after the growing fatigue crack weakened the bar. It is noteworthy that the fatigue crack did not start from the bottom of the bar. Rather it started along the side of the bar, at the base of one of the transverse lugs. This is a common characteristic of most bar fatigue fractures.

Quite a number of laboratory investigations of the fatigue strength of reinforcing bars have been reported in recent years from the United States,¹⁸⁻²⁶ Canada,^{27,28} Europe,²⁹⁻³⁴ and Japan.³⁵⁻³⁹ In most of these investigations, the relationship between stress range, S_r , and fatigue life, N , was determined by a series of repeated load tests on bars which were either embedded in concrete or tested in air.

There is contradiction in the technical literature as to whether a bar has the same fatigue strength when tested in air or embedded in a concrete beam. In an investigation³¹ of hot-rolled cold-twisted bars, it was found that bars embedded in beams had a greater fatigue strength than when tested in air. However, in another investigation,²⁹ the opposite conclusion was reached. More recent studies^{28,32} indicate that there should be little difference in the fatigue strength of bars in air and embedded bars if the height and shape of the transverse lugs are adequate to provide good bond between the steel and concrete.

The influence of friction between a reinforcing bar and concrete in the vicinity of a crack has also been considered.³² In laboratory tests, an increase in temperature is frequently observed at the location where the fatigue failure occurs. However, rates of loading up to several thousand cycles per minute and temperatures up to several hundred degrees C are normally not considered to have a significant effect on fatigue strength.⁴⁰ In a statistical analysis⁴¹ of an investigation of reinforcing bars,²⁶ differences in fatigue strength due to rates of loading of 250 and 500 cycles per minute were not significant.

It is therefore believed that most of the data reported in investigations in North America and abroad is directly comparable, even though it may have been obtained under quite different testing conditions.

A number of S_r - N curves obtained from tests on concrete beams containing straight deformed bars made in North America^{18,21,24-28} are shown in Fig. 6. These curves are for bars varying in size from #5 to #11, with minimum stress levels ranging from -0.10 to 0.43 of the tensile yield strength of the bars.

Although only about one-third of the total number of S_r - N curves reported in the indicated references are shown in Fig.

* Dr. John M. Hanson was the chairman of the subcommittee that prepared this section of the report.

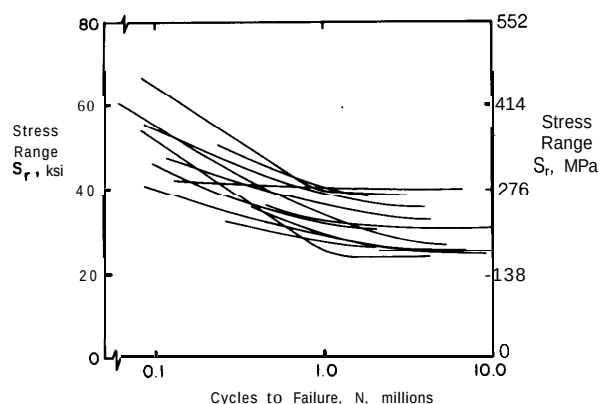


Fig. 6-Stress range-fatigue life curves for reinforcing bars

6, they include the highest and lowest fatigue strength. The varying characteristics of these curves suggest that there are many variables in addition to stress range that influence the fatigue strength of deformed reinforcing bars.

Most of the curves in Fig. 6 show a transition from a steeper to a flatter slope in the vicinity of one million cycles, indicating that reinforcing bars exhibit a practical fatigue limit. Fatigue strengths associated with the steeper or flatter part of the S_r-N curves will be referred to as being in the finite life or long life region, respectively. Because of the lack of sufficient data in the long life region, it is noted that many of the S_r-N curves in this region are conjectural.

The fatigue strength of the steel in reinforcing bars depends upon chemical composition, microstructure, inclusions, and other variables.⁴⁰ However, it has been shown^{26,28} that the fatigue strength of reinforcing bars may be only one-half of the fatigue strength of coupons machined from samples of the bars. In addition, reinforcing bar specifications are based on physical characteristics. Consequently, the variables related to the steel composition are of limited concern to practicing structural engineers. The variables related to the physical characteristics and use of the reinforcing bars are of greater concern. The main variables that have been considered in the technical literature are:

1. Minimum stress
2. Bar size and type of beam
3. Geometry of deformations
4. Yield and tensile strength
5. Bending
6. Welding

Each of these is discussed in the following sections.

2.2.2 Minimum stress-In several investigations,^{18,21,29} it has been reported that the fatigue strength of reinforcing bars is relatively insensitive to the minimum stress level. However, in two recent investigations,^{26,28} it was concluded that minimum stress level does influence fatigue strength to the extent

approximately indicated by a modified Goodman diagram with a straight line envelope. This indicates that fatigue strength decreases with increasing minimum stress level in proportion to the ratio of the change in the minimum stress level to the tensile strength of the reinforcing bars.

