Collapse of Older RC Frames during Earthquakes

– Ongoing Project and Joint Strength Estimation

A Collaborative Study: UBC / NCREE / PEER

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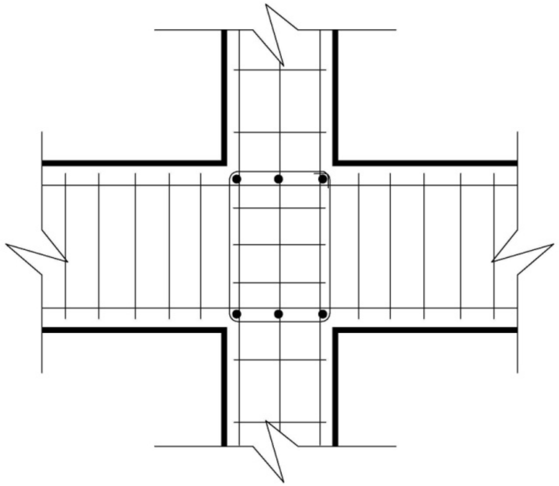


Ongoing Project

- Scheduling
- Proof Tests
- Constant Axial Load Applying System
- Lead Weight Fixture

Scheduling

Activity	Jul		Aug		Sep		Oct		Nov		Dec	
Construction of RC frame specimen												
Construction of steel supporting frame												
Proof tests for high axial load applying system												
Shake table tests												

Proof Tests

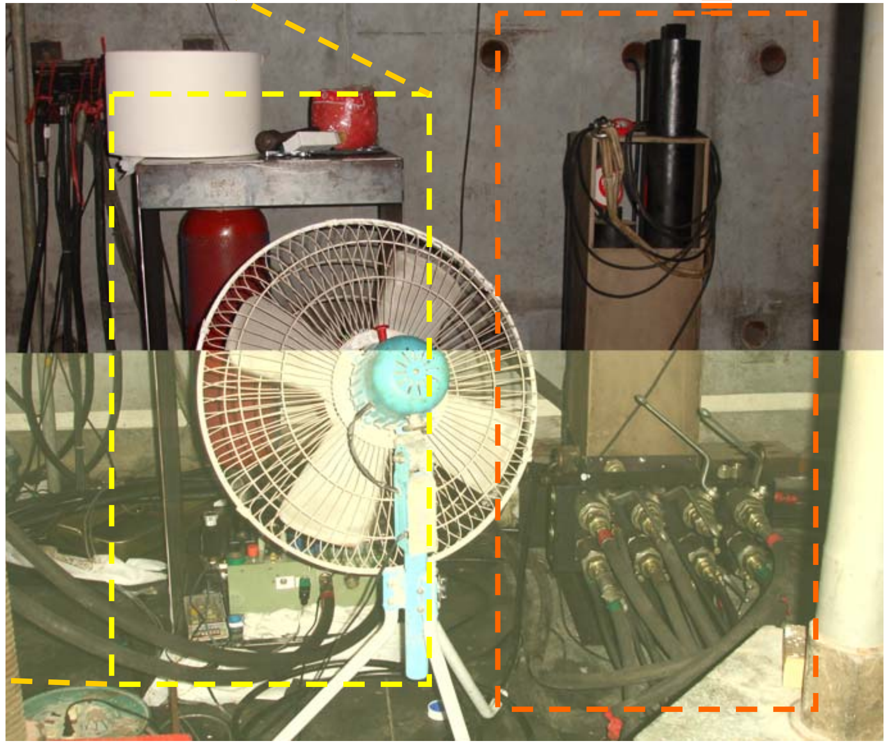
(1) Cross-sectional area of column: 20cmx40cm
(2) 100cm clear column height
(3) Flexure, and flexure-shear failures

embedded PVC sleeves for bolting lead packets

4 embedded bolts for connecting axial load applying system to the column

Purposes of single column tests:
(1) Performance verification of high axial load applying system
(2) Performance verification of lead weight fixture mechanism

Constant Axial Load Applying System



MTS Pumping System
(e.g., 200kgf/cm^2)

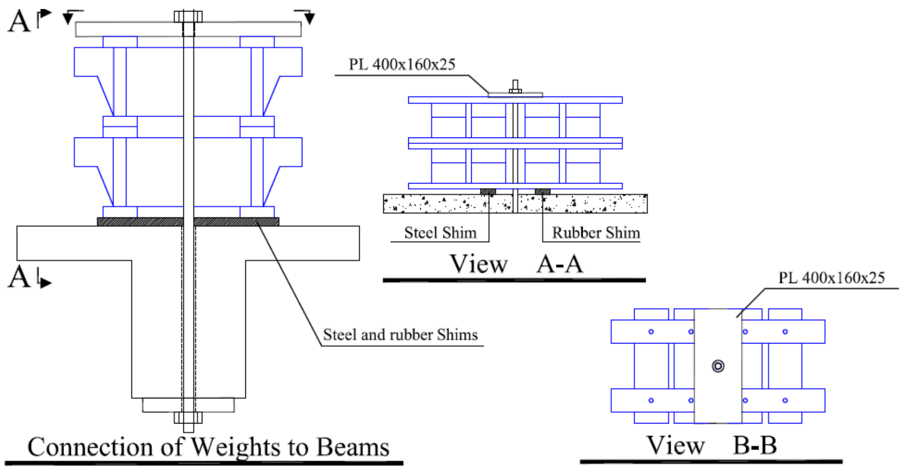
Pressure reducing valve

Pressure reducing and relieving valve
(fine tuning to keep a constant pressure at 150kg/cm^2 level to minimize the influence from column lengthening/shortening)

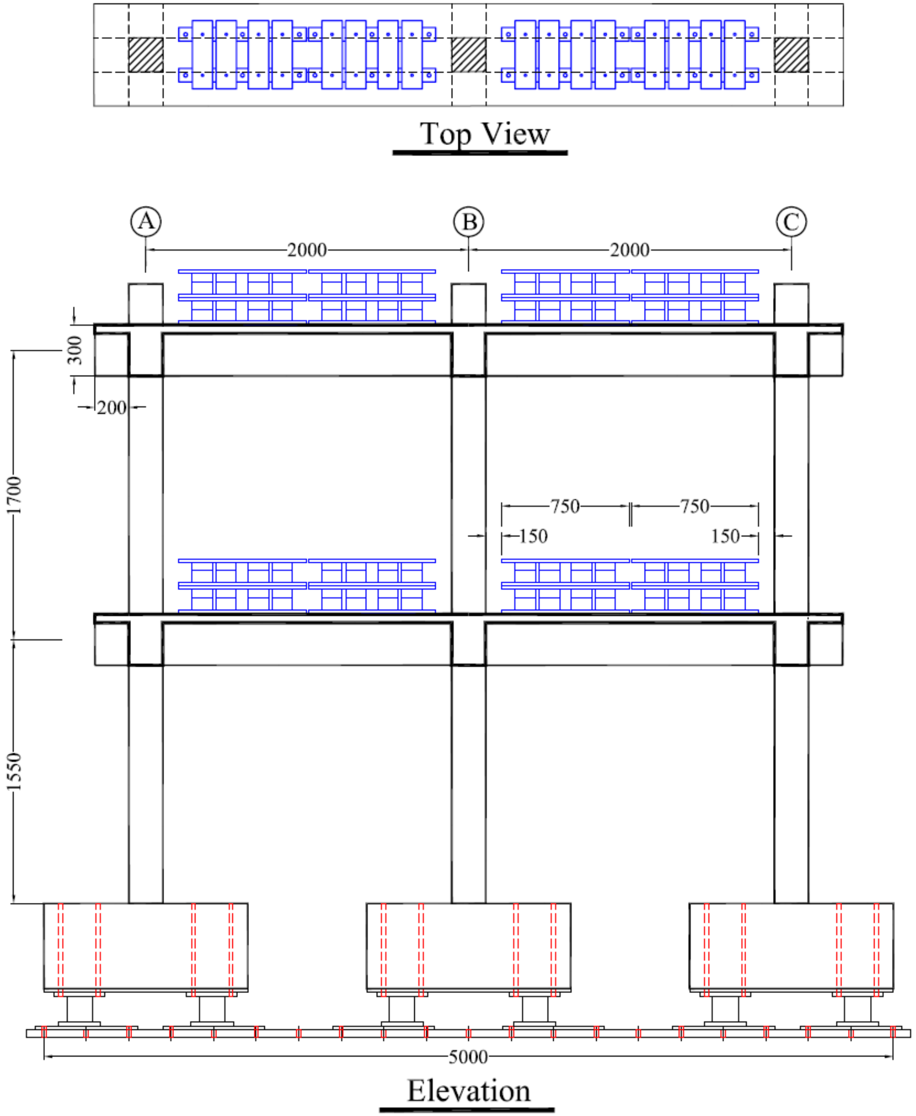
Performance requirements:

- ✓ No more than 10% pressure loss in cylinder under a vertical setback of 25mm
- ✓ Synchronizing valves to ensure simultaneous axial load applications

