5.51 ANCHORAGE TO CONCRETE: CAST-IN ANCHORS

5.51.1 GENERAL

This BDM provides practical aids for the design of anchorage to concrete using cast-in (CI) anchors, based on ACI 318-14, Chapter 17, Anchoring to Concrete [1]. Simplified and conservative design tables for hex headed bolts are provided within this BDM, subject to the stated limitations.

The cast-in anchors are used to transmit structure loads by tension, shear, or a combination of both, between connected structural elements or safety-related attachments and structural elements.

5.51.2 DEFINITIONS

anchor—steel element either cast into concrete or post-installed into a hardened concrete member and used to transmit applied loads to the concrete.

anchor, cast-in—a headed bolt, headed stud, or hooked bolt installed before placing concrete.

anchor group—a number of similar anchors having approximately equal effective embedment depths with spacing s between adjacent anchors such that the projected areas overlap.

anchor pullout strength—the strength corresponding to the anchoring device or a major component of the device sliding out from the concrete without breaking out a substantial portion of the surrounding concrete.

breakout strength, concrete—strength corresponding to a volume of concrete surrounding the anchor or group of anchors separating from the member.

effective embedment depth—overall depth through which the anchor transfers force to or from the surrounding concrete; effective embedment depth will normally be the depth of the concrete failure surface in tension applications; for cast-in headed anchor bolts and headed studs, the effective embedment depth is measured from the bearing contact surface of the head.

edge distance—distance from the edge of the concrete surface to the center of the nearest anchor.

headed bolt—cast-in steel anchor that develops its tensile strength from the mechanical interlock provided by either a head or nut at the embedded end of the anchor.

headed stud—a steel anchor conforming to the requirements of AWS D1.1 and affixed to a plate or similar steel attachment by the stud arc welding process before casting; also referred to as a welded headed stud.

hooked bolt—cast-in anchor anchored mainly by bearing of the 90-degree bend (L-bolt) or 180-degree bend (J-bolt) against the concrete, at its embedded end, and having a minimum e_h equal to $3d_a$.

plastic hinge region—length of frame element over which flexural yielding is intended to occur due to earthquake design displacements, extending not less than a distance *h* from the critical section where flexural yielding initiates.

pryout strength, concrete—strength corresponding to formation of a concrete spall behind short, stiff anchors displaced in the direction opposite to the applied shear force.

reinforcement, supplementary—reinforcement that acts to restrain the potential concrete breakout but is not designed to transfer the design load from the anchors into the structural member.

side-face blowout strength, concrete—strength of anchors with deep embedment and thin side-face cover such that spalling occurs on the side face around the embedded head without breakout occurring at the top concrete surface.

steel element, ductile—element with a tensile test elongation of at least 14 percent and reduction in area of at least 30 percent; steel element meeting the requirements of ASTM A307 shall be considered ductile; except as modified by for earthquake effects, deformed reinforcing bars meeting the requirements of ASTM A615, A706, or A955 shall be considered as ductile steel elements.

strength, design—nominal strength multiplied by a strength reduction factor ϕ.

strength, required—strength of a member or cross section required to resist factored loads or related internal moments and forces in such combinations as stipulated in the ACI 318-14 Code.

5.51.3 NOTATIONS

A_{Nc} = projected concrete failure area of a single anchor, for calculation of strength in tension (in.^{2})

A_{Nco} = projected concrete failure area of a single anchor, for calculation of strength in tension if not limited by edge distance or spacing (in.^{2})

A_{Vc} = projected concrete failure area of a single anchor, for calculation of strength in shear (in.^{2})

A_{Vco} = projected concrete failure area of a single anchor, for calculation of strength in shear if not limited by edge distance or spacing (in.^{2})

$c_{a,Min}$ = minimum distance from center of anchor shaft to edge of concrete (inches)

c_{a1} = distance from center of an anchor shaft to the edge of concrete in one direction, in. If shear is applied to anchor, c_{a1} is taken in the direction of the applied shear. If tension is applied to the anchor, c_{a1} is the minimum edge distance.

c_{a2} = distance from center of an anchor shaft to the edge of concrete in the direction perpendicular to c_{a1} (inches)

d_a = outside diameter of anchor (inches)

f'_c = specified compressive strength of concrete (psi)

h_a = thickness of member in which an anchor is located, measured parallel to anchor axis (inches)

h_{ef} = effective embedment depth of anchor (inches)

