Tensile Performance of Deeply Embedded Cast-In-Place Anchors in Cracked Concrete: Implications for Structural Resilience

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Background - Anchors in NPPs

- Safety-related components in NPPs
  - heat exchangers, storage tanks, pumps, EDG, etc.
  - is typically anchored to the concrete floor using CIP anchors
  - Deeply embedded anchors (h_{ef} > 60cm) are often used.
- Failure modes of components during seismic events
  - Failure of anchorage system: **<u>concrete breakout failure</u>**, bolt steel failure

Components	Diameter(cm)	Embedment depth(cm)	Failure mode
Pressurizer	5.08	60.96	Conc. Breakout
Volume Control Tank	3.81	39.04	Bolt Steel
Excess Letdown Heat Exchanger	2.54	71.20	Conc. Breakout
Boron Injection Tank	4.45	60.33	Conc. Breakout
Residual Heat Removal Heat Exchanger	5.08	37.47	Conc. Breakout
Emergency Diesel Generator	5.08	103.19	Conc. Breakout
Diesel Generator Air Starting System	3.81	61.29	Conc. Breakout
Essential Service Water Pump	3.81	61.29	Conc. Breakout
Component Cooling Water Surge Tank	2.86	30.48	Bolt Steel
125V DC Battery & Rack	1.27	26.67	Bolt Steel
CONT SPRAY ENCAPSULATION TANK	3.18	42.67	Bolt Steel



Residual Heat Removal(RHR) Heat Exchanger



Nuclear Service Cooling Water(NSCW) pump

Research Motivation

- Scarcity of empirical data for deeply embedded anchors
  - Experimental data for deeply embedded anchors are rare.
  - Experiments on deeply embedded anchors in cracked concrete are even rarer.

NUREG/CR-5563

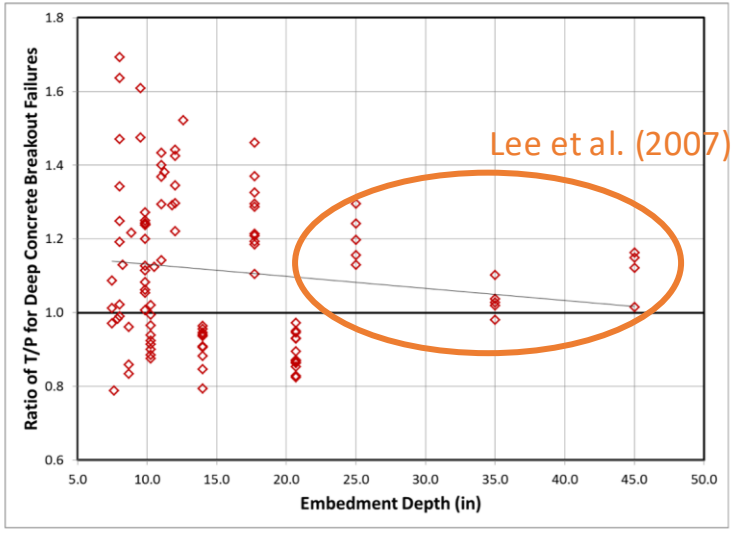


Figure 2-2
Embedment depth error plots for existing (NUREG 5563) deep anchor equation

Code background paper in ACI structural journal

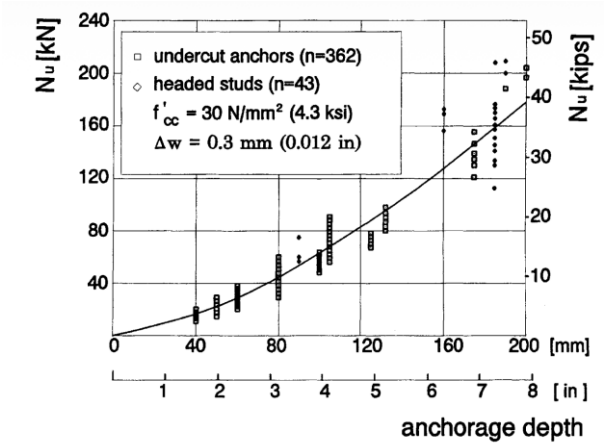


Fig. 9—Concrete cone failure loads of undercut anchors and headed studs in cracked reinforced concrete (line cracks) as function of embedment depth. Failure loads of undercut anchors multiplied by 15.5/13.5 = 1.15