Lead Weight Fixture



prestressing rod + steel shim + rubber shim

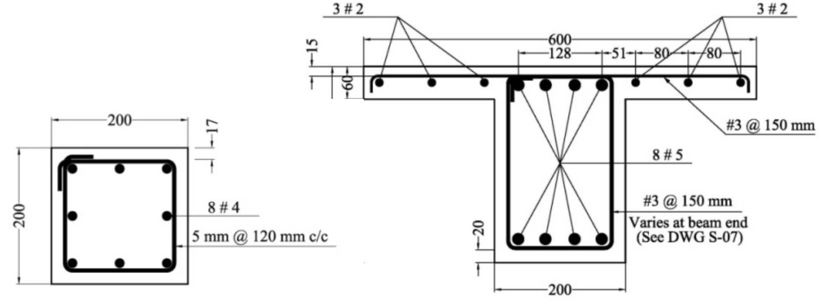


Joint Strength Estimation

- Demand Analysis
- Strength Analysis (ACI 318)
- Strength Analysis (SST)
- Discussion

Demand Analysis

Demand Analysis



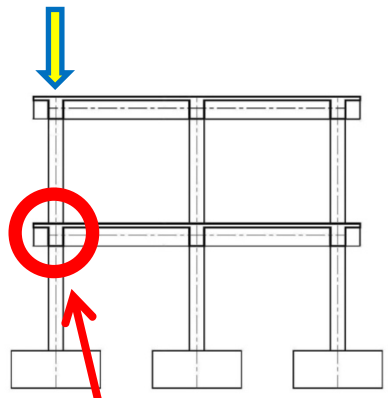
Column Section C-C

Beam Section A-A (First Level)

Beam

Analysis

$0.175P_0$



Joint A1

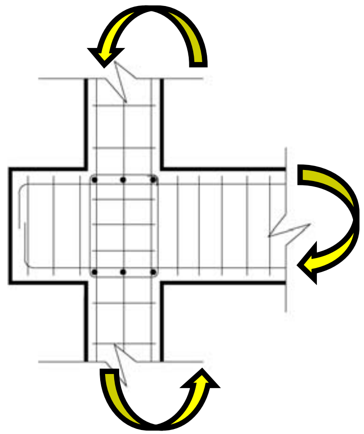
$M_{nb} = 135kN\text{-}m$

P-M curve

Analysis

M_{nc}

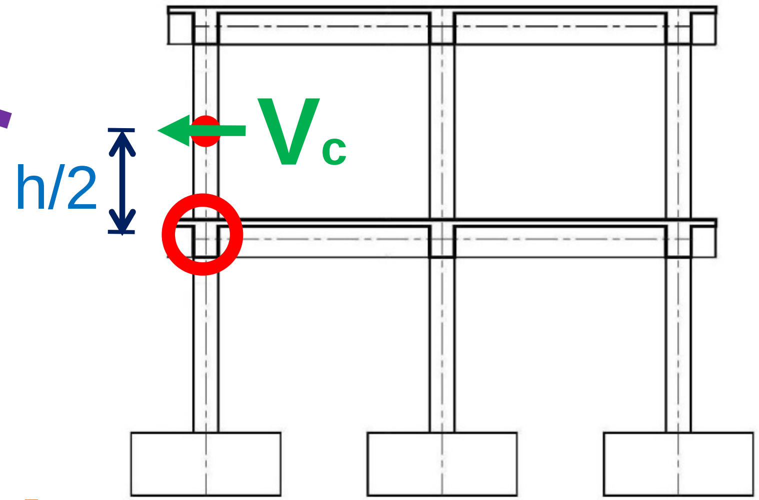
$M_{nc} = 46kN\text{-}m$

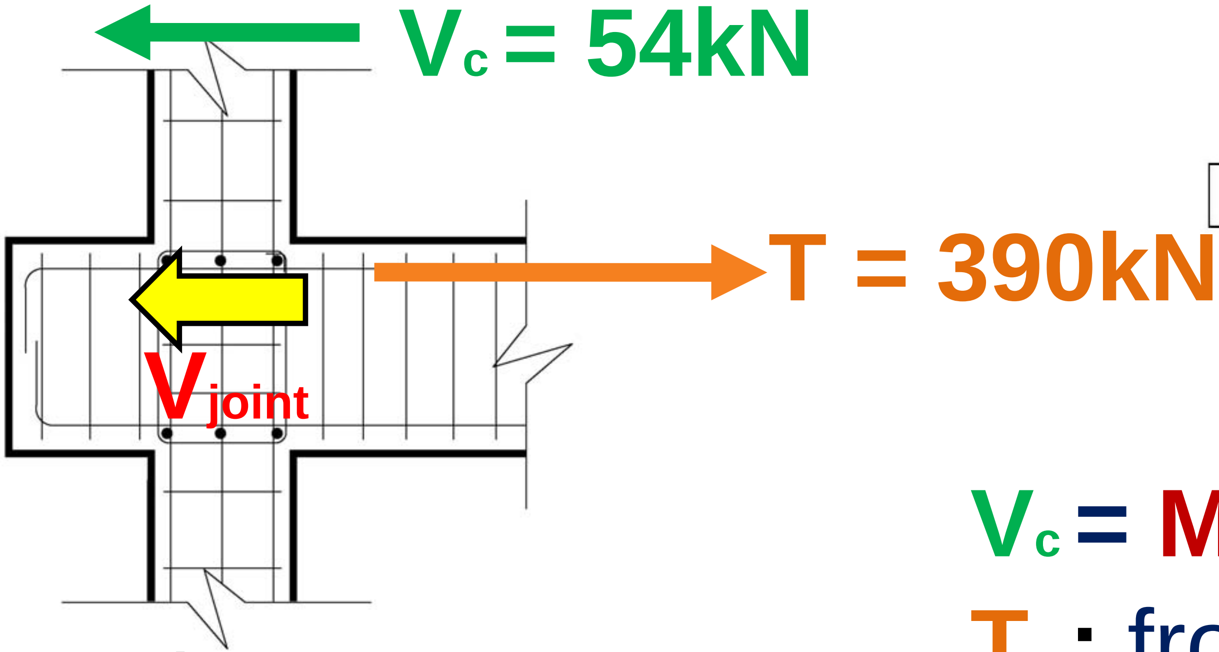


$M_b = 0.68M_{nb}$

$M_{nc} = 46kN\text{-}m$

Acting Horizontal Shear Force





Joint A1

$V_c = M_{nc} \,/\, h/2$

T : from analysis

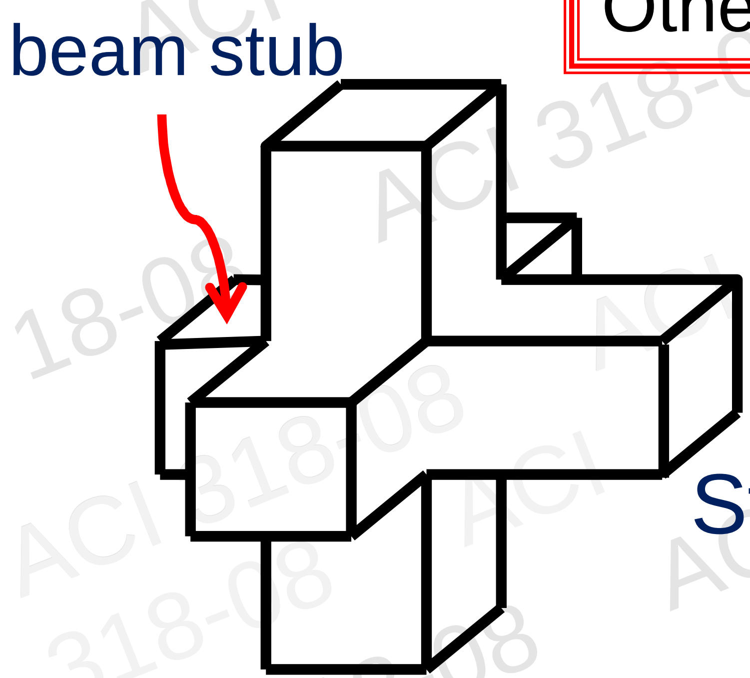
$V_{joint} = T - V_c = 336\text{kN}$

Strength Analysis (ACI 318)

Strength Analysis

ACI 318-08 Seismic Provisions

Four faces confined	$V_n = 1.67\sqrt{f'_c}A_j$
Three faces confined	$V_n = 1.25\sqrt{f'_c}A_j$
Others	$V_n = 1.00\sqrt{f'_c}A_j$



Joint A1

We choose :

