

An abstract:

State-of-the-Art Report: Bond under Cyclic Loads

Reported by ACI Committee 408

Denis Mitchell,
Chairman

Roberto LEON,
Secretary

William C. Black
Rolf Eligehausen*
Narendra K. Gosain
David W. Johnston
S. Ali Mirza
Mikael P. J. Olsen

David Darwin*
Fernando E. Fagundo
Neil M. Hawkins
Le Roy A. Lutz*
Jack P. Mochle
Telvin Rezansoff*
Parviz Soroushian

Mohammad R. Ehsani
Peter Gergely*
James O. Jirsa*
John F. McDermott
Kenneth H. Murray
Morris Schupack

Editorial Committee on Repeated Load Effects.
ACI Committee on Repeated Load Effects

This State-of-the-art report summarizes the most recent background on bond behavior under cyclic loads. The report provides a background to bond problems, discusses the main variables affecting bond performance, and describes its behavior under cyclic loads. Two general types of cyclic loads are addressed: high-cycle (fatigue) and low-cycle (earthquake and similar) loads. The behavior of straight anchorages, hooks, and splices is included. Design recommendations are provided for both high- and low-cycle fatigue, and suggestions for further research are given.

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

SCOPE

The purpose of this document is to review the current state-of-the-art on bond, with particular emphasis on bond under cyclic loading. Two general types of cyclic loads are addressed: high-cyclic (fatigue) and low-cyclic (earthquake and similar) loads. The behavior of straight anchorages, hooks, and splices under both load regimes is discussed. The report is intended to serve both designers and researchers, and is organized into eight chapters. Chapters 1, 2, and 3 present background information on bond under cyclic loading and should be of interest to all readers. Chapters 4, 5, and 6 deal with results of research and development of analytical bond models, and should be of use primarily to

researchers. Chapter 7 presents a review of current design guidelines, from both the U.S. and abroad, dealing with bond under cyclic loads, and should be of particular interest to designers. Chapter 8 provides a summary of the research results and research needs. The document is meant also to serve as an introduction for designers to the basic mechanisms involved in bond, the variables that effect them, and the differences between behavior under cyclic and non-cyclic loads. An extensive reference list, including similar reports, is provided for readers desiring additional details. Bond behavior of prestressing tendons and behavior under shock or impact loading are not addressed in this report.

BOND STRESS

“Bond stress” refers to the stress along the bar-concrete interface which modifies the steel stress along the length of the bar by transferring load between the bar and the surrounding concrete. Bond stresses in rein-

ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be apart of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

ACI 408.2R-92 became effective August 1, 1992.

