Bond, Anchorage and Development Length

Chapter 5
Fundamentals of flexural bond

In a RC beam, if plain bars are used and greased, it will behave like figure.

Strain compatibility will not be valid

To reinforced concrete to behave as intended, sufficient bond stress must develop at interface of concrete and steel.
• Plain bars- bond provided by chemical adhesion and mechanical friction between concrete and steel.
• This bond is rather small and easily slipped.
• End anchorage are provided with hooks.
• Steel stress is almost constant along length, elongation and deflection, cracking are higher.
• Deformed bars overcome this problem
FIGURE 5.3
Forces acting on elemental length of beam: (a) free-body sketch of reinforced concrete element; (b) free-body sketch of steel element.
For reinforcing bars in Tension, two types of bond failure occur:

- Direct pull-out - where ample confinement is provided
- Splitting of concrete - where cover, confinement, bar spacing is insufficient

- Both types of failures need to be considered.
• When there is sufficient cover, as the tensile force in reinforcement increase, the adhesive bond and friction are overcome, concrete eventually crushes in front of the bar deformations, pull-out occurs.
• Bond failure from splitting is more common- either in vertical or horizontal plain. Horizontal failure frequently occurs at diagonal crack.
• Shear and bond failures are intricately related.
Development length is defined as the length of embedment necessary to develop full tensile strength of bar, controlled either by pull-out or splitting.
Factors Influencing Development Length

- Tensile Strength of Concrete
- Cover distance
- Bar Spacing
- Transverse reinforcement
- Vertical location of bar
- Epoxy coating
- Excess reinforcement
- Diameter of bar
ACI Code Provisions For Development of Tension Reinforcement

a. Basic Equation for Development of Tension Bars

According to ACI Code 12.2.3, for deformed bars or deformed wires,

\[ l_d = \left( \frac{3}{40} \frac{f_y}{\lambda \sqrt{f_c}} \left[ \frac{\psi_t \psi_e \psi_s}{(c_b + K_{tr})} \right] \right) d_b \]  

(5.4)

in which the term \((c + K_{tr})/d_b\) shall not be taken greater than 2.5. In Eq. (5.4), terms are defined and values established as follows.

\[ \psi_t = \text{reinforcement location factor} \]

Horizontal reinforcement so placed that more than 12 in. of fresh concrete is cast in the member below the development length or splice:

<table>
<thead>
<tr>
<th>Situation</th>
<th>(\psi_t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other situations</td>
<td>1.3</td>
</tr>
</tbody>
</table>

1.3
\( \psi_e = \text{coating factor} \)
- Epoxy-coated bars or wires with cover less than \( 3d_b \) or clear spacing less than \( 6d_b \):
  1.5
- All other epoxy-coated bars or wires:
  1.2
- Uncoated and zinc-coated (galvanized) reinforcement:
  1.0
- However, the product of \( \psi_t \psi_e \) need not be taken greater than 1.7.

\( \psi_s = \text{reinforcement size factor} \)
- No. 6 (No. 19) and smaller bars and deformed wires:
  0.8\(^\dagger\)
- No. 7 (No. 22) and larger bars:
  1.0

\( \lambda = \text{lightweight aggregate concrete factor} \)
- When lightweight aggregate concrete is used:
  0.75
- However, when \( f_{ct} \) is specified, \( \lambda = f_{ct}/(6.7 \sqrt{f_c'}) \leq 1.0. \)
- When normalweight concrete is used:
  1.0

\( c = \text{spacing or cover dimension, in.} \)
- Use the smaller of either the distance from the center of the bar to the nearest concrete surface or one-half the center-to-center spacing of the bars being developed.

