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Report on Bond of Steel Reinforcing Bars Under Cyclic Loads

Reported by Joint ACI-ASCE Committee 408

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.
Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

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[*] Member, Subcommittee on Repeated Load Effects
[†] Chair and Editor, Subcommittee on Repeated Load Effects
Note: The contributions of Brett Baker are gratefully acknowledged.

This report summarizes research on bond strength and behavior of steel reinforcing bars under cyclic loads. The report provides a background to bond problems, discusses the main variables affecting bond performance, and describes bond behavior under cyclic loads. Two general types of cyclic loads are addressed: high-cycle (fatigue) and low-cycle (earthquake and similar). The anchorage behaviors of straight bars, hooked bars, and lap splices are included. Analytical bond models are described, design recommendations are provided for both high- and low-cycle fatigue, and suggestions for further research are given.

Keywords: anchorage; bar slip; bond; bond models; cyclic loads; design recommendations; development length; fatigue; hooks; earthquake loads; splices.

CONTENTS

ACI 408.2R-12 superseds ACI 408.2R-92 and was adopted and published September 2012.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The transfer of forces across the interface between concrete and steel by bond stresses is of fundamental importance to many aspects of reinforced concrete behavior. Satisfactory bond performance is an essential goal in detailing reinforcement in structural components. Many detailing provisions in ACI 318 are aimed at preventing bond failures.

Bond stresses in reinforced concrete members arise from two distinct situations. The first is anchorage or development where bars are terminated. The second is flexural bond or the change of force along a bar due to a change in bending moment along the member. Bond performance under static monotonically increasing deformations—referred to as monotonic loading—has been summarized in ACI 352R, ACI 408R, and ACI Committee 408 (1966, 1970, 1979). Bond behavior under cyclic loads received little attention until design for earthquake and wave loads became important design topics (ACI Committee 408 1979). Investigations over the past 40 years have clarified some of the important parameters influencing bond behavior under cyclic loads. However, the influence of many of these parameters is understood only qualitatively.

In this report, “bar” means “reinforcing bar” and “ribs” refer to the deformations on deformed reinforcing bars. Longitudinal deformations on reinforcing bars are not classified as ribs. “Bond stress” refers to the stresses along the bar-concrete interface. The steel stresses along the length of the reinforcing bar are modified by transfer of force between the bar and the surrounding concrete along the interface (refer to Fig. 1.1).

The change in bar tensile force ΔF between two cracked sections along a flexural member ΔF is given by

$$\Delta F = T_1 - T_2 = \left(\frac{M_1}{jd_1}\right) - \left(\frac{M_2}{jd_2}\right) \tag{1.1a}$$

The average bond stress u_b is usually expressed as

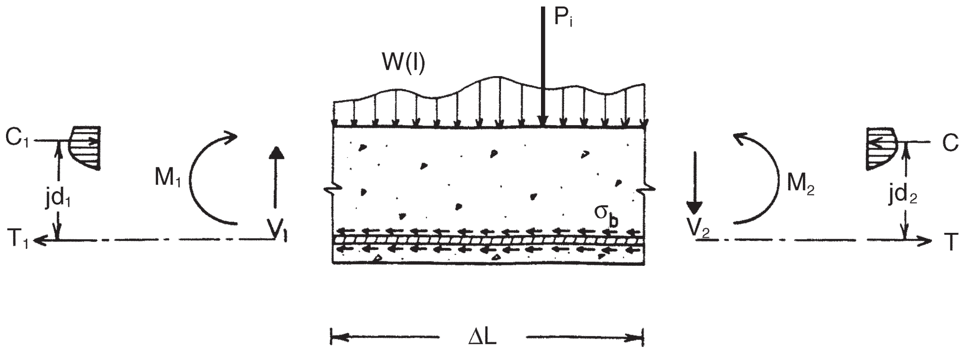

Fig. 1.1—Definition of bond stress.

$$u_b = \frac{q}{\Sigma_o} = \frac{\Delta F}{\Delta L \Sigma_o} = \frac{\Delta f_s\left(\pi d_b^2/4\right)}{\Delta L\left(\pi d_b\right)} = \frac{d_b \Delta f_s}{4\Delta L} \qquad (1.1b)$$

Cyclic loadings are divided into two general categories. The first is designated low-cycle or low-cycle, high-stress loading, or a load history containing less than 100 cycles and having bond stress ranges (u_r) greater than 600 psi (4 MPa). Low-cycle loadings commonly result from earthquake and high-wind loadings. The second category is designated high-cycle or fatigue loading with a load history containing thousands or millions of cycles, but at a low bond stress range (u_r) typically less than 300 psi (2 MPa). Bridge members, offshore structures, and members supporting vibrating machinery are often subjected to high-cycle or fatigue loading. High-cycle loadings can be a problem at service load levels whereas low-cycle loadings can produce problems at the ultimate limit state.

