Experimental Evaluation of Effects of Dead Loads on Capacities of Anchors in Shear Induced by Earthquake in Highway Bridge

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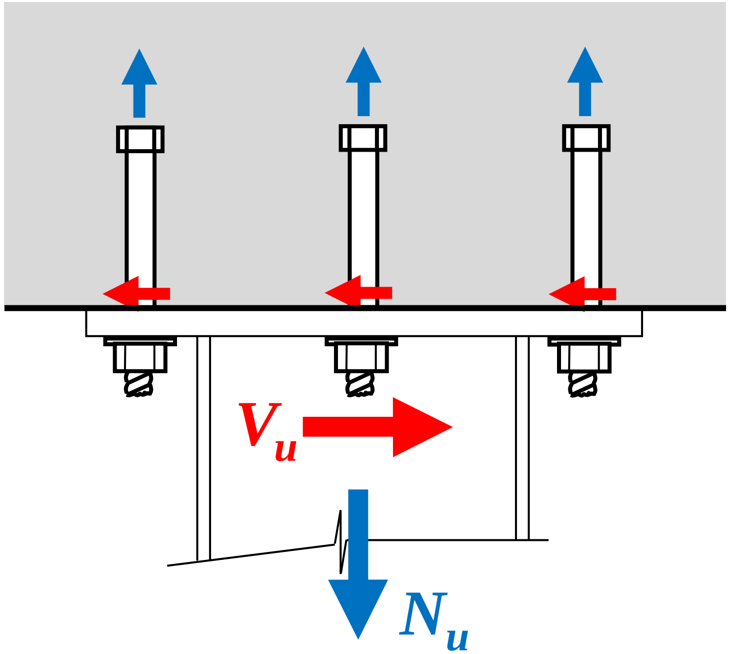
ACI 318-19: Tension and shear interaction



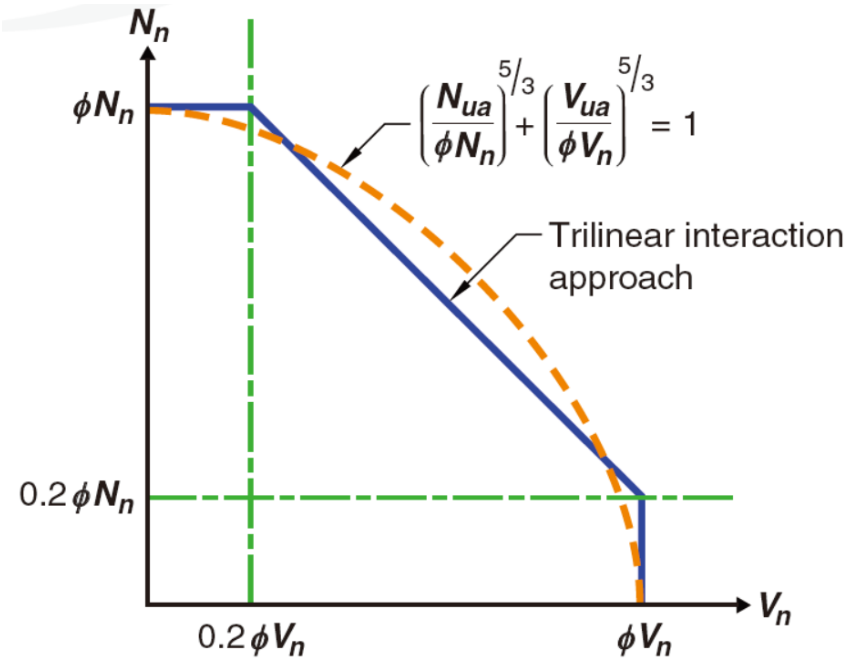
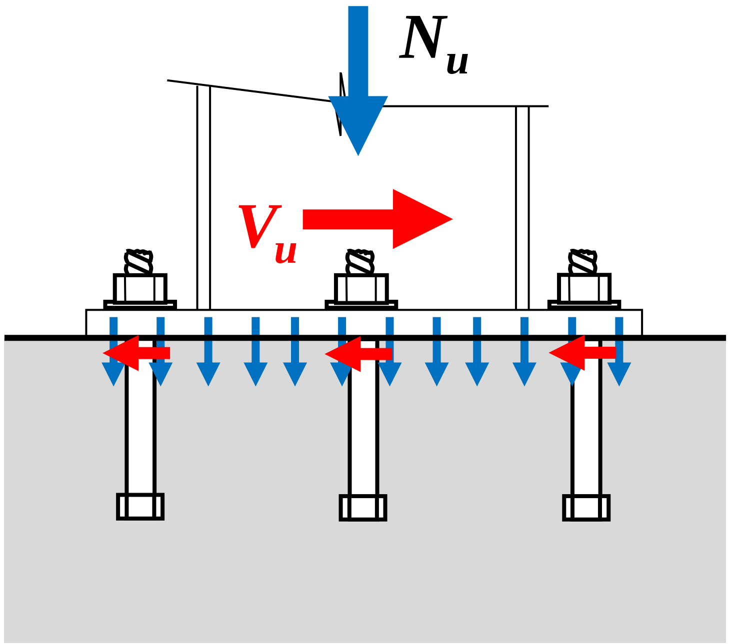


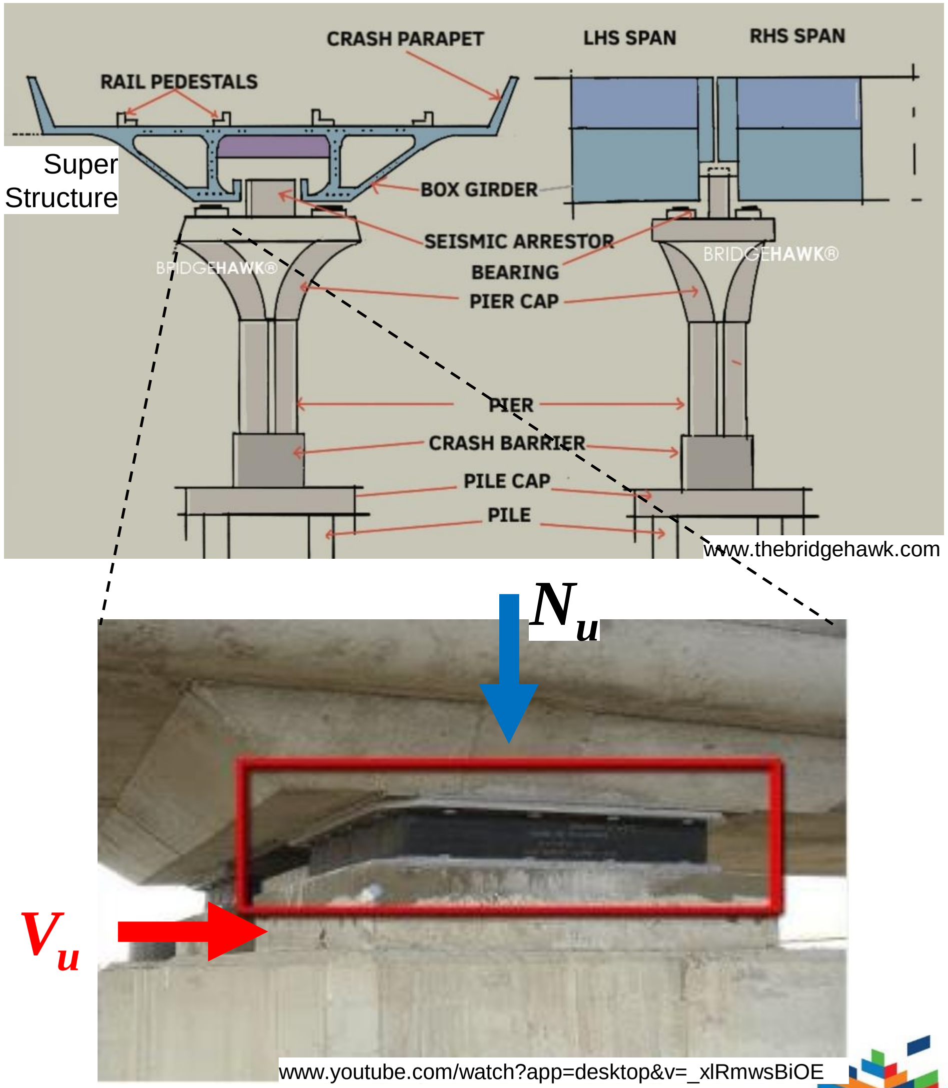
Fig. R17.8—Shear and tensile load interaction equation.

