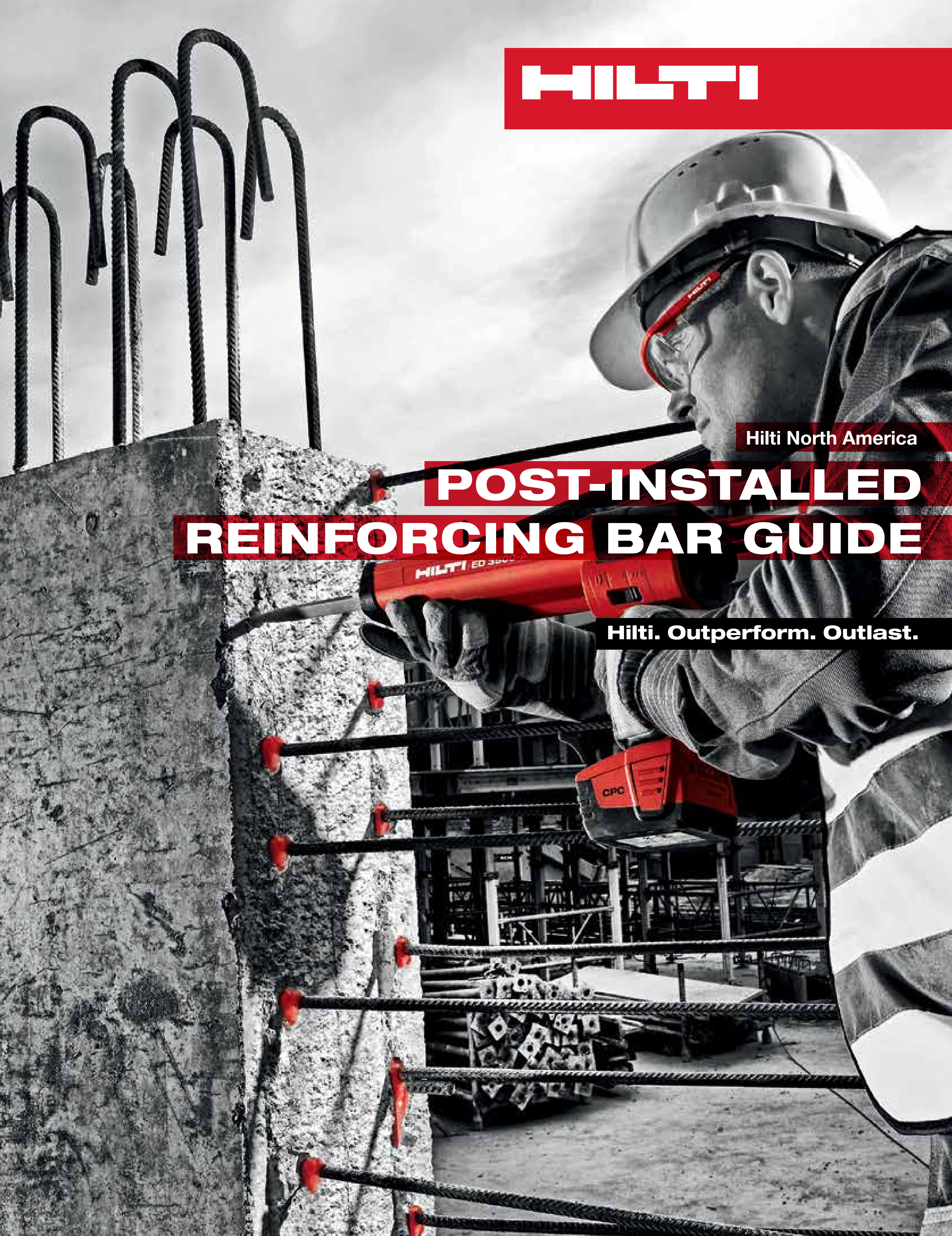

HILTI
Hilti North America
POST-INSTALLED
REINFORCING BAR GUIDE
HILTI ED 3500-A
Hilti. Outperform. Outlast.
CPC

Table of Contents

11/15 DBS

1.0 Post-installed reinforcing bars — what are they?

1.1 Post-installed reinforcing bars and their application in construction

Since the mid-1970s, adhesive anchors have been used extensively in construction. In the U.S. and Canada, they are regulated by a variety of codes and standards, including ACI 318, ACI 355.4, CSA A23.3, as well as acceptance criteria issued by the ICC Evaluation Service. Adhesive anchor systems for concrete typically employ threaded steel rod as the anchor element (see Figure 1) and are designed using an extension of the concrete capacity design method (CCD-Method) used for headed anchors and post-installed mechanical anchors[1].

Figure 1 — Adhesive anchor installation (using Hilti HIT-ICE for low temperature conditions, Säntis, Switzerland).

In this design environment the focus (for tension loads) is on bond failure/pullout failure and concrete breakout. Splitting of the concrete is deemed not relevant in view of limitations placed on edge distances, concrete thickness, and anchor spacing. Shear loads are resisted by the body of the anchor with the associated concrete failure modes as defined by the CCD method. From a design perspective, adhesive anchors are typically addressed in the same manner as other structural elements; i.e., the required strength is established as follows:

$$\Phi R_n \geq U \qquad [1]$$

where U is the factored load, Φ is a strength reduction factor, and R_n is the nominal resistance (generally taken as the 5% fractile).

Another common and long-standing application of anchoring adhesives is the installation of deformed reinforcing bars in holes drilled in concrete to emulate the behavior of cast-in-place reinforcing bars (Figure 2). These are commonly referred to as post-installed reinforcing bars. This application, which until 2013 was largely unregulated in the U.S.[2], can be characterized as follows:

a. **Post-installed reinforcing bars** are embedded in adhesive in a hole drilled into existing concrete on one side of the interface and are cast into new concrete on the other side of the interface. (Figure 3) The bars may be equipped with hooks or heads on the cast-in end, but are by necessity straight on the post-installed end;

b. **Post-installed reinforcing bars**, in contrast to adhesive anchors, are often installed with minimal edge distance. In such cases, the strength under tension loading of the post-installed reinforcing bar connection is typically limited by the splitting strength of the concrete (as characterized by splitting cracks forming along the length of the bar);

c. **Post-installed reinforcing bars** are typically not designed to resist direct shear loading in the manner of an anchor bolt (i.e., exclusively via dowel action[3]); and

d. **Post-installed reinforcing bars** are generally embedded as required to "develop" their yield strength using the development and splice length provisions of the code.

Figure 2 — Injecting Hilti HIT adhesive in a drilled hole with Hilti pneumatic dispenser P 5000 D to facilitate installation of post-installed reinforcing bars.

The assumption of bar development is perhaps the most fundamental distinction separating post-installed reinforcing

1 ACI 318-11, "Committee 318: Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary," American Concrete Institute, Farmington Hills, MI [2].
2 The suitability of an injectable adhesive for installing post-installed reinforcing bar applications should be verified by ICC Evaluation Service acceptance criteria AC308, June 2013 revision [9] or equivalent.
3 In some cases, the use of dowel action alone may be appropriate for resisting shear; however, it should be noted that this resistance is typically associated with larger displacements. Dowel action may also lead to premature edge failure where bars are close to an edge.

1.0 Post-installed reinforcing bars — what are they?

bars from adhesive anchors. Although instances do arise where post-installed reinforcing bars are designed for an applied force as described by Eq. [1], the typical case conforms to the assumption of bar development.

This Guide provides information regarding the design, detailing and installation of post-installed reinforcing bars. It does **not** address their design as governed by ACI adhesive anchor qualification and design provisions.

1.2 Application range

As noted above, post-installed reinforcing bars are typically used to facilitate connections between new and existing concrete elements or structures. Post-installed reinforcing bars are used in both retrofit work and in new construction and are suitable for a wide range of applications (i.e., as adhesive anchors) outside of the context of bar development.

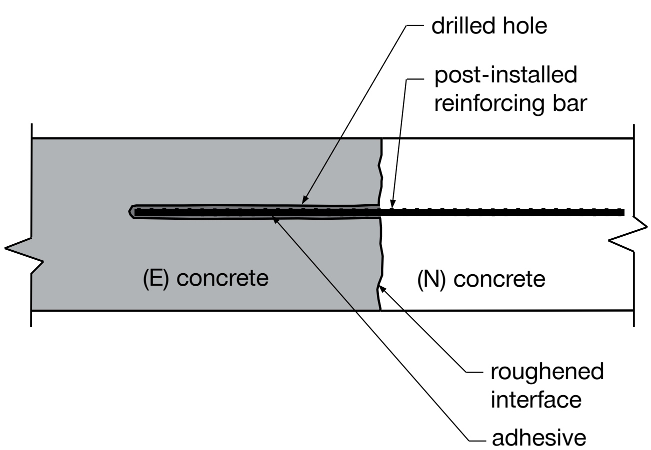


Figure 3 — Post-installed reinforcing bar.

Perhaps the most common class of applications for post-installed reinforcing bars is the **extension of existing reinforced concrete (R/C) structural elements** such as slabs, walls, and columns (Figure 4), either to facilitate expansion of floor space or to address other functional changes in the use of the structure. Such applications usually involve the placement of large numbers of bars with close spacing. In some cases the post-installed reinforcing bars are installed close to the surface of the concrete (e.g., at close to minimum cover distance) whereby the presence of existing reinforcing must be taken into account. Where applicable, such as in a column, slab, or wall extension, it is generally preferable to place the post-installed reinforcing bars inside of the existing reinforcing bar cage, both to minimize spalling during drilling and to ensure adequate cover. Avoidance of existing reinforcing is facilitated by use of reinforcing detection equipment, such as the Hilti PS 250 or Hilti PS 1000 scanning systems (Figure 5).

Another class of applications involves the **strengthening of existing concrete structures**, often to improve performance under earthquake loads (Figure 6). These applications are simplified by the fact that the bars typically do not carry gravity loads, are not subject to fire design considerations, and often involve doweling into concrete elements without close edge distances. On the other hand, the required embedments for development and splicing of bars subject to seismic loads may be greater than for bars designed only for static or wind loads.

A third application class with unique requirements is the **extension, rehabilitation, and strengthening of existing concrete bridges** and other civil engineering structures (Figure 7). These applications are often distinguished by the need for enhanced resistance to corrosion and temperature extremes. Hilti has developed unique shear-friction solutions for bridge deck overlays[5] and offers hybrid adhesives (e.g., Hilti HIT-HY 200) with superior resistance to elevated temperatures.

Since the required embedments to satisfy development length provisions of the building code (typically 25 to 40 bar diameters) often exceed typical anchoring embedment lengths (generally limited to 20 bar diameters[4]), special measures may be necessary to ensure that the holes are straight and that the drilling process does not damage the concrete, existing reinforcing or other embedded elements. These may include the use of specialized tools such as the Hilti drilling alignment system and Hilti ferric- and GPR-based detection systems.

1.3 Compatibility of post-installed reinforcing bars with cast-in-place reinforcing

Post-installed reinforcing bars are designed to transfer tension loads only. Extensive research programs have been conducted[6] at laboratories in Europe and the U.S. to verify that post-installed reinforcing bars installed with Hilti adhesive systems (HIT-HY, HIT-RE) demonstrate load transfer and load vs. displacement behavior comparable to cast-in-place reinforcing.

When installed well away from edges (i.e., where splitting does not limit the strength), post-installed reinforcing bars typically exhibit higher pull-out strength than cast-in-place bars of equivalent bar diameter and embedment.

4 See ACI 318-11 D.4.2.3.
5 Contact Hilti for further information.
6 See references and suggestions for further reading: [8], [10], [11], [12], [17], [18], [19], [20].

1.0 Post-installed reinforcing bars — what are they?

a. Starter bars

b. New bridge rail

c. Diaphragm slab

d. Wall extension

e. Steel column encasement

f. Slab extension

Figure 4 — Applications involving extension of existing construction with new elements using Hilti HIT-RE 500 and Hilti HIT-HY 200.

Figure 5 — Scanning for reinforcing bars and other embedded elements with a Hilti GPR scanner.

a. Slab-to-wall connection

b. Wall-to-wall connection

c. Onlay shotcrete wall

d. Slab-to-column connection strengthening

Figure 6 — Structural strengthening applications using Hilti HIT-RE 500.

1.0 Post-installed reinforcing bars — what are they?

a. Bridge widening b. Bridge deck rehabilitation c. Bridge deck augmentation

Figure 7 — Applications in bridge rehabilitation with post-installed reinforcing bars.

For near-edge bars subjected to tension loads (see Figure 8a below) the ultimate limit state behavior is characterized by splitting of the concrete along the bar or splice in response to the hoop stresses developed around the bar. Provided that the adhesive used can accommodate redistribution of stress along the bar length in a manner similar to cast-in-place bars, post-installed reinforcing bars exhibit ultimate strengths that are on a par with those obtained for cast-in-place bars.

Figure 8 depicts typical applications for post-installed reinforcing bars. Some of these applications have been verified experimentally while others have been investigated using advanced simulation (FEM) techniques.

These applications may be categorized as follows:

(a) **Non-contact lap splices** in which tension loads are transferred between adjacent bars via compression struts and hoop stresses in the concrete directly surrounding the spliced bars (see Figure 8a).

(b) **Shear dowels** used to resist interface shear across a shear plane, usually the roughened joint between existing and new concrete (see Figure 8b). The primary shear mechanism, friction across the irregular surface, is enabled by the reinforcing bars (shear dowels) that hold the surfaces together, and as such the usual design assumption, e.g., in the shear friction concept utilized by ACI, is that the shear dowels are placed in direct tension as the irregular shear plane is translated laterally. To a much lesser degree, or in the case of a smooth interface, shear may also be transferred by dowel action; that is, bearing of the concrete on the reinforcing bars.

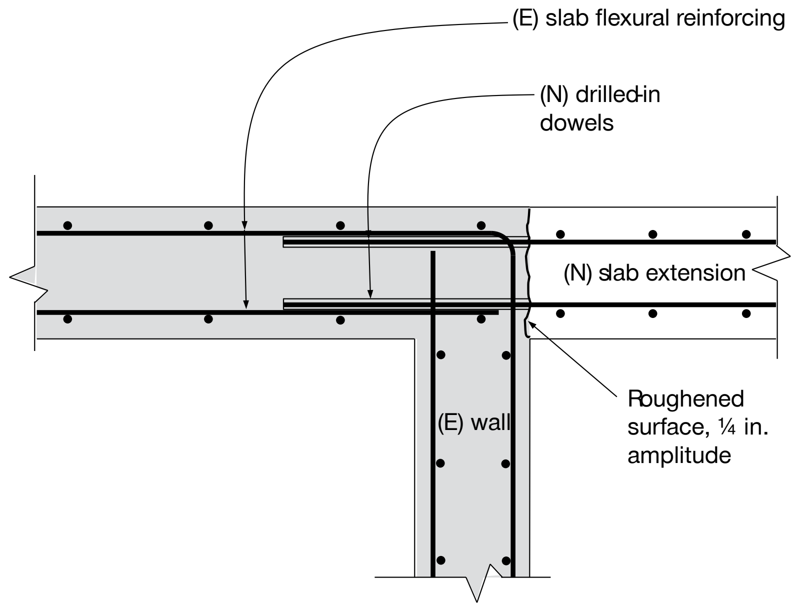
(c) **Starter bars**, which are typically used to resist tension and shear forces across beam-to-column and column-to-foundation joints. Starter bars are oriented perpendicular to the primary reinforcing of the existing concrete member in which they are installed. In cast-in-place construction, starter bars are usually hooked. Post-installed starter bars are straight, and as such their design must be based on straight bar development length provisions (see Figure 8c).

It should be noted that with the sole exception of dowel action as noted in (b) above, the method of load transfer between post-installed reinforcing bars and the concrete in which they are anchored is bearing of the reinforcing deformations (lugs) on the adhesive surrounding them. These bearing stresses in turn are transferred from the adhesive to the surrounding concrete via adhesion and micro-friction, whereby the lateral dilation of the adhesive layer in response to the bearing stresses enhances the friction mechanism. The concrete in turn develops circumferential (hoop) stresses around the bars that can result in splitting cracks at certain load levels. This response is identical to that observed for cast-in-place reinforcing bars loaded in tension.

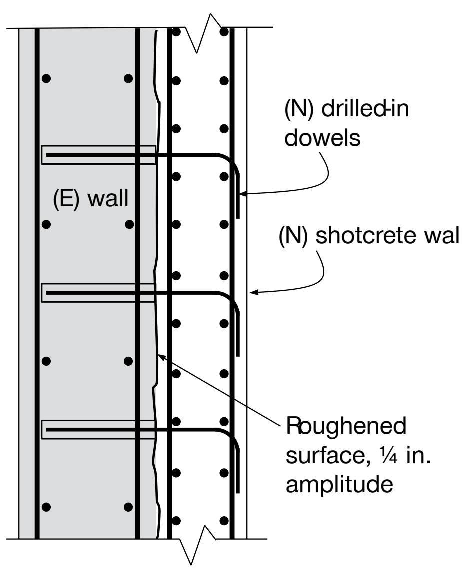
Note: Where it is has been verified through appropriate qualification testing (in accordance with AC308 or similar procedures[7]) that a given post-installed reinforcing bar system results in similar bond strength and displacement behavior as cast-in-place reinforcing bars, the design of post-installed reinforcing bar connections employing that system can proceed using the provisions for cast-in-place reinforcing bars.

