Bond and Development of Straight Reinforcing Bars in Tension

Reported by ACI Committee 408

David Darwin[*]
Chair

Adolfo B. Matamoros[*]
Secretary

John H. Allen
Atorod Azizinamini
Gyorgy L. Balazs
JoAnn Browning[*†]
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John F. McDermott
Denis Mitchell
Stavroula J. Pantazopoulou
Max L. Porter
Julio A. Ramirez
John F. Silva
Jun Zuo[*]

[*]Members of the subcommittee who prepared this report.
[†]Members of the editorial subcommittee.

The performance of reinforced concrete structures depends on adequate bond strength between concrete and reinforcing steel. This report describes bond and development of straight reinforcing bars under tensile load. Bond behavior and the factors affecting bond are discussed, including concrete cover and bar spacing, bar size, transverse reinforcement, bar geometry, concrete properties, steel stress and yield strength, bar surface condition, bar casting position, development and splice length, distance between spliced bars, and concrete consolidation. Descriptive equations and design provisions for development and splice strength are presented and compared using a large database of test results. The contents of the database are summarized, and a protocol for bond tests is presented.

Test data and reliability analyses demonstrate that, for compressive strengths up to at least 16,000 psi (110 MPa), the contribution of concrete strength to bond is best represented by the compressive strength to the 1/4 power, while the contribution of concrete to the added bond strength provided by transverse reinforcement is best represented by compressive strength to a power between 3/4 and 1.0. The lower value is used in proposed design equations. These values are in contrast with the square root of compressive strength, which normally is used in both descriptive and design expressions. Provisions for bond in ACI 318-02 are shown to be unconservative in some instances; specifically, the 0.8 bar size factor for smaller bars should not be used and a ϕ-factor for bond is needed to provide a consistent level of reliability against bond failure. Descriptive equations and design procedures developed by Committee 408 that provide improved levels of reliability, safety, and economy are presented. The ACI Committee 408 design procedures do not require the use of the 1.3 factor for Class B splices that is required by ACI 318.

Keywords: anchorage; **bond**; concrete; **deformed reinforcement**; **development length**; reinforced concrete; reinforcement; relative rib area; **splice**; stirrup; tie.

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PREFACE

The bond between reinforcing bars and concrete has been acknowledged as a key to the proper performance of reinforced concrete structures for well over 100 years (Hyatt 1877). Much research has been performed during the intervening years, providing an ever-improving understanding of this aspect of reinforced concrete behavior. ACI Committee 408 issued its first report on the subject in 1966. The report emphasized key aspects of bond that are now well understood by the design community but that, at the time, represented conceptually new ways of looking at bond strength. The report emphasized the importance of splitting cracks in governing bond strength and the fact that bond forces did not vary monotonically and could even change direction in regions subjected to constant or smoothly varying moment. Committee 408 followed up in 1979 with suggested provisions for development, splice, and hook design (ACI 408.1R-79), in 1992 with a state-of-the-art report on bond under cyclic loads (ACI 408.2R-92), and in 2001 with design provisions for splice and development design for high relative rib area bars (bars with improved bond characteristics) (ACI 408.3-01). This report represents the next in that line, emphasizing bond behavior and design of straight reinforcing bars that are placed in tension.

For many years, bond strength was represented in terms of the shear stress at the interface between the reinforcing bar and the concrete, effectively treating bond as a material property. It is now clear that bond, anchorage, development, and splice strength are structural properties, dependent not only on the materials but also on the geometry of the reinforcing bar and the structural member itself. The knowledge base on bond remains primarily empirical, as do the descriptive equations and design provisions. An understanding of the empirical behavior, however, is critical to the eventual development of rational analysis and design techniques.

Test results for bond specimens invariably exhibit large scatter. This scatter increases as the test results from different laboratories are compared. Research since 1990 indicates that much of the scatter is the result of differences in concrete material properties, such as fracture energy and reinforcing bar geometry, factors not normally considered in design. This report provides a summary of the current state of knowledge of the factors affecting the tensile bond strength of straight reinforcing bars, as well as realistic descriptions of development and splice strength as a function of these factors. The report covers bond under the loading conditions that are addressed in Chapter 12 of ACI 318; dynamic, blast, and seismic loading are not covered.

