ACI 355.2-04

Qualification of Post-Installed Mechanical Anchors in Concrete

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ACI 355.2 prescribes testing programs and evaluation requirements for post-installed mechanical anchors intended for use in concrete under the design provisions of ACI 318. Criteria are prescribed for determining whether anchors are acceptable for use in uncracked concrete only, or in cracked as well as uncracked concrete. Performance categories for anchors are established, as are the criteria for assigning anchors to each category. The anchor performance categories are used by ACI 318 to assign capacity reduction factors and other design parameters.

Keywords: anchors; cracked concrete; expansion anchors; fasteners; mechanical anchors; post-installed anchors; undercut anchors.

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ACI 355.2-04 supersedes ACI 355.2-01 and became effective October 27, 2004.

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CHAPTER 1—SCOPE

1.1 ACI 355.2 prescribes testing and evaluation requirements for post-installed mechanical anchors intended for use in concrete designed under the provisions of ACI 318. Criteria are prescribed to determine whether anchors are acceptable for use in uncracked concrete only, or in cracked as well as uncracked concrete. Criteria are prescribed to determine the performance category for each anchor. The anchor performance categories are used by ACI 318 to assign capacity reduction factors and other design parameters.

1.2 ACI 355.2 describes the tests required to qualify a post-installed mechanical anchor or anchor system for use under the provisions of ACI 318.

1.3 ACI 355.2 applies to post-installed mechanical anchors (torque-controlled expansion anchors, displacement-controlled expansion anchors, and undercut anchors) placed into predrilled holes and anchored within the concrete by mechanical means.

1.4 ACI 355.2 applies to anchors with a nominal diameter of 1/4 in. (6 mm) or larger.

1.5 The values stated either in inch-pound units or SI units are to be separately regarded. Within the text, the SI units are shown in parentheses. The values in each system are not exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems shall result in nonconformance with ACI 355.2.

CHAPTER 2—DEFINITIONS AND NOTATION

2.1—Definitions

2.1.1 *Anchor category*—The classification for an anchor that is established by the performance of the anchor in reliability tests (refer to Chapter 10).

2.1.2 *Anchor group*—A number of anchors of approximately equal effective embedment depth with each anchor spaced at less than three times its embedment depth from one or more adjacent anchors.

2.1.3 *Anchor system*—Similar anchors that vary only due to diameter or embedment depth; a product line of a single manufacturer.

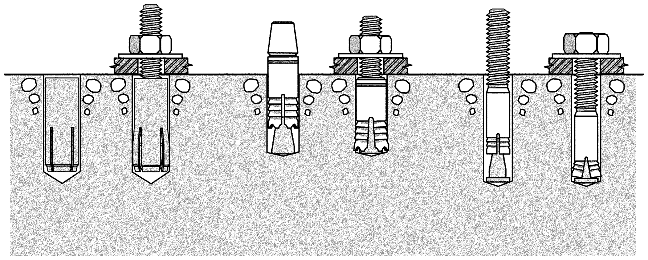
2.1.4 *Characteristic value*—The 5% fractile (value with a 95% probability of being exceeded, with a confidence of 90%).

2.1.5 *Concrete breakout failure*—A concrete failure mode that develops a cone or edge failure of the test member due to setting of the anchor or to applied loads.

2.1.6 *Cracked concrete*—A concrete test member with a single, full depth, approximately uniform width crack.

2.1.7 *Displacement-controlled expansion anchor*—A post-installed anchor that is set by expansion against the side of the drilled hole through movement of an internal plug in the sleeve or through movement of the sleeve over an expansion element (plug) (Fig. 2.1); once set, no further expansion can occur.

2.1.8 *Pullout failure*—A failure mode in which the anchor pulls out of the concrete without development of the full steel or concrete capacity.



(1) Drop-in anchor (2) Self-drilling anchor (3) Stud anchor

Fig. 2.1—Examples of displacement-controlled expansion anchors.

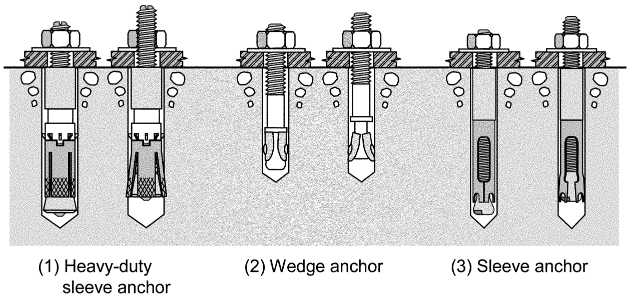


Fig. 2.2—Examples of torque-controlled expansion anchors.

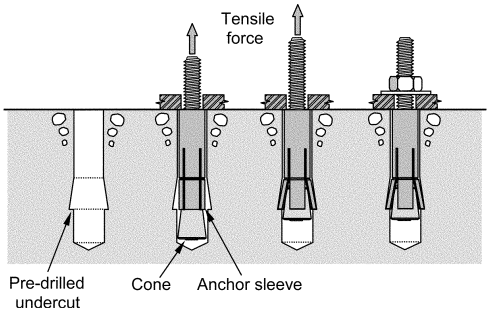


Fig. 2.3(a)—Type 1 undercut anchor. Load-controlled anchor installed by tensioning anchor causing sleeve to expand into predrilled undercut.

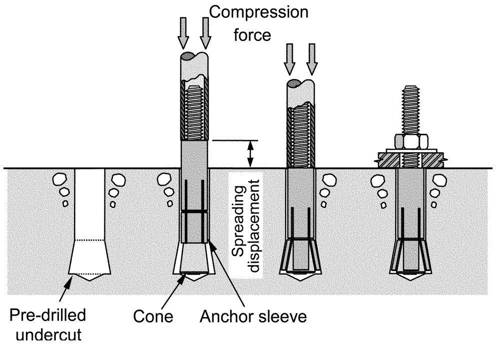


Fig. 2.3(b)—Type 2 undercut anchor. Displacement-controlled anchor set in predrilled undercut by hammering sleeve over cone.

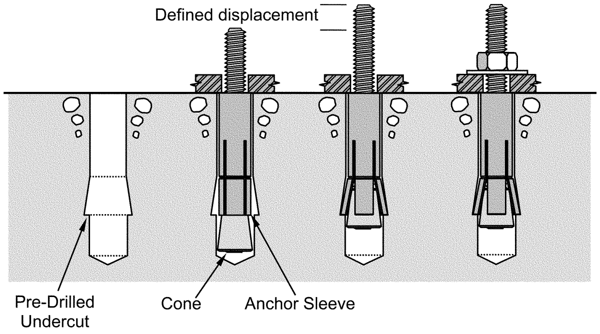


Fig. 2.3(c)—Type 3 undercut anchor. Displacement-controlled anchor installed in predrilled undercut and set by defined displacement, causing expansion sleeve to expand into undercut.

2.1.9 *Pull-through failure*—A failure mode in which the anchor body pulls through the expansion mechanism without development of the full steel or concrete capacity.

2.1.10 *Setting of an anchor*—The process of activating the load-transfer mechanism of an anchor in a drilled hole.

2.1.11 *Splitting failure*—A concrete failure mode in which the concrete fractures along a plane passing through the axis of the anchor or anchors.

2.1.12 *Statistically equivalent*—Two groups of test results shall be considered statistically equivalent if there are no significant differences between the means of the two groups; statistical equivalence of the means of two groups shall be evaluated using the small sample statistical concepts associated with one-sided *t*-test at a confidence of 90%.

2.1.13 S*teel failure*—A failure mode in which the steel anchor parts fracture.

2.1.14 *Test series*—A group of tests having the same parameters.

2.1.15 *Torque-controlled expansion anchor*—A post-installed expansion anchor that is set by the expansion of one

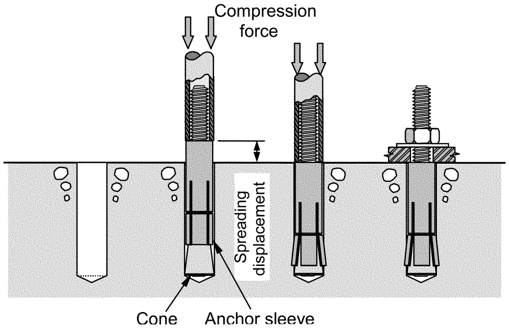


Fig. 2.3(d)(continued)—Type 4 undercut anchor. Displacement-controlled anchor that cuts its own undercut while being set by hammering sleeve over cone.

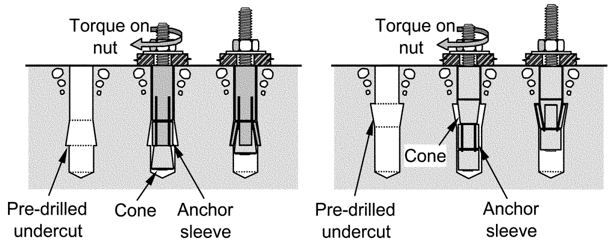


Fig. 2.3(e)—Type 5 undercut anchor. Torque-controlled anchor set into predrilled undercut by application of torque forcing sleeve over cone (two examples shown).

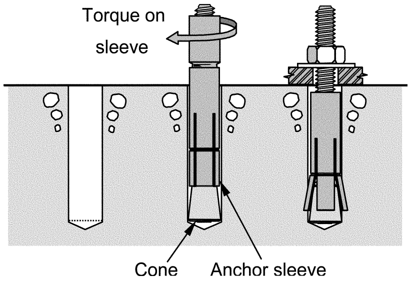


Fig. 2.3(f)—Type 6 undercut anchor. Torque-controlled anchor that cuts it own undercut by application of setting torque that forces sleeve over cone.

or more sleeves or other elements against the sides of the drilled hole through the application of torque, which pulls the cone(s) into the expansion sleeve(s) (Fig. 2.2); after setting, tensile loading can cause additional expansion (follow-up expansion).

2.1.16 *Uncracked concrete*—A test member that remains uncracked, unless the crack is part of a failure mode.

2.1.17 *Undercut anchor*—A post-installed anchor that derives tensile holding strength by the mechanical interlock provided by undercutting the concrete, achieved either by a special tool or by the anchor itself during installation (Fig. 2.3).

2.2—Notation

A_{se} = effective cross-sectional area of anchor, in.^{2} (mm^2)
c_{cr} = edge distance required to develop full concrete capacity of a post-installed anchor in the absence of reinforcement to control splitting, in. (mm)
c_{min} = minimum allowable edge distance as determined from testing and given in the manufacturer's data sheets, in. (mm)
d_m = diameter of a carbide-tipped drill bit with a diameter on the low end of the tolerance range for a new bit, representing a moderately used bit, in. (mm)
d_{max} = diameter of a carbide-tipped drill bit with a diameter on the high end of the tolerance range for a new bit, representing a bit as large as would be expected in use, in. (mm)
d_{min} = diameter of a carbide-tipped drill bit with a diameter below the low end of the tolerance range for a new bit, representing a well-used bit, in. (mm)
d_o = outside diameter of post-installed anchor, in. (mm)
$F_{5\%}$ = characteristic capacity in a test series, as calculated using Eq. (A2-1), lb (N)
F_m = mean failure capacity, lb (N)
$F_{m,i}$ = mean normalized capacity in test series i, as calculated using Eq. (A1-1), lb (N)
F_{ut} = mean normalized anchor capacity in test series i as calculated using Eq. (A1-2), lb (N)
$F_{u,test,i}$ = mean anchor capacity as determined from test series i, lb (N)
f'_c = specified compressive strength of concrete, psi (MPa)
$f_{c,m,i}$ = concrete compressive strength to which test results for test series i are to be normalized using Eq. (A1-1), psi (MPa)
$f_{c,test,i}$ = mean concrete compressive strength measured with standard cylinders, for concrete of test series i, psi (MPa)
f_{ut} = specified ultimate tensile strength of anchor steel, psi (MPa)
$f_{u,test}$ = mean ultimate tensile strength of anchor steel as determined by test, psi (MPa)
f_y = specified yield strength of anchor steel, psi (MPa)
h = thickness of structural member, measured perpendicular to the concrete surface where the anchor is installed, in. (mm)
h_{ef} = effective embedment depth, measured from the concrete surface to the deepest point at which the anchor tension load is transferred to the concrete (Fig. 2.4), in. (mm)
h_{min} = minimum member thickness, specified by the anchor manufacturer, in. (mm)
K = statistical constant (one-sided tolerance factor) used to establish the 5% fractile with a 90% confidence, whose value depends on the number of tests (Appendix A2)
k = effectiveness factor, whose value depends on the type of anchor
k_c = effectiveness factor for anchors tested in cracked concrete
k_{uncr} = effectiveness factor for anchors tested in uncracked concrete
N = normal force (generally tensile), lb (N)
N_1 = minimum tension load above which variations in the load-displacement curve are acceptable, as prescribed in 5.5.1.1, lb (N)
$N_{10\%}$ = mean load at 10% of the ultimate load measured in the tension test, lb (N)
$N_{30\%}$ = mean load at 30% of the ultimate load measured in the tension tests, lb (N)
N_b = characteristic tensile capacity of an anchor with a concrete failure mode (5% fractile of test results), lb (N)
$N_{b,o}$ = characteristic tensile capacity in reference tests, lb (N)
$N_{b,r}$ = characteristic tensile capacity in reliability tests, lb (N)
N_{eq} = maximum seismic tension test load, equal to 50% of the mean tension capacity in cracked concrete from reference tests, lb (N)
N_k = lowest characteristic tensile capacity in reference tests in uncracked concrete for concrete, steel, or pullout failures for the concrete strength of the test member, lb (N)
N_p = characteristic tensile pullout or pull-through capacity of an anchor (5% fractile of test results), lb (N)
N_{st} = characteristic tensile steel capacity of an anchor, lb (N)
N_u = ultimate load measured in a tension test, lb (N)
N_w = tensile load in tests of anchors located in cracks whose opening width is cycled, lb (N)
n = number of anchors in a test series

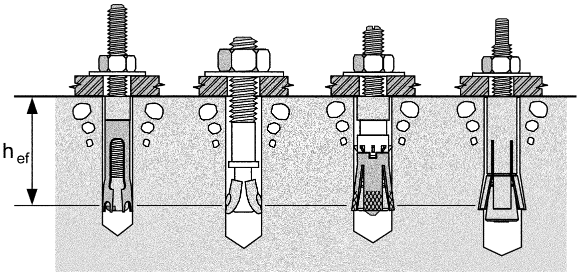


Fig. 2.4—Effective embedment depth.

s_{min} = minimum spacing used in Table 4.1, Test 8 and Table 4.2, Test 10, in. (mm)

T = applied torque in a test, ft·lb (N·m)

T_{inst} = specified or maximum setting torque for expansion or prestressing of an anchor, ft·lb (N·m)

V_{eq} = maximum seismic shear test load in the seismic shear tests, determined by calculation or by test, lb (N)

V_{st} = characteristic shear capacity for steel failure, lb (N)

w = crack width, in. (mm)

β = axial stiffness of anchor in service load range, lb/in. (kN/mm)

Δw = change in crack width, in. (mm)

$\Delta_{10\%}$ = mean displacement measured at 10% of ultimate load in tension test, in. (mm)

$\Delta_{30\%}$ = mean displacement measured at 30% of ultimate load in tension test, in. (mm)

ν = sample coefficient of variation (standard deviation divided by the mean) expressed as decimal fraction or in percent

$\psi_{c,N}$ = factor used to modify tensile strength of anchors based on presence or absence of crack in concrete. (Note this term was defined as ψ_3 in 355.2-01.)

CHAPTER 3—SIGNIFICANCE AND USE

3.1 ACI 355.2 applies to post-installed mechanical anchors intended for use in structural applications addressed by ACI 318 and subjected to static or seismic loads in tension, shear, or combined tension and shear. Examples of applicable anchors are shown in Fig. 2.1, 2.2, and 2.3. ACI 355.2 does not apply to anchors loaded in compression when the expansion mechanism is also loaded in compression, or to anchors subjected to long-term fatigue loading. Anchors meeting the requirements of ACI 355.2 are expected to sustain their design loads (in tension, shear, and combined tension and shear) while providing adequate stiffness. The behavior of anchors in plastic hinge zones of reinforced concrete structures is not simulated in the requirements of this document for the qualification of anchors.

CHAPTER 4—GENERAL REQUIREMENTS

4.1—Testing sequence

Perform four types of tests in the following sequence:

1. Identification tests to evaluate the anchor's compliance with the critical characteristics (Chapter 6);

2. Reference tests to establish baseline performance against which subsequent tests are to be compared (Chapter 7);

3. Reliability tests to confirm the reliability of the anchor under adverse installation procedures and long-term use (Chapter 8); and

4. Service-condition tests to evaluate the performance of the anchor under expected service conditions (Chapter 9).

Test requirements are summarized in Tables 4.1 and 4.2. Determine the acceptability of the anchor using the criteria prescribed in Chapters 6 through 9. Determine the anchor category (an index of the anchor's sensitivity to conditions of installation and use) using the criteria prescribed in Chapter 10. Report the lowest anchor category by diameter as prescribed in Chapter 11. For anchors with multiple embedment depths, refer to Table 5.7.

Table 4.1—Test program for evaluating anchor systems for use in uncracked concrete

Test number	Section	Purpose	Description	Concrete strength	Member thickness	Drill bit diameter	Minimum sample size[*] n
Reference tests							
1	7.2	Reference test in uncracked low-strength concrete	Tension—single anchor with no edge influence	Low	$\geq h_{min}$	d_m	5
2	7.2	Reference test in uncracked concrete in high-strength concrete	Tension—single anchor with no edge influence	High	$\geq h_{min}$	d_m	5
Reliability tests							
3	8.2	Sensitivity to reduced installation effort	Tension—single anchor with no edge influence	Varies with anchor type	$\geq h_{min}$	d_m[†]	5
4	8.3	Sensitivity to large hole diameter	Tension—single anchor with no edge influence	Low	$\geq h_{min}$	d_{max}	5
5	8.4	Sensitivity to small hole diameter	Tension—single anchor with no edge influence	High	$\geq h_{min}$	d_{min}	5
6	8.5	Reliability under repeated load	Repeated tension—single anchor with no edge influence, residual capacity	Low	$\geq h_{min}$	d_m	5[‡]
Service-condition tests							
7	9.2	Verification of full concrete capacity in corner with two edges located at $1.5h_{ef}$	Tension—single anchor in corner with two edges located at $1.5h_{ef}$	Low	h_{min}	d_m	4
8	9.3	Minimum spacing and edge distance to preclude splitting on installation	High installation tension (torque or direct)—two anchors near edge	Low	h_{min}	d_m	5
9	9.4	Shear capacity of anchor steel[§]	Shear—single anchor with no edge influence	Low	$\geq h_{min}$	d_m	5

[*] Minimum sample size for each anchor diameter, unless otherwise noted.

