Evaluating the Performance of Post-Installed Mechanical Anchors in Concrete (ACI 355.2-00)

Reported by ACI Committee 355

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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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CHAPTER 1—SCOPE

1.1 ACI 355.2 prescribes testing and evaluation requirements for post-installed mechanical anchors intended for use in concrete according to the design criteria of ACI 318 *Building Code Requirements for Structural Concrete*. Criteria are prescribed for determining whether anchors are acceptable for use in uncracked concrete only, or in cracked as well as uncracked concrete. Criteria are prescribed for determining the performance category into which each anchor shall be placed. 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 only 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 only 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 on the basis of the performance of the anchor in reliability tests (see Section 10.0).

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*—A set of similar anchors that vary only due to diameter or embedment length; 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 cone or edge failure of the test member due to setting of the anchor or to applied loads, in either tension or shear.

2.1.6 *Cracked concrete*—A test member with a uniform crack width over the depth of the concrete member.

2.1.7 *Displacement-controlled expansion anchor*—A post-installed anchor that derives its tensile holding strength 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) (see 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 a steel failure and without a concrete cone failure at the installed embedment depth. The anchor may displace toward the surface, resulting in a concrete cone failure at a load that is not consistently repeatable.

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

2.1.10 *Setting of an anchor*—The process of expanding 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 or between the standard deviations of the two groups. Statistical equivalence of the means of two groups shall be evaluated using a one-sided t-test at a confidence of 90%.

2.1.13 S*teel failure*—Failure mode characterized by fracture of the steel anchor parts transmitting tension loads, shear loads, or both to the point of load introduction into the concrete.

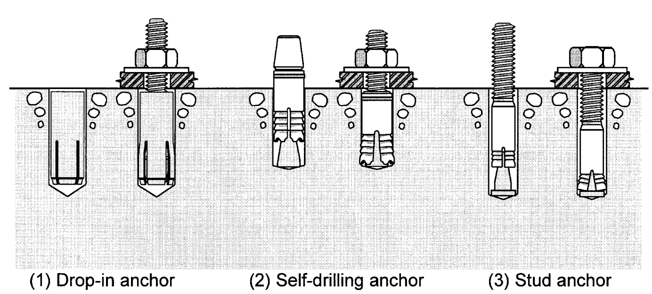


Fig. 2.1—Examples of displacement-controlled expansion anchors.

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

2.1.15 *Torque-controlled expansion anchor*—A post-installed expansion anchor that derives its tensile holding strength from the expansion of one 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) (see Fig. 2.2). After setting, tensile loading can cause additional expansion (follow-up expansion).

2.1.16 *Uncracked concrete*—In these tests, concrete elements that are expected to remain uncracked unless the crack is part of the anchor failure mode.

2.1.17 *Undercut anchor*—A post-installed anchor that derives its 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 (see Fig. 2.3).

2.2—Notation

A_N = projected area of the failure surface for an anchor or group of anchors, approximated as the base of the pyramid that results from projecting the failure surface outward 1.5 h_{ef} from the centerline of the anchor, or in the case of a group of anchors, from a line through the centerlines of a row of adjacent anchors (Fig. 2.4); not to be taken greater than nA_{NO}, in.^{2} (mm^2)

A_{NO} = projected area of the failure surface of a single anchor remote from edges: 9 h^2_{ef}, (see Fig. 2.5), in.^{2} (mm^2)

A_{se} = effective tensile stress area of anchor, in.^{2} (mm^2)

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 carbide diameter 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 carbide diameter 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 carbide diameter tolerance range for a new bit, representing a well-used bit, in. (mm)

d_o = outside diameter of post-installed anchor, in. (mm)

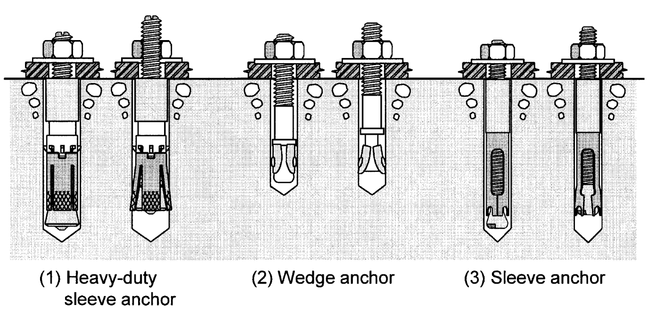


Fig. 2.2—Examples of torque-controlled expansion anchors.

$f_{c,m,i}$ = concrete compressive strength to which test results for Test Series *i* are to be normalized using Eq. A1.1, lb/in.^{2} (MPa)

$f_{c,test,i}$ = mean concrete compressive strength measured with standard cylinders, for concrete of Test Series *i*, lb/in.^{2} (MPa)

f_{ut} = specified ultimate tensile strength of anchor steel, lb/in.^{2} (MPa)

$f_{u,test}$ = mean ultimate tensile strength of anchor steel as determined by test, lb/in.^{2} (MPa)

f_y = specified yield strength of anchor steel, lb/in.^{2} (MPa)

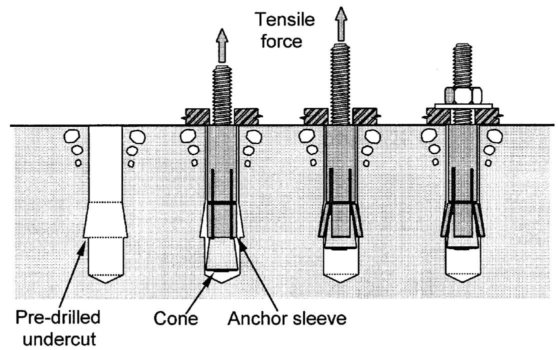


Fig. 2.3(a)—Type 1 undercut anchor. Load-controlled anchor installed by tensioning anchor causing sleeve to expand into predrilled undercut.

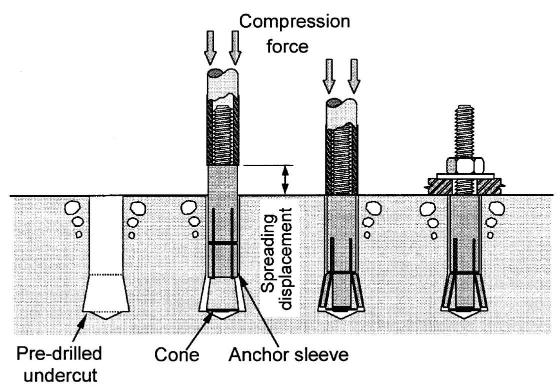


Fig. 2.3(b)—Type 2 undercut anchor. Displacement-controlled anchor set in predrilled undercut by hammering sleeve over cone.

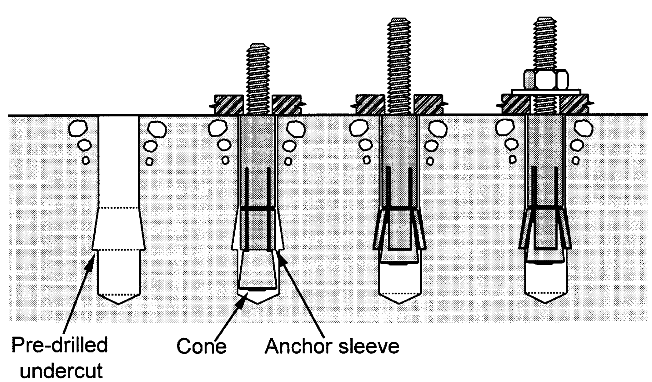


Fig. 2.3(c)—Type 3 undercut anchor. Displacement-controlled anchor set in predrilled undercut by pulling cone up, causing expansion sleeve to expand into undercut.

$F_{m,i}$ = mean normalized capacity in Test Series *i*, as calculated using Eq. (A1-1), lb (N)

F_{ut} = normalized anchor capacity, lb (N)

$F_{u,test,i}$ = mean anchor capacity as determined from Test Series *i*, lb (N)

$F_{5\%}$ = characteristic capacity in a test series, calculated according to Appendix A2, lb (N)

h = thickness of structural member in which an anchor is installed, measured perpendicular to the concrete surface at the point 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 (see Fig. 2.6), in. (mm)

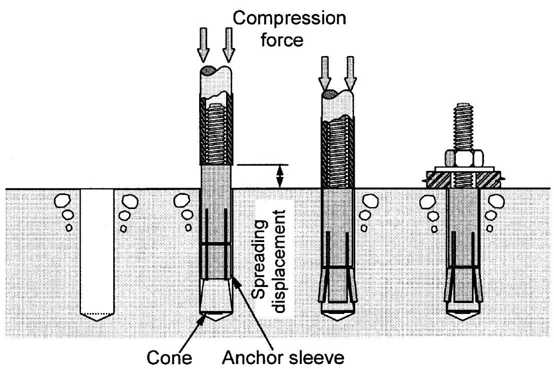


Fig. 2.3(d)(continued)—Type 4 undercut anchor. Displacement-controlled anchor that cuts its own undercut while being set by hammering sleeve over cone.

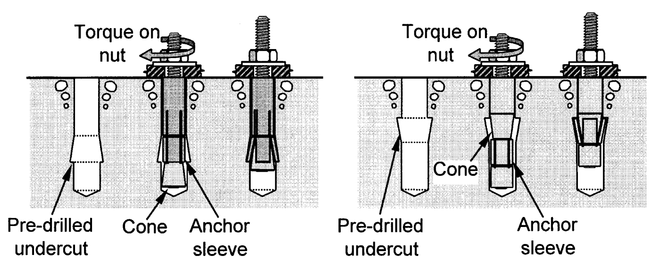


Fig. 2.3(e)—Type 5 undercut anchor. Torque-controlled anchor set into predrilled undercut by application of torque forcing sleeve over cone (two examples shown).

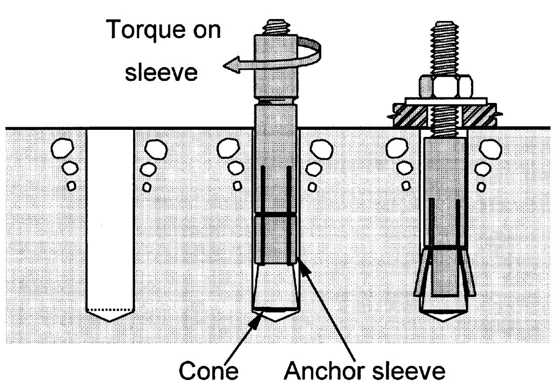


Fig. 2.3(f)—Type 6 undercut anchor. Torque-controlled anchor that cuts its own undercut by application of setting torque that forces sleeve over cone.

h_{min} = minimum member thickness as specified by the anchor manufacturer, in. (mm)

k = effectiveness factor, whose value depends on the type of anchor

K = statistical constant (one-sided tolerance factor) used to establish the 5% fractile with a 90% confidence, and whose value depends on the number of tests (Appendix A2)

n = number of anchors in a test series; also, number of anchors in a group

N = normal force (generally tensile), 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 capacity in reference tests, lb (N)

$N_{b,r}$ = characteristic 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)

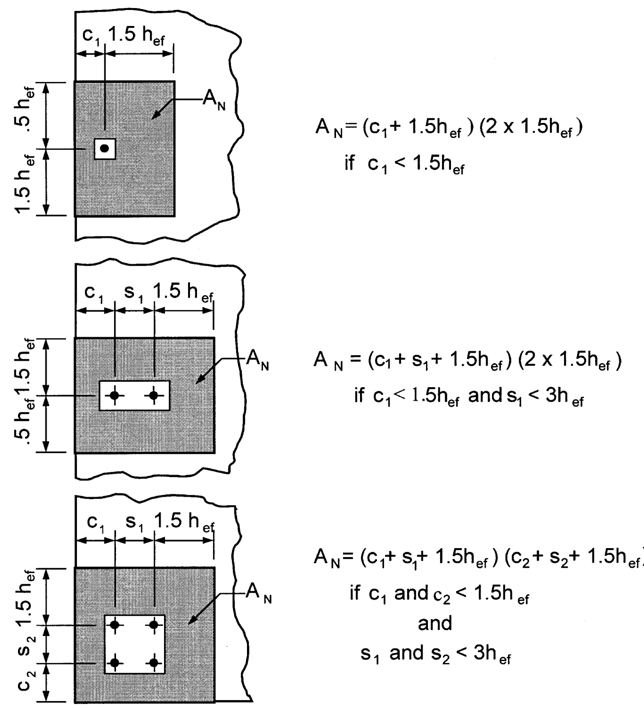


Fig. 2.4—Projected areas A_N *for single anchors and groups of anchors.*

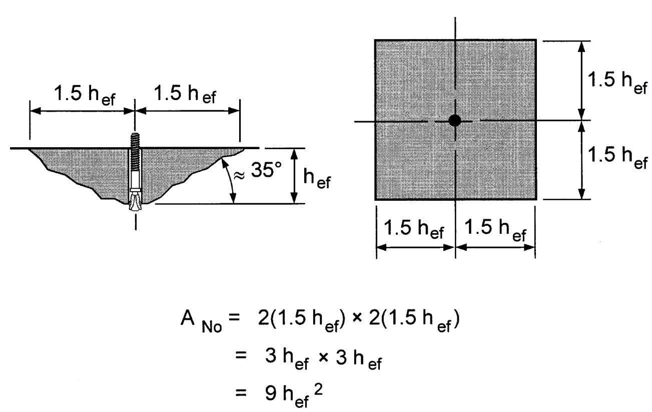


Fig. 2.5—Projected area A_{No} *for single anchor.*

N_k = lowest characteristic 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 in cracks whose opening width is cycled, lb (N)

N_1 = minimum tension load above which variations in the load-displacement curve are acceptable, as prescribed in Section 6.5.1.1, lb (N)

$N_{10\%}$ = load at 10% of the ultimate load measured in the tension test, lb (N)

$N_{30\%}$ = load at 30% of the ultimate load measured in the tension tests, lb (N)

s_{min} = minimum spacing used in Table 5.1, Test 8 and Table 5.2, 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 cyclic 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-opening width, in. (mm)

Δw = change in crack-opening width, in. (mm)

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

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

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

ϕ_{IR} = capacity reduction factor developed from tests for installation reliability

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

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. Applicable anchors are shown in Fig. 2.1, 2.2, and 2.3. It does not apply to anchors loaded in compression if the expansion mechanism is also loaded in compression, nor 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 requirements of ACI 355.2 related to qualification of anchors for seismic applications do not simulate the behavior of anchors in plastic hinge zones of reinforced concrete structures.