7 Hilti HIT-RE and HIT-HY adhesives have been verified as suitable for post-installed reinforcing bar applications through extensive research and testing.

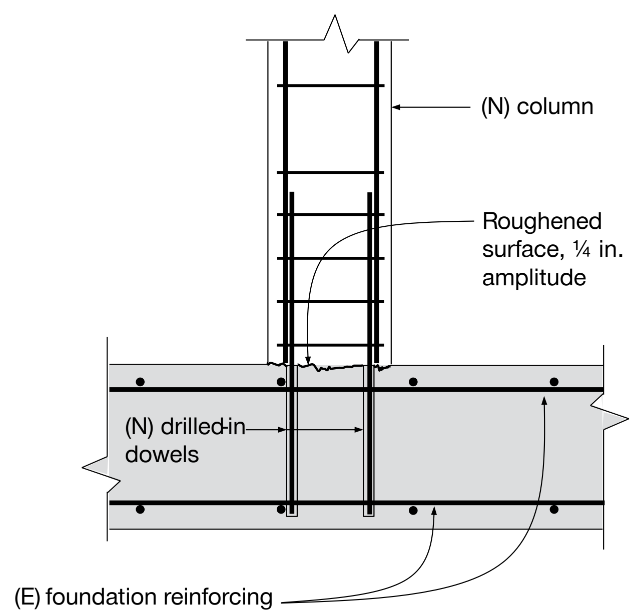
1.0 Post-installed reinforcing bars — what are they?



a. Tension lap splice with existing flexural reinforcement



b. Development of shear dowels for new onlay shear wall



c. Tension development of column dowels

Figure 8 — Examples of structural detailing with post-installed reinforcing bars.

2.0 How are they designed?

2.1 Design requirements

Design of post-installed reinforcing bar connections requires that the type, size, spacing and quantity be established for the connection. This is typically based on either direct calculation of section forces or a requirement to match existing reinforcement. Density and sizing of dowels for shear transfer between new overlays on existing structural elements such as slabs and walls may be based on other considerations.

Additional design considerations may include:

- loading type (sustained, seismic, shock)
- fire requirements
- corrosion resistance
- detailing requirements based on element type (integrity reinforcement, etc.)

2.2 Jobsite constraints

Prior to designing a post-installed reinforcing bar connection, identification of the jobsite constraints is vital. Key parameters that should be accounted for in the design may include:

- existing reinforcement layout as given in drawings and confirmed on site using detection equipment (see Section 3.1).
- required proximity of new to existing reinforcing to satisfy conditions for non-contact lap splices, etc.
- drilling method (hammer drill, core drill, Hilti Hollow Drill Bit)
- orientation of connection (downhole, overhead, etc.)
- ambient air and concrete temperatures at time of installation
- type and condition of the concrete e.g. cracked, carbonized
- access and geometrical constraints

2.3 Required bond length

In general, the required bar embedment is based on the development length and splice provisions of the code[8]. Where geometrical or other practical constraints dictate, alternate procedures may be appropriate to establish bond length. The size of the bar and required bond length may also guide the type of adhesive system to be used. Adhesives with longer working time (e.g., Hilti HIT-RE 500 V3) are usually more appropriate for large diameter bars in combination with deep holes, whereby for small and medium bar diameters and shorter holes, systems with accelerated cure (e.g., Hilti hybrid adhesive HIT-HY 200) can increase efficiency. These considerations may be affected by the anticipated job site conditions (e.g., access and ambient air and concrete temperatures).

2.4 Connection detailing

The location of post-installed reinforcing bars with respect to existing reinforcement should be clearly indicated in the project documentation. In addition, the specifications and details may include:

- adhesive system
- bar type and size
- required bar embedment
- hole diameters and drilling method(s)
- requirements for preparation/roughening of existing concrete surface
- instruction on inviolability of existing reinforcement and embedded items as required
- requirements on training/certification of installers as required
- inspection/proof loading requirements

2.5 System specification

Specifications should correlate to the design assumptions and the specific job site requirements addressed in the project documentation. Substitutions based on a simple specification of bond stress may not be sufficient to ensure proper execution of the work.

2.6 Design examples

The following design examples, based on the provisions of ACI 318-11[9], are intended for illustration purposes only.

2.6.1 Design example — shear dowel

Requirement: Design dowels used to connect a new 10-inch thick shotcrete (pneumatically-placed) shear wall to an existing concrete wall (Figure 9).

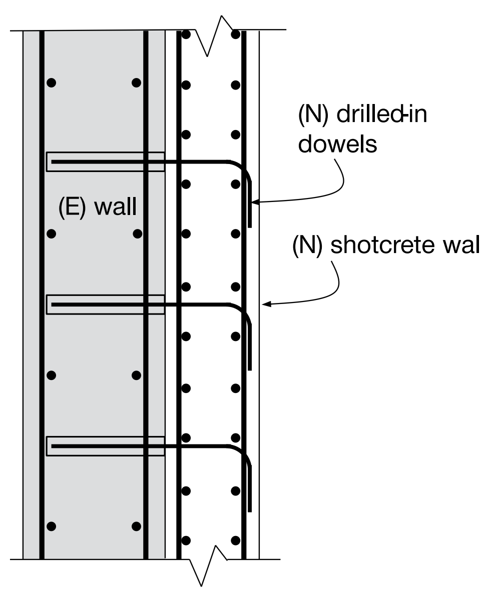


Figure 9 — Section through wall.

8 See e.g., ACI 318-11 12.2.
9 Similar equations and procedures may be found in CSA 23.3-14.

2.0 How are they designed?

Step 1: Determine area of dowel steel required.

Existing construction

(E) shear wall, 16 in. thick, 4 ksi normal weight concrete

Reinforcement requirement based on required shear transfer using shear friction	V_u=9k/ft^2
Required area of reinforcement per 11.6.4.1, Eq. (11-25) ACI318-11	$A_{vf} = \dfrac{V_u}{\Phi f_y \mu} = \dfrac{9}{0.75 \times 60 \times 1.0}$ 0.2 in^2/ft^2
Provided area of reinforcement	#5 at 16 in. x 12 in. over face of wall.

Step 2: Set design conditions.

- Drilling method : Rotary-hammer drilling
- Orientation of connection: Horizontal/ wall position
- Installation and in-service temperature: 70˚F
- Type of concrete: Normal weight, 4 ksi
- Condition of concrete : Dry
- Choice of adhesive based on condition: HIT-RE 500 V3
- Type and location of dowels: Hooked bars, in the face of the existing wall at uniform spacing vertically and horizontally

Step 3: Calculate the required embedment (development length).

ACI 318-11 development length equation (12-1):

$$\ell_d = \left[\frac{3}{40} \frac{f_y}{\lambda \sqrt{f'_c}} \frac{\Psi_s}{\dfrac{c_b + K_{tr}}{d_b}} \right] d_b$$

$$\ell_d = \left[\frac{3}{40} \frac{60000}{1.0\sqrt{4000}} \frac{0.8}{2.5} \right] 0.625 = 14 \text{ in. } (23d_b) > \text{minimum } \ell_d = 12 \text{ in.}$$

Available end cover = 16 – 14.2 = 1.8 in. Exterior wall exposure, required cover = 1.5 in. ok

Dowel length = 14 + (10 – 0.75) say 23 in. to outside of standard hook

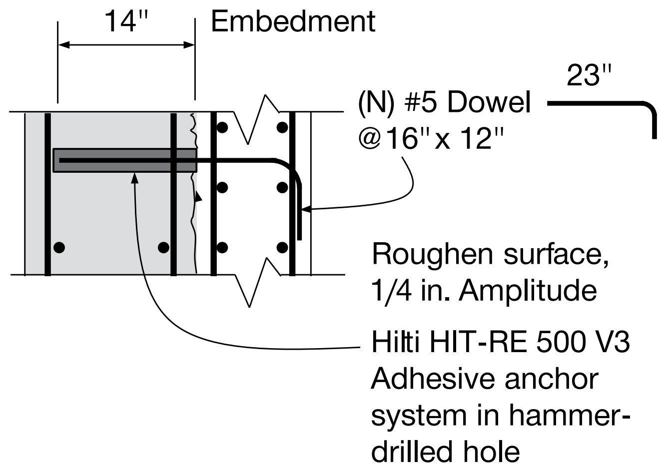


Figure 10 — Dowel detail (not to scale).

Step 4: Specification

Provide post-installed dowels at size, spacing and embedment as indicated on construction documents (see Figure 10).

Dowels: ASTM A615 Grade 60

Anchoring system: Hilti HIT-RE 500 V3 epoxy, install as per Manufacturer`s Printed Installation Instructions (MPII), concrete shall be dry during dowel installation unless otherwise permitted in the MPII.

Drill holes using a rotary-hammer drill with carbide bit. Locate existing reinforcing prior to drilling — do not damage (E) reinforcing without prior authorization of the EOR.

2.0 How are they designed?

2.6.2 Design example — lap splice

Requirement: Provide post-installed reinforcing for a new balcony extension on an existing concrete structure as shown in Figure 11.

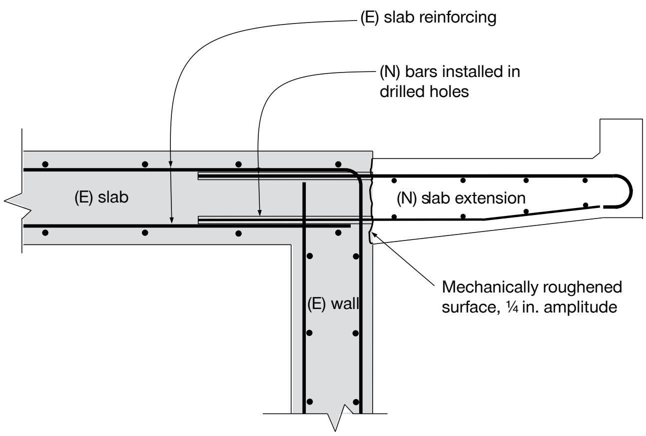


Figure 11 — Section through balcony.

Step 1: Determine area of flexural reinforcing for cantilever moment.

Existing construction: (E) slab, 10 in. thick, 4 ksi normal weight concrete, top bars #9 @ 8 in. on center, bottom bars #8 @ 12 in. on center, transverse bars #5 @ 16 in. on center top and bottom

New construction: (N) tapered slab as shown, 5000 psi sand lightweight concrete, ASTM A615 Gr. 60 reinforcement

Factored moment and shear at face of cantilever:
M_u = 25 ft-k / ft
V_u = 6k / ft
d = 8 inches (Figure 12)

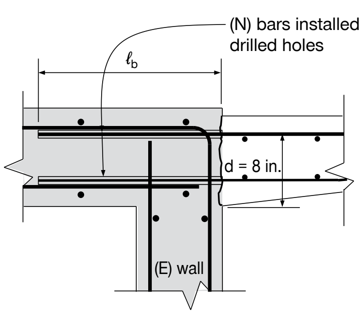


Figure 12 — Placement of new positive moment reinforcement.

Positive moment reinforcement: try #8 @ 12 in. o.c.

$$\rho = \frac{0.79}{12 \times 8} = 0.0082$$

$$K_n = \left[1 - \frac{\rho f_y}{1.7\lambda f'_c}\right]\rho f_y = \left[1 - \frac{0.0082\ (60000)}{1.7\ (0.85)\ (5000)}\right]0.0082\ (60000) = 458 \text{ psi}$$

$$\phi M_n = \phi b \cdot d^2 K_n = 0.9\ \frac{12\ (8)^2 \times 458}{12 \times 1000} = 26.3 \text{ ft-k / ft} > 25 \therefore \text{ ok}$$

use #8 @ 12 in. on center for top bars

Required area of reinforcement per 11.6.4.1, Eq. (11-25) ACI318-11

$$A_{vf} = \frac{V_u}{\phi f_y \mu} = \frac{V_u}{\phi f_y\ 1.0\lambda} = \frac{6000}{0.75 \times 60000 \times 1.0 \times 0.75} = 0.18 \text{ in}^2\text{/ft}$$

Note: although this is sand-lightweight concrete, the value of λ for use with the shear friction equation is taken conservatively as 0.75 in the absence of specific information to support a higher value — see 11.6.4.3 of ACI 318-11.

Shear reinforcement: use #5 at 16 in. on center for bottom bars

Step 2: Set design conditions.

- Drilling method: Rotary-hammer drilling
- Orientation of connection: Horizontal/ wall position
- Installation and in-service temperature: 90˚F
- Type of concrete: Normal weight, 4 ksi
- Condition of concrete : Dry
- Choice of adhesive based on condition: HIT-RE 500 V3
- Type and location of bars: As shown on drawings, position to avoid existing reinforcing, but no further than 4 inches from existing flexural reinforcing.

Step 3: Calculate the required embedment (splice length) for the new top and bottom bars

Top bars:

Note: Since the new #8 bars are being spliced with existing #9 bars, the required splice length per ACI 318-11 12.15.3 is the larger of the development length of the larger bar (#9) and the tension lap splice length of the smaller bar (#8).

2.0 How are they designed?

Development length of #9 existing reinforcing per Eq. (12-1):

#9 bars have 1-1/2 in. cover, transverse reinforcing is #5 @ 16 in. on center (see Figure 13)

$$K_{tr} = \frac{40A_{tr}}{s \cdot n} = \frac{40 \times 0.31}{16 \times 1} = 0.78$$

$$\frac{c_b + K_{tr}}{d_b} = \frac{\left(\frac{1.128}{2} + 1.5\right) + 0.78}{1.128} = 2.55 \therefore \text{ use } 2.5$$

$$\ell_d = \left[\frac{3}{40}\,\frac{f_y}{\lambda\sqrt{f'_c}}\,\frac{\psi_s}{\frac{c_b + K_{tr}}{d_b}}\right] d_b$$

$$\ell_d = \left[\frac{3}{40}\,\frac{60000}{1.0\sqrt{4000}}\,\frac{1.0}{2.5}\right] 1.128 = 32 \text{ in.}$$

Tension lap length (Class B) of #8 new reinforcing per 12.15.1:

$$1.3\ell_d = \left[\frac{1.3}{40}\,\frac{60000}{1.0\sqrt{4000}}\,\frac{1.0}{2.5}\right] 1.0 = 37 \text{ in.} > 32 \therefore \text{ use } 37 \text{ in.}$$

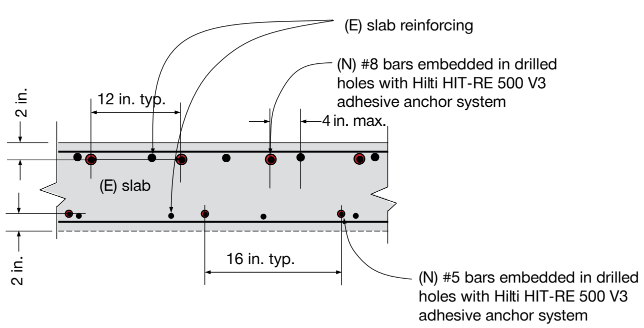


Figure 13 — Location of new bars (not to scale).

Bottom bars:
Development length of #5 bars with 1.5 in. cover
Assume $K_{tr} = 0$ (conservative)

$$\frac{c_b + K_{tr}}{d_b} = \frac{\left(\frac{0.625}{2} + 1.5\right) + 0}{0.625} = 2.9 \therefore \text{ use } 2.5$$

$$\ell_d = \left[\frac{3}{40}\,\frac{f_y}{\lambda\sqrt{f'_c}}\,\frac{\psi_s}{\frac{c_b + K_{tr}}{d_b}}\right] d_b$$

$$\ell_d = \left[\frac{3}{40}\,\frac{60000}{1.0\sqrt{4000}}\,\frac{0.8}{2.5}\right] 0.625 = 14 \text{ in.}$$

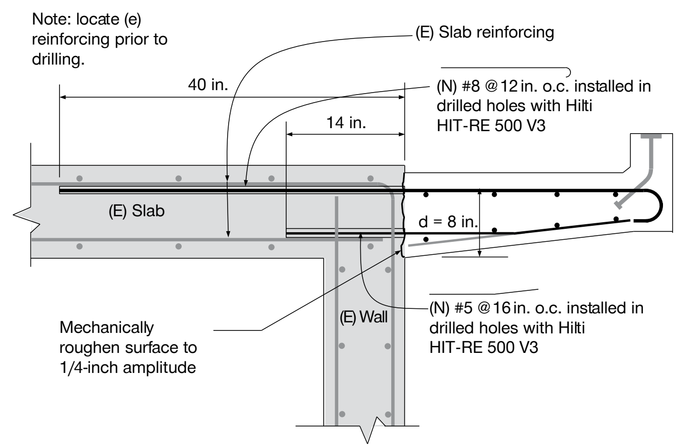


Figure 14 — Detail (not to scale).

Step 4: Specification

Provide post-installed dowels at size, spacing and embedment as indicated on construction documents (see Figure 14).

