The New Zealand Concrete Industry
Conference2012
Claudelands, Hamilton 11-13 October

ACI 355.2 – SEISMIC TESTING OF POST-INSTALLED CONCRETE AND MASONRY ANCHORS IN CRACKED CONCRETE

GILBERT BALBUENA

Simpson Strong-Tie Australia

In January 2002, the American Concrete Institute (ACI) issued a new standard, ACI355.2-01, which prescribed a comprehensive testing program to ascertain design parameters for post-installed adhesive anchors and/or mechanical anchors used in cracked or uncracked concrete. Clause 17.5.6 NZS 3101: Part 1:2006 or ACI 318 Appendix D may also be used for post-installed mechanical anchors that have passed the qualification test stipulated in ACI 355.2. Post-installed mechanical anchors intended to resist seismic actions shall have passed the seismic test of ACI 355.2"

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. It does not apply to anchors loaded in compression, or to anchors subjected to long-term fatigue loading. Anchors meeting the requirements of ACI 355.2 are expected to sustain their design loads (in tension, shear, and combined tension and shear) while providing adequate stiffness.

ACI355.2 prescribes testing and evaluation requirements for post-installed mechanical anchors (torque-controlled expansion anchors, displacement-controlled expansion anchors and undercut anchors) with nominal diameter of 6mm or larger intended for use in concrete designed under the provisions of ACI 318. Criteria are prescribed to determine whether anchors are acceptable for use in uncracked concrete only or in cracked as well as uncracked concrete. Criteria are prescribed to determine the performance category for each anchor. The anchor performance categories are used by ACI 318 to assign reduction factors and other design parameters.

CRACKED CONCRETE ANCHOR

"CRACKED CONCRETE" refers to a situation where a crack passes directly through the hole in which the anchor is installed. A "cracked concrete anchor," refers to an anchor that has been tested and qualified for applications where cracking could be expected.

Many types of anchors will not work well, or at all, when tested in cracked concrete, but some anchors are specifically designed and tested to perform in cracks. Since there have not been any documented real-life anchor failures resulting from cracked concrete in the past, there has been debate as to whether or not it is necessary to consider 'cracked concrete' in anchor testing and design. Regardless, anchor testing in cracked concrete has officially been adopted by the International Building Code and the code requires these test standards be met, in order to be used on jobsites.

However, since post-installed anchor shapes and designs vary greatly based on product type and manufacturer, post-installed anchors MUST be tested to the new standard in order to determine their behavior in a crack.

An anchor should be tested and qualified in cracked concrete anytime it is intended to be used in an application where the concrete is expected to crack at some point throughout its use.

For instance, the Clause 17.5.6 NZS 3101: Part 1:2006 states that cracked concrete anchors must be used anytime the concrete member will be used to resist seismic forces.

In general anchor testing is performed in cracks to try and simulate the conditions that could happen at some point throughout its use. ACI355.2 allows manufacturers to test for recognition into concrete under the following conditions: uncracked concrete, cracked and uncracked concrete, or cracked/uncracked concrete and seismic. The codes do not permit an anchor be used in most seismic regions if it has not been tested to the last condition.

The tests required to earn recognition in the latter condition requires the anchor to pass tests that are performed in cracked concrete with a moving load and/or moving crack width. Not only must the anchor stay in the hole and resist a minimum load, it must also be within acceptable displacement limits. This is a very difficult test to pass and often only anchors that have been intentionally designed to perform in this test will pass it.

WHAT CAUSES CONCRETE TO CRACK?

Common conditions that cause cracking:

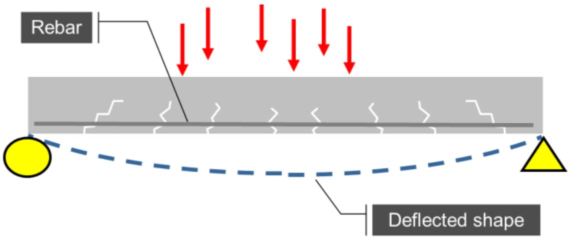
- Concrete in tension – such as in the underside of a slab
- Seismic Areas
- Other factors that contribute to cracking include:
  - External short term loads (such as high winds)
  - Temperature variations
  - Shrinkage during curing
  - Improper design

Concrete is prone to cracking in areas called the ‘tension zone’. Any area of a member that has tension is called a tension zone, however, that does not necessarily mean that cracking will occur in every tension zone.

