Mitigation of Collapse Risk in Older Concrete Buildings

Advisor : Professor Mosalam

Student Researcher : SANGJOON PARK

Beam-Column Connection Test

1. Motivation (reference : Moehle, “Collapse Assessment of Reinforcement Concrete Structure”)

-. ACI Joint Strength is determined by two factor : (1) connection type (2) joint planar dimension

$$V_n = \gamma \sqrt{f_c^{'}} b_j h_c$$

-. Some joints designed per ACI show joint shear failure with brittle behavior

⇨ J3 failure (refer to (1)Hwang)

-. Other joints even without transverse hoops show good performance with ductile behavior

⇨ BJ failure (refer to (1)Hwang, (2)Anderson et el).

-. **The failure modes are influenced by the beam flexural strength** which is directly connected to joint shear demand.

-. Prof. Moehle presentation suggested the envelope for **BJ failure** in terms of joint shear demand and drift ratio

-.Little report about the loss of vertical load capacity of beam-column joints

-. Most tests have low column axial loads $P \le 0.25 f_c^{'} A_g$

=> still possible to carry vertical load at relatively large drift ratios

-. Questionable about higher axial loads and bi-directional loading

=> corner beam-column connection subject to overturning effect of earthquake

Fig. A
quake.
Enginee

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Beam-Column Connection Test

2. Target Building Type (reference : NCEER92-0025)

-. Existing RC Building in California, designed per ACI318(reference : NCEER92-0025)

-. No more than about 2% longitudinal reinforcement in the columns

-. Widely spaced column ties that provide little confinement to the concrete(about 10'')

-. Little or no transverse reinforcement within the joint region

-. Discontinuous positive beam reinforcement with a short embedment into the column

-. Bending moment capacity of columns close to that of beams

3. Pre-Analysis

-. Biaxial loading analysis :

simply check if the joint strength is less than its demand for both direction(?)

-. Joint strength : (1) SST model (2) OpenSees (3) Other Analysis Software ; IDARC, DRAIN2DX

-. Reinforcement Buckling : Mohamed's bucking model

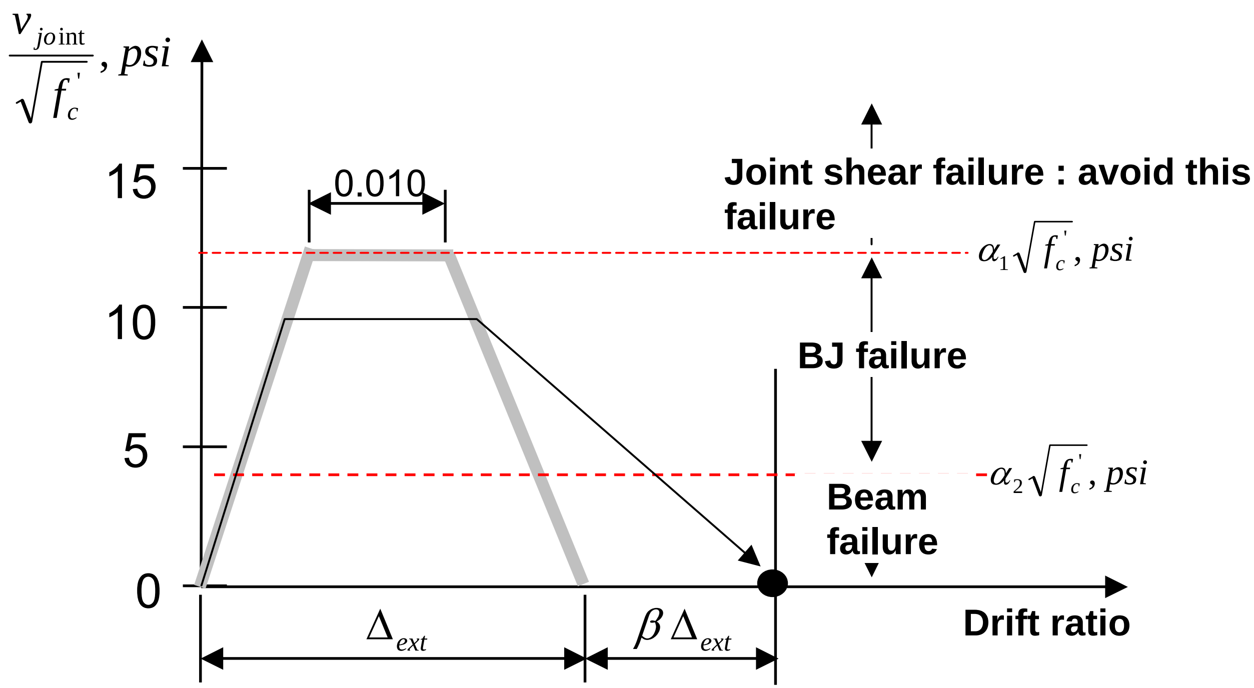
Beam-Column Connection Test

4. Test Objectives

-. Effect of High Axial Force : (1) concrete crushing, (2) column reinforcement buckling

-. Effect of Bi-directional loading

-. Suggest the Corner Joint Strength (Limit State) Model Considering High Axial force



Beam-Column Connection Test

▣ Expected Parameters Example

For $P \le 0.25 f_c^{'} A_g$: $\alpha_1 = 12,\ \alpha_2 = 4,\ \Delta_{ext} = 0.02,\ \beta = 0.5$

For $P > 0.25 f_c^{'} A_g$: find $\alpha_1,\ \alpha_2,\ \Delta_{ext},\ \beta$

consider two failures, concrete crushing and reinforcement buckling

▣ Concrete Crushing

-. The ratio $P / f_c^{'} A_g$

-. Transverse reinforcement ratio

-. Bond strength

▣ Reinforcement Buckling

-. The ratio P / P_{cr}, $P_{cr} = \dfrac{\pi^2 E_t I}{(kS)^2}$ $ex)\ k\ also\ depends\ on\ S$

-. Transverse reinforcement ratio

-. …

Beam-Column Connection Test

- Design of older type building

Table 5.3: Average Parameters for Pre-1967 Buildings

	Axial Load Ratio	Column Lap Splice Length (d_{bc})*	v_j/f'_c	Vol. Joint Reinf. Ratio	$\Sigma M_c/\Sigma M_b$
Average:	0.12	28	0.21	0.000	2.2
Standard Deviation:	0.07	8	0.09	0.000	2.8
Minimum:	0.03	20	0.03	0.000	0.2
Maximum:	0.28	38	0.37	0.002	9.4

* = typically spliced above floor

Table 5.4: Average Parameters for 1967-1979 Buildings

	Axial Load Ratio	Column Lap Splice Length	v_j/f'_c	Vol. Joint Reinf. Ratio	$\Sigma M_c/\Sigma M_b$
Average:	0.17	Variable	0.15	0.009	2.04
Standard Deviation:	0.10	in location	0.06	0.008	1.29
Minimum:	0.03	and length	0.06	0.000	0.70
Maximum:	0.33		0.29	0.021	5.18

Beam-Column Connection Test

▣ Design of older type building

1. A. Beres et el, Experimental Results of Repaired and Retrofitted Beam-Column Joint Tests….
NCEER Report

beam : 14''x24'' with 2-#6 (continuous) and 2-#8(discontinuous) for positive $\rho = 0.0073$ $\rho' = 0.0026$
with #3 stirrups at 5'' spacing

column : 16''x16'' with 1% and #3 ties at 14'' ,first tie placed 7''
with 2%(4-#10) and #3 ties at 16'', first tie placed 8''
extra #3 ties at the lower bending point of the offset vertical reinforcement

cover : 1.5''

fc = 3500 psi and fy=60 ksi

distance from top to bottom of column = 58.5''(upper)+24.0''(beam depth)+51.0''(lower)

distance from left to right of beam = 47.0''(left)+16.0''(column depth)+47.0''(right)