[†] Drill bit diameters for undercuts are specified in Table 5.6.

[‡] Tests are not required for each anchor diameter. Test smallest, middle, and largest anchor diameter.

[§] Required only for anchors whose cross-sectional area, within five anchor diameters of the shear failure plane, is less than that of a threaded bolt of the same nominal diameter as the anchor, or for sleeved anchors when shear capacity of the sleeve will be considered.

4.2—Test samples

For anchors in production, the testing agency shall randomly select anchors to be used in this qualification program from the manufacturing or distribution facility, and verify that the samples are representative of the production of the manufacturer as supplied to the marketplace.

To test newly developed anchors that are not in production, use samples produced by the expected production methods. After production has begun, perform identification and reference tests to verify that the constituent materials have not changed, and that the performance of the production anchors is statistically equivalent to that of the anchors originally tested (2.1.12).

4.2.1 When internally threaded anchors are supplied without fastening items, such as bolts, the manufacturer shall specify the bolts to be used. To achieve concrete breakout failure for comparison with Eq. (7-1), it shall be permitted to use bolts of higher strength than those specified, provided that those bolts do not change the functioning, setting, or follow-up expansion of the anchors.

4.2.2 Perform separate reference and reliability tests in accordance with Tables 4.1 or 4.2 for each anchor material and production method. If the results of the reference and reliability tests for the anchors of each material and production method are statistically equivalent, the service-condition tests of Table 4.1 (Tests 7, 8, and 9), and of Table 4.2 (Tests 9, 10, and 11) shall be permitted to be performed for one anchor material and production method only. Otherwise, perform the complete test program for each anchor material and production method.

4.2.3 The sample sizes given in Tables 4.1 and 4.2 are the minimum required to satisfy the requirements of this standard. At the discretion of the independent testing and evaluation agency or manufacturer, the sample size shall be permitted to be increased.

4.3—Testing by independent testing and evaluation agency and by manufacturer

All reference and reliability tests shall be performed by the independent testing and evaluation agency (Chapter 12).

Not more than 50% of the service-condition tests required by ACI 355.2 shall be performed by the manufacturer. All tests performed by the manufacturer shall be witnessed by an independent testing laboratory or engineer meeting the

Table 4.2—Test program for evaluating anchor systems for use in cracked and uncracked concrete

Test number	Section	Purpose	Description	Crack opening width w, in. (mm)	Concrete strength	Member thickness	Drill bit diameter	Minimum sample size[*] n
			Reference tests					
1	7.2	Reference test in uncracked low-strength concrete	Tension—single anchor with no edge influence	—	Low	$\geq h_{min}$	d_m	5
2	7.2	Reference test in uncracked high-strength concrete	Tension—single anchor with no edge influence	—	High	$\geq h_{min}$	d_m	5
3	7.2	Reference test in low-strength, cracked concrete	Tension—single anchor with no edge influence	0.012 (0.3)	Low	$\geq h_{min}$	d_m	5
4	7.2	Reference test in high-strength, cracked concrete	Tension—single anchor with no edge influence	0.012 (0.3)	High	$\geq h_{min}$	d_m	5
			Reliability tests					
5	8.2	Sensitivity to reduced installation effort	Tension—single anchor with no edge influence	0.012 (0.3)	Varies with anchor type	$\geq h_{min}$	d_m[†]	5
6	8.3	Sensitivity to crack width and large hole diameter	Tension—single anchor with no edge influence	0.020 (0.5)	Low	$\geq h_{min}$	d_{max}	5
7	8.4	Sensitivity to crack width and small hole diameter	Tension—single anchor with no edge influence	0.020 (0.5)	High	$\geq h_{min}$	d_{min}	5
8	8.6	Test in cracks whose opening width is cycled	Sustained tension—single anchor with no edge influence, residual capacity	0.004 to 0.012 (0.1 to 0.3)	Low	$\geq h_{min}$	d_{max}[§]	5
			Service-condition tests					
9	9.2	Verification of full concrete capacity in corner with two edges located at $1.5h_{ef}$	Tension—single anchor in corner with two edges located at $1.5h_{ef}$	—	Low	h_{min}	d_m	4
10	9.3	Minimum spacing and edge distance to preclude splitting on installation in uncracked concrete	High installation tension (torque or direct)—two anchors near edge	—	Low	h_{min}	d_m	5
11	9.4	Shear capacity of anchor steel[‡]	Shear—single anchor with no edge influence	—	Low	$\geq h_{min}$	d_m	5
12[‖]	9.5	Seismic tension	Pulsating tension, single anchor, with no edge influence	0.020 (0.5)	Low	$\geq h_{min}$	d_m	5
13[‖]	9.6	Seismic shear	Alternating shear, single anchor, with no edge influence	0.020 (0.5)	Low	$\geq h_{min}$	d_m	5

[*] Minimum sample size for each anchor diameter, unless otherwise noted.

[†] Drilling diameters for undercuts are specified in Table 5.6.

[‡] Required only for anchors whose cross-sectional area, within five anchor diameters for the shear failure plane, is less than that of a threaded bolt of the same nominal diameter as the anchor, or for sleeved anchors when shear capacity of the sleeve will be considered.

[§] Test of undercut anchors use d_m.

[‖] These tests are optional.

requirements of Chapter 12. The manufacturer's tests shall only be considered in the evaluation if the results are statistically equivalent to those of the independent testing and evaluation agency.

4.4—Changes to product

Before an anchor is changed, the manufacturer shall report the nature and significance of the change to the independent testing and evaluation agency (Chapter 12), which shall determine which tests, if any, shall be performed. For all changes that might affect the anchor performance, the testing and evaluation agency shall perform the reference tests and the reliability tests. If test results of the modified product are statistically equivalent to those of the originally tested product, then no additional testing is required. Otherwise, test the changed products in accordance with Table 4.1 or 4.2.

CHAPTER 5—REQUIREMENTS FOR TEST SPECIMENS, INSTALLATION OF ANCHORS, AND CONDUCT OF TESTS

5.1—Concrete for test members

Concrete used in testing shall meet the requirements of 5.1.1 through 5.1.4.

5.1.1 *Aggregates*—For normalweight concrete, aggregates shall conform to ASTM C 33, and the maximum aggregate size shall be 3/4 or 1 in. (19 or 25 mm).

5.1.2 *Cement*—Use only portland cement conforming to ASTM C 150. The concrete mixture shall not include any other cementitious materials (for example, slag, fly ash, silica fume, or limestone powder) or chemical admixtures (for example, air-entraining agents, water reducers, high-range water reducers, shrinkage-compensating admixtures, corrosion inhibitors, set retarders, and set accelerators).

5.1.3 *Concrete strength*—Test anchors in test members cast of concrete within two nominal compressive strength ranges, based on compressive strength specimens prepared and tested in accordance with ASTM C 31 and ASTM C 39 (refer to Appendix A3.3.1). These strength ranges are:

- low-strength concrete: 2500 to 3500 psi (17 to 24 MPa); and
- high-strength concrete: 6500 to 8000 psi (46 to 55 MPa).

5.1.4 *Test members*—Test members shall conform to the requirements of Appendix A3.

5.2—Anchor installation

5.2.1—*General requirements*

5.2.1.1 Install anchors according to the manufacturer's instructions, except as otherwise prescribed in ACI 355.2.

5.2.1.2 Install anchors in a formed face of the concrete or in concrete with a steel-troweled finish.

5.2.1.3 The components of the anchor, on which the performance will depend, shall not be exchanged. Bolts, nuts, and washers not supplied with the anchors shall conform to the specifications given by the manufacturer, and these specifications shall be included in the evaluation report.

Table 5.1—Required diameters of carbide hammer-drill bits, inch-pound

Nominal diameter, in.	Tolerance ranges		
	d_{min}, in.	d_m, in.	d_{max}, in.
1/4	0.252 to 0.256	0.260 to 0.263	0.266 to 0.268
5/16	0.319 to 0.323	0.327 to 0.331	0.333 to 0.335
3/8	0.381 to 0.385	0.390 to 0.393	0.396 to 0.398
7/16	0.448 to 0.452	0.458 to 0.462	0.465 to 0.468
1/2	0.510 to 0.514	0.520 to 0.524	0.527 to 0.530
9/16	0.573 to 0.577	0.582 to 0.586	0.589 to 0.592
5/8	0.639 to 0.643	0.650 to 0.654	0.657 to 0.660
11/16	0.702 to 0.706	0.713 to 0.717	0.720 to 0.723
3/4	0.764 to 0.768	0.775 to 0.779	0.784 to 0.787
13/16	0.827 to 0.831	0.837 to 0.841	0.846 to 0.849
27/32	0.858 to 0.862	0.869 to 0.873	0.878 to 0.881
7/8	0.892 to 0.896	0.905 to 0.909	0.914 to 0.917
15/16	0.955 to 0.959	0.968 to 0.972	0.977 to 0.980
1	1.017 to 1.021	1.030 to 1.034	1.039 to 1.042
1-1/8	1.145 to 1.149	1.160 to 1.164	1.172 to 1.175
1-3/16	1.208 to 1.212	1.223 to 1.227	1.235 to 1.238
1-1/4	1.270 to 1.274	1.285 to 1.289	1.297 to 1.300
1-5/16	1.333 to 1.337	1.352 to 1.356	1.364 to 1.367
1-3/8	1.395 to 1.399	1.410 to 1.414	1.422 to 1.425
1-7/16	1.458 to 1.462	1.472 to 1.476	1.484 to 1.487
1-1/2	1.520 to 1.524	1.535 to 1.539	1.547 to 1.550
1-9/16	1.570 to 1.574	1.588 to 1.592	1.605 to 1.608
1-5/8	1.637 to 1.641	1.655 to 1.659	1.673 to 1.675
1-3/4	1.754 to 1.758	1.772 to 1.776	1.789 to 1.792
2	1.990 to 1.994	2.008 to 2.012	2.025 to 2.028

Table 5.2—Required diameters of carbide hammer-drill bits, SI

Nominal diameter, mm	Tolerance ranges		
	d_{min}, mm	d_m, mm	d_{max}, mm
6	6.05 to 6.15	6.20 to 6.30	6.35 to 6.40
7	7.05 to 7.20	7.25 to 7.35	7.40 to 7.45
8	8.05 to 8.20	8.25 to 8.35	8.40 to 8.45
10	10.10 to 10.20	10.25 to 10.35	10.40 to 10.45
11	11.10 to 11.20	11.25 to 11.35	11.45 to 11.50
12	12.10 to 12.20	12.25 to 12.35	12.45 to 12.50
13	13.10 to 13.20	13.25 to 13.35	13.45 to 13.50
14	14.10 to 14.20	14.25 to 14.35	14.45 to 14.50
15	15.10 to 15.20	15.25 to 15.35	15.45 to 15.50
16	16.10 to 16.20	16.25 to 16.35	16.45 to 16.50
18	18.10 to 18.20	18.25 to 18.35	18.45 to 18.50
19	19.10 to 19.20	19.30 to 19.40	19.50 to 19.55
20	20.10 to 20.20	20.30 to 20.40	20.50 to 20.55
22	22.10 to 22.20	22.30 to 22.40	22.50 to 22.55
24	24.10 to 24.20	24.30 to 24.40	24.50 to 24.55
25	25.10 to 25.20	25.30 to 25.40	25.50 to 25.55
28	28.10 to 28.20	28.30 to 28.40	28.50 to 28.55
30	30.10 to 30.20	30.30 to 30.40	30.50 to 30.55
32	32.15 to 32.25	32.35 to 32.50	32.60 to 32.70
34	34.15 to 34.25	34.35 to 34.50	34.60 to 34.70
35	35.15 to 35.25	35.35 to 35.50	35.60 to 35.70
37	37.15 to 37.25	37.35 to 37.50	37.60 to 37.70
40	40.15 to 40.25	40.40 to 40.60	40.70 to 40.80
44	44.15 to 44.25	44.40 to 44.60	44.70 to 44.80
48	48.15 to 48.25	48.40 to 48.60	48.70 to 48.80
52	52.15 to 52.25	52.40 to 52.60	52.80 to 52.95

5.2.2 *Drill bit requirements*—Drill bit requirements are given in Tables 5.1 and 5.2. Drill holes for anchors perpendicular (within a tolerance of ±6 degrees) to the surface of the concrete member. Except for self-drilling anchors and as specified in 5.2.2.3 and 5.2.2.5, holes shall be made using carbide-tipped, hammer-drill bits meeting the requirements of ANSI B212.15.

5.2.2.1 The cutting diameter of drill bits shall conform to the tolerances given in Table 5.1 or 5.2, and shall be checked after every 10 holes are drilled to ensure continued compliance.

5.2.2.2 When performing tests with bits of diameter d_{max}, d_m, *or* d_{min}, it shall be permitted to use test bits ground to the desired diameter.

5.2.2.3 Drill bits with diameter d_{min} correspond to well-worn bits. These diameters are less than the minimum diameters specified for new bits in ANSI B212.15.

5.2.2.4 All service-condition tests (Tables 4.1 and 4.2) use a bit of diameter d_m.

5.2.2.5 For drill bits not included in the range of diameters given in Tables 5.1 or 5.2, and for drill bits not covered by ANSI B212.15, the independent testing and evaluation agency shall develop diameters for the bits that conform to the concept of d_{max}, d_m, and d_{min}, as represented in those tables.

5.2.3—*Setting requirements for testing*

Table 5.3—Required degree of setting torque for torque-controlled expansion anchors

Table 4.1, test number	Table 4.2, test number	Required degree of setting torque
3	5	Partial, $0.5T_{inst}$
1,2,4,5,6,7,9	1,2,3,4,6,7,9,11,12,13	Full[*]
8	10	Special requirements in 9.3

[*] According to manufacturer's installation instructions, then reduced to 50% per 5.2.3.1.1.

Table 5.4—Required degree of expansion of displacement-controlled expansion anchors

Table 4.1, test number	Table 4.2, test number	Required degree of expansion
3	5	Partial
4,5,6	6,7,8	Reference
1,2,7,9	1,2,3,4,9,11,12,13	Full[*]
8	10	Special requirements in 9.3

[*] According to manufacturer's installation instructions.

Table 5.5—Parameters for establishing partial and reference expansion of displacement-controlled anchors

Anchor size	1/4 in. (M6)	5/16 in. (M8)	3/8 in. (M10)	1/2 in. (M12)	5/8 in. (M16)	3/4 in. (M20)
Weight, lb (kg)	10 (4.5)	10 (4.5)	10 (4.5)	10 (4.5)	33 (15)	33 (15)
Height of fall, in. (mm)	18 (450)	18 (450)	18 (450)	18 (450)	24 (600)	24 (600)
Number of drops for evaluation of partial expansion	2	3	4	5	3	4
Number of drops for evaluation of reference expansion	3	5	6	7	4	5

5.2.3.1 *General torque requirements*—When the application of torque for an anchor is specified by the manufacturer, torque each anchor as required in 5.2.3.1.1 and 5.2.3.2, except for reliability tests where reduced installation effort is required, in 8.2. If no torque for the anchor is specified by the manufacturer, the anchor shall be finger-tight before testing.

5.2.3.1.1 Apply the specified torque, T_{inst}, using a calibrated torque wrench having a measuring error within ±5% of the specified torque. Remove the torque wrench and wait 10 min. Completely loosen the anchor. Apply a torque of $0.5T_{inst}$ using the calibrated torque wrench.

5.2.3.2 *Setting of torque-controlled expansion anchors*—Install torque-controlled expansion anchors in accordance with Table 5.3 and requirements Section 5.2.3.1.

5.2.3.2.1 For the reliability tests performed with reduced installation effort (Table 4.1, Test 3 and Table 4.2, Test 5), install and set the anchor with a setting torque of $0.5T_{inst}$. Do not reduce the torque from this amount.

5.2.3.2.2 For the seismic tests (Table 4.2, Tests 12 and 13), follow the torque application procedures in 5.2.3.1.1 before the crack is widened.

5.2.3.3 *Setting of displacement-controlled expansion anchors*—Install displacement-controlled expansion anchors with the degree of expansion specified in Table 5.4. The specified degrees of expansion are obtained using setting tools based on the number of drops specified in Table 5.5 for partial and reference expansion, developed in 5.2.3.3.1 and 5.2.3.3.2. See Fig. 5.1 for the test fixture used to establish the partial and reference setting expansions. These tests shall be performed in high-strength concrete and with a drill bit of diameter d_m.

5.2.3.3.1 *Partial expansion*—Set a minimum of five anchors using the weight and number of drops from Table 5.5 for partial expansion. For each anchor, measure the depth of

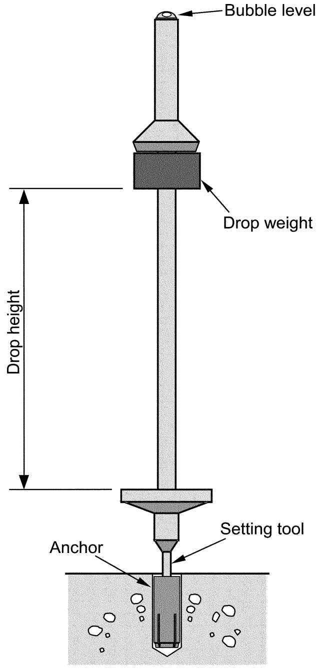


Fig. 5.1—Installation tool for setting tests of displacement-controlled expansion anchors.

the plug from the upper end of the anchor. Calculate the average depth of the plug for the set anchors. Modify (shorten) the manufacturer's setting tool to provide the calculated setting depth. Use this setting tool for Test 3 in Table 4.1 or Test 5 in Table 4.2.

5.2.3.3.2 *Reference expansion*—Prepare a setting tool for Tests 4, 5, and 6 of Table 4.1, or Tests 6, 7, and 8 of Table 4.2 using the same method described in 5.2.3.3.1, but using the number of drops for evaluation of reference expansion from Table 5.5.

5.2.3.4 *Setting of undercut anchors*—Install undercut anchors as specified in Table 5.6. Table 5.6 provides for combinations of parameters for various undercut anchor types. In other tests prescribed in Tables 4.1 and 4.2, drill a cylindrical hole with a diameter as given in Tables 4.1 or 4.2 and produce the undercut as per manufacturer's instructions. In tests of Table 4.1, Test 3, and Table 4.2, Test 5, set undercut anchors using a combination of the specified setting tolerances that produces the minimum bearing surface in the concrete.

5.3—Test methods

Test anchors in conformance with ASTM E 488 and the appropriate Chapter 7, 8, or 9 of ACI 355.2.

5.4—Tests in cracked concrete

Use the procedure specified in 5.4.1 through 5.4.4 for testing anchors in cracked concrete.

