Bonded (Adhesive) Anchors
Overall Webinar Outline

• Three part presentation
• Part 1
  ▪ Cast-in-place and mechanical expansion anchors
• Part 2
  ▪ Bonded (adhesive) anchors
• Part 3
  ▪ Example problem showing application of design provisions
Learning Objectives

• Briefly review ACI history of anchoring to concrete
• Review failure modes for post-installed adhesive anchors
• Review basic design models
• Review relationship between ACI 318 and anchor qualification requirements
Part 2 Outline

- Anchor types
- Fundamentals of “structural” anchors
- Code provisions in ACI 318
- Anchor qualification procedures
- Questions
Definitions

Attachment

Anchor

Embedment
Types of Anchors

Cast-in

Post–Installed
Mechanical

Post–Installed
Bonded

Undercut  Expansion  Adhesive  Grouted

Not included in ACI 318
Adhesive Anchors

- Chemical bond
  - Resin mixed with activator
- Rods are typically deformed reinforcing bars or continuously threaded bars
  - Qualification procedure does not cover development length

Photograph courtesy of Hilti AG
Anchor Systems

- Cast-in place
  - Headed
  - J & L Bolts
  - Studs

- Post-installed
  - Bonded
  - Mechanical
    - Expansion
    - Undercut
  - Grouted
    - Cementitious
      - Polymer
    - Polymer
  - Adhesive
    - Hybrid System
BOSTON I-90 TUNNEL

Central Artery/Tunnel (CA/T)

July 10, 2006

Ceiling Panel Collapse
Boston “Big Dig” Tunnel
Failure Sequence
Boston Big Dig Tunnel

Collapse Sequence

Support beam N
Boston Big Dig Tunnel

Displaced Anchors
Photos from NTSB Files
FHWA Laboratory Testing

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Description</th>
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</thead>
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<tr>
<td>Fast Set Epoxy</td>
<td>Initial Protrusion 3.1875&quot;</td>
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<tr>
<td>Peak Load</td>
<td>14,983 lbs</td>
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<td>Bond Area</td>
<td>7.69 in²</td>
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<tr>
<td>Peak Stress</td>
<td>1969 psi</td>
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<tr>
<td>Distortion</td>
<td>Yes</td>
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<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Description</th>
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<tbody>
<tr>
<td>Regular Set Epoxy</td>
<td>Initial Protrusion 3.15625&quot;</td>
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<tr>
<td>Peak Load</td>
<td>2094 lbs</td>
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<tr>
<td>Bond Area</td>
<td>9.61 in²</td>
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<tr>
<td>Peak Stress</td>
<td>2140 psi</td>
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<td>Distortion</td>
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**Graphs:**
- Load vs. Average Displacement
- Time vs. Load
- Displacement vs. Time

**Figure Legends:**
- Fast Set
- Regular Set
- Standard Set
• NTSB – Cause: poor creep resistance of fast-set adhesive anchors subjected to sustained tension load
• NTSB – Conclusion: insufficient understanding by designers and lack of standards on adhesive anchors in sustained tension
• NTSB – Recommendation: prohibit use of adhesive anchors in sustained loading
NTSB Comments to Organizations

- **FHWA** – prohibit use
- **AASHTO** – develop standards for testing
- **DOTs** – prohibit use
- **ICC** – revise building codes
- **Powers** – revise packaging to state for short-term loading
- **Sika** – revise product literature
- **ACI** – use codes, forums, educational materials to inform
- **ASCE** – inform members of creep characteristics
- **AGC** – inform members of creep characteristics
Cause – *Poor Installation in combination with other factors*
Loadings and behavior models

Photograph courtesy of Hilti AG
General Loads on Adhesive Anchors

• Tension load
  ▪ Sustained load – tension (creep)
• Compression load
• Shear load
## Adhesive Anchors – Failure Modes in Tension

<table>
<thead>
<tr>
<th>Concrete cone failure</th>
<th>Adhesive/substrate Bond failures</th>
<th>Mixed</th>
<th>Anchor steel failure</th>
</tr>
</thead>
</table>