Chapter 1 provides an overview of bond behavior, including bond forces, test specimens, and details of bond response. Chapter 2 covers the factors that affect bond, discussing the impact of structural characteristics as well as bar and concrete properties. The chapter provides insight not only into aspects that are normally considered in structural design, but into a broad range of factors that control anchorage, development, and splice strength in reinforced concrete members. Chapter 3 presents a number of widely cited descriptive equations for development and splice strength, including expressions recently developed by ACI Committee 408. The expressions are compared for accuracy using the test results in the ACI Committee 408 database. Chapter 4 summarizes the design provisions in ACI 318, ACI 408.3, the 1990 CEB-FIP Model Code, as well as design procedures recently developed by Committee 408. The design procedures are compared for accuracy, reliability, safety, and economy using the ACI Committee 408 database. The observations presented in Chapters 3 and 4 demonstrate that $f_c'^{1/4}$ provides a realistic representation of the contribution of concrete strength to bond for values up to at least 16,000 psi (110 MPa), while $f_c'^{3/4}$ does the same for the effect of concrete strength on the increase in bond strength provided by transverse reinforcement. This is in contrast to $\sqrt{f_c'}$, which is used in most design provisions. The comparisons in Chapter 4 also demonstrate the need to modify the design provisions in ACI 318 by removing the bar size γ factor of 0.8 for small bars and addressing the negative impact on bond reliability of changing the load factors while maintaining the strength reduction factor for tension in the transition from ACI 318-99 to ACI 318-02. Design procedures recommended by ACI Committee 408 that provide both additional safety and economy are presented. Chapter 5 describes the ACI Committee 408 database, while Chapter 6 presents a recommended protocol for bond tests. The expressions within the body of the report are presented in inch-pound units. Expressions in SI units are presented in Appendix A.

A few words are appropriate with respect to terminology. The term *bond force* represents the force that tends to move a reinforcing bar parallel to its length with respect to the surrounding concrete. *Bond strength* represents the maximum bond force that may be sustained by a bar. The terms *development strength* and *splice strength* are, respectively, the bond strengths of bars that are not spliced with other bars and of bars that are spliced. The terms *anchored length*, *bonded length*, and *embedded length* are used interchangeably to represent the length of a bar over which bond force acts; in most cases, this is the distance between the point of maximum force in the bar and the end of the bar. Bonded length may refer to the length of a lap splice. *Developed length* and *development length* are used interchangeably to represent the bonded length of a bar that is not spliced with another bar, while *spliced length* and *splice length* are used to represent the bonded length of bars that are lapped spliced. When used in design, development length and splice length are understood to mean the "length of embedded reinforcement required to develop the design strength of reinforcement at a critical section," as defined in ACI 318.

CHAPTER 1—BOND BEHAVIOR

In reinforced concrete construction, efficient and reliable force transfer between reinforcement and concrete is required for optimal design. The transfer of forces from the reinforcement to the surrounding concrete occurs for a deformed bar (Fig. 1.1) by:

- Chemical adhesion between the bar and the concrete;
- Frictional forces arising from the roughness of the interface, forces transverse to the bar surface, and relative slip between the bar and the surrounding concrete; and
- Mechanical anchorage or bearing of the ribs against the concrete surface.

After initial slip of the bar, most of the force is transferred by bearing. Friction, however, especially between the concrete and the bar deformations (ribs) plays a significant role in force transfer, as demonstrated by epoxy coatings, which lower the coefficient of friction and result in lower bond capacities. Friction also plays an important role for plain bars (that is, with no deformations), with slip-induced friction resulting from transverse stresses at the bar surface caused by small variations in bar shape and minor, though significant, surface roughness. Plain bars with suitably low allowable bond stresses were used for many years for reinforced concrete in North America and are still used in some regions of the world.