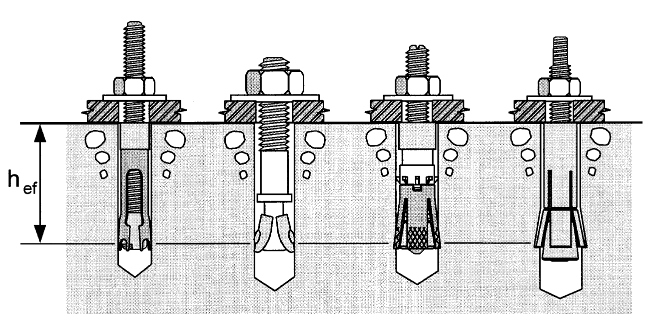


Fig. 2.6—Effective embedment depth.

CHAPTER 4—REQUIREMENTS FOR ANCHOR IDENTIFICATION

4.1—Determination of critical characteristics of anchors

The anchor manufacturer, in consultation with the independent testing and evaluation agency (Section 12.0), 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.

4.2—Specification of critical characteristics of anchors

The manufacturer shall include in the drawings and specifications for the anchor those characteristics determined to be critical (Section 4.1).

4.3—Verification of conformance to drawings and specifications

4.3.1 *Dimensions*—Dimensions determined to be critical (Section 4.1) shall be checked by the independent testing and evaluation agency (Section 12.0) for conformance to the drawings and specifications (Section 4.2).

4.3.2 *Constituent materials*—Constituent materials determined to be critical (Section 4.1) shall be checked by the independent testing and evaluation agency (Section 12.0) for conformance to mechanical and chemical specifications (Section 4.2), using certified mill test reports for steels, and using similar certified documents for other materials.

4.3.3 *Surface finishes*—Surface finishes determined to be critical (Section 4.1) shall be checked by the independent testing and evaluation agency (Section 12.0) for conformance to drawings and specifications (Section 4.2). This check may include characteristics such as surface hardness or roughness.

4.3.4 *Coatings*—Coatings determined to be critical (Section 4.1) shall be checked by the independent testing and evaluation agency (Section 12.0) for compliance with drawings and specifications (Section 4.2). This check may include characteristics such as coating thickness or surface roughness.

4.3.5 *Fabrication techniques*—Fabrication techniques determined to be critical (Section 4.1) shall be checked by the independent testing and evaluation agency (Section 12.0) for compliance with the drawings and specifications (Section 4.2). These fabrication techniques might include machining techniques (for example, cold-forming versus machining), or surface treatment (for example, heat-treatment or shot-peening).

4.3.6 *Markings*—Markings determined to be critical (Section 4.1) shall be checked by the independent testing and evaluation agency (Section 12.0) for compliance with drawings and specifications (Section 4.2).

4.3.7 *Quality control*—Anchors shall be manufactured under a quality-assurance program certified under ISO 17025 to ensure performance consistent with the results of qualification testing and evaluation in accordance with ACI 355.2. This quality-assurance program shall be monitored by an independent quality agency at least twice yearly.

CHAPTER 5—GENERAL REQUIREMENTS

5.1—Testing sequence

Perform four types of tests in the following sequence:

1. Identification tests to evaluate the anchor's compliance with the critical characteristics determined in Section 4.1;
2. Reference tests to establish baseline performance against which subsequent tests are to be compared (Section 7.0);
3. Reliability tests to confirm the reliability of the anchor under adverse installation procedures and long-term use (Section 8.0); and
4. Service-condition tests to evaluate the performance of the anchor under expected service conditions (Section 9.0).

Test requirements are summarized in Tables 5.1 and 5.2. Determine the acceptability or unacceptability of the anchor using the criteria prescribed in Sections 4.0, 7.0, 8.0, and 9.0. Determine the anchor category (an index of the anchor's sensitivity to conditions of installation and use) using the criteria prescribed in Section 10.0. Report the lowest category by diameter as prescribed in Section 11.0. For anchors with multiple embedments, refer to Table 6.7.

5.2—Test samples

The independent testing and evaluation agency (Section 12.0) shall visit the manufacturing or distribution facility, shall randomly select anchors for testing, and shall 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 evaluated. See Section 2.1.12.

5.2.1 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.

5.2.2 Perform separate reference and reliability tests in accordance with Table 5.1 or Table 5.2 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 (Section 2.1.12), the service-condition tests of Table 5.1 (Tests 7, 8, and 9), and of Table 5.2 (Tests 9, 10, and 11) shall be permitted to be per-

Table 5.1—Test program for evaluating anchor systems for use in uncracked concrete

Test number	Reference	Purpose	Description	Concrete strength	Member thickness	Drill bit diameter	Minimum sample size,* n
Reference tests							
1	7.2	Low-strength concrete	Tension—single anchor away from edges	Low	$\geq h_{min}$	d_m	5
2	7.2	High-strength concrete	Tension—single anchor away from edges	High	$\geq h_{min}$	d_m	5
Reliability tests							
3	8.2	Sensitivity to reduced installation effort	Tension—single anchor away from edges	Varies with anchor type	$\geq h_{min}$	d_m†	5
4	8.3	Sensitivity to large hole diameter	Tension—single anchor away from edges	Low	$\geq h_{min}$	d_{max}	5
5	8.4	Sensitivity to small hole diameter	Tension—single anchor away from edges	High	$\geq h_{min}$	d_{min}	5
6	8.5	Reliability under repeated load	Repeated tension—single anchor away from edges, residual capacity	Low	$\geq h_{min}$	d_m	5‡
Service-condition tests							
7	9.3	Verification of full concrete capacity in corner with edges located at 1.5 h_{ef}	Tension—single anchor in corner with edges located at 1.5 h_{ef}	Low	h_{min}	d_m	4
8	9.4	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	9.5	Shear capacity of steel§|	Shear—single anchor away from edges	Low	$\geq h_{min}$	d_m	5

*All diameters unless noted otherwise.

†Drilling diameters for undercuts are different and are given in Table 6.6.

‡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.

formed for one anchor material and production method only. Otherwise, perform the complete test program for each anchor material and production method.

5.2.3 The sample sizes given in Table 5.1 and 5.2 are the minimum. At the discretion of the independent testing and evaluation agency or manufacturer, the sample size shall be permitted to be increased.

5.3—Testing by manufacturer

All reference and reliability tests shall be performed by the independent testing and evaluation agency (Section 12.0). Not more than 50% of the service-condition tests required by ACI 355.2 shall be permitted to be performed by the manufacturer. All such tests shall be witnessed by an independent testing laboratory or engineer meeting the requirements of Section 12.0. The manufacturer's tests shall be considered in the evaluation only if the results are statistically equivalent to those of the independent testing and evaluation agency.

5.4—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 (Section 12.0), which shall determine which tests (if any) shall be performed. For all changes that might affect the anchor performance, perform

Table 5.2—Test program for evaluating anchor systems for use in cracked and uncracked concrete

Test number	Reference	Purpose	Description	Crack opening width *w*, in.	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 away from edges	—	Low	$\geq h_{min}$	d_m	5
2	7.2	Reference test in uncracked high-strength concrete	Tension—single anchor away from edges	—	High	$\geq h_{min}$	d_m	5
3	7.2	Reference test in low-strength, cracked concrete	Tension—single anchor away from edges	0.012	Low	$\geq h_{min}$	d_m	5
4	7.2	Reference test in high-strength, cracked concrete	Tension—single anchor away from edges	0.012	High	$\geq h_{min}$	d_m	5
Reliability tests								
5	8.2	Sensitivity to reduced installation effort	Tension—single anchor away from edges	0.012	Varies with anchor type	$\geq h_{min}$	d_m†	5
6	8.3	Sensitivity to crack width and large hole diameter	Tension—single anchor away from edges	0.020	Low	$\geq h_{min}$	d_{max}	5
7	8.4	Sensitivity to crack width and small hole diameter	Tension—single anchor away from edges	0.020	High	$\geq h_{min}$	d_{min}	5
8	8.6	Test in cracks whose opening width is cycled	Sustained tension—single anchor away from edges, residual capacity	0.004 to 0.012	Low	$\geq h_{min}$	d_{max}§	5
Service-condition tests								
9	9.3	Verification of full concrete capacity in corner with edges located at 1.5 h_{ef}	Tension—single anchor in corner with edges located at 1.5 h_{ef}	—	Low	h_{min}	d_m	4
10	9.4	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	9.5	Shear capacity in uncracked concrete steel‡	Shear—single anchor away from edges	—	Low	$\geq h_{min}$	d_m	5
12	9.6	Seismic tension	Pulsating tension, single anchor, away from free edge	0.020	Low	$\geq h_{min}$	d_m	5
13	9.7	Seismic shear	Alternating shear, single anchor, away from free edge	0.020	Low	$\geq h_{min}$	d_m	5

*All diameters unless noted otherwise.

†Drilling diameters for undercuts are different and are given in Table 6.6.

‡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.

§Test for undercut anchors use d_m.

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 5.1 or Table 5.2.

CHAPTER 6—REQUIREMENTS FOR TEST SPECIMENS, INSTALLATION OF ANCHORS, AND CONDUCT OF TESTS

6.1—Concrete for test members

Concrete used in testing shall meet the requirements of Sections 6.1 through 6.1.4. To verify the performance of an anchor in a particular type of concrete (for example, concrete with higher strength and lower strength than given in ACI 355.2), specify that same type of concrete for the tests of ACI 355.2.

6.1.1 *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). For lightweight concrete, aggregates shall conform to ASTM C 330.

6.1.2 *Cement*—Use 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), unless otherwise specified by the manufacturer. Report if such cementitious materials or admixtures are used in the concrete.

6.1.3 *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 (see Appendix A3.3.1). These strength ranges are:

- Low-strength concrete: 2500 to 3500 lb/in.^{2} (17 to 24 MPa); and
- High-strength concrete: 6500 to 8000 lb/in.^{2} (46 to 57 MPa).

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

Table 6.1—Required diameters of carbide hammer-drill bits, in.

