Applying Appendix D of ACI 318

Sizing Anchor Bolts Makes Me "Sigh" (ψ)

By Peter Carrato, Ph.D., P.E., S.E.

In 2002, the American Concrete Institute's *Building Code Requirements for Structural Concrete* (ACI 318 – 2002) for the first time published criteria for Anchoring to Concrete in Appendix D. The current version of Appendix D (ACI 318 – 2005) comprises 26 pages of code and commentary. A first look at this volume of information may appear intimidating to those engineers who are accustomed to designing a base plate in a one page calculation. Appendix D is based on the Concrete Capacity Design (CCD) method that allows the designer to account for many anchorage configurations through the use of a number of *psi* (ψ) factors. The design of concentrically loaded cast-in-place anchor bolts located far from the edge or corner of a slab remains a relatively simple task. Understanding the ψ factors is the key to unlocking Appendix D.

Designing anchors bolts is basically a two step process: check the steel design strength then check the concrete design strength. Evaluating the steel has always been easy: take the steel area and multiply by its design strength. Evaluating concrete design strength is not so simple. Depending on the configuration of the anchorage, multiple concrete failure modes are possible, including splitting and cone pullout. These failure modes are influenced by the installation arrangement of the anchors; such as close to the slab edge, near a slab corner, installed in a thin floor, anchors that are close to each other, groups of anchors that are not uniformly loaded, etc. The CCD method uses various ψ factors to help account for all of these potential failure modes and arrangements.

Appendix D defines eight ψ factors that are uniquely identified using multiple subscripts; $\psi_{ec,N}$ $\psi_{ec,V}$ $\psi_{ed,N}$ $\psi_{ed,V}$ $\psi_{c,N}$ $\psi_{c,V}$ $\psi_{c,P}$ and $\psi_{cp,N}$. The subscripts are a guide to the effect addressed by the factor. The first subscript identifies parameters that will modify an ideal concrete stress block that would resist a concentrically applied load on an anchor or group of anchors far from an edge. They include **ec** for non-uniform loads that would result in **ec**centric load on a group of anchors, **ed** for close **ed**ges, **c** for **c**racking and **cp** anchor that are not **c**ast-in-**p**lace. The second subscript covers the type of anchor resistance mechanism, N for tension, P for pullout or V for shear. Here is the good news, for a concentrically loaded group of cast-in-place bolts located away from the edge of a slab that is assumed to be cracked, all eight factors are equal to 1.0.

The least understood of the ψ factors is $\psi_{ec,N}$, the modification factor for anchor groups loaded eccentrically in tension (Appendix D Section D.5.2.4). An engineer who is designing the anchor bolts for a column base plate that carries an overturning moment and axial tension typically thinks of eccentricity as the distance from the centroid of the anchor group to the resultant axial force. Unfortunately this is not the eccentricity that is being addressed in Section D.5.2.4.

Figure 1 shows an example of an eccentrically loaded base plate. To calculate the concrete capacity for this example, apply equation D-5 of ACI 318 Appendix D.

$$N_{cbg} = (A_{Nc}/A_{Nco})\, \psi_{ec,N}\, \psi_{ed,N}\, \psi_{c,N}\, \psi_{cp,N}\, N_b$$

Equation D-5

Note that the 10 kips uplift load is applied at a twelve inch eccentricity from the centroid of the anchor bolt group. Twelve inches is not the e'_N to be used in equation D-9 of ACI 318. Also note that by assuming concrete is cracked, all of the ψ factors except for $\psi_{ec,N}$ are equal to 1.0.

If we assume that for a thick base plate the applied load will cause the plate to rotate as a rigid body about the left edge, then a simple hand calculation can be performed to determine the loads on the anchor bolts (*Figure 2*). The 120 in-kip moment applied to the centroid of the plate will result in 5.77 kips per bolt on the right side of the attachment, and 1.15 kips per bolt on the left side of the attachment. The 10 kip tension load is assumed to be distributed equally to all four bolts. Combining the bolt loads from the applied moment with those from the direct tension give the bolt loads shown in *Figure 2*.