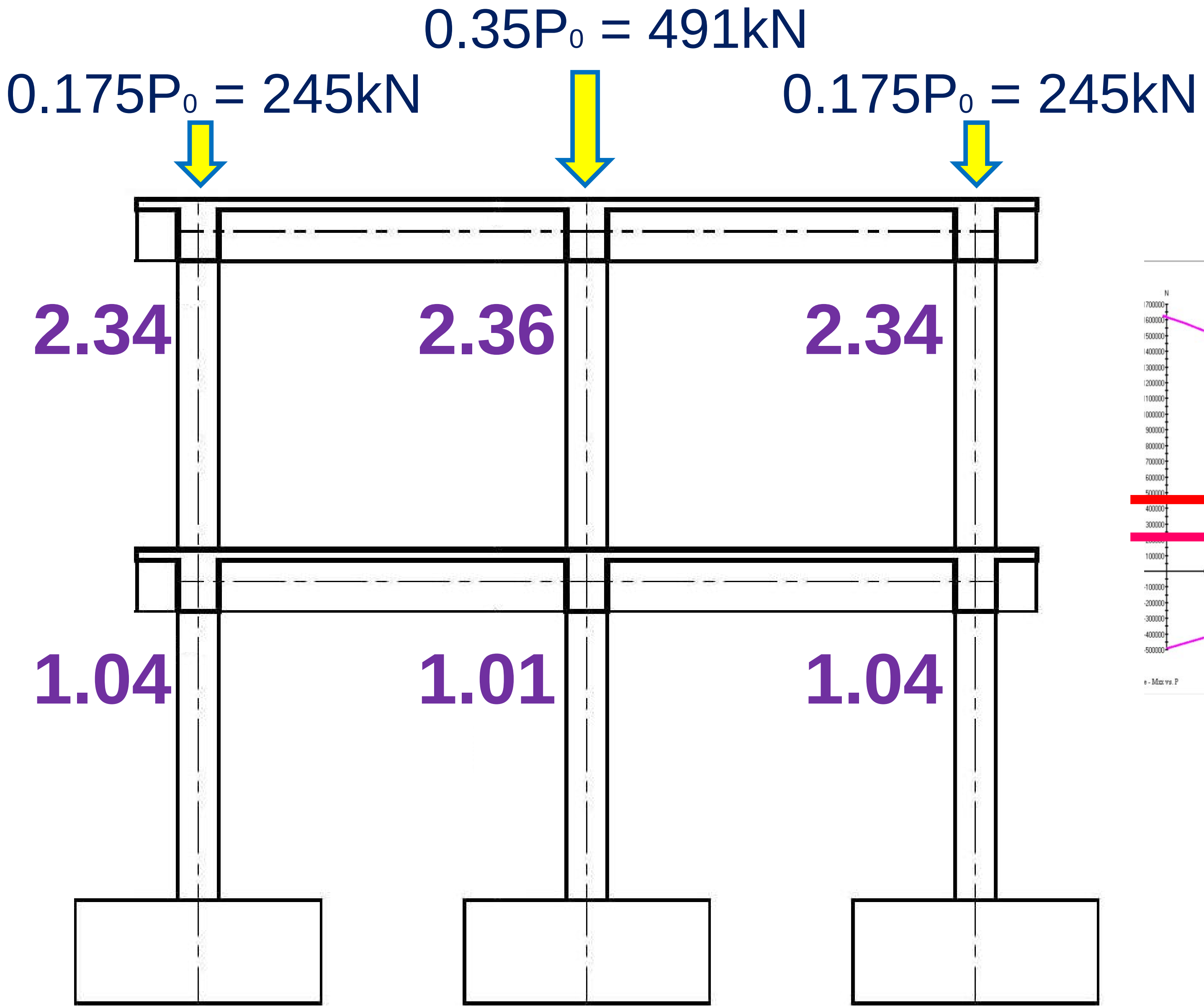
$V_n = 1.67\sqrt{f'_c}A_j$ **= 350kN**

Strength-to-Demand Ratio (β)