Nominal diameter, in.	Tolerance ranges		
	d_{min}, in.	d_m, in.	d_{max}, in.
3/16	0.190 - 0.194	0.198 - 0.201	0.204 - 0.206
1/4	0.252 - 0.256	0.260 - 0.263	0.266 - 0.268
5/16	0.319 - 0.323	0.327 - 0.331	0.333 - 0.335
3/8	0.381 - 0.385	0.390 - 0.393	0.396 - 0.398
7/16	0.448 - 0.452	0.458 - 0.462	0.465 - 0.468
1/2	0.510 - 0.514	0.520 - 0.524	0.527 - 0.530
9/16	0.573 - 0.577	0.582 - 0.586	0.589 - 0.592
5/8	0.639 - 0.643	0.650 - 0.654	0.657 - 0.660
11/16	0.702 - 0.706	0.713 - 0.717	0.720 - 0.723
3/4	0.764 - 0.768	0.775 - 0.779	0.784 - 0.787
13/16	0.827 - 0.831	0.837 - 0.841	0.846 - 0.849
27/32	0.858 - 0.862	0.869 - 0.873	0.878 - 0.881
7/8	0.892 - 0.896	0.905 - 0.909	0.914 - 0.917
15/16	0.955 - 0.959	0.968 - 0.972	0.977 - 0.980
1	1.017 - 1.021	1.030 - 1.034	1.039 - 1.042
1-1/8	1.145 - 1.149	1.160 - 1.164	1.172 - 1.175
1-3/16	1.208 - 1.212	1.223 - 1.227	1.235 - 1.238
1-1/4	1.270 - 1.274	1.285 - 1.289	1.297 - 1.300
1-5/16	1.333 - 1.337	1.352 - 1.356	1.364 - 1.367
1-3/8	1.395 - 1.399	1.410 - 1.414	1.422 - 1.425
1-7/16	1.458 - 1.462	1.472 - 1.476	1.484 - 1.487
1-1/2	1.520 - 1.524	1.535 - 1.539	1.547 - 1.550
1-9/16	1.570 - 1.574	1.588 - 1.592	1.605 - 1.608
1-5/8	1.637 - 1.641	1.655 - 1.659	1.673 - 1.675
1-3/4	1.754 - 1.758	1.772 - 1.776	1.789 - 1.792
2	1.990 - 1.994	2.008 - 2.012	2.025 - 2.028

6.2—Anchor installation

6.2.1—*General requirements*

6.2.1.1 Install anchors according to the manufacturer's instructions, except as otherwise prescribed in ACI 355.2, and report any deviations.

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

6.2.1.3 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.

6.2.2 *Drill bit requirements*—Drill bit requirements are given in Tables 5.1 and 5.2. Drill holes for anchors shall be perpendicular (within a tolerance of ±6 degrees) to the surface of the concrete member. Except for self-drilling anchors and except as specified in Section 6.2.2.3 and 6.2.2.5, holes shall be made using carbide-tipped, hammer-drill bits meeting the requirements of ANSI B212.15.

6.2.2.1 The cutting diameter of drill bits shall conform to the tolerances given in Table 6.1 or 6.2, and shall be checked every 10 drilling operations to ensure continued compliance.

6.2.2.2 When performing tests with bits of diameter d_{max}, use special test bits. Special test bits ground to the desired diameter shall be permitted to be used.

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

6.2.2.4 All service-condition tests (Tables 5.1 and 5.2) use a bit of diameter d_m.

6.2.2.5 For drill bits not included in the range of diameters given in Table 6.1 or Table 6.2, 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.

6.2.3—*Torque requirements*

6.2.3.1 *General torque requirements*—When the application of torque for any type of anchor is required by the manufacturer, torque each anchor specified in Sections 6.2.3.1.1 and 6.2.3.2, except as specified in Section 8.2. If no torque for the anchor is specified by the manufacturer, the anchor shall be finger-tight before testing.

6.2.3.1.1 Apply the specified torque T_{inst} using a calibrated torque wrench having a measuring error within ±5% of the specified torque. After waiting 10 min, remove the torque on the anchor and apply a torque of 0.5 T_{inst}.

6.2.3.2 *Setting of torque-controlled expansion anchors*—Install torque-controlled expansion anchors in accordance with Table 6.3 and the general torque requirements.

6.2.3.2.1 For tests performed with partial setting torque (Table 5.1, Test 3 and Table 5.2, Test 5; see also Table 6.3, Test 3), install and set the anchor with a setting torque of 0.5 T_{inst}. Do not reduce the torque from this amount.

6.2.3.2.2 For the seismic tests (Table 5.2, Tests 12 and 13), apply T_{inst} and then reduce to 0.5 T_{inst} before the crack is widened.

6.2.3.3 *Setting of displacement-controlled expansion anchors*—Install displacement-controlled expansion anchors with the degree of expansion specified in Table 6.4. The specified degrees of expansion are obtained using setting tools based on the number of drops specified in Table 6.5 for partial and reference expansion, developed in Sections 6.2.3.3.1 and 6.2.3.3.2. See Fig. 6.1 for the test fixture used to establish the partial and reference setting expansions.

6.2.3.3.1 *Partial expansion*—Set a minimum of five anchors using the weight and number of drops from Table 6.5 for partial expansion. For each anchor, measure the depth of the plug from the upper end of the anchor. Calculate the average depth of the plug for the set anchors and shorten the setting tool to give this setting depth. Install anchors using the shortened setting tool for partial expansion.

6.2.3.3.2 *Reference expansion*—Prepare a setting tool for reference expansion using the same method as in Section 6.2.3.3.1, using the weight and number of drops from Table 6.5.

6.2.3.4 *Setting of undercut anchors*—Install undercut anchors as specified in Table 6.6. In tests of Table 5.1, Test 3 and Table 5.2, Test 5, set undercut anchors using a combination of the specified setting tolerances that produces the minimum bearing surface in the concrete. Table 6.6 provides for such combinations for various undercut anchor types. In other tests prescribed in Tables 5.1 and 5.2, drill a cylindrical hole with a diameter as given in Tables 5.1 or 5.2 and produce the undercut as per manufacturer's instructions.

6.3—Test methods

Test anchors in conformance with ASTM E 488 and to the appropriate sections (Section 7.0, 8.0 or 9.0) of ACI 355.2.

6.4—Tests in cracked concrete

Use the procedure specified in Sections 6.4.1 through 6.4.3 for testing anchors in cracked concrete.

6.4.1 Perform tests in concrete specimens meeting the requirements of Appendix A3. Use the crack-opening width w as specified for the given test. Initiate the crack and install the anchor according to Section 6.2, so that the axis of the anchor lies approximately in the plane of the crack. Install the instrumentation for measuring crack-opening widths, and widen the crack to the specified crack-opening width while the anchor is not loaded. Measure the crack opening using two dial gages or electronic transducers, one on either side of the anchor, oriented perpendicular to the crack.

6.4.2 Subject the anchor to the specified loading sequence while monitoring the crack opening width at the surface. See Appendix A3.

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

Table 6.2—Required diameters of carbide hammer-drill bits, SI.

Nominal diameter, mm	Tolerance ranges		
	d_{min}, mm	d_m, mm	d_{max}, mm
5	5.05 - 5.15	5.20 - 5.30	5.35 - 5.40
6	6.05 - 6.15	6.20 - 6.30	6.35 - 6.40
7	7.05 - 7.20	7.25 - 7.35	7.40 - 7.45
8	8.05 - 8.20	8.25 - 8.35	8.40 - 8.45
10	10.10 - 10.20	10.25 - 10.35	10.40 - 10.45
11	11.10 - 11.20	11.25 - 11.35	11.45 - 11.50
12	12.10 - 12.20	12.25 - 12.35	12.45 - 12.50
13	13.10 - 13.20	13.25 - 13.35	13.45 - 13.50
14	14.10 - 14.20	14.25 - 14.35	14.45 - 14.50
15	15.10 - 15.20	15.25 - 15.35	15.45 - 15.50
16	16.10 - 16.20	16.25 - 16.35	16.45 - 16.50
18	18.10 - 18.20	18.25 - 18.35	18.45 - 18.50
19	19.10 - 19.20	19.30 - 19.40	19.50 - 19.55
20	20.10 - 20.20	20.30 - 20.40	20.50 - 20.55
22	22.10 - 22.20	22.30 - 22.40	22.50 - 22.55
24	24.10 - 24.20	24.30 - 24.40	24.50 - 24.55
25	25.10 - 25.20	25.30 - 25.40	25.50 - 25.55
28	28.10 - 28.20	28.30 - 28.40	28.50 - 28.55
30	30.10 - 30.20	30.30 - 30.40	30.50 - 30.55
32	32.15 - 32.25	32.35 - 32.50	32.60 - 32.70
34	34.15 - 34.25	34.35 - 34.50	34.60 - 34.70
35	35.15 - 35.25	35.35 - 35.50	35.60 - 35.70
37	37.15 - 37.25	37.35 - 37.50	37.60 - 37.70
40	40.15 - 40.25	40.40 - 40.60	40.70 - 40.80
44	44.15 - 44.25	44.40 - 44.60	44.70 - 44.80
48	48.15 - 48.25	48.40 - 48.60	48.70 - 48.80
52	52.15 - 52.25	52.40 - 52.60	52.80 - 52.95

Table 6.3—Required degree of setting torque for torque-controlled expansion anchors

Table 5.1, test number	Table 5.2, test number	Required degree of setting torque
3	5	Partial
1, 2, 4, 5, 6, 7, 8, 9, 10	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14	Full*

*According to manufacturer's installation instructions, then reduced to 50% per Section 6.2.3.1.1.

Table 6.4—Required degree of expansion of displacement-controlled expansion anchors

Table 5.1, test number	Table 5.2, test number	Required degree of expansion
3	5	Partial
4, 5, 6	6, 7, 8	Reference
1, 2, 7, 8, 9, 10	1, 2, 3, 4, 9, 10, 11, 12, 13, 14	Full*

*According to manufacturer's installation instructions.

Table 6.5—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

6.5—General requirements for anchor behavior

6.5.1 *Overall load-displacement behavior*

6.5.1.1 The tensile load-displacement behavior of single anchors shall be predictable; that is, uncontrolled slip of the anchor generally is not acceptable. Figure 6.2 provides examples of acceptable and unacceptable load-displacement curves for the types of anchors covered by ACI 355.2. For each anchor tested, a plateau with a slip larger than 5% of the displacement at ultimate load, or a temporary drop in load, is not acceptable at load levels less than N_1. N_1 is taken as the smaller of 0.8 N_u or $A_{se} f_y$ for tests in uncracked concrete or the smaller of 0.7 N_u or $A_{se} f_y$ for tests in cracked concrete.

6.5.1.2 Within a test series, if at most one test shows a load-displacement curve not complying with Section 6.5.1.1, the anchor shall still be considered to be acceptable provided that two conditions are met. These two conditions are:

1. There is no drop in load; and

2. The deviation is justified as 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 Section 6.5.1.1.

6.5.2 *Load-displacement behavior at service loads*—For each reference test series (combination of anchor diameter and embedment), determine the mean anchor stiffness value β and coefficient of variation in the service-load range from Eq. (6-1) and report with Table 11.1.

$$\beta = \frac{N_{30\%} - N_{10\%}}{\Delta_{30\%} - \Delta_{10\%}} \qquad (6\text{-}1)$$

6.5.3 *Modes of failure*—The failure mode in each test is important because each failure mode is associated with a different strength. 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 preceded by concrete spall and concrete breakout near an edge. Figures 6.3 and 6.4 give examples of these failure modes. Report the failure mode for each test series and the strength (k values for concrete, $f_{u,test}$ for steel failure, and N_p for pullout and pull-through failure). Where different failure modes occur within a single test series, report various failure modes observed with their corresponding characteristic strengths.

6.5.3.1 If an anchor of a particular diameter has 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. Alternately, to determine k for concrete failure, it shall be permitted to use a shallower embedment or a higher-strength steel bolt, as long as it does not affect the functioning of the anchor.

6.5.3.2 If there is more than one embedment depth specified for an anchor diameter, perform tests according to Table 6.7. Report the respective failure modes and the lowest k value for concrete failure, $f_{u,test}$ for steel failure, and N_p for pullout

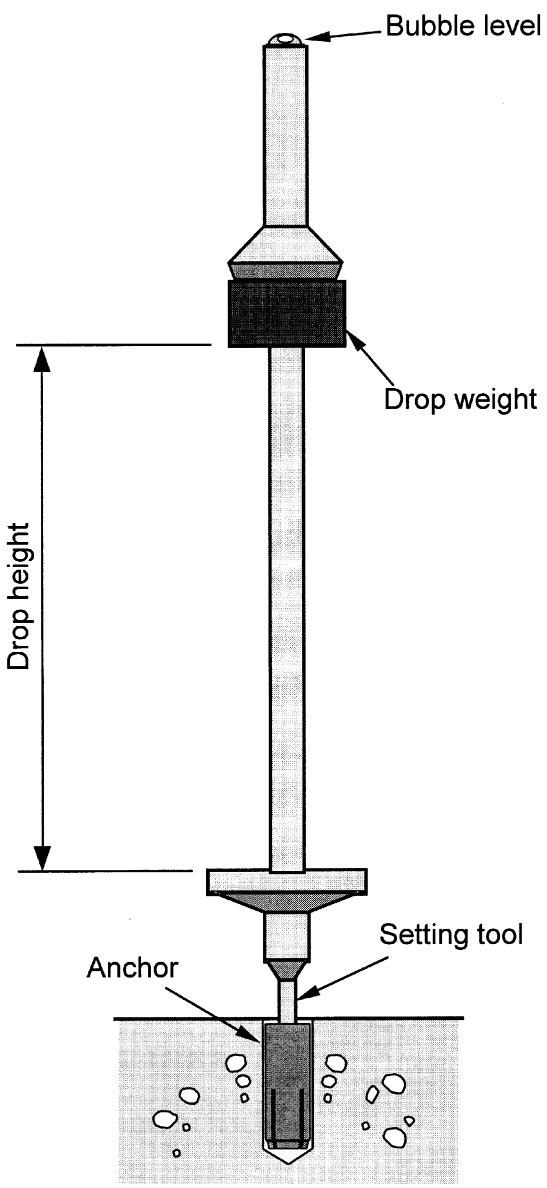
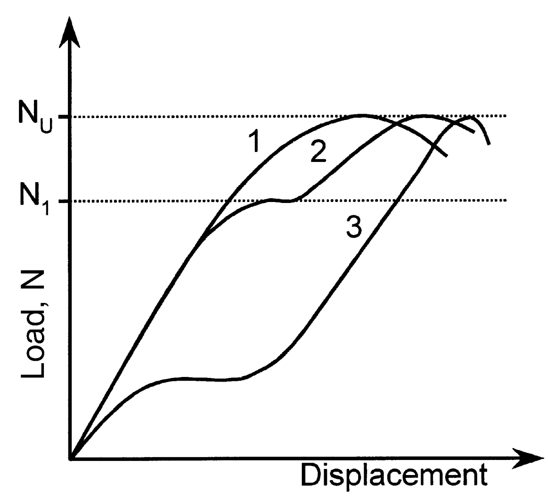


Fig. 6.1—Installation tool for setting tests of displacement-controlled expansion anchors.



