IN-LB	Inch-Pound Units
SI	International System of Units

Concrete Structure Design for Fatigue Loading—Report

Reported by ACI Committee 215

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Fatigue is a mechanical degradation process caused by repeated loads, such as traffic loading or wind loads on a bridge, that results in irreversible damage in concrete structures. Many types of concrete elements are subjected to repeated loads, such as airport and roadway pavements, bridge girders, bridge decks, wind turbines, and prestressed concrete railroad ties. This document provides information that will benefit practicing engineers interested in the design or rehabilitation of concrete structures subjected to high-cycle fatigue—that is, stress cycles in which the material behavior remains within the elastic range. The effects of repeated loads on plain concrete, reinforcing materials, and reinforced concrete systems are discussed based on a summary of available literature. This report does not contain detailed design procedures but rather should be considered a general resource providing a comprehensive overview of fatigue issues in reinforced concrete structures.

Keywords: design; fabric-reinforced cementitious matrix; fatigue; fiber-reinforced concrete; fiber-reinforced polymers; prestressed concrete; rehabilitation; reinforced concrete; reinforcing materials; service life.

CONTENTS

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Fatigue is a mechanical degradation process caused by repeated loads, such as traffic loading or normal wind loads on a bridge, that results in irreversible damage in concrete structures. Because individual application of these service loads would not cause significant deformation or damage, fatigue damage occurs gradually from the cumulative effects of thousands or millions of load cycles. This report does not discuss the effects of high-amplitude load cycles associated with extreme events such as an earthquake or unintentional overload.

Many types of concrete elements are subjected to repeated low stress loads; common examples include airport and roadway pavements, bridge girders, bridge decks, wind turbines, and prestressed concrete railroad ties. Although in-service fatigue failures of concrete structures and their components are rare, the fatigue behavior of reinforced concrete structures is important to consider for numerous reasons. For example, fatigue behavior can be a controlling parameter that determines the service life of concrete pavements. In other cases, fatigue damage can lead to increased cracking with resulting loss of stiffness and strength in concrete members under service loads, which can lead to failure. In statically indeterminate structural systems, changes in stiffness caused by fatigue will also influence the distribution of loads. In summary, fatigue behavior affects the serviceability, safety, and durability of concrete structures, and its effects should be recognized in design to ensure that in-service cyclic stress ranges remain at an acceptably low level.

Live load amplitudes applied to a structure tend to grow over time, while new structures are becoming more lightweight through greater design optimization and the use of high-performance materials; this increases the ratio of live to dead loads. As a result, the importance of transient, cyclic stresses in proportion to an element's total load capacity is likely to increase over the service life of a structure. Furthermore, increasing use of construction materials such as post-tensioned concrete, fiber-reinforced polymers (FRPs), and fiber-reinforced concrete (FRC) requires engineers to have a broad understanding of the fatigue characteristics of various materials and systems.

Although service loads nominally produce stresses that are within the elastic range of the material or structure, small defects or geometric discontinuities can result in local amplified stress concentrations that exceed the elastic capacity of the material and form small damage zones or nucleation sites. The preliminary stage of the degradation process, where the development of these damage zones occurs, is often referred to as the initiation period. As these loads may be repeatedly applied thousands or millions of times, the damage zones grow in size (propagation) or in number (accumulation), leading to changes in the behavior of the larger material or composite component. In reinforced concrete members, this damage manifests through the formation of cracks in the concrete, reinforcement, or at their interface. The result of propagation and accumulation is usually a net reduction in the effective cross section of the member, its reinforcement, or in the bond strength between the reinforcement and the concrete, typically resulting in a loss of member stiffness and strength.

Although real live loads vary greatly in magnitude and application time sequence, for the purposes of design, an equivalent constant amplitude load cycle (for example, a sine function) with a well-defined maximum and minimum stress or strain level is normally assumed. This constant amplitude fatigue model presents many advantages for fatigue analysis, including the use of *S-N* curves for presenting and interpreting fatigue life data. In those curves, *S* represents normalized applied stress or strain amplitude and is plotted on a vertical axis using a linear (or sometimes logarithmic) scale against *N*, which is the number of load cycles to failure (also called fatigue life) and is plotted on the horizontal axis using a logarithmic scale. As the stress amplitude decreases, the number of cycles to failure increases. Thus, the fatigue strength is lower than that of the undamaged material under a monotonic (that is, static) load.