5.4.1 Perform tests in concrete specimens meeting the requirements of Appendix A3, with the crack width, w, as specified for the given test. Initiate the crack and install the anchor according to 5.2 so that the axis of the anchor lies approximately in the plane of the crack. Install the instrumentation for measuring crack widths, and widen the crack by the specified crack width while the anchor is not loaded. Measure the crack opening using two dial gauges or electronic transducers, one on either side of the anchor, oriented perpendicular to the crack.

5.4.2 Subject the anchor to the specified loading sequence while monitoring the crack width at the surface. Refer to Appendix A3.

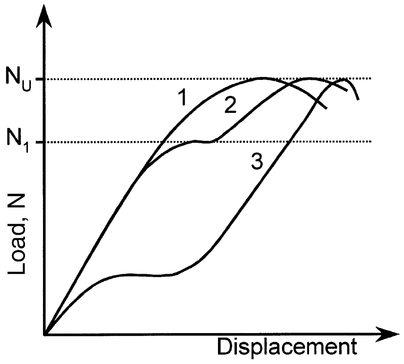
5.4.3 During the test, maintain a continuous record of the load applied to the anchor, the displacement of the anchor, and the crack width.

5.4.4 *Tolerance on crack width*—The average of the crack widths for each test series, measured by the two crack measurement devices for each anchor, before the load application shall be equal to or greater than the specified crack width for that test series. Individual crack widths shall be within ±15% of the specified crack width for the test series.

5.5—General requirements for anchor behavior

5.5.1 *Overall load-displacement behavior*

5.5.1.1 To be acceptable, the tensile load-displacement behavior of single anchors shall be predictable except as noted in 5.5.1.2. Figure 5.2 provides examples of acceptable and unacceptable load-displacement curves for the types of anchors covered by ACI 355.2. For each anchor tested, a load plateau with a corresponding slip greater than 5% of the displacement at ultimate load, or a temporary drop in load, is



Curves 1 and 2 show acceptable behavior.

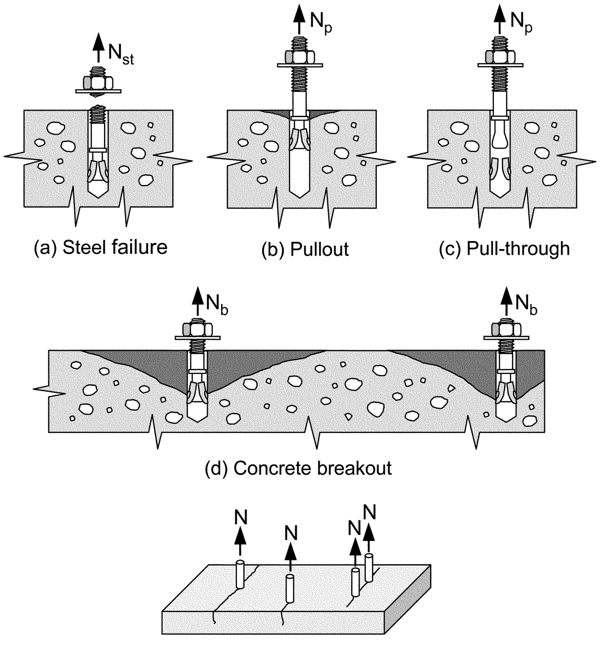
Curve 3 shows unacceptable behavior.

Fig. 5.2—Requirements for load-displacement curves.

Table 5.6—Installation requirements for undercut anchors in reliability tests

	Type of undercut anchor (Fig. 2.3)				
	Load-controlled	Displacement-controlled		Torque-controlled	
Installation requirements	Type 1 undercut, predrilled	Types 2 and 3 undercut, predrilled	Type 4 undercut, self-drilled	Type 5 undercut, predrilled	Type 6 undercut, self-drilled
Bit diameter for cutting cylindrical hole	Maximum	Maximum	Maximum	Maximum	Maximum
Undercutting tool diameter	Minimum specification	Minimum specification	—	Minimum specification	—
Tolerances on length of undercutting tool (where applicable)	Maximum tolerance length	Maximum tolerance length	Maximum	Maximum tolerance length	Maximum tolerance length
Length of sleeve	—	Minimum tolerance length	—	—	—
Length of cylindrical hole	—	Maximum tolerance length	Maximum tolerance length	—	—
Setting of anchor	75% of specified load	Sleeve flush with concrete surface[*]	Sleeve flush with concrete surface	50% of specified torque	50% of specified torque or flush to surface

[*] If the anchor system is designed to provide consistent and visual verification of full set by marks on the bolt or sleeve, alternative methods of achieving reduced setting shall be permitted after establishment by the independent test and evaluation agency in collaboration with the anchor manufacturer.

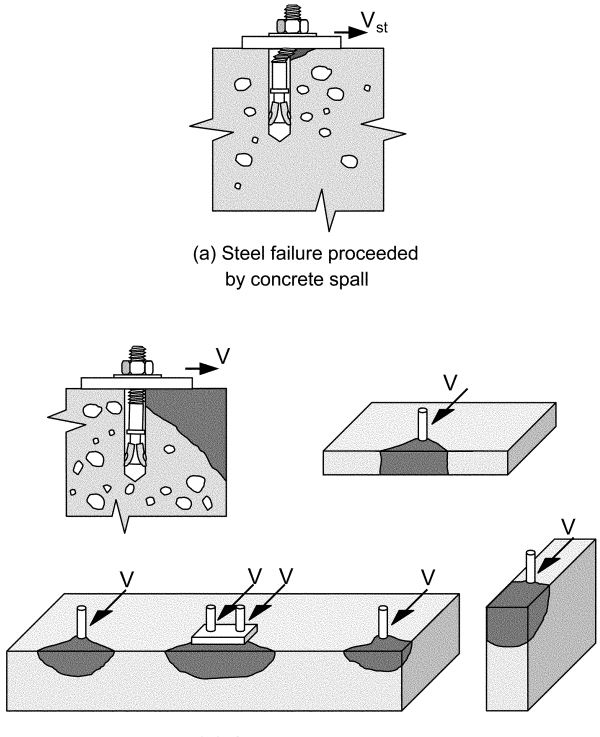


(a) Steel failure (b) Pullout (c) Pull-through

(d) Concrete breakout

(e) Concrete splitting

Fig. 5.3—Failure modes for anchors under tensile loading.



(a) Steel failure proceeded by concrete spall

(b) Concrete breakout

Fig. 5.4—Failure modes for anchors under shear loading.

not acceptable at load levels less than N_1. For tests in uncracked concrete, N_1 is taken as the smaller of $0.8N_u$ and $A_{se}f_y$. For tests in cracked concrete, N_1 is taken as the smaller of $0.7N_u$ and $A_{se}f_y$. These requirements shall be fulfilled in the reference tests (Tests 1 and 2 of Table 4.1 and Tests 1 through 4 of Table 4.2), reliability tests (Tests 3, 4, 5, and the initial loading and residual capacity of Test 6 of Table 4.1 and Tests 5, 6, 7, and the residual capacity of Test 8 of Table 4.2), and service-condition tests (Tests 7 and 8 of Table 4.1 and Tests 9 and 10, and the residual capacity of Test 12 of Table 4.2).

Table 5.7—Required embedment depths for test program

Embedment depth to be tested for given diameter	Test number for embedment depths		
	Shallow	Deep	All
Table 4.1	3,4,5,6,7,8,9	3,4,5,6,7	1,2
Table 4.2	5,6,7,8,9,10,11,12,13	5,6,7,8,9,12,13	1,2,3,4

5.5.1.2 Within a test series, if not more than one test shows a load-displacement curve not complying with 5.5.1.1, the anchor shall be considered acceptable provided that two conditions are met:

1. There is no drop in load; and
2. The deviation is justified as being uncharacteristic of the anchor behavior and is due, for example, to a defect in the test procedure or the base material. Such defects shall be described in detail in the evaluation report, and the results of an additional 10 tension tests shall display load-displacement curves meeting the requirements of 5.5.1.1.

5.5.2 *Load-displacement behavior at service loads*—For each reference test series (combination of anchor diameter and embedment depths), determine the mean anchor stiffness value β from Eq. (5-1) and coefficient of variation, ν, in the service-load range, and report these values in Table 11.1 or Table 11.2, as applicable.

$$\beta = \frac{N_{30\%} - N_{10\%}}{\Delta_{30\%} - \Delta_{10\%}} \qquad (5\text{-}1)$$

5.5.3 *Modes of failure*—The failure modes for tension loading are concrete cone failure, steel fracture, pullout or pull-through, test member splitting, and side-face blowout. The failure modes for shear loading are steel failure and concrete breakout for anchors located near an edge. Figures 5.3 and 5.4 give examples of these failure modes. Report the failure mode for each individual anchor tested and the strength (k values for concrete, $f_{u,test}$ for steel failure, and N_p for pullout and pull-through failure) for each test series.

If during a test series different failure modes occur, and one failure mode predominates and other failure modes occur, and are of similar capacities, note the failure modes and failure loads of the tests in the test report. Report the average failure load, taking into account all results as the failure load associated with the predominate failure mode.

If no failure mode predominates in a test, test additional anchors to obtain at least five samples for each failure mode and conduct a significant difference test to see if the capacities for the different failure modes are statistically different.

5.5.3.1 If an anchor of a particular diameter has only one embedment depth, then tests are performed to establish the appropriate data. If steel failure is the only failure mode, report $f_{u,test}$ for steel failure, and report the minimum permissible k value for concrete from Table 7.1. Alternatively, to determine k for concrete failure, it shall be permitted to use a shallower embedment depth or a higher-strength steel bolt, as long as it does not affect the functioning of the anchor.

5.5.3.2 If there is more than one embedment depth specified for an anchor diameter, perform tests according to Table 5.7. Report the respective failure modes and the lowest k value for concrete failure, $f_{u,test}$ for steel failure, and N_p for pullout and pull-through failure. Where different failure modes occur in a test series involving a single diameter and different embedment depths, report each observed failure mode and its corresponding characteristic strength.

5.5.3.3 For pullout or pull-through failure, calculate N_p (5% fractile) based on the test sample size. Report k as the minimum permissible value from Table 7.1.

CHAPTER 6—REQUIREMENTS FOR ANCHOR IDENTIFICATION

6.1—Determination of critical characteristics of anchors

The anchor manufacturer, in consultation with the independent testing and evaluation agency, shall determine the characteristics affecting the identification and performance of the anchor being evaluated. These characteristics can include, but are not limited to, dimensions, constituent materials, surface finishes, coatings, fabrication techniques, and the marking of the anchors and components.

6.2—Specification of critical characteristics of anchors

The manufacturer shall include in the drawings and specifications for the anchor those characteristics determined to be critical.

6.3—Verification of conformance to drawings and specifications

6.3.1 The following characteristics shall be checked by the independent testing and evaluation agency for conformance to the drawings and specifications:

- Critical dimensions;
- Surface finishes;
- Coatings;
- Fabrication techniques; and
- Markings.

6.3.2 *Constituent materials*—Critical constituent materials shall be checked by the independent testing and evaluation agency for conformance to mechanical and chemical specifications using certified mill test reports for steels and using similar certified documents for other materials.

6.3.3 *Quality control*—Anchors shall be manufactured under a certified quality system meeting the requirements of the ISO 9000 quality management system or equivalent. Manufacturers shall undergo a conformity assessment by an accredited quality-system registrar and shall maintain a certification or registration in conformance to that standard.

CHAPTER 7—REFERENCE TESTS

7.1—Purpose

Reference tests are performed to obtain baseline values for the reliability and service-condition tests. The reference test requirements are given in 7.2 through 7.3, and in Table 4.1 for uncracked concrete and in Table 4.2 for both cracked and uncracked concrete. The results of the reference tests shall be used to establish the anchor category in accordance with Chapter 10.

Table 7.1—Minimum and maximum values of effectiveness factor *k*

	Minimum permissible value of k		Maximum reportable value of k	
Type of test	Inch-pound	SI	Inch-pound	SI
Cracked concrete	17	7	21	9
Uncracked concrete	24	10	30	13

7.2—Reference tension tests for single anchors without spacing and edge effects (Table 4.1, Tests 1 and 2, or Table 4.2, Tests 1, 2, 3, and 4)

7.2.1 *Requirements for reference tests*—Perform tension tests in accordance with Table 4.1, Test 1 and 2, or Table 4.2, Tests 1, 2, 3, and 4. Perform the tests on anchors installed in low-strength and high-strength concrete. The coefficient of variation ν of the ultimate tension load in any test series, including those performed with an increased number of replicates, shall not exceed 15%. If the coefficient of variation obtained from the original or cumulative test series does not meet this requirement, the sample size shall be permitted to be increased. If this requirement is not met, the anchor shall be considered unqualified.

7.3—Required calculations using results of reference tests

7.3.1 *For concrete failure*—Calculate the value of the effectiveness factor, k, from test results, using Eq. (7-1) and considering the test conditions and sample size in evaluating N_b (Refer to Appendix A1).

$$k = \frac{N_b}{\sqrt{f_{c,\,test,\,i}}\,h_{ef}^{1.5}} \quad (7\text{-}1)$$

If the calculated k values do not meet the minimum permissible values of Table 7.1, determine the characteristic tension resistance in accordance with 7.3.3. The k values reported in Table 11.1 or 11.2, as applicable, shall not exceed the maximum reportable k values of Table 7.1.

7.3.2 *For steel failure in tension, cracked and uncracked concrete*—When steel failure occurs for the embedment depth and steel strength reported in Table 11.1 or 11.2, as applicable, report k as the minimum permissible value prescribed by Table 7.1. Alternatively, k shall be permitted to be determined by Eq. (7-1), using tests on the same anchor with a reduced embedment depth, a higher-strength steel, or both, to produce failure by concrete breakout.

7.3.3 *For pullout failure in tension, cracked and uncracked concrete*—For pullout or pull-through failures, calculate the characteristic tensile capacity, N_p, using the test data in accordance with the procedure in Appendix A2, and report N_p.

CHAPTER 8—RELIABILITY TESTS

8.1—Purpose

Reliability tests are performed to establish that the anchor is capable of safe, effective behavior under normal and adverse conditions, both during installation and in service. The reliability test requirements for uncracked concrete (Table 4.1) and both cracked and uncracked concrete (Table 4.2) are given in this chapter. The results of the reliability tests shall be used to establish the anchor category in accordance with Chapter 10.

8.2—Reliability tests using reduced installation effort (Table 4.1, Test 3, and Table 4.2, Test 5)

8.2.1 *Purpose*—These reliability tests are performed to determine the sensitivity of the anchor to adverse installation conditions. Perform these tests under tension loading.

8.2.2 *General test conditions*—In cracked concrete, use a minimum crack-opening width of 0.012 in. (0.3 mm), except as noted.

8.2.2.1 *Torque-controlled expansion anchors*—Perform tests on anchors installed in high-strength concrete with setting torque $T = 0.5T_{inst}$ and a drill bit of diameter d_m. Refer to Fig. 2.2 for anchor types.

8.2.2.2 *Displacement-controlled expansion anchors*—Perform tests on anchors installed in low-strength concrete, using a drill bit of diameter d_m. Refer to Fig. 2.1 for anchor types. Installation requirements for displacement-controlled expansion anchors are prescribed in Table 5.4 and 5.5 for partial expansion.

8.2.2.3 *Torque, load, and displacement-controlled undercut anchors*—For torque-controlled and load-controlled undercut anchors, perform tension tests using low- and high-strength concrete. For displacement-controlled undercut anchors, perform tension tests using low-strength concrete. Refer to Fig. 2.3 for anchor types. Installation requirements for undercut anchors are prescribed in 5.2.3.4.

8.2.3 *Requirements*—The coefficient of variation ν of the ultimate tension load in any test series, including those performed with an increased number of replicates, shall not exceed 20%. If the coefficient of variation of the original or cumulative test series does not meet this requirement, the sample size shall be permitted to be increased. If the requirement for maximum coefficient of variation is not met, the anchor shall be considered unqualified. The capacity of the anchor as determined in this test series shall be used to establish the anchor category according to Chapter 10.

8.3—Reliability in low-strength concrete with large drill bit (Table 4.1, Test 4, and Table 4.2, Test 6)

8.3.1 *Purpose*—These reliability tests are performed in uncracked concrete (Table 4.1) to evaluate the sensitivity of the anchor to low-strength concrete and oversized holes. They are performed in cracked concrete (Table 4.2) to evaluate the sensitivity of the anchor to low-strength concrete, oversized holes, and opened cracks.

8.3.2 *General test conditions*—Perform tests under tension loading in low-strength concrete for all anchor types with a drill bit of diameter d_{max}. For anchor tests in cracked concrete, use a minimum crack-opening width of 0.020 in. (0.5 mm). The anchor capacity as determined in this test series shall be used to establish the anchor category according to Chapter 10.

8.3.3 *Requirements*—The coefficient of variation ν of the ultimate tension load in any test series, including those performed with an increased number of replicates, shall not exceed 20%. If the coefficient of variation of the original or cumulative test series does not meet this requirement, the sample size shall be permitted to be increased. If the requirement for maximum coefficient of variation is not met, the anchor shall be considered unqualified.

8.4—Reliability in high-strength concrete with small drill bit (Table 4.1, Test 5, and Table 4.2, Test 7)

8.4.1 *Purpose*—These reliability tests are performed in uncracked concrete to evaluate the sensitivity of the anchor to undersized holes in high-strength concrete. They are performed in cracked concrete to evaluate the sensitivity of the anchor to undersized holes and opened cracks in high-strength concrete.

8.4.2 *General test conditions*—Perform tests under tension loading in high-strength concrete for all anchor types. Use a drill bit of diameter d_{min}. In cracked concrete tests, use a minimum crack-opening width of 0.020 in. (0.5 mm). The anchor capacity as determined in this test series shall be used to establish the anchor category according to Chapter 10.

8.4.3 *Requirements*—The coefficient of variation ν of the ultimate tension load in any test series, including those performed with an increased number of replicates, shall not exceed 20%. If the coefficient of variation of the original or cumulative test series does not meet this requirement, the sample size shall be permitted to be increased. If the requirement for maximum coefficient of variation is not met, the anchor shall be considered unqualified.

8.5—Reliability under repeated load (Table 4.1, Test 6)

8.5.1 *Purpose*—These reliability tests are performed to evaluate the performance of the anchor under repeated load in uncracked concrete subjected to normal building movements.