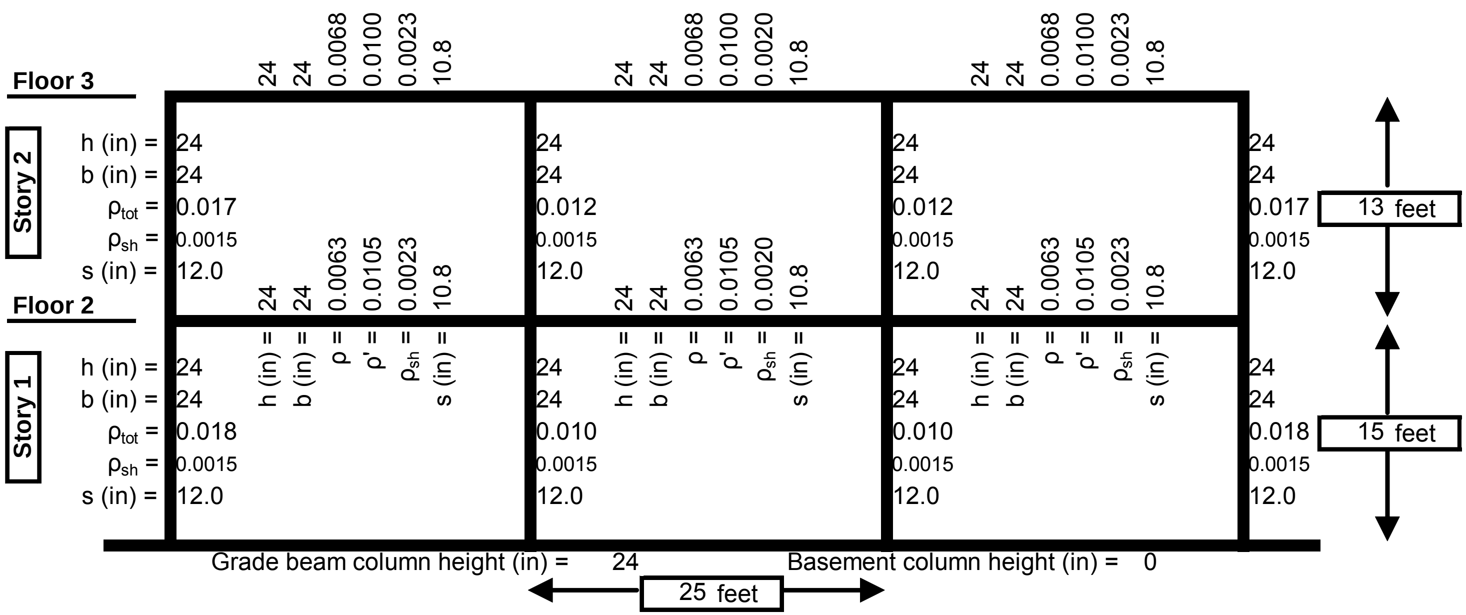
Ex) 0.45 fc x Ag = 308.7kips

Beam-Column Connection Test

▣ Design of older type building

2. Abbie Liel's Hypothetical design

(1) 2 story building

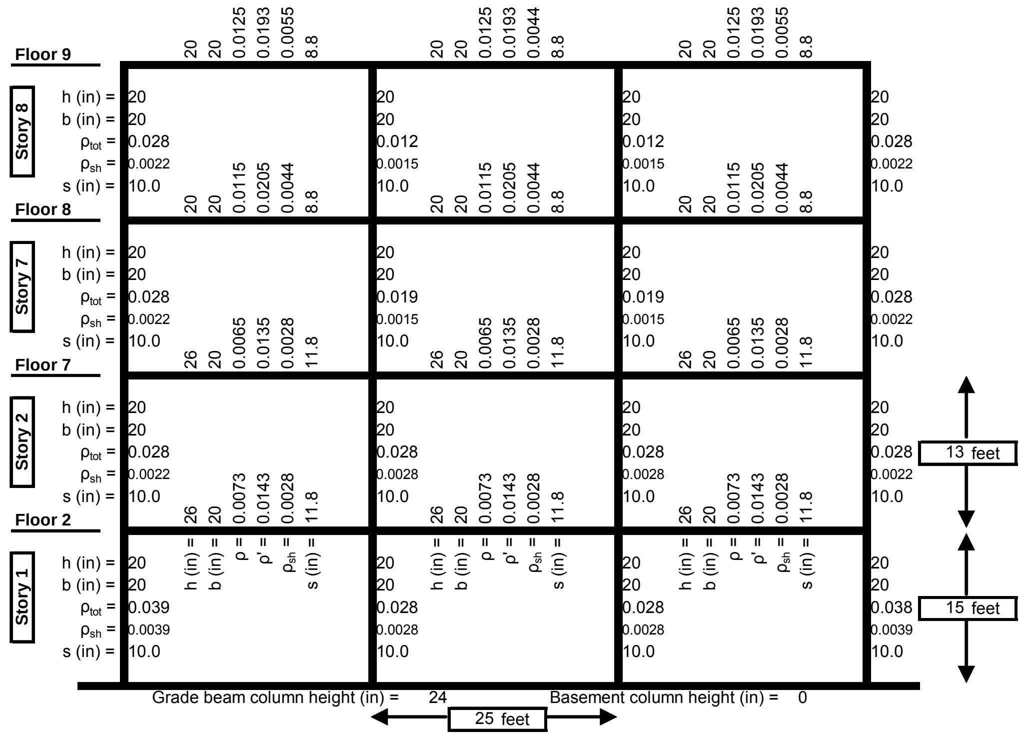


Design base shear =		0.085	g,	62	k		
f'_c beams =	4.0	ksi		$f'_{c,cols,upper}$ =	4.0	ksi	
$f_{y,rebar,nom.}$ =	60	ksi		$f'_{c,cols,lower}$ =	4.0	ksi	

Ex) 0.45 fc x Ag = 871.2kips

Beam-Column Connection Test

- ▣ Design of older type building
  - 2. Abbie Liel's Hypothetical design
    - (2) 4 story building