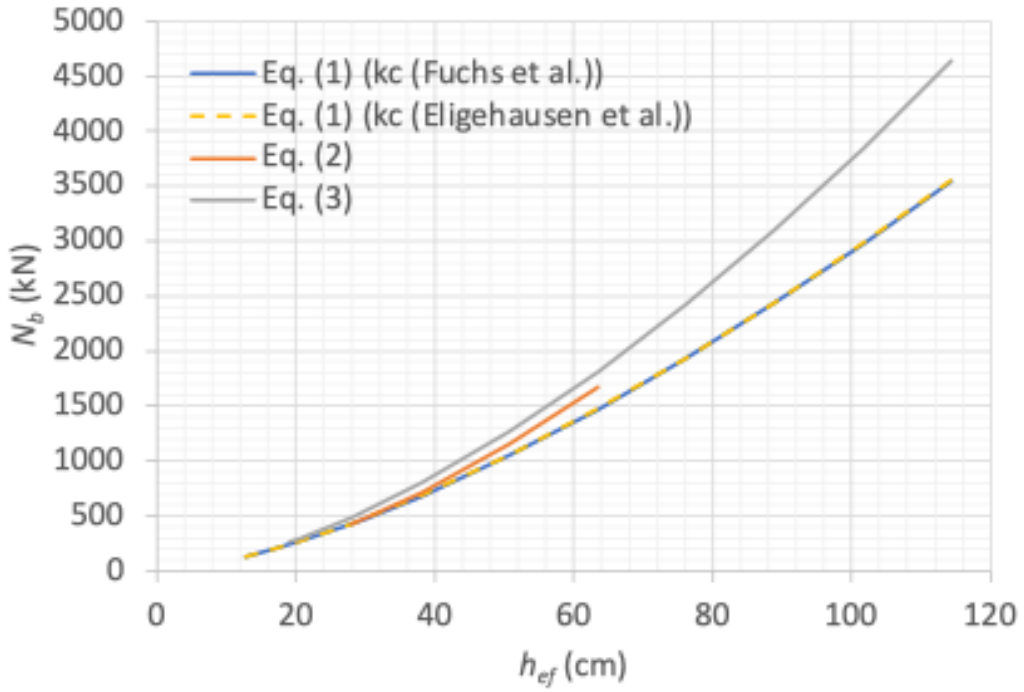
EPRI 3002012994
- factors for cracking in ACI is not applicable due to lack of empirical data

The basic strength equations defined in Equations 4-58 and 4-59 should be modified by the reduction factors $\Psi_{ec,N}$ and $\Psi_{ed,N}$ from ACI 349-13 [46] to account for eccentricity and edge distance effects. Strengths for anchors in groups and those affected by nearby edges should also be modified by the ratio of the projected area of a 35° rectangular cone following Equations D-4 and D-5 of ACI 349-13 [46]. Factors $\Psi_{c,N}$ and $\Psi_{cp,N}$ for cracking and post-installed anchors are not applicable because the k_c values recommended here are for cast-in-place anchors in uncracked concrete.

U.S. Nuclear Regulatory Commission, "A Technical Basis for Revision to Anchorage Criteria," NUREG/CR-5563, Washington, D.C., 1999.
Rolf Eligehausen and Tamas Balogh, "Behavior of Fasteners Loaded in Tension in Cracked Reinforced Concrete", ACI structural journal, 1995,
Electric Power Research Institute(EPRI), " Seismic Fragility and Seismic Margin Guidance for Seismic Probabilistic Risk Assessments," 3002012994, Palo Alto, CA, 2018.

Research Motivation

- Conservatism in the existing prediction models
  - Current models conservatively estimate the performance of deeply embedded anchors.
    - ACI suggests an alternative equation for 11 in.<h_{ef}<25 in.



No,	Embedment depth	Basic concrete breakout strength	k (uncracked)		COV (tested/predicted)
			5% fractile *(ACI 349)*	Mean	
(1)	No specific restrictions	$N_b = k\sqrt{f_c'}h_{ef}^{1.5}$	24*1.25= 30	40 (Fuchs et al.)	0.18 – 0.20
(2)	11 in. $\leq h_{ef} \leq$ 25 in.	$N_b = k\sqrt{f_c'}h_{ef}^{1.67}$	16*1.25= 20	26.4 (NUREG/CR-5563)	0.18 – 0.20
(3)	7.5 in. $\leq h_{ef} \leq$ 45 in.	$N_b{}^{(1)} = k f_c'^{3/4} h_{ef}^{1.6}$		4.4 (EPRI 3002008099)	0.16

(1) $f_c' \leq 7000$psi.

American Concrete Institute(ACI) Committee 349, "Code Requirements for Nuclear Safety-Related Concrete Structures (ACI 349-13) and Commentary," Farmington Hills, MI, 2013.
Electric Power Research Institute(EPRI), "Seismic Fragility Strength Equation Recommendations for Embedded Anchors," 3002008099, Palo Alto, CA, 2016.

Research Motivation

- Need for realistic seismic fragility assessment
  - Conservatism is acceptable in design, but realistic median capacity is required for seismic fragility assessment.
  - Reduce conservatism for critical equipment that affects core damage frequency (CDF)

    → Achieve safety goals & Service life extension

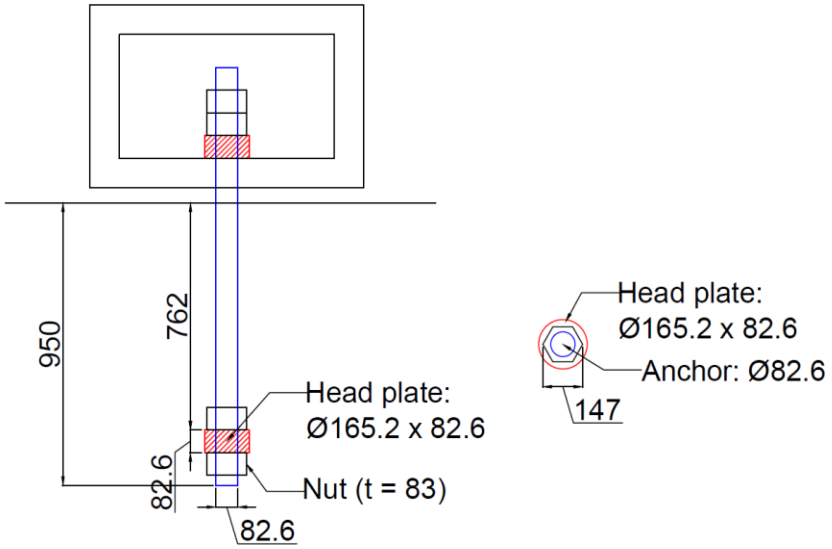
- Resilience perspective
  - Once CIP anchor is damaged or fails, repairing or replacing it is nearly impossible.
  - The key to resilience lies entirely in ‘Robustness’.
  - How robust the system remains when initial damage occurs, such as cracking from EQ.