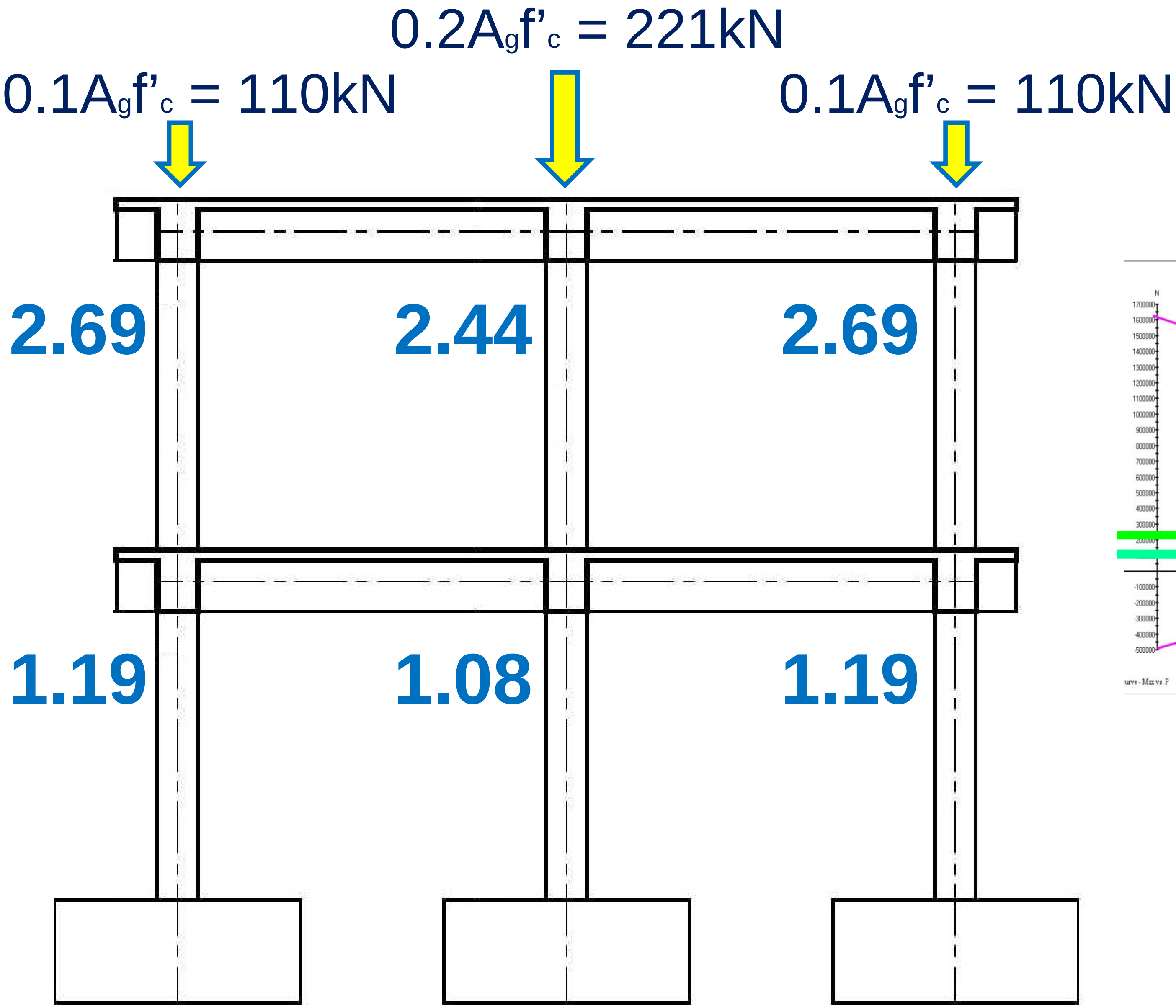
β **= 1.04**

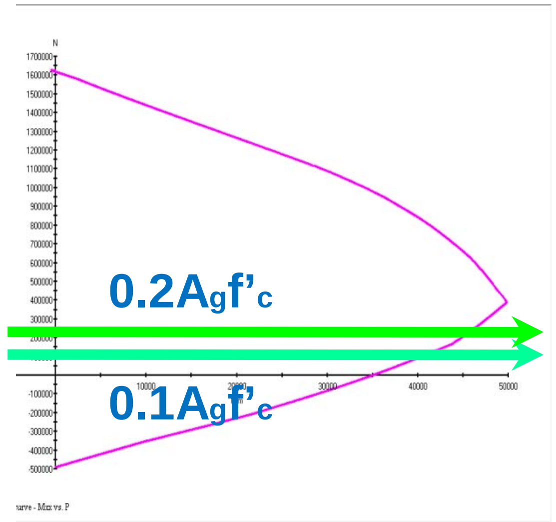
Strength-to-Demand Ratio

High Axial Load



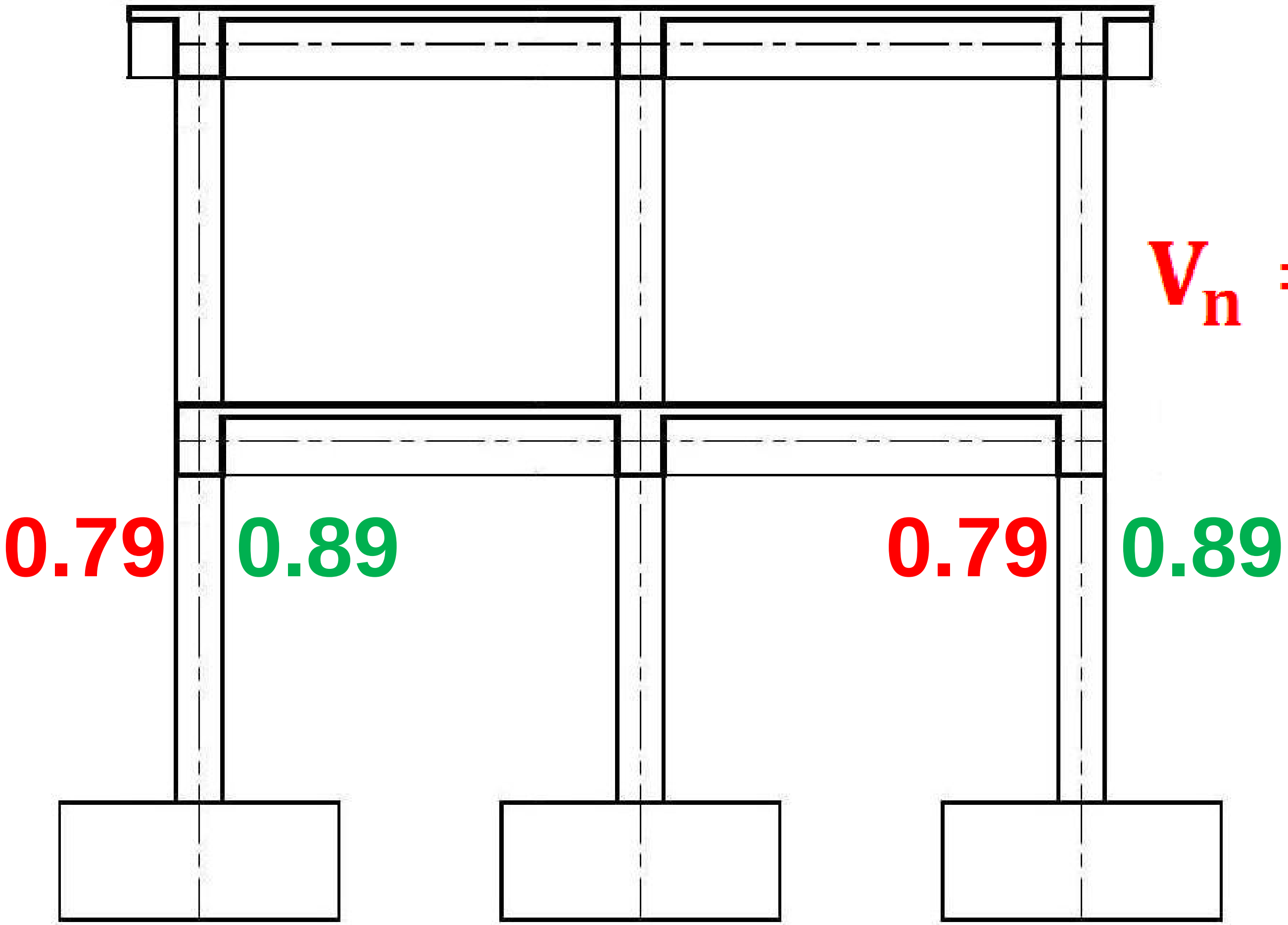
Low Axial Load





W/O beam stub

- High Axial Load
- Low Axial Load



$$V_n = 1.25\sqrt{f'_c}A_j$$

Strength Analysis (Softened Strut-and-Tie)

Strength Analysis

Strut-and-Tie Model

$$\Rightarrow V_{joint} = C_{d,n}\cos\theta = K\zeta f'_c A_{str}\cos\theta$$

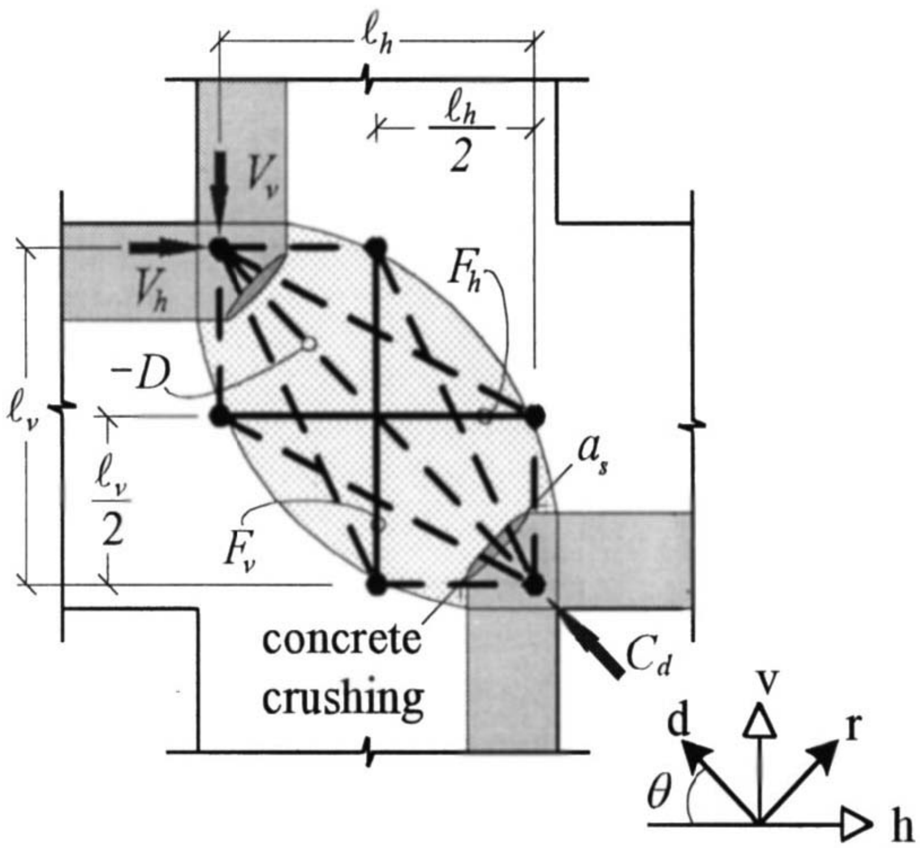
$C_{d,n}$: the nominal diagonal compressive strength

K: strut-and-tie index

ζ: the softening coefficien

A_{str} : The effective area of the diagonal strut

θ : the diagonal angle



Strength Prediction for Discontinuity Regions by Softened Strut-and-Tie Model

Strength Analysis

Strut-and-Tie Model

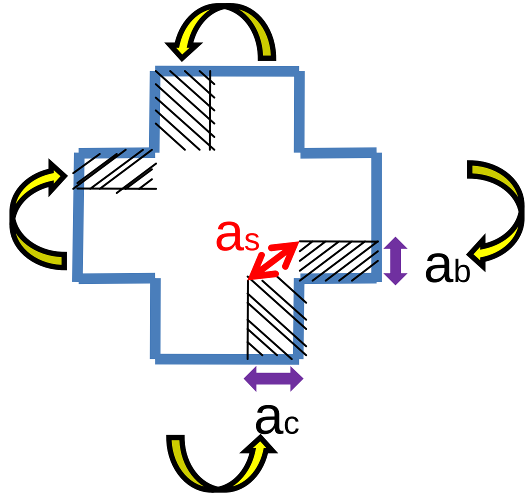
➡ A_{str} : $a_s \times b_s$

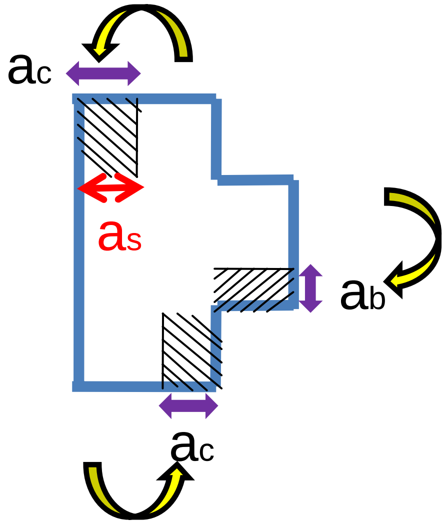
a_s: depth of the diagonal strut

→ **interior joint :** $a_s = \sqrt{a_b^2 + a_c^2}$

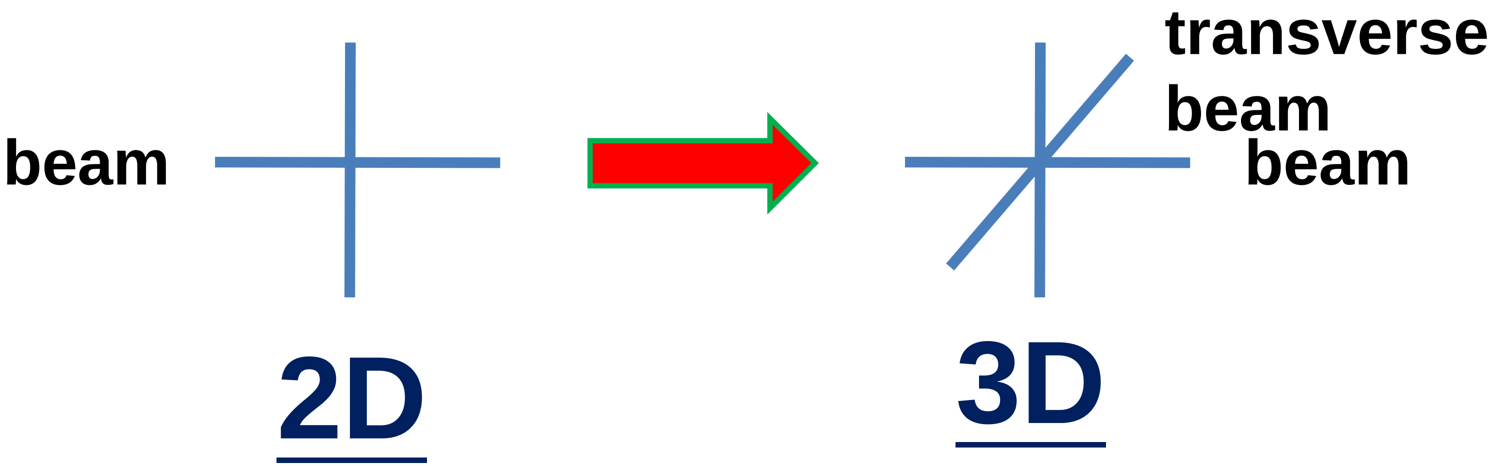
→ **exterior joint :** $a_s = a_c$

b_s: width of the diagonal strut





Strength Analysis Strut-and-Tie Model



$$Ratio = \frac{20\sqrt{f'_c}}{15\sqrt{f'_c}} = 1.33$$

Strength-to-Demand Ratio (β)