Copyright © 1999, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

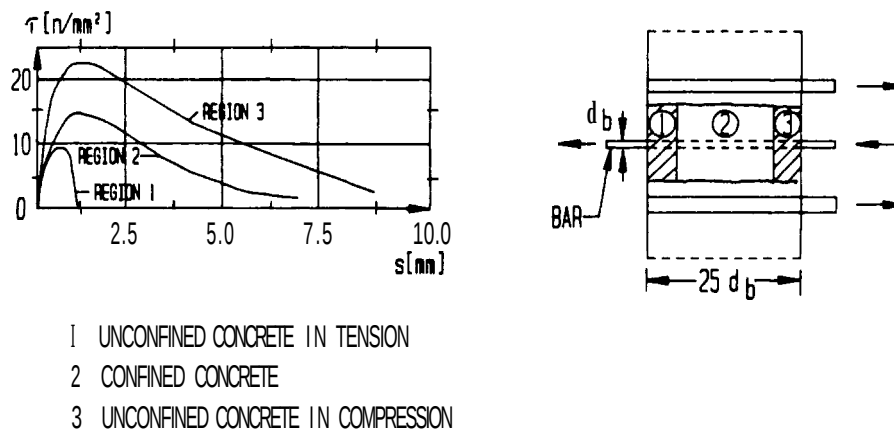


Fig. 1—Typical bond stress versus slip curve for monotonic loading

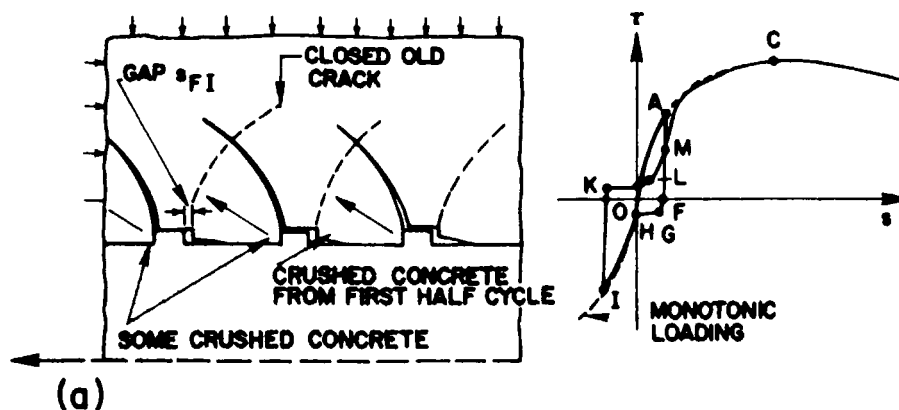


Fig. 2—Cracking under cyclic loads

forced 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.

The efficiency of bond can be conveniently quantified by looking at bond stress versus bar slippage curves that represent the change in local stress in the bar σ_b versus the total movement of the bar relative to the surrounding concrete s (Fig. 1). The slip s represents the rigid body motion of the bar with respect to some fixed point in the surrounding concrete. Bond stress, as used in this report, refers to an average bond stress computed along a length of bar at least 15 diameters long, and not to the local stress at an individual bar deformation or at a point along the interface between bar and concrete. The limit of 15 bar diameters is somewhat arbitrary and constitutes a lower bound to typical anchorage lengths, but it is the values of average bond stress over typical anchorage lengths that are of importance in design. For monotonically increasing slips, values for maximum bond (a strength measured over short distances) are reported in the literature to vary from about 1500 to 3000 psi (10.3 to 20.7 MPa). Average values of bond stress for use in design range from 560 to 800 psi (3.8 to 5.5 MPa). The values of slip at maximum bond stress show considerable scatter, de-

pending primarily on the deformation pattern,² but typically maximum bond stress will be reached at values of slip of 0.01 to 0.1 in. (0.25 to 2.5 mm).

LOADS

Loads on structural members can be subdivided into monotonic and cyclic loads. Monotonic loading implies that some parameter, in this case slip, is always increasing. Cyclic loads imply that the same parameter reverses in direction many times during the load history. Cyclic loadings are divided into two general categories. The first category is the so-called "low-cycle" loading, or a load history containing few cycles (less than 100) but having large ranges of bond stress ($\sigma_{br} > 600$ psi). The bond stress range σ_{br} is the difference between the average bond stresses at the maximum and minimum load, taking into account the direction of the loading. Low-cycle loadings commonly arise in seismic and high wind loadings. The loading is also referred to as "low-cycle, high-stress" loading. The second category is the so-called "high-cycle" or fatigue loading, which is a load history containing many cycles (typically thousands or millions), but at a low bond stress range ($\sigma_{br} < 300$ psi). Bridge members, offshore structures, and members supporting vibrating machinery are often subjected to "high-cycle" or fatigue loading. High-cycle loadings are considered a problem at service

load levels, while low-cycle loading produce problems at the ultimate limit state.

The 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 change sense (tension to compression) during a loading cycle, as is the usual situation for fatigue loading. The second is stress reversal, where the bar is subjected alternatively to tension and compression. Stress reversals are the typical case for seismic loading.

FAILURE MODES

Under monotonic loading, two types of bond failures are typical. The first is a direct pullout of the bar, which occurs when ample confinement is provided to the bar. The second type of failure is a splitting of the concrete cover when the cover or confinement is insufficient to obtain a pullout failure. Failure loads under low-cycle loading are very similar to those under monotonic loading, but cracking occurs in both directions with cycling (Fig. 2) and fatigue failures of both reinforcing bar and concrete need to be considered.

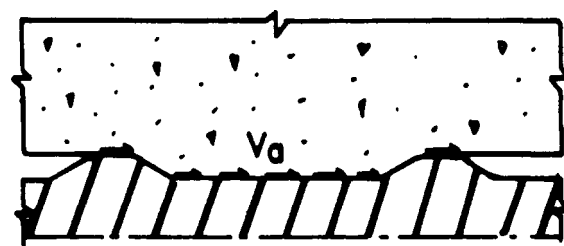
COMPONENTS OF BOND RESISTANCE

Although the concept of average bond stress is convenient, the force transfer is a combination of resistance due to adhesion V_a , mechanical anchorage due to bearing of the lugs V_b , and frictional resistance V_f (Fig. 3). Adhesion is related to the shear strength of the steel-concrete interface, and is primarily the result of chemical bonding. Mechanical anchorage arises from bearing forces perpendicular to the lug face as the bar is loaded and tries to slide. These bearing forces, in turn, give rise to frictional forces along the bar-concrete interface. The latter forces are an important component when failure is governed by splitting.