Curves 1 and 2 show acceptable behavior.

Curve 3 shows unacceptable behavior.

Fig. 6.2—Requirements for load-displacement curves.

and pull-through failure for each diameter. 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.

6.5.3.3 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 7—REFERENCE TESTS

7.1—Purpose

Perform reference tests to obtain baseline values for the reliability and service-condition tests. The reference test requirements are given in Sections 7.2 through 7.3.3, and in Table 5.1 for uncracked concrete and in Table 5.2 for cracked concrete.

7.2—Reference tension tests for single anchors without spacing and edge effects (Table 5.1, Tests 1 and 2, or Table 5.2, Tests 1, 2, 3, and 4)

7.2.1 *Requirements for reference tests*—Perform tension tests in accordance with Table 5.1, Test 1 and 2, or Table 5.2, Tests 1, 2, 3, and 4. Perform the tests according to ASTM E 488 on anchors installed in low-strength and high-strength concrete. The coefficient of variation ν of the ultimate tension

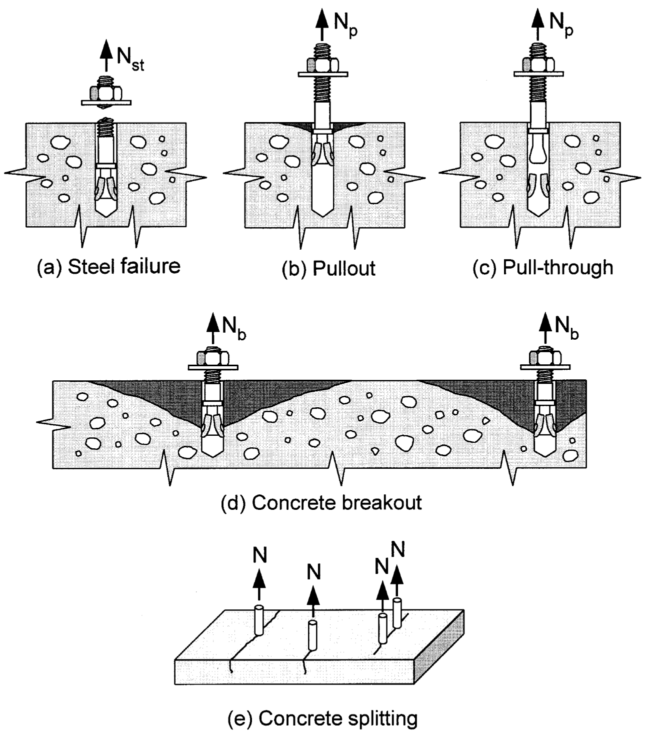


Fig. 6.3—Failure modes for anchors under tensile loading.

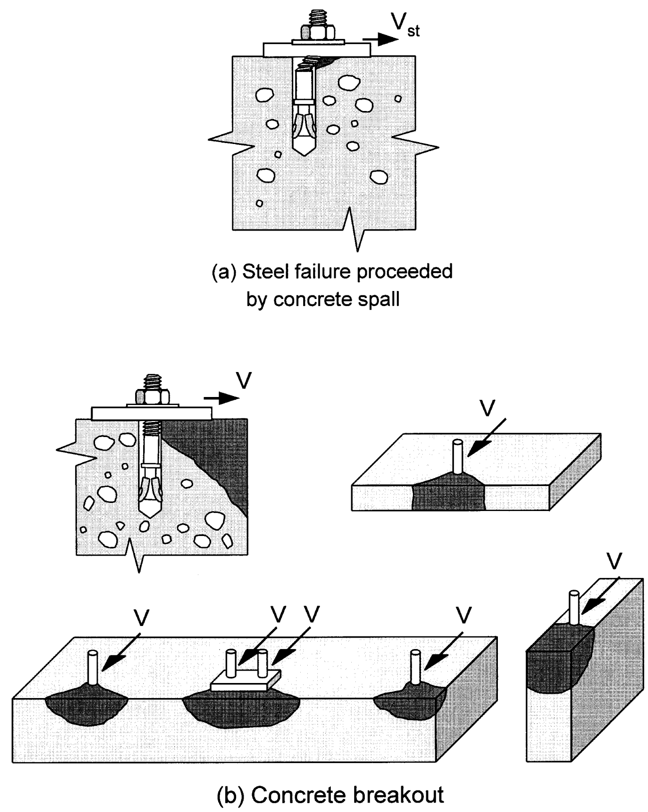


Fig. 6.4—Failure modes for anchors under shear loading.

Table 6.6—Installation requirements for undercut anchors

	Type of undercut anchor (See Fig. 2.3)				
	Load-controlled	Displacement-controlled		Torque-controlled	
Installation requirements	Type 1 undercut, predrilled	Type 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 value	50% of specified torque or flush to surface

Table 6.7—Required embedments for test program

Embedment depth to be tested for given diameter	Test number for embedment depths		
	Shallow	Deep	All
Table 5.1	3, 4, 5, 6, 7, 8, 9, 10	3, 4, 5, 6, 7	1, 2
Table 5.2	5, 6, 7, 8, 9, 10, 11, 12, 13, 14	5, 6, 7, 8, 9, 12, 13	1, 2, 3, 4

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

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

load in any test series shall not exceed 15%. The sample size shall be permitted to be increased if the coefficient of variation obtained from the original sample size does not meet this requirement. 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.

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

If the calculated k values do not meet the minimum permissible values of Table 7.1, determine the characteristic tension resistance in accordance with Section 7.3.3. The k values reported in Table 11.1 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 and steel strength reported in Table 11.1, 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, 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

The purpose of the reliability tests is 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 are given here and in Table 5.1 for uncracked concrete and in Table 5.2 for cracked concrete.

8.2—Reliability tests using reduced installation effort (Table 5.1, Test 3, and Table 5.2, Test 5)

8.2.1 *Purpose*—These reliability tests are intended 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 $T = 0.5\,T_{inst}$ and drill bit of diameter d_m. See Fig. 2.2 for anchor types.

8.2.2.2 *Displacement-controlled expansion anchors*—Perform tests on anchors installed in low-strength concrete, using drill bit of diameter d_m. See Fig. 2.1 for anchor types. Installation requirements for displacement-controlled expansion anchors are prescribed in Tables 6.4 and 6.5 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. See Fig. 2.3 for anchor types. Installation requirements for undercut anchors are prescribed in Table 6.6.

8.2.3 *Requirements*—The coefficient of variation n of the ultimate tension load in any test series shall not exceed 20%. The sample size shall be permitted to be increased if the coefficient of variation of the original sample size does not meet this requirement. If this requirement is not met, the anchor shall be considered unqualified.

8.3—Reliability in low-strength concrete with large drill bit (Table 5.1, Test 4, and Table 5.2, Test 6)

8.3.1 *Purpose*—These reliability tests are performed in uncracked concrete to evaluate the sensitivity of the anchor to low-strength concrete and oversized holes. They are performed in cracked concrete 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. Use a drill bit of diameter d_{max}. For tests of anchors in cracked concrete, use a minimum crack-opening width of 0.020 in. (0.5 mm).

8.3.3 *Requirements*—The coefficient of variation n of the ultimate tension load in any test series shall not exceed 20%. The sample size shall be permitted to be increased if the coefficient of variation of the original sample size does not meet this requirement. If this requirement is not met, the anchor shall be considered unqualified.

8.4—Reliability in high-strength concrete with small drill bit (Table 5.1, Test 5, and Table 5.2, Test 7)

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

8.4.2 *General test conditions*—Perform these tests under tension 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).

8.4.3 *Requirements*—The coefficient of variation n of the ultimate tension load in any test series shall not exceed 20%. The sample size shall be permitted to be increased if the coefficient of variation of the original sample size does not meet this requirement. If this requirement is not met, the anchor shall be considered unqualified.

8.5—Reliability under repeated load (Table 5.1, 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 minimum load of 0.25 N_k or [0.6 (A_{se} x 17,400 lb/in.^{2} (120 MPa))], whichever is larger; and a maximum load of 0.6 N_k or 0.8 A_{se} f_y, whichever is smaller. The loading frequency shall be 6 Hz or less. Measure displacements 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.

8.5.3 *Requirement*—Anchor displacements shall show a stabilization of movement, and the average residual capacity of the anchor shall be not less than 80% of the mean capacity in the corresponding reference test. The coefficient of variation n of the ultimate tension load in any test series shall not exceed 20%. The sample size shall be permitted to be increased if the coefficient of variation of the original sample size does not meet this requirement. If this requirement is not met, the anchor shall be considered unqualified.

8.6—Reliability in cracks where opening width is cycled (Table 5.2, Test 8)

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

8.6.2 *General test conditions*—Before installing the anchor, 10 opening and closing cycles shall be permitted to be applied to stabilize crack formation. Install the anchor according to Section 6.2, so that the axis of the anchor lies approximately in the plane of the crack. Open the crack to a crack-opening width w_1 = 0.012 in. (0.3 mm). Apply a tensile load of N_w from Eq. (8-1). Cycle the crack-opening width between the maximum crack opening width of w_1 = 0.012 in. (0.3 mm) and the initial minimum crack opening width of w_2 = 0.004 in. (0.1 mm).

$$N_w = 0.9N_b(0.7\phi_{IR}) \quad (8\text{-}1)$$

where:

N_b = characteristic tensile resistance in low-strength cracked concrete as determined from reference tests;

ϕ_{IR} = capacity reduction factor based on category developed from reliability tests;
= 1.0 for a Category 1 anchor
= 0.85 for a Category 2 anchor
= 0.7 for a Category 3 anchor

As the crack-opening 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 opening width w_1 constant. The crack opening width w_2 will increase during the test (see Fig. 8.1). The difference between the maximum and minimum crack-opening widths during the 1000 cycles shall be at least 0.004 in. (0.1 mm). If at any time during the conduct of the test, the value of $w_1 - w_2$ falls below 0.004 in. (0.1 mm), then either the lower-bound load shall be reduced, the upper-bound load shall be increased, or both shall be implemented, 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 behavior 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 displacement, and perform a tension test to failure with an initial crack opening width w = 0.012 in. (0.3 mm). During the test, monitor but do not control the crack width.

8.6.5 *Requirement*—In each test in cracks whose opening width is cycled, 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. This maximum allowable displacement shall not be exceeded in more than 5% of the tests. If this requirement is not met, increase the number of replicates, or repeat the tests with a reduced sustained load on the anchor, until the requirement is met. 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 Section 10.0. 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 n of the ultimate tension load in any test series shall not exceed 20%. The sample size shall be permitted to be increased if the coefficient of variation of the original sample size does not meet this requirement. If this requirement is not met, the anchor shall be considered unqualified.

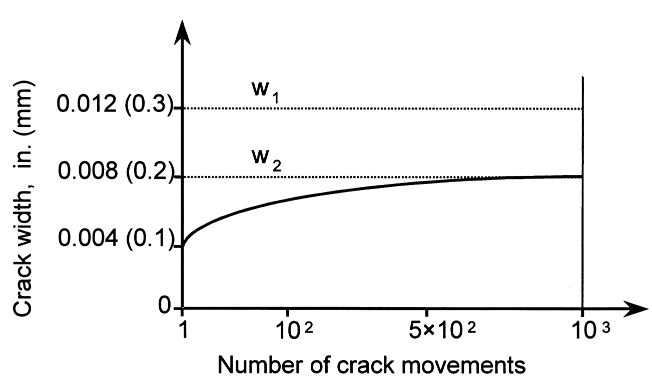


Fig. 8.1—Crack-width requirements for cyclic tests in cracked concrete.