- **Concrete cone failure**
- **Adhesive/substrate Bond failures**
- **Mixed**
- **Anchor steel failure**
Bond Models

Uniform  Elastic
Uniform Bond Failure Model

\[ N_{bond} = \tau \pi d_a h_{ef} \]

- \( d_a \) = diameter of anchor rod
- \( h_{ef} \) = embedment depth
- \( \tau \) = average bond stress
Uniform Bond Model and Tests

Only 17 of 891 data points below 5% fractile (1.9%)
Uncracked Bond Stress at Ultimate – Adhesive Anchors

Adhesive $\tau$ mean = 1850 psi

Average Uncracked Uniform Bond Stress, [psi]

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<thead>
<tr>
<th>Product</th>
<th>Stress [psi]</th>
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<tr>
<td>A</td>
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<td>B</td>
<td>1659</td>
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<tr>
<td>C</td>
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<tr>
<td>S</td>
<td>2104</td>
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</tbody>
</table>

Product
Key Variables Affecting Tension Strength

- Hole cleanliness
- Temperature
- Sustained load
- Moisture in hole
- Cracking

Adhesive anchors are affected by many factors, these are a few key factors and are product dependent – Prequalification of anchor necessary
ACI 318 Code
Adhesive Anchor Scope

- Adhesive anchors must meet the assessment criteria in ACI 355.4
  - This is an ACI standard
  - Similar to ACI 355.2 (qualification standard for mechanical expansion anchors)
- Can be used in seismic applications
- Can be installed horizontally or upwardly inclined
  - Installer certification required for these positions
Anchor Qualification
ACI 355.4
What is ACI 355.4 for Post-installed Adhesive Anchors

• Variable load-displacement behavior, particularly in cracked concrete
• Behavior sensitive to installation
• Must verify basic behavior and reliability using standard tests
• Based on reliability, assign anchor performance category and corresponding strength reduction factor phi (ϕ)
ACI 355.4 Identification Tests

• Check conformance to product description
  ▪ Generic or trade name
  ▪ Anchor element
  ▪ Adhesive components
  ▪ Quality-control requirements
Establish baseline performance of anchors for comparison with Reliability and Service-Condition tests

- Test in Uncracked Concrete
  - Tension tests in low-strength and high-strength concrete

- Test in Cracked Concrete:
  - Tension tests in low-strength concrete and high-strength concrete with crack width 0.012 in. (0.3 mm)
ACI 355.4 Reliability Tests

• Sensitivity to hole cleaning
  ▪ Dry installation
  ▪ Water-saturated installation
  ▪ Water-filled installation
  ▪ Submerged installation

• Sensitivity to mixing effort
ACI 355.4 Reliability Tests (continued)

• Sensitivity to cracking
  ▪ Installation in cracked concrete
  ▪ Crack width cycling with sustained load
• Sensitivity to freeze and thaw cycling
• Sensitivity to sustained load
• Sensitivity to installation direction
ACI 355.4 Classification

- Classify anchor based on ratio between performance in reliability and reference tests

% of Reference Capacity

- Category 1: 80 or above
- Category 2: 70 - 79
- Category 3: 60 - 69
ACI 355.4 Service-Condition Tests

• Verify anchor behavior under
  ▪ Elevated temperature installation
  ▪ Curing time at low temperatures
  ▪ Resistance to alkalinity
  ▪ Resistance to sulfur
  ▪ Seismic tension
  ▪ Establish minimum spacing and edge distances to preclude splitting during installation (torqueing) and tension loading
  ▪ Establish shear capacity of anchor steel (may be calculated)
Qualification Standard Report

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

| Anchor class | Anchor type | Test method | Anchor diameter (mm) | Anchor length (mm) | Test anchor length (mm) | Test anchor load (kN) | N | N
|--------------|-------------|-------------|----------------------|--------------------|------------------------|-----------------------|---|---
| A            | A           | ASTM 487-02 | 12                   | 200                | 150                    | 100                   | 5 | 5
| B            | B           | ASTM 487-02 | 12                   | 300                | 250                    | 200                   | 10| 10
Scope of ACI 318 – Adhesive Anchor Provisions

APPENDIX D — ANCHORING TO CONCRETE

CODE

D.1 — Definitions

Adhesive anchor — A post-installed anchor, inserted into hardened concrete with an anchor hole diameter not greater than 1.5 times the anchor diameter. The anchor transfers total load to the concrete by bond between the anchor and the adhesive, and bond between the adhesive and the concrete.