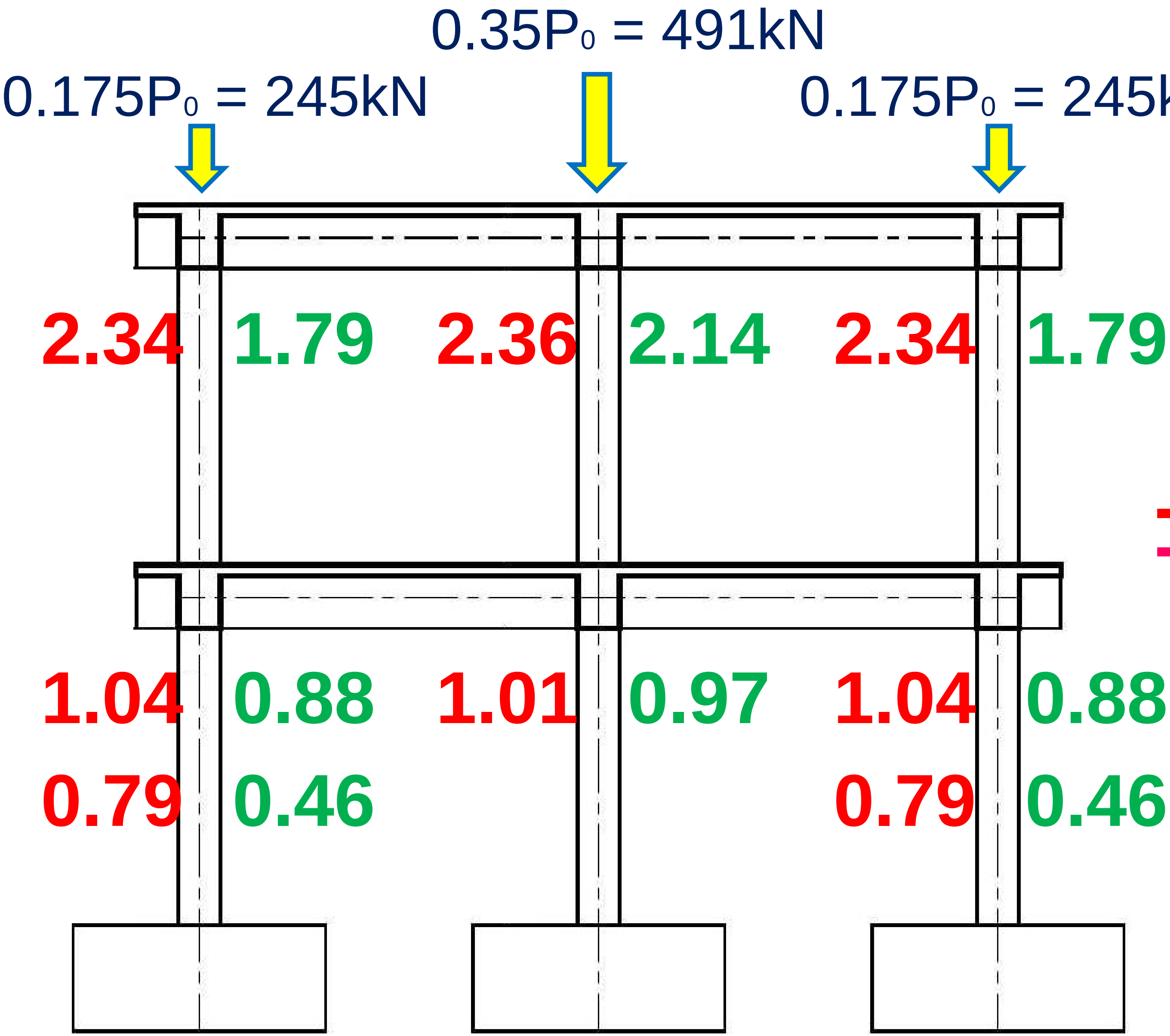
V_n = 220 kN

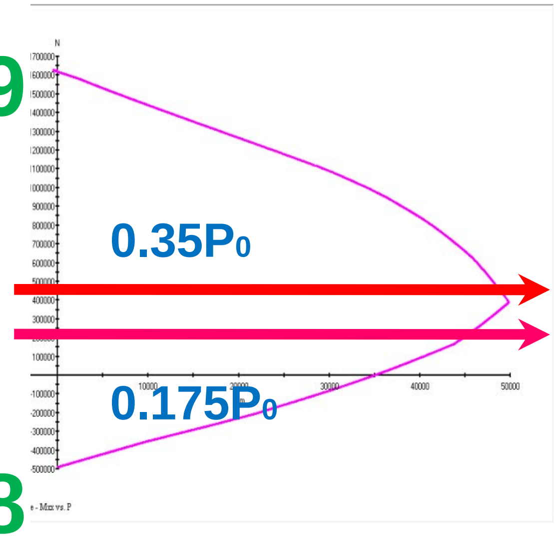
β = 0.88

Strength-to-Demand Ratio

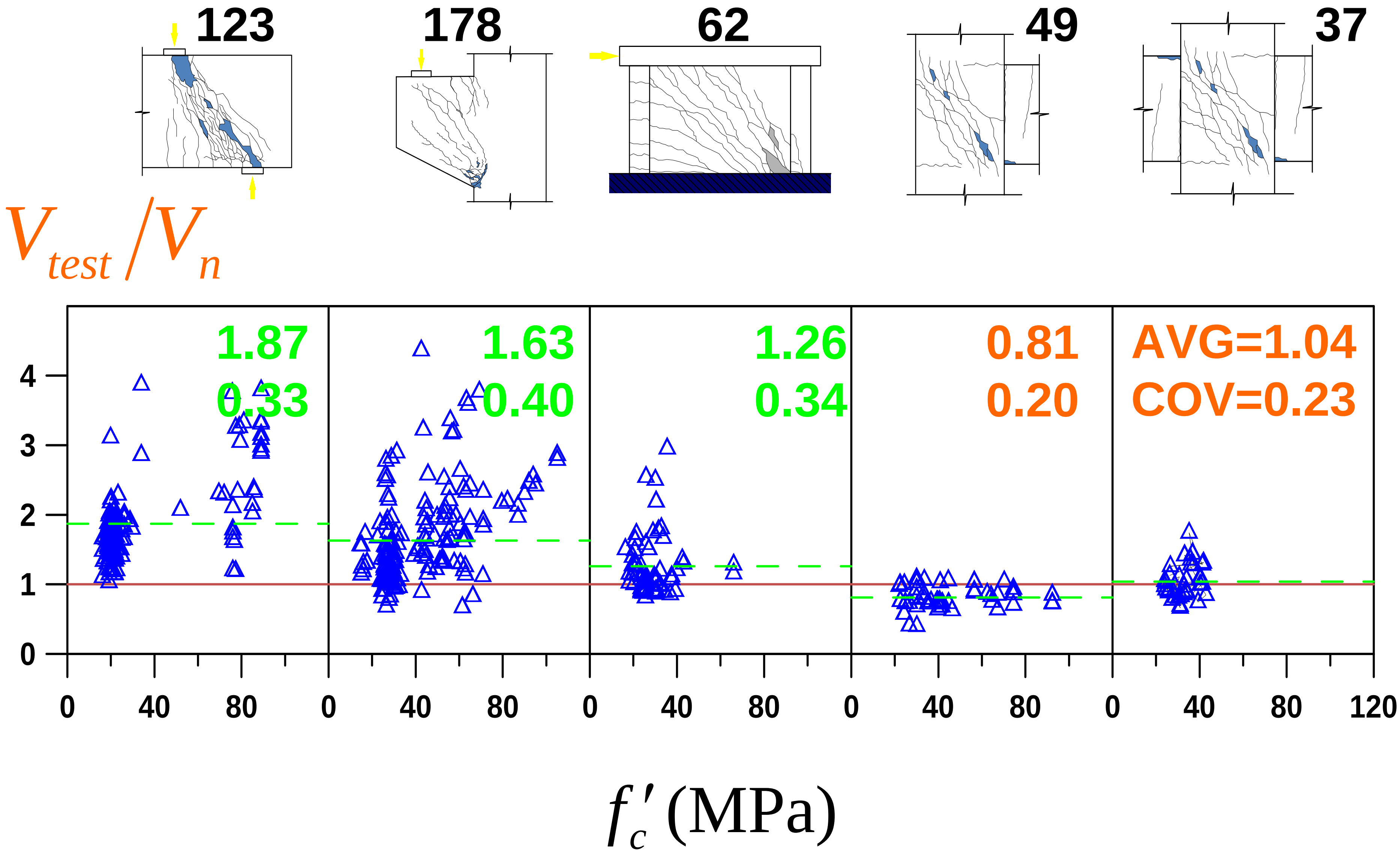
High Axial Load

- ACI
- SST
- *ACI w/o stub*
- *SST w/o stub*

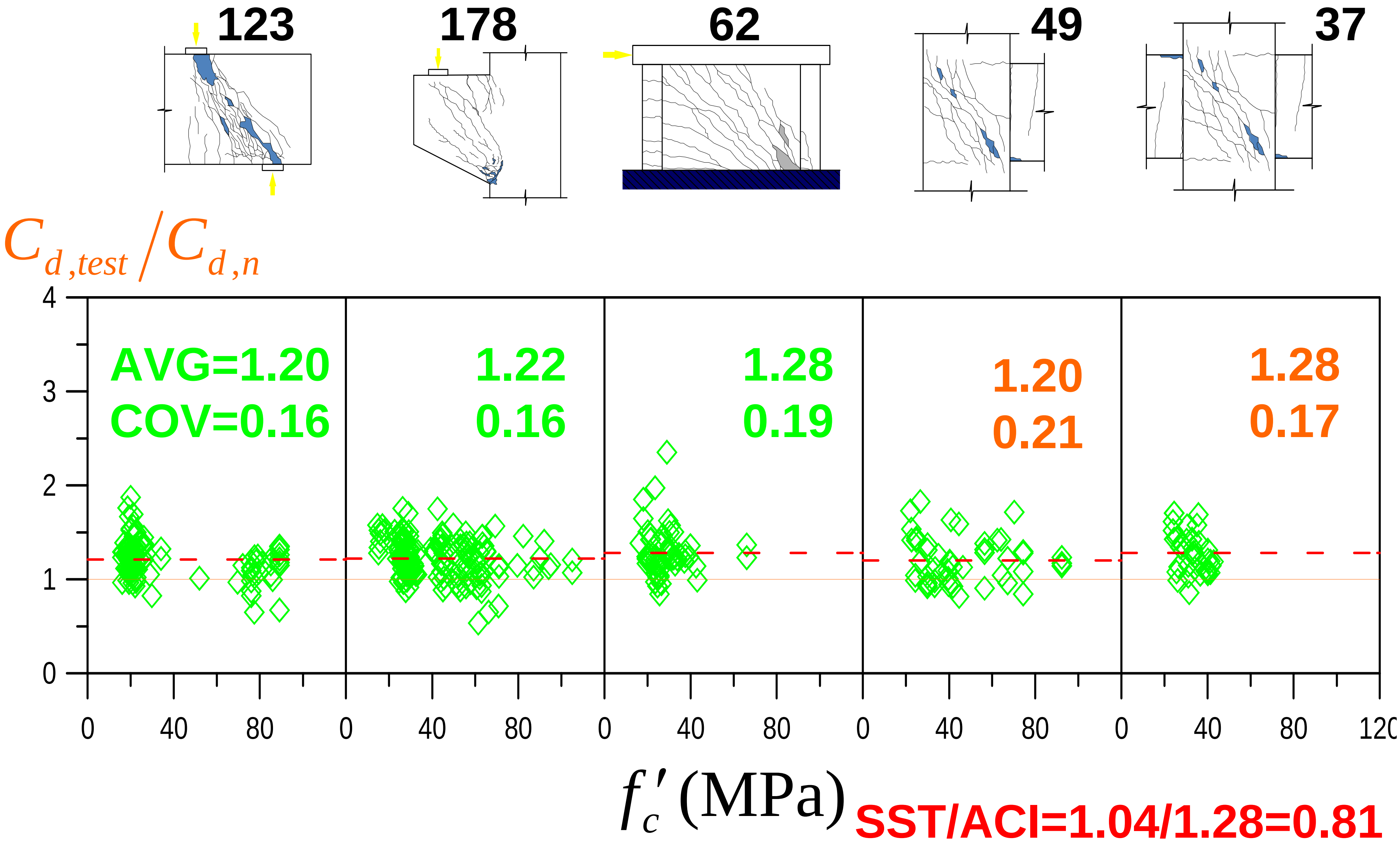




Shear Strength Analysis - ACI 318-95



Shear Strength Analysis - SST



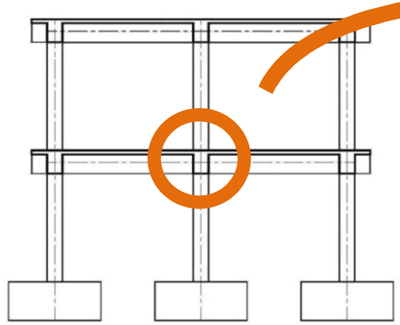
SST/ACI=1.04/1.28=0.81

Discussion

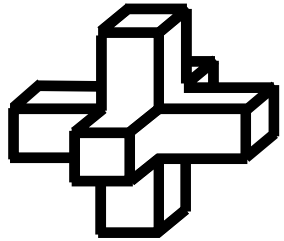
Compare with the specimens tested by :