8.5.2 *General test conditions*—Subject the anchor to a pulsating tensile load that varies sinusoidally between a maximum and minimum load. The maximum load N_{max} shall be the smaller of $0.6N_k$ or $0.7A_{se} \cdot f_y$. The minimum load N_{min} shall be the greater of $0.25N_k$ or the maximum load N_{max}, as determined previously, minus $A_{se} \cdot$ 17,400 psi (120 MPa). The loading frequency shall be 6 Hz or less. Measure anchor displacement continuously, or, up to the maximum load during the first loading, and then after 10, 10^2, 10^3, 10^4, and 10^5 load cycles. At the end of the cyclic loading, test the anchor in tension to failure. This residual capacity shall be used to establish the anchor category according to Chapter 10.

8.5.3 *Requirement*—Anchor displacements shall show a stabilization of movement, and the mean residual capacity of the anchor shall be not less than 80% of the mean capacity in the corresponding reference test. The coefficient of variation ν of the ultimate tension load in any test series, including those performed with an increased number of replicates, shall not exceed 20%. If the coefficient of variation of the original or cumulative sample size does not meet this requirement, the sample size shall be permitted to be increased. If the requirement for maximum coefficient of variation is not met, the anchor shall be considered unqualified.

8.6—Reliability in cracked concrete where crack width is cycled (Table 4.2, Test 8)

8.6.1 *Purpose*—These reliability tests are performed to evaluate the performance of anchors located in cracks whose width is cycled.

8.6.2 *General test conditions*—Before installing the anchor, 10 opening and closing cycles shall be permitted to stabilize crack formation. Install the anchor according to 5.2 such that the axis of the anchor lies approximately in the plane of the crack. Open the crack to a crack width w_1 = 0.012 in. (0.3 mm). Apply a sustained tensile load of N_w as calculated from Eq. (8-1). Cycle the crack width between the maximum crack opening width of w_1 = 0.012 in. (0.3 mm) and the initial minimum crack width of w_2 = 0.004 in. (0.1 mm).

$$N_w = 0.3 \cdot N_p \cdot \sqrt{\frac{f_{c,test}}{f'_c}} \qquad (8\text{-}1)$$

where

N_w = static tension load applied to anchor during crack width cycling;

N_p = characteristic pullout resistance for the minimum specified concrete strength of 2500 psi (17 MPa);

f'_c = specified concrete compressive strength of 2500 psi (17 MPa); and

$f_{c,test}$ = mean concrete compressive strength as measured at time of testing.

For anchors not failing by pullout or pull-through, the characteristic tensile resistance in low-strength cracked concrete N_b as determined from reference tests shall be substituted for N_p in Eq. (8-1).

As the crack width is varied cyclically, keep N_w constant within a tolerance of ±5%. Open and close the crack 1000 times at a maximum frequency of 0.2 Hz. During cycling of the crack, keep the crack width w_1 constant. The crack width w_2 is expected to increase during the test (Fig. 8.1). The difference between the maximum and minimum crack widths during the 1000 cycles shall be at least 0.004 in. (0.1 mm). If at any time during the test, the value of $w_1 - w_2$ falls below 0.004 in. (0.1 mm), either reduce the lower-bound load, increase the upper-bound load, or change both, until the minimum value of $w_1 - w_2$ = 0.004 in. (0.1 mm) is restored. Note that an increase in the upper-bound load corresponds to an increase in the maximum crack width w_1 beyond 0.012 in. (0.3 mm).

8.6.3 Measure the load-displacement relationship up to load N_w. Afterward, under N_w, measure the displacements of the anchor and the crack-opening widths w_1 and w_2, either continuously or at least after 1, 2, 5, 10, 20, 50, 100, 200, 500, and 1000 cycles of crack opening and closing.

8.6.4 After completing the cycles of crack opening and closing, unload the anchor, measure the residual displacement, and perform a tension test to failure with a crack width w = 0.012 in. (0.3 mm) at the start of the tension test to failure. During the test, monitor, but do not control, the crack width. This residual capacity shall be used to establish the anchor category according to Chapter 10.

8.6.5 *Requirement*—In each test, the anchor displacement shall be less than 0.080 in. (2.0 mm) after the initial 20 cycles of crack opening and closing, and less than 0.120 in. (3.0 mm) after 1000 cycles, except as permitted in the following.

If the anchor displacement exceeds these limits during the crack cycling portion of the test, it shall be permitted to increase the number of replicates. For a sample size of 10 to 20 replicates, one of the tested anchors shall be permitted to exhibit a maximum displacement of 0.120 in. (3.0 mm) after the initial 20 cycles and 0.160 in. (4.0 mm) after 1000 cycles. For sample sizes larger than 20, 5% of the tested anchors shall be permitted to exhibit these increased displacements. If the requirements are not met, repeat the tests with a reduced sustained tension load, $N_{w,red}$, on the anchor until the requirements are met. If the tests are performed with a reduced tension load $N_{w,red}$, pullout or pull-through data reported in Table 11.2 shall reflect tests conducted with $N_{w,red}$. The characteristic capacity N_p shall be calculated by Eq. (8-2).

$$N_p = k_p\sqrt{f'_c} \qquad (8\text{-}2)$$

where

N_p = characteristic pullout or pull-through capacity to be reported in Table 11.2;

$N_{w,red}$ = reduced static tension load applied to anchor during crack cycling portion of test; and

k_p = $\dfrac{N_{w,red}}{0.3\sqrt{f_{c,test}}}$.

Then reduce the characteristic pullout or pull-through capacity in proportion to the reduction in the sustained load; this reduced characteristic capacity shall be used in establishing the anchor category in Chapter 10. The mean residual capacity of the anchor shall be not less than 90% of the mean capacity in the corresponding reference test. The coefficient of variation ν of the ultimate tension load in any test series shall not exceed 20%. If the coefficient of variation of the original or cumulative test series does not meet this requirement, the sample size shall be permitted to be increased. If the requirement for maximum coefficient of variation is not met, the anchor shall be considered unqualified.

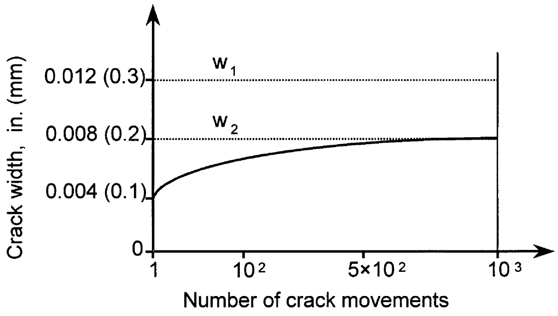


Fig. 8.1—Crack-width requirements for cyclic tests in cracked concrete.

CHAPTER 9—SERVICE-CONDITION TESTS

9.1—Purpose

The service-condition tests are performed to determine the basic data required to predict the performance of the anchor under service conditions.

9.2—Service-condition tension test with a single anchor and with two edges (corner) (Table 4.1, Test 7, and Table 4.2, Test 9)

9.2.1 *Purpose*—This test is performed to determine whether the anchor meets the requirement that the critical edge distance shall be $\leq 1.5h_{ef}$, in members with the minimum specified thickness for that anchor. Perform tests on single anchors in uncracked, low-strength concrete at a corner with equal edge distances of $1.5h_{ef}$, and test member thickness h_{min}.

9.2.2 *Requirements for critical edge distance*—The capacity of the anchor with two edge distances of $1.5h_{ef}$ shall be statistically equivalent to the capacity from the reference tests performed with no edge influence. If anchors do not satisfy this requirement, the distance from the two edges shall be increased until the requirement is met. Report the critical edge distance c_{cr} and the corresponding minimum member thickness in Table 11.1 or 11.2.

9.3—Service-condition test at minimum edge distance and minimum spacing (Table 4.1, Test 8, and Table 4.2, Test 10)

9.3.1 *Purpose*—This test is performed to check that the concrete will not experience splitting failure during anchor installation.

9.3.2 *General test conditions*—Test anchors in uncracked, low-strength concrete, with a drill bit of diameter d_m. Install two anchors at the minimum spacing, s_{min}, and the minimum edge distance, c_{min}, in test members with the minimum thickness, h_{min}, to be reported for the anchor. Place the two anchors in a line parallel to the edge of a concrete test element at a distance of at least $3h_{ef}$ from other groups. Select s_{min}, c_{min}, and h_{min}, depending on the anchor characteristics.

Separate bearing plates shall be permitted to be used for each anchor to simplify the detection of concrete cracking. The distance to the edge of the bearing plate from the centerline of the corresponding anchor shall be three times the diameter, d_o, of the anchor being tested plus or minus 10%.

9.3.3 For torque-controlled anchors, torque the anchors alternately in increments of $0.2T_{inst}$. After each increment, inspect the concrete surface for cracks. Stop the test when splitting or steel failure prevents the torque from being increased further. For each test, record the maximum torque. Record the torque at the formation of the first hairline crack at one or both anchors and the maximum torque that can be applied to the anchors.

9.3.4 For load-controlled undercut anchors, install the anchors according to the manufacturer's installation instructions and load the group of two anchors in tension to failure.

9.3.5 For displacement-controlled anchors and undercut anchors that are intended to perform properly without an installation torque, install the anchors according to the manufacturer's installation instructions and load the group of two anchors in tension to failure.

9.3.6 *Requirement*—For torque-controlled expansion and undercut anchors, the 5% fractile of the maximum recorded torque calculated according to Appendix A and normalized to $f_c = 2500$ lb/in.^{2} (17 MPa) by Eq. (A1-1) shall be larger than the smaller of $1.7T_{inst}$ or $1.0T_{inst}$ + 100 ft-lb (135 Nm). If this requirement is not met, repeat the tests with increased values c_{min} and for s_{min} until the requirement is met. For displacement-controlled expansion and undercut anchors and load-controlled anchors, the edge shall not be damaged during the setting process and the characteristic failure load shall be equal to or greater than the characteristic resistance for concrete cone breakout failure calculated according to provisions of ACI 318 Appendix D. If anchors do not meet these requirements, determine c_{min} and s_{min} according to:

- Hold c_{min} constant and increase s_{min}, and install the anchors according to 9.3.3, 9.3.4, or 9.3.5 until no splitting occurs;
- Hold s_{min} constant and increase c_{min}, and install the anchors according to 9.3.3, 9.3.4, or 9.3.5 until no splitting occurs; or
- Increase c_{min} and s_{min}, and install the anchors according to 9.3.3, 9.3.4, or 9.3.5 until no splitting occurs.

Report these minimum edge and spacing distances.

9.4—Service-condition shear test for single anchors without spacing and edge effects (Table 4.1, Test 9, and Table 4.2, Test 11)

9.4.1 *Purpose*—This test is performed to evaluate the shear capacity of anchors as governed by steel failure in situations where the shear capacity cannot be reliably calculated. Perform shear tests in uncracked low-strength concrete with a drill bit diameter d_m for anchors whose cross-sectional area is less than that of a threaded bolt of the same nominal diameter as the anchor within five anchor diameters of the shear failure plane. Also perform shear tests in uncracked concrete for sleeved anchors when the shear capacity of the sleeve is taken into account to resist shear loading. Calculate V_{st} using Appendix A2. When shear tests are not required, the anchor steel shear strength shall be determined by the methods of ACI 318, Appendix D.

9.4.2 For anchors evaluated according to Table 4.2 in cracked concrete, at the option of the manufacturer, shear tests shall be permitted to be performed in cracked concrete with a crack width of 0.012 in. (0.3 mm) with the load applied parallel to the crack. Characteristic shear capacities V_{st} obtained shall be reported in Table 11.2.

9.5—Service-condition, simulated seismic tension tests (Table 4.2, Test 12)

9.5.1 *Purpose*—These optional tests are performed to evaluate the performance of anchors in seismic tension, including the effects of cracks and without edge effects. If these seismic tests are performed, they shall only be acceptable as part of the total cracked concrete test program of Table 4.2.

9.5.2 *Tests*—Perform tests that simulate pulsating seismic tension loading on anchors at the shallowest embedment depth for which the anchor is to be qualified for use in cracked concrete. Anchors shall be permitted to be tested at deeper embedment depths to verify load capacities at deeper embedment depths. Install the anchor in a closed crack

Table 9.1—Required history of seismic tension load

Load level	N_{eq}	N_i	N_m
Number of cycles	10	30	100

Table 9.2—Required history of seismic shear load

Load level	$\pm V_{eq}$	$\pm V_i$	$\pm V_m$
Number of cycles	10	30	100

according to 5.4. Open the crack to 0.020 in. (0.5 mm). Test internally threaded anchors with a bolt as specified by the manufacturer and report in Table 11.2. Subject the anchors to the sinusoidally varying tension loads specified in Table 9.1 and Fig. 9.1, using a loading frequency between 0.1 and 2 Hz, where

N_{eq} = the maximum seismic tension test load, equal to 50% of the mean tension capacity in cracked concrete from reference tests;
N_m = one-fourth the mean tension capacity in cracked concrete from reference tests; and
N_i = $(N_{eq} + N_m)/2$.

After the anchor has undergone the simulated seismic-tension cycles, load the anchor in tension to failure using an initial crack width not less than the crack width at the end of the cyclic test. Record the peak of each load cycle and the corresponding anchor displacement. If the anchor fails before completing the cycles required in Table 9.1, record the number of cycles and the load at failure.

9.5.3 *Requirements*—All anchors tested to simulated seismic conditions shall pass the simulated seismic-tension load test. Anchors that are tested in cracked concrete (w = 0.020 in. [0.5 mm]) at 50% of the mean static capacity, normalized to the concrete strength of the test member, shall be rated at full capacity. Anchors that fail during the cyclic tension tests shall be permitted to be tested at lower maximum cyclic loads to establish a reduced nominal pullout capacity. Anchors that are tested at lower maximum cyclic test loads shall have their nominal tensile capacity lowered by the ratio of the tested maximum cyclic load to 50% of the mean static capacity. The mean residual capacity of the anchors in the test series in the tension test shall be at least 80% of the mean capacity of the corresponding reference tests lowered by the ratio of the tested maximum cyclic load to 50% of the mean static tension capacity.

9.6—Service condition, simulated seismic shear tests (Table 4.2, Test 13)

9.6.1 *Purpose*—These optional tests are performed to evaluate performance under simulated alternating seismic shear loading. If these seismic tests are performed, they shall only be acceptable as part of the total cracked concrete test program of Table 4.2.

9.6.2 *Tests*—Test anchors at the shallowest embedment depth for which the anchor is to be qualified for use in cracked concrete. Anchors shall be permitted to be tested at deeper embedment depths to verify load capacities at deeper embedment depths. Install the anchors in cracked concrete according to 5.2. For internally threaded anchors, test with a bolt as specified by the manufacturer and reported in Table 11.2. Subject the anchors to the sinusoidally varying shear loads specified in Table 9.2 and Fig. 9.2. Separate reference tests shall be permitted to be performed in 0.020 in. (0.05 mm) cracks to determine the shear capacity as an alternate to the procedure of 9.4 (Table 4.2, Test 11). The test parameters of embedment depth, crack orientation, and concrete strength shall be the same as in the seismic shear test. Load parallel to the direction of the crack, with a frequency of loading between 0.1 and 2 Hz. To reduce uncontrolled sliding during load reversal, the alternating shear loading shall be permitted to be approximated by the application of two half-sinusoidal load cycles at the desired frequency, connected by a reduced-speed, ramped load as shown in Fig. 9.3. Record the peak shear load of each half cycle and the corresponding anchor displacement in the direction of load. Plot the load-displacement results in the form of hysteresis loops, where

V_{eq} = the maximum seismic shear test load, equal to one-half of the mean capacity in cracked concrete from shear tests or calculated shear capacity of the steel according to ACI 318, Appendix D;

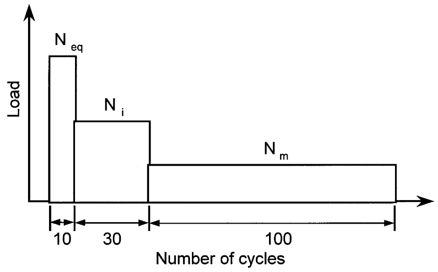


Fig. 9.1—Loading pattern for simulated seismic-tension test.

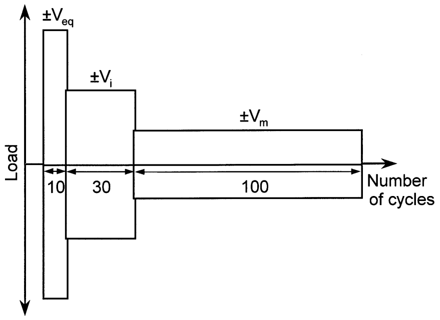


Fig. 9.2—Loading pattern for simulated seismic-shear test.

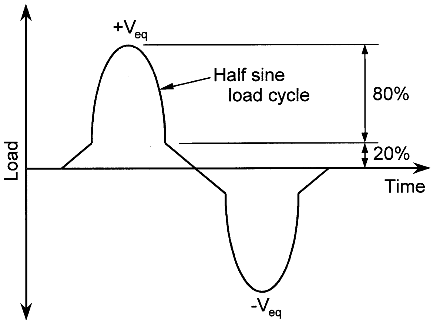


Fig. 9.3—Permitted approximation of alternating seismic-shear cycle.

V_m = one-fourth of the mean shear capacity in cracked concrete from tests or calculated from steel capacity; and

V_i = $(V_{eq} + V_m)/2$.

After the simulated seismic-shear cycles have been run, test the anchors to failure in static shear.

9.6.3 *Requirements*—All anchors tested to simulated seismic conditions shall pass the simulated seismic-shear load test. Anchors that are tested at a cyclic shear of 50% of the mean ultimate shear capacity shall be rated at full capacity as determined in the static tests. Anchors that fail during the tests shall be permitted to be tested at lower maximum cyclic loads. Anchors that are tested at lower maximum cyclic test loads shall have their nominal shear capacity lowered by the ratio of the tested maximum cyclic load to 50% of the static shear capacity. The mean residual capacity of the anchors in the test series in the shear test shall be at least 80% of the mean capacity in the corresponding reference tests lowered by the ratio of the tested maximum cyclic load to 50% of the ultimate shear capacity.

CHAPTER 10—ESTABLISHING ANCHOR CATEGORIES

10.1—For each combination of anchor diameter and embedment depth, compute the ratio of the characteristic capacity $N_{b,r}$ in each reliability test to the characteristic tension capacity $N_{b,o}$ in the corresponding reference test. The corresponding reference test shall have the same concrete strength range and crack width. Determine the characteristic capacities in accordance with Appendix A2. The K value used in calculating the characteristic capacity in each reliability test and in the corresponding reference test shall be the K value associated with the reliability test or reference test and the number of respective replicates. When the reference capacity is associated with tests in which the concrete breakout failure mode predominates, $N_{b,o}$ shall be permitted to be calculated according to ACI 318 Appendix D, Eq. (D-7), using the effectiveness factor k determined in accordance with 7.3.1. Using the smallest ratio of $N_{b,r}/N_{b,o}$ from all reliability tests, establish the anchor category from Table 10.1. For each diameter, report a single category that represents the lowest category determined by the tests.