\( K_{tr} = \text{transverse reinforcement index: } 40A_{tr}/sn \)
- where \( A_{tr} = \text{total cross-sectional area of all transverse reinforcement that is within the spacing } s \) and that crosses the potential plane of splitting through the reinforcement being developed, in\(^2\)
- \( s = \text{maximum spacing of transverse reinforcement within } l_d \text{ center to center, in.} \)
- \( n = \text{number of bars or wires being developed along the plane of splitting} \)
### TABLE 5.1
Simplified tension development length in bar diameters according to the ACI Code

<table>
<thead>
<tr>
<th>Clear spacing of bars being developed or spliced</th>
<th>No. 6 (No. 19) and Smaller Bars and Deformed Wires†</th>
<th>No. 7 (No. 22) and Larger Bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq d_b$, clear cover $\geq d_b$, and stirrups or ties throughout $l_d$ not less than the Code minimum</td>
<td>$l_d = \left( \frac{f_y \psi_i \psi_e}{25\lambda \sqrt{f'_c}} \right) d_b$</td>
<td>$l_d = \left( \frac{f_y \psi_i \psi_e}{20\lambda \sqrt{f'_c}} \right) d_b$</td>
</tr>
<tr>
<td>Clear spacing of bars being developed or spliced $\geq 2d_b$, and clear cover $\geq d_b$</td>
<td>Same as above</td>
<td>Same as above</td>
</tr>
<tr>
<td>Other cases</td>
<td>$l_d = \left( \frac{3f_y \psi_i \psi_e}{50\lambda \sqrt{f'_c}} \right) d_b$</td>
<td>$l_d = \left( \frac{3f_y \psi_i \psi_e}{40\lambda \sqrt{f'_c}} \right) d_b$</td>
</tr>
</tbody>
</table>

† For reasons discussed in Section 5.3a, ACI Committee 408 recommends that $l_d$ for No. 7 (No. 22) and larger bars be used for all bar sizes.

---

Appendix A.10
**Example 5.1**

**Development length in tension.** Figure 5.8 shows a beam-column joint in a continuous building frame. Based on frame analysis, the negative steel required at the end of the beam is 2.90 in\(^2\); two No. 11 (No. 36) bars are used, providing \(A_s = 3.12\) in\(^2\). Beam dimensions are \(b = 10\) in., \(d = 18\) in., and \(h = 21\) in. The design will include No. 3 (No. 10) stirrups spaced four at 3 in., followed by a constant 5 in. spacing in the region of the support, with 1.5 in. clear cover. Normalweight concrete is to be used, with \(f'_c = 4000\) psi, and reinforcing bars have \(f_y = 60,000\) psi. Find the minimum distance \(l_d\) at which the negative bars can be cut off, based on development of the required steel area at the face of the column, (a) using the simplified equations of Table 5.1, (b) using Table A.10, of Appendix A, and (c) using the basic Eq. (5.4).
Example 5.1

\[ A_{s, \text{reqd}} = 2.9 \text{ in}^2 \quad A_{s, \text{prov}} = 3.12 \text{ in}^2 \]

\[ b = 10'' \quad d = 18'' \quad h = 21'' \quad \text{stirrup} \Rightarrow \# 3@3'' 4\text{Nos} + @ 5\text{c/c} \]

\[ \text{cover} = 1.5'' \quad f' = 4\text{ksi}, \quad f_y = 60\text{ksi} \]

Find \( l_d \to \text{negative bar cutoff} \)

(a) Simplified using Table 5.1

Clear distance
\[
= 10 - 2(1.5 + 0.375 + 1.41) \\
= 3.43'' = 2.43\text{db} 
\]

Clear cover side
\[
= 1.5 + 0.375 = 1.88'' = 1.33\text{db} 
\]

Clear cover top
\[
= 3.0 - \frac{1.41}{2} = 2.30'' = 1.63\text{db} 
\]

Table 5.1 \( \Rightarrow \) 2nd row

\[ \psi_t = 1.3, \quad \psi_e = 1.0 \quad \lambda = 1.0 \]

\[ l_d = \frac{f_y \psi_t \psi_e}{20A \sqrt{f'_c}} \]

\[
= \frac{60,000 \times 1.3 \times 1}{20 \times 1 \times \sqrt{4000}} + 1.41 \\
= 62 + 1.41 = 87 \text{ in.} 
\]

Can be reduced
\[
= 87 + \frac{2.9}{3.12} = 81 \text{ in.} 
\]

(b) Using Table A.10

\[ \frac{l_d}{d_b} = 62 \quad \text{as before} \]
(c) Using the basic Eq. (5.4)

Centre to centre spacing  = 10 - 2(1.5 + 0.375 + \frac{1.41}{2})

= 4.84"