Kitayama, Kojima, Otani and Aoyama (1989; in Japan)

TAIWAN (2008)

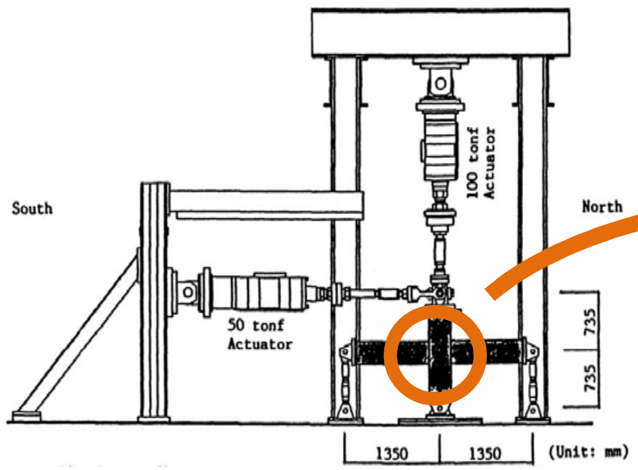


__Column Failed__

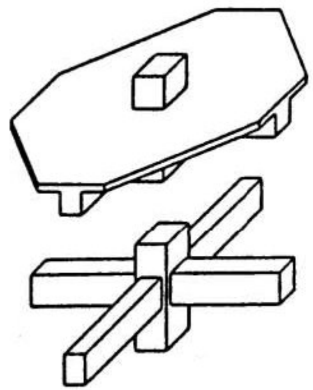


Joint B1

JAPAN (1989)



__Beam Failed__



Interior joint

Specimens A1, A2, A3, A4

tested by Kitayama, Kojima, Otani and Aoyama (1989; in Japanese)

- Beam:
  200x300 mm
- Column:
  300x300 mm
- Slab:
  70 mm

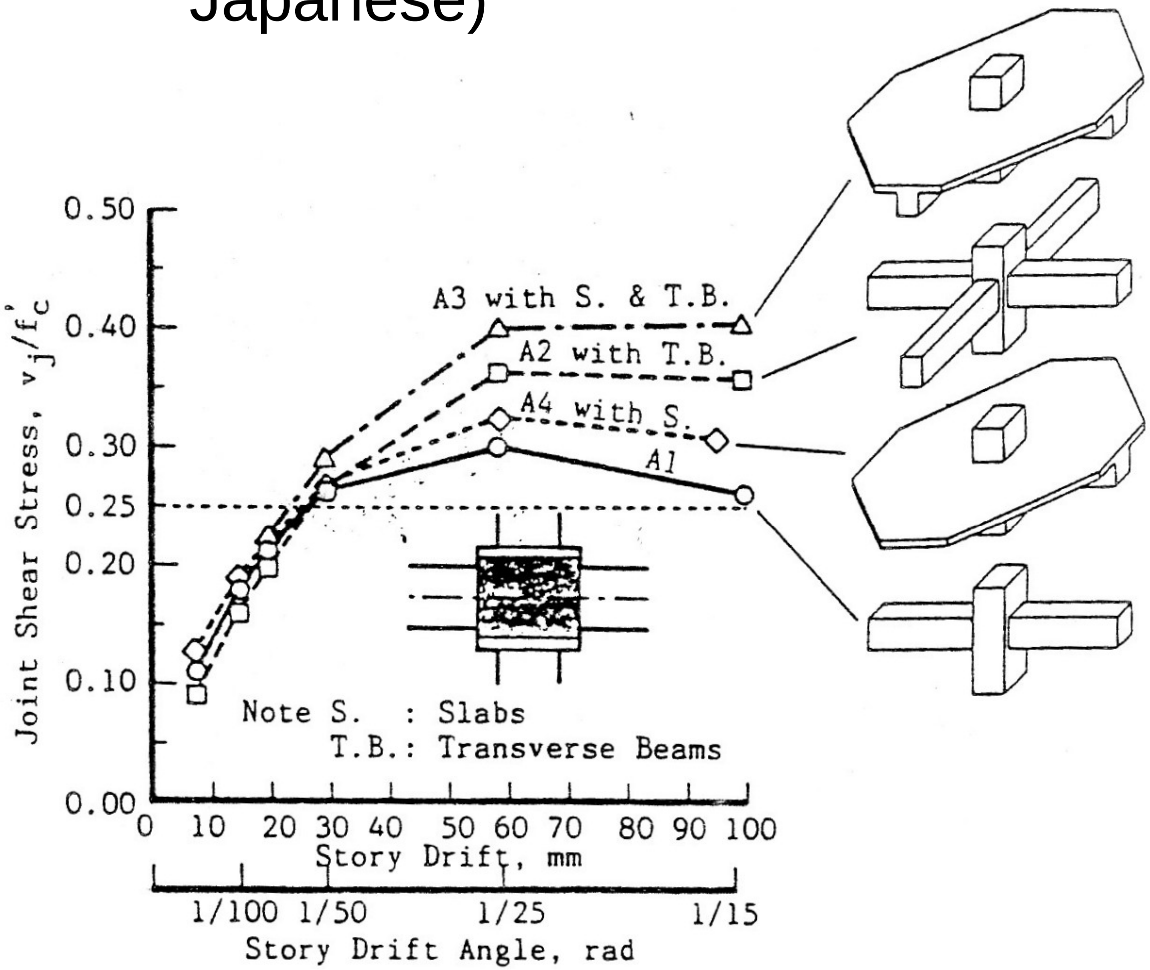


Fig. 15--Story drift -- joint shear stress relations

Compare with the specimens tested by :