- Axial tension reduces the shear strength.

$$\frac{N_{ua}}{\phi N_n} + \frac{V_{ua}}{\phi V_n} \leq 1.2$$

How about Compression?

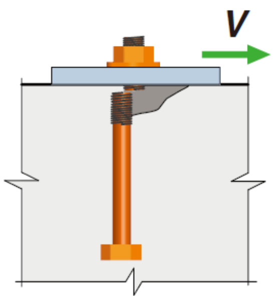




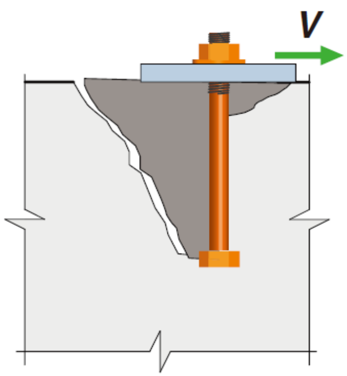
- Does axial compression decrease or increase the shear strength?
- Axial compression may enhance the shear strength.
- Due to gravity loads, permanent axial compression is applied to the base plate.

ACI 318-19: Anchors in shear

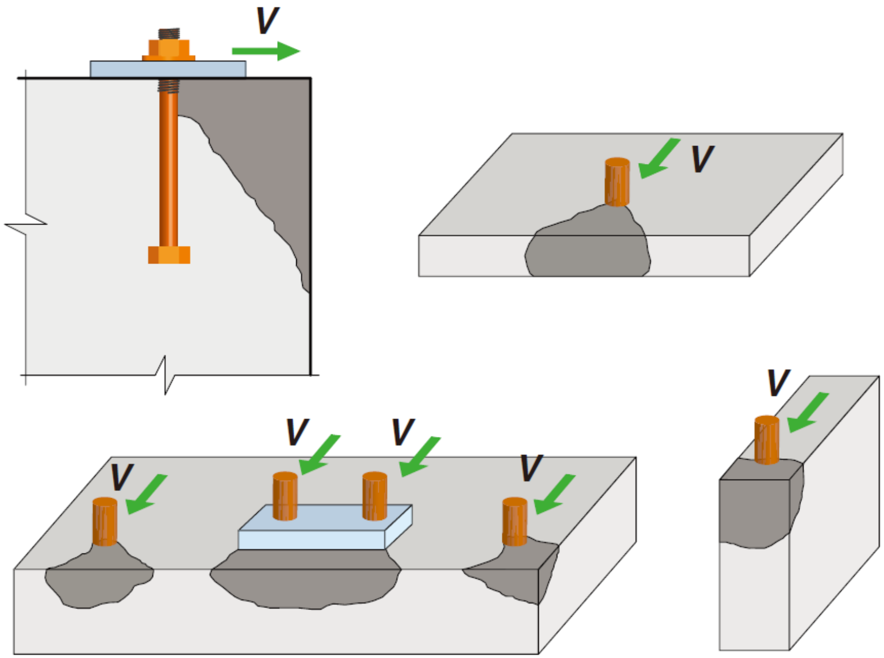
Failure modes



(i) Steel failure preceded by concrete spall



(ii) Concrete pryout for anchors far from a free edge

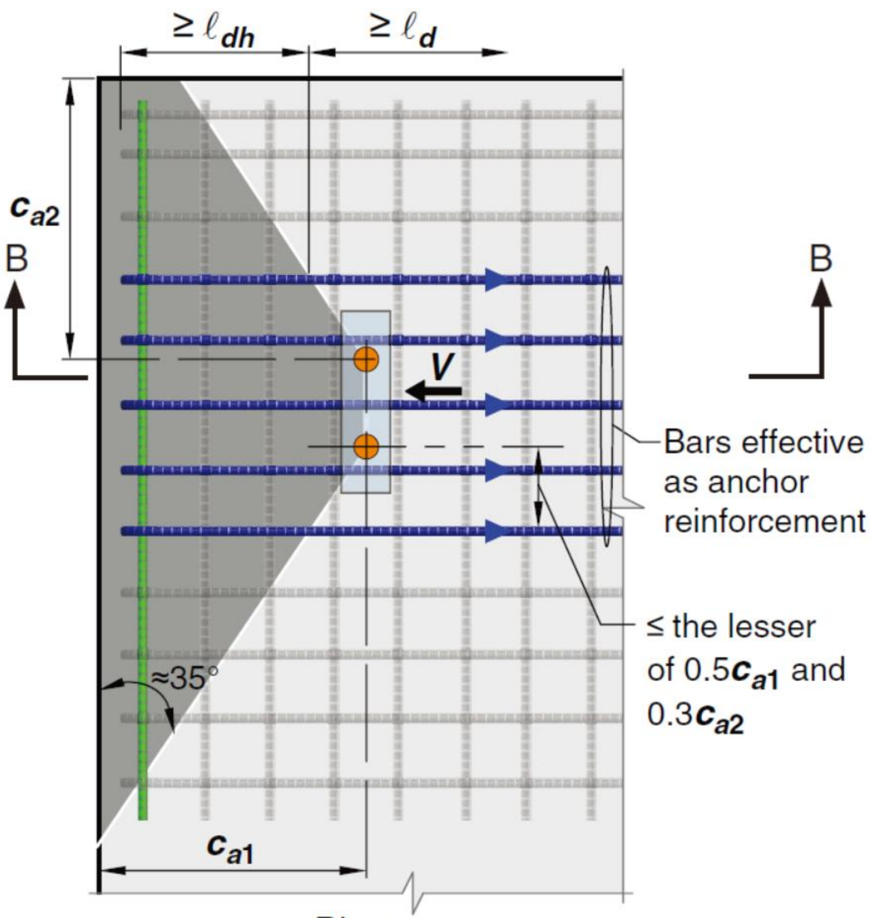


(iii) Concrete breakout

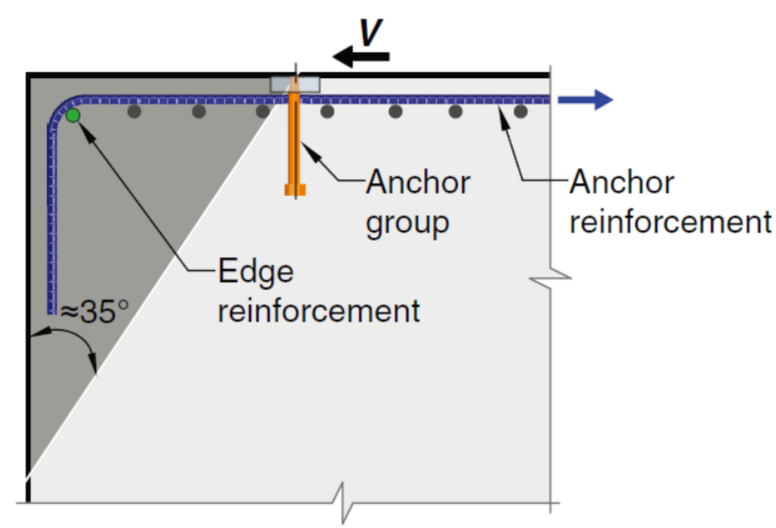
ACI 318-19: Anchors in shear

Anchor Reinforcement

- Anchor reinforcement strength can be used instead of the concrete breakout strength.