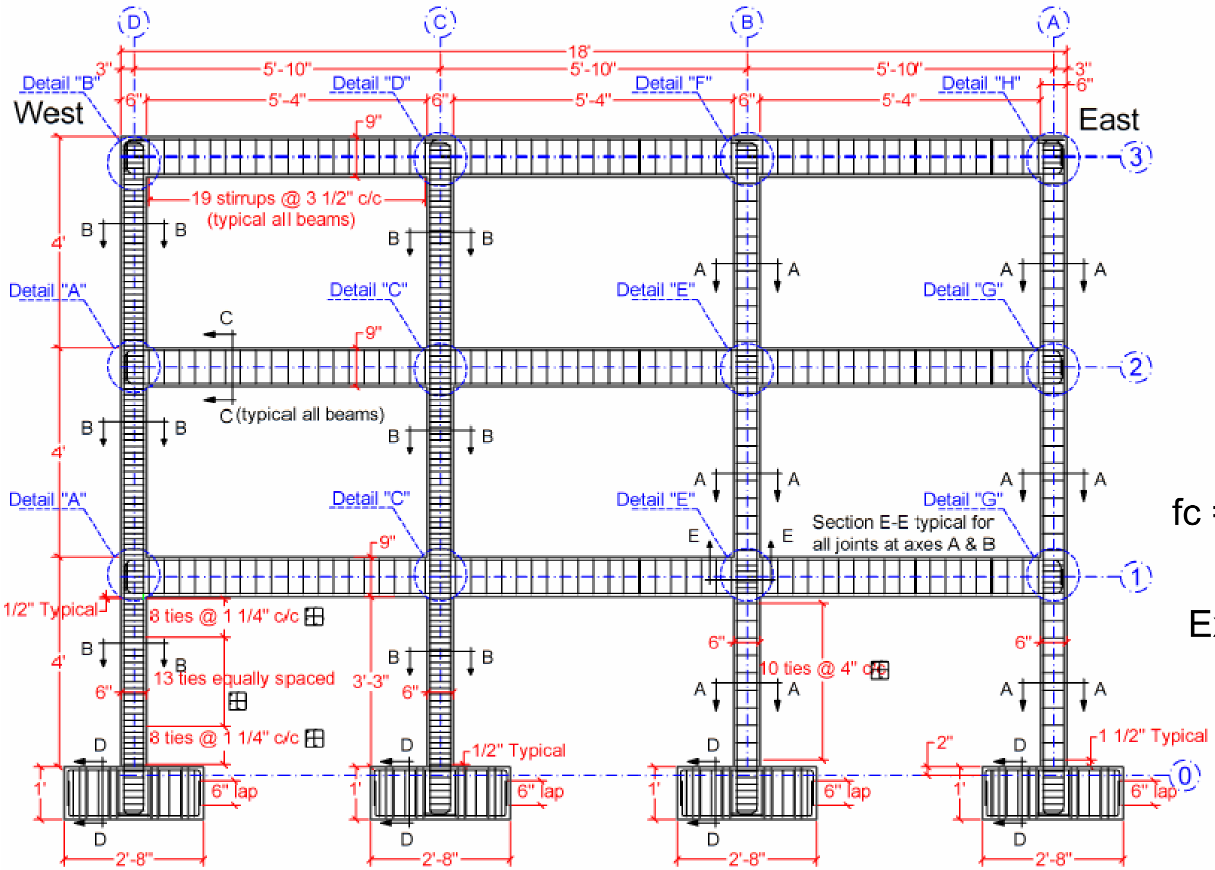
Ex) $0.45\ f_c \times A_g = 583.2$kips

Design base shear =	0.068	g,	99	k			
f'_c beams =	4.0	ksi		$f'_{c,cols,upper}$ =	4.0	ksi	
$f_{y,rebar,nom.}$ =	60	ksi		$f'_{c,cols,lower}$ =	4.0	ksi	

Beam-Column Connection Test

▣ Design of older type building

3. Wassim's Experiment : 1/3 Scale



Frame Dimensions and Reinforcing Details

fc = 3500 psi and fy=60 ksi

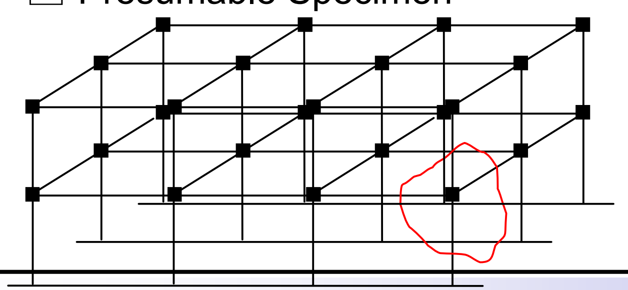
Ex) 0.4 fc x Ag = 403.2kips

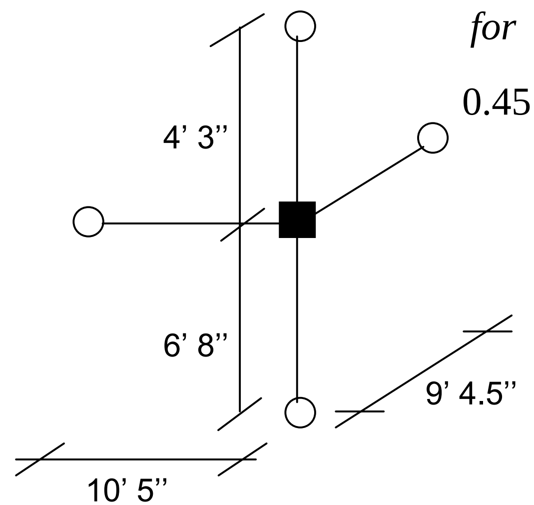
Beam-Column Connection Test

▣ Prototype Building : Van Nuys

1. The number of story : 7story
2. The ratio of longitudinal to transverse beam length : 20’ 10’’ to 18’ 9’’
3. Beam dimension : longitudinal(2FSB1) 16’’x30’’ vs transverse(2FSB6) 14’’x30’’
   2FSB1 : Top – 2 #9(discont.) 3#8(cont.) Bot – 2#8
   2FSB6 : Top – 2 #9(discont.) 2#9(cont.) Bot – 2#9
4. Column heights in 1st and 2nd floor : 13’ 6’’ to 8’ 6’’
5. Column dimension : C9 14’’x20’’
6. Material Properties
   Column : fc = 5 ksi(1st), 4 ksi(2nd), 3 ksi(3rd~7th)
   fy = grade 60
   Beam : fc = 4 ksi(2nd), 3 ksi(3rd~roof)
   fy = grade 40

▣ Presumable Specimen





$$for\ \ f_c^{'} = 4\,ksi$$

$$0.45\ \ f_c^{'} A_g = 388.8\,kips$$

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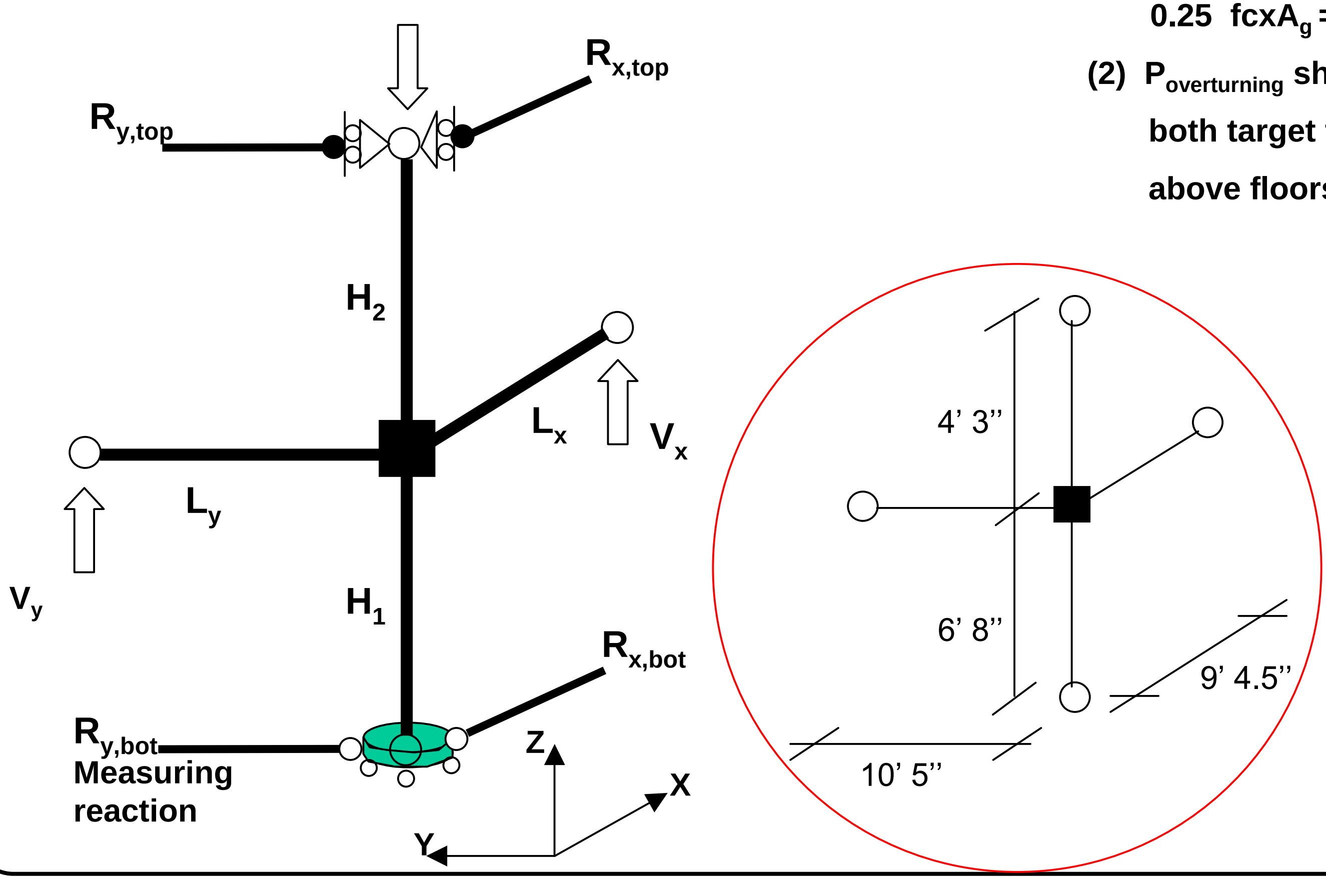
Beam-Column Connection Test

▣ Idealized Force and Reaction System

$P = P_{gravity}(216\ kips) + P_{overturning}(?)$ ⇨ (1) **Starting with the Gravity Load**

$0.25\ fc x A_g = 216kips$

(2) **$P_{overturning}$ should include the effect of both target floor beam shear and the above floors beam shear**



Beam-Column Connection Test

▣ Idealized Force and Reaction System

Approximate the relationship among P, V_x, V_y to control axial force P corresponding to each V_x, V_y during test

How?