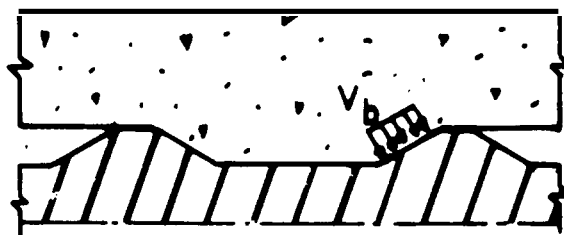
Under monotonic loading, typical values for adhesion range from 70 to 150 psi (0.48 to 1.03 MPa), while those for friction range from 60 to 1450 psi (0.41 to 10.0 MPa). It has generally been assumed that under monotonic loads, adhesion can be broken due to service loads or to shrinkage of the concrete, and that bearing against the lugs is the primary load-transfer mechanism at loads near ultimate. However, recent data comparing the performance of plain and epoxy-coated reinforcing bars under monotonic loads indicate that adhesion may play a much greater role in anchorage failures governed by splitting of the concrete cover.

Under cyclic loads, most of the bond stresses are transferred mechanically by bearing of the bar deformations against the surrounding concrete. The tensile and compressive strength of the concrete, the geometry and spacing of the deformations, cover and spacing, and amount of transverse reinforcement play a dominant role in controlling the bond behavior for this loading case.

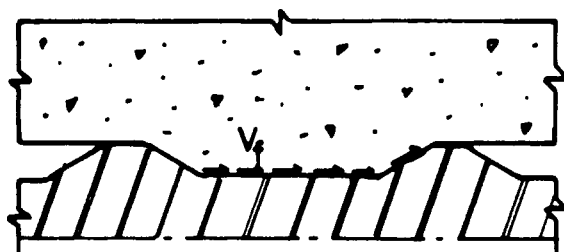
The bond stress-slip response of a bar loaded by low-cycle loads is shown in Fig. 4.² The initial part of the curve follows the monotonic envelope. If the load is re-



(a) Adhesion



(b) Bearing



(c) Friction

Fig. 3—Components of bond resistance

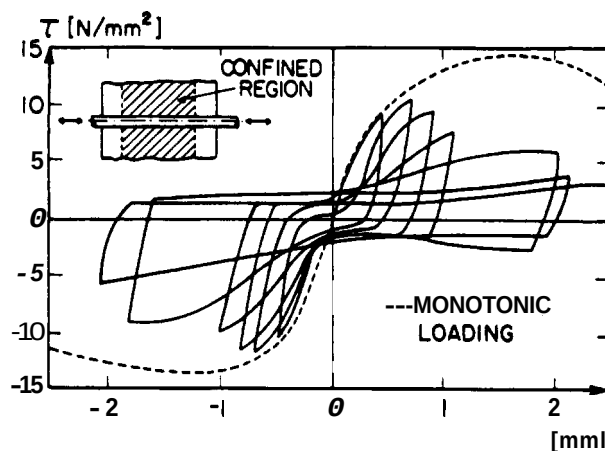


Fig. 4—Bond behavior under low-cycle loads

versed after the bond stress exceeds about half of its ultimate value, a significant permanent slip will remain when the bar is unloaded. If loading in the opposite direction occurs, then the bar must experience some rigid body motion before beginning to bear in the opposite direction. As cycling progresses, the concrete in front of the lugs is crushed and sheared. When the load is re-