Kitayama, Kojima, Otani and Aoyama (1989; in Japan)

*For **Interior Joint***

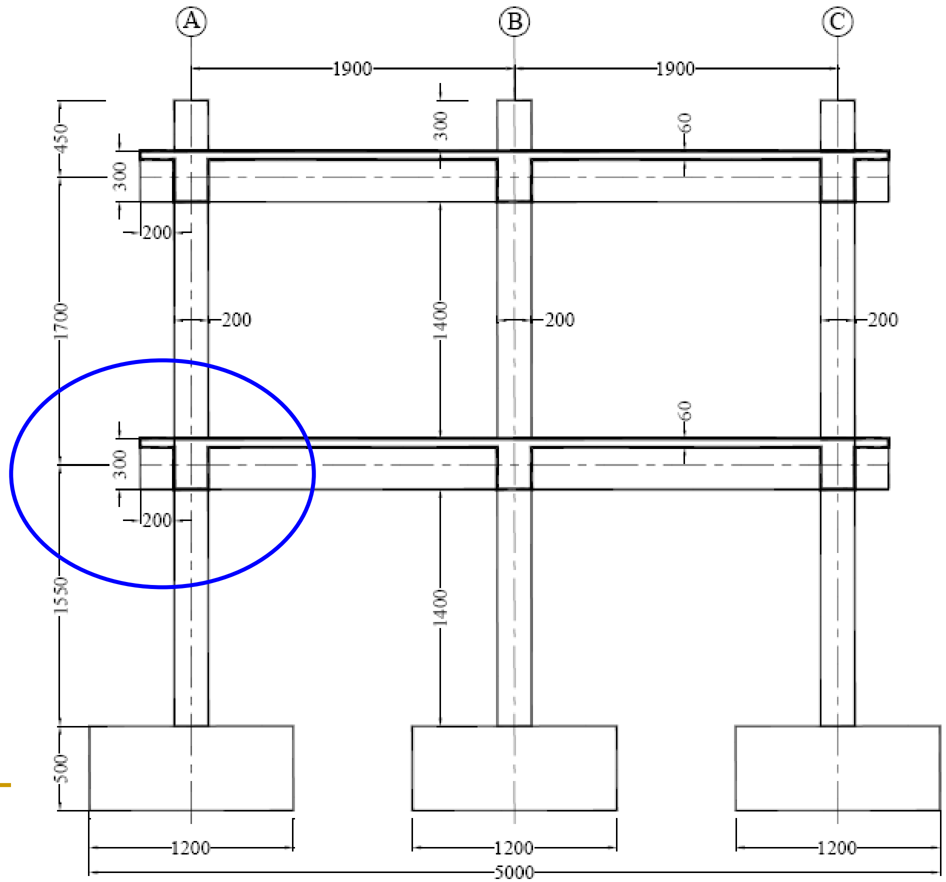
	BEAM	COLUMN	h_c / d_b	JOINT SHEAR STRESS
TAIWAN	200×300 (mm)	200×200 (mm)	**23.6**	**0.27 ~ 0.31 f'c**
JAPAN	200×300 (mm)	300×300 (mm)	**23.6**	**0.35 ~ 0.40 f'c**

Similar size to our shaking table specimen with weaker columns

- At 2% drift, joint shear stresses were 0.25 f’c
- At 4% drift, joint shear stresses between 0.30~0.40 f’c
- The target joint shear stress in the shake table specimen is 0.315 f’c (1260/4000 psi; $20\sqrt{f_c'}$).
- Hopefully we are fine.

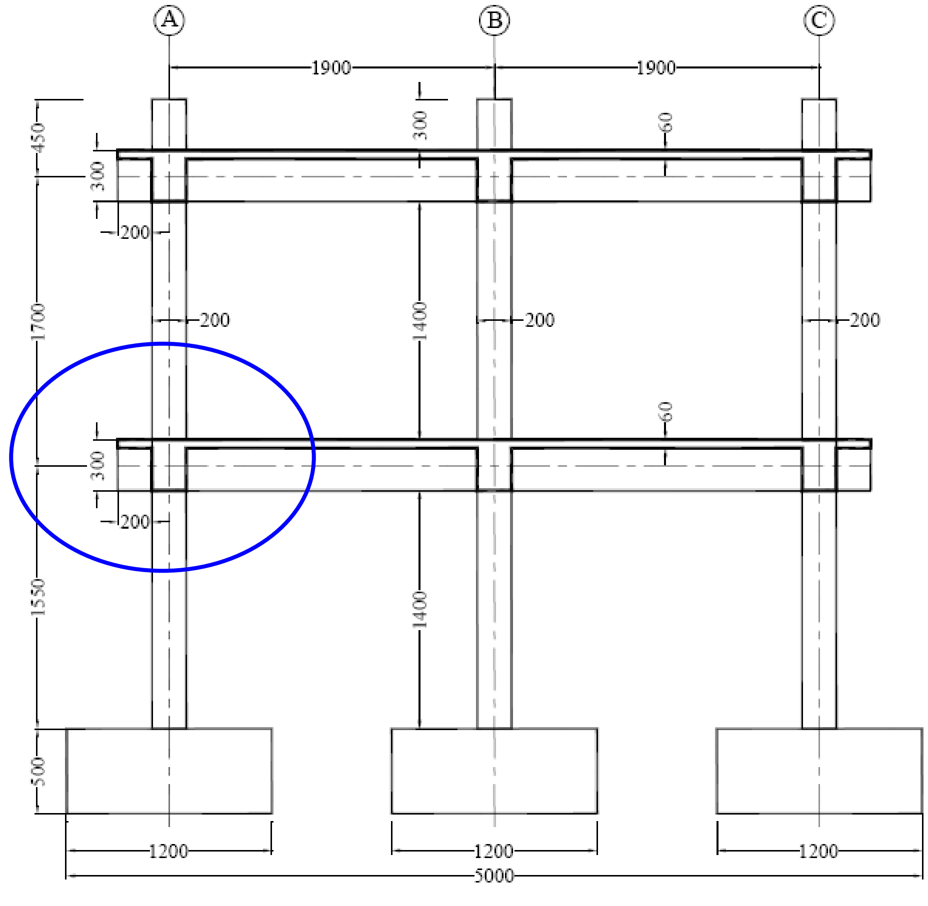
For the shake table specimen

- The joint is confined on all four vertical faces
- Column hinging rather beam hinging
- Type 1 or Type 2 ?



Comments

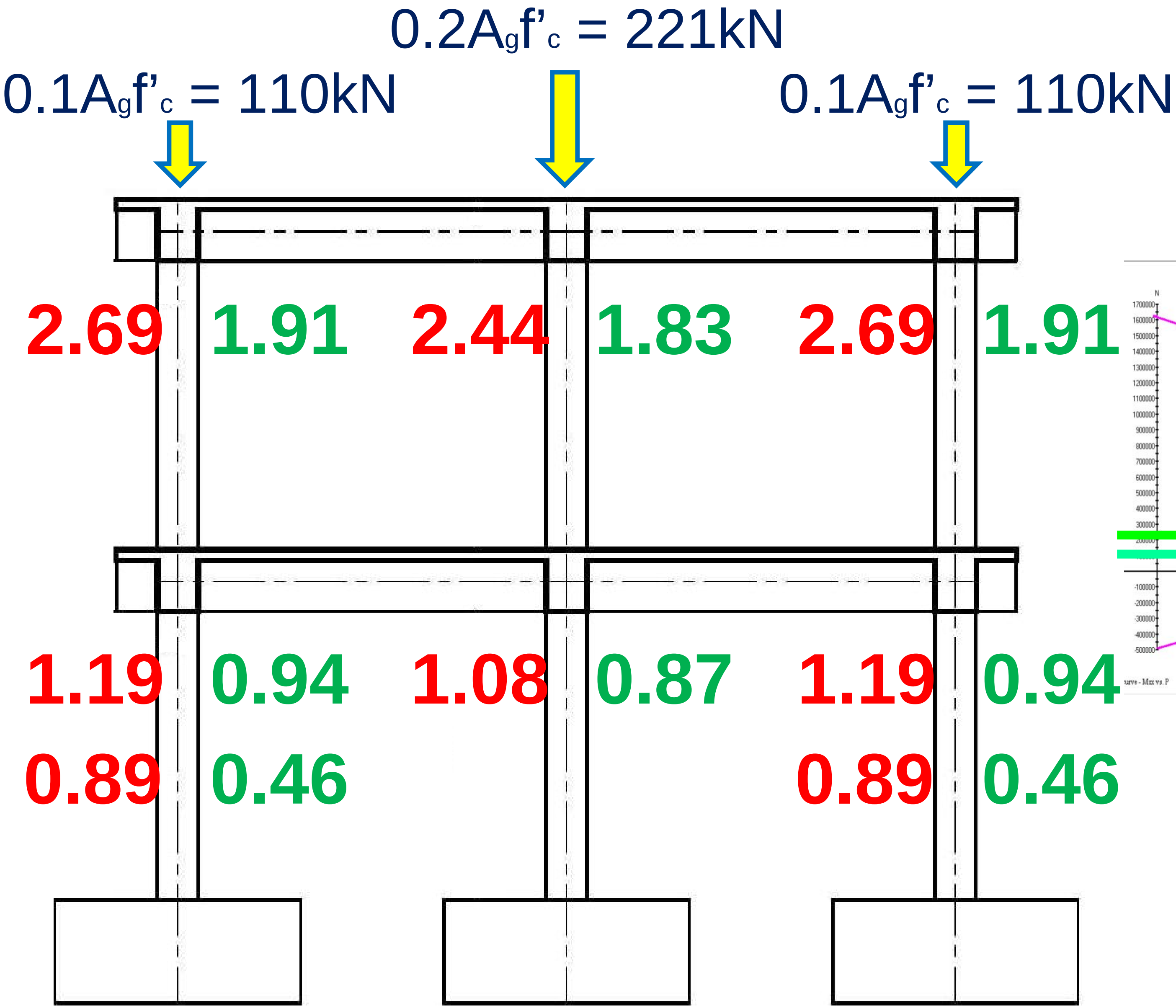
- We anticipated column hinging with limited joint damage, due to confinement of framing members and slabs.