Research Objectives

- Conduct experiments to evaluate the concrete breakout strength of deeply embedded CIP anchors.
- Quantify conservatism in existing prediction equations.
- Update the median capacity for deep CIP anchors using empirical results.
- Evaluate the robustness of deeply embedded anchors (cracked concrete: post-damage state)
- Provide insights for resilience of safety-related components

Test Plan

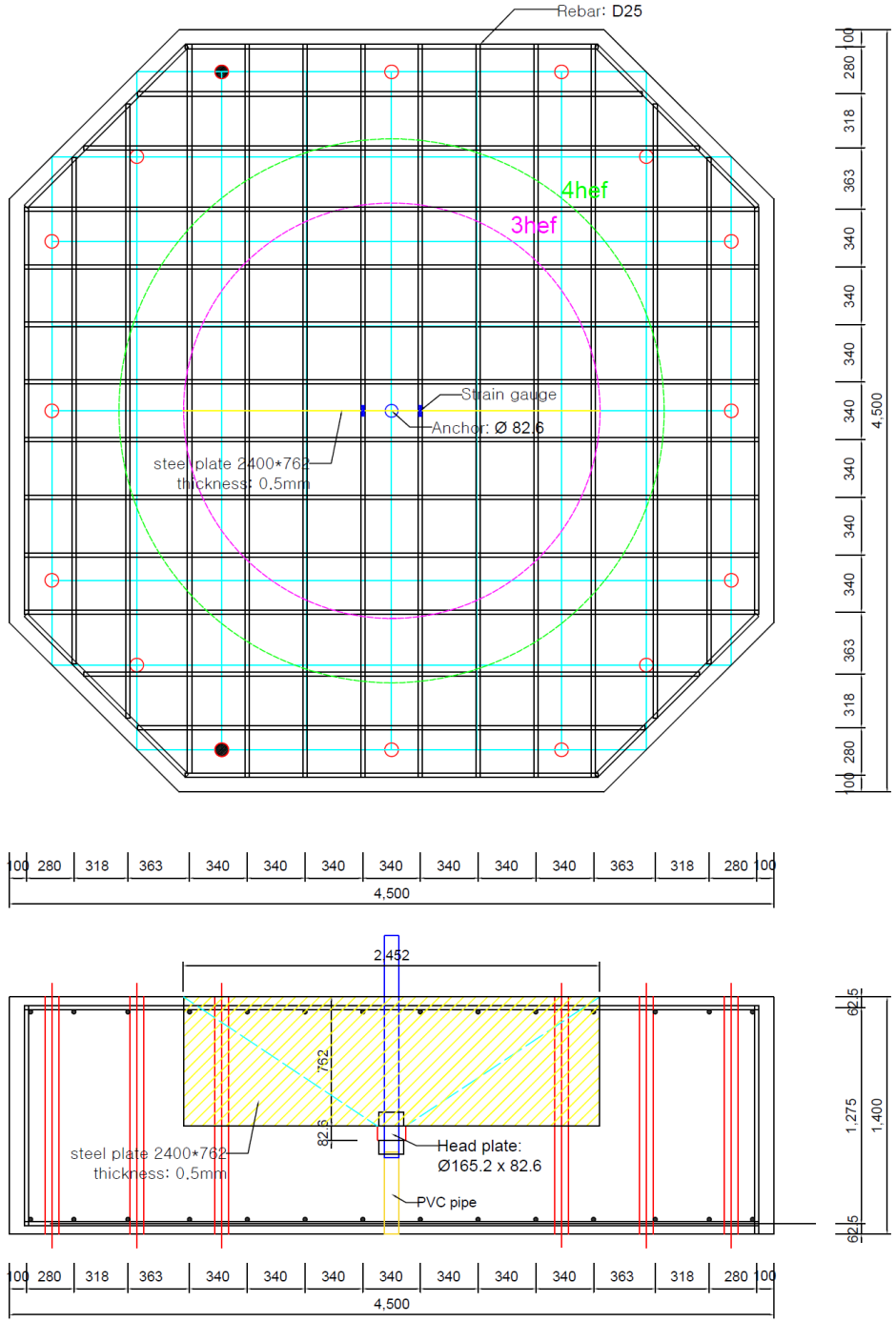
- Specifications of Korean NPPs
  - Anchor: ASTM A193 Gr. B7 (f_y = 655 MPa, f_u = 795 MPa)
  - f_{ck} = 27 MPa (3916 psi) (cylinder strength)
- h_{ef} = 762 mm (30 in.) – max. depth considering facility and budget
- Failure mode: Concrete breakout failure in tension
- Anchor and head plate diameter are designed to prevent steel or pullout failure
- Expected concrete breakout strength: 1830 - 2237 kN