Adhesive — Organic polymers used in adhesives can include, but are not limited to, epoxies, polyurethanes, polyethers, styrene butadiene, and vinyl esters.

ANCHOR — A steel element other than cast into concrete or post-installed into a hardened concrete member and inserted to transmit applied loads to the concrete. Cast-in anchors include headed bolts, headed studs (U- or L- bolts), and headed studs. Post-installed anchors include expansion anchors, screw anchors, and adhesive anchors. Steel elements for adhesive anchors include headed studs, deformed reinforcing bars, and internally threaded steel sleeves with external deformations.

Anchor group — A number of similar anchors having approximately equal effective embedment depths with spacing between adjacent anchors such that the protected areas overlap. See D.3.1.1.

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

Anchor reinforcement — Reinforcement used to transfer the full design load from the anchors into the structural member. See D.3.2.3 or D.4.2.5.

Anchor reconfiguration — Anchor reconfiguration is designed and detailed specifically for the purpose of transferring anchor loads from the anchors into the structural member. Hangers are generally used for this purpose (see 35.3.2.3 and 35.3.2.4); however, other configurations that can be shown to effectively transfer the anchor load are acceptable.

COMMENTARY

RD.1 — Definitions

Adhesive — Organic polymers used in adhesives can include, but are not limited to, epoxies, polyurethanes, polyethers, styrene butadiene, and vinyl esters.

Adhesive anchor — The design model included in Appendix D for adhesive anchors is based on the behavior of anchors with hole diameters not exceeding 1.5 times the anchor diameter. Anchors with hole diameters exceeding 1.5 times the anchor diameter behave differently and are therefore excluded from the scope of Appendix D and ACI 352.4. To limit shrinkage and reduce displacement under load, most adhesive anchor systems require the annular gap to be as narrow as practical while still maintaining sufficient clearance for insertion of the anchor element in the effectively filled hole and ensuring complete compaction of the bonded area over the embedded length. The annular gap for reinforcing bars is generally larger than that for threaded rods. The required hole size is provided in the Manufacturer’s Primed Installation Instructions (MPI).
• Post-installed adhesive anchors do not have a generically predictable pullout capacities
• Post-installed adhesive anchors must be qualified by testing according to ACI 355.4
• High-cycle fatigue and impact (blast) are excluded
Seismic Design Requirements

- Seismic load effects covered
  - Applicable to Seismic Design Categories (SDC) C, D, E, and F
- Anchors in plastic hinge zones excluded
- Post-Installed Anchors shall be qualified for earthquake loading per ACI 355.2 or ACI 355.4

Simulated Seismic Tests
General Requirements

- Adhesive anchors installed horizontally or upwardly inclined
  - Must be qualified by ACI 355.4
  - Must be installed by *certified installer* when subjected to sustained load
Lightweight Concrete

• Lightweight concrete modification factor, $\lambda_a$

• Modification factor
  - Cast-in and undercut concrete failure: $\lambda_a = 1.0 \lambda$
  - Expansion and adhesive anchors concrete breakout failure: $\lambda_a = 0.8 \lambda$
  - Adhesive anchor bond failure: $\lambda_a = 0.6 \lambda$
    - $\lambda = 1.0$ excluded

• $\lambda$ determined by Section 8.6.1
  - $\lambda = 1.0$ normal weight
  - $\lambda = 0.85$ sand-lightweight
  - $\lambda = 0.75$ all-lightweight
Concrete Strength

• Code equations are valid for:
  ▪ $f_c' \leq 10,000$ psi for cast-in anchors
  ▪ $f_c' \leq 8,000$ psi for post-installed anchors

• Post-installed anchors in concrete with $f_c' > 8,000$ psi must be tested according to ACI 355·4
Embedment Depth Limitations for Adhesive Anchors