Dowels: ASTM A615 Grade 60

Anchoring system: Hilti HIT-RE 500 V3 epoxy, install as per Manufacturer`s Printed Installation Instructions (MPII), permissible concrete temp. range for installation: 55˚F - 90˚F, concrete shall be dry during dowel installation.

Drill holes using a rotary-hammer drill with carbide bit. Locate existing reinforcing prior to drilling – do not damage (E) reinforcing without prior authorization of the EOR.

2.0 How are they designed?

2.6.3 Design example — development length in a special moment frame

Requirement: Provide post-installed reinforcement for an addition to a special moment frame in a structure assigned to Seismic Design Category D (high seismic).

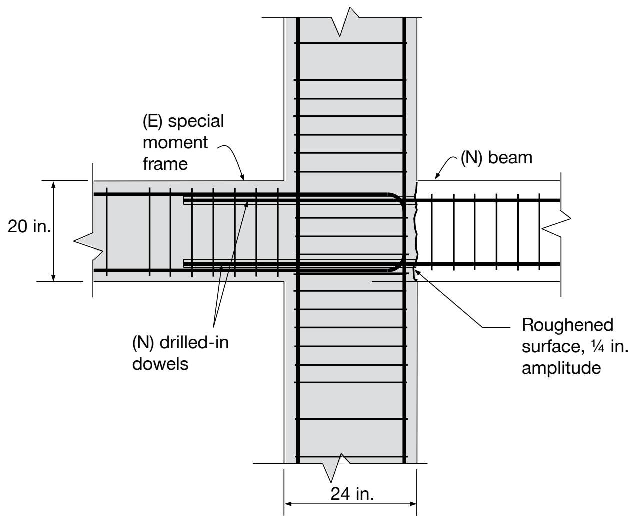


Figure 15 — Addition to a special moment frame.

Step 1: Establish requirements for new bars.

Existing construction: Special moment frame with 18 x 24-inch columns, 14 x 20-inch beams, 20-ft. bays, 4 ksi normal weight concrete, A706 Gr. 60 bar, 4 - #9 top bars, 2 - #9 bottom bars, #3 hoops and crossties @ 3-1/2 in. on center typical at joint. Factored w_u = D + L = 3.6 k/ft

New construction: (N) 14 x 20-inch beam as shown, 4 ksi normal weight concrete, ASTM A706 Gr. 60 reinforcement, 4 - #9 top bars, 2 - #9 bottom bars, #3 hoops and crossties at 3-1/2 in. on center

Determine shear force associated with plastic hinges at beam ends per ACI 318-11 Section 21.6.5.1 and 21.7.2.1

Effective depth of bars in beams:
d = 20 - 1.5 - 0.375 - 1.128/2 = 17.6 in.

For 4 - #9 top bars, probable moment strength:

$$\rho^- = \frac{4\,(1.0)}{14 \times 17.6} = 0.0162$$

$$K_{pr}^- = 1.25\,\rho^- f_y \left(1\text{-}0.735\,\rho^- \frac{f_y}{f'_c}\right)$$

$$= 1.25 \times 0.0162 \times 60000 \left(1\text{-}0.735 \times 0.0162 \frac{60000}{4000}\right) = 998 \text{ psi}$$

$$M_{pr}^- = \frac{K_{pr}^- \, b \cdot d^2}{12000} = \frac{998 \times 14 \times (17.6)^2}{12000} = 361 \text{ ft-k}$$

For 2 - #9 bottom bars:

$$\rho^+ = \frac{2\,(1.0)}{14 \times 17.6} = 0.0081$$

$$K_{pr}^+ = 1.25 \times 0.0081 \times 60000 \left(1\text{-}0.735 \times 0.0081 \frac{60000}{4000}\right) = 553 \text{ psi}$$

$$M_{pr}^+ = \frac{K_{pr}^- \, b \cdot d^2}{12000} = \frac{553 \times 14 \times (17.6)^2}{12000} = 200 \text{ ft-k}$$

Shear associated with formation of plastic hinges:

$$V_c = \frac{M_{pr1} + M_{pr2}}{\ell_n} \pm \frac{W_u \ell_n}{2} = \frac{361 + 200}{20} \pm \frac{3.6\,(20)}{2} = 64 \text{ k}$$

Step 2: Check ability of bottom bars to carry shear at joint face:

$$A_{vf} = \frac{V_u}{\phi f_y \mu} = \frac{V_u}{\phi f_y 1.0\lambda} = \frac{64000}{0.75 \times 60000 \times 1.0} = 1.42 \text{ in}^2 \; 2\text{-\#9}=2.0 \therefore \text{ ok}$$

Step 3: Calculate the required embedment for the new top and bottom bars using ACI 318-11 Eq. (21-6) and 21.7.5.2:

$$\ell_d = 2.5 \frac{f_y d_b}{65\sqrt{f'_c}} = 2.5 \times \frac{60000 \times 1.128}{65\sqrt{4000}} = 41 \text{ in.}$$

Per 21.7.5.3, portion of development length not within confined core =41-24=17in.

ℓ_d =24+1.6 x 17=51in.

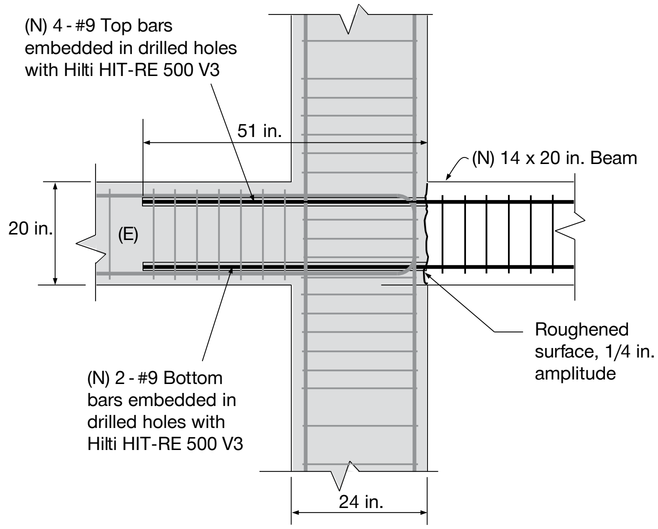


Figure 16 — Detail (not to scale).

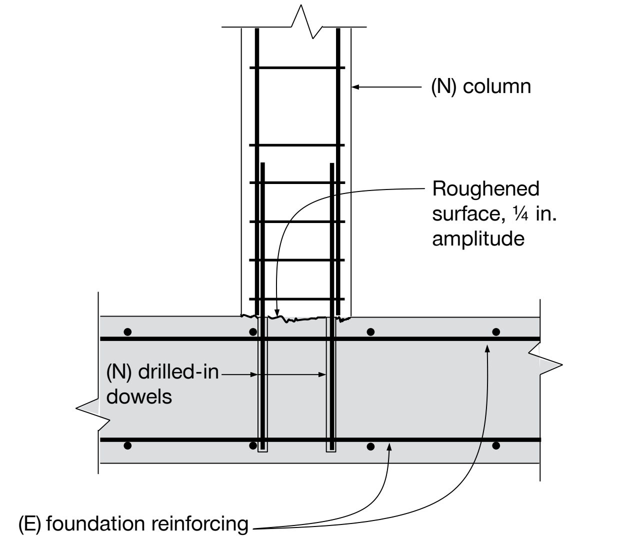


Figure 17 — New column on existing foundation.

Step 4: Specification

Provide post-installed bars at size, spacing and embedment as indicated on construction documents (Figure 16).

Dowels: ASTM A706 Grade 60

Anchoring system: Hilti HIT-RE 500 V3 epoxy, install as per Manufacturer`s Printed Installation Instructions (MPII), permissible concrete temp. range for installation: 55˚F - 90˚F, concrete shall be dry during dowel installation.

Drill holes using a rotary-hammer drill with carbide bit. Locate existing reinforcing prior to drilling — do not damage (E) reinforcing without prior authorization of the EOR.

2.6.4 Design example — development length for column starter bars

Requirement: Provide post-installed starter bars for a new column on an existing foundation.

Step 1: Establish requirements for the new bars.

Existing construction: Foundation grade beam 24 x 36-in., 4 ksi concrete, A615 Gr. 60 reinforcing

New construction: (N) 18 x 18-inch column as shown, 4 ksi normal weight concrete, ASTM A615 Gr. 60 reinforcement, 4 - #7 column bars

The column resists moment and shear arising from wind loading.

Step 2: Determine the development length for the column bars.

Note that the confinement term can be taken as the maximum value of 2.5 given the edge distance and confinement condition.

Eq. (21-1):

$$\ell_d = \left[\frac{3}{40} \frac{f_y}{\lambda \sqrt{f'_c}} \frac{\psi_s}{\frac{c_b + K_{tr}}{d_b}} \right] d_b = \left[\frac{3}{40} \frac{60000}{1.0\sqrt{4000}} \frac{1.0}{2.5} \right] 0.875 = 25 \text{ in}$$

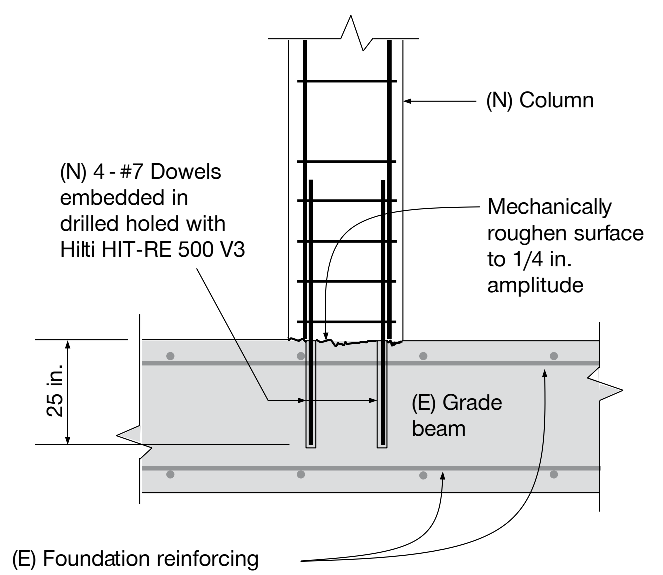


Figure 18 — Detail (not to scale).

2.0 How are they designed?

Step 3: Specification

Provide post-installed bars at size, spacing and embedment as indicated on construction documents (Figure 16).

Dowels: ASTM A615 Grade 60

Anchoring system: Hilti HIT-RE 500 V3 epoxy, install as per Manufacturer`s Printed Installation Instructions (MPII), permissible concrete temp. range for installation: 55˚F - 90˚F, concrete shall be dry during dowel installation.

Drill holes using a rotary-hammer drill with carbide bit. Locate existing reinforcing prior to drilling — do not damage (E) reinforcing without prior authorization of the EOR.

2.6.5 Design example — development length for starter bars in a special structural wall

Requirement: Provide starter bars for a new special structural (shear) wall in SDC D.

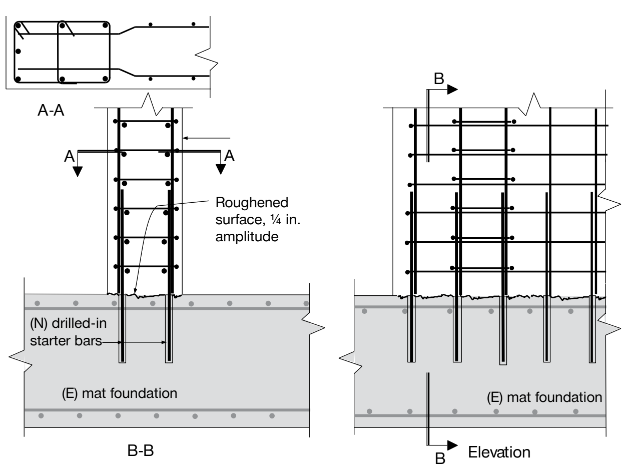


Figure 19 — New special structural wall.

Step 1: Establish requirements for the new bars.

Existing construction: Foundation mat 4-ft. thick, 5 ksi concrete, A615 Gr. 60 reinforcing.

New construction: (N) 18-inch thick wall detailed and constructed in accordance with 21.9 of ACI 318-11, two curtains of steel, boundary member reinforcement per 21.9.6, 6 ksi normal weight concrete, ASTM A706 Gr. 60 reinforcement, boundary member reinforcing 7 - #10 bars, web reinforcing is #8 @ 12 in. on center vertical and #6 @ 10 in. on center horizontal (see Figure 19).

Step 2: Determine the development length for the #10 chord bars.

As in the previous example (2.6.3) the confinement term can be taken as the maximum value of 2.5 given the edge distance and confinement condition. Also, per 21.9.2.3(c) of ACI 318-11, the development length must be increased by 25% to account for possible overstrength in the bars.

$$\ell_d = \left[\frac{3}{40} \frac{f_y}{\lambda \sqrt{f'_c}} \frac{\psi_s}{\frac{c_b + K_{tr}}{d_b}} \right] d_b = 1.25 \left[\frac{3}{40} \frac{60000}{1.0\sqrt{5000}} \frac{1.0}{2.5} \right] 1.27 = 40 \text{ in}$$

Step 3: Determine the development length for the #8 vertical wall bars, which are assumed to be exempt from the 1.25 increase factor of 21.9.2.3 (c).

$$\ell_d = \left[\frac{3}{40} \frac{60000}{1.0\sqrt{5000}} \frac{1.0}{2.5} \right] 1.0 = 26 \text{ in}$$

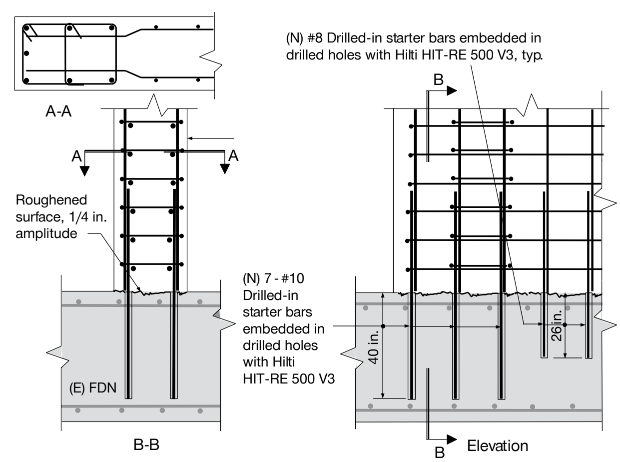


Figure 20 — Detail (not to scale).

Step 4: Specification

Provide post-installed bars at size, spacing and embedment as indicated on construction documents (Figure 20).

Dowels: ASTM A706 Grade 60

Anchoring system: Hilti HIT-RE 500 V3 epoxy, install as per Manufacturer`s Printed Installation Instructions (MPII), permissible concrete temp. range for installation: 55˚F - 90˚F, concrete shall be dry during dowel installation.

Drill holes using a rotary-hammer drill with carbide bit. Locate existing reinforcing prior to drilling — do not damage (E) reinforcing without prior authorization of the EOR.

Note: Hilti maintains a staff of qualified engineers available to answer inquiries related to design and installation of post-installed reinforcing bar connections.

Jobsite constraints should be taken into consideration while designing and installing post-installed reinforcing bars.

Note: In addition to state-of-the-art adhesive anchoring systems, Hilti offers best-in-class detection and drilling equipment to facilitate the installation of post-installed reinforcing bars over a wide range of bar diameters and embedments.

3.1 Location of existing reinforcement and other embedded items

The location of existing reinforcement is generally accomplished with one or more scanning methods. These may be generally categorized as:

a) Scanners that locate ferrous materials using magnetic fields (ferrous scanners, see Figure 21),

b) Scanners that utilize GPR (ground-penetrating radar technology), and

c) X-ray scanning equipment.

For reinforcing bars located within 8-10 inches of the concrete surface, ferrous scanners provide both bar location and size. For location of both ferrous and non-ferrous embedded items (e.g., aluminum conduit), GPR-based scanners are appropriate. For areas of heavy congestion or where existing reinforcing is too deep for ferrous or GPR systems, x-ray scanning methods may be necessary. Where available, it is generally preferable to supplement scanning results with as-built or original design documents.

Figure 21 — Using a Hilti PS 200 hand-held Ferroscan scanner to locate and map existing reinforcing prior to beginning drilling.

3.2 Roughening the existing concrete surface

Surface roughening prior to casting new concrete against existing provides not only for increased adhesion, but also increases the ability of the joint to transfer shear through shear friction. Where new concrete is to be applied to an existing concrete surface, roughening of the existing concrete surface is typically specified[10]. In cases where the surface layer of existing concrete is carbonated, the carbonated layer should be removed in areas that are to receive post-installed reinforcing bars. A rule of thumb is to remove the carbonated concrete over a circular area given by the diameter of the bar plus 2-1/2 inches.

ACI 318-11 Section 11.6.9 requires roughening "...to a full amplitude of approximately 1/4 in." This may be accomplished by mechanical means (e.g., using a Hilti TE 76 ATC equipped with a bushing tool, see Figure 22), sand-blasting or water-blasting. It should be ascertained that the resulting surface does not contain loose material prior to placing new concrete.

Figure 22 — Roughening a concrete surface with a Hilti TE 76 Combihammer.

10 See ICRI Technical Guideline No. 310.2 Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings and Polymer Overlays or ASTM E965 Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique.