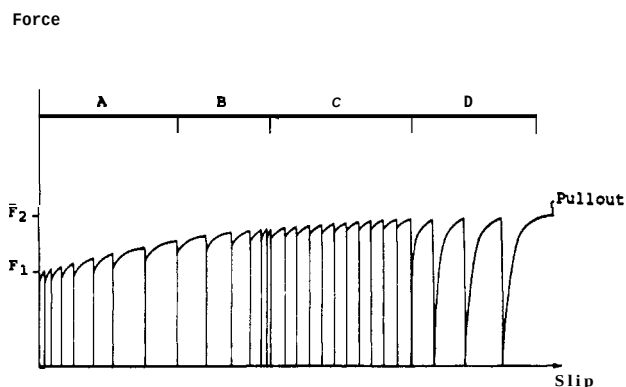


Fig. 5—Bond under high-cycle loads

versed, large slip occurs before the bar lug bears against the concrete and bond stresses increase. The main differences between monotonic and cyclic loads are that in the latter, adhesion is assumed to be lost after the first cycle, and the friction component (flat portion of the curve) decreases with cycling. In framed structures, the loss of bond in beam-column joints can lead to large drifts if the joints have been subjected to inelastic load reversals because of these horizontal portions (near zero stiffness) of the bond stress-slip curves.

Under high-cycle loads, the behavior is very dependent on the stress and/or strain amplitude and the number of cycles of load applied. Fig. 5 shows a typical curve for this case. Four separate regimes can be identified. First, large slips occur with constant loading (A), the slip then decreases (B), and stabilizes (C), and finally it increases rapidly with cycling until failure (D).

FACTORS AFFECTING BOND STRENGTH UNDER CYCLIC LOADS

The main factors affecting bond behavior under cyclic loads are:

1. Concrete compressive strength
2. Cover and bar spacing
3. Bar size
4. Anchorage length
5. Rib geometry
6. Steel yield strength
7. Amount and position of transverse steel
8. Casting position, vibration, and revibration
9. Strain (or stress) range
10. Type and rate of loading
11. Temperature
12. Surface condition (coatings)

The influence of these factors on bond strength and failure mechanism is understood only qualitatively in many cases. Chapters 3, 4, and 5 of the report deal with some of the research behind the observations just listed, and an extensive list of references (more than 160 citations) is attached to supplement the discussion.

DESIGN APPROACHES

Chapter 7 contains a description of code-proposed equations to design anchorages subjected to cyclic loads, intended to supplement those for monotonic

loads.⁴ The high-cycle fatigue equations are generally for use in offshore structures, bridges, and foundations of vibrating machinery. The low-cycle ones are generally for use in seismic design. Only two examples, one for fatigue and one for seismic loading, are cited subsequently

High-cycle loading (fatigue)

Some design recommendations for the allowable bond stress in straight anchorages in structures subjected to high-cycle fatigue can be given. Because tests have shown that either the concrete or steel will fail in fatigue before the bond fatigue limit is reached, most design equations refer to the stress range in concrete or steel rather than to any bond stress limit. For example, ACI 215R-74⁵ recommends that the stress range f_{cr} in concrete should not exceed $0.50 f'_c$ when the minimum stress is zero, or a linearly reduced stress range as the minimum stress f_{min} , is increased

$$f_{cr} = 0.4f_c + 0.47f_{min} \quad (1)$$

The relationship does not incorporate the number of cycles as a variable, but it is assumed valid in the infinite life region of the $S-N$ curve, where N is greater than one million cycles. ACI 215R-74 also recommends that for straight deformed bars, the stress range should not exceed 21 ksi.

Low-cycle loading (seismic loads)

The following recommendations apply to the anchorage of bars in beam-column joints for structures subjected to cyclic loads resulting from earthquakes. Committee 352 (ACI 352R-85) has issued the following recommendations for the anchorage in beam-column joints subjected to large load reversals:⁶

1. For hooked anchorages in exterior joints

$$l_d = f_y d_b / (75 \sqrt{f'_c}) \quad (2)$$

2. For straight anchorages terminating in exterior joints

$$l_d = f_y A_b / (25 \sqrt{f'_c}) \quad (3)$$

3. For straight anchorages in interior joints, tests have shown that satisfactory behavior can be obtained when

$$l_d \geq 20d_b \quad (4)$$

In all cases, the provisions are intended for well-confined concrete sections.

CONCLUSIONS

Monotonic loading

Under static monotonically increasing loads, the most important factors that affect bond behavior are the concrete strength, yield strength of flexural steel, bar size, cover, transverse reinforcement, casting posi-

tion, coatings, compaction of the concrete, and bar spacing.' The ACI Committee 408 (ACI 408-79) method produced results closer to the experimentally observed results than the current ACI 318-83 method.