When a deformed bar moves with respect to the surrounding concrete, surface adhesion is lost, while bearing

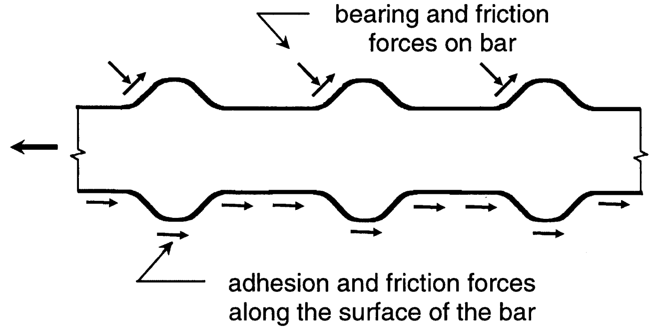


Fig. 1.1—Bond force transfer mechanisms.

forces on the ribs and friction forces on the ribs and barrel of the bar are mobilized. The compressive bearing forces on the ribs increase the value of the friction forces. As slip increases, friction on the barrel of the reinforcing bar is reduced, leaving the forces at the contact faces between the ribs and the surrounding concrete as the principal mechanism of force transfer. The forces on the bar surface are balanced by compressive and shear stresses on the concrete contact surfaces, which are resolved into tensile stresses that can result in cracking in planes that are both perpendicular and parallel to the reinforcement, as shown in Fig. 1.2(a) and 1.2(b). The cracks shown in Fig. 1.2(a), known as Goto (1971) cracks, can result in the formation of a conical failure surface for bars that project from concrete and are placed in tension. They otherwise play only a minor role in the anchorage and development of reinforcement. The transverse cracks shown in Fig. 1.2(b) form if the concrete cover or the spacing between bars is sufficiently small, leading to splitting cracks, as shown in Fig. 1.2(c). If the concrete cover, bar spacing, or transverse reinforcement is sufficient to prevent or delay a splitting failure, the system will fail by shearing along a surface at the top of the ribs around the bars, resulting in a "pullout" failure, as shown in Fig. 1.2(d). It is common, for both splitting and pullout failures, to observe crushed concrete in a region adjacent to the bearing surfaces of some of the deformations. If anchorage to the concrete is adequate, the stress in the reinforcement may become high enough to yield and even strain harden the bar. Tests have demonstrated that bond failures can occur at bar stresses up to the tensile strength of the steel.

From these simple qualitative descriptions, it is possible to say that bond resistance is governed by:

- The mechanical properties of the concrete (associated with tensile and bearing strength);
- The volume of the concrete around the bars (related to concrete cover and bar spacing parameters);
- The presence of confinement in the form of transverse reinforcement, which can delay and control crack propagation;
- The surface condition of the bar; and
- The geometry of the bar (deformation height, spacing, width, and face angle).

A useful parameter describing bar geometry is the so-called relative rib area R_r, illustrated in Fig. 1.3, which is the ratio of the bearing area of the bar deformations to the