Table 10.1—Establishment of anchor categories

Smallest ratio of characteristic capacities	Anchor category
$8.80 \le \frac{N_{b,r}}{N_{b,o}}$	1
$0.70 \le \frac{N_{b,r}}{N_{b,o}} < 0.80$	2
$0.60 \le \frac{N_{b,r}}{N_{b,o}} < 0.70$	3
If $\le \frac{N_{b,r}}{N_{b,o}} < 0.60$	Anchor is unqualified

Table 11.1—Sample format for reporting anchor data for anchors qualified for use in uncracked concrete only

Anchor systems qualified for use in uncracked concrete in accordance with test program of Table 4.1								
				Nominal anchor diameters				
Characteristic	Symbol	Units	Chapter reference	Smaller diameters (if any)	3/8 in. (M10)	1/2 in. (M12)	5/8 in. (M16)	Larger diameters (if any)
Installation information								
Outside diameter	d_o	in. (mm)	2.2					
Effective embedment depth	h_{ef}	in. (mm)	2.2					
Installation torque	T_{inst}	ft-lb (N-m)	2.2					
Minimum edge distance	c_{min}	in. (mm)	2.2					
Minimum spacing	s_{min}	in. (mm)	2.2					
Minimum concrete thickness	h_{min}	in. (mm)	2.2					
Critical edge distance	c_{cr}	in. (mm)	2.2					
Anchor data								
Category number	1, 2, or 3	—	10.1					
Yield strength of anchor steel	f_y	psi (MPa)	2.2					
Ultimate strength of anchor steel	f_{ut}	psi (MPa)	2.2					
Effective tensile stress area	A_{se}	$in.^2$ (mm^2)	2.2					
Effective shear stress area	A_{se}	$in.^2$ (mm^2)	2.2					
Shear strength of sleeved anchors	V_{st}	lb (N)	9.4					
Effectiveness factor for concrete breakout	k_{uncr}[*]	—	7.3.1					
Modification factor for absence of cracks	$\psi_{c,N}$[*]	—	2.2	1.0	1.0	1.0	1.0	1.0
Pullout or pull-through resistance from tests	N_p	lb (N)	7.3.3					
Axial stiffness in service load range	β	lb/in. (kN/mm)	5.5.2					
Coefficient of variation for axial stiffness in service load range	ν	%	5.5.2					

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

10.2 It shall be permitted to evaluate the ratio $N_{b,r}/N_{b,o}$ on the basis of mean test results provided that: a) the difference in the number of replicates in each test series is not greater than five; and, b) the coefficient of variation associated with the test results in each of the reliability test series is less than or equal to the coefficient of variation associated with the corresponding reference tests, or less than or equal to 10%. When the reference capacity is associated with tests in which the concrete breakout failure mode predominated, $N_{b,o}$ shall be permitted to be calculated according to ACI 318 Appendix D, Eq. (D-7), using the effectiveness factor k determined in accordance with 7.3.1, multiplied by a factor 1/0.75.

CHAPTER 11—PRESENTING ANCHOR DATA

11.1—Data analysis

Analyze data in accordance with Appendixes A1 and A2.

11.2—Format of the data sheet

Report the data required by ACI 355.2 in the format shown in Table 11.1 or 11.2. Add other observations as appropriate and include them in the evaluation report.

11.3—General requirements

The evaluation report shall meet the reporting requirements of ASTM E 488, and include sufficient information for complete product identification, explicit installation instructions, and design data.

11.4—Contents of evaluation report

The report shall include:

11.4.1 Description of types of anchors;

11.4.2 Constituent materials (6.3.2);

11.4.3 Markings (6.3.1); and

11.4.4 Anchor performance data in accordance with 11.2.

CHAPTER 12—REQUIREMENTS FOR INDEPENDENT TESTING AND EVALUATION AGENCY

12.1 The testing and evaluation of anchors under ACI 355.2 shall be performed or witnessed by an independent testing and evaluation agency listed by a recognized accreditation service conforming to the requirements of ISO 17025 and Guide 58. In addition to these standards, listing of the testing and evaluation agency shall be predicated on the documented experience in the testing and evaluation of anchors according to ASTM E 488, including demonstrated competence to perform the tests described in ACI 355.2.

Table 11.2—Sample format for reporting anchor data for anchors qualified for use in both cracked and uncracked concrete

Anchor system qualified for use in both cracked and uncracked concrete in accordance with test program of Table 4.2								
				Nominal anchor diameters				
Characteristic	Symbol	Units	Chapter reference	Smaller diameters (if any)	3/8 in. (M10)	1/2 in. (M12)	5/8 in. (M16)	Larger diameters (if any)
Installation information								
Outside diameter	d_o	in. (mm)	2.2					
Effective embedment depth	h_{ef}	in. (mm)	2.2					
Installation torque	T_{inst}	ft-lb (N-m)	2.2					
Minimum edge distance	c_{min}	in. (mm)	2.2					
Minimum spacing	s_{min}	in. (mm)	2.2					
Minimum concrete thickness	h_{min}	in. (mm)	2.2					
Critical edge distance	c_{cr}	in. (mm)	2.2					
Anchor data								
Category number	1, 2, or 3	—	10.1					
Yield strength of anchor steel	f_y	psi (MPa)	2.2					
Ultimate strength of anchor steel	f_{ut}	psi (MPa)	2.2					
Effective tensile stress area	A_{se}	in.^{2} (mm^2)	2.2					
Effective shear stress area	A_{se}	in.^{2} (mm^2)	2.2					
Shear strength for sleeved anchors	V_{st}	lb (N)	9.4					
Effectiveness factor for uncracked concrete	k_{uncr}	—	7.3.1					
Effectiveness factor for cracked concrete used for ACI 318 design	$k_{cr}{}^*$	—	7.3.1					
$\psi_{c,N}$ for ACI 318 design in cracked concrete	$\psi_{c,N}{}^*$	—	2.2	1.0	1.0	1.0	1.0	1.0
$\psi_{c,N} = k_{uncr}/k_{cr}$ for ACI 318 design in uncracked concrete	$\psi_{c,N}{}^*$	—	—					
Pullout or pull-through resistance from tests	N_p	lb (N)	7.3.3					
Tension resistance of single anchor for seismic loads	N_{eq}	lb (N)	9.5					
Shear resistance of single anchor for seismic loads	V_{eq}	lb (N)	9.6					
Axial stiffness in service load range	β	lb/in. (kN/mm)	5.5.2					
Coefficient of variation for axial stiffness in service load range	ν	%	5.5.2					

[*] 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.

12.2 The testing shall be certified by a licensed engineer employed or retained by the independent testing and evaluation agency.

CHAPTER 13—REFERENCES

13.1—Referenced standards

ASTM International

C 31/C 31M-03a	Standard Practice Making and Curing Concrete Test Specimens in the Field
C 33-03	Standard Specification for Concrete Aggregates
C 39/C 39M-03	Standard Test Method for Compression Strength of Cylindrical Concrete Specimens
C 42/C 42-03	Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 150-02ae1	Standard Specification for Portland Cement
E 488-96 (2003)	Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements

American Concrete Institute

ACI 318-05	Building Code Requirements for Structural Concrete

American National Standards Institute

ANSI B212.15-94	American National Standard for Cutting Tools—Carbide-Tipped Masonry Drills and Blanks for Carbide-Tipped Masonry Drills

International Standards Organization

ISO/IEC 17025-99	General Requirements for the Competence of Calibration and Testing Laboratories
ISO/IEC Guide 58-93	Calibration and Testing Laboratory Accreditation Systems—General Requirements for Operation and Recognition

These publications may be obtained from these organizations:

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428

American Concrete Institute
P. O. Box 9094
Farmington Hills, MI 48333-9094

American National Standards Institute
11 West 42nd Street
New York, NY 10036

International Standards Organization
1, rue de Varembé
Case postale 56
CH-1211 Genevé 20
Switzerland

MANDATORY APPENDIXES

APPENDIX A1—REQUIREMENTS FOR NORMALIZATION OF RESULTS

A1.1—Normalization of capacities to take account of concrete and steel strengths

When reporting results and data and comparing anchor capacities of tests that require normalization to a specific or a common strength, the type of failure shall be taken into account. The methods in A1.2 through A1.4 are to be used for this standard.

A1.2—Concrete breakout or splitting failure

Normalize capacities in proportion to $\sqrt{f_c}$ as prescribed by Eq. (A1-1).

$$F_{m,i} = F_{u,test,i} \cdot \sqrt{\frac{f_{c,m,i}}{f_{c,test,i}}} \qquad \text{(A1-1)}$$

A1.3—Pullout and pull-through failure

The influence of the concrete strength on the pullout or pull-through failure load shall be established by tests. Report the capacity at the lowest concrete compressive strength of the range and the capacity variation as a function of concrete strength (for example, linear, or as a specific mathematical function of the concrete compressive strength).

A1.4—Steel failure

Normalize the capacity by the nominal steel strength using Eq. (A1-2). For steels conforming to a national standard, the 5% fractile steel capacity shall be calculated as the minimum specified tensile strength, f_{ut}, multiplied by the effective tensile stress area of the anchor.

$$F_{ut} = F_{u,test,i} \cdot \frac{f_{ut}}{f_{u,test}} \qquad \text{(A1-2)}$$

APPENDIX A2—REQUIREMENTS FOR ESTABLISHING CHARACTERISTIC CAPACITIES

A2.1—Scope

The following gives the method of obtaining $F_{5\%}$ (characteristic capacity) from the mean failure capacity F_m and coefficient of variation ν for tests failing by concrete breakout, pullout, or pull-through.

A2.2—Procedure

Calculate the characteristic capacity by Eq. (A2-1) using the mean capacity from tests F_m and the appropriate K value from Table A2.1. The K values in Table A2.1 are factors for one-sided tolerance limits for normal distributions, and correspond to a 5% probability of nonexceedance with a confidence of 90%.[*]

$$F_{5\%} = F_m(1 - K\nu) \qquad \text{(A2-1)}$$

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[*] Natrella, M. G., 1996, "Experimental Statistics," *National Bureau of Standards Handbook 91*, U.S. Department of Commerce.

Table A2.1—*K* values for evaluating the characteristic capacity at 90% confidence

Number of tests	*K*
4	3.957
5	3.400
6	3.091
7	2.894
8	2.755
9	2.649
10	2.568
15	2.329
20	2.208
25	2.132
30	2.080
40	2.010
50	1.965
∞	1.645

APPENDIX A3—REQUIREMENTS FOR TEST MEMBERS

A3.1—Tests in uncracked concrete

Use test members that are unreinforced, except as permitted by A.3.1.1 and A.3.1.2.

A3.1.1 For service-condition tests to determine the minimum edge and spacing distances, it shall be permitted to provide a No. 3 (10 mm) straight reinforcing bar along the edges with a concrete cover of 5/8 in. (15 mm).

A3.1.2 The test member shall be permitted to contain reinforcement to allow handling, the distribution of loads transmitted by the test equipment, or both. Place such reinforcement so that the capacity of the tested anchor is not affected. This requirement shall be considered to be met if the reinforcement is located outside a cone of concrete whose vertex is at the anchor, whose base is perpendicular to the direction of load, and whose internal vertex angle is 120 degrees.

A3.2—Tests in cracked concrete

Test members shall be permitted to contain reinforcement to allow handling, the distribution of loads transmitted by test equipment, or both. Place the reinforcement so that the capacity of the tested anchor is not affected.

The crack width shall be approximately uniform throughout the member thickness. The thickness of the test member shall be not less than $1.5h_{ef}$ but at least 4 in. (100 mm). To control the location of cracks and to help ensure that the anchors are installed to the full depth in the crack, crack inducers shall be permitted to be installed in the member, provided they are not situated so as to influence the test results. An example of the test member is given in Fig. A3.1. For test members that use internal reinforcement to control the crack width, the reinforcement shall be placed so that there is no influence on the performance of the anchors. The cross-sectional reinforcement ratio of the concrete members used for the cracked concrete tests should be approximately 1%. The reinforcement shall be permitted to be in the failure cone of concrete. The centerline-to-centerline distance between the reinforcement and the anchor shall be greater than $0.4h_{ef}$ with a spacing of the top and bottom crack control reinforcement bars of ≤ 10 in. (250 mm). The reinforcement shall be permitted to be in the cone of concrete. The centerline-to-centerline distance between the reinforcement and the anchor shall be greater than $0.4h_{ef}$.

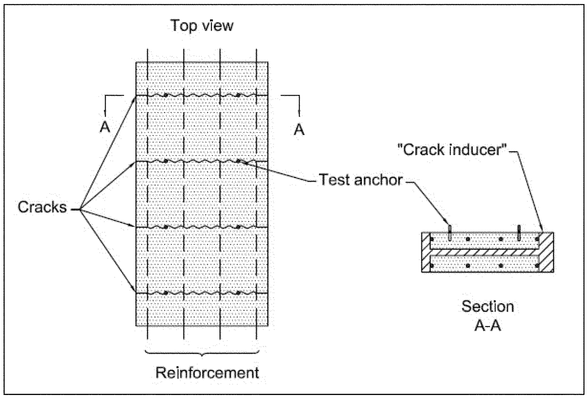

Fig. A3.1—Example of test member for anchors in tension in cracked concrete.

A3.3—Casting and curing of test members

Cast test members either horizontally or vertically. If the member is cast vertically, the maximum height of a concrete lift shall be 5 ft (1.5 m).

A3.3.1 Cure concrete cylinders in accordance with ASTM C 31 or C 39 under the same environmental conditions as the test members. Remove molds from the cylinders at the same time that the forms are removed from the test members. When testing anchors, the concrete shall be at least 21 days old, unless specified otherwise. Determine the compression strength of the test member when the anchors are tested in the member; for example, test a control sample or samples at the start of the testing and at the completion of the testing. Alternately, test enough control samples to plot strength versus age graph and use interpolation to estimate the concrete strength at the day of test. This procedure is rational and an accepted way of providing test member properties during testing.

A3.3.2 When evaluating the test results, if there is a question whether the strength of the concrete cylinders represents the concrete strength of the test member, take at least three cores with diameter from 3 to 6 in. (75 to 150 mm) from the test member outside of the zones where the concrete has been damaged by the anchor test, and test in compression. Prepare the core samples, test them in the dry condition, and evaluate the results in accordance with the provisions of ASTM C 42.

ACI 355.2R-04

Commentary on Qualification of Post-Installed Mechanical Anchors in Concrete

Reported by ACI Committee 355

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R1.1 ACI 355.2 prescribes the testing programs required to qualify post-installed mechanical anchors for use with the design method of ACI 318 Appendix D. In ACI 318 Appendix D, it is assumed that anchors have been tested either for use in uncracked concrete or for use in cracked and uncracked concrete. This testing is performed in concrete specimens controlled by the testing laboratory as a means of simulating concrete, both cracked and uncracked, that might occur in actual structures. Post-installed mechanical anchors exhibit a range of working principles, proprietary designs, and performance characteristics. ACI 318 Appendix D addresses this situation by basing capacity reduction factors for anchors on anchor performance categories. ACI 355.2 is intended to develop the data required by ACI 318 Appendix D to confirm an anchor's reliability and place it in the appropriate anchor category.

While this testing program includes tests in cracked concrete, detailed procedures or guidelines for making and controlling cracks have not been published. It is expected that this will be accomplished by either ACI Committee 355 as new business or in ASTM Subcommittee E06.13 and included in ASTM E 488.

R1.4 The design method deemed to satisfy the anchor design requirements of ACI 318 Appendix D, is based on an analysis of a database of anchors with a maximum diameter of 2 in. (50 mm) and an embedment depth not greater than 25 in. (635 mm). ACI 355.2 can be used for anchors with those maximum dimensions. While ACI 355.2 gives no limitations on maximum anchor diameter or embedment depth, for anchors beyond these dimensions, the testing authority should decide if the tests described herein are applicable or if alternative tests and analyses are more appropriate. The minimum diameter of 1/4 in. (6 mm) is based on practical considerations regarding the limit of structural anchor applications.

R2.1.4 The characteristic value is the value used for design in ACI 318 Appendix D. The characteristic value is less than the average by a percentage of the average and based on the number of tests conducted, the confidence level that the code writing body elects to use, and an accepted failure rate. The characteristic value or 5% fractile (value with a 95% probability of being exceeded, with a confidence of 90%), has been selected for the design of anchorages.

ACI 355.2R-04 supersedes ACI 355.2R-01 and became effective October 27, 2004.

R2.1.5 Concrete breakout failure includes concrete cone breakout under tension load, edge breakout from tension or shear, or combinations of these, as shown in Fig. 5.3 and 5.4.

R2.1.8 Pullout failure occurs when the anchor does not sufficiently engage the concrete to produce a steel or concrete cone failure. The entire anchor slips out of the drilled hole at a load lower than that corresponding to concrete cone breakout. While a concrete cone may occur as part of the pullout failure, it will be at a shallower embedment depth than for a full concrete cone failure.

R2.1.9 Pull-through failure occurs when the anchor shank pulls through the expansion mechanism, which remains in the drilled hole. The anchor shank slips out of the drilled hole at a load lower than that corresponding to concrete cone breakout.

R2.1.12 The statistical equivalence determination is based on calculating a z- or t-statistic using standard statistical procedures and equations. The value of the calculated t-statistic is then compared to tabulated values of the same statistic at a selected confidence and based on the sample size. The process is to propose an hypothesis and check whether the hypothesis is correct. The hypothesis is that the mean of the reference test is greater than (or less than) the mean of the second series of anchor tests. The t-test is a statistical test to examine the hypothesis that two samples are either from the same larger population or from the different populations.

R2.1.16 Under ACI 355.2, anchors for use in uncracked concrete are tested in concrete that is uncracked and is expected to remain so unless the anchor causes cracking as part of the failure mode.

R2.2—Notation

A_{se} = for expansion anchors with reduced cross-sectional area for the expansion mechanism, the effective cross-sectional area of the anchor should be provided by the manufacturer. For threaded bolts, ANSI/ASME B1.1 defines A_{se} as

$$A_{se} = \frac{\pi}{4}\left(d_o - \frac{0.9743}{n_t}\right)^2$$

where n_t is the number of threads per inch.

R3.1 ACI 318 Appendix D requires an anchor that is to be used under seismic loading to be qualified under a simulated seismic loading cycle.

Experience shows that plastic hinge regions in reinforced concrete structures subjected to earthquake loading typically develop crack widths well in excess of the crack widths anticipated by ACI 355.2.