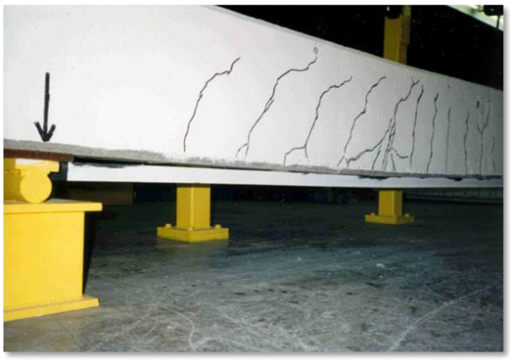
Concrete is strong in compression but relatively weak in tension, and even though it is weak it still has some ability to carry tension. The tension strength is approximately 10% of the compression strength.

The material property to measure concrete’s tension capacity is called the Modulus of Rupture (f_r). The Code gives an equation for calculating this Modulus as f_r = 7.5 times the square root of (f'_c), where f'_c is the compressive strength of the concrete.

In order for cracking to occur, the tension stress in the tension zone must exceed the Modulus of Rupture.



Steel works well in tension and will carry the tension force in areas where the concrete alone would most likely fail



Let’s look at an example to help show how to locate tension zones and where to expect cracking.

This concrete beam is being supported by the two yellow shapes. As this beam is loaded by any number of sources, it begins to deflect as shown by the blue dashed line. The area at the top of the concrete beam is in compression, as it is being squeezed together. The area at the bottom of the beam is being stretched apart and reflects a "tension zone". It is in the tension zone that cracking could be expected, but only if the tension force exceeds the concrete's tension capacity.

As you can imagine, when the unreinforced concrete does crack, it no longer has any tension carrying capacity. Engineers know that concrete will crack if enough tension force is developed and as a result they specify that the steel rebar be installed in tension zones of concrete members. Steel works well in tension and will carry the tension force in areas where the concrete alone would most likely fail. If we were to take a slice through the mid-span of the previous beam that was used as an example, you would see a lot more rebar in the bottom of the beam than in the top. Again, the top of the beam is in compression and concrete is strong in compression so it doesn't need as much reinforcement from rebar. But the bottom of the beam is in tension and since concrete is weak in tension, the rebar will be used to carry all the tension once the concrete cracks.

You may hear that rebar prevents concrete from cracking so there's no need to use cracked concrete anchors if rebar is in the concrete. This is not necessarily true.

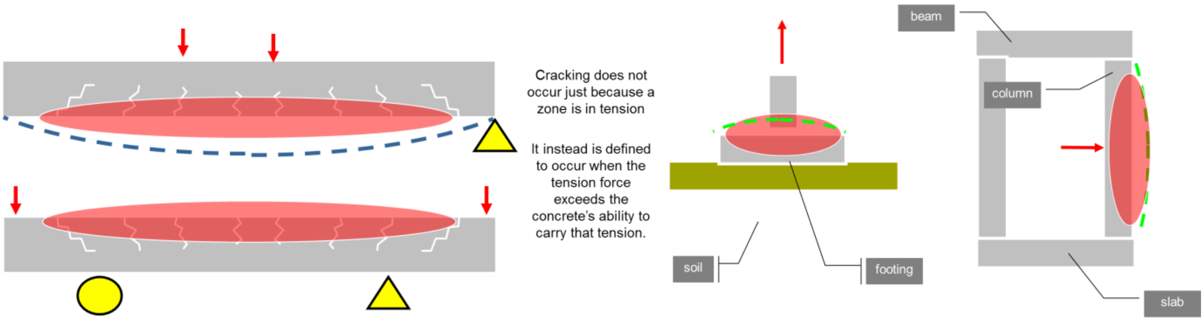
Rebar is used in concrete for both:
1.) tension strength, and
2.) to minimize cracks and deflections,

Unless rebar is intentionally over-designed to do so, a normal concrete member reinforced with rebar will still have some cracking in it.

The new anchor test standard ACI 355.2, DOES assume there will be some rebar in the cracked concrete zone to control the crack widths to a Code limit. It is this same Code crack width limit that is used to establish the crack widths that are tested to in the new 'cracked concrete' test criteria.

EXAMPLES OF TENSION ZONES

Tension Zones and cracks are not always located on the "underneath side" of a horizontal concrete member.



In addition, cracks do not only occur in beams. They can occur in footings, columns, and any other structural member where the tension load exceeds the concrete's ability to carry that tension load.