N_n = nominal tensile strength (lb)

N_{ua} = factored tensile force applied to an anchor (lb)

V_n = nominal shear strength (lb)

V_{ua} = factored shear force applied to an anchor (lb)

φ = strength reduction factor

$\psi_{ed,N}$ = factor used to modify tensile strength of anchors based on proximity to edges of concrete members

5.51.4 CAST-IN ANCHORS

ACI 318-14 should be consulted for cases beyond the scope of this memo, including design of L-bolts, J-bolts, and headed studs. Figure 5.51.4.1 shows the four categories for CI anchors: headed bolts, L-bolts, J-bolts, and welded headed studs.

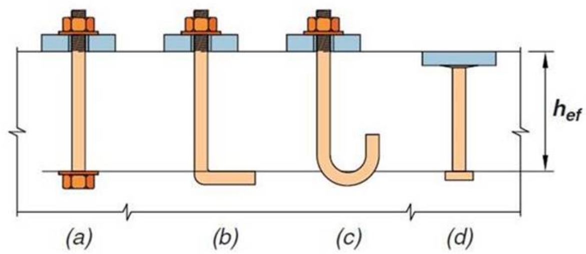

Figure 5.51.4.1 Cast-in Anchor Types

(ACI 318-14, Figure R2.1)

5.51.4.1 Applications, Advantages, and Disadvantages

This BDM applies to anchors in concrete used to transmit structural loads related to strength, stability, or life safety by means of tension, shear or a combination of tension and shear. ACI 318-14 provides guidance for group effects and special considerations including seismic loading.

By definition, CI anchors are placed into the formwork before concrete placement and are thus cast-in. Advantages include accurate placement relative to rebar and design flexibility with a wide variety of anchor sizes, configurations, and lengths. Disadvantages include the need to maintain position during casting, adverse performance due to concrete quality and consolidation, inability to move anchors, and the requirement to penetrate formwork [2].

5.51.4.2 Failure Modes

Figure 5.51.4.2.1 shows steel and concrete failure modes for concrete anchors. The four failure modes for CI headed anchors in tension include: steel failure (ductile failure mode), concrete breakout, anchor pullout, and side-face blowout (anchors close to an edge). The three shear failure modes are: steel failure, concrete breakout, and concrete pryout. Per ACI 318-14, splitting is assumed to be precluded by satisfying minimum edge distance and anchor spacing requirements.

Governing equations for each failure mode, provided in ACI 318-14, demonstrate that the design strength of a CI anchor is affected by many parameters such as material properties of the steel and concrete, bolt diameter, embedment depth, head or nut bearing area, edge distance, spacing between anchors, and other conditions (e.g., service level cracking and seismic conditions). Because these design aids do not address all of the variables, caution must be used in applying them for actual design conditions. In addition, these design aids show the governing failure mode (e.g., concrete breakout, CO; pullout, PO), so that the designer is clearly aware of this. Although it may be preferable for a ductile failure mode characterized by steel failure to govern design, often this is not possible due to actual conditions (e.g., available embedment depth, anchor spacing, etc.).