1. I[st] order linear regression from the analysis data

$ex)\ In\ \mathrm{Pr}iestley\ and\ Hart: 12\ story\ building$

$$\begin{cases} P = 178 \pm k_x V_x \pm k_y V \\ 178 - R_v\left(\left|\sum_{i=2}^{roof} V_{x,i}\right| + \left|\sum_{i=2}^{roof} V_{y,i}\right|\right) \le P \le 178 + R_v\left(\left|\sum_{i=2}^{roof} V_{x,i}\right| + \left|\sum_{i=2}^{roof} V_{y,i}\right|\right)_y \end{cases}$$

$R_v: reduction\ \ factor\ due\ to\ higher\ \mathrm{mod}e\ contribution$

$(refer\ to\ Pauly\ and\ \mathrm{Pr}iestley)$

$Applied\ \max imum\ axial\ \ force\ during\ the\ \ test$

$P_{\max} \approx 0.46\ \ f_c^{'} A_g$

Beam-Column Connection Test

▣ Idealized Force and Reaction System

2. Using the distribution of drift ratio along the height

-. Assuming that the vertical drift ratio distribution and the orthogonality between beam and column are preserved during cyclic excitation,

all beam shear forces are determined from their moments corresponding to their curvatures.

	Width (in.)	Height (in.)	7th Floor	6th Floor	5th Floor	4th Floor	3rd Floor	
FSB-1	16	22.5	@1 & 9 '2 #9'	2 #9	2 #9	3 #8	3 #8	2 #7
			@2 & 8 '2 #9'	same	same	same	same	

	Width (in.)	Height (in.)	Top Bars	Bottom Bars
RSB-1	16	22	@1 & 9 2 #6	2 #7
			@2 & 8 2 #8	
2FSB-1	16	30	@1 & 9 2 #9	2 #8
			@2 & 8 3 #8	

Model Type	T_A sec	S_A (g)	Maximum inter-story drifts (%)							Roof disp.(in)
			1	2	3	4	5	6	7	
Mean[20]			0.51	1.30	1.71	1.81	1.46	0.86	0.43	8.75

Beam-Column Connection Test

-. Procedure

(1) choose second floor beam shear $V_{x,2}$ ⇨ determine moment-curvature responses from section analysis

(2) calculate 1st story drift ratio Δ_1 from integration of curvature

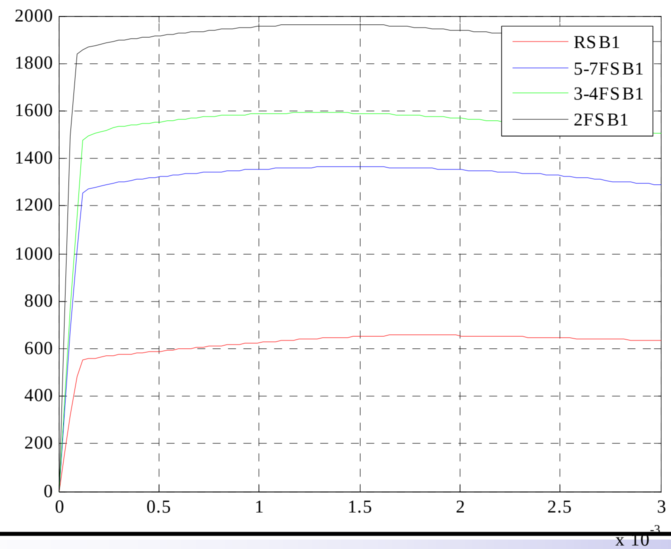
(3) determine the other stories drift ratio using the predefined drift ratio distribution

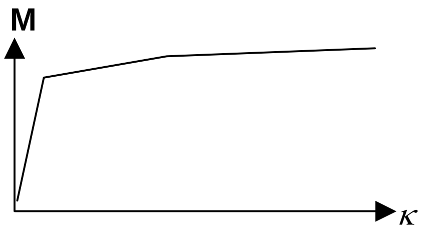
(4) calculate moment and curvature corresponding to each drift ratio

simply assuming trilinear moment curvature curve up to ultimate moment(rebar yielding, concrete softening)

(5) from the determined each beam moment, determine the vertical axial force

(6) formulate a simplified linear equation between the vertical axial force and $V_{x,2}$





Beam-Column Connection Test

-.Example

For the closing moment of 2FSB1 at the linear limit

$$\kappa_2 = 9\times10^{-5} \Rightarrow \Delta_1 = \int_0^l \frac{\kappa_2}{l} x\,dx = \frac{\kappa_2 l}{2} = 0.51\%,\ l = 112.5\ in(half\ \ span)$$

$$\Rightarrow M_2 = 1839\,kip-in \Rightarrow V_2 = \frac{M_2}{l} = 14.71\ kips$$

from the drift distribution

$$\Delta_2 = 1.30\%$$

approximate $M-\kappa$ *curve as trilinear curve*

$$\kappa_3 \geq \kappa_{peak} \Rightarrow take\ M_{ult} = 1591.7\,kip-in \Rightarrow V_3 = \frac{M_{ult}}{l} = 12.73\ kips$$

same assumption results in

$$V_4 = \frac{M_{ult}}{l} = 12.73\ kips\ , V_5 = \frac{M_{ult}}{l} = 10.91\ kips\ ,\ V_6 = \frac{M_{ult}}{l} = 10.91\ kips$$

$$\Delta_6 = 0.86\% \ \Rightarrow M_7 = 1321\,kip-in \Rightarrow V_7 = 10.57\,kips$$

$$\Delta_7 = 0.43\% \Rightarrow M_{roof} = 405\,kip-in \Rightarrow V_{roof} = 3.24\,kips$$

$$finally,\ P_{overturning} = 75.8\ kips \approx 5\times V_2$$

-. Maximum Moment Capacity

	Closing	Opening
RSB-1	657.1	842.7
5-7FSB-1	1364.3	879.6
3-44FSB-1	1591.7	881.8
2FSB-1	1964.4	1584.1
SUM	9897.8	6829.2
SUM/ half span	79.2 kips	54.6 kips

$$P_{max} = 216 + 88\times2 = 374 \approx 0.43\,f_c^{'}A_g$$

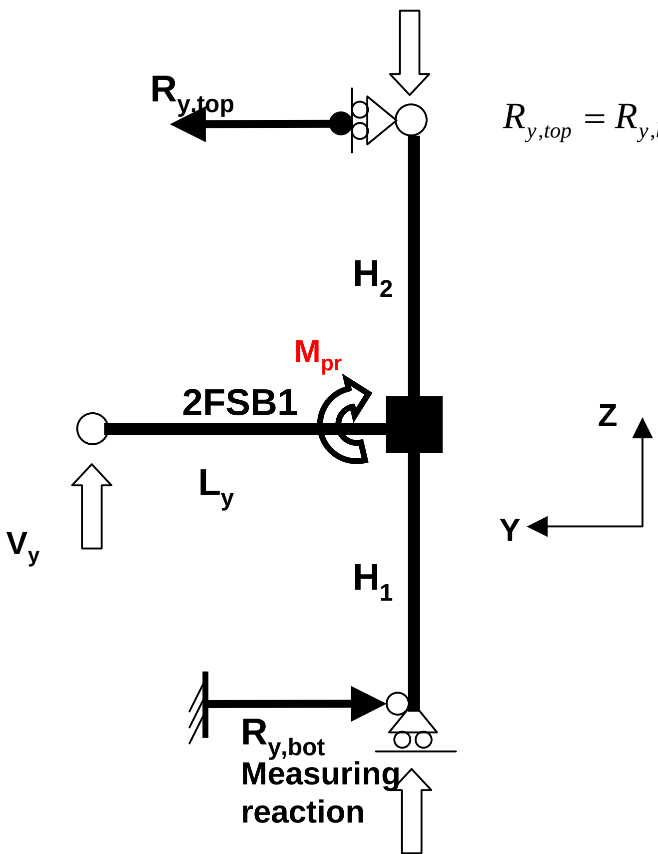
$$,\ \ f_c^{'} = 4ksi\ \ and\ \ A_g = (14-2)\times(20-2)$$