Type	Equation	Strength (kN)	Reference
Steel tensile strength	$N_{sa} = A_{se,N} f_{uta}$	4258	ACI 349-13
Pullout strength	$N_p = 8 A_{brg} f'_c$	3472	ACI 349-13
Concrete breakout strength	$N_{cb}(lb) = 1.25 \times 24 \sqrt{f_c} h_{ef}^{1.5}$	1372	ACI 349-13
	$N_{cb}(lb) = 40 \sqrt{f_c} h_{ef}^{1.5}$	1830	ACI with k (Fuchs et al.)
	$N_{cb}(lb) = 4.4 {f_c}'^{\frac{3}{4}} h_{ef}^{1.6}$	2237	EPRI 3002012994

Test Plan

- Dimension of concrete block and load application method
  - Reference: ASTM E488, EAD 330924-01-0601
- Concrete block size: $\mathbf{4.5}\times\mathbf{4.5}\times\mathbf{1.4}$ m (octagon)
  - Distance between the anchor and the support > 2 $\boldsymbol{h_{ef}}$
  - Thickness of block > 1.5 $\boldsymbol{h_{ef}}$
  - Octagonal shape: reduction of total volume of concrete
- Surface reinforcement ratio: 0.2% (fy: 410 MPa)
  - Control for temperature induced def. and shrinkage.
- Static tensile loading (loading rate: 0.02mm/s)
  - Dynamic loading generally increase the anchor tensile capacity governed by concrete breakout. (NUREG/CR-5563))

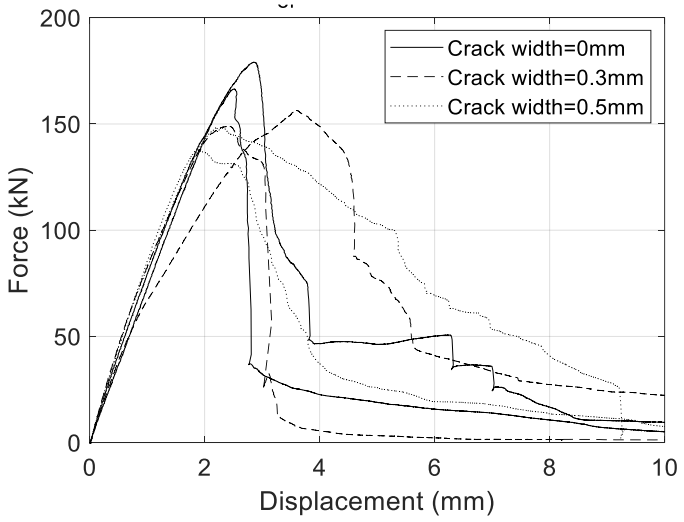


Test Plan

- Total 5 specimens: 3 uncracked & 2 cracked
  - To simulate crack, 0.5mm steel plate was inserted.
  - (RG 1.999): If cracks in the vicinity exceed about 0.01 inch (0.3 millimeter), the design strength should be appropriately reduced.
  - Experience has shown that crack with resulting from primarily quasi-permanent loads (dead load + a fraction of the live load) do not exceed 0.3~0.4mm.
  - Wider cracks are expected under maximum permissible service loads. 0.5~0.6mm

R. Eligehausen, R. Mallee and J. Silva, Anchorage in Concrete Construction, Berlin, Germany: Ernst & Sohn, 2006.





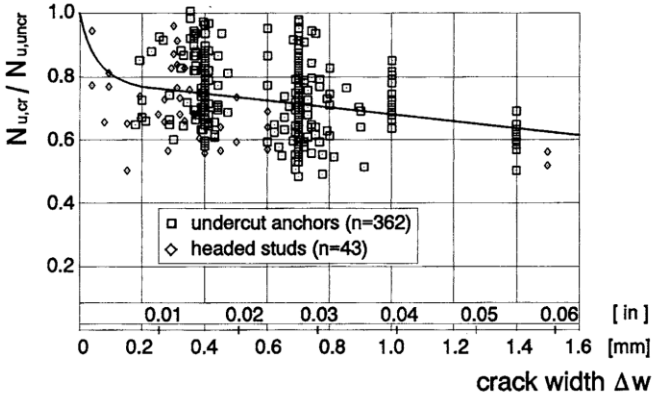
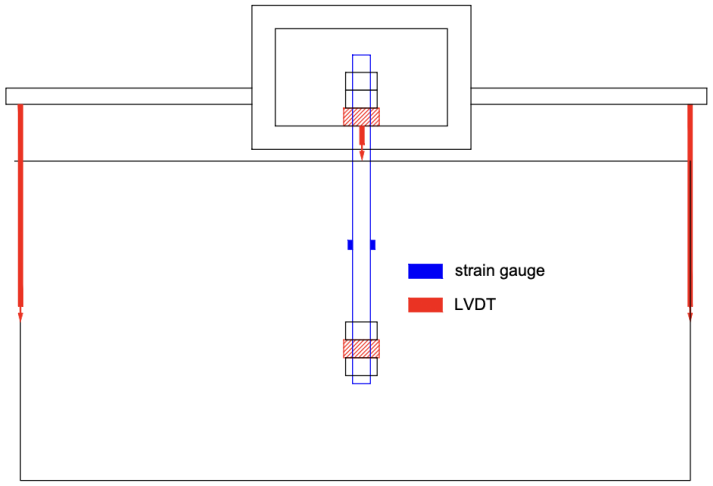