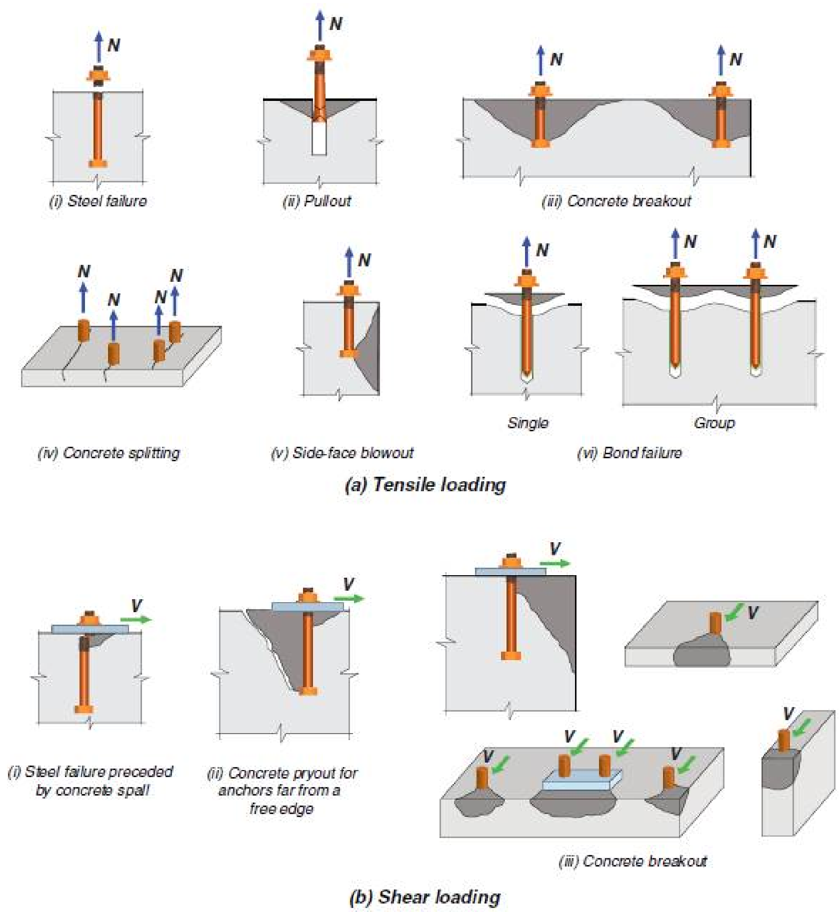

Figure 5.51.4.2.1 Steel and Concrete Failure Modes for Cast-In Anchors
(ACI Committee 318, Figure R17.3.1)

Tension-shear interaction is required in design for anchors subjected to simultaneous tension and shear, if the tension or shear demand exceeds 20% of the anchor's capacity.

5.51.4.3 Design Examples

Eight detailed design examples for CI anchors are provided in Reference 2. They address a range of conditions, including single anchors (headed and hooked) subject to tension, shear, and combined tension and shear under various Seismic Design Categories. They also address headed bolt and stud groups.

5.51.5 DESIGN TABLES

Tables 1 and 2 provide design strength values for tension (φNn) and shear (φVn) for CI headed anchors.

5.51.5.1 Table Assumptions

Tabulated values of design tensile and shear strengths are based on the following assumed conditions:

a) Concrete is cracked. - Concrete members are assumed to undergo cracking at or near the anchor and to have sufficient reinforcement to restrain expected cracking to acceptable widths under design loads. This restraint is normally satisfied by typical concrete member reinforcement. Tabulated values may be conservatively used for anchors located in a region where analysis indicates no cracking at service load levels. Where analysis indicates no cracking at service load levels, designers may alternatively use the provisions of ACI 318-14 to calculate an increase in capacity (up to 25% for anchors governed by concrete breakout and up to 40% for anchors governed by pullout).

b) Conditions are non-seismic. Design values assume a non-seismic condition, which is defined as follows: the tensile or shear component of the factored earthquake force on the anchor does not exceed 20% of the total factored anchor force for the load combination being checked.

   Where anchors resisting earthquake forces are to be designed (which cannot include the plastic hinge zone), the anchor design tensile strength for resisting earthquake forces is reduced by multiplying by a 0.75 factor for concrete breakout, pullout, and concrete side-face blowout. The reduction factor does not apply to steel failure modes. ACI 318-14 includes additional provisions for combined tension and shear.

   ACI 318-14 provisions do not apply to the design of anchors in plastic hinge zones.

c) Specified compressive strength of concrete, f'_c, equals 3600 psi. - Tabulated values may be conservatively used for cases in which the specified compressive strength is larger than 3600 psi. However, tabulated values must not be multiplied by a factor to account for the increase in compressive strength because f'_c does not affect strength for all failure modes uniformly. Designers may account for different values of f'_c by calculating anchor design strength values based on all failure modes using ACI 318-14. An upper limit of 10,000 psi is imposed on compressive strength used in formulas, regardless of actual compressive strength. In addition, compressive strengths must not be less than 2500 psi.

d) Specified yield and ultimate tensile strength of the ASTM F1554 Grade 36 steel anchor bolt equals 36 ksi and 58 ksi, respectively. It should be noted that the governing failure mode, including a ductile versus brittle failure mode, may change as specified values are changed.

e) Anchor bolts are hex headed. The bolt type and head affect assumed properties used in design such as bearing area.

f) No supplementary reinforcement is provided. Tabulated values may be conservatively used for cases in which supplementary reinforcement is provided. This provides more deformation capacity, when detailed per R17.4.2.9 and R17.5.2.9b of ACI 318-14.