Bond behavior under cyclic loading can further be subdivided according to the type of stress applied. The first is repeated or unidirectional loading, which implies that the bar stress does not reverse from tension to compression during a load cycle, the usual situation for fatigue loading. The second is stress reversal, where the bar is subjected alternatively to tension and compression. Earthquake loading typically causes stress reversals.

1.2—Scope

This report reviews bond and anchorage of steel reinforcing bars in normal and lightweight concrete, with emphasis on bond under cyclic loading. Although the amount of information about the bond behavior of epoxy-coated reinforcing bars subjected to cyclic loading is limited, available references on this topic were reviewed and are presented in the document. Bond and anchorage of prestressing steel and headed reinforcing bars are not addressed in this report. This report serves both designers and researchers, and is organized accordingly. Chapters 3 and 4 present background information on the issue of bond under cyclic loading. Chapters 5, 6, and 7 deal with results of research and development of analytical bond models. Chapters 8 and 9 review international design guidelines dealing with bond under cyclic loads and should be of interest to designers. This report also introduces designers to the basic mechanisms involved in bond, the variables that affect those mechanisms, and differences in bond behavior under cyclic and noncyclic loads.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_b = cross-sectional area of reinforcing bar, in.^{2} (mm^2)
A_c = area of concrete cross section, in.^{2} (mm^2)
A_{tr} = area of transverse reinforcement, in.^{2} (mm^2)
BI = representation of the severity of bond stresses relative to the bond strength
C = concrete cover, in. (mm)
c_b = smaller of: (a) the distance from center of a bar or wire to nearest concrete surface; and (b) one-half the center-to-center spacing of bars or wires being developed, in. (mm)
D = development length according to AIJ (1990), in. (mm)
DCH = ductility class high, based on the maximum behavior factor
DCM = ductility class medium, based on the maximum behavior factor
d = depth from extreme compression fiber to centroid of tensile reinforcement, in. (mm)
d_b = diameter of bar, or diameter of bar being developed, in. (mm)
d_{bL} = nominal diameter of longitudinal bars, in. (mm)
f_b = static bond strength as used for offshore structures, psi (MPa)
f_{br} = bond strength at 2,000,000 cycles as used for offshore structures, psi (MPa)
f_c' = specified concrete compressive strength, psi (MPa)
f_{cd} = design concrete compressive strength, psi (MPa)
f_{cr} = stress range in concrete, psi (MPa)
f_{ctm} = mean value of the tensile strength of concrete, psi (MPa)
f_{min} = minimum stress level, ksi (MPa)
f_r = stress range due to live loads and impact recommended by AASHTO, ksi (MPa)
f_{rup} = static modulus of rupture, psi (MPa)
f_s = existing reinforcement strength based on available development length, psi (MPa)
f_{sos} = yield strength divided by a factor of safety (typically = 1.15), offshore structures, psi (MPa)
f_y = yield strength of bar being developed, psi (MPa)
f_{yd} = design value of the yield strength of bars, psi (MPa)
f_{yt} = yield strength of transverse reinforcement, psi (MPa)
h = depth of member, in. (mm)
h_c = width of the column parallel to the bars, in. (mm)
h_j = joint dimension parallel to the bar, in. (mm)
jd_i = internal moment arm at section i, in. (mm)
K_{tr} = transverse reinforcement index
k_D = factor reflecting the ductility class equal to 1 for DCH and to 2/3 for DCM
ℓ = total length of the member, in. (mm)
ℓ_b = provided length of straight development, lap splice, or standard hook, in. (mm)
ℓ_d = development length, in. (mm)
ℓ_d' = equivalent straight bar anchorage length corresponding to a hooked bar anchorage, in. (mm)
ℓ_{dh} = lead embedment length for a hook, in. (mm)
ℓ_e = length of embedment of reinforcement, in. (mm)
M_i = moment at section i, lb-in. (N-m)
N = number of cycles to failure
N_{ed} = design axial force, lbf (N)
q = change of bar force per unit length of bar, lb/in. (N/mm)
r/h = ratio of base radius to height of rolled transverse rib
S = applied stress range, psi (MPa)
S_{bmax} = maximum bond strength as used for offshore structures, psi (MPa)
S_{br} = stress range as used for offshore structures, psi (MPa)