3.0 How are they installed?

3.3 Installation of post-installed reinforcing bars with small cover

As with cast-in bars, post-installed reinforcing bars must be provided with sufficient concrete cover to prevent corrosion. If the bar has been properly installed with adhesive surrounding the bar over its entire length, additional protection against corrosion is provided by the adhesive. Qualification of post-installed reinforcing bar systems under ICC-ES Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements (AC308) includes verification (through an accelerated aging test) that the adhesive provides adequate corrosion resistance.

In addition, sufficient distance must be provided from the concrete face to facilitate drilling without splitting and/or spalling the existing concrete, particularly where hammer- or rock-drilling equipment is used. Hilti drilling alignment aids can be employed with Hilti hand-held hammer drills to improve drilling accuracy (Figure 24). In the absence of other guidance, and where alignment aids or other techniques to maintain drilling accuracy are not used, the following relationships may be used to account for possible deviation of the drilled hole from its intended path[11]:

Hammer-drilled holes:

$c_{min,req} = 1.2 + 0.06\ \ell_d \geq 2d_b$ (in.) [2]

Compressed-air (rock) drilled holes:

$c_{min,req} = 2.0 + 0.08\ \ell_d \geq 2d_b$ (in.) [3]

Drill stand (e.g., core-drilled holes):

$c_{min,req} = 1.2 + 0.02\ \ell_d \geq 2d_b$ (in.) [4]

where,

ℓ_d is the hole length in inches; and

d_b is the diameter of the reinforcing bar in inches

$c_{min,req}$ is the distance from the concrete edge to the face of the drill bit (Figure 23).

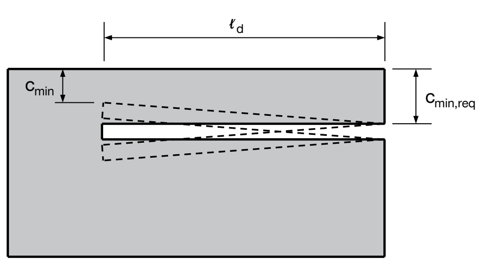


Figure 23 — $c_{min,reqc}$ is intended to increase the probability that the end of the installed bar will remain within the minimum required concrete cover c_{min}.

Figure 24 — Drilling with and without drilling alignment aids.

Clearance requirements for core-drilled holes vary according to the type, diameter and length of core bits being used.

Regardless of the drilling method used, embedded items may cause drill bits to deviate from the intended path.

As a matter of practicality, spacing of adjacent post-installed reinforcing bars should in general be maintained at 4 bar diameters or greater. **Where applicable, ACI provisions for cover and bar spacing should be observed**.

3.4 Drilling method

To satisfy development length requirements, post-installed reinforcing bars are usually associated with deeper embedments, and therefore longer drilled holes, than adhesive anchors. As noted previously, one of the following three drilling methods is typically employed:

- rotary-impact drills (hammer drills) equipped with standard or cruciform carbide bits or with Hilti Hollow Drill Bits (HDB)[12]
- percussive rock drills
- diamond core drills utilizing either wet or dry coring technology

Each method is associated with advantages and disadvantages. See section 3.3. Hammer drills (Figure 25) are readily available and are the preferred approach for most applications given their portability and ease of use. Hilti hammer drills produce a non-uniform hole surface especially suitable for enhancing bond (provided correct hole cleaning procedures are used). For longer holes, hammer drills may not be practical; they are also not always suitable for drilling through embedded steel where this is required.

The Hilti SafeSet™ system consists of Hollow Drill Bits (HDB) used in combination with Hilti Vacuum Cleaners (VC 40-U or VC 20-U). Hilti HDBs utilize the same state-of-the-art carbide drilling technology as Hilti TE-CX and Hilti TE-YX bits and they

11 Source: EOTA Technical Report TR023 [7]

12 Hilti Hollow Drill Bits automatically remove concrete dust during drilling as part of the HIT-HY 200 SafeSet™ System.

comply with the ANSI B212.15 standard for carbide drill bit dimensions. The Hilti SafeSet system performs equally well in dry and wet concrete.

Figure 25 — Drilling with a Hilti rotary-percussive drill equipped with Hilti SafeSet™ technology.

Rock drills offer speed and efficiency and produce a rough hole surface that is suitable for bond, but the larger impact energy associated with rock drills may increase the tendency for damage in the concrete member, particularly if used in applications with small edge distance or reduced backside cover. Rock drills typically require larger edge distances/ member thickness (see Section 3.3). For applications involving rock drilled holes, contact Hilti.

For longer embedment depths, core drills are generally the preferred option (Figure 26 and Figure 27).

Figure 26 —Core drilling with a hand-held Hilti wet core drill with water-capture technology.

Figure 27 —Inclined core drilling with a Hilti drill stand.

In contrast to hammer drills, which fracture the concrete with impact energy, core drill bits utilize a sacrificial matrix containing diamond fragments to abrade the concrete. Hilti diamond core bits with laser-welded segments offer long life and exceptional drilling efficiency. Using extensions, core drills can produce very long, straight holes. The stiffness of the core barrel permits holes to be drilled with less deviation from the intended path, and they are capable of drilling through embedded steel without great effort. On the other hand, where the existing reinforcing must be protected (e.g., as in the case of prestressing tendons), this feature of core drilling may be a liability. More importantly, core drills typically produce a very smooth hole that is usually covered with a thin film deleterious to bond. Accordingly, core drilled holes must be thoroughly cleaned prior to injecting adhesive. Note also that some adhesive systems are not suitable for use with core drilled holes. For qualified systems, specific hole cleaning procedures have been developed to optimize bond under these conditions, and are detailed in the Hilti Instructions for Use (generically, these instructions are known as the Manufacturer's Printed Installation Instructions, or MPII).

Note: Drilling through existing reinforcing or other embedded objects should in general not be undertaken prior to consultation with the engineer of record or other authority having jurisdiction.

Note: Correct hole drilling and cleaning are critical for the performance of post-installed reinforcing bars. Detailed instructions, referred to by Hilti as Instructions for Use, accompany all Hilti anchoring products. For questions regarding correct installation Hilti offers expert advice through Hilti field representatives, nationwide Hilti Centers, Hilti Customer Service, and online at www.us.hilti.com (USA), or www.hilti.ca (Canada).

Figure 28 illustrates the potential influence of drilling method on the load-displacement behavior of a post-installed reinforcing bar at shallow embedment. Where the drilling method to be used has not been predetermined, it is advisable to use an adhesive that is suitable for all drilling methods (e.g., Hilti HIT-RE 500 V3).

3.0 How are they installed?

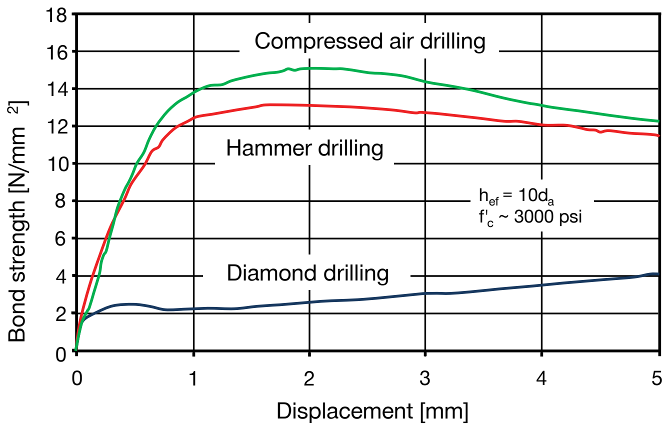


Figure 28 — Example of the influence of drilling method on the bond-displacement behavior of a post-installed reinforcing bar installed with an adhesive not suitable for diamond drilled holes.

3.5 Hole cleaning

Bond between adhesive and concrete is directly influenced by the condition of the hole wall at the time of adhesive injection. The concrete in which the post-installed reinforcing bar is to be installed may be dry, saturated or even partially or completely submerged at the time of installation.

Note: Where installation in water-saturated or submerged concrete is required, check that the adhesive system to be used is qualified for these conditions.

Wet diamond core drilling will necessarily result in a damp environment in the drilled hole. Hole cleaning generally involves a water-cleaning process, followed by sequential blowing out the hole with compressed air (Figure 29 and Figure 33) to remove debris and water, and the use of a wire brush (Figure 30) to mechanically scour the hole wall.

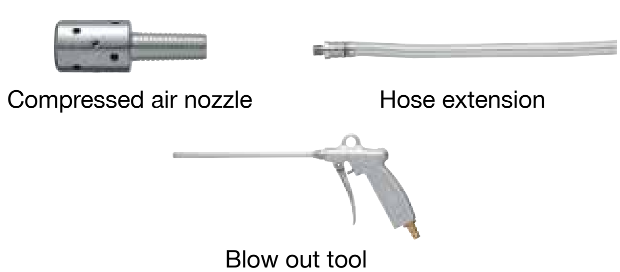


Figure 29 — Hilti accessories for compressed air hole cleaning operations (partial).

Figure 30 — Hilti extension rod and Hilti HIT-RB matched-tolerance steel brushes for hole cleaning.

All cleaning procedures finish with the use of compressed air. (It is important to note that the use of compressed air may produce flying debris — eye protection should be worn at all times.)

The importance of hole cleaning as specified in the Hilti Instructions for Use for the performance of post-installed reinforcing bars is indicated in Figure 32. For cases where adherence to multi-step hole cleaning procedures may not be possible, use of Hilti SafeSet™ technology with Hilti Hollow Drill Bits (HDB) is recommended.

Figure 31 — Hilti Profi Rebar Accessory Set.

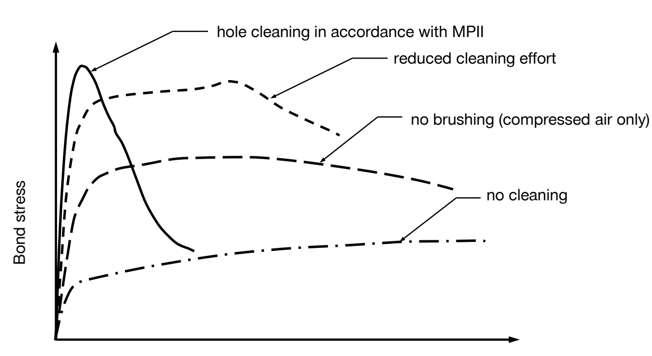


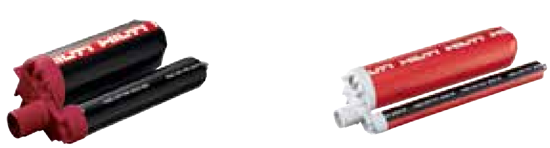
Figure 32 — Schematic representation of the potential influence of hole cleaning procedures on the measured bond and displacement of a post-installed reinforcing bar loaded in tension.

Figure 33 — Cleaning a hole using a compressed air blow-out tool.

Hilti provides a number of accessories for cleaning deep drilled holes in accordance with the Instructions for Use. These include matched-tolerance wire brushes, brush extensions for long holes, attachments to facilitate power brushing, air wands, hose extensions, couplers and air nozzles. Hilti Profi Rebar Accessory Sets (Figure 31) provide the necessary additional components for installation of post-installed reinforcing bars in a single package.

3.6 Selection of adhesive system

The suitability of Hilti adhesive systems for post-installed reinforcing bar applications has been verified for a wide variety of jobsite parameters. Nevertheless, the choice of the appropriate Hilti adhesive system (Figure 34) and injection equipment (Figure 35) for post-installed reinforcing bar installations is to a degree dependent on jobsite parameters; see Section 4.1.



Hilti HIT-RE 500 V3 Hilti HIT-HY 200-R

Figure 34 — Hilti anchoring adhesives suitable for post-installed reinforcing bar connections.

Note: Adhesives which have not been properly verified for post-installed reinforcing bar applications should not be used for structural or safety-related applications.

For example, if a rapid-cure adhesive is specified for a large and deep bar installation, the time required to inject the adhesive may exceed the working time of the polymer. In such cases it may be impossible to insert the bar fully into the hole and/or the adhesive may not reach full strength. In particular, when adhesives are delivered in bulk quantities into a large drilled hole, the exothermic reaction associated with polymerization can result in excessive temperature rise which in turn can result in accelerated cure, further complicating bar installation.

Figure 35 — Using Hilti ED 3500 battery dispenser in combination with Hilti HIT-RE 500 V3 / Hilti HIT-HY 200 for smaller bar diameters.

Conversely, injection of adhesives under sub-zero conditions can result in elevated viscosity, likewise making manual adhesive injection and bar installation difficult or impossible.

Basic considerations associated with adhesive selection should include:

- Can the adhesive be injected and the reinforcing bar installed within the gel time of the adhesive?
- Is the appropriate injection equipment available, including all necessary accessories, to ensure correct dispensing and mixing?
- Is the adhesive suitable for the concrete temperature and moisture conditions, hole orientation and drilling method?
- What mechanical effort or equipment is required to inject the adhesive and to install the reinforcing bar into the adhesive-filled hole?
- How will the bar be held in place during adhesive cure?

3.0 How are they installed?

3.7 Injection of the adhesive

The objective of adhesive injection is to achieve a void-free installation. Aside from reducing bond area and inhibiting cure, air voids in the injected adhesive may lead to increased effort associated with bar installation and can cause uncontrolled ejection of the adhesive from the hole during bar installation as air is forced out of the adhesive matrix.

Note: Proper skin and eye protection should always be worn during injection of Hilti adhesives.

In order to inject the adhesive with minimal air voids in drilled holes, the Hilti injection system utilizes matched-tolerance piston plugs (Figure 36). The Hilti piston plug system provides positive feedback to the operator for controlling the injection process through the pressure of the adhesive on the plug and has been shown to dramatically improve injection quality and efficiency.

Figure 36 — Hilti HIT-SZ piston plugs, available in diameters appropriate for #3 through #18 reinforcing bars.

Dispensing equipment used for injection is generally selected as a function of bar size and orientation, ambient temperature conditions and accessibility (Figure 37).

Figure 37 — The Hilti HIT-P8000D pneumatic dispenser, appropriate for large volume installations and large bar diameters.

3.8 Bar installation

Smaller bar diameters can be inserted in a vertical downward direction with (relatively) minimal effort. Large-diameter bars in horizontal and upward-inclined orientations may require substantial effort to lift and insert the reinforcing bar into the adhesive-filled hole (Figure 38). **In all cases, it is advisable to test the fit of the bar in the hole prior to injecting adhesive**.

For overhead installations, particularly of larger diameter bars, provision must be made for securing the bar during adhesive cure. In addition, certification requirements for installers performing installation of bars to carry sustained tension loads, as well as additional special inspection requirements, may apply.

Note: Hilti dispensers provide efficient, void-free adhesive injection at all orientations, hole diameters and depths, and temperature conditions.

Figure 38 — Installing large diameter bars.

4.0 How do I decide which system to use?

Options for the installation of post-installed reinforcing bars include cementitious grouts, polymer adhesives, and hybrid systems that combine cementitious components with polymers. The use of cementitious (e.g., baseplate) grouts is typically limited to down-hole applications and is not discussed further in this Guide. Adhesives (sometimes referred to as thixotropic adhesives) that have the correct viscosity to provide a void-free bond layer in the annular space between the bar and the concrete while still resisting unrestricted flow have been developed specifically for anchoring and bar embedment. These systems permit installation at all orientations with superior bond strength under a variety of use conditions. The proper selection of the system is dependent on a number of job-specific parameters.

4.1 System selection considerations

Jobsite constraints impact both design values (bond strength) as well as installation effectiveness. Typical parameters for Hilti adhesive systems are shown below:

Jobsite constraints	HIT-HY 200-R[1]	HIT-RE 500 V3
Typical reinforcing bar diameter range	#3 to #8	#3 to #11[2]
Embedment range	Up to 25 in.	Up to 7 ft.
Temperature of base material (installation)	14°F to 104°F	41°F to 104°F
Working time[3]	6 min. to 3 hrs.	12 min. to 4 hrs.
Cure time[3]	1 hrs. to 20 hrs.	4 hrs. to 72 hrs.
Holes drilled in dry and water-saturated concrete	Yes	Yes
Water-filled holes and underwater applications	No	Yes
Hammer-drilled holes	Yes	Yes
Core drilled holes	No	Yes
Hilti SafeSet™ technology using Hilti HDB and VC vacuum	Yes	Yes[4]
Earthquake/dynamic loading	Yes	Yes

1 HIT-HY 200-A (accelerated cure) available. Not suitable for larger bar diameters due to short gel time.
2 For larger bar sizes contact Hilti.
3 Temperature dependent.
4 Contact Hilti.

System selection is therefore dependent on the combination of design requirements and jobsite constraints. Note also that each system is offered with a variety of options for injection in terms of cartridge size and injection equipment (manual vs. battery or pneumatic drive). Additionally, Hilti offers specialized drilling systems that substantially reduce hole cleaning requirements.

An aspect of system selection that is sometimes overlooked is the absolute volume of adhesive that must be placed in the hole. Large diameter and very deep holes may require a greater volume of adhesive than can be reasonably placed even with pneumatic delivery equipment. Furthermore, injection of large quantities of adhesive can result in excessive heat generation due to the exothermic nature of polymerization. These issues should be carefully considered for cases outside of the normal range of post-installed reinforcing bar applications.