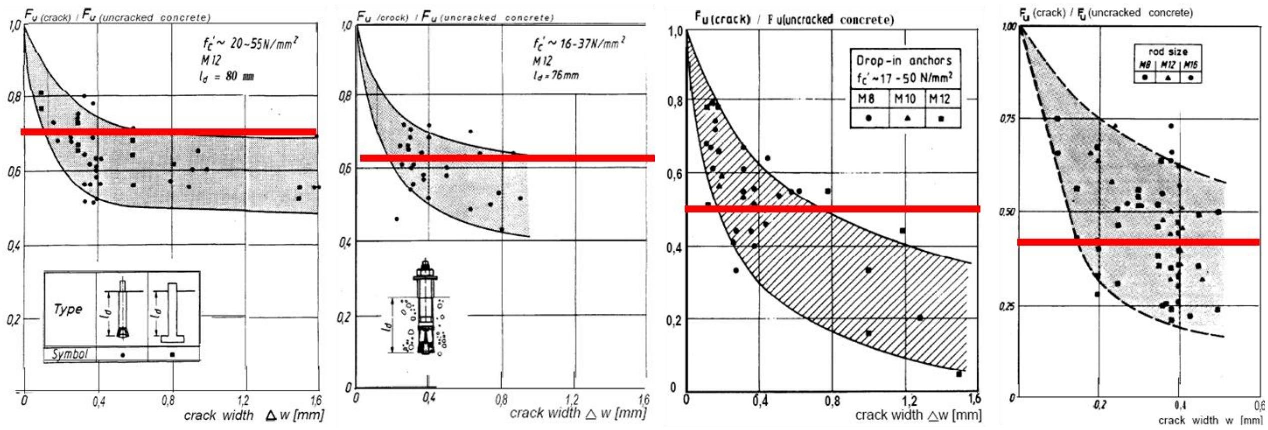
When designing concrete anchorages, designers are now being required to consider, among other things, whether conditions exist that may cause the concrete to crack. If it's determined such conditions do exist, anchors designed and tested for use in cracked concrete must be specified. If it's determined there is no risk of concrete cracking, the designer may choose to specify anchors that meet the 2006 IBC requirements for use in un-cracked concrete.

The Cast in place anchors tested, all conformed to a specific size and shape, as defined by an industry standard known as ANSI 18.2.1 and 18.2.6. As a result, if engineers design using a cast-in-place anchor that meets this size and shape standard, it does not need to be tested and qualified to the new anchor standard, it is basically “grandfathered” into the existing test database.

However, since post-installed anchor shapes and designs vary greatly based on product type and manufacturer, post-installed anchors MUST be tested to the new standard in order to determine their behavior in a crack.

Whether or not this cracking is expected can be calculated and is indicated by the Code. For instance, the Code states that cracked concrete anchors must be used anytime the concrete member will be used to resist seismic forces. Unlike gravity load which always acts downward, a seismic load can come from any direction –from either side or even up and down. Accordingly, the Code requires that a cracked concrete anchor be used for regions of medium to high seismicity. Even if the anchor is located in a region where cracking is not expected under gravity loads the Code still requires it be tested in a crack in these regions.

Cracked concrete anchors are also required in areas called tension zones. Although cracking will occur from applied structural loads and thermal effects (such as temperature and shrinkage cracks), the cracks covered by the new Code and test Standard are intended to address those resulting only from applied loads. In general anchor testing is performed in cracks to try and simulate the conditions that could happen at some point throughout its use.



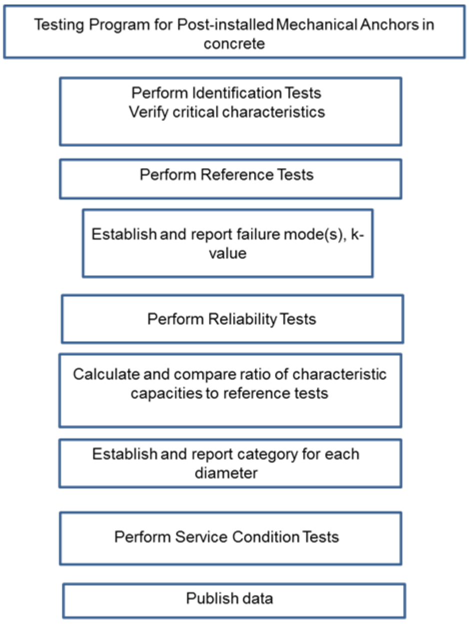
Much research has gone into anchor performance in cracks. Cast-in-place anchors were tested in cracks and consistently showed about a 25% loss from testing done in uncracked concrete. Many types of post-installed anchors were tested, wedge anchors, drop-in anchors, and adhesive anchors. And they all showed a loss in performance when tested in a crack. The expansion anchors tested, showed a loss of about 40% in a crack, drop-in anchors showed about an 80% loss and adhesive anchors showed a loss of 60%.