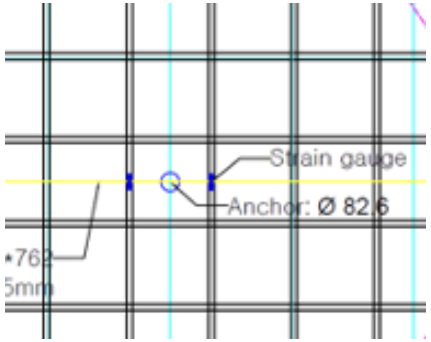
Fig. 6—Ratios of concrete cone failure loads of undercut anchors and headed studs in cracked reinforced concrete (line cracks) to values valid for uncracked concrete calculated according to Eq. (1) as function of crack width

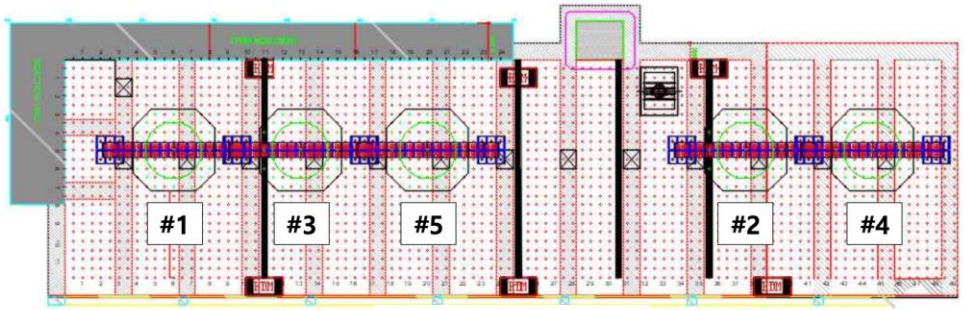
Rolf Eligehausen and Tamas Balogh, "Behavior of Fasteners Loaded in Tension in Cracked Reinforced Concrete", ACI structural journal, 1995,

Test Plan

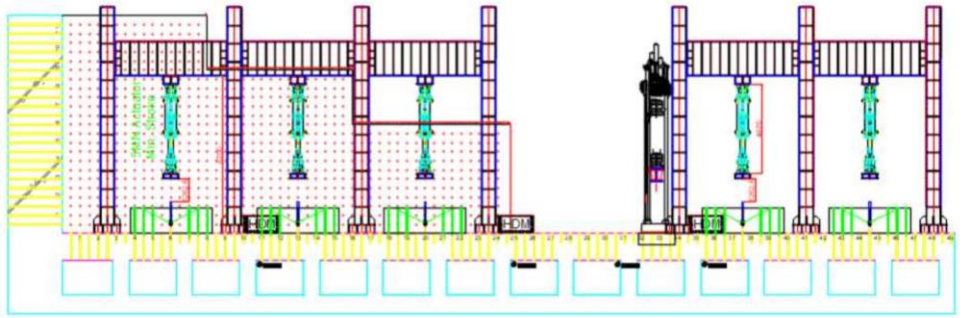
- Instrumentation: LVDTs - disp. relative to center and surface of the block.
  strain gauges - anchor and slab reinforcement.
- Testing schedule: Five tests were conducted sequentially at intervals of about one week.
  - Disassemble and reassemble of the frame







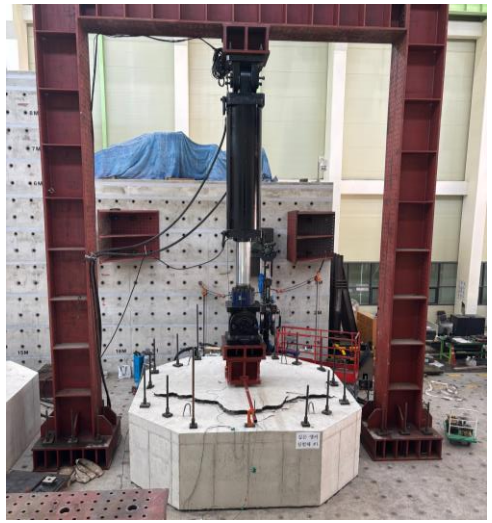
< Top view >



< Side view >

Test Results

- Test setup and the condition of the specimens during and after loading.
- Singe actuator → Dual actuator : due to load capacity limitations encountered.
- Circular cracks on the top surface and internal concrete breakout failure surfaces were observed.