A quick check of statics is used to determine the magnitude and location of the resultant of the bolt loads as shown in *Figure 3* (page 22). The 1.55 inches of eccentricity of the resultant bolt load to the centroid of the bolt group is used to determine $\psi_{ec,N}$. The eccentricity factor,

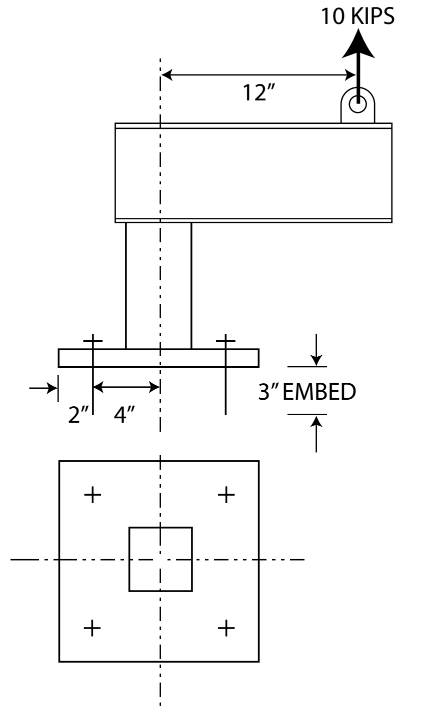

Figure 1: Eccentrically Loaded Plate.

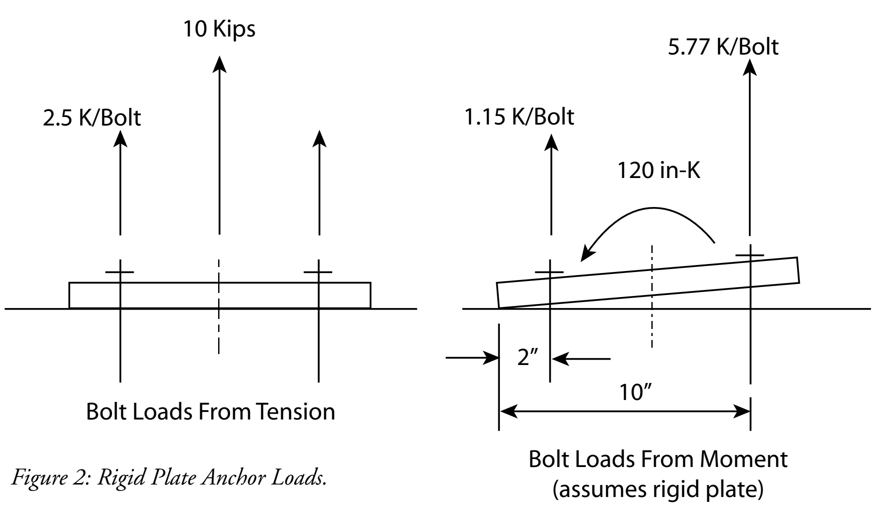

Figure 2: Rigid Plate Anchor Loads.

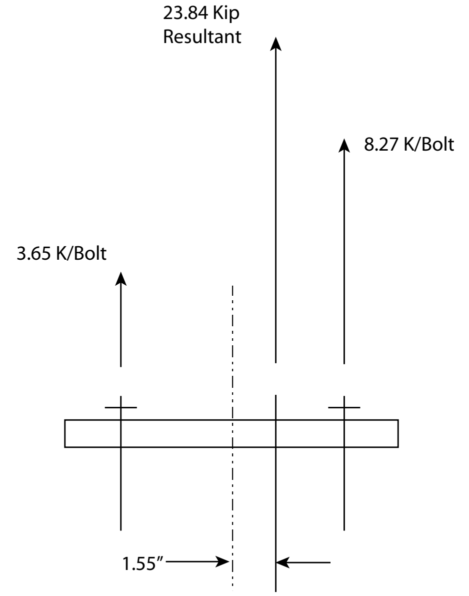

Figure 3: Resultant Anchor Force.

or 0.74 calculated below, is used to determine the concrete capacity for this example.

$$\psi_{ec,N} = \frac{1}{\left(1+\dfrac{2e'_N}{3h_{ef}}\right)} = \frac{1}{\left(1+\dfrac{2\times1.55''}{3\times3''}\right)} = 0.74 \le 1.0$$

Equation D-9

When using post-installed anchors located close to the edge of a relatively thin slab that connect plates with eccentric loads, using Appendix D can become relatively complex. The $\psi_{c,N}$ factor for post-installed anchors highlights a unique feature of this appendix. In order for post-installed anchors to be designed by ACI 318, post-installed anchors have to be tested in accordance with ACI 355.2, *Qualification of Post-Installed Mechanical Anchors in Concrete.*

ACI 355.2 defines a regime of three major test categories; reference tests, reliability test, and service-condition tests. Reference tests are used to establish the baseline performance on anchors under ideal conditions. Reliability tests are performed to establish that anchors are capable of safe, effective behavior under adverse installation and service conditions. Service-condition tests are used to establish that anchors can resist unique in-place effects, such as seismic loads. The results of reliability test are compared to those from the reference tests to determine anchor categories, which in turn lead to a range of φ factors in section D.4 of Appendix D. Factors can be as low as 0.45 for anchors with low reliability.

