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 materiak+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	StructuralWelding 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.

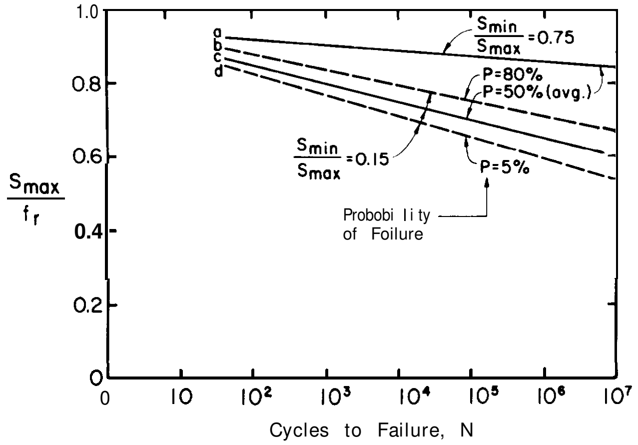

Fig. l-Fatigue strength of plain concrete beams

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*-Theeffect 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 beams[5] 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.

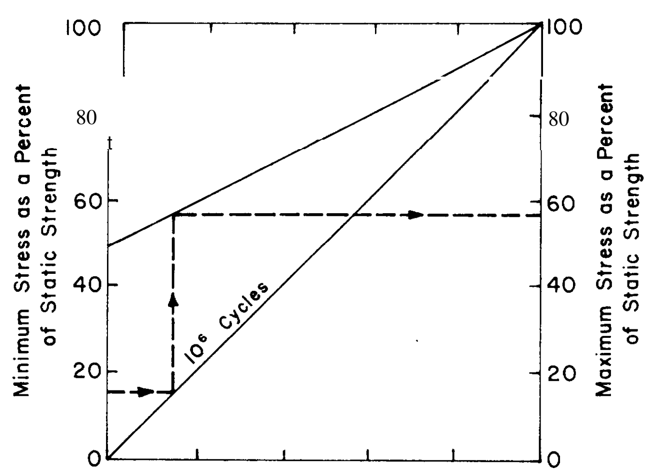

Fig. 2-Fatigue strength of plain concrete intension, compressionor flexure