Half  = 4.84 ÷ 2 = 2.42"

Centre to side  = 1.5 + 0.375 + \frac{1.41}{2} = 2.58"

Centre to top  = 3.0

C = Smallest = 2.42" (Horizontal plane splitting)

⇒ Atr = two times Av

Ktr = \frac{40 \times Atr}{s_n} = \frac{40 \times 0.11 \times 2}{5 \times 2} = 0.88

if top cover controls, splitting plane vertical ⇒ Atr = One time Av

C + Ktr  =  2.42 + 0.88  = 3.31 < 2.5 to avoid pull-out

\frac{d_b}{d_b} = 2.34 ÷ 1.5 in approx eqn.

\frac{b_d}{40} = \frac{1.3 + 1\times 1}{2.34} \times 1.41

= 40 \times 1.41 = 55.7"

Reqd. development length  = 55.7 + \frac{2.90}{3.12}

= 52"  (much smaller than simplified eqn ⇒ 81")
5.4 Anchorage Of Tension Bars By Hooks

a. **Standard Dimensions**

In the event that the desired tensile stress in a bar cannot be developed by bond alone, it is necessary to provide special anchorage at the ends of the bar, usually by means of a 90° or a 180° hook or a headed bar (the latter is discussed in Section 5.5). The dimensions and bend radii for hooks have been standardized in ACI Code 7.1 as follows (see Fig. 5.9):

1. A 180° bend plus an extension of at least 4 bar diameters, but not less than $2\frac{1}{2}$ in. at the free end of the bar, or
2. A 90° bend plus an extension of at least 12 bar diameters at the free end of the bar, or
3. For stirrup and tie anchorage only:
   (a) For No. 5 (No. 16) bars and smaller, a 90° bend plus an extension of at least 6 bar diameters at the free end of the bar, or
   (b) For Nos. 6, 7, and 8 (Nos. 19, 22, and 25) bars, a 90° bend plus an extension of at least 12 bar diameters at the free end of the bar, or
   (c) For No. 8 (No. 25) bars and smaller, a 135° bend plus an extension of at least 6 bar diameters at the free end of the bar.
FIGURE 5.9
Standard bar hooks: (a) main reinforcement; (b) stirrups and ties.

(a) No. 5 (No. 16) bar or smaller

4d_b ≥ 2\frac{1}{2}''

12d_b

(b) Nos. 6, 7, or 8 (Nos. 19, 22, or 25) bar

Fig 5.9: Standard bar Hooks: (a) Main reinforcement (b) stirrups and ties
For stirrup and tie hooks, for sizes No. 5 and smaller, the inside diameter of bend should not be less than 4 bar diameters, according to ACI Code.

For stirrups and tie hooks, greater than No. 5, Table 5.2 applies.

<table>
<thead>
<tr>
<th>Bar Size</th>
<th>Minimum Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nos. 3 through 8 (Nos. 10 through 25)</td>
<td>6 bar diameters</td>
</tr>
<tr>
<td>Nos. 9, 10, and 11 (Nos. 29, 32, and 36)</td>
<td>8 bar diameters</td>
</tr>
<tr>
<td>Nos. 14 and 18 (Nos. 43 and 57)</td>
<td>10 bar diameters</td>
</tr>
</tbody>
</table>
Development Length and Modification Factors for Hooked Bars

**FIGURE 5.10**
Bar details for development of standard hooks.

- Critical section
- $d_b$
- $12d_b$
- $4d_b \geq 2 \frac{1}{2}$
- $4d_b$ for Nos. 3 through 8 (Nos. 10 through 25) bars
- $5d_b$ for Nos. 9 through 11 (Nos. 29 through 36) bars
- $6d_b$ for Nos. 14 and 18 (Nos. 43 and 57) bars

Fig5.10: Bar details for development of standard hooks
\[ l_{dh} = \left( \frac{0.02 \psi_e f_y}{\lambda \sqrt{f'_c}} \right) d_b \]

with \( \psi_e = 1.2 \) for epoxy-coated reinforcement and \( \lambda = 0.75 \) for lightweight aggregate concrete. For other cases, \( \psi_e \) and \( \lambda \) are taken as 1.0.