R4.1 ACI 355.2 follows a four-step procedure (covering four types of tests) to check the suitability of the anchor for structural purposes (within the use limits established by ACI 318) and to establish a performance category for the anchor that can be used with the design approach established by ACI 318. The four test types are: identification, reference, reliability, and service-condition tests. Flow charts giving the testing sequences are presented in Fig. R1 through R6.

Identification tests are required to determine if the anchor complies with fabrication requirements and to establish a baseline for quality assurance.

Reference tests serve two functions. They establish the characteristic resistance to be used in the design of single anchors with large edge distances and spacings. They also are intended to be compared with results of the reliability tests. For the reference tests, anchors should be installed according to the manufacturer's instructions.

Reliability tests serve two functions. The first is to establish the anchor categories used in ACI 318, and the second is to check the reliability of the anchor under sustained loads and variable loads. The anchor should be capable of safe and

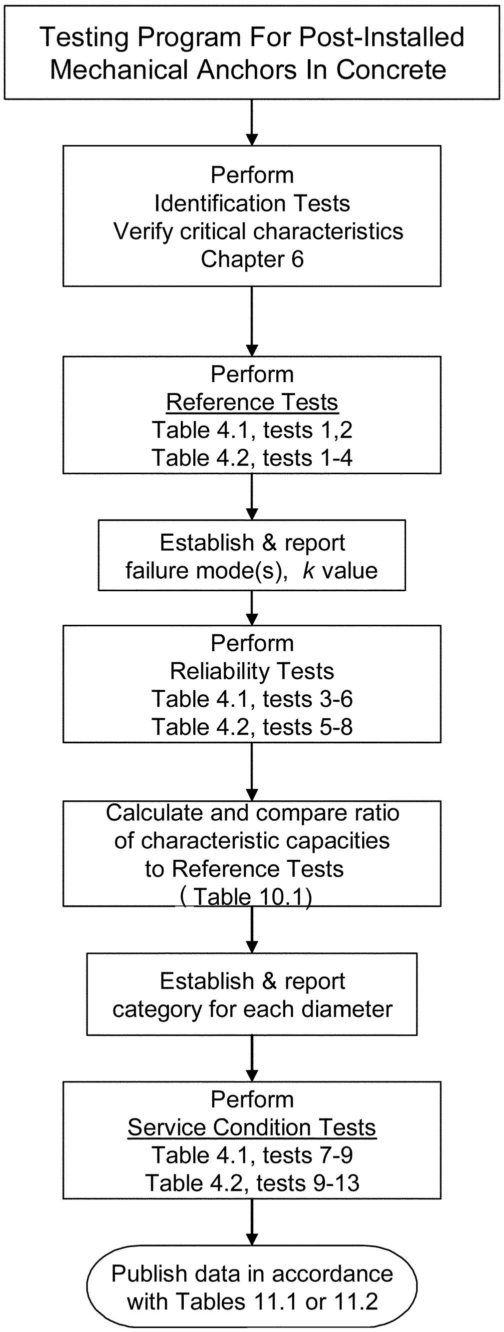

Fig. R1—Flow chart for overall testing program.

effective behavior under normal and adverse conditions, both during installation and in service. Factors included are sensitivity to variations of:

- Installation conditions in concrete;
- Drill bit diameter;
- Sustained and variable loads on the anchor;
- Crack width (for anchors being tested for use in cracked and uncracked concrete only); and
- Crack width associated with long-term and variable loading of the structure (for anchors for use in cracked and uncracked concrete).

To reduce the scope of the required test program, the effects of these factors on anchor performance are combined in the required tests using the most severe combination of conditions.

The procedures prescribed for checking the reliability of an anchor and assigning an anchor category to it consider possible on-site deviations from the manufacturer's specified installation procedure. ACI 355.2, however, does not cover gross installation errors, which are prevented by appropriate training and site inspection. Such gross errors include, but are not limited to: drill bits of the wrong diameter; inappropriate drilling methods; improper setting tools; inappropriate setting methods; and failure to clean, dry, or otherwise prepare the drilled hole as required by the manufacturer.

To represent normal conditions, the repeated load test (Table 4.1, Test 6) and the test in which the crack width is cycled (Table 4.2, Test 8) are performed with a drill bit of diameter d_m.

Test 6 of Table 4.1 specifies that only the smallest, middle, and largest diameter anchors are to be tested. For a given anchor system, the manufacturer usually offers several diameters, for example, 1/4, 3/8, 1/2, 5/8, 3/4, 1, and 1-1/4 in. In

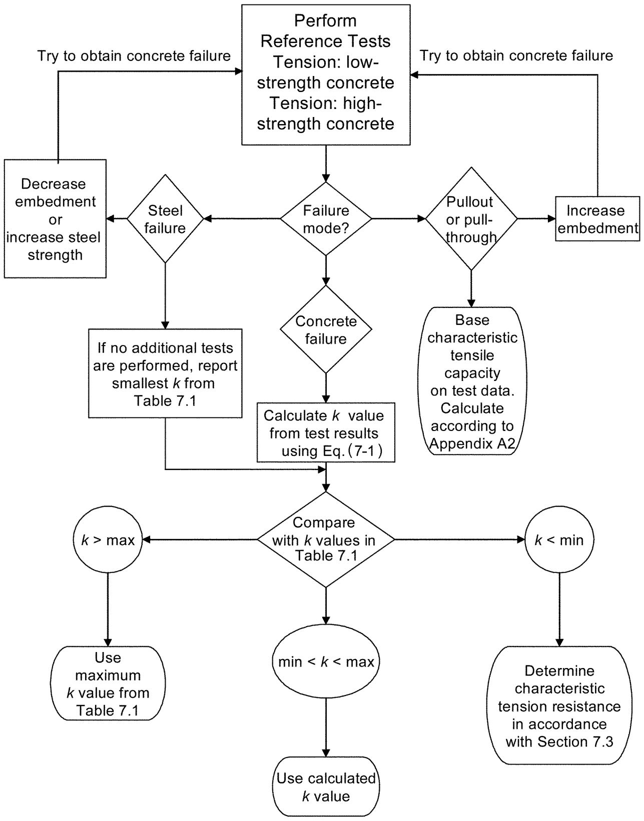

Fig. R2—Flow chart for reference tests.

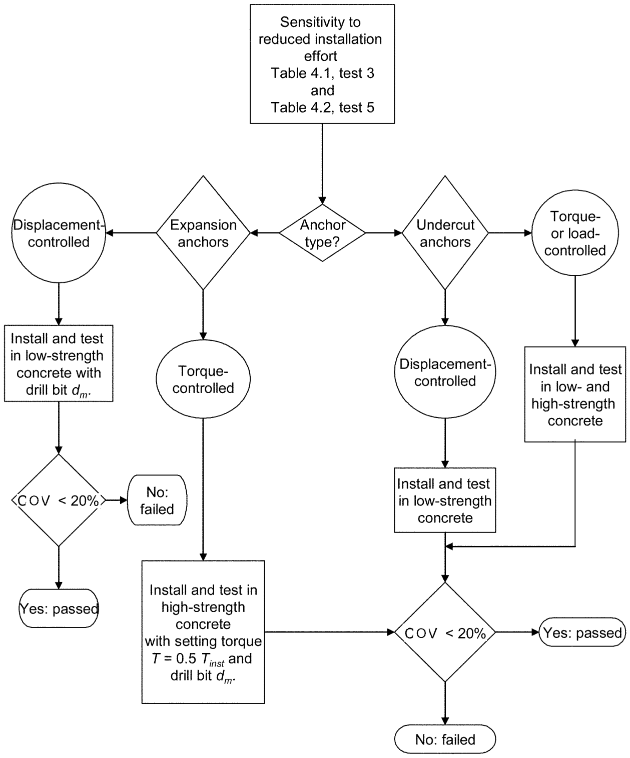

Fig. R3—Flow chart for tests with reduced installation effort.

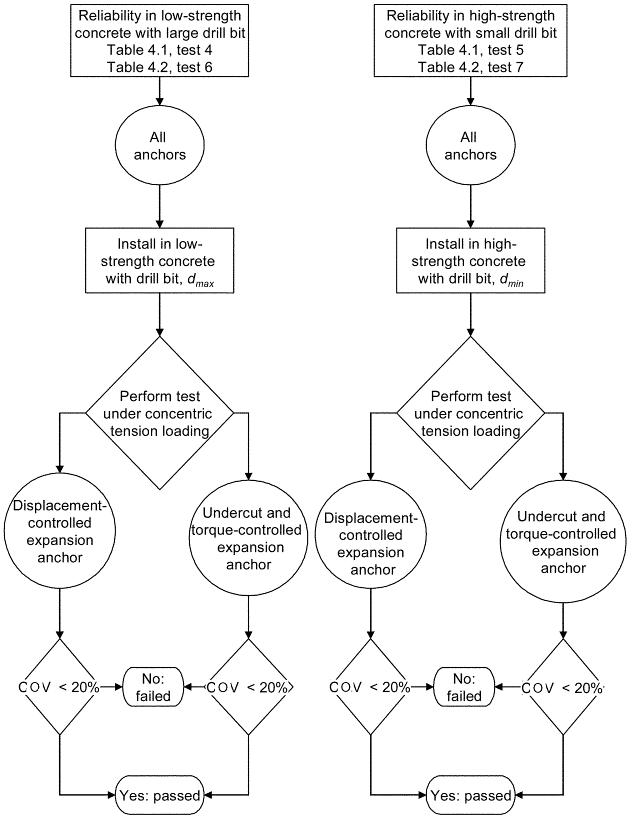

Fig. R4—Flow chart for reliability tests for sensitivity to large and small holes.

this example, the smallest (1/4 in.), middle (5/8 in.) and largest (1-1/4 in.) would be tested.

The selected combination of conditions is intended to minimize the test program while maintaining an acceptable level of safety of the entire connection. The observed anchor capacities from the reliability tests can be lower than from the reference tests, provided that the reduction is limited and well defined. The low probability of observed anchor capacity occurrence associated with the reference test conditions is assumed to compensate for the reduced capacity, in effect maintaining a relatively constant probability of failure. Based on the magnitude of the reduction, the anchor category is established.

When service-condition tests are performed by both the testing agency and the manufacturer, a complete test series of the minimum number of required tests are to be performed by one of the organizations, and not split between them.

The requirements in this document differ from the requirements of ASTM E 488 for minimum sample sizes based on coefficient of variation of test data. The minimum number of tests in this document as given in Tables 4.1 and 4.2 is considered to be sufficient.

The sample size of 4 for Test 7 of Table 4.1 and Test 9 of Table 4.2 (the corner test) is because a typical test specimen block has four corners. The concrete test blocks are to be at the minimum concrete thickness for which the anchor is qualified, so they are specially poured. Thus, the testing agency needs only one slab for these tests.

R4.2 Prototypes can be used for testing if the anchor samples are prepared in the same manner as expected for production. Identification and reference tests are performed on the production samples and their performance is compared statistically to the results of the tested prototypes to determine if additional tests need to be performed.

R4.2.2 If different materials, such as carbon steel rather than stainless steel, or different production methods, such as cold-forming rather than machining, are used for a given anchor diameter, reference and reliability tests should be performed for each type and compared statistically. If they are statistically equivalent, then only one set of service-condition tests needs to be performed for the anchors.

R5.1 The purpose of the requirements governing the concrete used in test specimens is to reduce the variables that might affect anchor performance, thereby making the test results more reproducible. Various cementitious materials and concrete admixtures can affect anchor performance, increasing the scatter of test data. The influence of different concrete mixtures on anchor performance is part of the consideration in establishing the capacity reduction factors in the

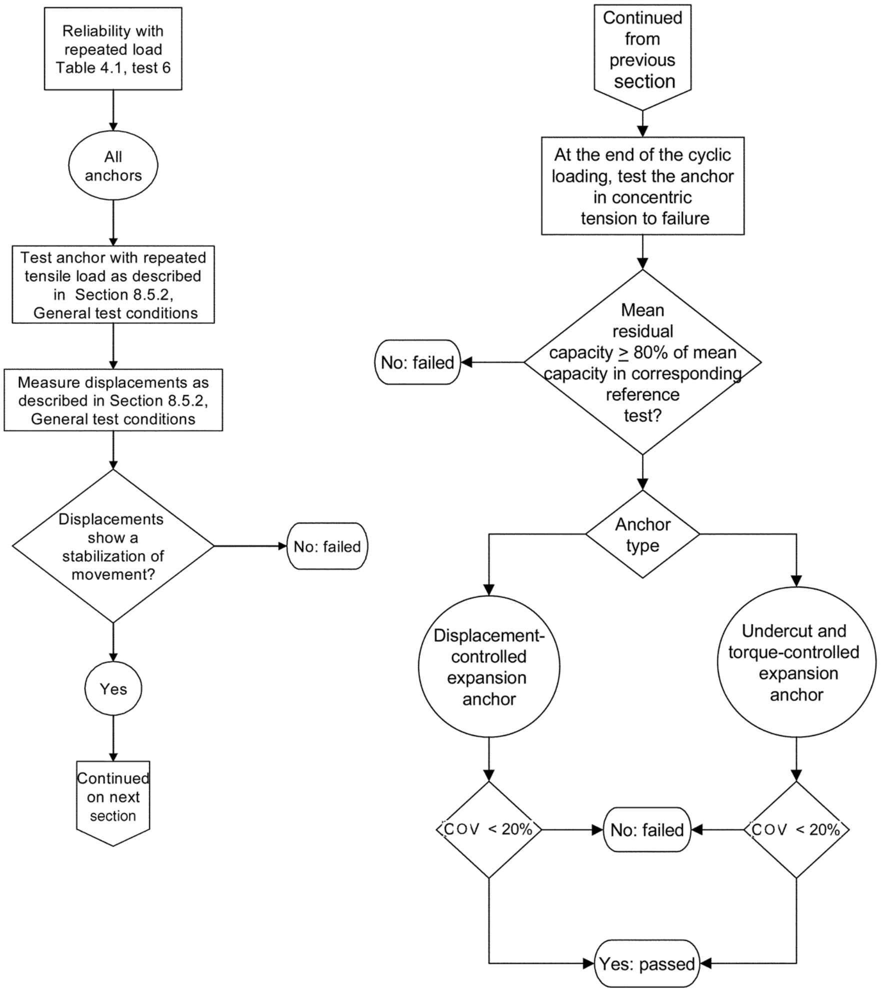

Fig. R5—Flow chart for reliability tests with repeated loads.

design method of ACI 318. To verify the performance of an anchor in concrete with higher or lower strength than given in ACI 355.2, or in lightweight concrete, tests specified in ACI 355.2 may be performed in that particular concrete.

Further information is given in the paper by Fuchs, Eligenhausen, and Breen (1995).

R5.1.1 All tests should be performed in normalweight concrete. ACI 318 Appendix D uses a generally accepted multiplying factor to establish capacities for structural lightweight concrete.

R5.1.2 Testing is performed in plain concrete with no cementitious replacements or concrete admixtures. With such concrete, the anchors are approved for use with mixtures that contain these materials. If the tests are performed with concrete mixtures that contain cementitious replacements or admixtures, then the anchors are approved only for that specific mixture design.

R5.1.3 Experience indicates that the performance of some expansion anchor types may be adversely affected in high-strength concrete. ACI 318 establishes an upper limit of 8000 psi (55 MPa) on the specified concrete compressive strength for which the design method is applicable. Elsewhere in ACI 318, a lower limit on specified compressive strength of 2500 psi (17 MPa) is established. Actual in-place concrete strength can be 15 to 20% higher than specified.

The measured concrete compressive strengths of the concrete test members are expected to be within the specified ranges for low- and high-strength concrete. If the measured strengths are outside these ranges, then those test members should not be used in this evaluation program.

R5.2.2 The tests in this program are based on the assumption that the holes are drilled by carbide-tipped, rotary-hammer drill bits. If the anchors are installed into holes drilled by another standard method, such as with diamond-core bits, the manufacturer should prescribe the drill bits, associated tolerances, and drilling procedures. The bit tolerances should be prescribed to approximate the d_{max}, d_m, and d_{min} expected for that type of drill bit in keeping with the intent of the definitions for these diameters.

If two different types of bits are allowed, such as carbide rotary-hammer bits and diamond-core bits, the reference and reliability tests should be performed with each type of bit. If it can be shown statistically that the results are from the same data population, the tests can be performed with only one of the bit types. Otherwise, the tests should be performed for both types of drill bits and reported.

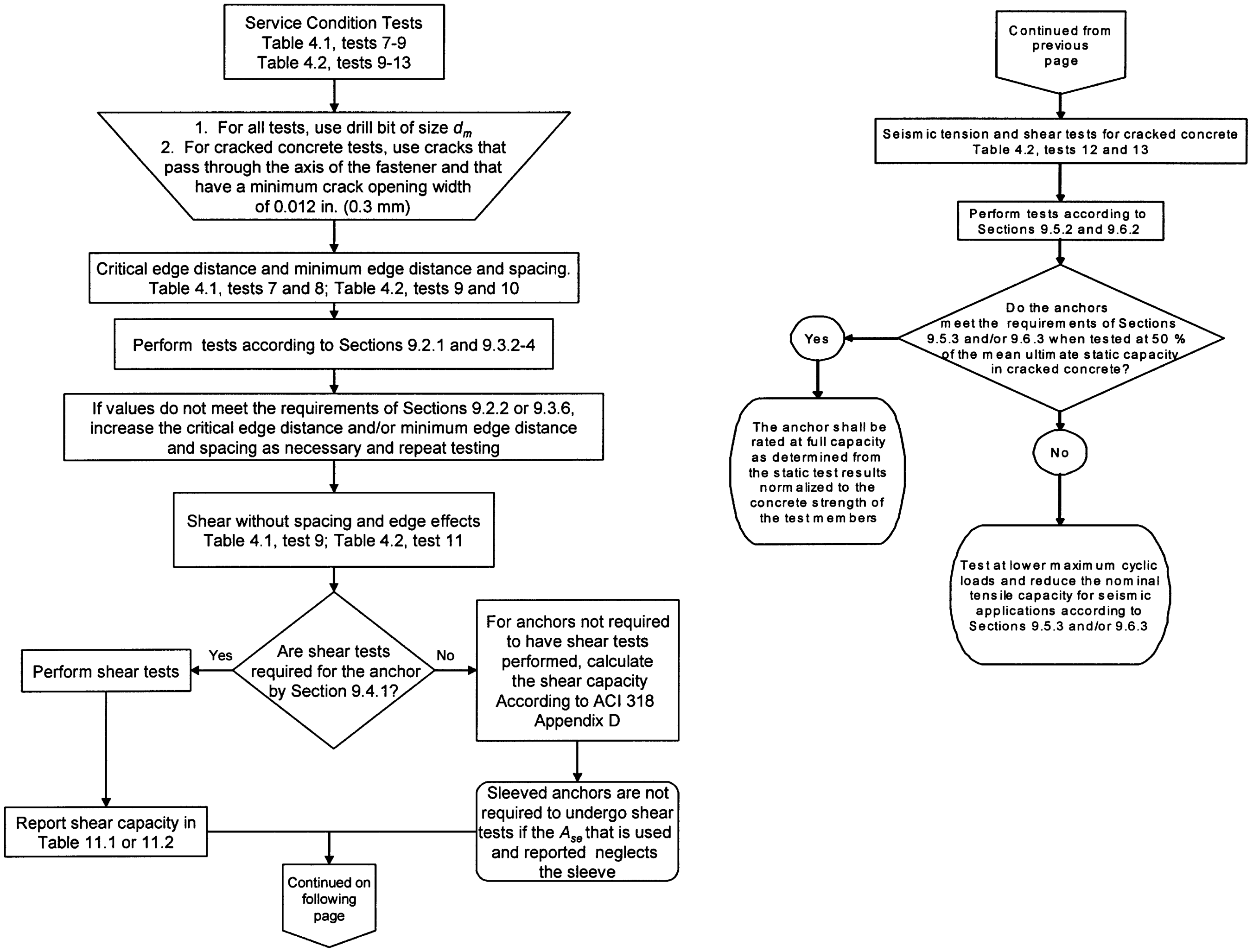

Fig. R6—Flow chart for service-condition tests.