CHAPTER 9—SERVICE-CONDITION TESTS

9.1—Purpose

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

9.2—General test conditions

9.2.1 General requirements are prescribed in Section 5.0.

9.2.2 For all tests, drill the holes with a drill bit of diameter d_m.

9.2.3 When anchors are tested in cracked concrete, use cracks that pass approximately through the plane of the axis of the anchor, and that have a minimum crack opening width of 0.012 in. (0.3 mm).

9.3—Service-condition tension test with a single anchor with two edges (corner) (Table 5.1, Test 7 and Table 5.2, Test 9)

9.3.1 *Purpose*—The purpose of this test is to determine whether the anchor meets the requirement that the critical edge distance shall be £ 1.5 h_{ef}, in test 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 1.5 h_{ef}.

9.3.2 *Requirements for critical edge distance*—Verify compliance with the requirement that the critical edge distance £ 1.5 h_{ef}. The ultimate capacity of the anchor with two edge distances of 1.5 h_{ef} shall be statistically equivalent (Section 2.1.12) to the capacity from the reference tests performed away from the edges.

9.4—Service-condition test at minimum edge distance and minimum spacing (Table 5.1, Test 8 and Table 5.2, Test 10)

9.4.1 *Purpose*—This test checks that the concrete will not experience splitting failure during anchor installation.

9.4.2 *General test conditions*—Test all diameters of all anchor types 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 3 h_{ef} from other groups. Select the minimum spacing s_{min}, minimum edge distance c_{min}, and minimum thickness h_{min}, depending on the characteristics of the anchor. Initial values recommended for these parameters by ACI 318 Appendix D are:

s_{min} = $6d_0$
c_{min} = $6d_0$ for undercut anchors
= $8d_0$ for torque-controlled anchors
= $10d_0$ for displacement-controlled anchors
h_{min} = $1.5h_{ef}$

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_0 of the anchor being tested.

9.4.3 For torque-controlled anchors, torque the anchors alternately in increments of 0.2 T_{inst} up to the lesser of 1.7 T_{inst} or 1.0 T_{inst} + 100 ft-lb (138 Nm). After each increment, inspect the concrete surface for cracks. Stop the test when splitting or steel failure prevents the torque from being increased further or the lesser of 1.7 T_{inst} or 1.0 T_{inst} + 100 ft-lb (138 Nm) is reached. 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.

9.4.4 For load-controlled anchors, install the anchors according to the manufacturer's instructions.

9.4.5 For displacement-controlled anchors that are intended to perform properly without an installation torque, install the anchors according to the manufacturer's specifications.

9.4.6 *Requirement*—For torque-controlled anchors, there shall be no splitting up to a torque of the lesser of 1.7 T_{inst} or 1.0 T_{inst} + 100 ft-lb (138 Nm). The 5% fractile of the recorded torque value calculated according to Appendix A2 and normalized to f_c = 2500 lb/in.^{2} (17 MPa) by Eq. (A 1-1) shall be larger than the lesser of 1.7 T_{inst} or 1.0 T_{inst} + 100 ft-lb (138 Nm). If this requirement is not met, repeat the tests with increased values for 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. If the anchors do not meet these requirements, do the following:

- Hold c_{min} constant, increase s_{min}, install the anchors according to Sections 9.4.3, 9.4.4, or 9.4.5 until no splitting occurs; and
- Hold s_{min} constant, increase c_{min}, install the anchors according to Sections 9.4.3, 9.4.4, or 9.4.5 until no splitting occurs.

Report these minimum edge and spacing distances.

9.5—Service-condition shear test for single anchors without spacing and edge effects (Table 5.1, Test 9 and Table 5.2, Test 11)

9.5.1 *Purpose*—This test is intended 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 concrete 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. Calculate V_s using Appendix A2. Where such shear tests are not required, the anchor shear steel strength shall be determined by the methods of ACI 318.

9.6—Service-condition, simulated seismic tension tests (Table 5.2, Test 12)

9.6.1 *Purpose*—These optional tests are intended to evaluate the performance of anchors in seismic tension, including the effects of cracks and without edge effects.

9.6.2 *Tests*—Perform tests that simulate pulsating seismic tension loading on anchors at the shallowest embedment for which the anchor is to be qualified for use in cracked concrete. Anchors shall be permitted to be tested at deeper embedments to verify higher load capacities at deeper embedments. Install the anchor in a closed crack according to Section 6.4. Open the crack to 0.020 in. (0.5 mm). If no torque is specified by the manufacturer, finger-tighten the anchor before testing. Test internally threaded anchors with a bolt as specified by the manufacturer and report in Table 11.1. 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-opening width not less than the crack-opening width at the end of the cyclic test. Record the peak of each load cycle and the corresponding anchor displacement at peak tension. If the anchor fails before completing the cycles required in Table 9.1, record the number of cycles and the load at failure.

9.6.3 *Requirements*—All anchors 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 ultimate static capacity shall be rated at full capacity as determined from the static test results normalized to the concrete strength of the test member. 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 ultimate 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 ultimate static tension capacity.

9.7—Service-condition, simulated seismic shear tests (Table 5.2, Test 13)

9.7.1 *Purpose*—These optional tests are intended to evaluate performance under simulated alternating seismic shear loading.

9.7.2 *Tests*—Test anchors at the shallowest embedment for which the anchor is to be qualified for use in cracked concrete. Anchors shall be permitted to be tested at deeper embedments to verify higher load capacities at deeper embedments. Install the anchors in cracked concrete according to Section 6.2. If no torque is specified by the manufacturer, the anchor shall be finger-tightened before testing. For internally threaded anchors, test with a bolt as specified by the manufacturer and reported in Table 11.1. Subject the anchors to the sinusoidally varying shear loads specified in Table 9.2 and Fig. 9.2. Separate reference tests to determine the shear capacity shall be performed in 0.020 in. (0.3 mm) cracks when the shear capacity cannot be determined according to Section 9.5, Table 5.2, 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. After the simulated seismic-shear cycles have been run, test the anchors to failure in static shear. 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;

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

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

9.7.3 *Requirements*—All anchors tested 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

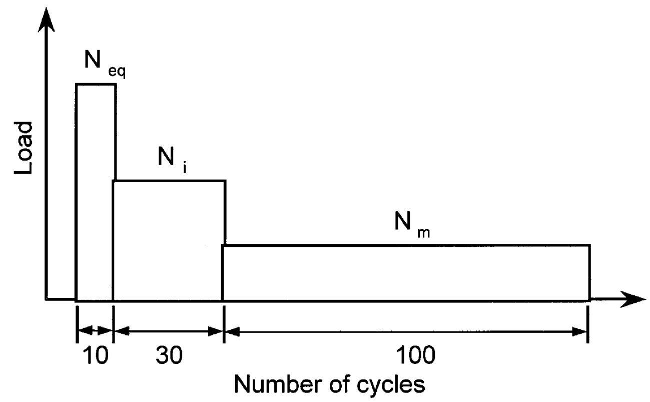


Fig. 9.1—Loading pattern for simulated seismic-tension test.

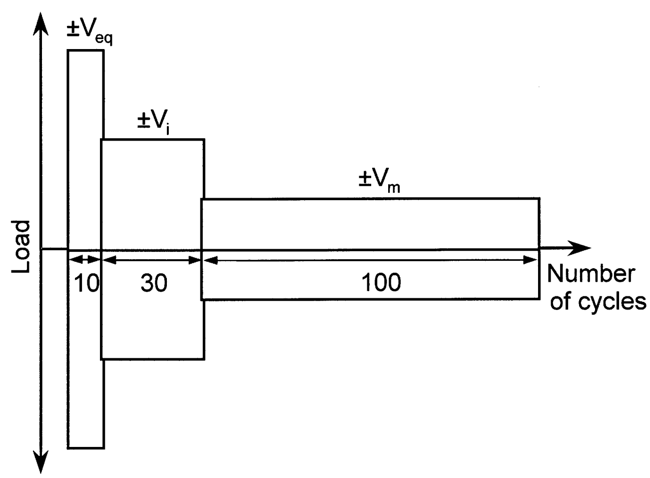


Fig. 9.2—Loading pattern for simulated seismic-shear test.

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

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, compute the ratio of the characteristic capacity in each reliability test to the characteristic capacity in the corresponding reference test. 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 test (reliability or reference) with the fewer number of replicates (smaller value of n). Using the smallest ratio of characteristic capacities 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.

CHAPTER 11—PRESENTING ANCHOR DATA

11.1—Data analysis

Analyze data in accordance with Appendices A1 and A2.

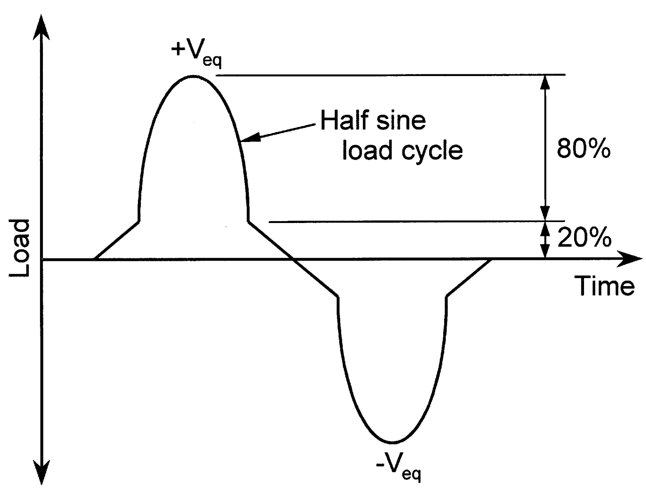


Fig. 9.3—Permitted approximation of alternating seismic-shear cycle.

Table 10.1—Establishment of anchor categories

Smallest ratio of characteristic capacities	Anchor category
$0.80 \le \frac{N_{b,r}}{N_{b,o}}$	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 $N_{b,r}/N_{b,o} < 0.60$	Anchor is unqualified

11.2—Format of the data sheet

Report the data required by ACI 355.2 in the format shown in Table 11.1. 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 shall include sufficient information for complete product identification, explicit installation instructions, and design data.

11.4—Contents of evaluation report

In particular, the report shall include:

11.4.1 Description of types of anchors.

11.4.2 Constituent materials (Section 4.3.2).

11.4.3 Markings (Section 4.3.6).

11.4.4 Anchor performance data in accordance with Section 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

Table 11.1—Sample format for reporting anchor data

Characteristic	Symbol	Anchor diameters: Smaller diameters (if any)	M8 5/16 in.	M10 3/8 in.	M12 1/2 in.	Larger diameters (if any)
Effective embedment depth	h_{ef}					
Outside diameter	d_o					
Effective cross-sectional area—tension where appropriate	A_{se}					
Steel shear capacity	V_s					
Minimum specified yield strength	f_y					
Minimum specified ultimate strength	f_{ut}					
Minimum spacing	s_{min}					
Installation torque	T_{inst}					
Critical edge distance	c_{cr}					
Minimum edge distance	c_{min}					
Minimum member thickness	h_{min}					
Category of anchor (calculated)	1, 2, or 3					
Effectiveness factor	k					
Pullout resistance—from tests—characteristic value calculated	N_p					
Seismic resistance determined from tests	N_{eq}, V_{eq}					
Anchor axial stiffness in service-load range	β, ν					

anchors according to ASTM E 488, including demonstrated competence to perform the tests described in ACI 355.2.

12.2 The testing shall be witnessed and evaluated by a registered engineer employed or retained by the independent testing and evaluation agency.

CHAPTER 13—REFERENCES

13.1—Referenced standards

C 31-96	Making and Curing Concrete Test Specimens
C 33-93	Standard Specification for Concrete Aggregates
C 39-96	Compression Strength of Cylindrical Concrete Specimens
C 42-94	Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 150-97	Specifications for Portland Cement
C 330-89	Lightweight Aggregates for Structural Concrete
E 18-94	Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials
E 488-96	Test Methods for Strength of Anchors in Concrete and Masonry Elements
ACI 318-02	*Building Code Requirements for Structural Concrete.* Note: ACI 355.2 was prepared in coordination with ACI Committee 318. ACI 355.2 completed ACI's provisional standardization procedures and was published before the ACI 318 Code completed ACI's full standardization procedures. Check with ACI Headquarters for the availability of ACI 318-02.

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
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 APPENDICES

A1—REQUIREMENTS FOR NORMALIZATION OF RESULTS

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

When comparing anchor capacities determined by tests in concrete of different strengths, the type of failure shall be taken into account.

A1.2—Concrete breakout or splitting failure

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

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

A1.3 *Pullout and pull-through failure* ¾ The influence of the concrete strength on the pullout or pull-through failure load shall be established by tests.