ACI 355.2 – QUALIFICATION OF POST-INSTALLED MECHANICAL ANCHORS

Testing and evaluation of anchors are performed or witnessed by an independent testing and evaluation agency accredited under ISO/IEC 17025 by a recognized accreditation body conforming to the requirements of ISO/IEC 17011. Also the testing shall be certified by a licensed engineer employed or retained by the independent testing and evaluation agency. Reference and reliability tests shall all be performed by an independent testing and evaluation agency. Service-condition tests performed by the manufacturer shall not be more than 50% of the total number of tests. Tests done by the manufacturer shall be witnessed by an independent testing laboratory or engineer meeting the requirement of ACI355.2 Chapter 12. Tests done by the manufacturer shall only be considered in the evaluation if the results are statistically equivalent to those of the independent testing and evaluation agency.

Testing Sequence (refer to flowchart)

1. Identification test – to evaluate the anchors compliance with the critical characteristics.
2. Reference tests – to establish baseline performance against which subsequent tests are to be compared.
3. Reliability tests – to confirm the reliability of the anchor under adverse installation procedures and long-term use.
4. Service-condition tests – to evaluate the performance of the anchor under expected service conditions.



Flowchart for overall testing program

Test program for evaluating anchor systems for use in uncracked concrete

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

[1] Minimum sample size for each diameter, unless otherw ise noted.

[2] Drill bit diameter for undercuts are specified in Table 5.6

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

[4] Required only for anchors w hose cross-sectional area, w ithin five anchor diamters 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 w hen shear capacity of the sleeve w ill be conside

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

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

[1] Minimum sample size for each diameter, unless otherw ise noted.

[2] Drill bit diameter for undercuts are specified in Table 5.6

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

[4] Required only for anchors w hose cross-sectional area, w ithin five anchor diamters 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 w hen shear capacity of the sleeve w ill be cons

[5] These tests are optional

Concrete strength for testing shall be within these ranges:
Low-strength concrete: 17 to 28 MPa
High-strength concrete: 46 to 60 MPa

Anchors installation shall be as per manufacturer installation instructions. Drill holes shall perpendicular (within a tolerance of +- 6 degrees) to the surface of the concrete member. Required diameter of carbide hammer-drill bits shall be as per the table below.

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

The crack width shall be approximately uniform throughout the member thickness. The thickness of the test member shall not be less than $1.5h_{ef}$ but at least 100mm. To control the location of the cracks and to ensure that the anchor are installed to the full depth in the cracks, cracks inducers shall be permitted to be installed in the member provided that they are not situated so as to influence the test results.

DIFFERENT TYPES OF CRACKED CONCRETE TESTING

There are essentially two types of cracked concrete tests: static-crack and moving-crack. In static-crack testing, the anchor is tested in the crack while the crack is held to a specified width. In moving-crack testing, the anchor is tested in a crack which is cycled between two widths.

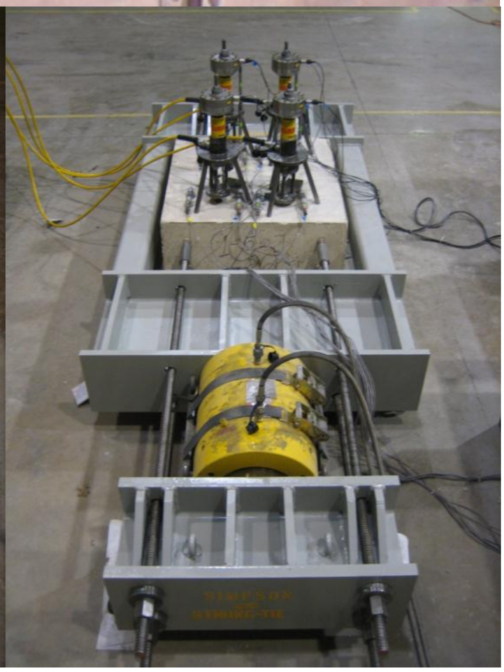
Engineers first create a hairline cracked in the concrete member using an established method. Then, they drill a hole perpendicular to the surface of the concrete member, effectively bisecting the crack, and thereby positioning the axis of the anchor in the plane of the crack. An anchor is installed and set pursuant to the manufacturer's instructions (as modified by the criteria). The subsequent testing is conducted as follows:

For static crack tests: The crack is opened to a specified width (either 0.012 or 0.020 inch) and held. Then the anchors are tested in tension or shear, while the crack width is monitored.