R5.2.3 In ACI 355.2, three procedures are specified for applying torque during installation of the anchors.

In all tests, except those tests addressing sensitivity to reduced installation effort, the anchor is first installed using the full installation torque; the torque is then reduced to 50% of that value to account for preload relaxation over time.

In those tests addressing sensitivity to reduced installation effort, anchors are installed with 50% of the manufacturer's prescribed installation torque. This test is intended to simulate installation error on the job site.

Anchors with no specified installation torque (displacement-controlled anchors and some undercut and torque-controlled anchors) are tested with nuts or anchors set finger-tight.

Installation torque requirements for undercut anchors, as required to check sensitivity to reduced installation effort, vary with anchor type. Requirements are prescribed in Table 5.6.

R5.2.3.1 Installation using only half the manufacturer's required torque is the partial setting for torque-controlled expansion anchors. This determines if the anchor will still function properly if set with a torque substantially below the recommended torque.

R5.2.3.3 Displacement-controlled anchors are tested with varying degrees of expansion as specified in Table 5.4. The reference and service-condition tests are done with full expansion as specified by the anchor manufacturer. Experience indicates that displacement-controlled anchors may not be fully set on site due to the large physical effort involved, particularly in overhead installations with larger anchors. The reference expansion test is intended to simulate a representative level of setting energy (human effort) as determined from field studies. Setting energy is held constant, and the degree of anchor expansion is determined by the anchor design. Properly designed displacement-controlled anchors will achieve nearly complete expansion with the representative level of setting energy. Finally, the test with partial expansion checks the effect of reduced installation effort on anchor performance. The setting energy is lower than in the reference expansion test to model the lower bound of setting energy determined by field studies. The degree of expansion associated with these two conditions is established in high-strength concrete. The setting energies associated with the parameters given in Table 5.5 were developed for high-strength concrete. Once the anchor expansion (plug displacement) associated with the specified setting energy (reference or partial expansion) is established, a setting tool is prepared to duplicate this degree of expansion for the balance of the required tests.

R5.2.3.4 Table 5.6 refers to products currently available in the marketplace. As other systems or types of products become available, the independent test and evaluation agency should prescribe the test parameters.

R5.4 Guidance for cracking the concrete and controlling the crack width is given in the technical article "Testing Anchors in Cracked Concrete" by Eligehausen et al. (2004).

R5.5.1 Reliable design of connections to concrete generally requires anchors with predictable load-displacement behavior. Scatter of the load-displacement curves adversely affects the behavior of multiple-anchor connections because it causes unreliable load redistribution among anchors.

Uncontrolled slip is generally unacceptable in the expected functioning load range of the anchor. The limits on load-slip behavior are intended to prevent uncontrolled slip of anchors under tension loading (refer to Fig. 5.2) because this behavior is generally difficult to predict. Furthermore, the design method in ACI 318 Appendix D for group effects is based on the minimum load-slip behavior represented by the curves in Fig. 5.2. Significant deviation from these curves could result in unconservative designs. Because the expansion mechanism cannot be observed directly during the test, aberrations in the load-slip behavior are the only practical means of identifying anchors that do not function acceptably. Allowance is made for the possibility that uncontrolled slip could be caused by local anomalies in the concrete. A larger number of test samples are required to make this determination. If there are defects in the load-slip behavior of the additionally tested anchors, then the anchor should be investigated for malfunction.

R5.5.3 The hypothetical behavior of a single anchor subjected to monotonically increasing tension loading is schematically shown in Fig. R7, in which the failure load is plotted against the embedment depth of the anchor. The failure mode of this hypothetical anchor changes with increasing embedment depth. The three controlling failure modes are concrete cone failure, pullout or pull-through failure, and steel failure. For anchors that are available in a variety of embedment depths for a particular diameter, it is

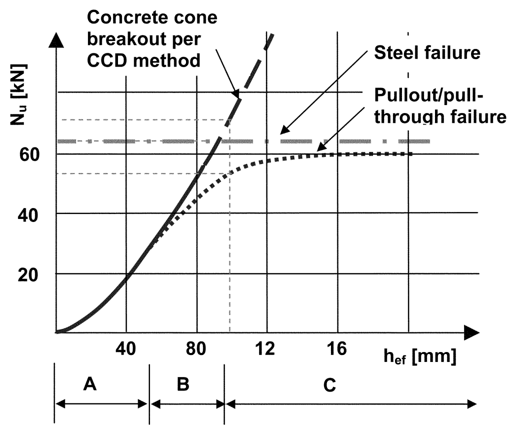

Fig. R7—Hypothetical behavior of single anchor as characterized by ACI 318.

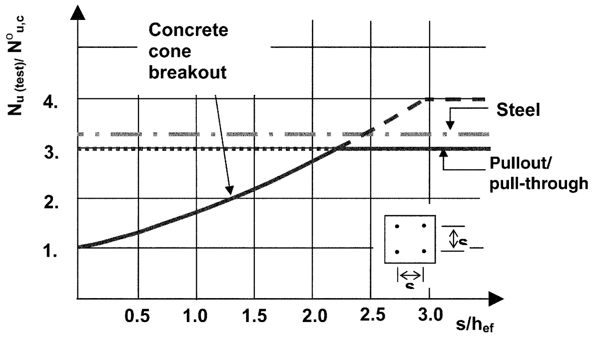

Fig. R8—Hypothetical behavior of group anchors as characterized by ACI 318.

necessary to establish the controlling failure mode and associated failure load for each embedment depth. As can be seen in Fig. R7, it is possible that multiple failure modes can be observed at a particular embedment depth if that embedment depth corresponds to a transition from one failure mode to another. The curves of Fig. R7 and R8 represent mean behavior.

Figure R7 shows three zones of behavior. In Zone A, concrete cone failure is observed in all tests. The value of k calculated from Eq. (7-1) is checked for compliance with the values of k given in Table 7.1. Compliance indicates conformance of anchor behavior with the equations used in ACI 318 Appendix D; that is, the effects of embedment depth, edge and spacing effects, concrete strength, and cracking are accounted for in the default design method of ACI 318.

In Zone C, pullout or pull-through is observed. The corresponding characteristic failure load N_p is determined based on an increased sample size. This load, like the steel failure load, then represents an upper limit on the anchor capacity. The characteristic value N_p is used in the determination of the lowest tensile capacity and establishment of the anchor category. The effectiveness factor k is taken as the minimum in Table 7.1 and, as before, the design procedure of ACI 318 Appendix D applies to calculate the concrete cone breakout failure load. For spacing and edge distance effects, the equations of ACI 318 Appendix D are still applicable because anchors without edge effects, spacing effects, or both, and that fail by pullout or pull-through at a given embedment depth, may still exhibit concrete cone failure when closely spaced or near an edge (refer to Fig. R8). In Zone B, mixed failure modes are possible. Again, the sample size is increased and the characteristic resistance for pullout or pull-through failure is calculated. For anchors in groups or near an edge, the concrete cone capacity is calculated according to ACI 318 using the lowest k value from Table 7.1.

R5.5.3.2 The manufacturer specifies embedments at which the anchor is to be qualified. The smallest embedment is defined as shallow and the largest as deep. These shallow and deep embedments are used in the tests according to Table 5.7.

R6.3.1 This check may include characteristics such as surface hardness or roughness and coating thickness or surface roughness. Fabrication techniques might include machining techniques (for example, cold-forming versus machining), or surface treatment (for example, heat-treatment or shot-peening).

R7.2.1 The coefficient of variation for the load capacities obtained in the reference tests is limited to 15%, while the coefficient of variation for the reliability tests is limited to 20%. The maximum variation expected for the reference tests would be from pullout, pull-through, or concrete cone breakout failure modes and almost all well-functioning anchors have been found, from experience, to be within this limit. The reliability tests use adverse setting conditions, so a larger coefficient of variation could be allowed with the performance.

R7.2 Anchors to be qualified for use in cracked concrete are installed in hairline cracks, which are then opened to a width w = 0.012 in. (0.30 mm) before loading. This crack width is consistent with the assumptions of ACI 318 under quasipermanent load.

R7.3.1 Table 7.1 prescribes the permissible range of values for the effectiveness factor k that may be reported for a particular anchor diameter. The lower bound represents the transition between pullout or pull-through failure and concrete cone failure and was established by evaluating a large database of test results. The upper bound represents the behavior of cast-in-place headed studs or bolts.

R8.2 Tests to check sensitivity to reduced installation effort are performed in low- and high-strength concrete, depending on the anchor type, to combine unfavorable conditions that may occur in practice.

For torque-controlled expansion anchors (8.2.2.1), the tests are performed in high-strength concrete because, for a given torque, the indentation of the expansion sleeve (and therefore the available frictional resistance between sleeve and concrete) is smaller than in low-strength concrete. These tests are intended to check the follow-up expansion capability of expansion anchors for applications in high-strength concrete.

For displacement-controlled expansion anchors (8.2.2.2), the tests are performed in low-strength concrete. The expansion force (and thus the holding capacity of the anchor for a given anchor expansion [R5.2.3.3]) is smaller in low-strength concrete than in high-strength concrete.

For displacement-controlled undercut anchors (8.2.2.3), the tests are performed in low-strength concrete because the effect of the variation of the undercutting on the anchor behavior is greater in low-strength concrete than in high-strength concrete.

For torque-controlled and load-controlled undercut anchors, the tests are performed in low- and high-strength concrete. For these anchors, it cannot be predetermined if installation sensitivity is greater in low-strength or in high-strength concrete.

In the tests to check the sensitivity to reduced installation effort, drill bits with a medium diameter d_m are used. This represents normal conditions.

R8.3 and **R8.4** Anchors should function properly in holes drilled with a drill bit whose cutting-edge diameter lies within the prescribed range. Anchors should also work when installed in low- and high-strength concrete. Therefore, variations in drill-bit diameter and concrete strength are combined. Tests are performed in low-strength concrete using a large drill-bit diameter, d_{max}. This drill bit diameter represents a new drill bit on the large side of the tolerance range. If an anchor is sensitive to a large drilled-hole diameter, the failure mode may change from concrete breakout (the normal condition) to pullout or pull-through.

Under the combination of high-strength concrete and a small (worn) drill bit, installation of an anchor may be difficult. To check this influence, the tests in high-strength concrete are performed with a smaller drill-bit diameter, d_{min}.

R8.5 Anchors should be capable of resisting sustained loads that may vary over time. Anchors to be used in uncracked concrete are tested under repeated loads. To simulate conditions that may occur in practice and still maintain a reasonable duration of the test, the tests are conducted with elevated loads. Experience shows that anchors that behave well under repeated loads will also behave well under a constant sustained load. Therefore, tests under sustained load are not included.

R8.5.3 The anchor should show a stabilization of movement. That is, during testing under repeated loading, the displacement of the anchor should show a trend of decreasing displacement or the displacement will not be increasing, so that the anchor will attain a residual capacity that meets the test requirements of Section 8.5.

R8.6 *Cycled crack tests*—Anchors to be used in cracked concrete are tested in the reference tests in cracks with a maximum width $w = 0.012$ in. (0.30 mm). This crack width will occur when the structure is loaded to the quasipermanent load, which is a fractile of the allowable service load. In design according to ACI 318, crack widths are controlled mainly for reasons of durability.

When the structure is loaded to the full service (unfactored) load, crack widths will increase. This is not taken into account by ACI 318 because the full service load will occur only briefly, and the durability of the structure is not appreciably affected. Anchor capacity, in contrast, is significantly reduced by increased crack widths. Therefore, a crack width of $w = 0.020$ in. (0.5 mm) is chosen in the tests. Refer to ACI Committee 224 documents and ACI 318-95, 10.6 and R10.6.

In structural concrete members that are cracked, the crack width may vary with time as live load varies on the structure. Therefore, anchors to be used in cracked concrete are tested in cracks under constant tension loads. The cracks are opened 1000 times between 0.004 and 0.012 in. (0.1 and 0.3 mm). This number of loading cycles is representative of the number of significant load variations on a typical structure during its lifetime (that is, about 20 annual load cycles over a 50-year life). The maximum crack width is consistent with the crack width contemplated by ACI 318 under quasipermanent load. The minimum crack width depends on the ratio of dead to live load on the structure. The value prescribed for the tests represents average conditions.

During the crack movement test, anchor displacement increases significantly with increasing number of crack-opening cycles under constant load on the anchor. Therefore, if the prescribed displacement limits after the crack openings are not met, the constant tension load N_w should be reduced, and the characteristic tensile resistance in low-strength concrete reported in Table 11.2 should be calculated using Eq. (8-2). Refer to Furche (1994) for background information on the crack movement test.

R9.2 According to the CCD Method, which is the default design method of ACI 318 Appendix D, this maximum capacity is assumed to be valid for edge distances $c \leq 1.5h_{ef}$. To check this assumption for the anchor being tested, tension tests are performed with single anchors in a corner with $c_1 = c_2 = 1.5h_{ef}$. This edge distance represents the critical edge distance; that is, the minimum edge distance at which there is no edge influence on the tensile capacity of the anchor. The tests are performed in concrete members having the smallest thickness for which the manufacturer wishes to qualify the anchor.

R9.2.2 Test experience shows that, due to splitting, many torque-controlled and displacement-controlled expansion anchors and some undercut anchors require edge distance larger than $1.5h_{ef}$ to achieve full concrete breakout or pullout capacity. This critical edge distance, c_{cr}, is determined by the corner test.

R9.3 The purpose of this test is to check that the concrete will not split during anchor installation. Tests are performed with two anchors installed parallel to an edge with the minimum edge and spacing distances and in a test member having the smallest thickness for which the manufacturer wishes to qualify the anchor. The design method of ACI 318 prescribes the minimum edge distance, c_{min}, and minimum spacing, s_{min}. These are:

$s_{min} = 6d_o$;

$c_{min} = 6d_o$ for undercut anchors;

$= 8d_o$ for torque-controlled anchors;

$= 10d_o$ for displacement-controlled anchors; and

$h_{min} = 1.5h_{ef}$.

These lower limits were chosen to prevent concrete splitting during installation and are only estimates. They could be used as starting points for the test. Anchors with different working principles will have different minimum values. These tests establish the product-specific values of c_{min} and s_{min} that will allow anchor installation without damage to concrete. The report can include different combinations of c_{min}, s_{min}, and h_{min}. These minimum values are usually based on a minimum concrete thickness, h_{min}, proposed by the manufacturer. A combination of c_{min} and s_{min} is determined from the testing program. The value of h_{min} can be changed as deemed appropriate from test data. There can be more than one combination of these three minimum values.

Anchors installed by applying a torque will cause splitting at close edge distances. Therefore, this test should be conducted for all anchors for which a torque is specified by the manufacturer. Because this torque level is intended to compensate for possible inaccuracies of torque wrenches on site, no splitting should occur for applied torques up to $1.7T_{inst}$.

The values of s_{min}, c_{min}, and h_{min} are related because c_{min} and s_{min} depend on member thickness. ACI 318 requires that h be greater than or equal to $1.5h_{ef}$; this may in turn require a larger value of c_{min} or s_{min}. Alternatively, the minimum member thickness may be increased so as not to reduce c_{min} or s_{min}.

For anchors that are not torqued, such as displacement-controlled anchors, the minimum edge distance is acceptable if the anchor can be set without failing the edge.

Displacement-controlled undercut anchors can be set close to an edge. They should be set to check if they are consistent with the design method of ACI 318.

In torque-controlled anchors, T_{inst} creates a temporary high prestress that drops after a few minutes to a stabilized anchor preload. This brief peak in imposed prestress usually produces a load in the anchor higher than the service load. For T_{inst} in the field, scatter is expected. Higher torques will cause edge splitting during installation. Therefore, a value of $1.7T_{inst}$ is required.

R9.4 Where the cross-sectional area of an anchor in the shear plane is less than of a threaded section of the same nominal diameter within five anchor diameters of the shear plane, the shear capacity may be affected by the reduced section. Tests need to be performed to establish the appropriate shear capacity. See Fig. R9.

R9.5 and **9.6** *Seismic tension and shear tests*—Seismic tension and shear tests are required by ACI 318 for the anchor to be used in seismic zones. Because it is assumed that concrete will crack during earthquakes and that such cracking will be more severe than under quasistatic loads, the anchors are tested in static cracks of w = 0.020 in. (0.5 mm) using a loading cycle simulating a seismic event.

R11.0 An example of the evaluation of a hypothetical anchor is given at the end of this commentary.

RA1.2 Normalization of anchor capacities is valid for the concrete compressive strength ranges between 2500 and 8000 psi. ACI 318 Appendix D limits the use of the design method for post-installed mechanical anchors to no greater than 8000 psi concrete compressive strength, unless testing is performed. The applicability of normalization to concrete compressive strengths higher than 8000 psi would have to be investigated.

RA1.3 The pullout or pull-through capacity of an anchor may vary as some mathematical function of the concrete strength. For example, the capacity may vary linearly or as the square root of the compressive strength. In general, a square root function is reasonable. This variation should be determined from the tests and included in the report. The reporting should give the capacity at the lowest concrete compressive strength (2500 psi [17 MPa]) and the variation, if any.

RA3.2 Concrete test members intended for use in tests with cracks may have crack inducers installed to assist in the development of uniform cracks throughout the depth of the test member. These crack inducers may be thin metal sheets placed in the expected plane of the crack, but should be sufficiently far from the anchor location to not influence test results.