Determine the total axial force at each predefined beam shear force

Beam-Column Connection Test

▣ Idealized Force and Reaction System

$$P = 216 \pm k_y V_y$$



$$R_{y,top} = R_{y,bot} = \frac{L_y}{H_1 + H_2} V_y$$

$$= \frac{125}{51+80} V_y \approx 0.95 V_y$$

$$M_{pr,1(closing)} = 2658\ kip-in$$

$$\Rightarrow V_{y,1} = 21.2\,kip \Rightarrow R_y = 20.1\,kip$$

$$M_{pr,1(opening)} = 2115\ kip-in$$

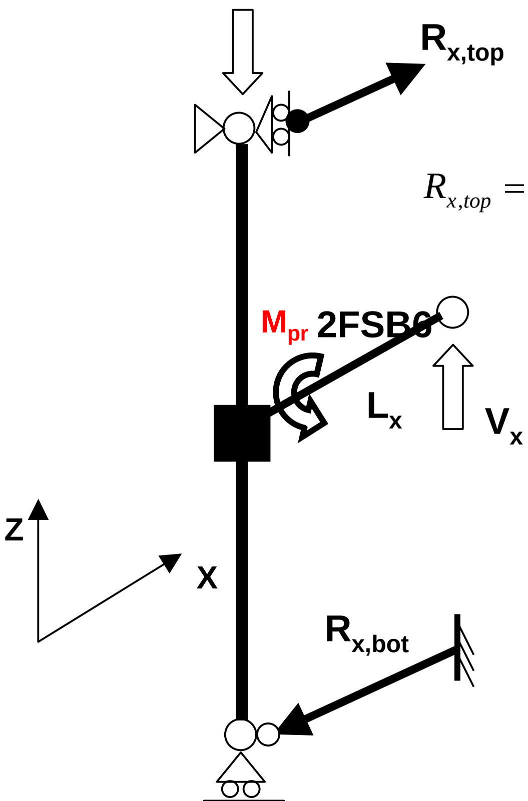
$$\Rightarrow V_{y,1} = 16.9\,kip \Rightarrow R_y = 16.1\,kip$$

$$note: \alpha = 1.25\ is\ used$$

Beam-Column Connection Test

▣ Idealized Force and Reaction System

$$P = 216 \pm k_x V_x$$



$$R_{x,top} = R_{x,bot} = \frac{L_x}{H_1 + H_2} V_x$$

$$= \frac{112.5}{51+80} V_y \approx 0.86 V_x$$

$$M_{pr} = 2645 \ kip - in$$

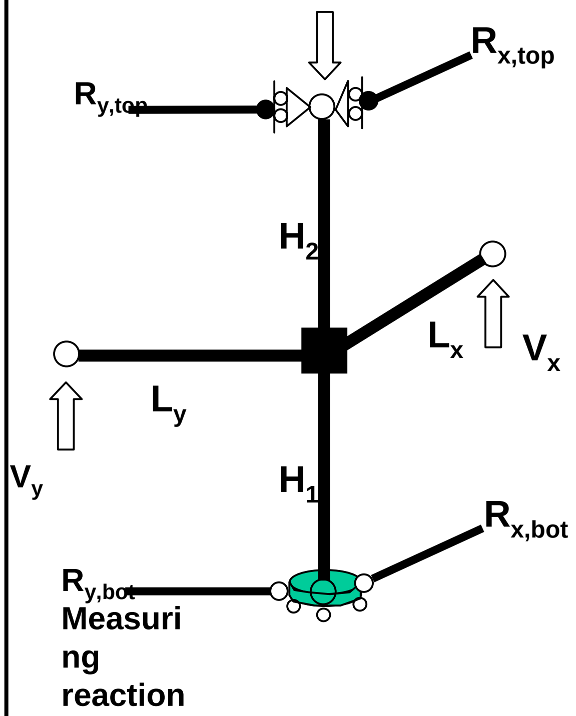
$$\Rightarrow V_x = 23.5 \, kip \Rightarrow R_x = 20.2 \, kip$$