For moving crack tests: The crack width is cycled between two widths, starting with 0.004 and 0.012 inch, while a static load is applied to the anchor. The crack is cycled one thousand times while any resulting displacement of the loaded anchor is recorded. After the cycling is completed, the crack is held static, and the anchor is pulled to failure.

"ADVERSE" CONDITIONS FOR DIFFERENT TYPES OF ANCHORS

The adverse conditions will vary depending on the type of the anchor, and in some cases, the preferences of the manufacturer. For mechanical anchors, the adverse conditions include drill holes at maximum tolerance or minimum tolerance and at lower installation torque (where applicable). For adhesive anchors, the adverse conditions include installation in saturated concrete, submerged in water, etc. In addition, testing for effects of freeze-thaw, sustained load and installation direction are commonly required.



Summary of test requirements			
Test number	Purpose	Description	Requirments
Reference tests			
1	Reference test in uncracked low-strength concrete	Tension - single anchor with no edge influence	Coefficient of variance of the ultimate tension load in any test series < 15%
2	Referecne test in uncracked high-strength concrete	Tension - single anchor with no edge influence	
3	Reference test in low-strength, cracked concrete	Tension - single anchor with no edge influence	
4	Referecne test in high-strength, cracked concrete	Tension - single anchor with no edge influence	
Reliability tests			
5	Sensitivity to reduced installation effort	Tension - single anchor with no edge influence	Coefficient of variance of the ultimate tension load in any test series < 20%
6	Sensitivity to crack width and large hole diameter	Tension - single anchor with no edge influence	
7	Sensitivity to crack width small hole diameter	Tension - single anchor with no edge influence	
8	Test in cracks whose opening width is cycled	Repeated tension - single anchor with no edge influence, residual capacity	
Service-condition tests			
9	Verification of full concrete capacity in corner with two edges located at $1.5h_{ef}$	Tension - single anchor in corner with two edges located at $1.5h_{ef}$	Capacity of the anchor with two edge distance of 1.5hef shall be statistically equivalent to the capcity of the reference tests performed with no edge influence.
10	Minimum spacing and edge distance to preclude splitting on installation	High installation tension (torque or direct) - two anchors near edge	5% fractile of the maximum recorded torque calculated > the smaller of $1.7T_{inst}$ or $1.0T_{inst}$ + 135Nm
11	Shear capacity of anchor steel [4]	Shear - single anchor with no edge influnce	
12	Seismic tension	Pulsating tension, single anchor, with no edge influence	All anchors in the test series shall complete the simulated seismic-tension load history specified
13	Seismic shear	Alternating shear, single anchor, with no edge influene	All anchors in the test series shall complete the simulated seismic-tension load history specified

ESTABLISHING ANCHOR CATEGORIES

In order to established the anchor category, for each combination of anchor diameter and embedment depth, the ratio of the characteristic capacity $N_{b,r}$ in each reliability test to the characteristic tension capacity $N_{b,o}$ in the corresponding reference test. Using the smallest ratio $N_{b,r}/N_{b,o}$ from the reliability tests, establish the anchor category as per the table below.

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

CONCLUSION

So now that we know testing shows anchor performance is in fact affected by cracks in the concrete. Anchor should be tested & qualified for cracked concrete anytime it is intended to be used in an application where the concrete is expected to crack at some point throughout its use.

For instance, the NZS3101 says that Cracked concrete anchors must be used anytime it will be used to resist seismic forces. Cracked concrete anchors can also be required in areas called tension zones.

REFERENCES

ACI 355.2-07 Qualification of Post-Installed Mechanical Anchors in Concrete and Commentary (Reported by ACI Committee 355), American Concrete Institute

ACI 355.4-11 Qualification of Post-Installed Adhesive in Concrete and Commentary (Reported by ACI Committee 355), American Concrete Institute

Anchorage in Concrete Construction, R.Eligehausen, R. Mallee, J. Silva (2006)