No. 6 (18 mm diameter). The same development length (Eq. 9.6) could have been obtained using Eq. 9.2b by specifying that $u = 8\sqrt{f'_c}/m_f d_b$ (psi).

Example, 7.1, featured in Fig. 7.38, demonstrates the curtailment of top-cast bars, with allowance for the development length $l_d$, in accordance with ACI requirements.[9.3]

### 9.4.2 Hook Anchorages for Bars with Tension

When the straight length of bar available for anchorage is insufficient, the reinforcement can be bent, or a hook may be formed to aid anchorage. Hooked anchorages for plain round bars have distinct advantages that were recognized by the pioneers of structural concrete.

In pullout tests specifically designed to obtain the strength of hooked anchorages, the bond along the straight portion of the bar in front of the hook was eliminated (see Fig. 9.15). Load-slip relationships obtained from such tests indicate the usable anchorage loads available from various types of hooks. The slip is measured at the point where the bar enters the concrete. For deformed bars the strain distribution in the steel measured along the hook in such a test reveals that the bar force is transferred rapidly into the

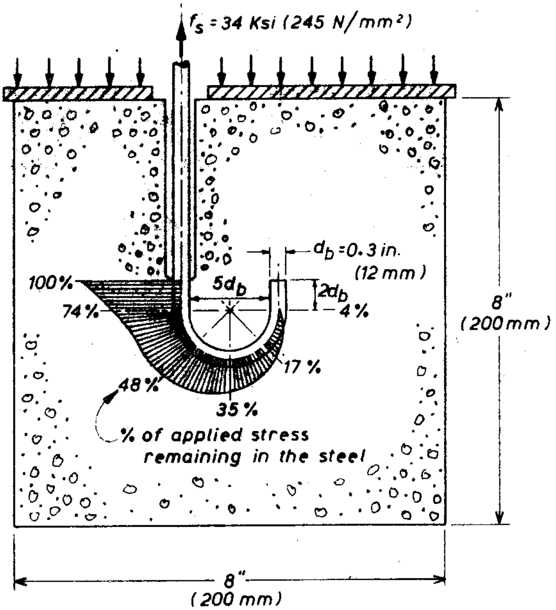

Fig. 9.15. Pullout test for hooked deformed bars.[9.22]

concrete and the straight portion following a hook is generally ineffective[9.22] (see Fig. 9.15). For plain bars the tensile stresses reduce more slowly along the hook; therefore extra anchorage strength may be obtained by extending the straight portion of the bar following the hook.

The useful strength of a hook is also related to an acceptable slip at the loaded end. Provided no splitting failure occurs in the plane of the hook, slip appears to be the governing criterion. A linear relationship between load and slip can be expected for slips up to 0.001 in (0.025 mm).[9.23] A suitable comparison of the load-carrying capacity of various types of hooked anchorages can be made at a slip of 0.01 in (0.25 mm).

The largest bearing stresses on the concrete are developed along the inside of the hook near the loaded part of the bar. In these areas, therefore, such properties of the surrounding concrete as porosity and strength, can significantly affect the slip at any given load. Figure 9.16 displays typical load-slip curves for 180° hooks, at various positions when cast. The load is expressed in terms of the $f_s/f'_{cu}$ ratio, where $f_s$ is tensile stress applied to the bar in front of the hook and $f'_{cu}$ is the cube strength of the surrounding concrete. Each curve represents the mean of 6 to 35 tests. Because of the random variation of the concrete quality (i.e., the degree of water gain) under the critical

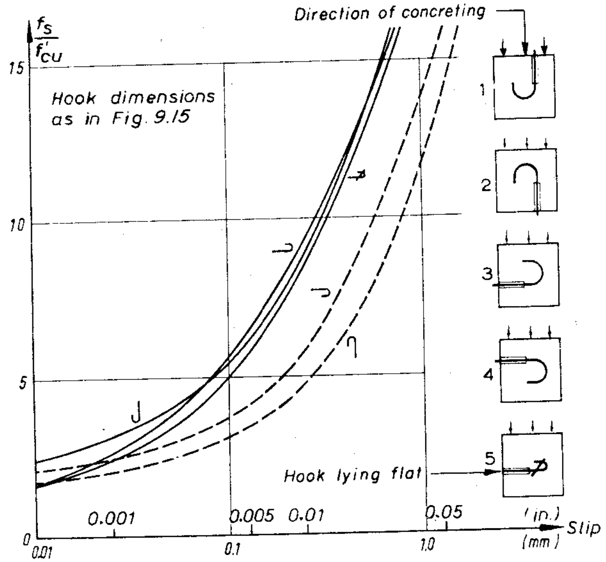

**Fig. 9.16.** Load-slip relationship for hooked anchorages of deformed bars.[9.24]

bearing area, considerable scatter has been observed in such tests. However, the inferior performance of topcast bars, such as types 2 and 4 in Fig. 9.16, is clearly evident. The average anchorage capacity of hooks, in terms of $f_s/f'_{cu}$ for three different bar sizes at various slips, are compared in Fig. 9.17.[9.24] For the tests featured in Figs. 9.16 and 9.17 deformed bars were used.