Crack widths in the concrete can be controlled by use of longitudinal reinforcing bars with appropriate ratios of reinforcing to concrete cross-sectional areas of approximately 1%. The reinforcement ratio should be increased if the reinforcement yields during the tests.

The surface reinforcement parallel to the surface may be located in the cone of concrete as long as the anchors are installed approximately midway between the bars. Finite element analysis and fracture mechanics have shown that the concrete failure is initiated by a crack at the load transfer mechanism of the anchor and propagates at approximately a 120-degree cone (included angle). By the time the crack in the concrete reaches the surface reinforcement, the anchor maximum capacity has been reached and the reinforcing has no affect on this capacity. Therefore, the surface reinforcement may be located within the concrete cone. In addition, surface reinforcement is desirable in cases involving large embedment depths because, without it, the capacity of the test specimens can be unrealistically governed by the flexural capacity of the test specimen rather than the breakout capacity of the anchor.

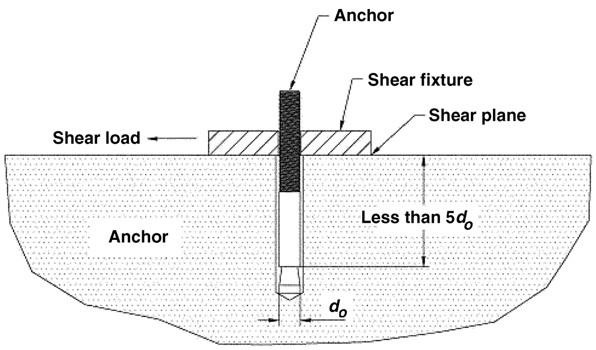

Fig. R9—Anchor with reduced cross-section within five anchor diameters of the shear plane.

Commentary references

ACI Committee 224, 1990, "Control of Cracking in Concrete Structures (ACI 224R-90)," American Concrete Institute, Farmington Hills, Mich., 43 pp.

ACI Committee 318, 1995, "Building Code Requirements for Structural Concrete (ACI 318-95) and Commentary (318R-95)," American Concrete Institute, Farmington Hills, Mich., 369 pp.

ACI Committee 318, 2005, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05)," American Concrete Institute, Farmington Hills, Mich., 430 pp.

ANSI/ASME B1.1, 1989, "Unified Inch Screw Threads (UN and UNR Thread Form)," ASME, Fairfield, N.J.

Burrows, R. W., 1998, "The Visible and Invisible Cracking of Concrete," *Monograph* No. 11, American Concrete Institute, Farmington Hills, Mich., 78 pp.

Eligehausen, R., and Balogh, T., 1995, "Behavior of Fasteners Loaded in Tension in Cracked Reinforced Concrete," *ACI Structural Journal*, V. 92, No. 3, May-June, pp. 365-379.

Eligehausen, R.; Mattis, L.; Wollmershauser, R.; and Hoehler, M., 2004, "Testing Anchors in Cracked Concrete," *Concrete International*, V. 26, No. 7, July, pp. 66-71.

Fuchs, W.; Eligehausen, R.; and Breen, J., 1995, "Concrete Capacity Design (CCD) Approach for Fastening to Concrete," *ACI Structural Journal*, V. 92, No. 1, Jan.-Feb., pp. 73-94.

Furche, J., 1994, "Zum Trag-und Verschiebungsverhalten von Kopfbolzen bei zentrischem Zug (Strength and Displacement Behavior of Headed Studs Loaded in Tension)," PhD discussion, Universität Stuttgart, Germany.

EXAMPLE OF EVALUATION OF A WEDGE-TYPE ANCHOR IN UNCRACKED CONCRETE

E1—ANCHOR SPECIFICATIONS

See Table E1.

E2—TEST RESULTS

See Table E2.

E3—EVALUATION

E3.1—General

All load-displacement curves for Table 4.1, Tests 1, 2, 3, 4, 5, and 7; and Table 4.2, Tests 1, 2, 3, 4, 5, 6, 7, 9, and 12 have to be checked. Uncontrolled slip is not allowed (5.5.1), and did not occur. The anchor stiffness β is calculated according to Eq. (5-1) of 5.5.2. For this anchor, the lowest mean value of all reference tension tests is β = 54,970 lb/in. (9.6 kN/mm).

$$\beta = \frac{0.3 \cdot 7036 - 0.1 \cdot 7036}{0.0260 - 0.0004} = 54{,}970 \text{ lb/in. } (9.6 \text{ kN/mm})$$

Table E1—Anchor specifications[*]

Characteristic	Symbol	in.-lb units	SI units
Nominal anchor diameter	—	1/2 in.	13 mm
Effective embedment depth	h_{ef}	2-3/4 in.	70 mm
Outside diameter	d_o	1/2 in.	12 mm
Effective tensile stress area	A_{se}	0.142 in.^{2}	92 mm^2
Effective shear stress area	A_{se}	0.13 in.^{2}	84 mm^2
Minimum specified yield strength	f_y	74,000 psi	510 MPa
Minimum specified ultimate tensile strength	f_{ut}	92,800 psi	640 MPa
Yield strength, test result	$f_{y,test}$	81,490 psi	562 MPa
Mean ultimate tensile strength, test result in shank section	$f_{u,test}$	99,300 psi	685 MPa
Mean ultimate tensile strength, test result in reduced section	$f_{u,test}$	119,600 psi	825 MPa
Installation torque	T_{inst}	45 ft-lb	60 N-m
Minimum member thickness	h_{min}	5-1/2 in.	140 mm

[*] This example uses a 1/2 in. (13 mm) anchor, and all data are shown with conversion SI units.

E3.2—Reference tests in uncracked low-strength concrete

The coefficient of variation of the failure load is less than 15%. The scatter is acceptable. In the tests, pull-through with a concrete cone failure was observed. For concrete cone failure, a minimum effectiveness factor of $k = 24(10)$ is expected.

$$N_{b,o} = 6445 \cdot (1 - 2.568 \cdot 0.059) = 5468 \text{ lb } (24.3 \text{ kN})$$

$$k = \frac{5468}{\sqrt{2800}(2.75)^{1.5}} = 22.6(8.94)$$

The calculated effectiveness factor is smaller than the minimum expected factor. That means that pull-through is the primary failure mode, and the concrete cone is the secondary failure mode.

For the design of anchors, the pullout resistance is critical. Concrete cone failure may be critical, but only for anchor groups or anchors close to an edge. The effectiveness factor has to be taken as the minimum, $k = 24(10)$.

For steel failure, a mean failure load of

$$N_{st} = 0.142 \cdot 119{,}600 = 16{,}983 \text{ lb } (75.6 \text{ kN})$$

is expected. So, steel failure is unlikely. The characteristic resistance is

$$N_k = 0.142 \cdot 92{,}800 = 13{,}178 \text{ lb } (58.6 \text{ kN})$$

Table E2—Test results

General test description and number	Test purpose	Reference	Sample size n	$f_{c,test}$, psi (MPa)	$F_{u,test}$, lb (kN)	Standard deviation s, lb (kN)	Coefficient of variation ν, %	Failure mode	Remarks and commentary reference
All tests	—	7, 8, 9	—	—	—	—	—	—	No uncontrolled slip observed
Reference test – 1	—	7.2	10	2800 (19.3)	6445 (28.7)	382 (1.70)	5.9	Pull through/ concrete	E3.2
Reference test – 2	—	7.2	10	6200 (42.7)	9734 (43.3)	605 (2.69)	6.2	Pull through/ concrete	E3.3
Reliability test – 3	Reduced installation	8.2	5	2800 (19.3)	5463 (24.3)	407 (1.81)	7.5	Pull through/ concrete	E3.4
Reliability test – 4	Large hole diameter	8.3	5	2600 (17.9)	5755 (25.6)	393 (1.75)	6.8	Pull through/ concrete	E3.5
Reliability test – 5	Small hole diameter	8.4	5	6200 (42.7)	9576 (42.6)	479 (2.13)	5.0	Pull through/ concrete	E3.6
Reliability test – 6	Repeated load	8.5	5	2800 (19.3)	6092 (27.1)	632 (2.81)	10.4	Pull through/ concrete	E3.7
Service condition test – 7	Corner with two edges	9.2	4	2600 (17.9)	6047 (26.9)	303 (1.35)	5.0	Pull through/ concrete	E3.8
Service condition test – 8	s_{min}, c_{min}	9.3	5	2600 (17.9)	130 ft-lb (177 N-m)	9.7 ft-lb (13 N-m)	10.2	Splitting	E3.9
Service condition test – 9	Shear	9.4	5	2800 (19.3)	8700 (38.7)	252 (1.12)	2.9	Steel	E3.10
From reference tension tests	N_u	—	7036 lb (31.3 kN)						
From all reference tests	$N_{10\%}$	5.5.2	703.6 lb (3.1 kN)						
From all reference tests	$N_{30\%}$	5.5.2	2110.8 lb (9.4 kN)						
From all reference tests	$\Delta_{10\%}$	5.5.2	0.0004 in. (0.01 mm)						
From all reference tests	$\Delta_{30\%}$	5.5.2	0.0260 in. (0.065 mm)						

For pullout or pull-through failure, the characteristic resistance is

$$N_p = 6445 \cdot (1 - 2.568 \cdot 0.059) = 5468 \text{ lb } (24.3 \text{ kN})$$

for a compressive strength of 2800 psi (19 MPa). In this example, it is assumed that the concrete compressive strength is determined from cylinder tests, although the committee recognizes that cube tests are more common in Europe.

E3.3—Reference tests in uncracked high-strength concrete

The coefficient of variation of the failure load is smaller than 15%. The scatter is acceptable. In the tests, pull-through with a concrete cone failure was observed. For concrete cone failure, an effectiveness factor of $k = 24$ is expected.

$$N_{b,o} = 9734 \cdot (1 - 2.568 \cdot 0.062) = 8184 \text{ lb } (36.4 \text{ kN})$$

$$k = \frac{8184}{\sqrt{6200}(2.75)^{1.5}} = 22.8(8.93)$$

The calculated effectiveness factor is smaller than the minimum expected factor, meaning that pull-through is the primary failure mode. The concrete cone is the secondary failure mode.

For steel failure, a mean failure load of

$$N_{st} = 0.142 \cdot 119{,}600 = 16{,}983 \text{ lb } (75.6 \text{ kN})$$

is expected. So, steel failure is unlikely. The characteristic resistance is

$$N_k = 0.142 \cdot 92{,}800 = 13{,}178 \text{ lb } (58.6 \text{ kN})$$

For pullout or pull-through failure, the characteristic resistance is

$$N_p = 9734 \cdot (1 - 2.568 \cdot 0.062) = 8184 \text{ lb } (36.4 \text{ kN})$$

for a compressive strength of 6200 psi (42.7 MPa).

The characteristic pullout resistance is proportional to the square root of the concrete compressive strength. This is shown by the effectiveness factors in low- and high-strength concrete, which are approximately equal, within the scatter of test results.

The pullout resistance for a specified concrete of 2500 psi (17 MPa) is calculated as

$$N_p = 5468 \cdot \sqrt{2500/2800} = 5167 \text{ lb } (23.0 \text{ kN})$$

Pullout resistance increases with the square root of the ratio of specified concrete compressive strength to minimum specified strength.

E3.4—Reliability tests, reduced installation effort

The coefficient of variation of the failure load is less than 20%. The scatter is acceptable. In the tests, pull-through with a concrete cone failure was observed.

$$N_{b,r} = 5463 \cdot (1 - 3.400 \cdot 0.075) = 4070 \text{ lb } (18.1 \text{ kN})$$

To establish anchor categories, the ratio of characteristic capacities has to be calculated.

$$\frac{N_{b,r}}{N_{b,o}} = \frac{4070}{5468} = 0.74$$

A correction related to concrete strength is not necessary because both test series were performed in the same concrete batch, with $f_{c,test} = 2800$ psi (19 MPa).

Remark: It is obvious that the characteristic resistance in these tests is decreased by the larger K value for evaluating the characteristic capacity at 90% confidence. There are only five reliability tests, compared with 10 reference tests. It may be possible to establish a better anchor category by increasing the number of reliability tests.

E3.5—Reliability tests, large hole diameter

The coefficient of variation of the failure load is less than 20%. The scatter is acceptable. In the tests, pull-through with a concrete cone failure was observed.

$$N_p = 5755 \cdot (1 - 3.400 \cdot 0.068) = 4424 \text{ lb } (19.7 \text{ kN})$$

To establish anchor categories, the ratio of characteristic capacities has to be calculated, including a correction for concrete strength.

$$\frac{N_{b,r}}{N_{b,o}} = \frac{4424}{5468} \cdot \sqrt{2800/2600} = 0.83$$

E3.6—Reliability tests, small hole diameter

The coefficient of variation of the failure load is less than 20%. The scatter is acceptable. In the tests, pull-through with a concrete cone failure was observed.

$$N_b = 9576 \cdot (1 - 3.400 \cdot 0.05) = 7948 \text{ lb } (35.4 \text{ kN})$$

To establish anchor categories, the ratio of characteristic capacities has to be calculated.

$$\frac{N_{b,r}}{N_{b,o}} = \frac{7968}{8184} = 0.97$$

Correction for concrete strength is not necessary because both test series were performed in the same concrete batch, with $f_{c,test} = 6200$ psi (43 MPa).

E3.7—Reliability tests, repeated load

Anchor displacements show a stabilization of movement. The coefficient of variation of the failure load in the tensile test after the repeated load is less than 15%. The scatter is acceptable. In the tests, pull-through with a concrete cone failure was observed.

$$\frac{N_{b,r}}{N_{b,o}} = \frac{6092}{6445} = 0.94 > 0.80$$

A correction related to concrete strength is not necessary because both test series were performed in the same concrete batch ($f_{c,test}$ = 2800 psi [19 MPa]).

E3.8—Service-condition tests, corner test

The coefficient of variation of the failure load is 5.0%. In the reference tests, the coefficient of variation is 5.9%, so the scatter of the failure loads is the same.

The distance to both edges was 4 in. (100 mm), which is $1.5h_{ef}$. The minimum member thickness was 5-1/2 in. (140 mm), which is $2h_{ef}$.

For a comparison to reference test results, a correction for concrete strength is necessary.

$$N_m = 6047\sqrt{2800/2600} = 6275 \text{ lb (27.9 kN)}$$

$$s_m = 303\sqrt{2800/2600} = 314 \text{ lb (1.39 kN)}$$

	Reference tests μ_1	Corner tests μ_2
Number of tests	10	5
Mean ultimate load, lb (kN)	6445 (28.7)	6275 (27.9)
Standard deviation, lb (kN)	382 (1.70)	314 (1.390)

t = test for statistical equivalence. Hypothesis: $\mu_1 = \mu_2$.

Confidence level 90%, degrees of freedom $n_1 + n_2 - 2 = 10 + 5 - 2 = 13$, from statistical table for t-distribution: $c = 1.35$

$$t_o = \sqrt{n_1 \cdot n_2 \cdot (n_1 + n_2 - 2)/(n_1 + n_2)} \cdot \frac{\bar{x} - \bar{y}}{\sqrt{(n_1 - 1) \cdot s_1^2 + (n_2 - 1) \cdot s_2^2}}$$

$$t_o = \sqrt{10 \cdot 5 \cdot (10 + 5 - 2)/(10 + 5)} \cdot \frac{6445 - 6275}{\sqrt{(10 - 1) \cdot 382^2 + (5 - 1) \cdot 314^2}} = 1.16$$

For $t_o \le c$ the hypothesis is accepted $t_o = 1.16 \le 1.35 = c$; therefore, the critical edge distance c_{ac} is less than $1.5h_{ef}$ for the specified member thickness of 5-1/2 in. (140 mm).

E3.9—Service-condition tests, minimum edge distance and spacing

In the tests, the minimum edge distance was 3 in. (75 mm), or $6d_o$; the minimum spacing was 6.7 in. (170 mm), or $14d_o$. The minimum member thickness was 5-1/2 in. (140 mm), or $2h_{ef}$.

The applied torque at observation of first hairline cracks was 130 ft-lb (177 Nm). This torque is larger than $1.7T_{inst}$ = 1.7 · 45 ft-lb (60 Nm) = 75 ft-lb (102 Nm). The chosen s_{min}, c_{min}, and h_{min} are acceptable.

E3.10—Service-condition tests, shear tests

The cross-sectional area of the threaded part of the anchor is 0.142 in.^{2} (92 mm^2). Steel failure occurred in this section.

The mean failure load in the tests was 8700 lb (38.7 kN), and lies within the expected range.

$$V_m = 0.6 \cdot f_{u,test} \cdot A_{se} = 0.6 \cdot 99{,}300 \cdot 0.142 = 8460 \text{ lb (37.6 kN)}$$

The characteristic resistance in the shear tests was

$$V_k = 8700 \cdot (1 - 3.400 \cdot 0.029) = 7842 \text{ lb (34.9 kN)}$$

The expected resistance is

$$V_{5\%} = 0.6 \cdot f_{ut} \cdot A_{se} = 0.6 \cdot 92{,}800 \cdot 0.142 = 7907 \text{ lb (35.2 kN)}$$

The expected characteristic resistance is smaller than the measured (and calculated) value.

E4.1—Establishment of anchor category

The following ratios of characteristic capacities were observed:

Reduced installation tests	0.74
Large hole-diameter tests	0.84
Small hole-diameter tests	0.97

The smallest ratio is 0.74, so the anchor category is 2.

E4.2—Report of anchor data

Characteristic	Symbol	Dimension	Anchor value
Anchor diameter	—	in. (mm)	1/2 (13)
Effective embedment depth	h_{ef}	in. (mm)	2.75 (70)
Outside diameter	d_o	in. (mm)	1/2 (13)
Effective tensile stress area	A_{se}	in.^{2} (mm^2)	0.142 (91.6)
Effective shear stress area	A_{se}	in.^{2} (mm^2)	0.142 (91.6)
Minimum specified yield strength	f_y	psi (MPa)	74,000 (510)
Minimum specified ultimate strength	f_{ut}	psi (MPa)	92,800 (640)
Minimum spacing	s_{min}	in. (mm)	6.7 (170)
Minimum edge distance	c_{min}	in. (mm)	3 (75)
Minimum member thickness	h_{min}	in. (mm)	5-1/2 (140)
Category of anchor	—	—	2
Effectiveness factor	k_c	—	24 (10)
Modification factor for absence of cracks	$\psi_{c,N}$	—	1.0
Characteristic pullout resistance in specified concrete	N_p	lb (kN)	5167 (22.98)*
Anchor axial stiffness in service load range	β	lb/in. (kN/mm)	54,970 (9.6)

*Increase characteristic pullout resistance for other specified concrete compressive strength by the square root of the specified strength divided by 2500 psi (17 MPa).