Uncracked #1



Uncracked #3







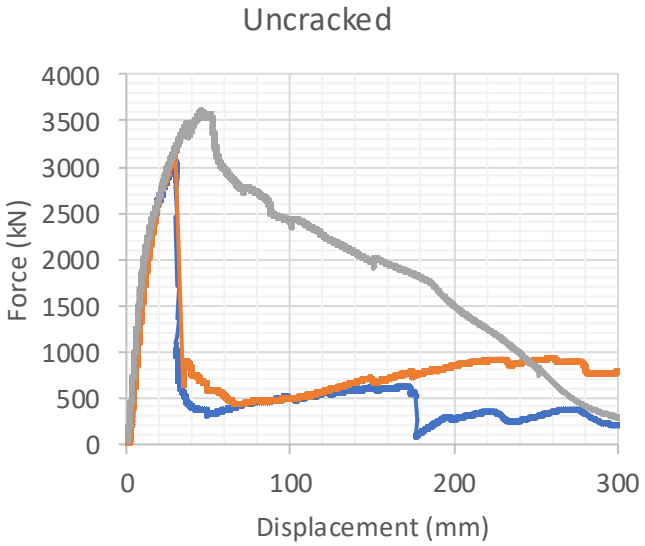


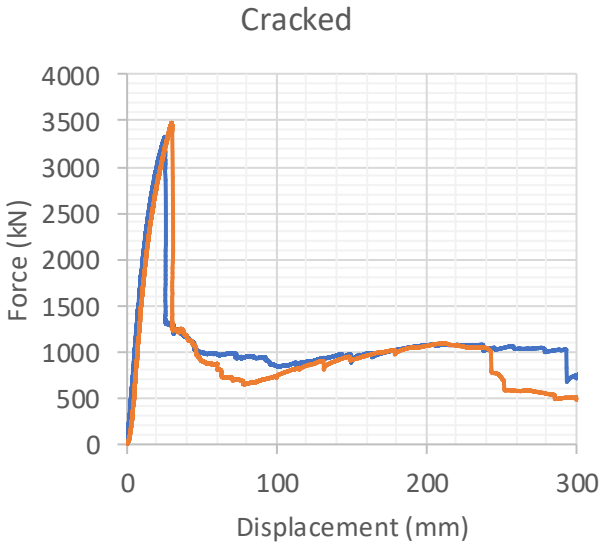


Angle of concrete cone
#1: 33~35 degrees
#2: 25~31 degrees
#3: 27~53 degrees
#4: 24 degrees
#5: 21~22 degrees

Test Results

- Force – displacement curves
  - One week gap between each test leads gradual increment of concrete breakout strength
  - Uncracked specimen #3 – pullout failure

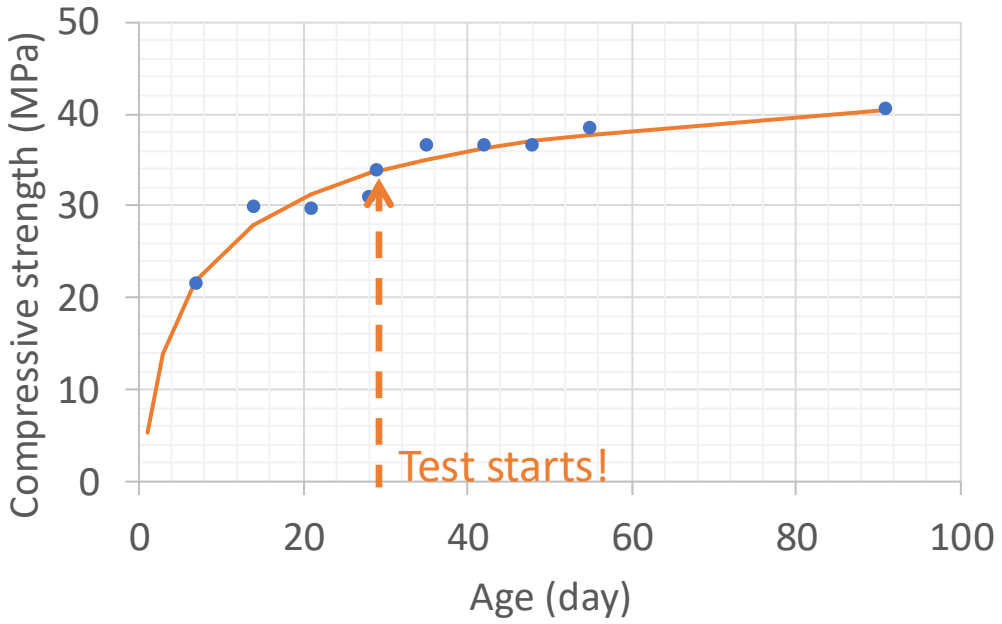


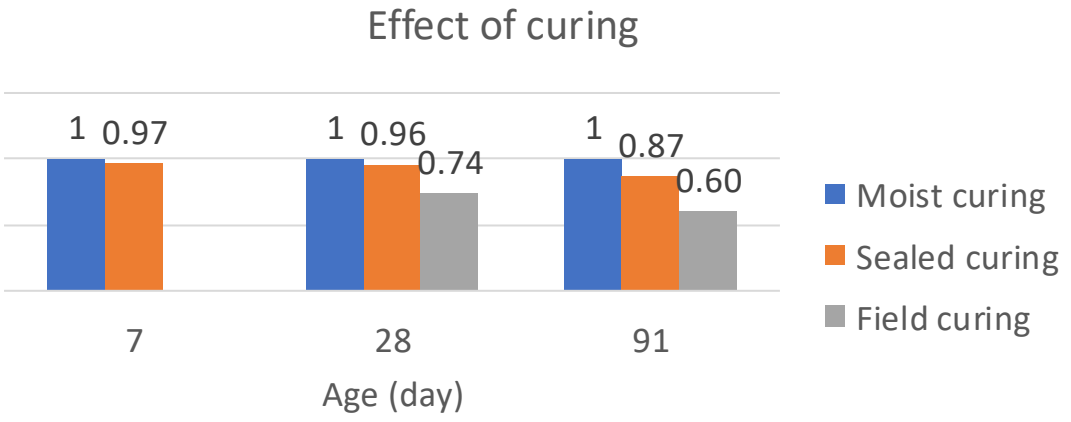


		Uncracked #1	Uncracked #2	Uncracked #3	Cracked #1	Cracked #2
Load		**3,059**	**3,186**	**3,615**	**3,325**	**3,478**
Disp.	LVDT	-	18.2	36.1	17.3	21.3
	Act.	28.8	30.0	45.4	25.4	30.2