Plan



Section B-B

ACI 318-19: Anchors in shear

Nominal & Mean strengths

$$V_n = \max\left(V_{cbg}, V_{ar}\right)$$

- Concrete breakout strength
- Anchor reinforcement strength

$$V_{cbg} = \frac{A_{Vc}}{A_{Vco}} \psi_{ec,v} \psi_{ed,v} \psi_{c,v} \psi_{h,v} V_b$$

$$V_{ar} = A_s f_y$$

$$V_b = 0.6 \left(\frac{l_e}{d_a}\right)^{0.2} \sqrt{d_a} \sqrt{f_{ck}} \left(c_{a1}\right)^{1.5} \leq 3.7 \sqrt{f_{ck}} \left(c_{a1}\right)^{1.5}$$ (SI unit)

<u>Mean strength (CCD method)</u>

$$V_{bo} = 1.8 \times 0.6 \left(\frac{l_e}{d_a}\right)^{0.2} \sqrt{d_a} \sqrt{f_{ck}} \left(c_{a1}\right)^{1.5} \leq 1.8 \times 3.7 \sqrt{f_{ck}} \left(c_{a1}\right)^{1.5}$$ (SI unit)

$$V_{cbgo} = \frac{A_{Vc}}{A_{Vco}} \psi_{ec,v} \psi_{ed,v} \psi_{c,v} \psi_{h,v} V_{bo}$$

Shear strength of compression member

ACI 318-19 (22.5.5.1)

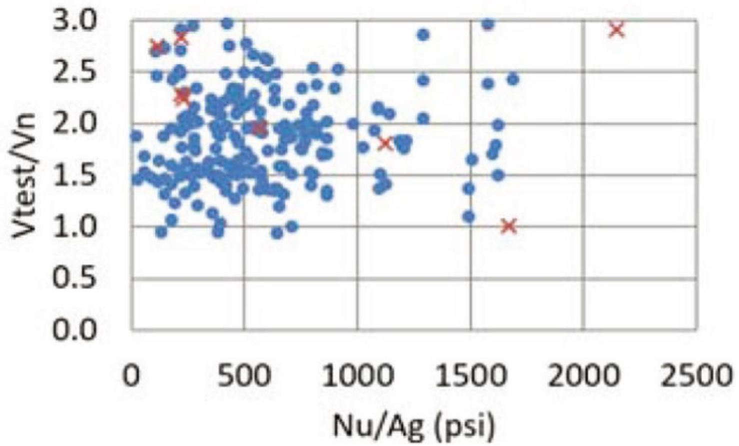
$$V_c = \left(0.17\sqrt{f_{ck}} + \frac{N_u}{6A_g}\right) b_w d$$

$$= \left(1 + \frac{N_u}{6A_g\left(0.17\sqrt{f_{ck}}\right)}\right) 0.17\sqrt{f_{ck}}\, b_w d$$

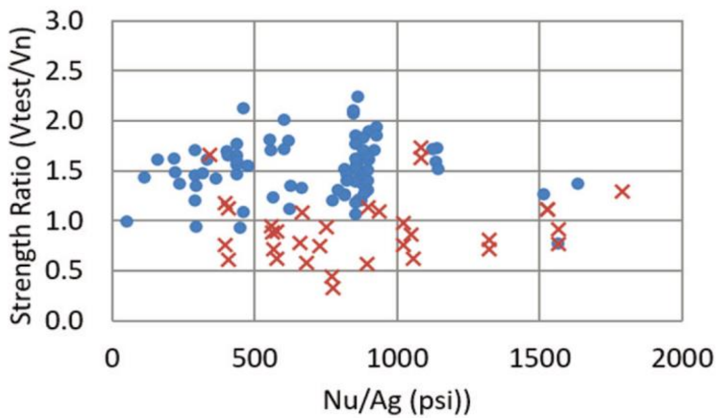
$$= \left(1 + \frac{0.17 N_u}{V_{co}}\right) V_{co}$$

(SI unit)

- The shear strength is enhanced due to the compression, and this effect has been verified through numerous tests.



(a) Without shear reinforcement

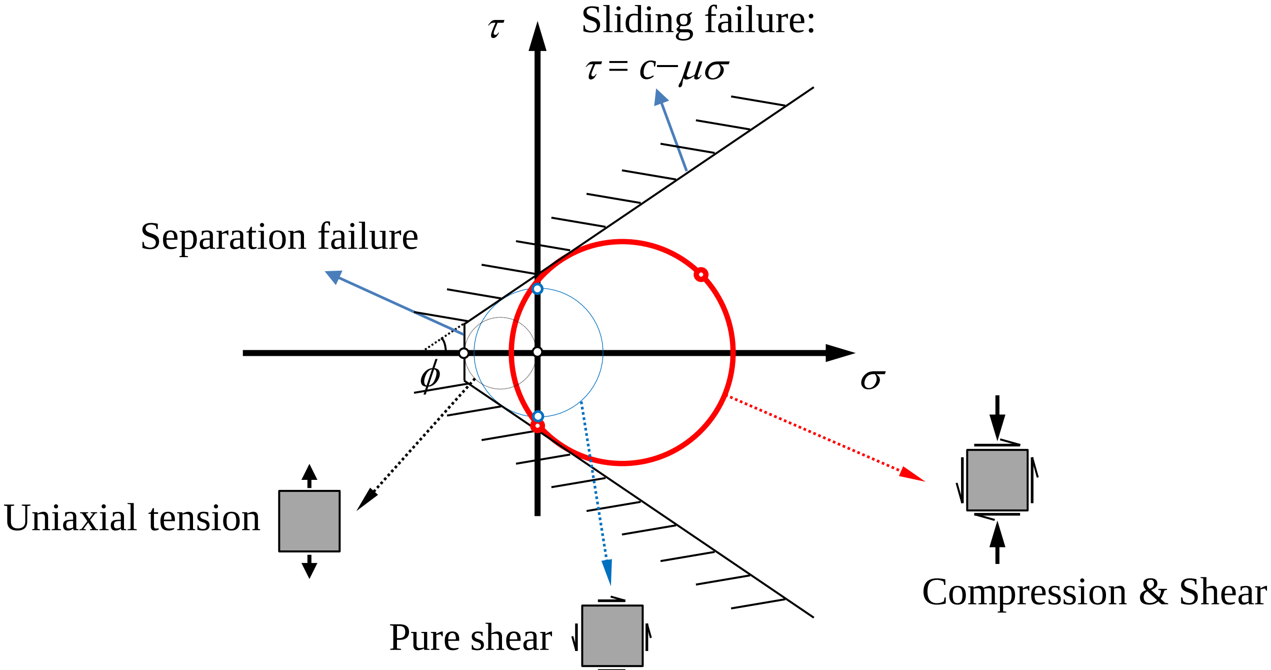


(b) With shear reinforcement

*Development of the One-Way Shear Design Provisions of ACI 318-19 for Reinforced Concrete (Kuchma et al., 2019)