- \( l_{dh} \) should not be less than 8 bar diameter or 6 in.
### TABLE 5.3
Development lengths for hooked deformed bars in tension

<table>
<thead>
<tr>
<th>Condition</th>
<th>Development length ( l_{dh} ) for hooked bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Development length ( l_{dh} ) for hooked bars</td>
<td>( \left( \frac{0.02\psi_y f_y}{\lambda \sqrt{f'_c}} \right) d_b )</td>
</tr>
<tr>
<td>B. Modification factors applied to ( l_{dh} )</td>
<td></td>
</tr>
<tr>
<td>For No. 11 (No. 36) and smaller bar hooks with side cover (normal to</td>
<td>0.7</td>
</tr>
<tr>
<td>plane of hook) not less than 2½ in., and for 90(^\circ) hooks with cover</td>
<td></td>
</tr>
<tr>
<td>on bar extension beyond hook not less than 2 in.</td>
<td></td>
</tr>
<tr>
<td>For 90(^\circ) hooks of No. 11 (No. 36) and smaller bars that are</td>
<td>0.8</td>
</tr>
<tr>
<td>either enclosed within ties or stirrups perpendicular to the bar being</td>
<td></td>
</tr>
<tr>
<td>developed, spaced not greater than 3(d_b) along the development</td>
<td></td>
</tr>
<tr>
<td>length ( l_{dh} ) of the hook; or enclosed within ties or stirrups</td>
<td></td>
</tr>
<tr>
<td>parallel to the bar being developed, spaced not greater than 3(d_b)</td>
<td></td>
</tr>
<tr>
<td>along the length of the tail extension of the hook plus bend</td>
<td></td>
</tr>
<tr>
<td>For 180(^\circ) hooks of No. 11 (No. 36) and smaller bars that are</td>
<td>0.8</td>
</tr>
<tr>
<td>either enclosed within ties or stirrups perpendicular to the bar being</td>
<td></td>
</tr>
<tr>
<td>developed, spaced not greater than 3(d_b) along the development</td>
<td></td>
</tr>
<tr>
<td>length ( l_{dh} ) of the hook</td>
<td></td>
</tr>
<tr>
<td>Where anchorage or development for ( f_y ) is not specifically required,</td>
<td></td>
</tr>
<tr>
<td>reinforcement in excess of that required by analysis</td>
<td></td>
</tr>
<tr>
<td>( \psi_e ):</td>
<td></td>
</tr>
<tr>
<td>For epoxy-coated bars</td>
<td>1.2</td>
</tr>
<tr>
<td>For other bars</td>
<td>1.0</td>
</tr>
<tr>
<td>( \lambda ):</td>
<td></td>
</tr>
<tr>
<td>For lightweight concrete</td>
<td>0.75</td>
</tr>
<tr>
<td>For normalweight concrete</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Fig. 5.11: Transverse reinforcement requirements at discontinuous ends of members with small cover distances (less than 2.5in.)

0.8 does not apply
Example 5.2

Development of hooked bars in tension. Referring to the beam-column joint shown in Fig. 5.8, the No. 11 (No. 36) negative bars are to be extended into the column and terminated in a standard 90° hook, keeping 2 in. clear to the outside face of the column. The column width in the direction of beam width is 16 in. Find the minimum length of embedment of the hook past the column face, and specify the hook details.

SOLUTION. The development length for hooked bars, measured from the critical section along the bar to the far side of the vertical hook, is given by Eq. (5.6):

\[ l_{dh} = \frac{0.02 \times 1.0 \times 60,000}{1.0 \times \sqrt{4000}} \]

\[ 1.41 = 27 \text{ in.} \]
In this case, side cover for the No. 11 (No. 36) bars exceeds 2.5 in. and cover beyond the bent bar is adequate, so a modifying factor of 0.7 can be applied. The only other factor applicable is for excess reinforcement, which is 0.93 as for Example 5.1. Accordingly, the minimum development length for the hooked bars is

\[ l_{dh} = 27 \times 0.7 \times 0.93 = 18 \text{ in.} \]

With \( 21 - 2 = 19 \text{ in.} \) available, the required length is contained within the column. The hook will be bent to a minimum diameter of \( 8 \times 1.41 = 11.28 \text{ in.} \). The bar will continue for 12 bar diameters, or 17 in. past the end of the bend in the vertical direction.
Headed bar