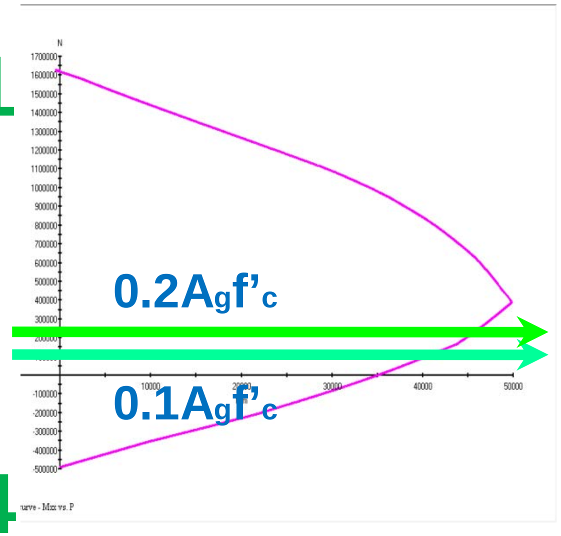


Thank you !!

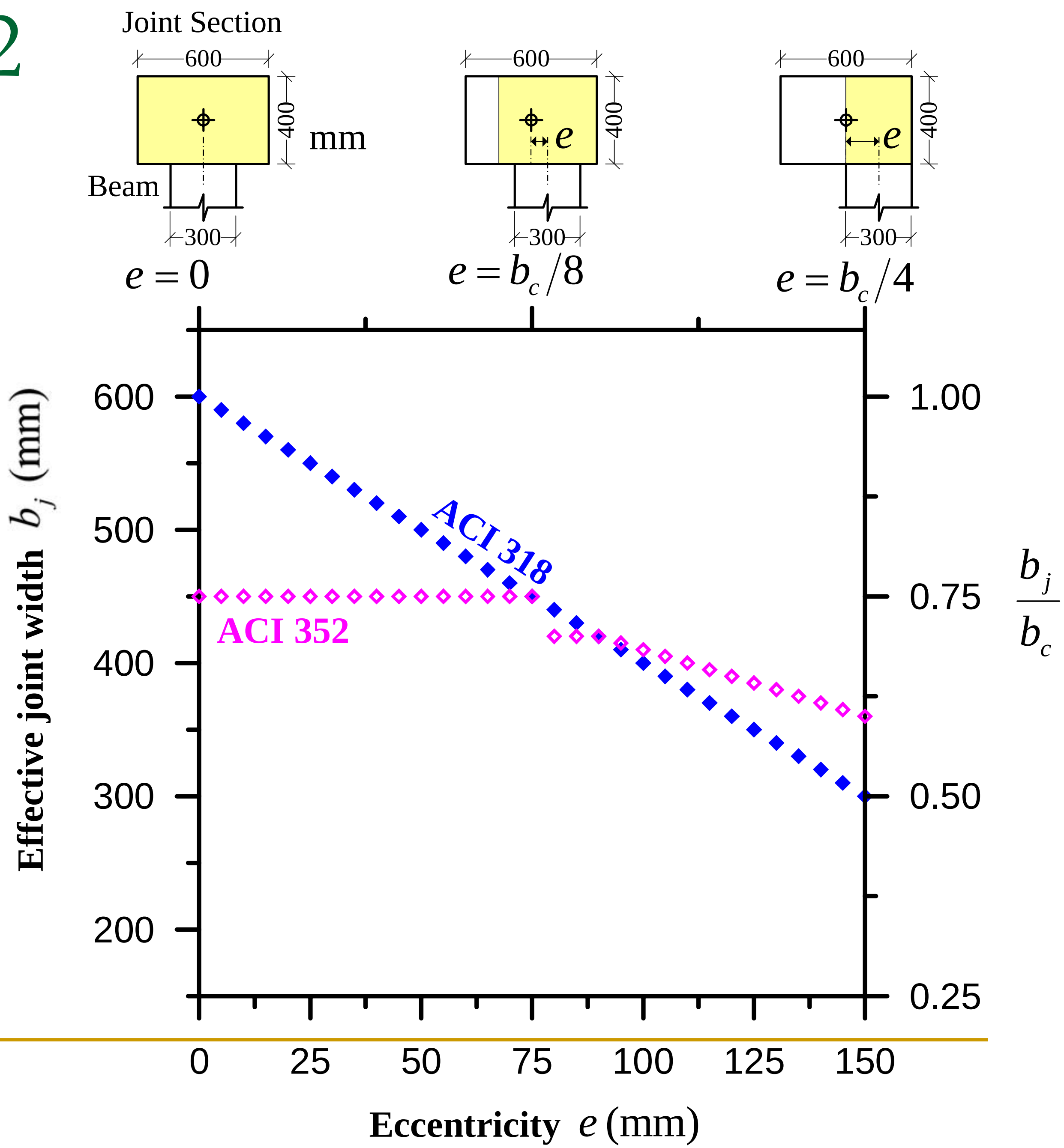
Low Axial Load

- ACI
- SST
- *ACI w/o stub*
- *SST w/o stub*





ACI 352R-02

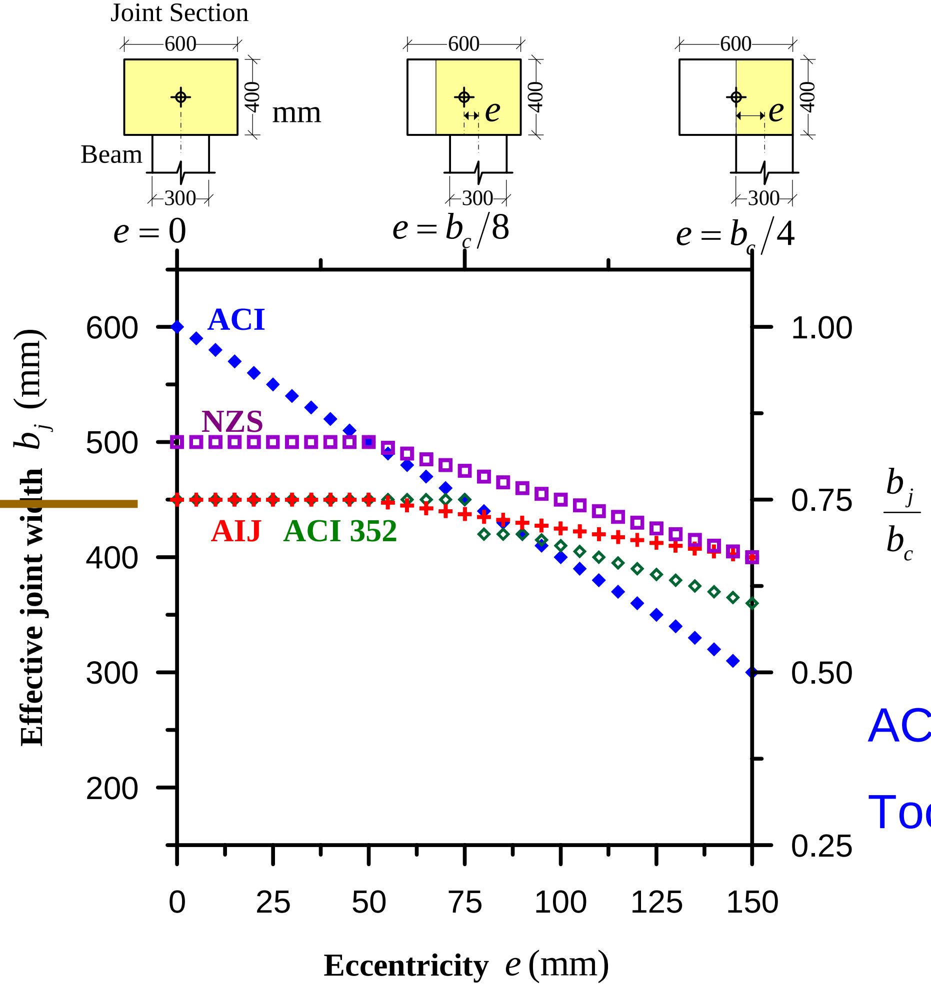


Joint Section
600
400
mm
Beam
300
e = 0
600
400
e
300
e = b_c/8
600
400
e
300
e = b_c/4
Effective joint width b_j (mm)
600
500
400
300
200
1.00
0.75
0.50
0.25
b_j / b_c
ACI 318
ACI 352
0
25
50
75
100
125
150
Eccentricity e (mm)

Comparison of bj formulas

ACI 318
Unconservative

$$\frac{b_b + b_c}{2}$$



ACI 318

Too conservative