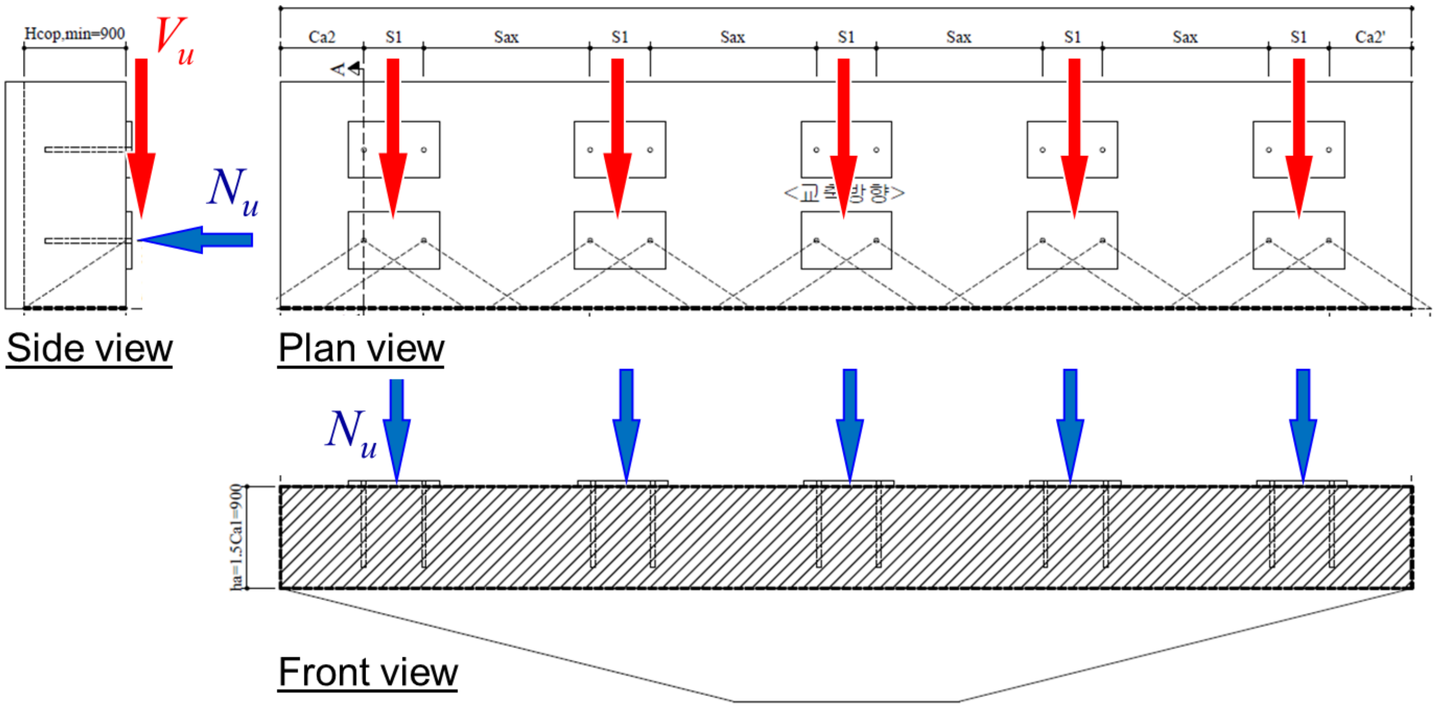
Shear strength of compression member

Modified Coulomb Yield Criteria



- Coulomb yield criteria of concrete plasticity theoretically explains the increased capacity of concrete under a combination of compression & shear.

Research purpose



- An axial compression force due to the self-weight of the super structure is usually applied to the bearing pad. Even when an earthquake induces shear force on the anchors, the bearing pads are subjected to axial compression.
- Main purpose: To experimentally evaluate the enhanced concrete breakout capacity of anchors under shear & compression.

Test Program: Test matrix

- A total of 30 specimens
- Eight series
- Anchor shaft diameter: 60mm
- Number of anchors per specimen: 2EA

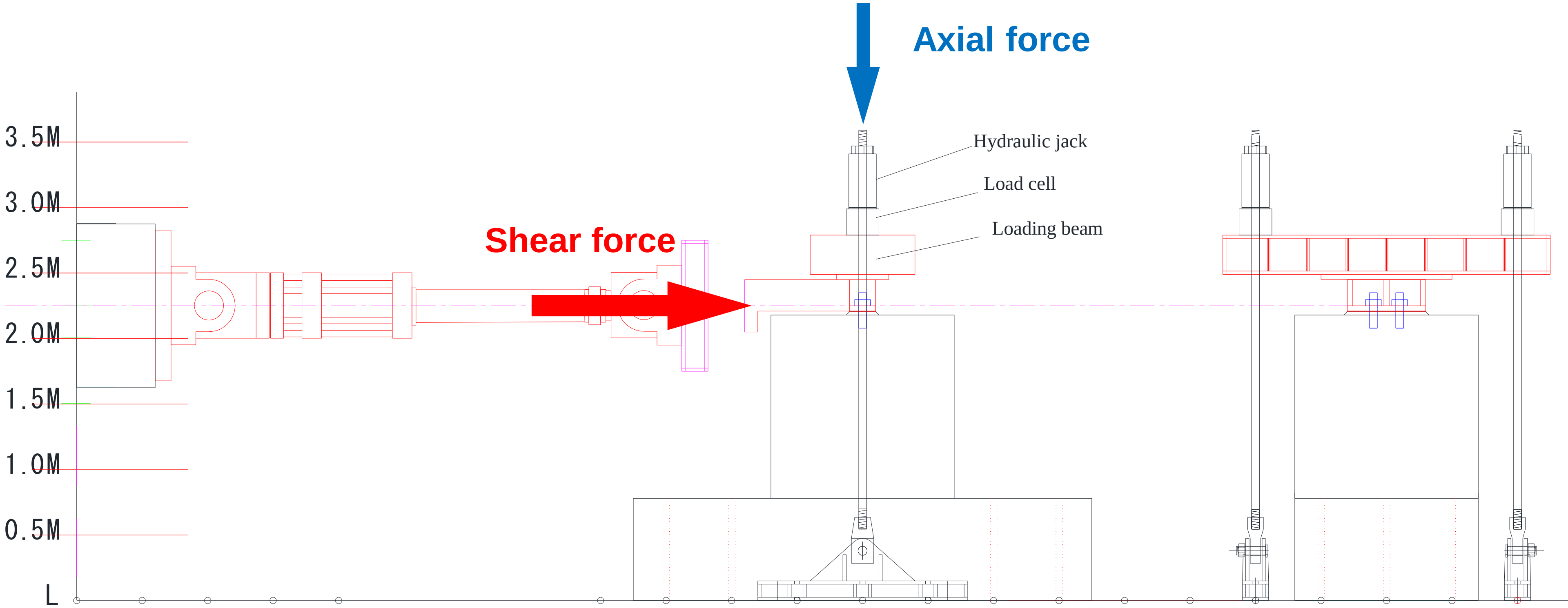
Test variables

- Axial compression: up to $3.5V_{cbgo}$
- Existence of anchor reinforcement
- Edge distance c_{a1} in the direction of the applied shear
- Edge distance c_{a2} in the direction perpendicular to c_{a1}