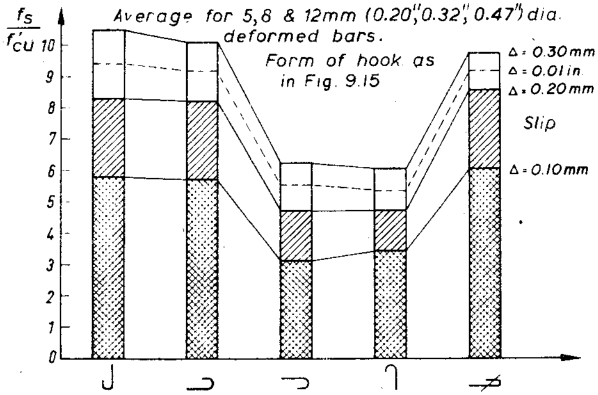

**Fig. 9.17.** The influence on bond strength at given slip of hook position at the casting of concrete.[9.24]

Rehm's pullout tests of hooked anchorages also demonstrated that a bend with less than 180° turn does not necessarily provide anchorage superior to a straight bar of the same length.[9.24] When it is realized that a bend introduces stress concentrations, consequently large local deformations in the concrete, which in turn lead to increased slip at the loaded end of an embedded bent bar, it is not surprising that for the same embedded length of bar, the straight vertical bar gives the best performance. Figure 9.18*a*, in which bars with different bend angles but identical embedded lengths (i.e., 10 bar diameters) are compared, illustrates this observation. The differences in performance between various bend angles become less significant when the bar pull is against the direction of concrete casting (see Fig. 9.18*b*), since in this case the anchored bars bear against concrete not affected by water gain and sedimentation.

A smaller bar curvature at a bend or a hook will mean a smaller load concentration, consequently a smaller slip, at the loaded end of the anchorage. Therefore, a large diameter hook will transmit a larger load for a given acceptable slip. Typical data relating to this observation[9.24] appear in Fig. 9.19.

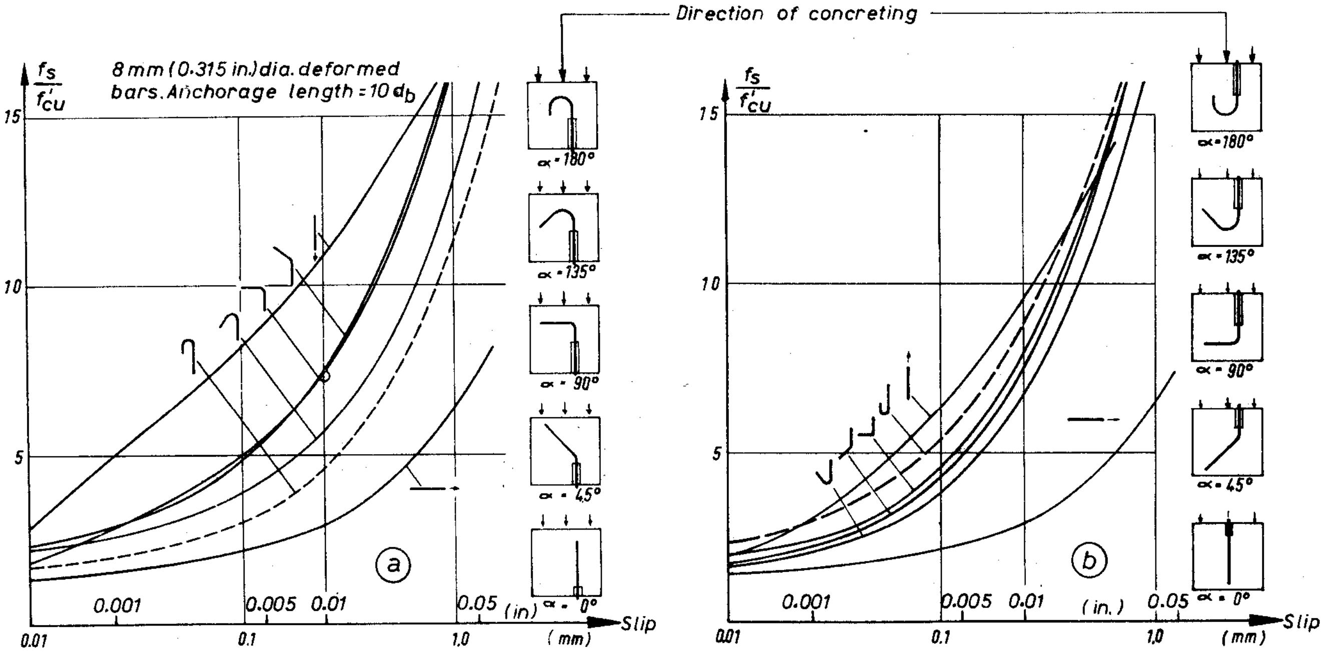

**Fig. 9.18.** The performance of anchorages of deformed bars with various degrees of bends.$^{9.24}$ (*a*) Top-cast bars. (*b*) Bottom-cast bars.