A1.4 *Steel failure* ¾ 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 ultimate tensile strength f_{ut} multiplied by the effective tensile stress area of the anchor.

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

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 **n** 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%.*

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

A3—REQUIREMENTS FOR TEST MEMBERS

General guidance is given in ASTM E 488.

A3.1—Tests in uncracked concrete

Use test members that are unreinforced, except as required by Section A.3.1.1 and permitted by Section 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 edge reinforcement with a No. 3 (9.5 mm) straight reinforcing bar with a concrete cover of 5/8 in. (15 mm).

*Natrella, M. G., 1966, *Experimental Statistics*, National Bureau of Standards Handbook 91, U.S. Department of Commerce.

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

Use test members that meet the requirements of Section A.3.1, and the additional requirements of Section A.3.2. The crack-opening width shall be approximately uniform throughout the member thickness. The thickness of the test member shall be not less than 1.5 h_{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 of 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. 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. This requirement shall be considered to be met if the crack inducers and the reinforcement are 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. The cross-sectional reinforcement ratio of the concrete members used for the cracked concrete tests should be about 1%. An example of a test member is given in Fig. A3.1.

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

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 Store concrete cylinders 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 test member strength using cylinder or core compression tests giving the best representation of the concrete strength for the anchor testing (for example, on the day of the test series, by averaging results at the beginning and at the end of several test series, or from the graphical plot of results versus age).

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. (100 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.

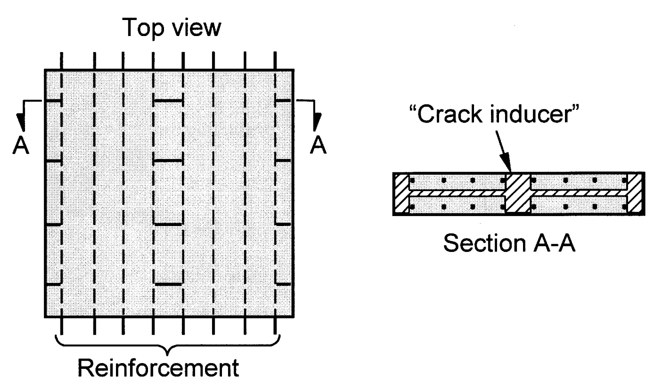


Fig. A3.1—Example of test member for anchors in tension in cracked concrete.

Commentary on Evaluating the Performance of Post-Installed Mechanical Anchors in Concrete (ACI 355.2R-00)

Reported by ACI Committee 355

Richard E. Wollmershauser
Chairman

Harry Chambers
Secretary

William H. Alderman	Richard J. Ernst	Harry B. Lancelot, III	Richard S. Orr
Tarek Aziz	Herman L. Graves, III	Alexander Makitka	Andrew Rossi
Ranjit L. Bandyopadhyay	Kevin D. Heinert	Lee Mattis	Dan R. Stoppenhagen
Peter J. Carrato	Christopher Heinz	Robert R. McGlohn	Patrick J. E. Sullivan
Ronald A. Cook	Bruce Ireland	Donald F. Meinheit	Harry Wiewel
Rolf Eligehausen	Richard E. Klingner	Francis A. Oluokun	

Note: Special recognition is made to Werner Fuchs for contributions to the development of this document.

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. ACI 318 differentiates between cracked and uncracked concrete. In ACI 318, it is assumed that anchors for anchoring to concrete have been tested either for use in uncracked concrete or for use in cracked and uncracked concrete. Today, many different post-installed mechanical anchors are available for use in concrete. These anchors exhibit a range of working principles, proprietary designs, and performance characteristics. ACI 318 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 to confirm an anchor's reliability and place it in the appropriate anchor category.

R1.4—While ACI 355.2 gives no limitations on maximum anchor diameter or embedment, 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. (51 mm) and an embedment not greater than 25 in. (0.64 m). ACI 355.2 can be used for anchors with those maximum dimensions. For anchors beyond these dimensions, the testing authority should decide if the tests described here are applicable or if alternative tests and analyses are more appropriate. The minimum diameter of 1/4 in. (6.4 mm) is based on practical considerations regarding the limit of structural anchor applications.

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. 6.3 and 6.4.

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 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.

ACI 355.2-00 became effective July 7, 2000.

R2.1.12—The statistical equivalence determination uses a one-sided *t*-test because the mean of a test series is compared to the mean of another reference test series. 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.

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

R2.2—Notation

A_{se} = The characteristic tensile steel capacity can be taken as the minimum specified steel strength or can be calculated from tests. 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—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.

R5.1—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 are also intended to be compared with results of the reliability tests. For the reference tests, anchors should be installed according to 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 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 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 only).

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

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 assumed to be 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.

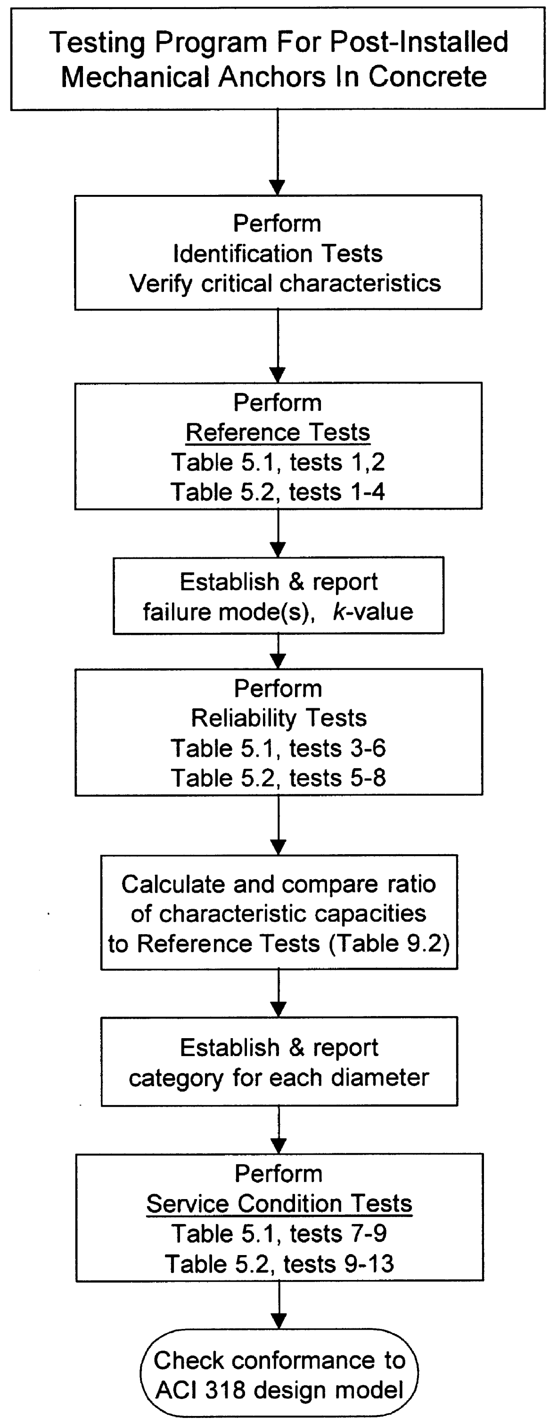


Fig. R1—Flow chart for overall testing program.

To represent normal conditions, the repeated load test (Table 5.1, Test 6) and the test in which the crack width is cycled (Table 5.2, Test 8) are performed with a drill bit of diameter d_m.

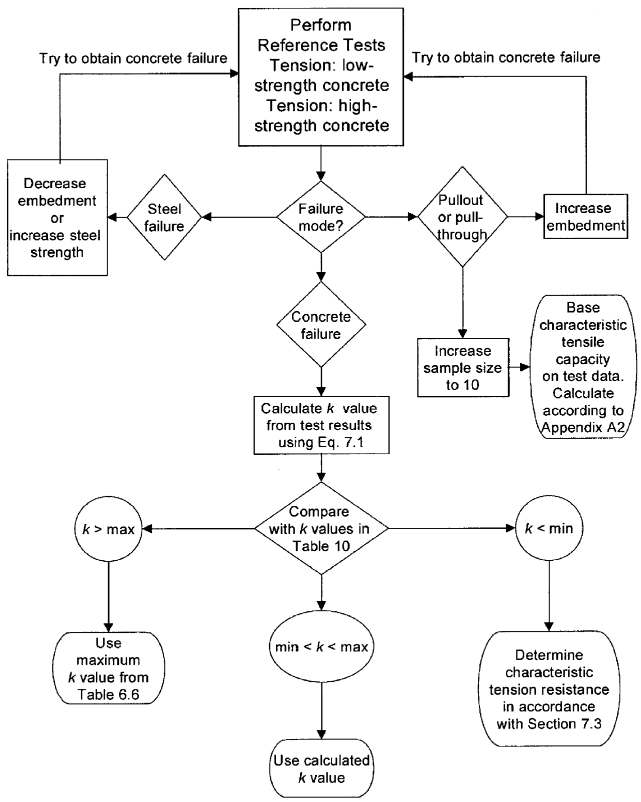


Fig. R2—Flow chart for reference tests.

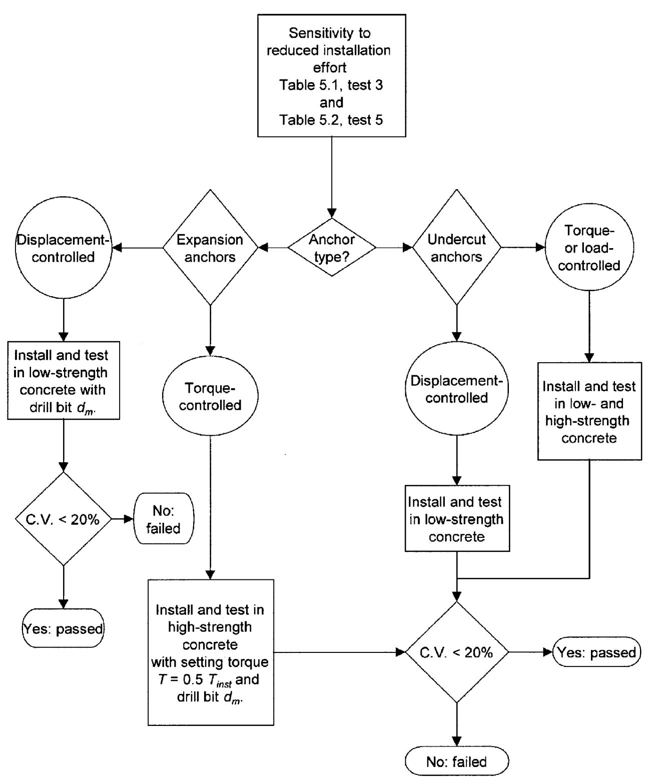


Fig. R3—Flow chart for tests with reduced installation effort.

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.

R5.2—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.

R5.2.2—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 tests should be performed for each type and compared statistically. If they are statistically equivalent, then only one set of reliability and service-condition tests needs to be performed for the anchors.