g) Single anchor is used, without group effects. Tabulated values apply for a single anchor and must not be multiplied by the actual number of anchors to establish a design value for a group of anchors. However, under some conditions, the capacity of a group of anchors may be determined by multiplying a single anchor's capacity. For example, for concrete breakout in tension when anchors are spaced at least 3hef apart, anchors act independently because failure surfaces for concrete breakout do not overlap in this failure mode. Therefore, the capacity of two anchors governed by concrete breakout may be determined by multiplying the capacity of a single anchor governed by concrete breakout by a factor of 2.0.

h) Base plates are not used. When base plates (flat supporting plate at base of a column) are used, the design must address many additional considerations, in accordance with ACI 318-14.

5.51.5.2 Table Use and Characteristics

Design Tables are separated into two sets: Tension (Tables 5.51.5.2.1 and 5.51.5.2.2) and Shear (Tables 5.51.5.2.3 and 5.51.5.2.4). The first table of each set (Tables 5.51.5.2.1 and 5.51.5.2.3) refers to Case 1, which corresponds to a specified minimum embedment depth and minimum edge distance. The second table of each set (Tables 5.51.5.2.2 and 5.51.5.2.4) refers to Case 2, which increases the minimum edge distance to achieve a greater capacity, as described below.

Features of the Design Tables include the following:

a) Design Strength - Based on ACI 318-14, Table 5.51.5.2.1 and Table 5.51.5.2.2 list the design tensile strength, and Table 5.51.5.2.3 and Table 5.51.5.2.4 list the shear strength for the specified bolt diameter and minimum edge distances and anchor conditions (one-edge vs. two-edge). These strengths are determined by multiplying the appropriate strength reduction factor by the governing nominal strength: φN_n for tension and φV_n for shear. For anchor design, the design strength should be compared to the appropriate required strength (i.e., factored load effect): the factored tensile force applied to the anchor, N_{ua}, the factored shear force applied to the anchor, V_{ua}, or to a combination based on the tension-shear interaction using Equation 17.6.3 of ACI 318-14.

For simplicity, these design tables address only a limited number of variables. For example, the anchor effective embedment depth, h_{ef}, is not varied for a given anchor size in the tables, although h_{ef} clearly affects capacity. The design methodology of ACI 318-14 may be used directly for cases that differ from the assumptions, specified edge distances, and conditions of the design tables. Insight into approaches to increase design strength may be gained by examining the appropriate design equations in ACI 318-14.

b) Governing Failure Mode – The tables below also list the governing failure mode corresponding to each condition, shown directly beneath the design strength value. As explained below, for design tensile strength, concrete breakout (CB) governs for Case 1 (Table 5.51.5.2.1), and pullout (PO) governs for Case 2 (Table 5.51.5.2.2), except for the 1-in diameter bolt (for which CB governs). For design shear strength, concrete breakout (CB) governs for both Cases 1 and 2 (Table 5.51.5.2.3 and Table 5.51.5.2.4, respectively).

c) Case 1 - Values for design tensile strength (Table 5.51.5.2.1) and design shear strength (Table 5.51.5.2.3) are based on a specified minimum edge distance together with a specified minimum embedment depth. The specified edge distance ranges from 4da to 5da, and the specified minimum embedment depth is 8da, where da is the shaft diameter of the headed bolt. For example, the specified Case 1 design tensile strength of 12.2 kips for a 1-in bolt diameter (one-edge condition) requires the use of an edge distance of at least 4 in (i.e., 4da) together with an embedment depth of at least 8 in (i.e., 8da).

d) Case 1: one-edge vs. two-edge (corner) condition - For Case 1, the anchorage capacity in tension or in shear varies based on the anchor's proximity to nearby edges. Figures that accompany Tables 5.51.5.2.1 (tension) and 5.51.5.2.3 (shear) illustrate the one-edge and two-edge conditions as well as associated terminology (e.g., minimum edge distance, ca1, and perpendicular edge distance, ca2). For a corner condition, the anchor is assumed to be located equidistant from each edge (i.e., ca2=ca1). For cases where ca2 does not equal ca1, the designer can conservatively assume the smaller of the two values in using the tabulated design strength values.