Test Results

- Concrete compressive strength
  - 21 ready-mixed concrete trucks, each with 6m^3 capacity, were required to make specimens
  - Test cylinders from 1st, 5th, 10th, 15th truck
  - Average and standard deviation
    - Average – graph
    - Standard deviation: 0.42~2.84 MPa
  - Effect of curing
    - (ASTM E488) Cure concrete cylinders under the same environmental conditions as the test members.
    - Moist-curing and sealed curing better represent the interior of the block





Test Results

- Comparison of the test results with prediction for uncracked specimens
  - For prediction, EPRI model was used. ($N_{cb}(lb) = 4.4 {f_c}'^{\frac{3}{4}} h_{ef}^{1.6}$)
    - The most non-conservative prediction
  - Experimental values were at least 16% higher than the predicted values.
    - Moist-cured compressive strength of concrete at the time of testing is used.
    - When field-curing strength is used, the N_T is at least 55% higher than $N_{P,UC}$

Test No.	Crack	Compressive strength (MPa)	Test, N_T (kN)	Prediction, $N_{P,UC}$ (kN) (by EPRI)	Test/Prediction (N_T / $N_{P,UC}$)
#1	Uncracked	33.4	3,059	2,625	1.165
#2		35.0	3,186	2,716	1.173
#3		36.2	3,615	2,785	1.298

Robustness of Deeply Embedded Anchors

- Deeply embedded cast-in-place anchors maintained almost 100% of their original tensile capacity in cracked concrete. (Negligible crack effect)
- Compared to relatively shallow CIP anchors, deep embedment provides significantly higher robustness.
  - Current codes capacity reduction factors: 0.8 in ACI 318; 0.7 in fib Model Code

Test No.	Crack	Compressive strength (MPa)	Test, N_T (kN)	Prediction, $N_{P,UC}$ (kN) (by EPRI)	Test/Prediction (N_T / $N_{P,UC}$)
#1	Uncracked	33.4	3,059	2,625	1.165
#2		35.0	3,186	2,716	1.173
#3		36.2	3,615	2,785	1.298
#4	Cracked	37.0	3,325	2,833	1.174
#5		37.8	3,478	2,879	1.208

Modification of Prediction Model

- Prediction model update
  - By adjusting several coefficients while maintaining it as a function of f_c and h_{ef}
  - The exponent for f_c: related to the elastic modulus and fracture energy
  - The exponent for h_{ef}: related to the size effect
  - Regression parameters A and B for $N_{cb} = A{f_c}'^{0.5} h_{ef}^{B}$

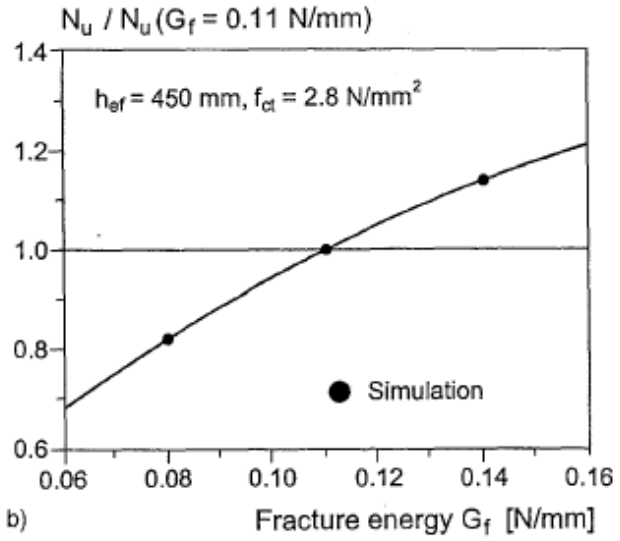
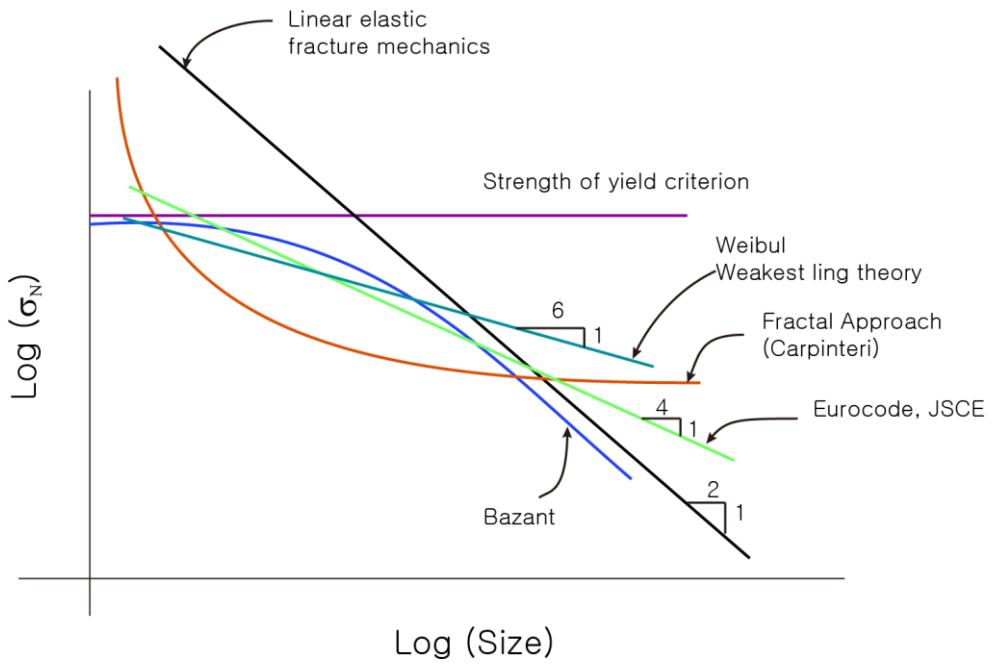
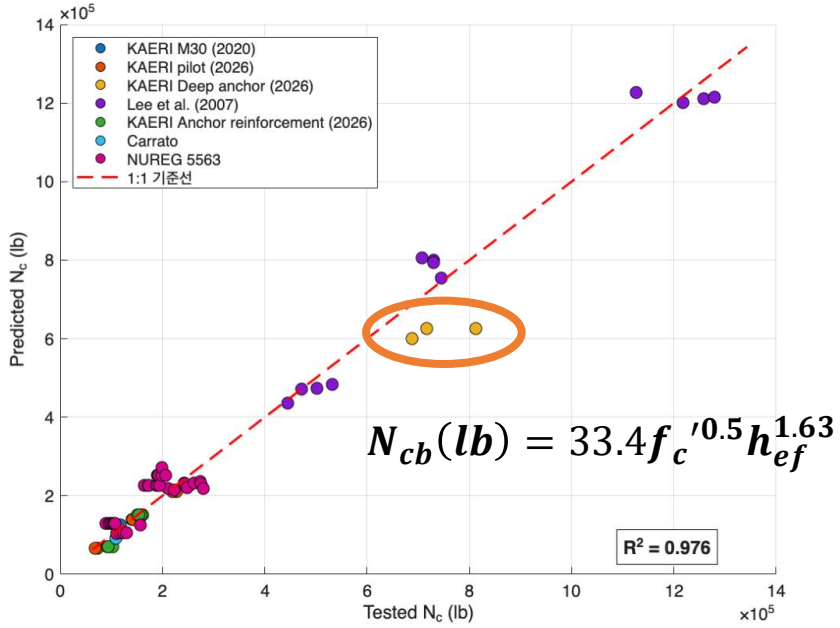