R6.1—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

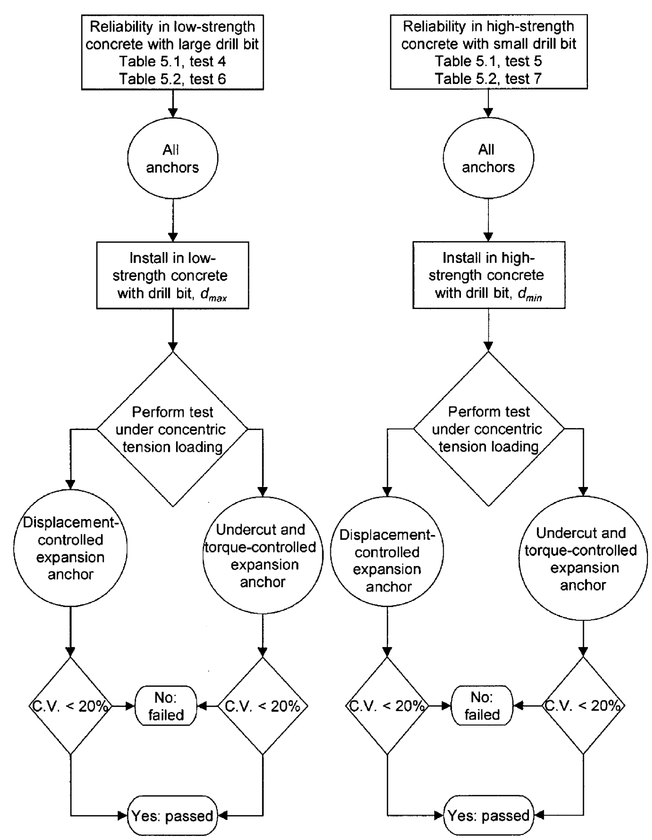


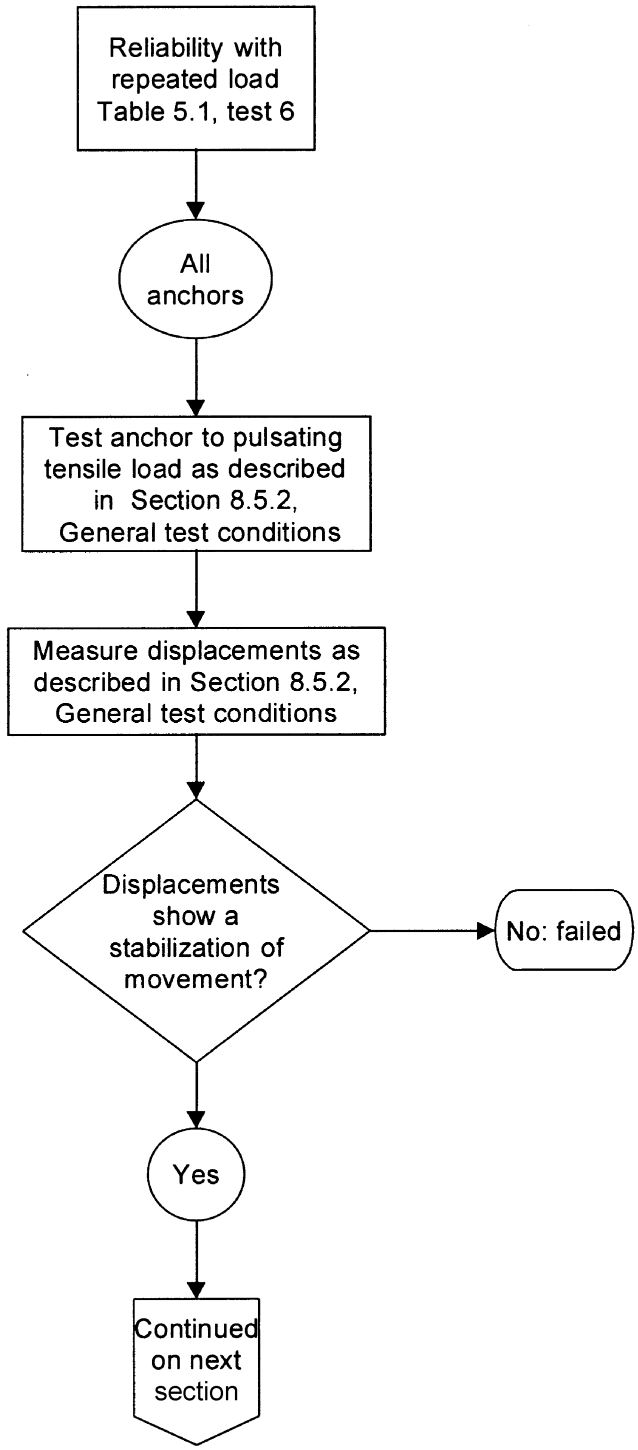
Fig. R4—Flow chart for reliability tests for sensitivity to large and small holes.

mixtures on anchor performance is part of the consideration in establishing the capacity reduction factors in the design method of ACI 318.

R6.1.2—Testing is performed in plain concrete with no cementitious replacements or concrete admixtures added to the concrete. 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 mixture proportion.

R6.1.3—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 8,000 lb/in.^{2} (55 MPa) on the specified concrete compressive strength for which the design method is applicable. Elsewhere in the Code, a lower limit on specified compressive strength of 2,500 lb/in.^{2} (17 MPa) is established. Actual in-place concrete strength can be 15 to 20% higher than specified.

R6.2.2—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 toler-



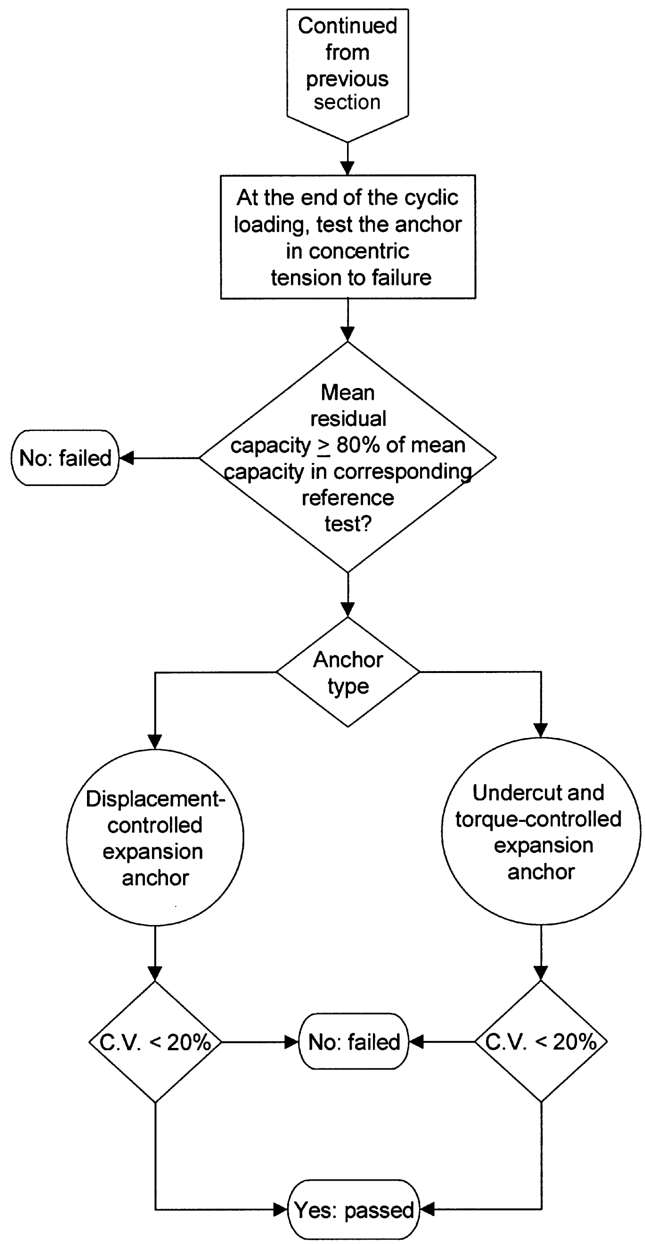


Fig. R5—Flow chart for reliability tests with repeated loads.

ances 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.

R6.2.3—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 6.6.

R6.2.3.1—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.

R6.2.3.3—Displacement-controlled anchors are tested with varying degrees of expansion as specified in Table 6.4. 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 partial expansion, due to 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 6.5 were developed for high-strength concrete. Once the anchor expansion (plug displacement) associated with the specified setting energy (reference or partial expansion)

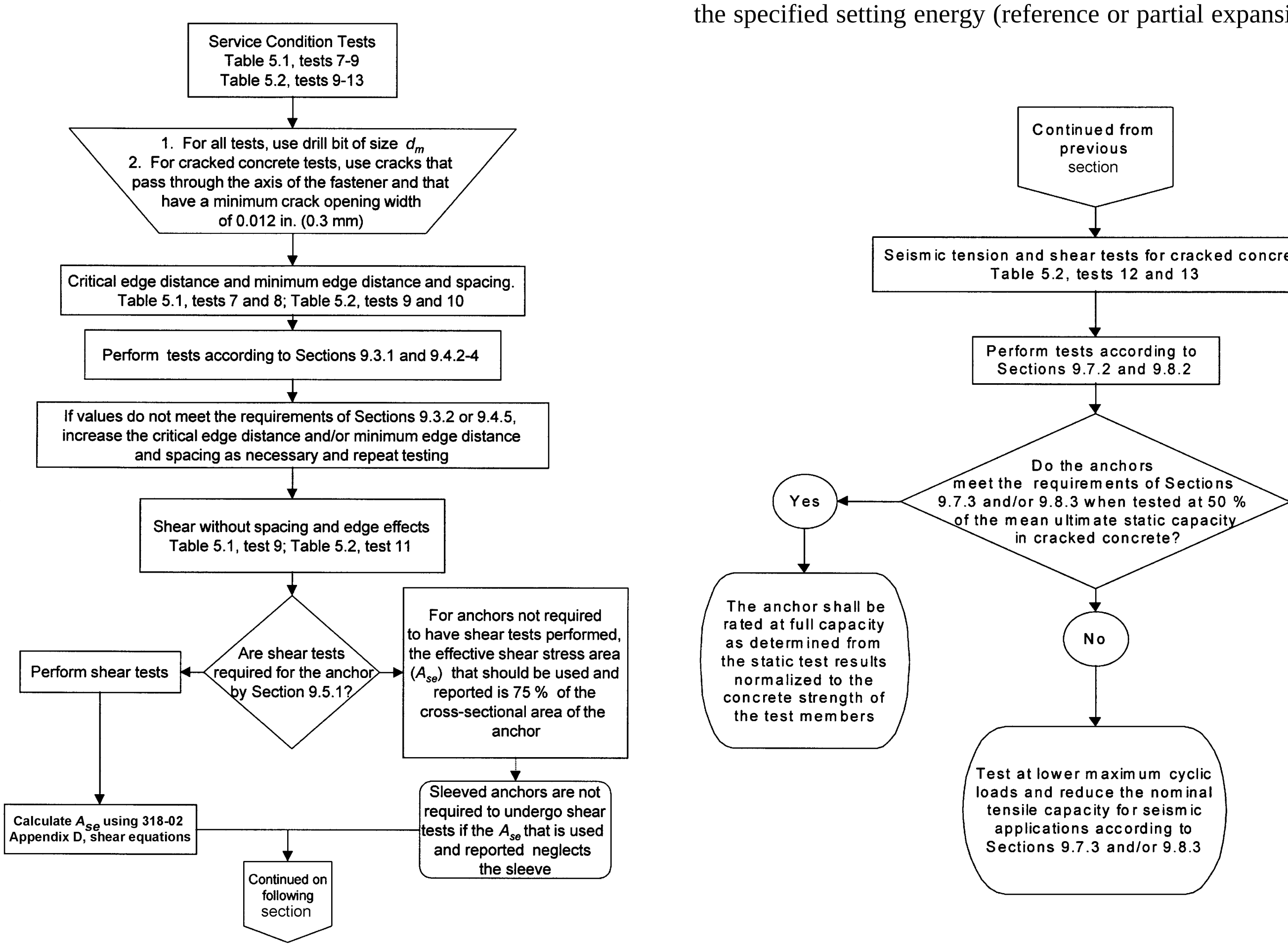


Fig. R6—Flow chart for service-condition tests.

is established, a setting tool is prepared to duplicate this degree of expansion for the balance of the required tests.

R6.2.3.4—Table 6.6 refers to products currently available in the marketplace. If other systems or types of products become available, the independent test and evaluation agency should prescribe the test parameters.

R6.5.1—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.

The limits on load-slip behavior are intended to prevent uncontrolled slip of anchors under tension loading (see Fig. 6.2), because this behavior is generally difficult to predict. Furthermore, the design method in ACI 318 for group effects is based on the minimum load-slip behavior represented by the curves in Fig. 6.2. 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.

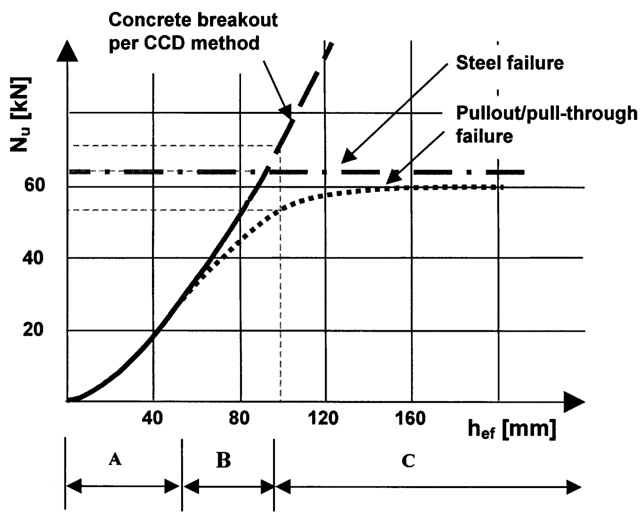


Fig. R7—Hypothetical behavior of single anchor as characterized by ACI 318.

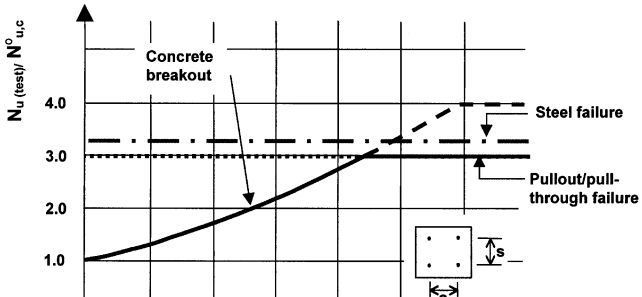


Fig. R8—Hypothetical behavior of group anchors as characterized by ACI 318.