- Limits of embedment depth for adhesive anchors
  \[ 4 \, d_a \leq h_{ef} \leq 20 \, d_a \]
  - Design using bond model is satisfactory
ACI 318 Code Design

Design for Tension, Shear, or Combinations of Tension and Shear

Photograph courtesy of Ambex
Tension Design

- Designer must consider the following tension failure modes for adhesive anchors:
  - Steel failure
  - Concrete breakout failure
  - Bond pullout failure
Steel Failure Mode - Tension

- Steel rupture

\[ N_{sa} = A_{se} f_{uta} (D - 2) \]

- \( f_{uta} < 1.9 f_y \)
- \( f_{uta} < 125,000 \text{ psi} \)
Concrete Failure Mode – Tension Cone Breakout

Courtesy of University of Stuttgart
Single Anchor Concrete Breakout

• Single anchor in tension in cracked concrete

\[ N_b = k_c \lambda_a \sqrt{f_c'} (h_{ef})^{3/2} \]  \hspace{1cm} (D – 6)

- \( k_c = 24 \) for cast-in anchors
- \( k_c = 17 \) for post-installed anchors
- \( \lambda_a = \) Lightweight concrete modification factor

Note: an adhesive anchor should be considered like a post-installed anchor even though there are no wedging forces developed at embedded end for concrete breakout
User Friendly CCD Design Model for Concrete Breakout – Projected Area $A_{Nco}$

$A_{Nco} = 9h_{ef}^2$
Concrete Breakout (Tension)

Single anchor not near an edge

Single anchor Near an edge

$N_n$
Concrete Breakout (Tension)

Anchor group with overlapping breakout cones

\[ N_n \]
Concrete Breakout with Groups and Edges - Projected Area $A_{Nc}$

- $c_{a1} \leq 1.5h_{ef}$
- $s_1 \leq 3.0h_{ef}$
- $A_{Nc} \leq nA_{Nco}$ Limit
- $c_{a2} \leq 1.5h_{ef}$
- $s_2 \leq 3.0h_{ef}$
Concrete Breakout Strength of Anchor Group (Tension)

\[ N_{cbg} = \left( \frac{A_{Nc}}{A_{Nco}} \right) \psi_{ec,N} \psi_{ed,N} \psi_{c,N} \psi_{cp,N} N_b \]  

(\textit{D-4})

- Accounts for eccentricity
- Accounts for edge effects
- Accounts for cracking
- Accounts for post-installed anchor (splitting)
- Accounts for projected area of failure surface
- Basic single anchor strength

Applies to only anchors in tension
• Tension design
  ▪ Sustained loading
    ► $0.55 \phi N_{ba} > N_{ua,\text{sustained}}$
Bond Pullout Strength

• Single anchor in cracked concrete

\[ N_{ba} = \lambda_a \, \tau_{cr} \, \pi \, d_a \, h_{ef} \]

\[ \tau_{cr} = 5\% \text{ fractile result in cracked concrete from } ACI \, 355.4 \]

\[ \lambda_a = \text{Lightweight concrete modification factor for adhesive anchors} \]

\[ \lambda_{a,\text{lightweight}} = 0.6 \, \lambda_{\text{normal}} \]

[0.6 factor not applicable for normal-weight concrete]
User Friendly CCD Adhesive Anchor Design Model

![Diagram showing plan view and elevation with bond failure/concrete breakout transition]

\[ A_{Nao} = (2c_{Na})^2 \]

Bond failure/concrete breakout transition

CCD model for edges and spacing
Critical Spacing and Edge Distance for Bond Failure

• Cast-in-place and post-installed mechanical anchors
  ▪ ACI 318
    \[ s_{critical} = 2c_{critical} = 3.0 \ h_{ef} \]

• Bonded anchors
  ▪ ACI 318
    \[ s_{critical} = 2c_{critical} \]

where: \[ c_{critical} = c_{Na} = 10 \ d_a \ (\tau_{uncr} / 1100)^{1/2} \]
Bond Failure of Adhesive Anchor Groups
Projected Area $A_{Na}$