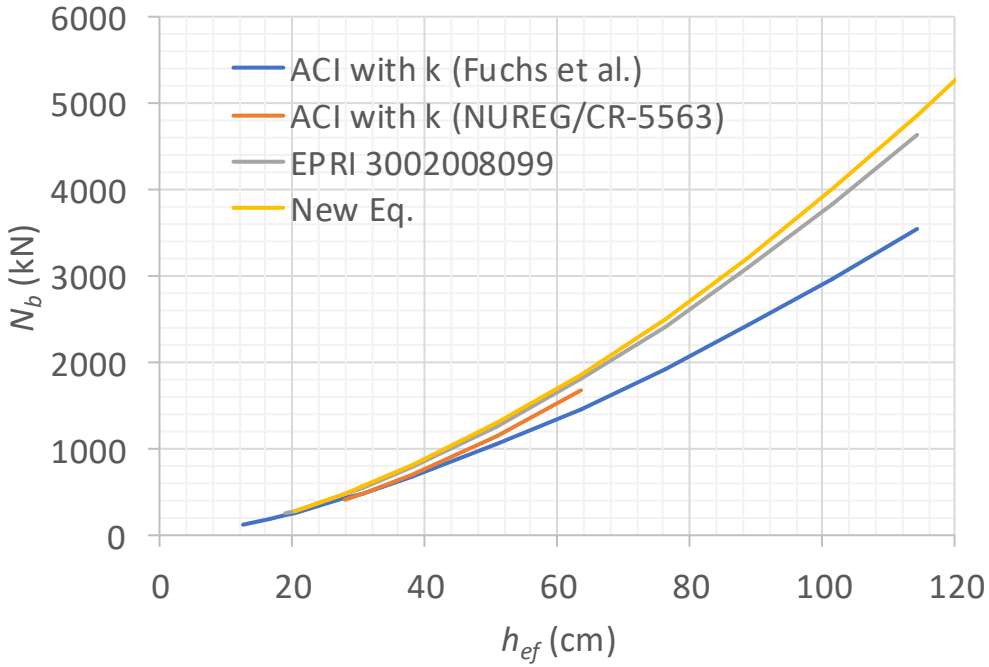
Fig. 3.18 Normalised failure load as a function of (a) concrete tensile strength and (b) concrete fracture energy (*Ozbolt* (1995))



Modification of Prediction Model

- Preliminary modification
  - By combining our new test data with existing data for h_{ef} over 30 cm
  - Data set is still quite small, the prediction from the modified model did not change drastically
- Final update: by incorporating results from numerical parametric studies in the future.





Conclusions

- A large-scale test specimen consisting of a deeply embedded CIP anchor and a concrete block was designed and tested to investigate the concrete breakout strength under tensile loading.
- Results from the uncracked concrete specimens revealed that the experimental concrete breakout strengths exceeded the predicted values by 16% to 30%, indicating that current predictive models yield conservative estimates for deeply embedded CIP anchors.
- Compared to relatively shallow CIP anchors, deep embedment provides significantly higher robustness.
- The findings are expected to contribute to improving prediction models for deeply embedded CIP anchors and to provide fundamental data for seismic fragility of safety-related equipment in nuclear power plants.