R6.5.3—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 necessary to establish the controlling failure mode and associated failure load for each embedment. As can be seen in Fig. R8, 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 predictable equations used in ACI 318; 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 applies to calculate the concrete cone failure load. For spacing and edge distance effects, the equations of ACI 318 are still applicable, because anchors without edge effects, spacing effects, or both, and that fail by pullout or pull-through at a given embedment, may still exhibit concrete cone failure when closely spaced or near an edge (see 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.

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. before loading. This crack width is consistent with the assumptions of ACI 318 under quasi-permanent load.

R7.3.1—Table 7.1 prescribes the permissible range of values for the effectiveness factor k that may be reported for any 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 (Section 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 (Section 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, see Section R6.2.3.3) is smaller in low-strength concrete than in high-strength concrete.

For displacement-controlled undercut anchors (Section 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 than in high-strength concrete.

For torque-controlled and load-controlled undercut anchors, the tests are performed in low- and high-strength concrete. In these cases 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. Furthermore, anchors should 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 load will also behave well under a constant sustained load. Therefore, tests under sustained load are not included.

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. This crack width will occur when the structure is loaded to the quasi-permanent 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. Experience shows that the characteristic crack width in structures agrees with the values assumed by ACI 318.

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 w = 0.020 in. is chosen in the tests. See ACI Committee 224 documents and ACI 318-95, Code Section 10.6 and related commentary.

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 in. (0.1 mm) and 0.012 in. (0.3 mm). This number of loading cycles is representative of the number of significant load variations on a typical structure during its lifetime. The maximum crack width is consistent with the crack width contemplated by ACI 318 under quasi-permanent 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 11.1 should be calculated using Eq. (8-1).

R9.3—According to the CCD Method, which is the default design method of ACI 318, this maximum capacity is assumed to be valid for edge distances $c \leq 1.5 h_{ef}$. To check this assumption for the anchor being tested, tension tests are performed with single anchors in a corner with $c_1 = c_2 = 1.5\ h_{ef}$. 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.

R9.4—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 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 c_{min} and s_{min} that will allow anchor installation without damage to concrete.

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. No splitting should occur even up to 1.7 T_{inst}; because this torque level is intended to compensate for possible inaccuracies of torque wrenches on site.

There is a relationship among c_{min}, s_{min}, and h, because c_{min} and s_{min} depend on member thickness. ACI 318 requires that $h \geq 1.5\ h_{ef}$; this may in turn require a larger 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 prestress that drops after a few minutes. 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, value of 1.7 T_{inst} is required.

R9.7 and **9.8**—*Seismic tension and shear tests:* Seismic tension and shear tests are required by ACI 318 in order 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 quasi-static 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 in Appendix A.

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 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 about 1%. The reinforcement ratio should be increased if, during the tests, the reinforcement yields.

Commentary references

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

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

APPENDIX A TO COMMENTARY FOR ACI 355.2

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

RA1—Anchor specifications

See Table RA1.

RA2—Test results

See Table RA2.

RA3—EVALUATION

RA3.1—General

All load-displacement curves for Table 5.1, Tests 1, 2, 3, 4, and 5 and Table 5.2, Tests 1, 2, 3, 4, 5, 6, and 7 have to be checked. Uncontrolled slip is not allowed (see Section 6.5.1), and did not occur. The anchor stiffness β is calculated according to Eq. (6-1) of Section 6.5.2. For this anchor the lowest value of all reference tension tests is β = 54,970 lb/in. (9.5 kN/mm)

$$\beta = \frac{0.3 \cdot 7036 - 0.1 \cdot 7036}{0.0260 - 0.0004} = 54,970 \text{ lb/in. } (9.5 \text{ kN/mm})$$

RA3.2—Reference tests in 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 <u>concrete cone failure</u> a minimum effectiveness factor of k = 24 (10) is expected.

$$N_b = 6445 \cdot (1 - 2.568 \cdot 0.059) = 5468 \text{ lb } (24.4 \text{ kN})$$

$$k = \frac{5468}{\sqrt{2800}\,(2 - 3/4)^{1.5}} = 22.6(8.94)$$

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.

<u>Remark:</u> 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 <u>steel failure</u>, a mean failure load of

$$N_{st} = 0.09 \cdot 119{,}625 = 10{,}766 \text{ lb } (47.9 \text{ kN})$$

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

$$N_k = 0.09 \cdot 92{,}800 = 8352 \text{ lb } (37.2 \text{ kN})$$

For <u>pullout or pull-through failure</u>, the characteristic resistance is

$$N_k = 6445 \cdot (1 - 2.568 \cdot 0.059) = 5468 \text{ lb } (24.4 \text{ kN})$$

for a compressive strength of 2800 lb/in.^{2} (23.7 N/mm^2).

Table RA1—Anchor specifications

Characteristic	Symbol	in.-lb units	SI units
Anchor size	—	1/2 in.	12 mm
Embedment depth	h_{ef}	2-3/4 in.	68 mm
Outside diameter	d_o	1/2 in.	12 mm
Effective tensile stress area	A_{se}	0.09 in.^{2}	58.1 mm^2
Effective shear stress area	A_s	0.13 in.^{2}	84.3 mm^2
Minimum specified yield strength	f_y	74,000 lb/in.^{2}	512 N/mm^2
Minimum specified ultimate tensile strength	f_{ut}	92,800 lb/in.^{2}	640 N/mm^2
Yield strength, test result	$f_{y,test}$	81,490 lb/in.^{2}	562 N/mm^2
Mean ultimate tensile strength, test result in shank section	$f_{u,test}$	99,325 lb/in.^{2}	685 N/mm^2
Mean ultimate tensile strength, test result in reduced section	$f_{u,test}$	119,625 lb/in.^{2}	825 N/mm^2
Installation torque	T_{inst}	45 ft-lb	60 Nm
Minimum member thickness	h_{min}	5-1/2 in.	140 mm

RA3.3—Reference tests in 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 $k = 10$ is expected.

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

$$k = \frac{8184}{\sqrt{6200} \cdot (2 - 3/4)^{1.5}} = 22.8(8.93)$$

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

$$N_m = 0.09 \cdot 119{,}625 = 10{,}766 \text{ lb (47.9 kN)}$$

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

$$N_k = 0.09 \cdot 92{,}800 = 8352 \text{ lb (37.2 kN)}$$

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

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

for a compressive strength of 6200 lb/in.^{2} (52.8 N/mm^2).

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 equal.

Remark: The pullout resistance for a specified concrete of 21 N/mm^2 (2500 lb/in.^{2}) is calculated as

$$N_p = 5468 \cdot \sqrt{2500/2800} = 5167 \text{ lb (20.7 kN)}$$

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

RA3.4—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.

$$N_p = 5463 \cdot (1 - 3.400 \cdot 0.075) = 4070 \text{ lb (18.1 kN)}$$

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 lb/in.^{2} (23.7 N/mm^2).

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.

RA3.5—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.

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

Table RA2—Test results

General test	Specific test	Test number and reference	Sample size n	$f_{c,test}$ lb/in.^{2} (MPa)	$N_{u,m}$, lb (kN)	Standard deviation s, lb (kN)	Coefficient of variation v,%	Failure mode	Remarks and commentary reference
All tests	—	7, 8, 9	—	—	—	—	—	—	No uncontrolled slip observed
Reference test	—	7.3	10	2800 (23.7)	6445 (28.8)	382 (1.70)	5.9	Pull-through/concrete	RA.3.2
Reference test	—	7.3	10	6200 (52.8)	9734 (43.3)	605 (2.69)	6.2	Pull-through/concrete	RA.3.3
Reliability test	Reduced installation	8.2	5	2800 (23.7)	5463 (24.3)	407 (1.81)	7.5	Pull-through/concrete	RA.3.4
Reliability test	Large hole diameter	8.3	5	2630 (22.3)	5755 (25.6)	393 (1.75)	6.8	Pull-through/concrete	RA.3.5
Reliability test	Small hole diameter	8.4	5	6230 (52.8)	9576 (42.6)	479 (2.13)	5.0	Pull-through/concrete	RA.3.6
Reliability test	Repeated load	8.5	5	2800 (23.7)	6092 (27.1)	632 (2.81)	10.4	Pull-through/concrete	RA.3.7
Service condition test	Corner	9.3	4	2630 (22.3)	6047 (26.9)	303 (1.35)	5.0	Pull-through/concrete	RA.3.8
Service condition test	s_{min}, c_{min}	9.4	5	2630 (22.3)	95 ft-lb 129.2 Nm	9.7 ft-lb 13.12 Nm	10.2	Splitting	RA.3.9
Service condition test	Shear	9.5	5	2800 (23.7)	8700 (38.7)	252 (1.12)	2.9	Steel	RA.3.10

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

$$\frac{N_{b,r}}{N_{b,o}} = \frac{4424}{5468} \cdot \sqrt{2800/2{,}630} = 0.83$$

RA3.6—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

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

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 lb/in.^{2} (52.8 N/mm^2).

RA3.7—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

$$\frac{N_{b,r}}{N_{b,0}} = \frac{6092}{6445} = 0.94 > 0.80$$

A correction related to concrete strength is not necessary, because both test series were performed in the same concrete batch [$f_{c,test}$ = 2800 lb/in.^{2} (23.7 N/mm^2)].

RA3.8—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 1.5 h_{ef}. The minimum member thickness was 5-1/2 in. (140 mm), which is 2 h_{ef}.

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

$$N_m = 6047 \cdot \sqrt{2800/2{,}360} = 6239 \text{ lb (27.7 kN)}$$

$$s_m = 303 \cdot \sqrt{2800/2360} = 330 \text{ lb (1.39 kN)}$$

	Reference tests μ_1	Corner tests μ_2
Number of tests	10	5
Ultimate load, lb (kN)	6445 (28.8)	6227 (27.7)
Standard deviation, lb (kN)	382 (1.70)	312 (1.39)

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: $c = 1.35$

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

$$t_o = \sqrt{10 \cdot 5 \cdot (10 + 5 - 2)/(10 + 5)} \cdot \frac{6445 - 6227}{\sqrt{(10 - 1) \cdot 382^2 + (5 - 1) \cdot 312^2}} = 1.25$$

For t_0 £ c the hypothesis is accepted t_0 = 1.25 £ 1.35 = c; therefore, the chosen edge distance of 4 in. (100 mm) is acceptable.

RA3.9—Service-condition tests, minimum edge distance and spacing

In the tests, the minimum edge distance was 3 in. (75 mm), or 6 d_0; the minimum spacing was 6.7 in. (170 mm), or 14 d_0. The minimum member thickness was 5-1/2 in. (140 mm), or 2 h_{ef}.

The applied torque at observation of first hairline cracks was 95 ft-lb (129.2 Nm). This torque is larger than 1.7 T_{inst} = 1.7 x 45 ft-lb (60 Nm) = 75 ft-lb (102 Nm). The chosen s_{min}, c_{min}, and h_{min} are acceptable.

RA3.10—Service-condition tests, shear tests

The cross-sectional area of the threaded part of the anchor is 0.13 in.^{2} (84.3 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

$$V_m = 0.6 \cdot f_{u,test} \cdot A_{sv} = 0.6 \cdot 99{,}325 \cdot 0.13 = 7747 \text{ lb (34.5 kN)}$$

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

$$V_{5\%} = 0.6 \cdot f_{ut} \cdot A_{sv} = 0.6 \cdot 92{,}800 \cdot 0.13 = 7238 \text{ lb (32.2 kN)}$$

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

RA4.1—Establishment of anchor category

The following ratios of characteristic capacities were observed:

Reduced installation tests	0.74
Large hole diameter tests	0.83
Small hole diameter tests	0.97

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

RA4.2—Report of anchor data

Characteristic	Symbol	Dimension	Anchor value
Anchor diameter	—	—	1/2 in. M12
Effective embedment depth	h_{ef}	in. (mm)	2-3/4 (68)
Outside diameter	d_o	in. (mm)	1/2 (12)
Effective cross-sectional area—tension	A_{se}	in.^{2} (mm^2)	0.09 (58.1)
Effective cross-sectional area—shear	A_{sv}	in.^{2} (mm^2)	0.13 (84.3)
Minimum specified yield strength	f_y	lb/in.^{2} (N/mm^2)	74,000 (510)
Minimum specified ultimate strength	f_{ut}	lb/in.^{2} (N/mm^2)	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	—	22.6 (10)
Characteristic pullout resistance in specified concrete	N_p	lb/kN	5167 (20.7*)
Anchor axial stiffness in service load range	β	lb/in. (kN/mm)	54,970 (14.2)

*Increase characteristic pullout resistance for other specified concrete compressive strength by the square root of the specified strength divided by 2500 lb/in.^{2} (21 N/mm^2).