Cyclic loading

All parameters that are of importance under monotonic loading are also of importance under cyclic loading. In addition, however, bond stress range, type of loading (unidirectional or reversed, strain or load controlled), and maximum imposed bond stress are of great importance under cyclic loads. The following conclusions can be made from the data currently available.

High-cycle fatigue

1. From the various studies it appears that the most significant effect of high-cycle repeated loads is to reduce the bond at failure. Stress ranges in excess of 40 percent of the yield strength of the reinforcement in anchorages consistent with ACI 318-83 (ACI 381-83) recommendations appear to reduce bond strength. Studies show that these losses can be as high as 50 percent of the static ultimate pullout bond strength.

2. Reversed cyclic stresses tend to deteriorate bond at a higher rate and to precipitate early failures. This occurs at a smaller number of cycles or at lower loads than monotonic statically applied stresses. An important factor in high-cycle fatigue is the fatigue strength of the concrete itself; internal damage (propagation of microcracks with repeated loading) to the concrete is the most important parameter affecting bond strength in this case.

3. The mechanism governing failure is a progressive crushing of the concrete in front of the deformations. Test data indicate very similar behavior under both fatigue and sustained loading.

4. Bond failures under fatigue loading are unlikely if current provisions for anchorage lengths under monotonic loading (ACI 318) and the limits for concrete and steel fatigue (ACI 215) are followed.

Low-cycle loading

The problem of low-cycle loading gives rise to bond deterioration, particularly at the internal joints of the moment resisting frames. Similarly, cyclic loading places severe demands on the strength and ductility of splice regions. The various observations about the low-cycle loading can be summarized as follows:

1. The higher the load amplitude, the larger the additional slip, especially after the first cycle. Some permanent damage seems to occur if 60 to 70 percent of the static bond capacity is reached. For design considerations, a damage threshold can be suggested at 50 percent of the bond strength (400 psi).

2. When loading a bar to an arbitrary bond stress or slip value below the damage threshold (about 60 percent of ultimate) and unloading to zero, the monotonic stress slip relationship for all practical purposes can be attained again during reloading. This behavior also occurs for a large number of loadings, provided that no bond failure occurs during cyclic loadings.

3. Loading a bar to a bond stress higher than 80 percent of its ultimate bond strength will result in significant permanent slip. Loading beyond the slip corresponding to the ultimate bond stress results in large losses of stiffness and bond strength.

4. Bond deterioration under large stress ranges (greater than 50 percent of ultimate bond strength) cannot be prevented, except by the use of very long anchorage lengths (at least a factor of 1.5 on the development lengths currently used) and substantial transverse reinforcement (two to three times that required by the current codes). Even in this case, bond damage near the most highly stressed areas cannot be totally eliminated.

REFERENCES

1. Comité Euro-International Du Béton, "State-of-the-Art Report: Bond Action and Bond Behavior of Reinforcement," *Bulletin* No. 151, Paris, Dec. 1981.
2. Eligehausen, R.; Popov, E. P.; and Bertero, V. V., "Local Bond Stress-Slip Relationships of Deformed Bars Under Generalized Excitations," *Report No. UCB/EERC 83-23*, Earthquake Engineering Research Center, University of California, Berkeley, Oct. 1983.
3. Rehm, G., and Eligehausen, R., "Bond of Ribbed Bars Under High-Cycle Repeated Loads," *ACI JOURNAL, Proceedings* V. 76, No. 2, Feb. 1979, pp. 297-310.
4. ACI Committee 408, "Suggested Development, Splice, and Standard Hook Provisions for Deformed Bars in Tension," *Concrete International: Design & Construction*, V. 1, No. 7, July 1979, pp. 44-46.
5. ACI Committee 215, "Considerations for Design of Concrete Structures Subjected to Fatigue Loading," *ACI JOURNAL, Proceedings* V. 71, No. 3, Mar. 1974, pp. 97-121.
6. ACI Committee 352, "Recommendations for Design of Beam-Column Joints in Monolithic Reinforced Concrete Structures," *ACI JOURNAL, Proceedings* V. 82, No. 3, May-June 1985, pp. 266-284.
7. Orangun, C. O.; Jirsa, J. O.; and Breen, J. E., "Re-evaluation of Test Data on Development Length and Splices," *ACI JOURNAL, Proceedings* V. 74, No. 3, Mar. 1977, pp. 114-122.

The full report was submitted to letter ballot of the committee and approved according to Institute balloting procedures.