Note: Hilti technical staff can provide assistance with unique or non-standard applications.

5.0 Development of design data

5.1 Background

At the reinforcing bar-adhesive interface, load is transferred by adhesion and mechanical interlock. At the adhesive-concrete interface, load is transferred by adhesion and micro-mechanical interlock. Bond strength is typically defined as the maximum average bond over embedded length of bar.

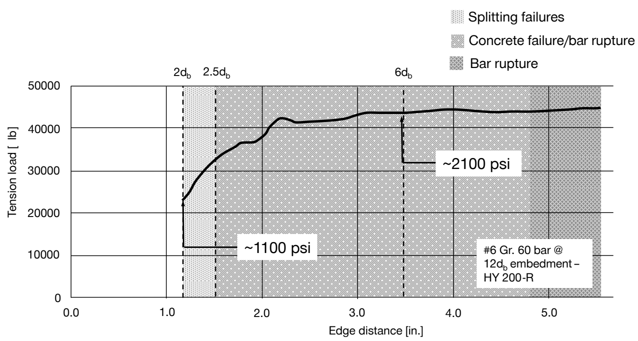


Figure 39 — Unconfined tension failure load as a function of edge distance.

Over the past two decades, extensive investigations have been conducted to evaluate post-installed reinforcing bar connections subjected to a variety of loading conditions. Much of this work has been conducted at leading research institutions in Europe and the U.S.[13] The tests have consistently shown that post-installed reinforcing bars installed with qualified systems exhibit performance that is at least equivalent to cast-in reinforcing bars under similar conditions.

Figure 39 plots tension failure loads for increasing edge distance for a #6 reinforcing bar embedded to a depth of 12 bar diameters in a Hilti HIT hybrid adhesive. Near-edge bond strength is limited by the splitting strength of the concrete and is on the order of 1100 psi. At larger edge distances, the average ultimate bond strength increases to approximately 2100 psi.

In 2006, the European Organization for Technical Approvals (EOTA) issued TR023 Assessment of Post-installed Reinforcing Bar Connections [7]. This document provides a path for verifying that post-installed reinforcing bar connections performed with a specific system will exhibit comparable behavior to cast-in-place reinforcing bar connections in terms of load and displacement behavior.

In 2013, ICC-ES amended their acceptance criteria[14] to include testing to verify adhesive anchor systems for post-installed reinforcing bar applications. These qualification provisions include the procedures developed for TR023 and add additional tests to check cyclic tension performance (seismic) and near-edge performance over deep embedment depths.

5.2 Establishment of required system performance (qualification)

The suitability of an adhesive system for post-installed reinforcing bar applications is dependent on many factors. Systems that may be otherwise appropriate for anchoring applications will not necessarily fulfill the requirements for safe and reliable reinforcing bar installations.

A critical aspect of adhesive systems intended for post-installed reinforcement is the behavior of the system in configurations where splitting controls. Figure 40 shows tension testing of #8 bars embedded 35 bar diameters in the corner of a column. These tests, which were developed specifically for qualification of post-installed reinforcing bar systems under AC308, directly compare cast-in and post-installed bar behavior under conditions where splitting is the limiting failure mode. If the adhesive is too stiff, excessive shear lag can lead to zipper-like failure of a near edge bar. If the bond is too "soft", relaxation of the post-installed bar may permit excessive opening of the joint between old and new concrete, leading to loss of shear transfer or corrosion.

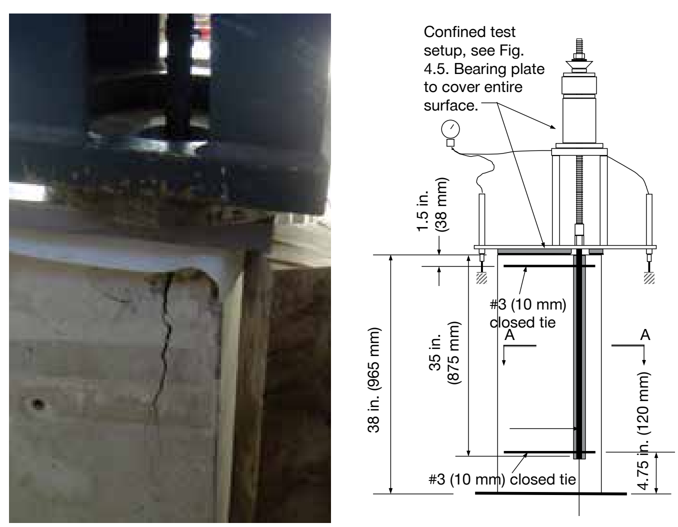


Figure 40 — Test for bond/splitting behavior per AC308 [9].

Figure 41 lists the full range of tests required to qualify adhesive anchor systems for post-installed reinforcing bar applications as provided in Table 3.8 of AC308.

13 See references and suggestions for further reading: [8], [10], [11], [12], [17], [18], [19], [20].
14 AC308 — Acceptance Criteria for Post-installed Adhesive Anchors in Concrete Elements, approved June 2013, ICC Evaluation Service, LLC. [9].

5.0 Development of design data

Figure 41 — AC308 Table 3.8: Test Program for Evaluating Deformed Reinforcing Bars for Use in Post-installed Reinforcing Bar Connections* [9].

Testing				Bar size	Assessment		f_c [1]	Bar Embedment ℓ_b	Minimum sample size n_{min}
Test no.	Test ref.	Purpose	Test parameters	US/M [3,4]	α_{req}	Load and displ.			
Service condition tests									
1a	9.4.3.1	Bond resistance	Tension confined, single reinforcing bar [2]	#4/12	–	10.25.2 10.25.3	low	$7d_b$	Five
1b	9.4.3.1	Bond resistance	Tension confined, single reinforcing bar [2]	#8/25	–	10.25.2 10.25.3	low	$7d_b$	Five
1c	9.4.3.1	Bond resistance	Tension confined, single reinforcing bar [2]	$d_{b,max}$	–	10.25.2 10.25.3	low	$7d_b$	Five
1d	9.4.3.1	Bond resistance	Tension confined, single reinforcing bar [2]	$d_{b,max}$	–	10.25.2 10.25.3	high	$7d_b$	Five
2	9.4.3.2	Bond/splitting behavior	Tension confined, reinforcing bar in corner condition [2]	#8/25	–	10.25.6	low	$35d_b$	Six [6]
Reliability tests									
3	9.4.4.1	Sensitivity to hole cleaning, dry substrate [5,7]	Tension confined, single reinforcing bar [2]	$d_{b,max}$	≥0.8	10.25.7	low	$7d_b$	Five
4	9.4.4.2	Sensitivity to installation in saturated concrete [5,7]	Tension confined, single reinforcing bar [2]	$d_{b,max}$	≥0.8	10.25.7	low	$7d_b$	Five
5	9.4.4.3	Sensitivity to freezing/ thawing conditions [5]	Tension confined, single reinforcing bar [2]	#4/12	≥0.9	10.25.7	high	$7d_b$	Five
6	9.4.4.4	Sensitivity sistained load at elevated temperature [5]	Tension confined, single reinforcing bar [2]	#4/12	≥0.9	10.25.7	low	$7d_b$	Five
7	9.4.4.5	Decreased installation temperature [5]	Tension confined, single reinforcing bar [2]	#4/12	≥0.9	10.25.7	low	$7d_b$	Five
8	9.4.4.6	Sensitivity to installation direction [5]	Tension confined, single reinforcing bar [2]	$d_{b,max}$	≥0.9	10.25.7	low	$7d_b$	Five
Installation procedure verification									
9	9.4.5.1	Installation at deep embedment	Bar installation in injected hole, horizontal	$d_{b,max}$	–	10.25.8	–	$60d_b$	Three
10	9.4.5.2	Injection verification	Injection in clear tube	$d_{b,max}$	–	10.25.8	–	$60d_b$	Three
Durability									
11a	9.4.6.1.1	Resistance to alkalinity [5]	Slice test	#4/12	–	10.25.10	low	–	Ten
11b	9.4.6.1.2	Resistance to sulfur [5]	Slice test	#4/12	–	10.25.10	low	–	Ten
12	9.4.7	Corrision resistance	Current and potential test	#4/12	–	10.25.9	high	2-3/4"	Three
Special conditions									
13	9.4.8	Seismic qualification for reinforcing bar connections [9]	Cyclic tension, confined, single reinforcing bar	$d_{b,max}$	–	10.25.11	low	$7d_b$	Five

1 For definition of high- and low-strength concrete, refer to 4.3.4.
2 Tests performed in test specimens in accordance with Fig. 4.5 and having minimum length/thickness of ℓ_b + 2 in. (ℓ_b + 50 mm)
3 Sizes are U.S. customary and European metric $d_{b,max}$ is maximum size sought for recognition.
4 Perfom tests with deformed reinforcing bars conforming to the mechanical requirements of 9.4.3.2.1.
5 Tests are not required if corresponding test has been performed in accordance with the Table 3.1, 3.2 or 3.3.
6 Test bars in three test specimens for a total of six tests with cast-in bars and six tests with post-installed bars.
7 Tests shall be required if hole cleaning equipemnt and technique varies from that used for tests in accordance with Table 3.1, 3.2 or 3.3.
8 Optional test. If this test is not perfomed, the evaluation report shall note that the value of f'_c to be used in the determination of develpoment and splice lengths in accordance with ACI 318 shall not exceed 2500 psi (17.2 MPa)
9 Optional test.

5.0 Development of design data

In addition to the bond/splitting tests described above, tests are conducted to establish the suitability of the system for use in post-installed reinforcing bar applications in terms of:

1. The ability of the adhesive to develop the required bond resistance;
2. The sensitivity of the bond resistance to hole cleaning, freezing and thawing conditions, concrete temperature extremes in service, installation orientation, and alkalinity/sulfur exposure;
3. The ability of the system to successfully execute long bar installations (up to 60 bar diameters) without substantial voids in the adhesive around the post-installed reinforcing bar;
4. The corrosion resistance of the post-installed reinforcing bar;
5. The ability of the adhesive to develop bond resistance over the development length when splitting controls the behavior; and
6. The cyclic tension load behavior of the post-installed reinforcing bar compared to cast-in-place bar response as documented in the literature.

While it is generally the case that modern structural-grade adhesives are capable of developing bond resistances well beyond those given in Figure 45, the effects of job-site installation conditions, temperature, and other factors included in the assessment can reduce bond resistance substantially. Therefore, system performance is critical for qualification, not just adhesive bond strength as determined under optimum conditions.

6.0 What's the back story?

6.1 Establishing the required bar embedment

Systems qualified under AC308 are required to demonstrate bond resistance and stiffness characteristics that are compatible with cast-in reinforcement. Therefore, post-installed reinforcing bars installed with qualified systems can be designed and detailed using the same provisions that are applicable to the development of straight cast-in-place bars.

6.2 Overview of ACI 318-11[15] development length provisions for straight reinforcing bars

The ACI concept of development length is based on the attainable average bond stress over the length of embedment of the reinforcement. Development length can be defined as the shortest length in which the bar stress increases from zero to the nominal yield strength. This definition incorporates two very important concepts — bar stress and nominal yield strength. Bar stress is the force per unit area of the bar cross-section. The nominal yield strength is the minimum bar stress at which permanent (inelastic) deformation occurs. Structural reinforced concrete design is based on the assumption that the reinforcing bar will develop its yield strength before premature failure occurs due to inadequate bond. Development length is intended to ensure that the nominal yield strength of the bar can be developed under structure loading.

Orangun, et al. [13] proposed an expression for determining the development length ℓ_d of deformed reinforcing bars in tension as follows:

$$\ell_d = \left[\frac{\left(\dfrac{f_s}{4\sqrt{f'_c}} - 50 \right)}{\left(1.2 + 3\dfrac{c_b}{d_b} + \dfrac{A_{tr} f_{yt}}{500 s \cdot d_b} \right)} \right] d_b \quad \text{(lb, in.)} \qquad [5]$$

where,

A_{tr} The total cross-sectional area of all transverse reinforcement within spacing that crosses the potential plane of splitting through the reinforcement being developed

c_b Smaller of: (a) center of bar to nearest concrete surface, and (b) one-half the center-to-center spacing of bars being developed

d_b Diameter of bar being developed

f'_c Specified 28-day compressive strength of concrete

f_s The maximum stress in the bar

f_{yt} Specified yield strength f_y of transverse reinforcement

U.S. reinforcing bar size

Imperial bar size	"Soft" metric size	Mass per unit length		Nominal diameter		Nominal area	
		lb/ft	(kg/m)	(in)	(mm)	(in²)	(mm²)
#2	#6	0.167	0.249	0.250 = 1/4	6.35	0.05	32
#3	#10	0.376	0.561	0.375 = 3/8	9.525	0.11	71
#4	#13	0.668	0.996	0.500 = 4/8	12.7	0.20	129
#5	#16	1.043	1.556	0.625 = 5/8	15.875	0.31	200
#6	#19	1.502	2.24	0.750 = 6/8	19.05	0.44	284
#7	#22	2.044	3.049	0.875 = 7/8	22.225	0.60	387
#8	#25	2.670	3.982	1.000	25.4	0.79	509
#9	#29	3.400	5.071	1.128	28.65	1.00	845
#10	#32	4.303	6.418	1.270	32.26	1.27	819
#11	#36	5.313	7.924	1.410	35.81	1.56	1006
#14	#43	7.650	11.41	1.693	43	2.25	1452
#18	#47	13.60	20.257	2.257	57.3	4.00	2581
#18J		14.60	21.775	2.337	59.4	4.29	2678

Canadian reinforcing bar size

Metric bar size	Mass per unit length (kg/m)	Nominal diameter (mm)	Cross-sectional area (mm²)
10 M	0.785	11.3	100
15 M	1.570	16.0	200
20 M	2.355	19.5	300
25 M	3.925	25.2	500
30 M	5.495	29.9	700
35 M	7.850	35.7	1000
45 M	11.775	43.7	1500
55 M	19.625	56.4	2500

Figure 42 — North American reinforcing bars.[16]

15 American Concrete Institute, "Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary," Farmington Hills, MI, 2011 [2].
16 http://en.wikipedia.org/wiki/Rebar

6.0 What's the back story?

This equation was modified in 2003 to include the confinement term, K_{tr}, and a strength reduction factor of 0.8 as follows:

$$\ell_d = d_b \frac{\left(\frac{f_s}{\sqrt{f'_c}} - 200\right)}{12\left(\frac{c_b + K_{tr}}{d_b}\right)} \quad \text{(lb, in.)} \qquad [6]$$

where

$$K_{tr} = \frac{A_{tr} f_{yt}}{1500 s \cdot n}$$

= contribution of confining reinforcement to increased splitting resistance, with n being the number of bars being spliced or developed along the plane of splitting (K_{tr} may be conservatively taken as zero).

The basic tension development length equation in ACI 318-11 is obtained from this expression by removing the constant (200), replacing 1/12 with 3/40, replacing f_s in Equation [6]with the nominal yield stress f_y, and taking the yield strength of the transverse reinforcement as f_{yt} = 60000 psi.

Development length for straight deformed bars in tension is given in Section 12.2.3 of ACI 318-11 as follows:

$$\ell_d = \left[\frac{3}{40}\,\frac{f_y}{\lambda\sqrt{f'_c}}\,\frac{\psi_t \psi_e \psi_s}{\frac{c_b + K_{tr}}{d_b}}\right] d_b \geq 12 \text{ in} \quad \text{(lb, in.)} \qquad [7]$$

where

K_{tr}	=	$\frac{40A_{tr}}{s \cdot n}$	whereby *s* is the bar spacing and *n* is the no. of bars being developed
ψ_t	=	1.3	for horizontal reinforcement placed with more than 12 in. of fresh concrete cast below the bars
	=	1.0	for other situations (applies to post-installed bars)
ψ_e	=	1.5	for epoxy coated bars, zinc and epoxy dual coated bars with cover less than $3d_b$, or clear spacing less than $6d_b$
	=	1.2	for all other epoxy coated bars, zinc and epoxy dual-coated bars
	=	1.0	for uncoated and zinc-coated reinforcement (applies generally to post-installed bars
ψ_s	=	0.8	for no. 6 and smaller bars
	=	1.0	for no. 7 and larger bars
$\frac{c_b + K_{tr}}{d_b}$	≤	2.5	

λ = modification factor for lightweight concrete

Note: ACI Committee 408 (Bond and Development) has issued a report on the current development length provisions in ACI 318. The report, ACI 408R-03 [1], makes specific recommendations for the improvement of the development length equation, including a reduction in the exponent on concrete compressive strength, and reconsideration of the small bar factor.

6.3 Other straight bar provisions in ACI 318-11 [2]

ACI 318-11 contains many provisions relevant for straight bar anchorage. Selected provisions are summarized here. For further information, please consult the code.

Section 12.2.5 (Excess reinforcement) permits reduction of development length in direct proportion to the amount of excess reinforcement provided over that required by analysis. This provision applies to reinforcement in flexural members "…except where anchorage or development for f_y is specifically required or the reinforcement is designed under (seismic) provisions of 21.1.1.6."