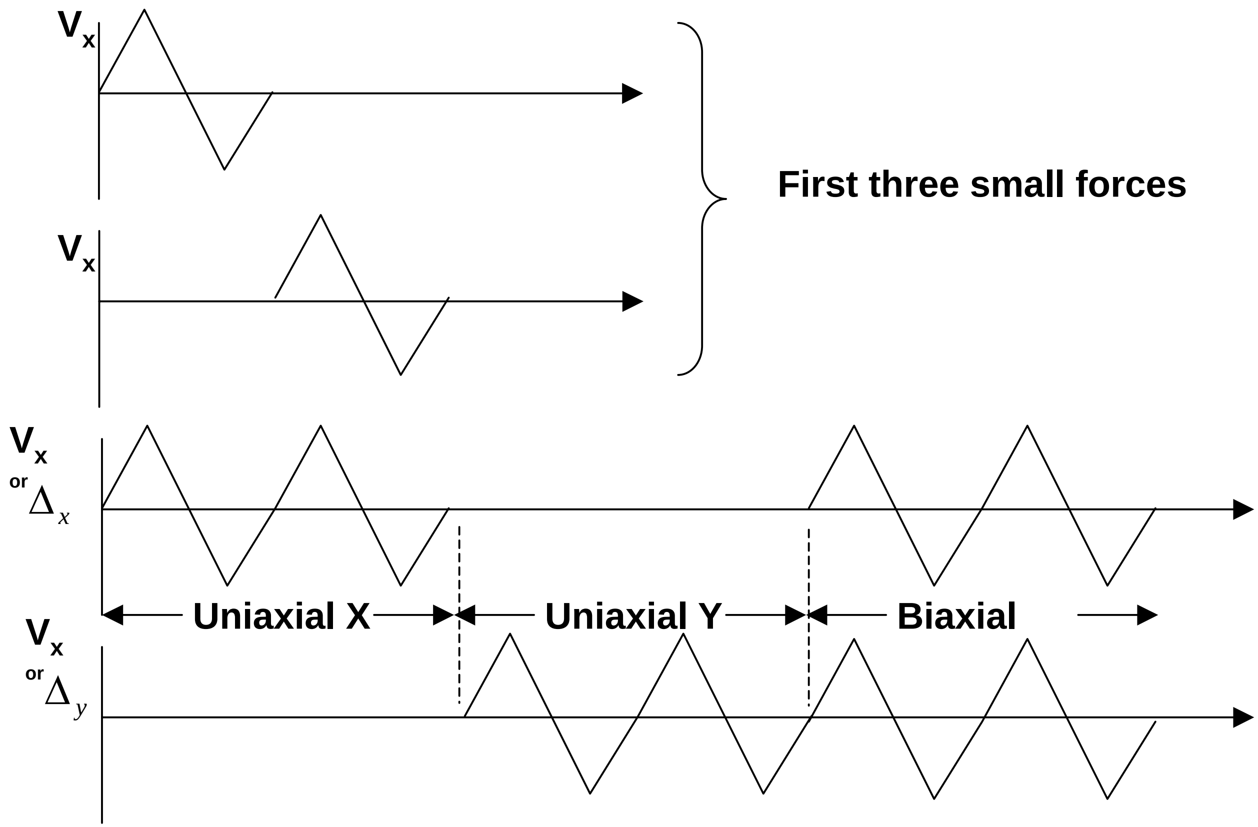
$$note: \alpha = 1.25 \ is \ used$$

Beam-Column Connection Test

▣ Sequence of forces and displacements

$$P = 216 \pm k_x V_x \pm k_y V_y$$

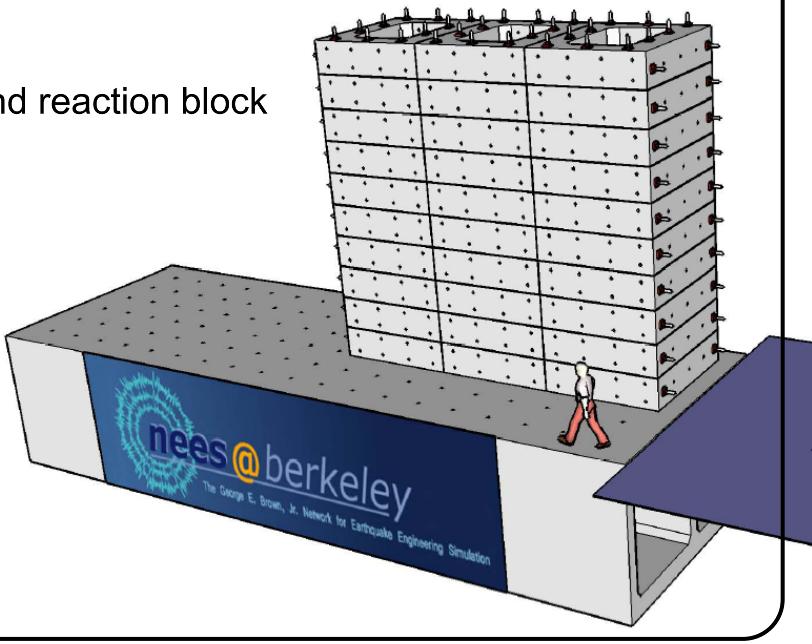




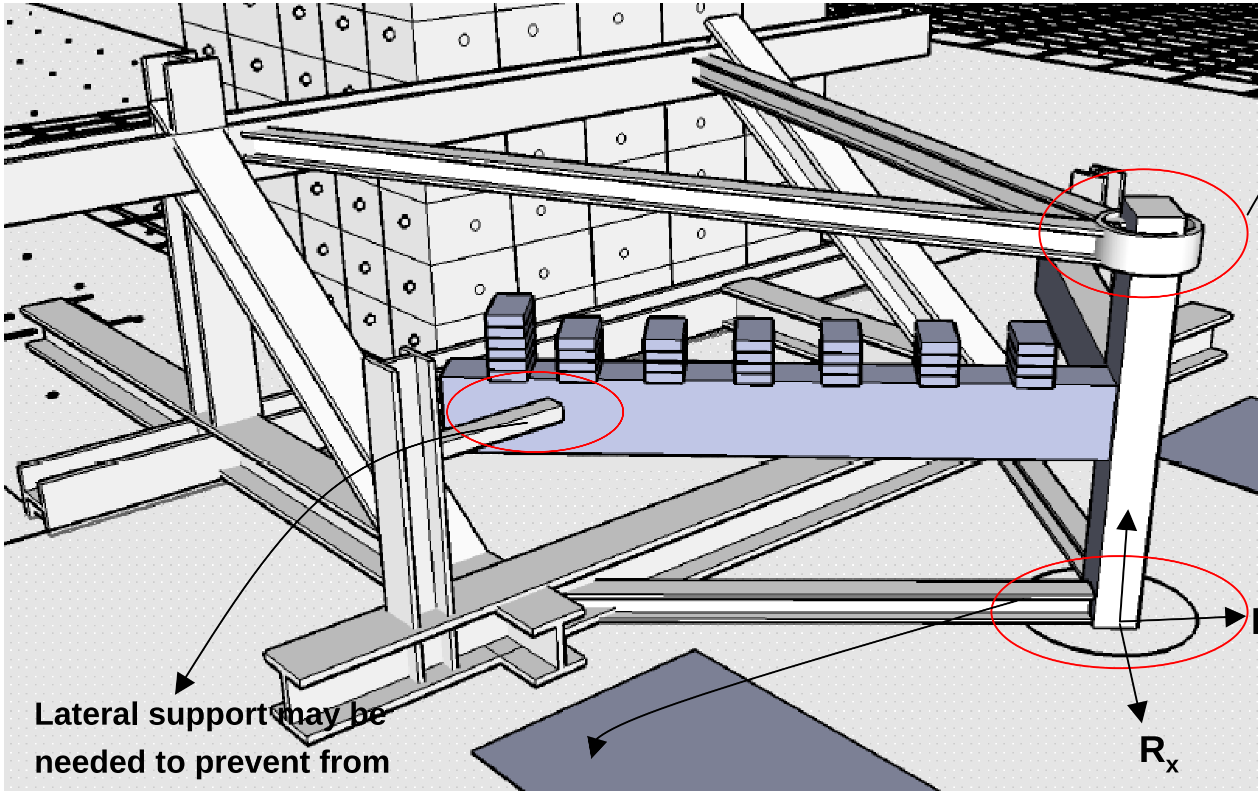
Beam-Column Connection Test

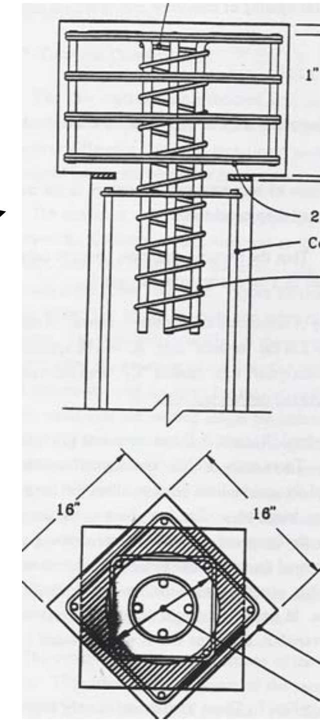
▣ Lab constraining conditions

1. Current positions of reaction blocks are not movable
2. No hole for anchorage in the floor below 4M UTM
3. Need on the lateral supports at the top and bottom of column
4. Placing two actuators below the two beams to control applied forces and displacements
5. From the above, test frame is needed
6. Test frame should be connected to the strong floor and reaction block