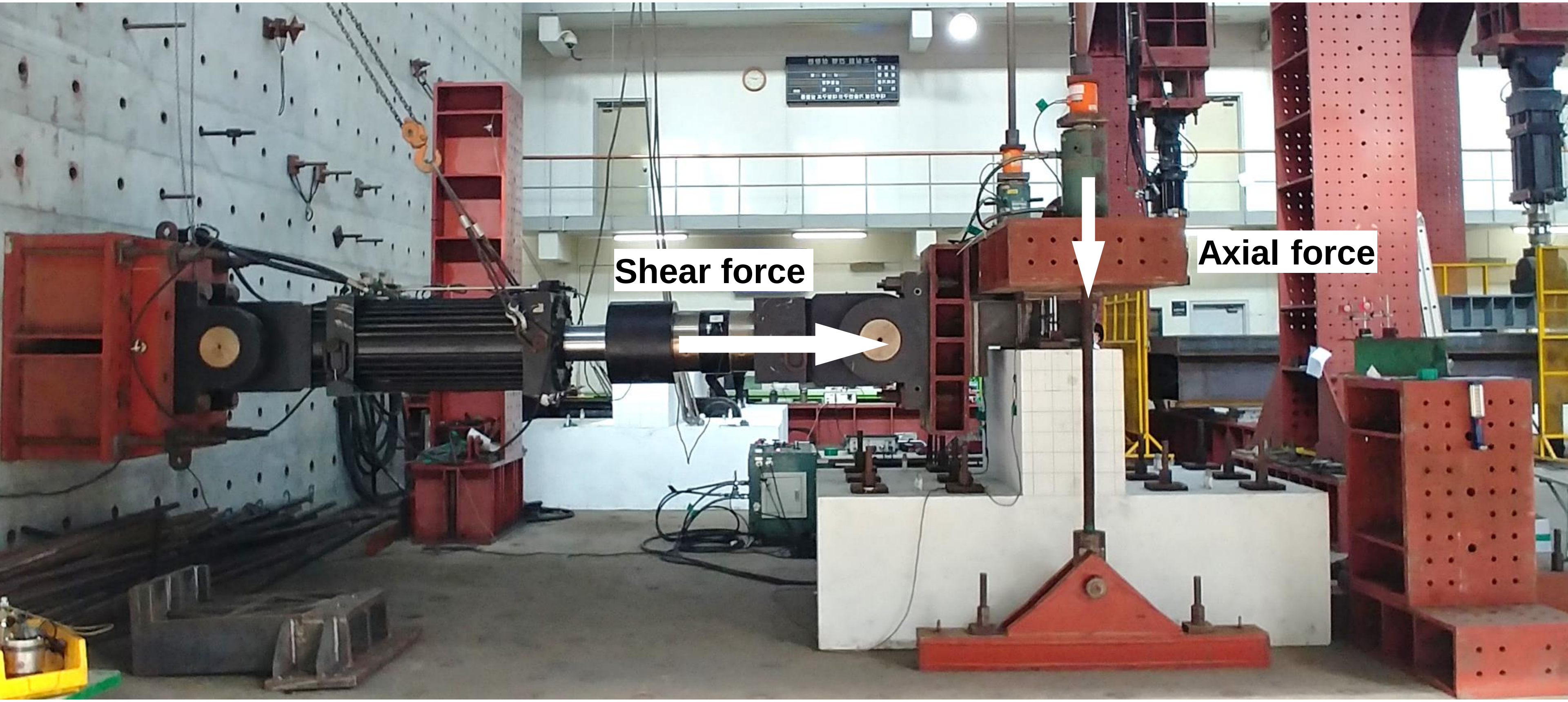
Specimens	V_{cbgo}	V_{ar}	max (V_{cbgo}, V_n)	N	N/V_{cbgo}	V_p/V_{cbgo}
CB-0	260.1		260.1	0	0	1.0
CB-N250	260.1		260.1	250	1.0	1.6
CB-N500	260.1		260.1	500	1.9	2.2
CP-0	361.1		361.1	0	0	1.0
CP-N225	361.1		361.1	225	0.6	1.4
CP-N450	361.1		361.1	450	1.2	1.7
C40-LS-AR-D0	440.9	843.3	716.3	0	0	1.9
C40-LS-AR-D0.6	440.9	843.3	716.3	264.5	0.6	1.9
C40-LS-AR-D0.8	440.9	843.3	716.3	352.7	0.8	1.9
C40-LS-AR-D2.0	480.6	843.3	716.3	961.2	2.0	2.2
C24-L-AR-D0	475.3	684.0	573.0	0	0	1.4
C24-L-AR-D0.5	475.3	684.0	573.0	237.7	0.5	1.4
C24-L-AR-D1.7	404.6	684.0	684.0	684.0	1.7	2.0
C24-L-AR-D2.5	404.6	684.0	684.0	1026.0	2.5	2.5
C40-L-N-D0	652.8		652.8	0	0	1.0
C40-L-N-D0.5	647.4		580.8	323.7	0.5	1.3
C40-L-N-D2.5	647.4		580.8	1618.6	2.5	2.5
C40-L-N-D2.0	652.8		652.8	1305.6	2.0	2.2
C40-L-AR-D0	622.0	803.1	803.1	0	0	1.3
C40-L-AR-D0.3	641.3	843.3	716.3	192.4	0.3	1.3
C40-L-AR-D1.3	622.0	803.1	803.1	803.0	1.3	1.8
C40-L-AR-D2.5	641.3	843.3	716.3	1603.3	2.5	2.5
C24-T-AR-D0	339.5	684.0	573.0	0	0	2.0
C24-T-AR-D0.5	339.5	684.0	573.0	169.7	0.5	2.0
C24-T-AR-D1.5	343.2	684.0	573.0	514.8	1.5	2.0
C24-T-AR-D3.5	343.2	684.0	573.0	1201.3	3.5	3.1
C40-T-AR-D0	441.1	843.3	716.3	0	0	1.9
C40-T-AR-D0.5	441.1	843.3	716.3	220.6	0.5	1.9
C40-T-AR-D1.6	494.0	803.1	803.1	803.0	1.6	2.0
C40-T-AR-D3.4	470.7	803.1	803.1	1606.0	3.4	3.0

(SI unit)