**TABLE 5.4**

Development lengths for headed deformed bars in tension

A. Development length $l_{de}$ for headed bars

\[
\left( \frac{0.016 \psi f_y}{\sqrt{f_c^2}} \right) d_b
\]

B. Modification factors applied to $l_{de}$

Where anchorage or development for $f_y$ is not specifically required, reinforcement in excess of that required by analysis

\[
\frac{A_r \text{ required}}{A_r \text{ provided}}
\]

- $\psi_r$
  - For epoxy-coated bars
    - $\psi_r = 1.2$
  - For other bars
    - $\psi_r = 1.0$

**FIGURE 5.12**

Headed deformed reinforcing bar with an obstruction of the deformations that extends less than 2 bar diameters from the bearing face of the head.

**FIGURE 5.15**

Headed deformed bar extended to far side of column with anchorage length that exceeds $l_{de}$. 

\[ l_{de} \]
ACI Code 12.13 includes special provisions for anchorage of web reinforcement. The ends of single-leg, simple-U, or multiple-U stirrups are to be anchored by one of the following means:

1. For No. 5 (No. 16) bars and smaller, and for Nos. 6, 7, and 8 (Nos. 19, 22, and 25) bars with $f_{yt}$ of 40,000 psi or less, a standard hook around longitudinal reinforcement, as shown in Fig. 5.17a.

2. For Nos. 6, 7, and 8 (Nos. 19, 22, and 25) stirrups with $f_{yt}$ greater than 40,000 psi, a standard hook around a longitudinal bar, plus an embedment between midheight of the member and the outside end of the hook equal to or greater than $0.014d_e f_{yt}/\lambda \sqrt{f'_c}$ in., as shown in Fig. 5.17b.
FIGURE 5.17
ACI requirements for stirrup anchorage: (a) No. 5 (No. 16) stirrups and smaller, and Nos. 6, 7, and 8 (Nos. 19, 22, and 25) stirrups with yield stress not exceeding 40,000 psi; (b) Nos. 6, 7, and 8 (Nos. 19, 22, and 25) stirrups with yield stress exceeding 40,000 psi; (c) wide beam with multiple-leg U stirrups; (d) pairs of U stirrups forming a closed unit. See Fig. 5.9 for alternative standard hook details.
According to ACI Code 12.3, the development length in compression is the greater of

\[ l_{dc} = \left( \frac{0.02 f_y}{\lambda \sqrt{f_c^*}} \right) d_b \]  \hspace{1cm} (5.10a)

and

\[ l_{dc} = 0.0003 f_y d_b \]  \hspace{1cm} (5.10b)

Modification factors summarized in part B of Table 5.5, as applicable, are applied to the development length in compression to obtain the value of development length \( l_{dc} \) to be used in design. In no case is \( l_d \) to be less than 8 in., according to the ACI Code. Basic and modified compressive development lengths are given in Table A.11 of Appendix A.

- Development length should not be less than 8 in.
## TABLE 5.5
Development lengths for deformed bars in compression

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
</table>
| A. Basic development length $l_{dc}$ | \[
N = \left( \frac{0.02 f_y}{\lambda \sqrt{f_c'}} \right) d_b
\]
|   | $\geq 0.0003 f_y d_b$ |
| B. Modification factors to be applied to $l_{dc}$ | $A_s$ required |
|   | $A_s$ provided |
| Reinforcement in excess of that required by analysis |   |
| Reinforcement enclosed within spiral |   |
| reinforcement not less than $\frac{1}{4}$ in. diameter and |   |
| not more than 4 in. pitch or within No. 4 (No. 13) | 0.75 |
| ties spaced at not more than 4 in. on centers |   |

*Appendix Table A11*
5.9 Bundled Bars

It was pointed out in Section 3.6c that it is sometimes advantageous to “bundle” tensile reinforcement in large beams, with two, three, or four bars in contact, to provide for improved placement of concrete around and between bundles of bars. Bar bundles are typically triangular or L-shaped for three bars, and square for four. When bars are cut off in a bundled group, the cutoff points must be staggered at least 40 diameters.