Beam-Column Connection Test Setup





Lateral support may be needed to prevent from twisting

How to measure two(+axial) reactions

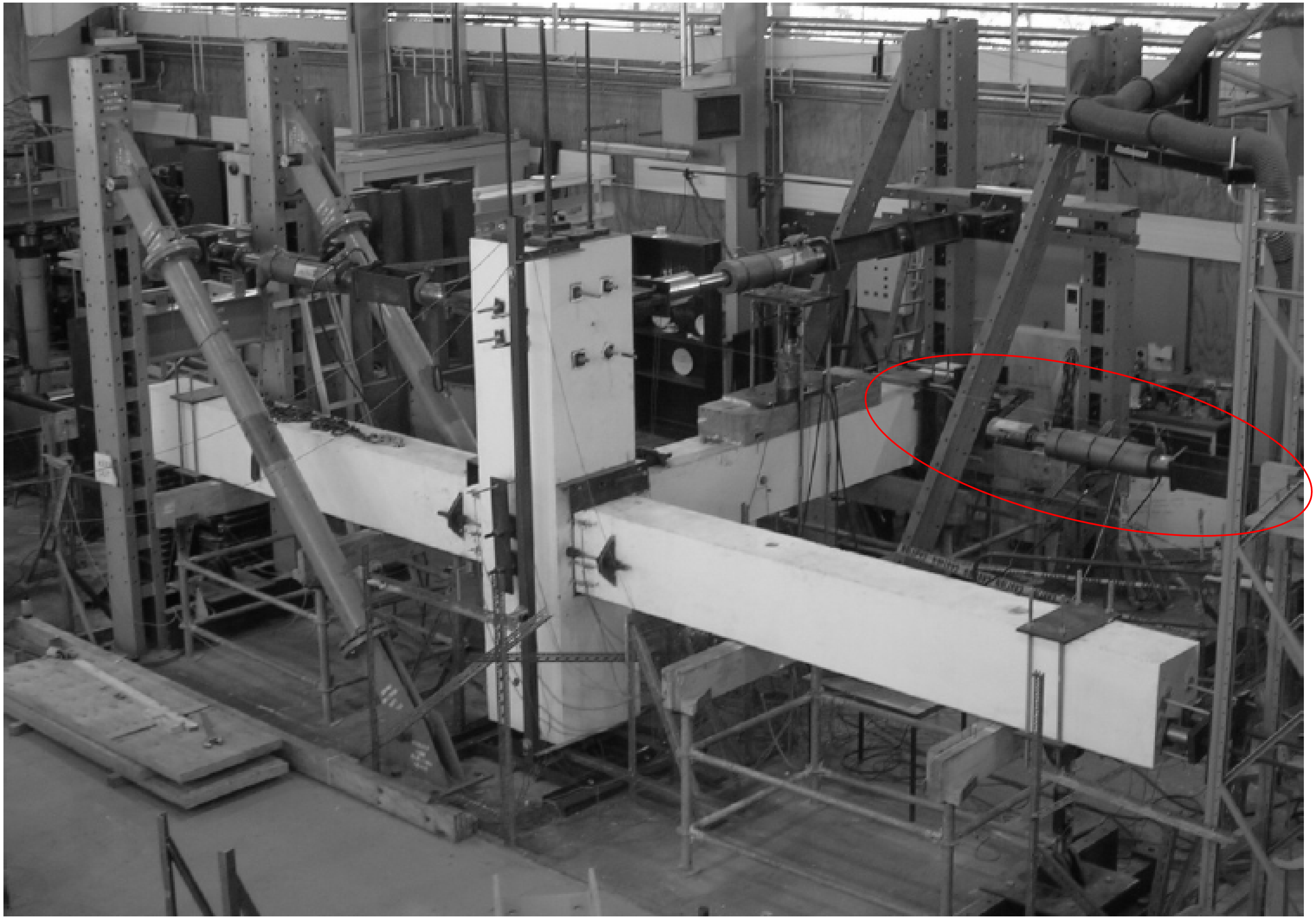
: 1. attach additional actuators

hard to measure exact reactions due to the friction

2. use 6 component load cell(if possible)

3. Not necessarily to measure R_x, R_y by using static equilibrium

Beam-Column Connection Test



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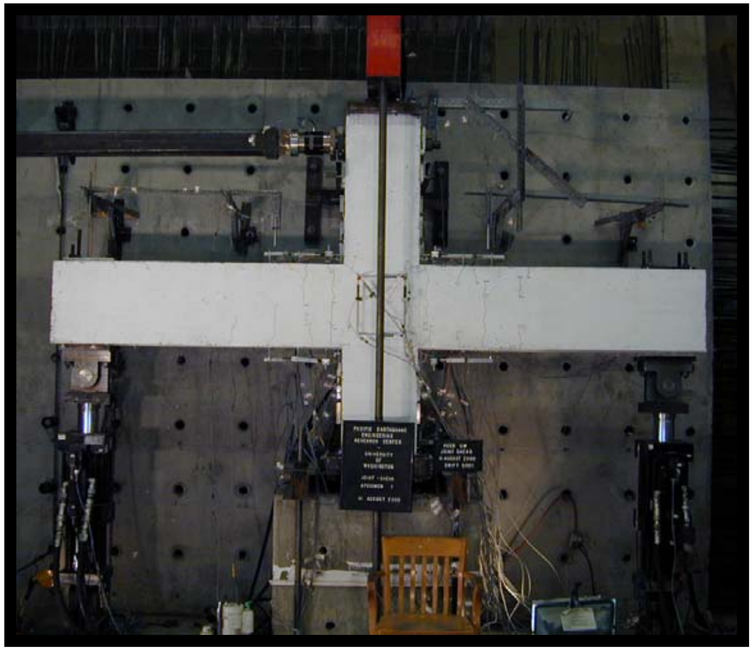