Test Program: Test setup

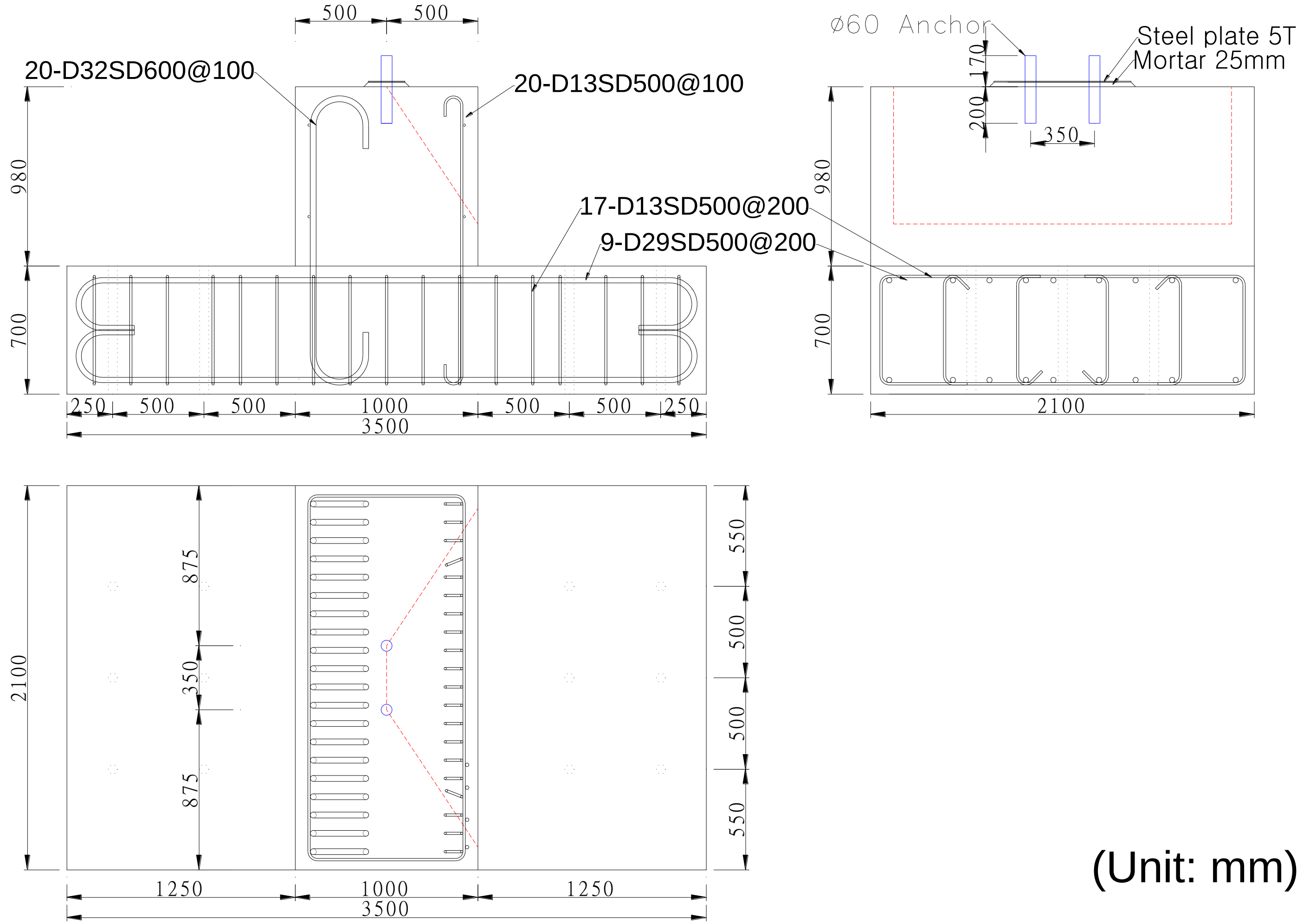


Test Program: Test setup



Test Program: Specimens

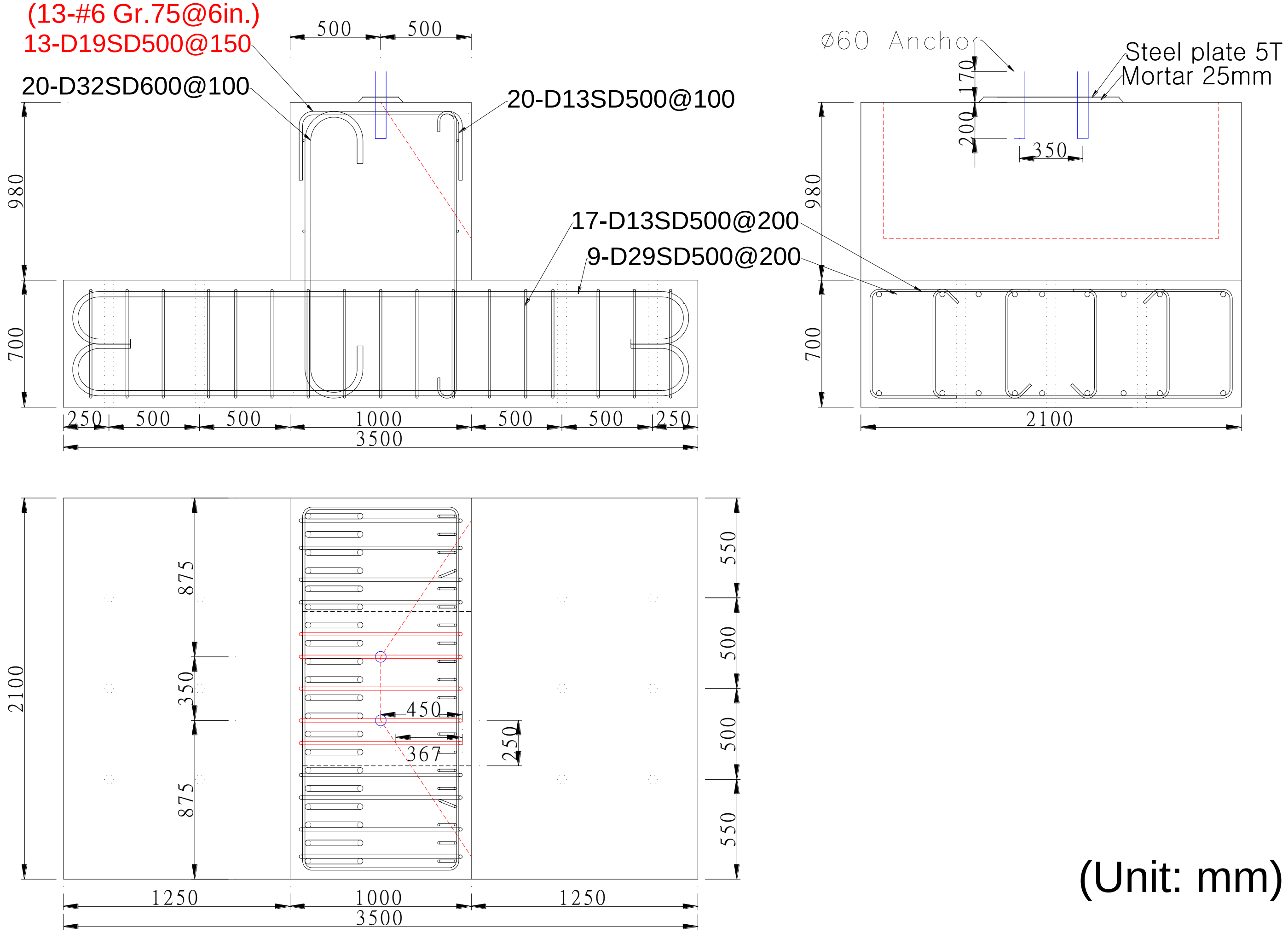
Unconfined specimen



(Unit: mm)

Test Program: Specimens

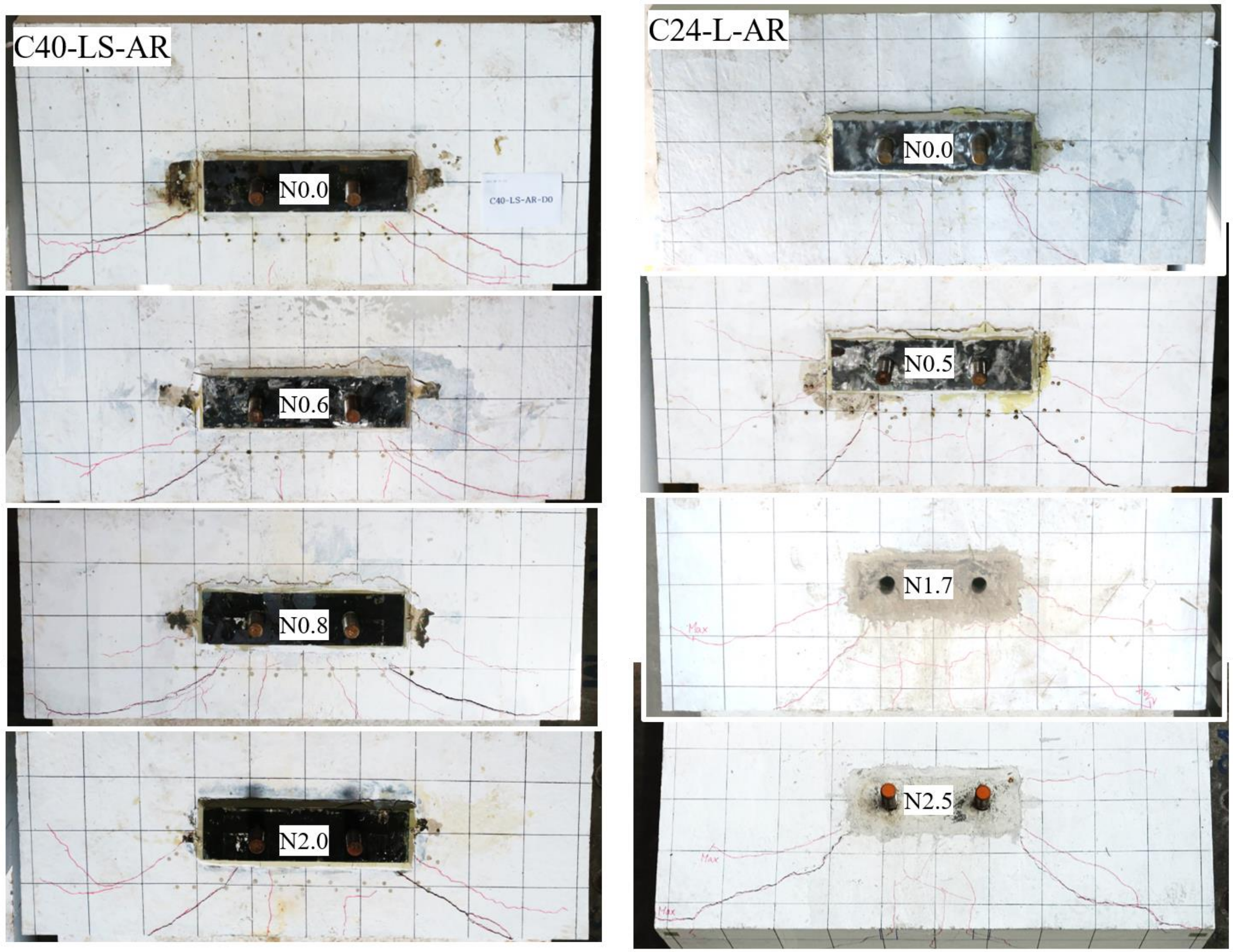
Confined specimen by anchor reinforcement