The development length requirement for straight bars in compression in Section 12.3.2 is given by:

$$\ell_d = \max\left[\left(\frac{0.02 f_y}{\lambda\sqrt{f'_c}}\,d_b\right)(0.0003\, f_y d_b);\ 8 \text{ in.}\right] \quad \text{(lb, in.)} \qquad [8]$$

Section 12.10.3 notes that reinforcement "…shall extend beyond the point at which it is no longer required to resist flexure for a distance equal to d or $12d_b$, whichever is greater, except at supports of simple spans and at free end of cantilevers."

Section 12.10.4 requires that continuing reinforcement in a flexural member be embedded for a distance "…not less than ℓ_d beyond the point where bent or terminated tension reinforcement is no longer required to resist flexure."

Section 12.10.5 prohibits the termination of flexural reinforcement in a tension zone unless either (a) the shear stress at the bar cutoff does not exceed 67% of ϕV_n, (b)

excess stirrup reinforcement is present, or (c) excess reinforcement is provided and the shear stress does not exceed 75% of ϕV_n.

Section 12.11.2 requires that positive moment reinforcement in flexural members that are "part of a primary seismic-load-resisting system" be anchored to develop f_y in tension at the face of the support.

Section 12.11.4 requires that positive moment reinforcement in deep beams be anchored to develop f_y at simple supports unless the design is carried out using the strut and tie provisions of Appendix A.

Section 12.12.1 requires that straight bars acting as negative reinforcement be anchored with development length in the supporting member.

Section 12.14.2.3 requires that bars spliced by noncontact lap splices in flexural members be spaced not more than the lesser of 1/5 the required splice length and 6 inches.

Section 12.15.1 provides requirements for Class A and Class B tension lap splices. Class A splices (ℓ_d) are permitted where at least twice the required reinforcement is provided and 1/2 or less of the total reinforcement is spliced within the required lap length. Class B splices (1.3 ℓ_d) are permitted in all other cases.

Section 12.15.3 requires that bars of different size be spliced over a length not less than ℓ_d of the larger bar or the tension lap splice length (1.3 ℓ_d) of the smaller bar.

Section 21.5.2.3 requires that hoops or spiral reinforcement is provided over the lap splice length of flexural reinforcement in special moment frames. Splices are not permitted within joints, within a distance of twice the member depth from the joint face, and "...where analysis indicates that flexural yielding is caused by inelastic lateral displacements of the frame."

Section 21.7.5.2(a) requires that the development length of #3 through #11 straight bars in tension in special moment frames be taken as follows (low lift, applicable to post-installed bars):

$$\ell_d = \frac{f_y d_b}{(26\sqrt{f'_c})} \qquad [9]$$

Section 21.7.5.3 requires that straight bars terminated at a joint pass through the confined core of a column or boundary element, and any portion of ℓ_d not within the core be increased 160%.

Section 21.9.2.3(c) stipulates that development length ℓ_d be increased by 125% "...where yielding of longitudinal reinforcement is likely to occur as a result of lateral displacements..." in special structural walls and coupling beams.

Section 21.9.6.4 (e) permits horizontal reinforcement in the wall web to be anchored to develop f_y in tension within the confined core of the boundary element provided the required area of web reinforcement does not exceed the required area of the boundary element transverse reinforcement parallel to the web reinforcement.

Section 21.11.7.3 requires that all reinforcement "used to resist collector forces, diaphragm shear, or flexural tension..." be developed or spliced for f_y in tension.

6.4 Design of post-installed reinforcing bars based on development length concepts

Figure 43 provides a comparison of the performance of post-installed and cast-in reinforcing bars from tension tests conducted at the University of Stuttgart. For small concrete cover (approx. 2 in.) the failure loads of post-installed and cast-in reinforcing bars are shown to be nearly identical, verifying that, for splitting failure, qualified post-installed reinforcing bars behave the same as cast-in-place bars. At larger concrete cover, splitting no longer controls the behavior and the bars fail by pullout. In such cases, the bond strength of a post-installed reinforcing bar may be significantly higher than that of a cast-in reinforcing bar, depending on the adhesive used.

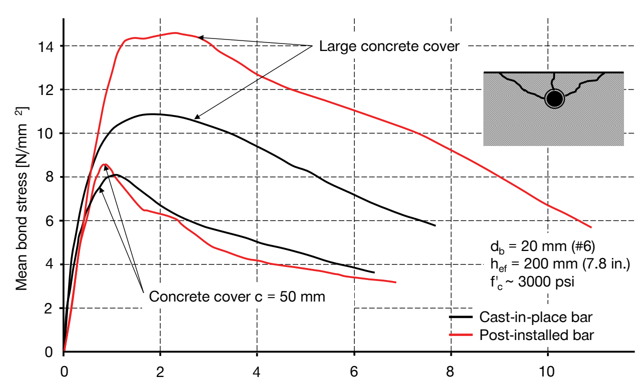


Figure 43 — Comparison of bond stresses as a function of edge distance[17].

17 Spieth, H., "Structural Behavior and Design of Bonded Reinforcing Bars," doctoral thesis, University of Stuttgart [20].

6.0 What's the back story?

In addition, the load-slip performance of post-installed reinforcing bars installed with a qualified system is similar to that of cast-in-place reinforcing bars. Thus, the design provisions for cast-in reinforcing bars in tension can be extended to qualified post-installed reinforcing bars as well.

ACI 318-11 Equation (12-1) for deformed bars in tension can be recast in terms of an equivalent bond stress equation as follows:

$$A_s f_y = \tau_{bond} \pi d_b \ell_d \qquad [10]$$

where

τ_{bond} is the equivalent bond stress

Substituting $A_s = \pi d_b^2/4$, the following expression for bond can be derived from the development length equation given in Section 12.2.3:

$$\tau_{bond} = 3.33\lambda\sqrt{f'_c}\left(\frac{c_b + K_{tr}}{d_b}\right)\left(\frac{1}{\psi_t\psi_e\psi_s}\right) \quad \text{(lb, in.)} \qquad [11]$$

For post-installed reinforcing bars, the "top bar" modification factor, ψ_t, which accounts for defects associated with concrete placement, can be taken as unity.

Note that the ACI code limits the extent to which bond stresses in the concrete may be utilized via a 2.5 cap on the value of the quotient $(c_b + K_{tr})/d_b$ in the development length equation in Section 12.2.3. Figure 44 provides a schematic representation of this limit, whereby for bars located well away from edges, it is assumed that splitting no longer controls the behavior at ultimate load. Hilti anchoring adhesives can generate bond stresses that far exceed this limit; however, strain compatibility and serviceability considerations often dictate the use of the more conservative embedments associated with the code.

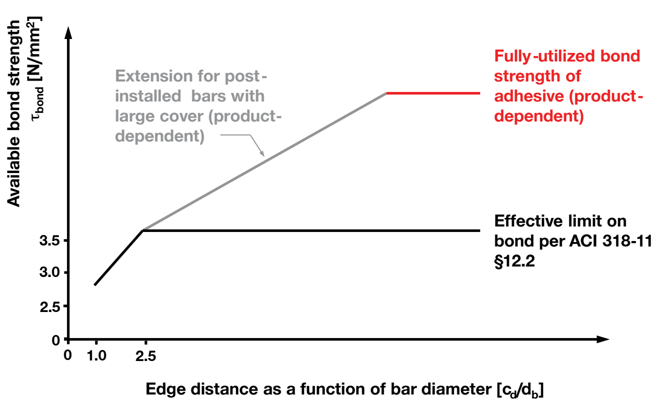


Figure 44 — Effective limit on bond stress.

Equivalent (uniform) bond stress values corresponding to development lengths determined in accordance with ACI 318-11 are shown in Figure 45:

Bar size	Concrete Compressive Strength (psi)					
	3000	4000	5000	6000	7000	8000
≤ #6	570	658	735	806	870	930
≥ # 7	456	527	589	645	697	745

Figure 45 — Equivalent bond strengths (psi) for bars developed in accordance with ACI 318-11 Section 12.2.3 in normal weight concrete with $(c_b + K_{tr})/d_b = 2.5$**.**

In the absence of confining reinforcement, the confinement term achieves the limiting value when the ratio of c_b to d_b equals 2.5. Theoretically, the development length of a reinforcing bar with cover equal to or greater than $2.5d_b$ is no longer controlled by splitting. Since practical considerations often dictate edge distances for post-installed reinforcing bars greater than $2.5d_b$, the presence of transverse reinforcement is often not a factor for determining the development length.

6.5 Alternative approaches to establishing bar embedment

The development length provisions of the ACI code are predicated on the assumption that bars may be closely spaced and may be placed at cover depth from the concrete surface.

Limited reduction in development length is afforded for bars placed at or greater than $2.5d_b$ away from edges, since it is assumed that pullout should control for these bars (as opposed to splitting). Increases in edge distance should permit further reductions in development length; however, closely spaced bars carrying higher bond stresses could lead to concrete breakout failure, a failure mode not anticipated in the development length formulation.

However, when post-installed reinforcing bars are not lapped with existing reinforcing and are installed sufficiently far from edges, it may be appropriate to employ other design approaches as described in the following sections.

6.5.1 Design of post-installed reinforcing bars using anchor design concepts[18]

The use of anchor design concepts for determining the embedment of post-installed reinforcing bars is discussed in the literature and is appropriate for systems that have also been qualified under anchor qualification provisions (e.g., ACI 355.4, AC308). The use of anchor design concepts is relatively straightforward, but appropriate assumptions are required

18 Charney, F., et al., "Recommended Procedures for Development and Splicing of Post-installed Bonded Reinforcing Bars in Concrete Structures," ACI Structural Journal [4].

with respect to the embedment. For example, is achievement of bar yield required? If so, should overstrength be applied to the nominal bar yield stress? The answers to these and other questions are situation dependent.

This approach can be subdivided into two categories:

Category 1 — Bars installed far away from edges in the face of walls, slabs, and foundations. In this case, post-installed reinforcing bars are assumed to be located sufficiently far from any edge to preclude splitting failure. Concrete breakout and bond resistances are likewise assumed to be unaffected by edge conditions.

Category 2 — Bars installed away from edges but still potentially affected by edge distance when determining the concrete breakout strength. The use of anchor design concepts is still possible in such cases, but is complicated by the edge proximity and requires iteration to find an optimal solution.

ACI 318-11 specifies that the design strength for adhesive anchors in tension be taken as the minimum value of the steel, concrete breakout and bond strengths as determined for a given bar diameter and anchorage length (embedment depth), and including the appropriate strength reduction factors. Significantly, ACI limits the uniform bond model that is the basis for the design provisions to embedment depths between 4 and 20 anchor diameters. Beyond 20 diameters, the nonlinearity of the bond stress distribution can lead to a reduction in the usable bond stress at failure that must be assessed with engineering judgment.

The nominal steel strength in tension, N_{sa}, of a single anchor element (e.g., threaded rod or reinforcing dowel) is determined per Eq. (D-2) of ACI 318-11 as the product of the tensile stress area of the anchor element and the anchor element nominal ultimate strength. ACI 318 notes that the ultimate strength is used because many anchor elements do not exhibit well-defined yield plateaus. As such, a limit of $1.9f_y$ is placed on the value of the nominal ultimate stress that can be used in Eq. (D-2) in order to avoid yielding of the anchor element at service load levels. In the case of reinforcing bars, the nominal yield strength is not generally well controlled. Generally speaking, yield strengths may exceed specified values by 25%. ASTM A706 Grade 60 bars are controlled such that the actual tested yield cannot exceed 78 ksi, and the tested ultimate cannot be less than 125% of the actual yield.[19]

In accordance with ACI 318-11 D.5.2.1, the nominal concrete breakout strength in tension of headed anchors is obtained as follows:

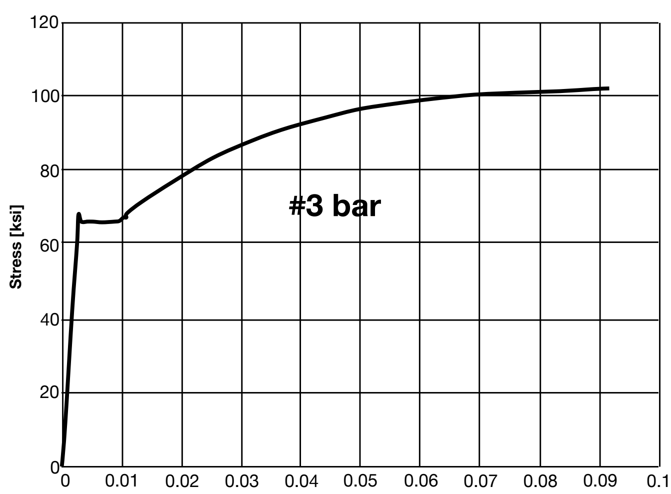
$$N_{cbg} = \frac{A_{Nc}}{A_{Nco}} \Psi_{ed,N}\Psi_{ec,N}\Psi_{c,N}\Psi_{cp,N} \left[k_c \lambda_a \sqrt{f'_c}\,(h_{ef})^{1.5}\right] \quad \text{(lb, in.)} \qquad [12]$$

where

A_{Nco} $9(h_{ef})^2$

A_{Nc} Projected area of theoretical breakout body based on critical anchor spacing of $3h_{ef}$ and anchor edge distance of $1.5h_{ef}$

$\Psi_{ed,N}$ Factor that accounts for near-edge anchors that reflects the disturbed stress state caused by the presence of an edge



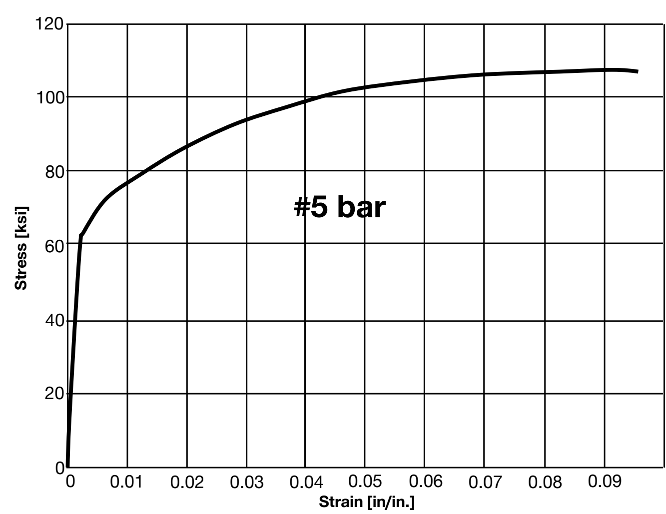


Figure 46 — Stress strain curves for #3 and #5 ASTM A706 Gr. 60 reinforcing bars.[20]

19 ASTM Standard A706/A706M, 2014, "Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement," ASTM International, West Conshohocken, PA, 2003, DOI: 10.1520/A0706_A0706M, www.astm.org.

20 Publication No. FHWA-HIF-13-038, "Laboratory Tests of Column-to-Drilled Shaft Socket Connections," Federal Highway Administration, June 2013, p. 11.

6.0 What's the back story?

$\psi_{ec,N}$ Factor to account for eccentrically-loaded groups

$\psi_{c,N}$ Increase factor that accounts for uncracked concrete

$\psi_{cp,N}$ Factor to account for splitting hoop stresses

λ_a Lightweight concrete adjustment factor

k_c Efficiency factor for concrete breakout (characteristic value, cracked concrete); for adhesive anchors, this value is determined by testing in accordance with ACI 355.4.

h_{ef} Effective embedment depth

Similarly, in accordance with ACI 318-11 D.5.5.1, the characteristic bond strength, N_{ag}, of adhesive anchors in cracked concrete is determined as follows:

$$N_{ag} = \frac{A_{Na}}{A_{Nao}} \psi_{ed,Na}\psi_{ec,Na}\psi_{cp,Na} \left[\tau_{cr}\, \lambda_a\, \pi\, d_a\, h_{ef}\right] \quad \text{(lb, in.)} \qquad [13]$$

where

A_{Nca} $= (2c_{Na})^2$

A_{Na} Projected influence area based on critical anchor edge distance, c_{Na}

c_{Na} $= 10d_a\sqrt{\frac{\tau_{uncr}}{1100}}$ (lb, in.)

τ_{cr} Characteristic bond stress in cracked concrete per evaluation in accordance with ACI 355.4

τ_{uncr} Characteristic bond stress in uncracked concrete per evaluation in accordance with ACI 355.4

d_a Diameter of anchor element (threaded rod, reinforcing bar)

Other terms are analogous to the expression for concrete breakout.

Strength reduction factors (ϕ) given in D.4 are applied to the nominal steel, concrete breakout, and bond strengths, and the minimum value is compared to the factored design load N_{ua}. Additional design checks are made in accordance with Section D.4.1.2 for adhesive anchors subjected to sustained tension loads. Where anchors are used in structures assigned to Seismic Design Categories C, D, E or F, additional requirements in accordance with D.3.3 are placed on the anchor behavior.