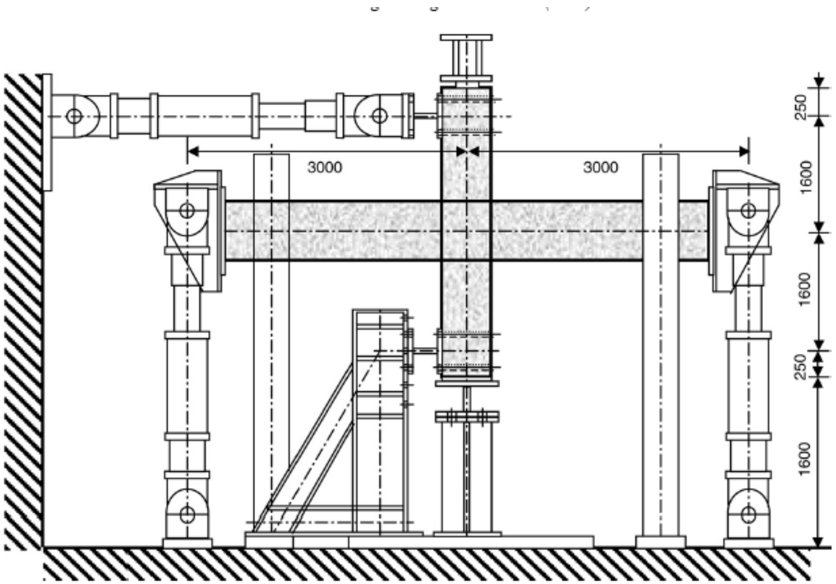

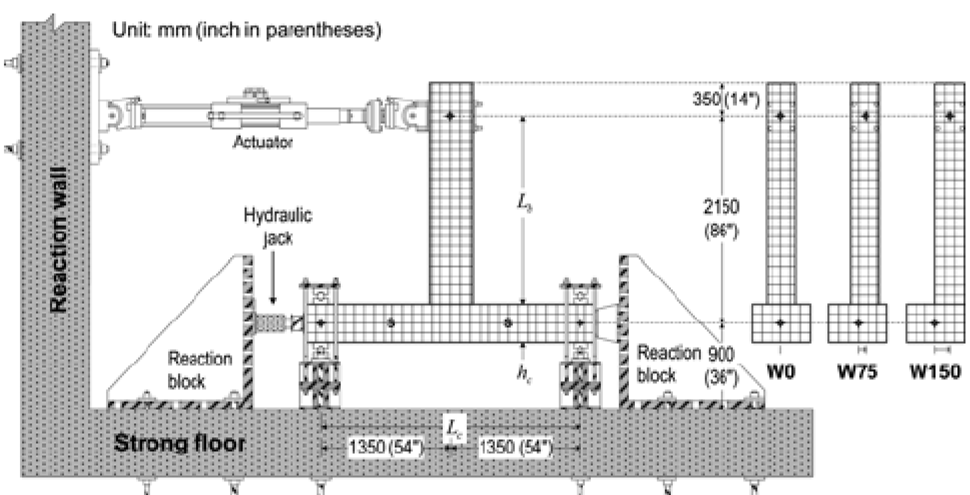

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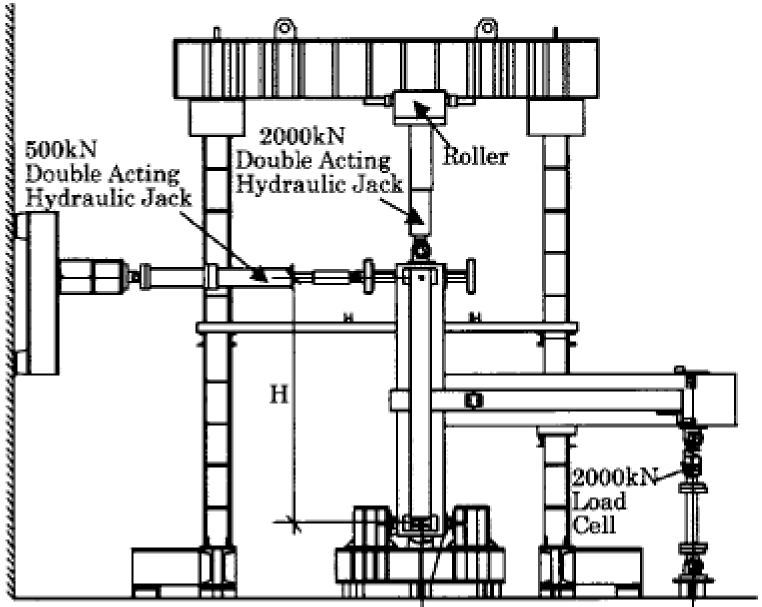
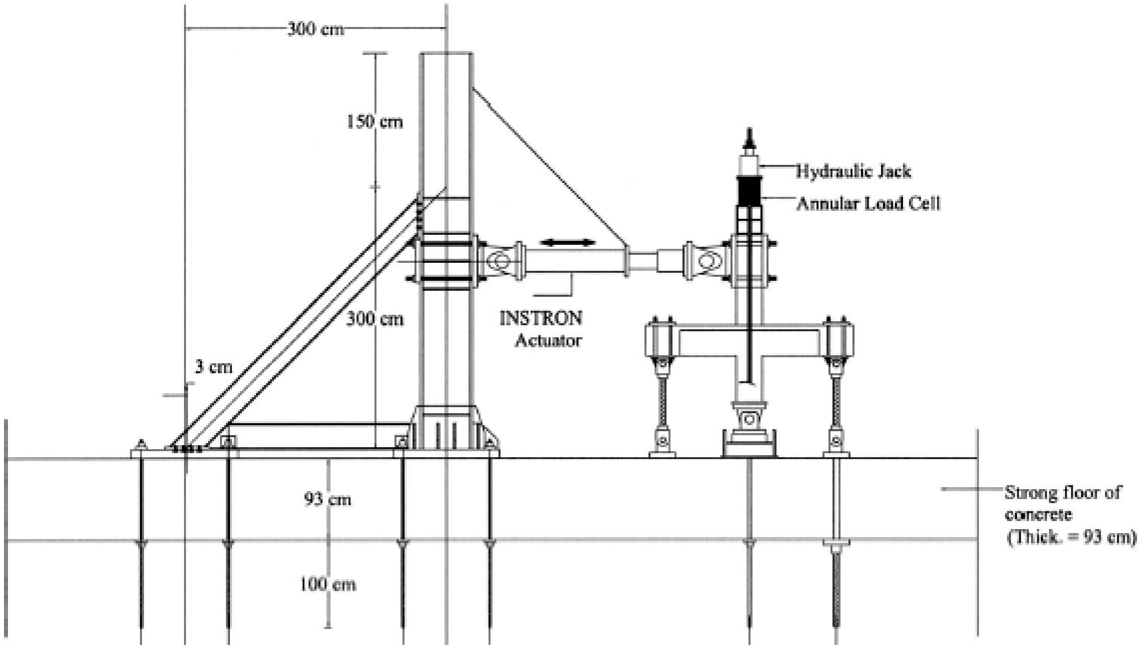
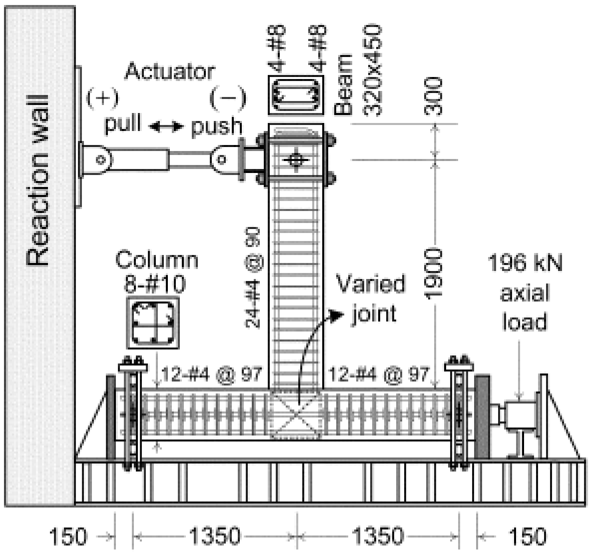
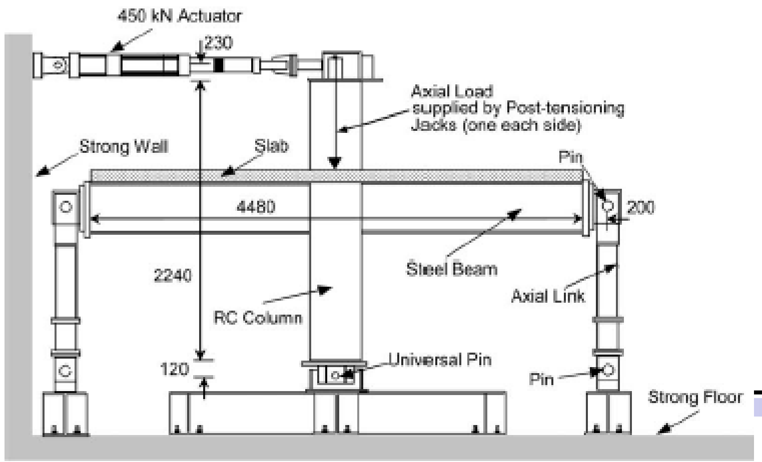


Beam-Column Connection Test



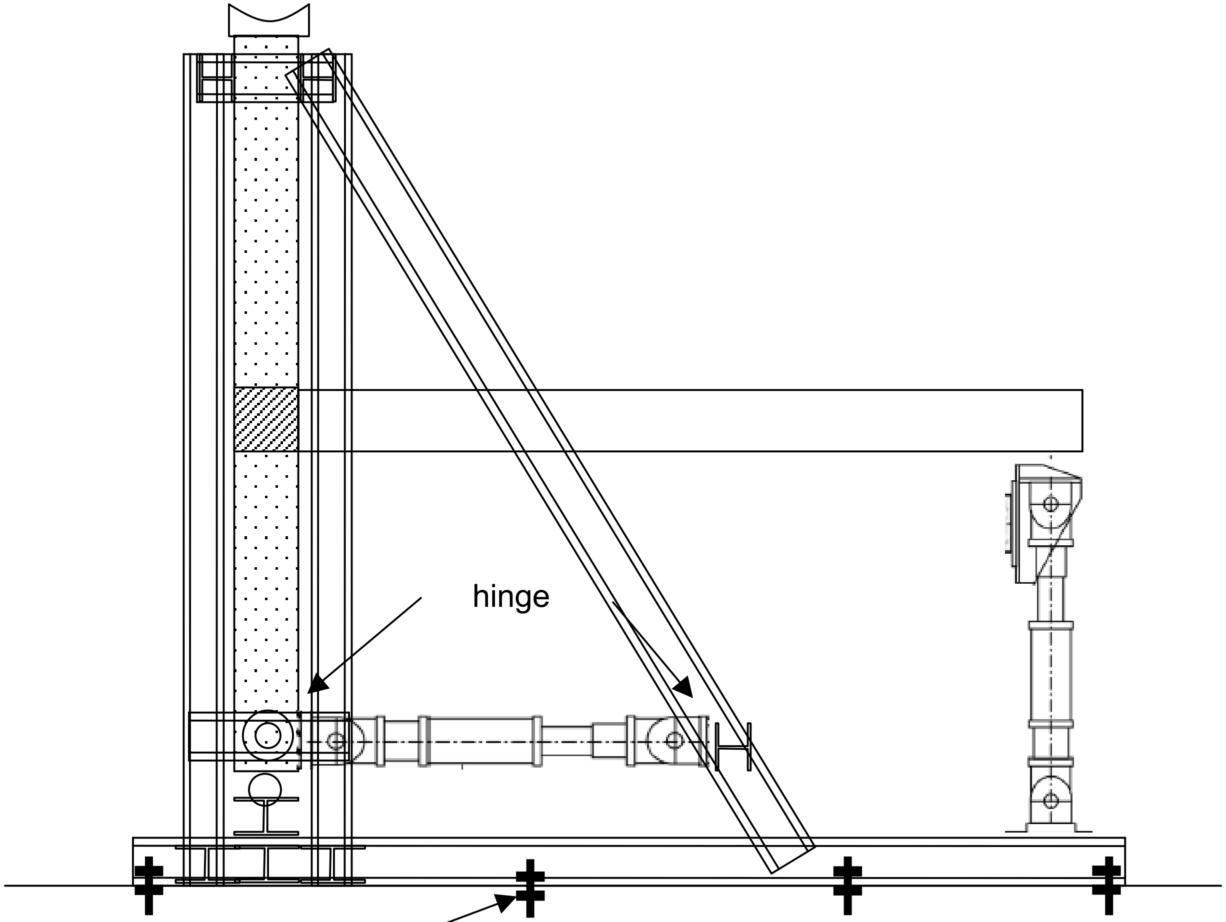




Dimensions in mm

Student Researcher：SANGJOON PARK

Beam-Column Connection Test



The problem is how to strongly connect bottom steel with bottom floor because here is not strong floor