2.2.3 Bar size and type of beam-These two factors are related because bars embedded in concrete beams have a stress gradient across the bar. In design, it is only the stress at the midfibers of the bar that is generally considered. Large bars in shallow beams or slabs may have a significantly higher stress at the extreme rather than the midfibers of the bar.

The effect of bar size is examined in Table 1 using data from three investigations.^{28,32,36} Since #8 bars or their equivalent were tested in each of these investigations, the fatigue strength of other bar sizes was expressed as a ratio relative to the fatigue strength of the #8 bars. For each comparison, the bars were made by the same manufacturer, and they also were tested at the same minimum stress level. The fatigue strength is the stress range causing failure at 2 million or more cycles.

The tests reported in Reference 32 were on bars subjected to axial tension. Therefore, there was no effect of strain gradient in this data, yet the fatigue strength of the #5 bars was about 8 percent greater than that of the #8 bars.

Tests in Reference 28 were on bars in concrete beams. The strain gradients in these beams resulted in stresses at the extreme fibers for the different size bars that were about the same. Still, an effect of bar size was found that was of about the same order of magnitude.

In the tests in Reference 36 the strain gradient was greater across the #8 bars than the #6 bars. Therefore, part of the difference in fatigue strength should be attributed to the higher stress at the extreme fibers of the #8 bars. However, the differences, compared to the other test results, are about the same.

Table 1-Effect of bar size

Tests reported in	Grade of bar	Fatigue strength relative to fatigue strength of No. 8 bars			
		No. 5	No. 6	No. 8	No. 10
Reference 28	40	1.06	—	1.00	0.99
	60	1.08	—	1.00	0.96
	75	1.20	—	1.00	0.95
Reference 32	40	1.11	—	1.00	—
	40	1.05	—	1.00	—
	60	1.05	—	1.00	—
	75	1.10	—	1.00	—
Reference 36	40	—	1.12	1.00	—
	60	—	1.04	1.00	—
	60	—	1.10	1.00	—

In another investigation^{26,41} where both bar size and type of beam were controlled variables, the former was found to be significant and the latter was not significant. This investigation included bars of 5 different sizes—#5, 6, 8, 10, and 11—made by a major United States manufacturer. These bars were embedded in rectangular or T-shaped concrete beams having effective depths of 6, 10, or 18 in. (152, 254, or 457 mm). In this investigation, the fatigue life of #8, Grade 60 bars subjected to a stress range of 36 ksi (248 MPa) imposed on a minimum stress of 6 ksi (41.4 MPa) was 400,000 cycles. Under identical stress conditions, the fatigue life of the #5, 6, 10, and 11 bars were found to be 1.22, 1.30, 0.76, and 0.85 times the life of the #8 bars, respectively. This trend is the same as that for the data shown in Table 1. The irregular variation was attributed to differences in surface geometry.

2.2.4 Geometry of deformations—Deformations on reinforcing bars provide the means of obtaining good bond between the steel and the concrete. However, these same deformations produce stress concentrations at their base, or at points where a deformation^{20,21,23} intersects another deformation or a longitudinal rib. These points of stress concentrations are where the fatigue fractures are observed to initiate.

Any evaluation of the influence of the shape of the deformations on fatigue properties of the bar must recognize that the rolling technique and the cutting of the rolls necessarily requires specific limitations and variations in the pattern. This applies to the height of the deformations, the slopes on the walls of the deformations, and also to the fillets at the base of the deformations.

An analytical study⁴² has shown that stress concentration of an external notch on an axially loaded bar may be appreciable. This study indicated that the width, height, angle of rise, and base radius of a protruding deformation affect the magnitude of the stress concentration. It would appear that many reinforcing bar lugs may have stress concentration factors of 1.5 to 2.0.

Tests on bars having a base radius varying from about 0.1 to 10 times the height of the deformation have been reported.^{25,26,28,36} These tests indicate that when the base radius is increased from 0.1 to about 1 to 2 times the height of the deformation, fatigue strength is increased appreciably. An increase in base radius beyond 1 to 2 times the height of the deformation does not show much effect on fatigue strength. However, Japanese tests³⁶ have shown that lugs with radii larger than 2 to 5 times the height of the deformation have reduced bond capacity.

Tests have indicated^{30,31,39} that decreasing the angle of inclination of the sides of the deformations with respect to the longitudinal axis increases the fatigue strength of a reinforcing bar. This increase occurs for bars with lugs having abrupt changes in slope at their bases. It has been noted⁴³ that the base radius should be determined in a plane through the longitudinal axis of the bar, since this is the direction of the applied stress. The base radius determined in this plane will be substantially larger than a base radius determined in a plane perpendicular to a sharply inclined lug.