- $c_{a1} \leq c_{Na}$
- $s_1 \leq 2c_{Na}$
- $A_{Na} < nA_{Nao}$
- Limit
- $c_{a2} \leq c_{Na}$
- $s_2 \leq 2c_{Na}$

Corner
\[ N_{ag} = \left( \frac{A_{Na}}{A_{Nao}} \right) \psi_{ec,Na} \psi_{ed,Na} \psi_{cp,Na} N_{ba} \]

\[ < \left( \frac{A_{Nc}}{A_{Nco}} \right) \psi_{ec,N} \psi_{ed,N} \psi_{c,N} \psi_{cp,N} N_{b} \]

Tension failure = Bond failure < Concrete failure
• Steel failures
  ▪ Ductile steel $\phi = 0.75$
  ▪ Brittle steel $\phi = 0.65$

• Concrete breakout and adhesive bond failures

<table>
<thead>
<tr>
<th>Category</th>
<th>Condition A</th>
<th>Condition B</th>
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<tbody>
<tr>
<td>Category 1</td>
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<tr>
<td>Category 2</td>
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<tr>
<td>Category 3</td>
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<td>0.45</td>
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Condition A – Supplemental steel
Condition B – Plain concrete
## Code Guidance for Bond Stress Design

<table>
<thead>
<tr>
<th>Environment</th>
<th>Concrete moisture</th>
<th>Peak service temperature</th>
<th>( \tau_{cr} )</th>
<th>( \tau_{uncr} )</th>
</tr>
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<tbody>
<tr>
<td>Outdoor</td>
<td>Dry to fully saturated</td>
<td>175° F</td>
<td>200 psi</td>
<td>650 psi</td>
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<tr>
<td>Indoor</td>
<td>Dry</td>
<td>110° F</td>
<td>300 psi</td>
<td>1000 psi</td>
</tr>
</tbody>
</table>

For sustained tension load, multiply table \( \tau_{cr} \) and \( \tau_{uncr} \) values by 0.4

For seismic design in SDC C, D, E, and F, multiply table \( \tau_{cr} \) value by 0.8 and \( \tau_{uncr} \) value by 0.4
Shear Design

- No changes because anchor is adhesively bonded
- Choice of two equations; use smaller value for design

\[ V_b = 7 \lambda_a \left( \frac{\ell_e}{d_a} \right)^{0.2} \sqrt{d_a} \sqrt{f_c'} (c_{a1})^{1.5} \]

or

\[ V_b = 9 \sqrt{f_c'} (c_{a1})^{1.5} \]

\[ \ell_e \]

\[ d_a \]

\[ f_c' \]

\[ c_{a1} \]
Tension - Shear Interaction

\[
\frac{N_u}{\phi N_n} + \frac{V_u}{\phi V_n} = 1.2
\]

\[
\left( \frac{N_u}{\phi N_n} \right)^{\frac{5}{3}} + \left( \frac{V_u}{\phi V_n} \right)^{\frac{5}{3}} = 1.0
\]
Installer Certification

Courtesy of Hilti AG
Anchor Installation and Inspection

- Anchors to be installed by qualified personnel
- Installation in accordance with Manufacturer’s Printed Installation Instructions (MPII)
- Extensive installation, inspection, and proof load requirements
AAI Certification

• Training for installers
  ▪ Provided by manufacturers
• Written test – test baseline knowledge
  ▪ Environmental conditions
  ▪ Equipment / materials
  ▪ OSHA issues
• Performance test
  ▪ Downhand vertical into concrete
  ▪ Vertical overhead into a tube or pipe
Downhand Vertical

- Hole depth
- Hole cleaning technique
- Adhesive dispensing
- Rod / bar installation
Hole Drilling

- Hole normal to surface
- Correct depth
- Removal of concrete dust spoil
Express Initial Material

- Initial material is typically not well mixed
- Need to discard
- Did the installer do this?
Installation – All Thread
Blind Overhead Vertical

- Install adhesive in a upside-down hole
- Use insertion tube to feel depth of hole
Adhesive Anchor Installer Certification (AAI)

- Written test
- Performance exam
- Program is live!
  - Administered by ACI
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    - Example problem showing application of design provisions
Questions and Answers