(Unit: mm)

Test results: Failures

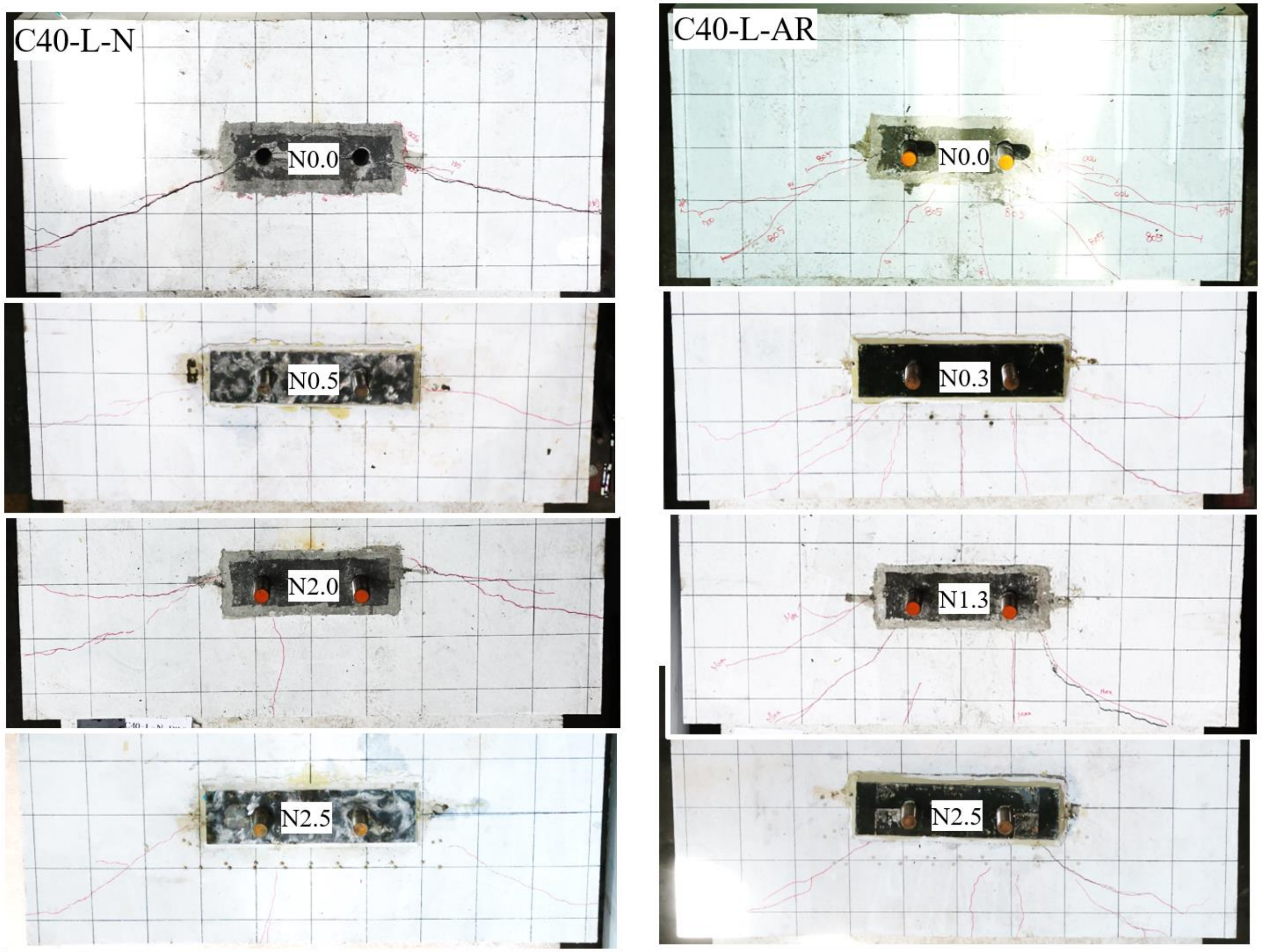
Plan views (1/2)



Axial compression N_u increases

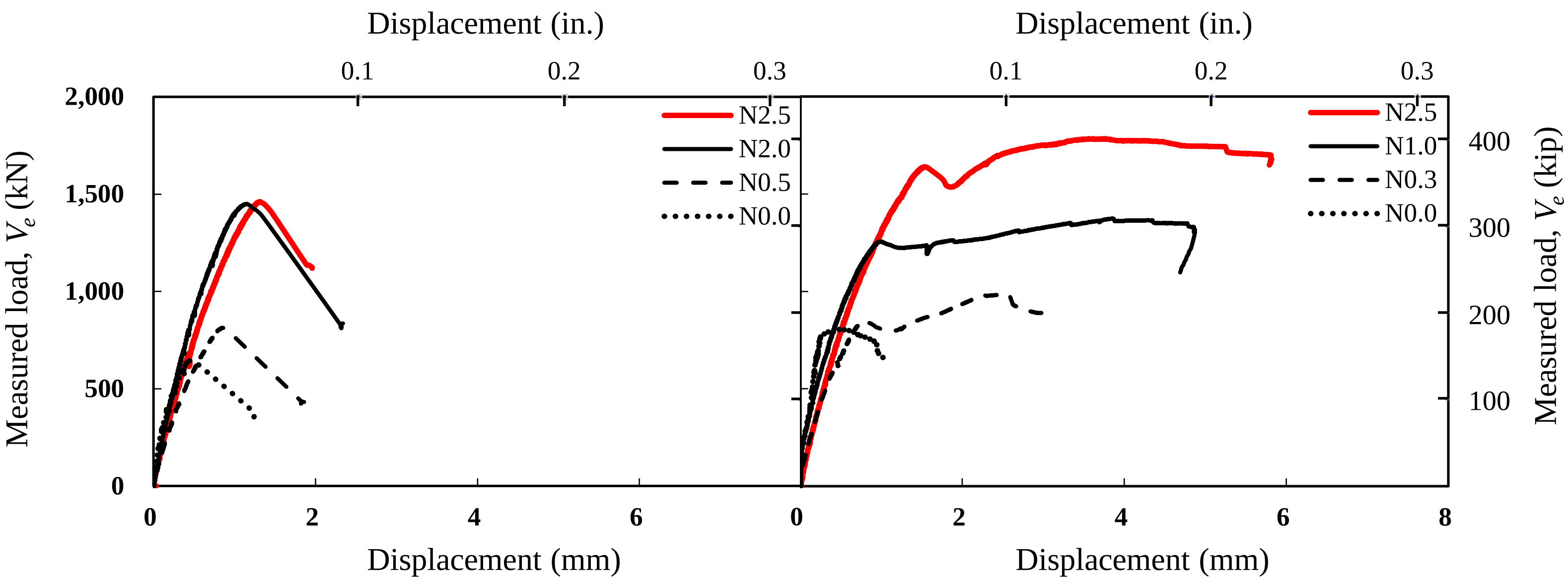
Test results: Failures

Plan views (2/2)