The complete results of an ACI 355.2 testing program are documented by the anchor manufacturer in a data sheet similar to the example shown in *Figure 4*. This data sheet includes; dimensional information such as diameter, spacing and embedment; load capacities for steel failure, pull-through, etc;

Characteristic	Symbol	Units	Nominal anchor diameter							
Installation Information										
Outside diameter	d_o	*in.*	3/8		1/2		5/8		3/4	
Effective embedment depth	h_{ef}	*in.*	1.75		2.5		3		3.5	
			2.75		3.5		4.5		5	
			4.5		5.5		6.5		8	
Installation torque	T_{inst}	*ft.-lb.*	30		65		100		175	
Minimum edge distance	c_{min}	*in.*	1.75		2.5		3		3.5	
Minimum spacing	s_{min}	*in.*	1.75		2.5		3		3.5	
Minimum concrete thickness	h_{min}	*in.*	$1.5h_{ef}$		$1.5h_{ef}$		$1.5h_{ef}$		$1.5h_{ef}$	
Critical edge distance @ h_{min}	c_{ac}	*in.*	2.1		3.0		3.6		4.0	
Anchor Data										
Anchor material	ASTMF 1554 Grade 55 (meets ductile steel element requirements)									
Category number	1, 2, or 3	—	2		2		1		1	
Yield strength of anchor steel	f_{ya}	*psi*	55,000		55,000		55,000		55,000	
Ultimate strength of anchor steel	f_{uta}	*psi*	75,000		75,000		75,000		75,000	
Effective tensile stress area	A_{ze}	*in.*^{2}	0.0775		0.142		0.226		0.334	
Effective shear stress area	A_{ze}	*in.*^{2}	0.0775		0.142		0.226		0.334	
Effectiveness factor for uncracked concrete	k_{uncr}	—	24		24		24		24	
Effectiveness factor for cracked concrete used for ACI 318 design	k_{cr}*	—	17		17		17		17	
$\psi_{c,N}$ for ACI 318 design in cracked concrete	$\psi_{c,N}$*	—	1.0		1.0		1.0		1.0	
$\psi_{c,N} = k_{uncr}/k_{cr}$ for ACI 318 design in uncracked concrete	$\psi_{c,N}$*	—	1.4		1.4		1.4		1.4	
Pullout or pull-through resistance from tests	N_p	*lb.*	h_{ef}	N_p	h_{ef}	N_p	h_{ef}	N_p	h_{ef}	N_p
			1.75	1,354	2.5	2,312	3	4,469	3.5	5,632
			2.75	2,667	3.5	3,830	4.5	8,211	5	9,617
			4.5	5,583	5.5	7,544	6.5	14,254	8	19,463
Tension resistance of single anchor for seismic loads	N_{eq}	*lb.*	1.75	903	2.5	1,541	3	2,979	3.5	3,755
			4.5	3,722	5.5	5,029	6.5	9,503	8	12,975
Shear resistance of single anchor for seismic loads	V_{eq}	*lb.*	2,906		5,321		8,475		12,543	
Axial stiffness in service load range	β	*lb./in.*	55,000		57,600		59,200		62,000	
Coefficient of variation for axial stiffness in service load range	v	%	12		11		10		9	

**These are values used for k_c and $\psi_{c,N}$ in ACI 318 for anchors qualified for use only in both cracked and uncracked concrete.*

Figure 4: Example of Anchor Data Sheet.

and the value for $\psi_{c,N}$. This ψ value is used to ascertain the difference between a post-installed anchor's performance in cracked and uncracked concrete.

Appendix D of ACI 318 provides engineers with design requirements for anchors in concrete. This appendix applies to both cast-in-place and post-installed anchors. By incorporating the CCD method, the design rules in this appendix can cover relatively complex anchoring problems. Understanding the many ψ values used by this design method will assist the designer in proper application of these code provisions.▪

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