According to ACI Code 12.4, the development length of individual bars within a bundle, for both tension and compression, is that of the individual bar increased by 20 percent for a three-bar bundle and by 33 percent for a four-bar bundle, to account for the probable deficiency of bond at the inside of the bar group.

For bundled bars, to determine the appropriate spacing and cover values (1) for use in Table 5.1, (2) when calculating the confinement term $K_{tr}$ in Eq. (5.4), or (3) when selecting the epoxy coating factor $\psi_e$, the unit of bundled bars is treated as a single bar with a diameter derived from the equivalent total area and having a centroid that coincides with that of the bar group.
5.10 Bar cutoff and bend points in beams

FIGURE 5.18
Bar cutoff points from moment diagrams.
FIGURE 5.18
Bar cutoff points from moment diagrams.
Practical Considerations and ACI Code requirements

FIGURE 5.19
Bar cutoff requirements of the ACI Code.
Cutoff or bend points

**FIGURE 5.20** Cutoff or bend points for bars in approximately equal spans with uniformly distributed loads.
Structural integrity provisions

• Read article
• Integrated beam design example 5.12
Bar Splices

- Bars are supplied at 40ft lengths
- Splice at maximum stress should be avoided
- Lapping on sufficient distance to transfer stress through bond from one bar to the other.
- Tension splice, compressions splice.
- Splices for No. 11 and smaller are usually made the bars a sufficient distance to transfer stress by bond from one bar to the other. Lapped bars are usually placed in contact and lightly wired.

- Splices may also be by welding, sleeves or mechanical devices.
a. **Lap Splices in Tension**

The required length of lap for tension splices is stated in terms of the development length $l_d$. In the process of calculating $l_d$, the usual modification factors are applied except that the reduction factor for excess reinforcement should not be applied because that factor is already accounted for in the splice specification.

Two different classifications of lap splices are established, corresponding to the minimum length of lap required: a Class A splice requires a lap of $1.0l_d$, and a Class B splice requires a lap of $1.3l_d$. In either case, a minimum length of 12 in. applies. For Class B splices, the 12 in. minimum applies to $1.3l_d$, not to the value of $l_d$ used to calculate the lap length. Lap splices, in general, must be Class B splices, according to ACI Code 12.15.2, except that Class A splices are allowed when the area of reinforcement provided is at least twice that required by analysis over the entire length of the splice and when one-half or less of the total reinforcement is spliced within the required lap length. The effect of these requirements is to encourage designers to locate splices away from regions of maximum stress, to a location where the actual steel area is at least twice that required by analysis, and to stagger splices.

Spiral reinforcement is spliced with a lap of $48d_b$ for uncoated bars and $72d_b$ for epoxy-coated bars, in accordance with ACI Code 7.10.4.5. The lap for epoxy-coated bars is reduced to $48d_b$ if the bars are anchored with a standard stirrup or tie hook.
b. **Compression Splices**

Reinforcing bars in compression are spliced mainly in columns, where bars are most often terminated just above each floor or every other floor. This is done partly for construction convenience, to avoid handling and supporting very long column bars, but it is also done to permit column steel area to be reduced in steps, as loads become lighter at higher floors.

Compression bars may be spliced by lapping, by direct end bearing, or by welding or mechanical devices that provide positive connection. The minimum length of lap for compression splices is set according to ACI Code 12.16:

\[
\begin{align*}
&\text{For bars with } f_y \leq 60,000 \text{ psi} & 0.0005f_y d_b \\
&\text{For bars with } f_y > 60,000 \text{ psi} & (0.0009f_y - 24)d_b
\end{align*}
\]

but not less than 12 in. For \( f_c' \) less than 3000 psi, the required lap is increased by one-third. When bars of different size are lap-spliced in compression, the splice length is to be the larger of the development length of the larger bar and the splice length of the smaller bar. In exception to the usual restriction on lap splices for large-diameter bars, No. 14 and No. 18 bars *may* be lap-spliced to No. 11 and smaller bars.