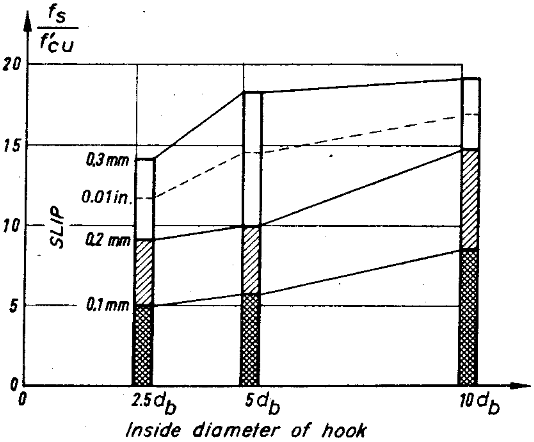

**Fig. 9.19.** The effect of hook curvature on anchorage performance.[9.24]

When a bar is bent around a transverse bar, as is the case of stirrup anchorages, 10 to 30% larger tensile stresses can be developed for the same amount of slip.[9.22] However, this benefit can be obtained only if direct contact between the hook and the transverse bar exists. Under normal site conditions, contact between stirrups and main beam reinforcement cannot be assured (see Fig. 9.20). Also, in the vicinity of the contact point between a stirrup and a longitudinal bar, some deterioration in the quality of the concrete can be expected. These two factors are likely to lead to larger slips at relatively low stirrup stresses. The effect of this slip on the width of diagonal cracks and on the participation of stirrups in shear resistance, particularly in shallow beams, could be significant.

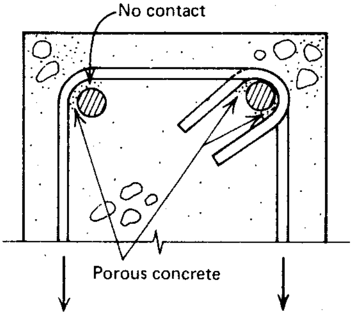

**Fig. 9.20.** The anchorage of stirrups.

For a hook of the type shown in Fig. 9.15, the bar diameter does not appear to influence the steel stress-slip relationship[9.22] up to a slip of 0.02 in (0.5 mm). For a given slip, in the usual grades of concrete, the hook capacity is proportional to the concrete strength. Experiments at the Technical University of Munich[9.22] established the following relationship

$$f_s^* = k_h f'_{cu} \tag{9.7}$$

where $f_s^*$ = steel stress at the loaded end of the hook at a slip of 0.004 in (0.01 mm)

$f'_{cu}$ = compressive cube strength of the concrete

$k_h$ = experimental constant given in Table 9.1

**Table 9.1 Value of $k_h$**

| Position of Hooks | Type[a] | Plain Bars | Deformed Bars |
|---|---|---|---|
| Bottom-cast hooks | 1, 3 | 1.70 | 3.75 |
| Top-cast hooks | 2, 4 | 1.20 | 2.00 |

[a] For identification of hook type, see Fig. 9.16.

At ultimate load the tensile strength of the concrete might limit the capacity of a hook, unless transverse compression or appropriate confining reinforcement prevents a splitting failure in the plane of a hook. This is why the ACI code[9.3] indicates that the hook capacity is dependent on the tensile strength of the surrounding concrete and considers that standard hooks can anchor a bar with a tensile stress equal to $f_h = K\sqrt{f'_c}$ psi, where $f'_c$ is in psi (1 psi = 0.00689 N/mm$^2$) and $K$ is given in Table 9.2. The value of $K$ may be increased by 30% when enclosure is provided perpendicular to the plane of the hook. The code[9.3] also specifies the shapes and dimensions of standard hooks.

### 9.4.3 Anchorage for Bars with Compression

The mechanisms by which tensile and compressive bar forces are anchored differ significantly. There is less tendency for splitting to occur along a bar in compression, and a part of the compression force can be transferred to the concrete by end bearing.[9.25] However, significant bearing stresses at the end of a square-cut bar can be developed only if there is sufficient mass of concrete behind the end of the bar. Codes recognize the improved development conditions for bars in compression and accordingly specify considerably smaller