According to ACI 318-11 R12.2, splitting governs the behavior of reinforcing bars placed at minimum cover with no transverse or other confining reinforcement. Bars placed with increased cover and/or provided with transverse reinforcing are governed by pullout failure, but, it is noted, "... an increase in cover or transverse reinforcement (beyond that assumed to ensure pullout behavior) is unlikely to increase the anchorage capacity." Note that in no case is concrete breakout anticipated, regardless of the density of bars placed in a specific volume of concrete. This assumption is likely predicated on the relatively low bond stresses associated with the development length equation (see Figure 45). For post-installed reinforcing bars designed in accordance with anchor theory, however, the full tested bond strength of the adhesive is utilized and as such evaluation of both the bond and breakout capacities in accordance with ACI 318 is required.

Post-installed reinforcing bars can be designed by recasting the concrete breakout and bond strength expressions in ACI 318 into development length equations; that is, by equating the strength associated with concrete failure or bond failure with the yield strength of the embedded bar and solving for the embedment. This may be particularly useful where cover (edge distance) is large but embedment depth is limited, such as the development of bars into the face of a wall.

Note: For additional information on this approach, see Charney, et al., "Recommended Procedures for Development and Splicing of Post-installed Bonded Reinforcing Bars in Concrete Structures," ACI Structural Journal, Vol. 110, No. 3, May-June 2013 [4].

Per Charney et al., when a single post-installed reinforcing bar is installed in normal weight concrete away from edges such that the concrete break out strength is not affected by edge distance, the concrete breakout-associated embedment required to achieve yield in the embedded reinforcing bar may be expressed as:

$$\ell_{d,breakout} = 1.2\left(\frac{A_b f_y}{k_c\sqrt{f'_c}}\right)^{2/3} \quad \text{(lb, in.)} \qquad [14]$$

Similarly, when a single post-installed reinforcing bar is installed away from any edges, the bond-controlled embedment required to achieve yield in the embedded reinforcing bar can be expressed as:

$$\ell_{d,bond} = \frac{0.3 d_b f_y}{\tau_{cr}} \quad \text{(lb, in.)} \qquad [15]$$

The design development length for this particular case may be taken as the greater of and , $\ell_{d,breakout}$ and $\ell_{d,bond}$, i.e.,

$$\ell_d = max \,|\, \ell_{d,breakout} \,;\, \ell_{d,bond} \,| \quad \text{(in.)} \qquad [16]$$

The particular assumptions used for the application of anchor theory to bar development (e.g., bar yield and bond strength values) are a matter of engineering judgment and will in part depend on the specific circumstances of the design. For groups of bars and for bars near edges, this approach obviously becomes more complex, but can be solved by inclusion of the necessary edge distance and spacing adjustments in ACI 318-11 Appendix D.

Note: ACI 318-11 D.4.2.3 states: "For adhesive anchors with embedment depths $4d_a \le h_{ef} \le 20d_a$, the bond strength requirements shall be considered satisfied by the design procedure of D.5.5." This requirement recognizes the limits of the uniform bond model adopted by ACI. In some cases it may be justifiable to specify embedment in excess of 20 bar diameters in order to ensure the desired margin of safety. Contact Hilti for further information.

Example: Shear dowels (compare with example provided in 2.6.1)

Requirement: Determine the embedment requirement for post-installed reinforcing bars used to connect a new 10-inch thick shotcrete (pneumatically-placed) shear wall to an existing concrete wall (9). Bars are #5 at 24 in. x 24 in. over face of wall. Existing shear wall is 12 in. thick with 4 ksi normal weight concrete. Based on an assessment in accordance with AC308, the bond strength, τ_{cr}, of the adhesive is 1090 psi and the k_c value is 17. The bond strength of the adhesive in uncracked concrete, τ_{uncr}, is 1560 psi.

Assume spacing is sufficient to use simplified expressions for development of bars based on application of anchor theory in accordance with Charney, et al.

$$\ell_{d,breakout} = 1.2\left(\frac{0.31 \times 60000}{17\sqrt{4000}}\right)^{2/3} = 8 \text{ in.}$$

$$\ell_{d,bond} = \frac{0.3 \times 0.625 \times 60000}{1090} = 10.3 \text{ in.}$$

Check spacing assumption for concrete breakout:
$3 \times 8 = 24$ in. ≤ 24 in. $\therefore$ ok

Check spacing assumption for bond failure:

$$2c_{Na} = 20 \times 0.625\sqrt{\frac{1560}{1100}} = 15 \text{ in.} \le 24 \text{ in.} \therefore \text{ok}$$

Use #5 hooked dowels embedded 10-1/2 inches = 16.8 bar diameters < 20 (limit of uniform bond model per ACI 318-11 D.4.2.3).

6.5.2 Use of confinement to increase bond efficiency

As shown in Figure 45, the bond stresses associated with typical development lengths are low relative to the bond strengths that can be achieved with post-installed adhesives (compare, e.g., with Figure 39). The term associated with confinement in Equation (12-2) of ACI 318-11 is

$$\frac{c_b + \left(\frac{40 A_{tr}}{s \cdot n}\right)}{d_b} \le 2.5 \qquad \text{(lb, in.)} \qquad [17]$$

where

c_b a factor to represent the smallest of the side cover, the cover over the bar as measured to the bar centerline, or one-half the center-to-center spacing of the bars (in.)

A_{tr} area of transverse reinforcement effective to prevent splitting (in^2)

s spacing of transverse bars (in.)

n no. of bars being spliced or developed along the line of splitting (in.)

The limit of 2.5 placed by Section 12.2.3 on the confinement term reflects the relatively conservative assumption regarding the effectiveness of confinement in suppressing splitting and pullout failures. Research sponsored by Hilti [17] indicates that, for specific adhesives, the limit on this term can be increased by nearly 100%, to 4.5. The particular conditions under which this adjustment can be made are given in the literature. In addition, testing of laterally loaded columns anchored with post-installed bars has demonstrated that the confinement effect provided by the compression toe of the column can effectively be used to reduce the required development length for these cases [12].

6.5.3 Strut-and-tie models

ACI 318-11 Appendix A provides procedures for the development of strut-and-tie models to design reinforced concrete structures or members that contain D-regions (an area around a force or geometric discontinuity). This approach is particularly suitable for the design of post-installed reinforcing bars where the bar is installed perpendicular to the primary reinforcement in the existing concrete member. The structure is divided into B- and D-regions. B-regions are parts of a structure in which Bernoulli's hypothesis of straight-line strain profiles applies. The internal stress state of B-regions

6.0 What's the back story?

can be easily derived from the sectional forces and the region can be designed on the basis of classical beam theory.

D-regions are parts of a structure with a complex variation in strain. They include portions near abrupt changes in geometry (geometrical discontinuities) or concentrated forces (statistical discontinuities). D-regions are assumed to extend a distance *h* from the force or geometric discontinuity (see Figure 47).

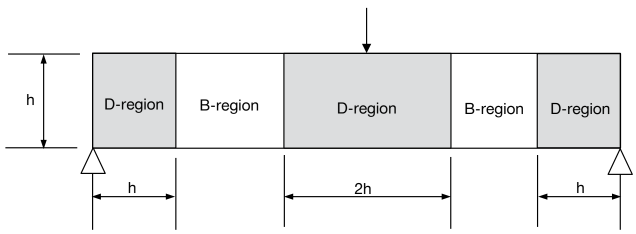


Figure 47 — Idealized D- and B-regions in a concrete beam.

The design of D-regions is complex and requires a clear understanding of force flow. In strut-and-tie modelling, the complex state of internal forces is idealized as a truss. The compression (struts) and tension (ties) members are identified in the region. The points of equilibrium where struts, ties, and concentrated forces intersect are denoted as nodes (Figure 48).

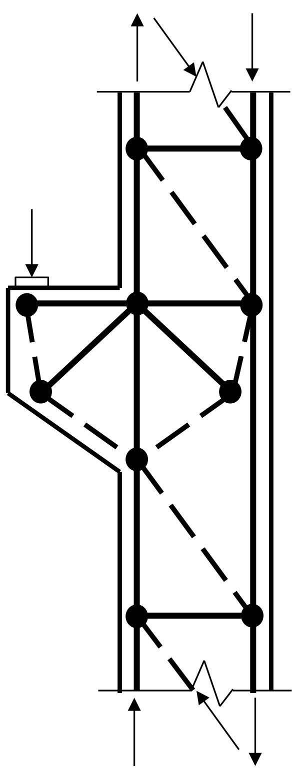


Figure 48 — Strut-and-tie model of a corbel.

Nodes are represented by extended nodal zones, which are in turn classified according to the sense and orientation of intersecting the ties and struts (Figure 49). The proper modeling and assessment of extended nodal zones requires a thorough understanding of the limits of the strut-and-tie model approach.

Most post-installed reinforcing bar problems can be expressed with some variant of a C-C-T node, as shown in Figure 50.

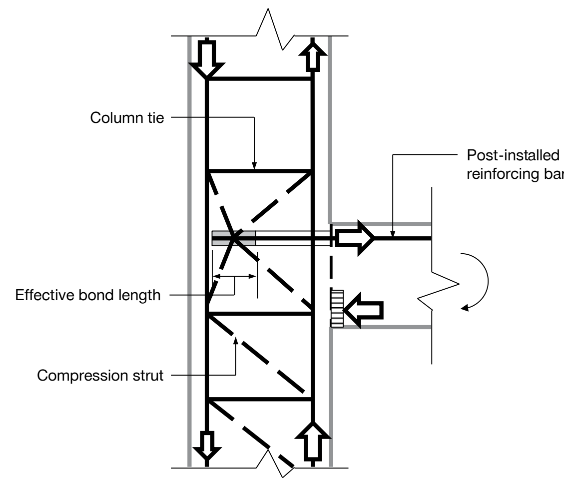


Figure 49 — Strut-and-tie model for a post-installed reinforcing bar connection.

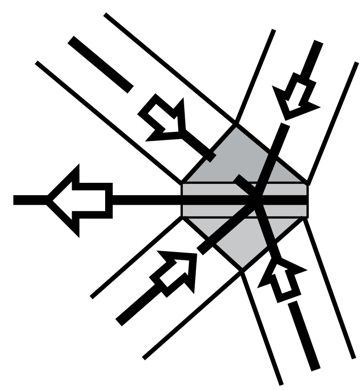


Figure 50 — Extended nodal zone.

Note: A detailed description of strut-and-tie modeling of a post-installed reinforcing bar connection in a column-foundation joint subject to overturning moment is provided in Hamad, B., et al., "Evaluation of Bond Strength of Bonded-In or Post-Installed Reinforcement," ACI Structural Journal V. 103, No. 2, pp. 207-218 [8]. Additional experimental verification of this connection is described in Kupfer, et al. [11].

Example: Column starter bars (compare with example provided in 2.6.4)

Requirement: Establish the embedment requirement for post-installed starter bars for a new column to be cast on an existing grade beam 15-in. wide by 30-in. deep with 4 ksi concrete and A615 Gr. 60 reinforcing. The new column is 15 x 15-inch square with ASTM A615 Gr. 60 #7 column bars (see Figure 17). The column must resist moment and shear arising from wind loading.

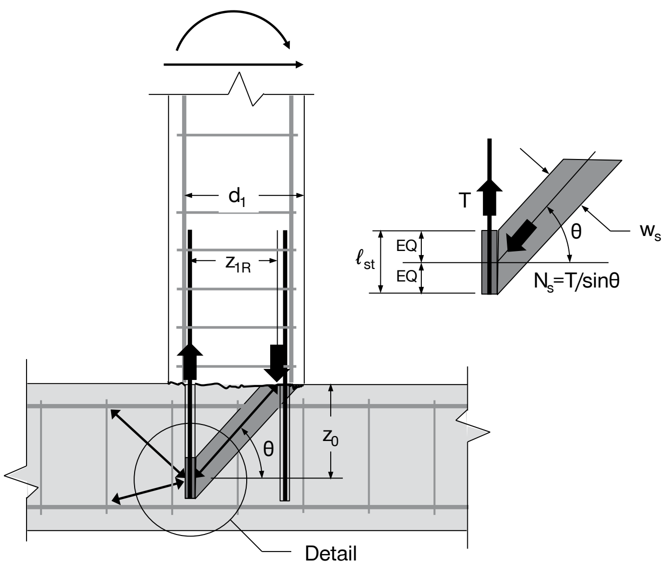


Figure 51 — Strut-and-tie model for column to grade beam connection.

Determine the bond length based on the geometry of the compression strut required to develop the bar (see Figure 51):

$$N_s = \frac{T}{sin\theta}$$

$T = \phi \cdot A_s \cdot f_y = 0.9 \times 2 \times 0.60 \times 60000 = 64800$ lb

$f_{ce} = 0.85 \times \beta_s \times f'_c = 0.85 \times 0.6 \times 4000 = 2040$ psi
ACI 318-11 Section A.3.2

$\phi_c = 0.65$

Assume a strut angle θ of 60 degrees:

$$w_s = \frac{N_s}{t \times \phi_c \times f_{ce}} = \frac{64800}{15 \times 0.65 \times 2040 \times sin60^0} = 3.8$$

$$\ell_{st} = \frac{W_s}{cos60^0} = 7.5 \text{ in.}$$

$$\ell_d = Z_0 + \frac{\ell_{st}}{2} = Z_{1R} \times tan\theta + \frac{\ell_{st}}{2} \approx 12 \times tan60 + \frac{7.5}{2} = 25 \text{ in.}$$

Note: Additional checks for the adequacy of the model may be required. For further information, see Hamad, B., et al. "Evaluation of Bond Strength of Bonded-In or Post-Installed Reinforcement," ACI Structural Journal V. 103, No. 2, pp. 207-218 [8].

6.6 Design of shear dowels

According to shear friction theory as adopted by ACI 318, reinforcing bars that cross a shear plane serve to clamp the two faces of the shear interface together, enabling shear transfer through friction acting over the interface surface area. Although often referred to as dowels, the reinforcing bars that cross the shear interface are not assumed to resist shear forces through dowel action; shear friction presumes that the reinforcing acts in tension only.

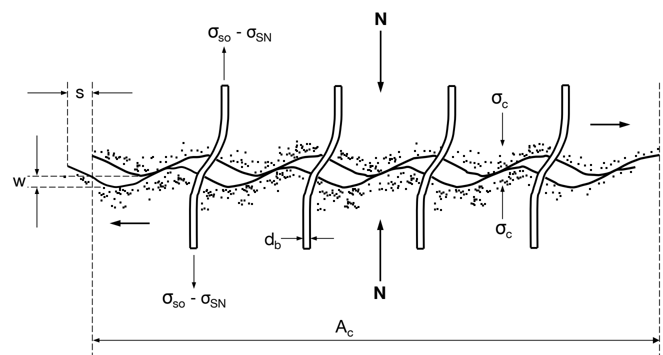


Figure 52 — The main mechanisms of shear transfer along a reinforced concrete interface: dowel action and aggregate interlock, from [21].

However, recent work by Palieraki, et al. [16] has demonstrated that the static and cyclic strengths of the shear friction interface can accurately be described as the sum of friction and dowel action mechanisms. This approach also permits the determination of shear force transfer for reduced dowel embedment depths.

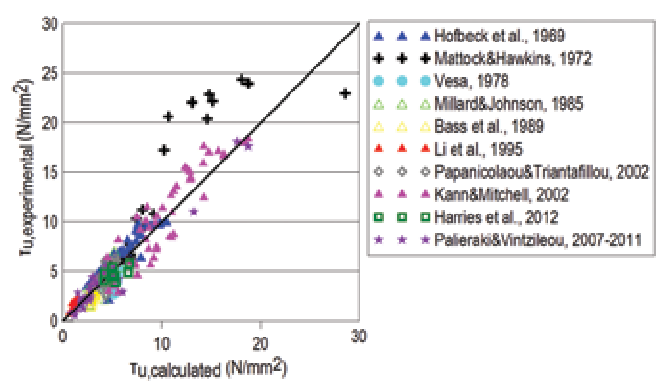


Figure 53 — Prediction of static interface shear plotted against test results.

6.0 What's the back story?

The following formulation of the interface shear design method proposed by Palieraki [14] is a simplification based on conservative assumptions. It consists of the summation of friction and dowel action effects (see Eq. (18)) with modification terms that account for surface roughness, reinforcing quantity and grade, reinforcing embedment and bond strength, and loading type (i.e., static vs. cyclic). As shown in Figure 53, the approach proposed by Palieraki provides excellent agreement with an extensive database of test results.

$$V_n = A_c\,(\beta_f \cdot \tau_f + \beta_d \cdot \tau_d) \qquad [18]$$

where

V_n = nominal interface shear strength (lb.)

τ_f = nominal interface shear contribution from friction (lb./in^2)

τ_d = nominal interface shear contribution from dowel action (lb./in^2)

β_f = contribution factor for friction

β_d = contribution factor for dowel action

A_c = surface area of interface (in^2)

Friction:

$$\tau_f = 0.33\,[\,(f'_c)^2 \cdot (f_{c,vf} + f_{ext})\,]^{1/3} \qquad \text{(lb., in.)} \qquad [19]$$

where

$f_{c,vf}$ = compression stress over interface due to action of dowel reinforcement

$= \dfrac{f_y \cdot A_{vf}}{A_c}$ for fully embedded dowels (i.e., dowels embedded ℓ_d (lb., in.)