Test results: Load-displacement

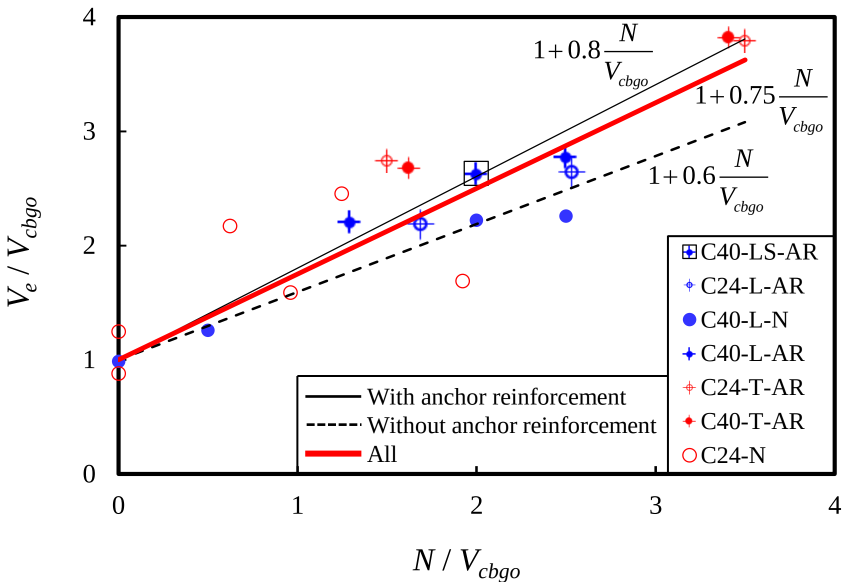
Unconfined specimen | **Confined specimen**



C40-L-N-series | C40-L-AR-series

Predicted strength

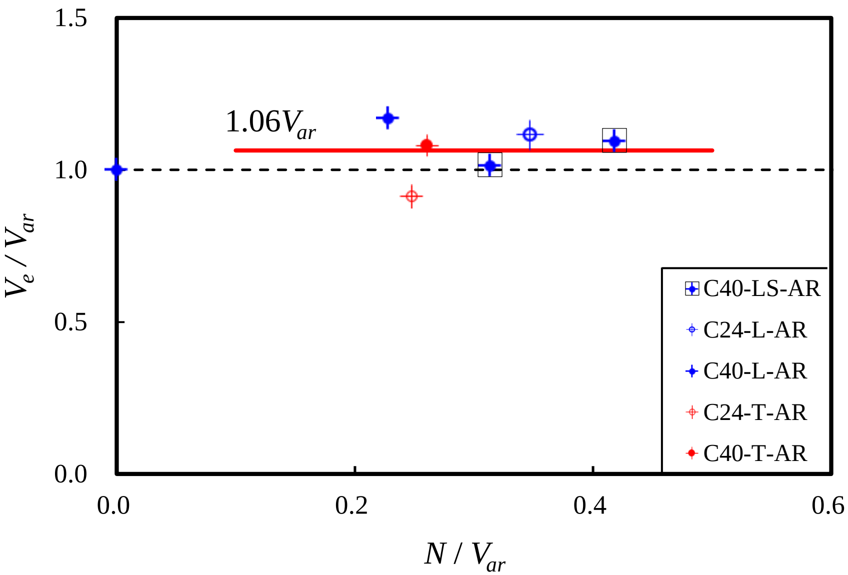
Breakout failure (n=16)



$$V_{cbgp} = V_{cbgo} + 0.75N$$

- As the applied axial forces increase, the concrete breakout strengths linearly increase.
- The increment of anchors confined by anchor reinforcement is higher than unconfined anchors by 33%.

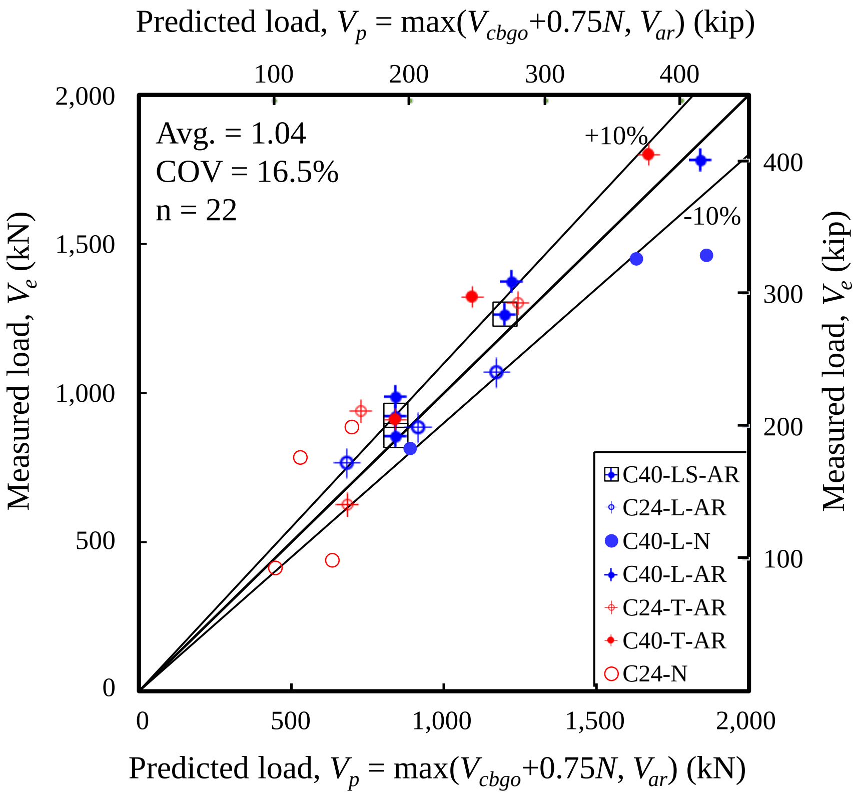
Anchor reinforcement (n=6)



$$V_{arp} = V_{ar}$$

- The axial forces enhanced the strengths by anchor reinforcement.
- However, the increments are not proportional to the applied axial forces.
- For 6 specimens, the average increment is only 6%.

Comparison of tests to predictions



$$V_p = \max\left(V_{cbgo} + 0.75N, V_{ar}\right)$$

- The average and COV values of the test-to-prediction ratios are 1.04 and 16.5%, respectively.
- The COV value is comparable to that of the CCD method (ACI 318 provisions).

Conclusions

1. The concrete breakout strengths of anchors in shear can be enhanced by axial compression.
2. The increment of the concrete breakout strength is 75% of the axial compression, on average of 16 specimens.
3. The anchor reinforcement strength increased slightly with axial compression.
4. From the test results, an equation to predict enhanced shear strength by axial compression was proposed. The COV of the test-to-prediction ratios of 22 specimens is comparable to that of the CCD method.

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Thank you !!

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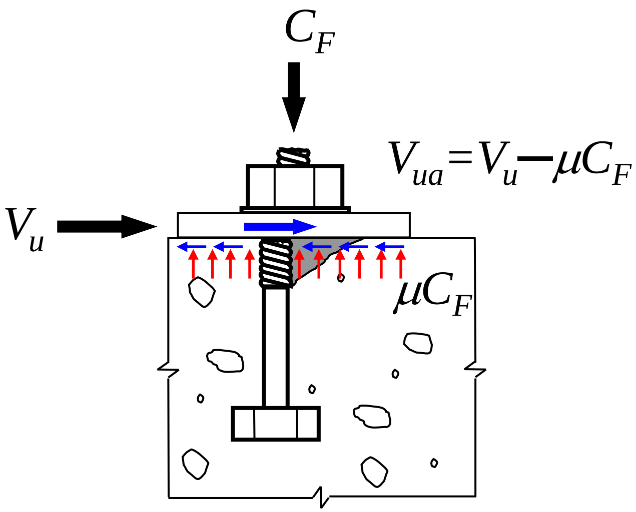
Anchors in shear & compression

Steel strength ACI 349-13

D.6.1.4 Friction between the baseplate and concrete shall be permitted to be considered to contribute to the nominal steel shear strength of the anchor in shear. The nominal shear strength resulting from friction between the baseplate and concrete—that is, without any contribution from anchors—shall be taken as $0.40C_F$.

- Compression concurrent with shear the shear force induces the friction force between the base plate and concrete.
- The shear resistance is a combination of friction strength and shear strength.
- The coefficient of friction is approximately 0.4. Therefore, if the compression is greater than 2.5 times of shear force, the base plate will not slip.



Failures

Plan views (3/3)