Anchors located near one edge have a higher capacity than anchors located near two edges. For example, when an anchor subjected to tension is located within $1.5h_{ef}$ of an edge, a potential concrete breakout surface is intercepted by the edge, reducing the projected concrete failure area (A_{nc}) and, hence, the tensile capacity. In addition, there is a disturbance in the stress field, which further reduces its capacity (based on the $\psi_{ed,N}$ factor). Similarly, when an anchor subjected to tension is located within $1.5h_{ef}$ along both edges (i.e., a corner condition), its capacity is reduced even further. Tables 5.51.5.2.1and 5.51.5.2.3 show this reduction in capacity for tension and shear, respectively.

Case 2 - Provides significantly larger design strengths for cases where greater edge distances are available for anchors in tension or shear. The specified minimum embedment depth, h_{ef}, remains at the Case 1 value of $8d_a$.

For tensile capacity, the Case 2 values of Table 1B assume an edge distance of $1.5h_{ef}$ in both c_{a1} and c_{a2} directions, such that the concrete breakout capacity is achieved without the projected concrete failure area intercepting an edge (i.e., A_{Nc}/A_{Nco}=1.0). As Table 5.51.5.2.2 demonstrates, a significant increase in capacity results, especially for larger diameter anchors, even though the failure mode shifts from concrete breakout (CB) to pullout (PO) in most cases.

For shear capacity, the Case 2 values of Table 5.51.5.2.4 assume a minimum edge distance in the direction of anchor shear, c_{a1}, such that a concrete breakout is achieved without the projected concrete failure area intercepting an edge at the bottom of the member or sides of the anchor (i.e., A_{Vc}/A_{Vco}=1.0). This corresponds to a thickness of the member, h_a, assuming 2 in of concrete below the minimum embedment depth, h_{ef}, as well as a minimum perpendicular edge distance, c_{a2}, of at least $1.5c_{a1}$. Because concrete breakout governs for shear, a very significant increase in capacity develops for Case 2 over Case 1, as shown in Table 5.51.5.2.4.

Table 5.51.5.2.1 Design Tensile Strength (φN_n)

Cast-In, Hex Head Anchor Bolt -

Case 1

Bolt Diameter (in)	Minimum Embedment Depth, h_{ef} (in)	Minimum Edge Distance, c_{a1} (in)	Design Tensile Strength, φN_n (kips)	
			1-Edge Condition ($c_{a2} \geq 1.5c_{a1}$)	2-Edge (Corner) Condition ($c_{a2}=c_{a1}$)
1/2	4.0	2.5	4.7 CB	3.3 CB
5/8	5.0	3.0	6.5 CB	4.5 CB
3/4	6.0	3.0	7.9 CB	5.3 CB
7/8	7.0	4.0	10.5 CB	7.3 CB
1	8.0	4.0	12.2 CB	8.1 CB

Note: CB: Concrete Breakout failure governs.

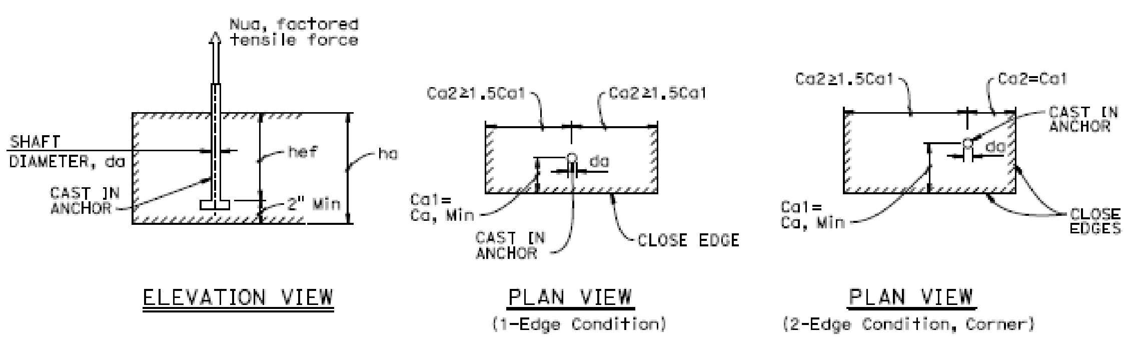

Figure 5.51.5.2.1 Tension

Table 5.51.5.2.2 Design Tensile Strength (φN_n)

Cast-In, Hex Head Anchor Bolt

Case 2

Bolt Diameter (in)	Minimum Embedment Depth, h_{ef} (in)	Minimum Edge Distance, c_{a1} (in)	Design Tensile Strength, φN_n (kips)
			No Edge Influence ($c_{a2} \geq 1.5 c_{a1}$)
1/2	4.0	6.0	5.9 PO
5/8	5.0	7.5	9.2 PO
3/4	6.0	9.0	13.2 PO
7/8	7.0	10.5	18.0 PO
1	8.0	12.0	22.8 CB

Note: CB: Concrete Breakout failure governs. PO: Pullout failure governs.