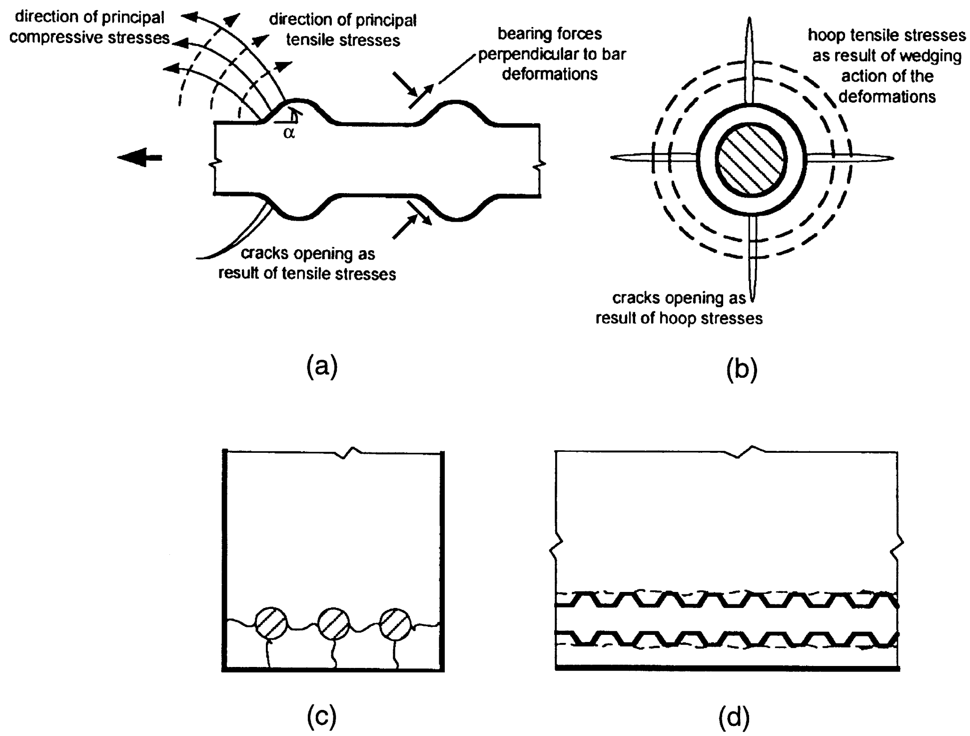
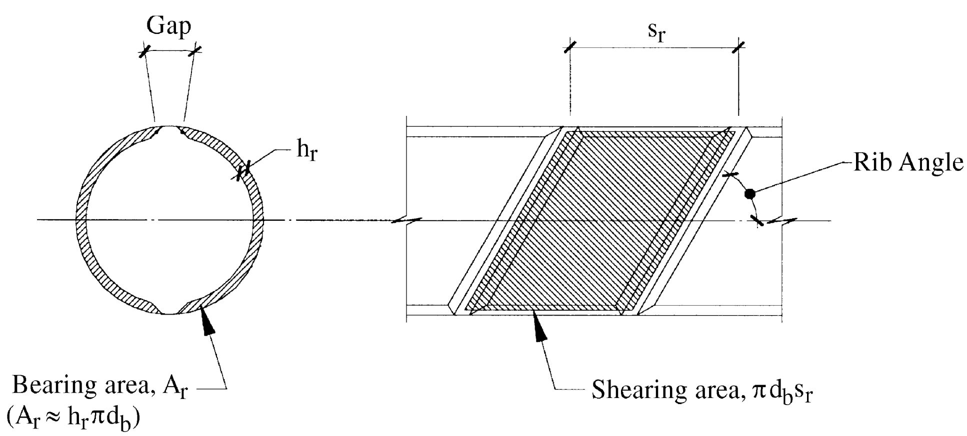


Fig. 1.2—Cracking and damage mechanisms in bond: (a) side view of a deformed bar with deformation face angle α showing formation of Goto (1971) cracks; (b) end view showing formation of splitting cracks parallel to the bar; (c) end view of a member showing splitting cracks between bars and through the concrete cover; and (d) side view of member showing shear crack and/or local concrete crushing due to bar pullout.



$$R_r = \frac{\text{Bearing area}}{\text{Shearing area}} \approx \frac{h_r}{s_r}$$

$$\left(\text{Actual } R_r \text{ values range from 0.8 to 0.9 } \frac{h_r}{s_r}\right)$$

Fig. 1.3—Definition of R_r *(ACI 408.3R).*

shearing area between the deformations (in U.S. practice, this is taken as the ratio of the bearing area of the ribs to the product of the nominal bar perimeter and the average spacing of the ribs). Relative rib area is discussed at greater length in Section 2.2.2.

1.1—Bond forces—background

To understand the design procedures used for selecting development and splice lengths of reinforcement, it is instructive to review the nature of bond forces and stresses in a reinforced concrete flexural member. Historically, the difference in tensile force ΔT between two sections located at flexural cracks along a member (Fig. 1.4) was calculated as

$$\Delta T = T_1 - T_2 = \frac{M_1}{jd_1} - \frac{M_2}{jd_2} \qquad (1\text{-}1)$$

where T_i ($T_2 > T_1$), M_i ($M_2 > M_1$), and jd_i are the tensile force, moment, and internal moment arm at section i (i = 1, 2). For

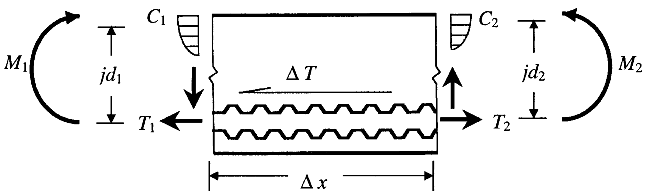


Fig. 1.4—Variation in bar force due to changes in moment in a beam.

an infinitesimally small distance between Sections 1 and 2, Eq. (1-1) becomes

$$dT = \frac{dM}{jd} \tag{1-2}$$

If the bond force per unit length U is defined as the change in tensile force per unit length, then

$$U = \frac{dT}{dl} = \frac{1}{jd}\frac{dM}{dl} \tag{1-3a}$$

$$U = \frac{1}{jd}V \tag{1-3b}$$

where V is the shear on the section.