In two experimental investigations,^{23,34} it was found that

the condition of the rolls, whether new or worn, had little effect on fatigue strength. However, a conflicting opinion has been expressed in Reference 32.

Tests³² also show a substantial effect on the fatigue resistance of reinforcing bars due to brand marks. The brand marks cover the identification of the bar as to size, type of steel (billet, rail, or axle), mill that rolled the steel, and yield strength (Grade 40, 60, or 75).⁴⁴ The stress concentration at a bar mark is similar to that caused by bar deformations.

It has also been demonstrated²⁴ that the fatigue strength of a reinforcing bar may be influenced by the orientation of the longitudinal ribs. In that study, an increased fatigue life was obtained when the longitudinal ribs were oriented in a horizontal position rather than a vertical position. This phenomenon is apparently associated with the location at which the fatigue crack initiates. In other words, if there is a particular location on the surface of a bar which is more critical for fatigue than other locations, then the positioning of that location in the beam will influence the fatigue strength.

2.2.5 Yield and tensile strength—In three investigations,^{21,27,28} the fatigue strength of different grades⁴⁴ of bars made by the same North American manufacturer were compared. The results of these comparisons, all of which are in the long life region of fatigue life, are shown by the bar graphs in Fig. 7. It was concluded in References 21 and 28 that the fatigue strength of the bars was relatively insensitive to their yield or tensile strength. References 21 and 28 include 157 and 72 tests, respectively. Reference 27, which includes 19 tests, indicated that fatigue strength may be predicted for grade of steel as a function of the stress range.

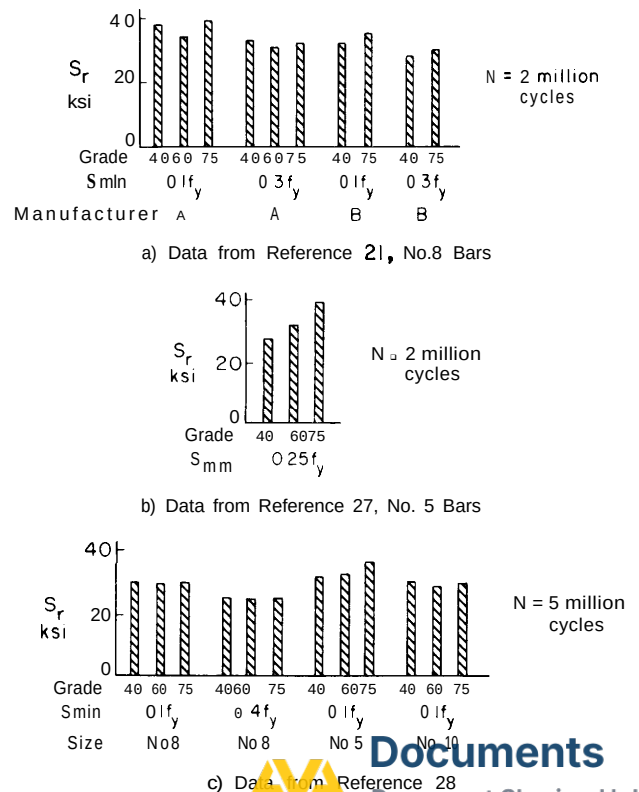


Fig. 7—Effect of grade of bar

In another investigation^{26,41} on bars made by a major United States manufacturer, the fatigue life of Grade 40, Grade 60, and Grade 75 #8 bars, subjected to a stress range of 36 ksi (248 MPa) imposed on a minimum stress of 6 ksi (41.4 MPa), varied linearly in the ratio of 0.69 to 1.00 to 1.31, respectively. The ratio of 1.0 corresponds to a fatigue life of 400,000 cycles, and is therefore in the finite life region.

Axial tension fatigue tests³² on unembedded reinforcing bars made in Germany were carried out on four groups of bars having yield strengths of 49, 53, 64, and 88 ksi (338, 365, 441, and 607 MPa). All of the bars were rolled through the same stand for elimination of variation in the deformed surfaces. When tested with a minimum stress level of 8.5 ksi (58.6 MPa), the stress ranges causing failure in two million cycles were determined to be 28, 28, 28, and 31 ksi (193, 193, 193, and 214 MPa) respectively.

In a Japanese investigation,³⁶ bars of the same size and made by the same manufacturer but with yield strengths of 50, 57, and 70 ksi (345, 393, and 483 MPa) were tested. The stress range causing failure in two million cycles was between 30 and 31.5 ksi (207 and 217 MPa) for all three groups of bars.