Table 5.51.5.2.3 Design Shear Strength (φVn)

Cast-In, Hex Head Anchor Bolt

Case 1

Bolt Diameter (in)	Minimum Embedment Depth, h_{ef} (in)	Minimum Edge Distance, c_{a1} (in)	Design Shear Strength, φV_n (kips)	
			1-Edge Condition	2-Edge (Corner) Condition (c_{a2}=c_{a1})
1/2	4.0	2.5	1.1 CB	0.9 CB
5/8	5.0	3.0	1.6 CB	1.4 CB
3/4	6.0	3.0	1.8 CB	1.5 CB
7/8	7.0	4.0	2.7 CB	2.3 CB
1	8.0	4.0	2.7 CB	2.3 CB

Note: CB: Concrete Breakout failure governs.

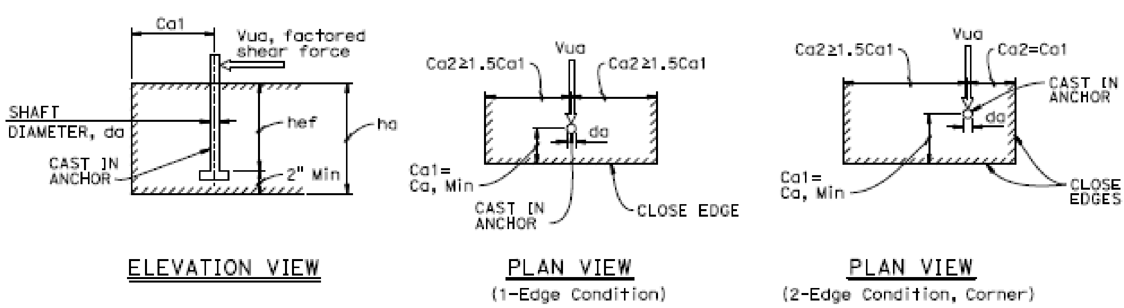

Figure 5.51.5.2.2 Shear

Table 5.51.5.2.4 Design Shear Strength (φV_n)

Cast-In, Hex Head Anchor Bolt

Case 2

Bolt Diameter (in)	Minimum Embedment Depth, h_{ef} (in)	Minimum Edge Distance, c_{a1} (in)	Minimum Perpendicular Edge Distance, c_{a2} (in)	Design Shear Strength, φV_n (kips)
1/2	4.0	4.0	6.0	2.5 CB
5/8	5.0	4.5	6.8	3.4 CB
3/4	6.0	5.0	7.5	4.2 CB
7/8	7.0	6.0	9.0	5.6 CB
1	8.0	6.5	9.8	6.3 CB

Note: CB: Concrete Breakout failure governs.

5.51.6 REFERENCES

1. ACI Committee 318, 2014, *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary*, American Concrete Institute, Farmington Hills, MI.
2. *The Reinforced Concrete Design Handbook*, ACI SP17(14), Volume 2, Chapter 15, Anchoring to Concrete, American Concrete Institute, Farmington Hills, MI, 2015.
3. R. A. Swirsky, J. P. Dusel, W. F. Crozier, J. R. Stoker and E. F. Nordlin, 1977, *Lateral Resistance of Anchor Bolts Installed in Concrete*, Report No. FHWA-CA-ST-4167-77-12.
4. J. P Dusel, J. H. Andersen and J. R. Stoker, 1979, *Evaluation of Rock Bolts for Installation in Existing Concrete*, Report No. FHWA-CA-TL-79-03.
5. John P. Dusel and Craig N. Harrington, 1986, *Evaluation of Mechanical expansion anchors* – Vol. 1 & 2, Report No. FHWA/CA/TL-86/09.
6. Abid A. Mir and John P. Dusel, 1993, *Evaluation of New Bonding Materials for Anchoring Dowels in Existing Concrete*, Report No. FHWA/CA/TL-93/11.