Equation (1-3b) indicates that, away from concentrated loads, bond forces vary as a function of the applied shear along the length of reinforced concrete flexural members, and for many years, the bond force used in design U was based on this expression. Over time, however, it became apparent that the change in force in reinforcing bars dT does not vary strictly with the change in moment per unit length, as suggested in Eq. (1-3a), but simply with the force in the bar T, which varies from a relatively high value at cracks to a low value between cracks, where the concrete shares the tensile force with the reinforcing steel. Using the definition $U = dT/dl$, bond forces vary significantly along the length of a member, even varying in direction, as shown in Fig. 1.5. The real distribution of bond forces along the length of a bar, therefore, cannot be predicted because it depends on the locations of the flexural cracks and the amount of tensile load carried by the concrete—neither of which can be calculated. Given these facts and because a principal goal of design is to ensure that the bar is adequately anchored so that failure will manifest itself in some way other than in bond, it is both convenient and realistic for design purposes to treat bond forces as if they were uniform over the anchored, developed, or spliced length of the reinforcement.

Until adoption of the 1971 ACI Building Code (ACI 318-71), bond design was based on bond stress u, which is equal to bond force per unit length U divided by the sum of the perimeters of the bars developed at a section Σ_o.

$$u = \frac{U}{\Sigma_o} = \frac{\Delta T}{\Delta l \Sigma_o} = \frac{\Delta f_s A_b}{\Delta l \Sigma_o} = \frac{\Delta f_s d_b}{4\Delta l} \tag{1-4}$$

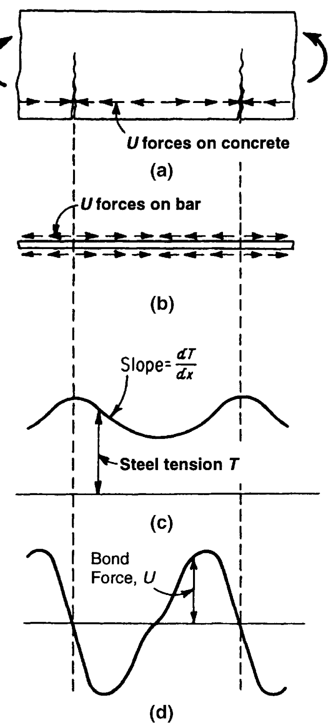


Fig. 1.5—Variation of steel and bond forces in reinforced concrete member subjected to pure bending: (a) cracked concrete segment; (b) bond stresses acting on reinforcing bar; (c) variation of tensile force in steel; and (d) variation of bond force along bar (adapted from Nilson et al. [2004]).

where A_b = area of bars; d_b = diameter of bars; and Δf_s = change in steel stress over length Δl.

For design purposes, the change in stress Δf_s equals the yield stress of the steel f_y and Δl equals the development length l_d. In ACI 318-63, the maximum bond stress was set at*

$$u = 9.5\frac{\sqrt{f_c'}}{d_b} \le 800 \text{ psi} \tag{1-5}$$

Substituting Eq. (1-5) into Eq. (1-4), solving for $\Delta l = l_d$, and multiplying the resultant value by 1.2 to account for the reduced bond strength of closely spaced bars (due to the interaction of splitting cracks) gives the development length

$$l_d = 0.04 A_b \frac{f_y}{\sqrt{f_c'}} \tag{1-6}$$

Equation (1-6) was used for design, beginning with ACI 318-71, until a design approach that more closely matched observed behavior was adopted in ACI 318-95.

While convenient, equations for development length [like Eq. (1-6) and some of those presented in Chapter 4] have led many designers to believe that the real force that must be developed is equal to the product of the area and yield

*SI conversions of equations that contain terms that depend on units of measure are presented in Appendix A.