$= \dfrac{5 \cdot f_{bu} \cdot \ell_e \cdot A_{vf}}{d_b \cdot A_c}$ for dowels embedded less than ℓ_e (lb., in.)

f_{ext} = uniform stress over interface due to externally applied normal force (positive for compression, negative for tension) (lb./in^2)

f_{bu} = bond strength associated with the post-installed bar (lb./in^2)

ℓ_e = embedment length of the dowel (in.)

A_{vf} = area of interface dowel reinforcement (in^2)

f_y = yield stress of interface dowel reinforcement (lb./in^2)

f'_c = concrete uniaxial compressive strength (lb./in^2)

Dowel action:

$$\tau_d = \frac{1.3 \cdot n \cdot d_b^2\,\sqrt{f'_c \cdot f_y}}{A_c} \qquad \text{(lb, in.)} \qquad [20]$$

where

d_b = diameter of interface dowel reinforcement (in.)

n = number of dowels crossing interface

A_c = area of interface transected by n dowels (in^2)

The contribution factors have been experimentally established as follows:

Friction contribution factor, β_f, for non-cyclic shear loading across the interface:

Surface roughness	β_f
shear keys, or where $f_{ext} \geq +0.1\,f'_c$	0.8
mechanically roughened (1/4-in. amplitude)	0.6
not roughened	0.4
not roughened, steel formed surface (very smooth)	0.2

Friction contribution factor, β_f, for cyclic (seismic) shear loading across the interface = 0.2.

Dowel action contribution factor, β_d, for non-cyclic shear loading across the interface:

Dowel embedment	β_d
$\ell_e > 8d_b$	0.75
$\ell_e \leq 8d_b$	0.5

For cyclic shear, use $\ell_e \geq 12d_b$ and $\beta_d = 0.75$.

Example: Shear dowels (compare with examples provided in 2.6.1 and 6.5.1)

Requirement: Determine the embedment requirement for post-installed reinforcing bars used to connect a new 8-inch thick shotcrete (pneumatically-placed) shear wall to an existing concrete wall (Figure 9). Bars are #5 at 12 in. x 16 in. over face of wall. Existing shear wall is 10 in. thick with 4 ksi normal weight concrete. Try dowels embedded the minimum of 12 diameters (cyclic shear).

v_u = 9 ksf = 63 lb. / in^2

A_c = 12 · 16 = 192 in^2

f_{bu} = 1090 lb. / in^2 (characteristic bond strength in cracked concrete per ACI 355.4)

$$V_n = A_c\,(\beta_f \cdot \tau_f + \beta_d \cdot \tau_d)$$

6.0 What's the back story?

$$f_{c,vf} = \frac{5 \cdot f_{bu} \cdot \ell_e \cdot A_{vf}}{d_b \cdot A_c} = \frac{5 \cdot 1090 \cdot 12\,(0.625) \cdot 0.31}{0.625 \cdot 192} = 106 \text{ lb.} / \text{in}^2$$

$f_{ext} = 0$

$\tau_f = 0.33\,[(f'_c)^2 \cdot (f_{c,vf} + f_{ext})]^{1/3} = 0.33\,[(4000)^2 \cdot (106 + 0)]^{1/3} = 394 \text{ lb.} / \text{in}^2$

$$\tau_d = \frac{1.3 \cdot n \cdot d_b^2 \sqrt{f'_c \cdot f_y}}{A_c} = \frac{1.3 \cdot 1 \cdot (0.625)^2 \sqrt{4000 \cdot 60000}}{192} = 41 \text{ lb.} / \text{in}^2$$

$V_n = A_c\,(\beta_f \cdot \tau_f + \beta_d \cdot \tau_d) = 192\,(0.2 \cdot 394 + 0.75 \cdot 41) = 21030 \text{ lb.}$

$$\phi v_n = \frac{0.75 \cdot 21030}{192} = 82 \text{ lb.} / \text{in}^2 > 63 \;\therefore\; \text{ok}$$

Use #5 hooked dowels embedded 7-1/2 inches ($12d_b$).

7.0 What else do I need to know?

7.1 Sustained loads, etc.

Sustained tension loading of adhesive anchors has been associated with excessive creep in certain anchor applications. For post-installed reinforcing bar applications, judgment is required to determine whether additional precautions for sustained tension load applications may be required. For specific cases, e.g., where a small number of bars are subjected to direct tension as a result of dead loads, use of the reduced bond stress check required by ACI 318-11 Section D.4.1.2 may be appropriate. Additionally, reductions on bond strength for concrete temperature, presence of water (e.g., saturated concrete), and installation in lightweight concrete should be adopted as appropriate.

7.2 Fatigue

High-cycle fatigue loading is not specifically addressed in the qualification requirements contained in AC308. Where high-cycle fatigue loading is relevant for a connection to be performed with post-installed reinforcing bars, contact Hilti technical staff for additional guidance.

7.3 Fire

Organic adhesives are affected by high temperatures. For post-installed reinforcing bar connections that are part of a fire-rated assembly (floor, roof, etc.) it is important that the fire resistance of the connection be evaluated using test data for the time-dependent reduction in bond strength associated with typical geometries and time-temperature loading protocols. Contact Hilti technical staff for additional guidance on this topic.

7.4 Corrosion

Concrete is a naturally alkaline material and under normal conditions corrosion of embedded reinforcing is prevented by passivation of the bar surface. However, when concrete undergoes carbonation, the decreased pH can lead to incipient corrosion. Furthermore, faster corrosion rates (pitting corrosion) are observed if the concrete is contaminated with chlorides.

The qualification of adhesive systems for post-installed reinforcing bar applications includes a specific test for the susceptibility of the system to long-term bar corrosion. Bars installed with qualified systems should exhibit similar corrosion rates to cast-in-place bars in the same concrete. It is important that the adhesive surrounding the bar be relatively void-free to minimize corrosion. Therefore, installation quality is important for corrosion resistance as well as for high bond strength. Contact Hilti technical staff for additional guidance on this topic.

8.0 Useful reference information

8.1 ASTM standard reinforcing bars

Bar size	Bar properties [1]	Installation parameters [2]				
	Nominal diameter [in]	Nominal area [in²]	Nominal weight [lb/ft]	Bit diameter [3] [in]	Adhesive volume per inch of embedment [4]	
					[cu in]	[fl oz]
#3	0.375	0.11	0.376	1/2	0.110	0.061
#4	0.500	0.20	0.668	5/8	0.146	0.081
#5	0.625	0.31	1.043	3/4	0.176	0.098
#6	0.750	0.44	1.502	7/8	0.218	0.121
#7	0.875	0.60	2.044	1	0.252	0.140
#8	1.000	0.79	2.670	1-1/8	0.299	0.166
#9	1.128	1.00	3.400	1-3/8	0.601	0.333
#10	1.270	1.27	4.303	1-1/2	0.659	0.365

1 Source: ACI 318-11 Appendix E.
2 See Hilti Product Technical Guide for further information.
3 Values shown are typical. Refer to Hilti Instructions for Use.
4 Waste not included.

8.2 Canadian reinforcing bars

Bar size	Bar properties [1]	Installation parameters [2]				
	Nominal diameter [mm]	Nominal area [mm²]	Nominal weight [kg/m]	Bit diameter [3] [mm]	Adhesive volume per mm of embedment [4]	
					[mm]	[mL]
10M	11.3	100	0.785	14	86.4	0.0864
15M	16.0	200	1.570	19	121.8	0.1218
20M	19.5	300	2.355	26	296.2	0.2962
25M	25.2	500	3.925	32	418.0	0.4180
30M	29.9	700	5.495	38	630.7	0.6307

1 Source: CSA G30.18 M92.
2 See Hilti Product Technical Guide for further information.
3 Refer to Hilti Instructions for Use.
4 Waste not included.

8.3 Common grades of reinforcing steel

Specification		Minimum specified yield strength, f_{ya}	Minimum specified ultimate strength, f_{uta}
ASTM A615 Grade 40	psi	40,000	60,000
	(MPa)	(276)	(414)
ASTM A615 Grade 60	psi	60,000	90,000
	(MPa)	(414)	(620)
ASTM A706 Grade 60	psi	60,000	80,000
	(MPa)	(414)	(550)
CAN/CSA-G30.18 Gr. 400	psi	400	540
	(MPa)	(78,300)	(58,000)

8.0 Useful reference information

8.4 Calculated tension development and lap splice lengths for Grade 60 reinforcing bars in walls, slabs and footings per ACI 318-11 with $(c_b+K_{tr})/d_b \geq 2.5$ [in] [1,2,3,4]

Bar size	System [5]			Concrete compressive strength [psi] [6]							
				2500		3000		4000		6000	
	HIT RE 500 V3	HIT-HY 200-A	HIT-HY 200-R	ℓ_d	1.3 ℓ_d	ℓ_d	1.3 ℓ_d	ℓ_d	1.3 ℓ_d	ℓ_d	1.3 ℓ_d
#3	●	◐	◐	12	14	12	13	12	12	12	12
#4	●	◐	◐	14	19	13	17	12	15	12	12
#5	●	◐	◐	18	23	16	21	14	18	12	15
#6	●	■	◐	22	28	20	26	17	22	14	18
#7	●	■	◐	32	41	29	37	25	32	20	26
#8	●	■	◐	36	47	33	43	28	37	23	30
#9	●	■	◐	41	53	37	48	32	42	26	34
#10	●	■	◐	46	59	42	54	36	47	30	38

◐ See Hilti Instructions for Use (IFU) for recommended application range.
● Suitable for all tabulated embedments.
■ Not recommended.

1 Values calculated for $(c_b+K_{tr})/d_b \geq 2.5$. See ACI 318-11 §12.2.2.
2 ψ_t = 1.0 after Charney, F., et al., "Recommended Procedures for Development and Splicing of Post-installed Bonded Reinforcing Bars in Concrete Structures," ACI Structural Journal [4]. See ACI 318-11 §12.2.4 (a).
3 ψ_e = 1.0 for non-epoxy coated bars. See ACI 318-11 §12.2.4 (b).
4 ψ_s = 0.8 for #6 bars and smaller bars, 1.0 for #7 and larger bars. See ACI 318-11 §12.2.4 (c).
5 Applicable for hammer-drilled holes. For rock-drilled and core-drilled holes, contact Hilti.
6 Values are for normal weight concrete. For sand-lightweight concrete, multiply by 1.18, for all-lightweight concrete multiply by 1.33. See ACI 318-11 §8.6.

8.5 Calculated tension development and lap splice lengths for Canadian 400 MPa reinforcing bars in walls, slabs and footings per CSA A23.3-14 with $(d_{cs}+K_{tr}) \geq 2.5d_b$ [mm] [1,2,3,4]

Bar size	System [5]			Concrete compressive strength [psi] [6]							
				2500		3000		4000		6000	
	HIT RE 500 V3	HIT-HY 200-A	HIT-HY 200-R	ℓ_d	1.3 ℓ_d	ℓ_d	1.3 ℓ_d	ℓ_d	1.3 ℓ_d	ℓ_d	1.3 ℓ_d
10M	●	◐	◐	300	380	300	340	300	310	300	300
15M	●	◐	◐	410	540	370	480	340	440	300	380
20M	●	◐	◐	510	660	450	590	410	540	360	460
25M	●	■	◐	820	1,060	730	950	670	870	580	750
30M	●	■	◐	960	1,250	860	1,120	790	1,020	680	890

◐ See Hilti Instructions for Use (IFU) for recommended application range.
● Suitable for all tabulated embedments.
■ Not recommended.

1 Values calculated for $(d_{cs}+K_{tr}) \geq 2.5$ db. See CSA A23.3-14 §12.2.2.
2 K_1 = 1.0 after Charney, F., et al., "Recommended Procedures for Development and Splicing of Post-installed Bonded Reinforcing Bars in Concrete Structures," ACI Structural Journal [4]. See CSA A23.3-14 §12.2.4 (a).
3 K_2 = 1.0 for non-epoxy coated bars. CSA A23.3-14 §12.2.4 (b).
4 K_4 = 0.8 for 20M and smaller bars, 1.0 for 25M and larger bars. CSA A23.3-14 §12.2.4 (d).
5 Applicable for hammer-drilled holes. For rock-drilled and core-drilled holes, contact Hilti.
6 Values are for normal weight concrete. For sand-lightweight concrete, multiply by 1.2, for all-lightweight concrete multiply by 1.3. See CSA A23.3-14 §12.2.4 (c).

9.0 References and suggestions for further reading

[1] ACI (2003). "Committee 408: Bond and Development of Straight Reinforcing Bars in Tension (ACI 408R-03)." ACI Manual of Concrete Practice, American Concrete Institute, Farmington Hills, MI.

[2] ACI (2011). "Committee 318: Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary," American Concrete Institute, Farmington Hills, MI.

[3] Appl, J. (2008). "Tragverhalten von Verbunddübeln unter Zugbelastung," (Structural Behavior of Bonded Anchors under Tensile Load), doctoral thesis, University of Stuttgart (in German).

[4] Charney, F., Pal, K., and Silva, J. (2013). "Recommended Procedures for Development and Splicing of Post-installed Bonded Reinforcing Bars in Concrete Structures," ACI Structural Journal, Vol. 110, No. 3, pp. 437-447.

[5] Cook, R., Douglas, E., and Davis, T. (2009). "NCHRP Report 639: Adhesive Anchors in Concrete under Sustained Loading Conditions," Transportation Research Board of the National Academies, Washington, D.C., 139 pp.

[6] Eligehausen, R., Mallée, R., and Silva., J. (2006). Anchorage in Concrete Construction, Ernst & Sohn (A Wiley Company), Berlin, pp. 181-210.

[7] EOTA (2006). "TR023: Assessment of Post-Installed Reinforcing Bar Connections," ETA-Technical Report, European Organization for Technical Approvals, 20 pp.

[8] Hamad, B., Hammoud, R., and Kunz, J. (2006). "Evaluation of Bond Strength of Bonded-In or Post-Installed Reinforcement," ACI Structural Journal V. 103, No. 2, pp. 207-218.

[9] ICC-ES (2013). "AC308: Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements - approved June 2013," ICC Evaluation Service, LLC, Brea, CA, 122 pp.

[10] Kunz, J. (2005). "Splitting Design for Anchorages and Splices with Post-Installed Reinforcement," Proceedings, ICF XI - 11th International Conference on Fracture.

[11] Kupfer, H., Münger, F., Kunz, J., and Jähring, A. (2003). "Nachträglich Verankerte Gerade Bewehrungsstäbe bei Rahmenknoten," (Post-installed Straight Reinforcing Bars in Frame Joints), Bauingenieur, Band 78, 15 pp. (in German).

[12] Mahrenholtz, C. and Eligehausen, R. (2014). "Numerical Simulation of Column-to-Foundation Connections with Reduced Anchorage Lengths Loaded Monotonically and Cyclically," Proceedings of the Tenth U.S. National Conference on Earthquake Engineering, Earthquake Engineering Research Institute, Anchorage, AK.

[13] Orangun, C., Jirsa, J., and Breen, J. (1975). "The Strength of Anchored Bars: A Re-evaluation of Test Data on Development Length and Splices," Center for Highway Research, University of Texas, Austin, TX, 94 pp.

[14] Palieraki, V. (2014). "Seismic behavior of reinforced interfaces in repaired/strengthened reinforced concrete elements," doctoral thesis, National Technical University of Athens, Greece, 578 pp. (in Greek).

[15] Palieraki, V., Vintzileou, E., Silva, J. (2013). Discussion 109-S73/from the November-December 2012 ACI Structural Journal paper "Towards an Improved Understanding of Shear-Friction Behavior," ACI Structural Journal Sept.-Oct. 2013, pp. 887-888.

[16] Palieraki, V., Vintzileou, E., Trezos, K. (2014). "Shear Transfer Along Interfaces: Constitutive Laws," Proceedings of the 2nd European Conference on Earthquake Engineering and Seismology, Istanbul, Turkey (electronic source).

[17] Randl, N. and Kunz, J. (2012). "Concrete Splitting for Rebars Post-Installed with High Bond Adhesives," Proceedings of the 4th International Symposium on Bond in Concrete, Cairns, J., et al., eds., Manerbio, Brescia, Italy, pp. 521-526.

[18] Simons, I. (2007). "Verbundverhalten von Bewehrungsstahl Stäbe unter Zyklischer Belastung," (Bond Behavior of Reinforcing bar Rods under Cyclic Loading), doctoral thesis, University of Stuttgart (in German).

[19] Speith, H., Ozbolt, J., Eligehausen, R., and Appl, J. (2001). "Numerical and Experimental Analysis of Post-Installed Reinforcing Bars Spliced with Cast-In-Place Reinforcing Bars," Proceedings, International Symposium on Connections between Steel and Concrete, RILEM Publications, Stuttgart, pp. 889-898.

[20] Spieth, H. (2002). "Tragverhalten und Bemessung von Eingemörtelten Bewehrungsstäben," (Structural Behavior and Design of Bonded Reinforcing Bars), doctoral thesis, University of Stuttgart (in German).

[21] Tassios, T.P. and Vassilopoulou, I. (2003). "Shear transfer capacity along a RC crack, under cyclic sliding," Proceedings of fib Symposium "Concrete Structures in Seismic Regions", (electronic source, 12pp.), Athens.