Appropriate procedures for addressing variable amplitude stress cycles remain a topic of debate among researchers and are not discussed in depth in this document. In the absence of specified fatigue loading (for example, AASHTO), for the purposes of design, it is usually sufficient to consider a constant amplitude fatigue load model where the minimum stress value is the stress corresponding to the design dead load, and the maximum stress value corresponds to the total design dead and live loads.

1.2—Scope

This report provides information that will benefit practicing engineers interested in the design or rehabilitation of concrete structures subjected to fatigue cycles caused by regular service loads. This report does not contain detailed design procedures but rather should be considered a general resource providing a comprehensive overview of fatigue issues in reinforced concrete structures.

This document is divided into three thematic sections:

1) Chapters 1 and 2 provide a general introduction, and notation and definitions, respectively.

2) Chapters 3 and 4 discuss the fatigue behavior of plain unreinforced concrete and reinforcing materials (steel bars and tendons and FRP components), respectively. These chapters are likely to be of interest for those interested in applications of unreinforced concrete, as well as for practitioners seeking to develop a better understanding of the mechanisms of fatigue in various materials.

3) Chapters 5 through 8 focus on the fatigue behavior of reinforced concrete systems considering the interaction between constituent materials. These chapters are intended for practicing engineers dealing with the design or assessment of common applications of structural concrete subjected to repeated loads. The content is organized by the type of reinforcing system used: conventional reinforced concrete containing internal steel or FRP bars (Chapter 5); concrete reinforced with bonded or unbonded prestressed tendons (Chapter 6); concrete reinforced with discrete fibers (Chapter 7); and external strengthening sheets or laminates (Chapter 8).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_t = area of concrete below the neutral axis, in.^{2} (mm^2)
a = crack length, in. (mm)
c = neutral axis depth, in. (mm)
D = damage
d_a/d_n = crack length increment per cycle, in. (mm)
d_f = effective depth of FRP laminate, in. (mm)
d_s = effective depth of beam reinforcement, in. (mm)
E_c = Young's modulus of concrete, psi (MPa)
E_s = Young's modulus of steel, psi (MPa)
f = frequency, Hz
f_c' = concrete compressive strength, psi (MPa)
f_{fu} = design tensile strength of FRP, psi (MPa)
f_{pu} = ultimate strength of prestressing strands, psi (MPa)
f_t' = concrete tensile strength, psi (MPa)
f_y = yield stress of steel, psi (MPa)
ℓ_{bf} = distance from flexural crack to tip of interfacial debonding zone at FRP level, in. (mm)
ℓ_{bs} = distance from flexural crack to tip of interfacial debonding zone at steel level, in. (mm)
ℓ_c = crack spacing, in. (mm)
M_{cr} = cracking moment, lb-ft (kN-m)
M_D = applied bending moment due to dead loads, lb-ft (kN-m)
M_L = applied bending moment due to live loads, lb-ft (kN-m)
N = number of applied repeated load cycles n needed to cause failure—that is, fatigue life
n = number of applied repeated load cycles within the fatigue process
P = probability of failure, %
R = applied stress ratio, S_{max}/S_{min}
S = cyclic stress amplitude normalized with respect to equivalent static strength—that is, fatigue strength
S_{max} = maximum cyclic stress level normalized with respect to equivalent static strength
S_{min} = minimum cyclic stress level normalized with respect to equivalent static strength
S_n = steel stress at the primary crack after n load cycles, psi (MPa)
S_o = steel stress at the primary crack after first load cycle, psi (MPa)
S_2 = normalized confining stress in biaxial compression tests
S_3 = normalized axial stress in biaxial compression tests
T_g = glass transition temperature, °F (°C)
W = crack width after one load cycle, in. (mm)
W_N = crack width after n cycles, in. (mm)
β = ratio of distance between neutral axis and crack measurement location to distance between neutral axis and reinforcement location after first load cycle
β_n = ratio of distance between neutral axis and crack measurement location to distance between neutral axis and reinforcement location after n load cycles
ΔK = stress intensity range, ksi-in. (MPa-mm)
ΔS = stress range—that is, the difference between maximum and minimum cyclic stress level, psi (MPa)
δ_n = reinforcing bar slip after n cycles, in. (mm)
δ_o = initial reinforcing bar slip, in. (mm)
ε = strain
γ = applied load factor (AASHTO)
Σ_o = sum of perimeters of tension reinforcement, in. (mm)
σ_2 = confining stress in biaxial compression tests, psi (MPa)
σ_3 = axial stress in biaxial compression tests, psi (MPa)