Direct end bearing of the bars has been found by test and experience to be an effective means for transmitting compression. In such a case, the bars must be held in proper alignment by a suitable device. The bar ends must terminate in flat surfaces within 1.5° of a right angle, and the bars must be fitted within 3° of full bearing after assembly, according to ACI Code 12.16.4. Ties, closed stirrups, or spirals must be used.
c. **Column Splices**

Lap splices, butt-welded splices, mechanical connections, or end-bearing splices may be used in columns, with certain restrictions. Reinforcing bars in columns may be subjected to compression or tension, or, for different load combinations, both tension and compression. Accordingly, column splices must conform in some cases to the requirements for compression splices only or tension splices only or to requirements for both. ACI Code 12.17 requires that a minimum tension capacity be provided in each face of all columns, even where analysis indicates compression only. Ordinary compressive lap splices provide sufficient tensile resistance, but end-bearing splices may require additional bars for tension, unless the splices are staggered.

For lap splices, where the bar stress due to factored loads is compression, column lap splices must conform to the requirements presented in Section 5.13b for compression splices. Where the stress is tension and does not exceed $0.5f_y$, lap splices must be Class B if more than one-half the bars are spliced at any section, or Class A if one-half or fewer are spliced and alternate lap splices are staggered by $l_d$. If the stress is tension and exceeds $0.5f_y$, then lap splices must be Class B, according to ACI Code.

If lateral ties are used throughout the splice length having an area of at least $0.0015hs$ in both directions, where $s$ is the spacing of ties and $h$ is the overall thickness of the member, the required splice length may be multiplied by 0.83 but must not be less than 12 in. If spiral reinforcement confines the splice, the length required may be multiplied by 0.75 but again must not be less than 12 in.

End-bearing splices, as described above, may be used for column bars stressed in compression, if the splices are staggered or additional bars are provided at splice locations. The continuing bars in each face must have a tensile strength of not less than $0.25f_y$ times the area of reinforcement in that face.

As mentioned in Section 5.13b, column splices are commonly made just above a floor. However, for frames subjected to lateral loads, a better location is within the center half of the column height, where the moments due to lateral loads are much lower than at floor level. Such placement is mandatory for columns in "special moment frames" designed for seismic loads, as will be discussed in Chapter 20.
Compression splice of column reinforcement. In reference to Fig. 5.8, four No. 11 (No. 36) column bars from the floor below are to be lap-spliced with four No. 10 (No. 32) column bars from above, and the splice is to be made just above a construction joint at floor level. The column, measuring 12 in. × 21 in. in cross section, will be subject to compression only for all load combinations. Transverse reinforcement consists of No. 4 (No. 13) ties at 16 in. spacing. All vertical bars may be assumed to be fully stressed. Calculate the required splice length. Material strengths are \( f_y = 60,000 \) psi and \( f'_c = 4000 \) psi.
SOLUTION.  The length of the splice must be the larger of the development length of the No. 11 (No. 36) bars and the splice length of the No. 10 (No. 32) bars. For the No. 11 (No. 36) bars, the development length is equal to the larger of the values obtained with Eqs. (5.10a) and (5.10b):

\[ l_{dc} = \frac{0.02 \times 60,000}{\sqrt{4000}} 1.41 = 27 \text{ in.} \]

\[ l_{dc} = 0.0003 \times 60,000 \times 1.41 = 25 \text{ in.} \]

The first criterion controls. No modification factors apply. For the No. 10 (No. 32) bars, the compression splice length is 0.0005 \times 60,000 \times 1.27 = 38 \text{ in.} \] In the check for use of the modification factor for tied columns, the critical column dimension is 21 \text{ in.}, and the required effective tie area is thus 0.0015 \times 21 \times 16 = 0.50 \text{ in}^2. \] The No. 4 (No. 13) ties provide an area of only 0.20 \times 2 = 0.40 \text{ in}^2, \] so the reduction factor of 0.83 cannot be applied to the splice length. Thus the compression splice length of 38 \text{ in.} \], which exceeds the development length of 27 \text{ in.} \] for the No. 11 (No. 36) bars, controls here, and a lap splice of 38 \text{ in.} \] is required. Note that if the spacing of the ties at the splice were reduced to 12.8 \text{ in.} \] or less (say 12 \text{ in.}), the required lap would be reduced to 38 \times 0.83 = 32 \text{ in.} \] This would save steel, and, although placement cost would increase slightly, would probably represent the more economical design.