2.2.6 Bending—The effect of bends on fatigue strength of bars has been considered in two investigations.^{21,29} In the North American investigation,²¹ fatigue tests were carried out on both straight and bent #8 deformed bars embedded in concrete beams. The bends were through an angle of 45 deg around a pin of 6 in. (152 mm) diameter. The fatigue strength of the bent bars was a little more than 50 percent below the fatigue strength of the straight bars. In one test, a bent bar embedded in a reinforced concrete beam failed in fatigue after sustaining 900,000 cycles of a stress range of 18 ksi (124 MPa) imposed on a minimum stress of 5.9 ksi (40.7 MPa). In another test, application of 1,025,000 cycles produced a failure when the stress range and minimum stress were 16.4 ksi and 19.1 ksi (113 and 132 MPa), respectively.

Tests²⁹ have also been reported from Germany on both plain and deformed hot-rolled bars bent through an angle of 45 deg. However, these bars were bent around a pin having a diameter of 10 in. (254 mm). Compared to tests on straight bars, the fatigue strength of the plain bars was reduced 29 percent by the bend, while the fatigue strength of the deformed bars was reduced 48 percent.

2.2.7 Welding—In an investigation²⁴ using Grade 40 and Grade 60 reinforcement with the same deformation pattern, it was found that the fatigue strength of bars with stirrups attached by tack welding was about one-third less than bars with stirrups attached by wire ties. The results of the tests on the Grade 60 reinforcement are shown in Fig. 8. For both grades of steel, the fatigue strength of the bars with tack welding was about 20 ksi (138 MPa) at 5 million cycles. All of the fatigue cracks were initiated at the weld locations. It should be cautioned that tack welds that do not become a part of permanent welds are prohibited by AWS D1.4¹⁰⁹ unless authorized by the Engineer. Full penetration welds are permitted by AWS D1.4.

Investigations^{19,22} have also been carried out to evaluate the behavior of butt-welded reinforcing bars in reinforced

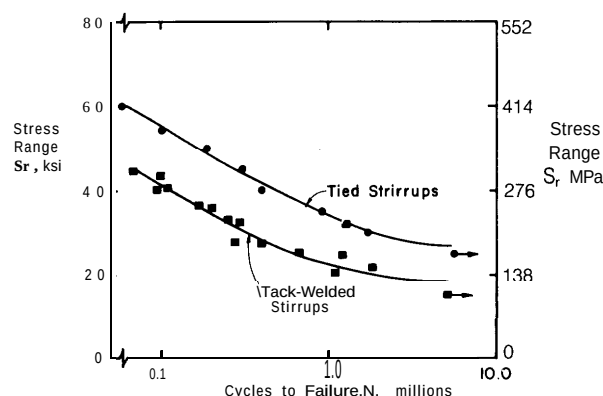


Fig. 8—Effect of tack welding stirrups to Grade 60 bars

concrete beams. In tests conducted at a minimum stress level of 2 ksi (13.8 MPa) tension, the least stress range that produced a fatigue failure was 24 ksi (165 MPa). It was observed that minimum stress level in the butt-welded joint was not a significant factor affecting the fatigue strength of the beams.

2.3 Welded wire fabric and bar mats*

Welded wire fabric may consist of smooth or deformed wires while bar mats usually consist of deformed bars. Often fabric and bar mats are not used in structures subject to significant repeated loads because of concern that the welded intersections will create significant stress concentrations. This feeling has been heightened by experience from abroad⁴⁵ and the relatively poor performance of smooth wire fabric in continuously reinforced concrete pavements.^{46,47,48} In some cases, pavements reinforced with this fabric performed adequately in service for 3 to 5 years. Then several wide cracks occurred, necessitating extensive repairs. While most of this cracking was caused by inadequate detailing of splices, field studies in Connecticut⁴⁷ have revealed failures at the welds in a significant number of instances.

Any assessment of welded wire fabric or bar mats based primarily on their performance in pavements is unrealistic. In any given length of pavement, wide variations are possible in the stress spectrum for the reinforcement. The average stress level in the reinforcement is strongly dependent on the pavement's age, its thermal and moisture history, and the longitudinal restraint offered by the subgrade. The stress range in the reinforcement caused by the traffic depends on the support offered by the subgrade as well as the magnitude of the loading.

Several recent investigations have examined the fatigue characteristics of fabric and bar mats in air.^{45,48,49} For smooth wire fabric^{45,49} the disturbance due to the welded intersection dominated over all other influences, so that failures were confined to the heat affected zone of the weld. For bar mats, the disturbance due to the welded intersection dominated only if the stress concentration caused by the intersection was greater than the concentration caused by the deformation. The available evidence does not indicate that the effects

* Dr. Neil M. Hawkins prepared this section of the report.