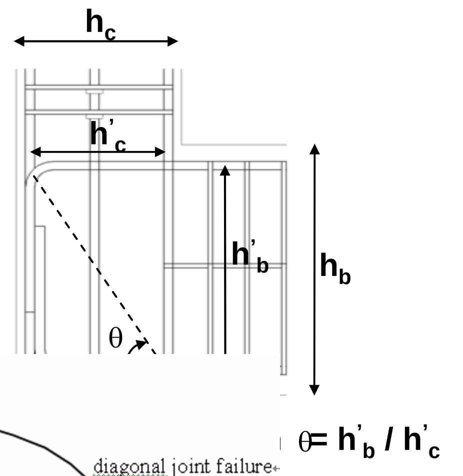
Specimen Design of Corner Beam-Column Connections

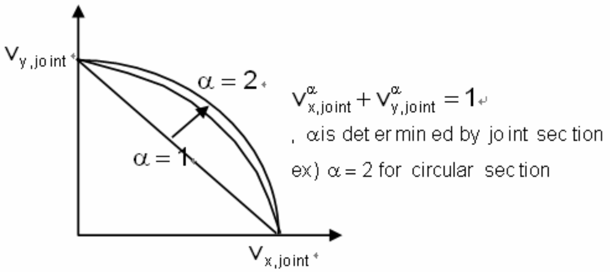
Advisor : Professor Mosalam

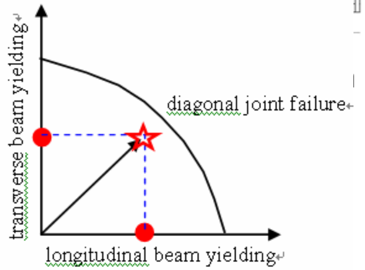
Student Researcher : SANGJOON PARK

Objectives of Experimental Investigation

- Joint Failure Modes vs Beam Flexural Strength
- Effect of Joint Aspect Ratios
- Effect of High Column Axial Load
- Joint Behavior a
- Effect of Biaxial l
- Effective Slab Width in Corner Joint







Prototype – Van Nuys Holiday Inn (7story)

	Con'c(ksi)		Rebar
Column	1st	5.0	Grade 60
	2nd	4.0	
	3-7	3.0	
Beam Slab	2nd	4.0	Grade 40
	3-roof	3.0	

- Gravity Design Information

  -. Beam : 16''x30''   Column : 14''x20''   Span : 20 ft

- Beam Shear and Column Axial Force Relation

  -. Linear equation : $P_{average}=185 + 3.5(V_{b,x}-10) +3.5(V_{b,y}-10)$

- Range of Corner Column Axial Force Variation

  -. $P_{overturning} \approx$ 60% of $P_{gravity}$ to each direction

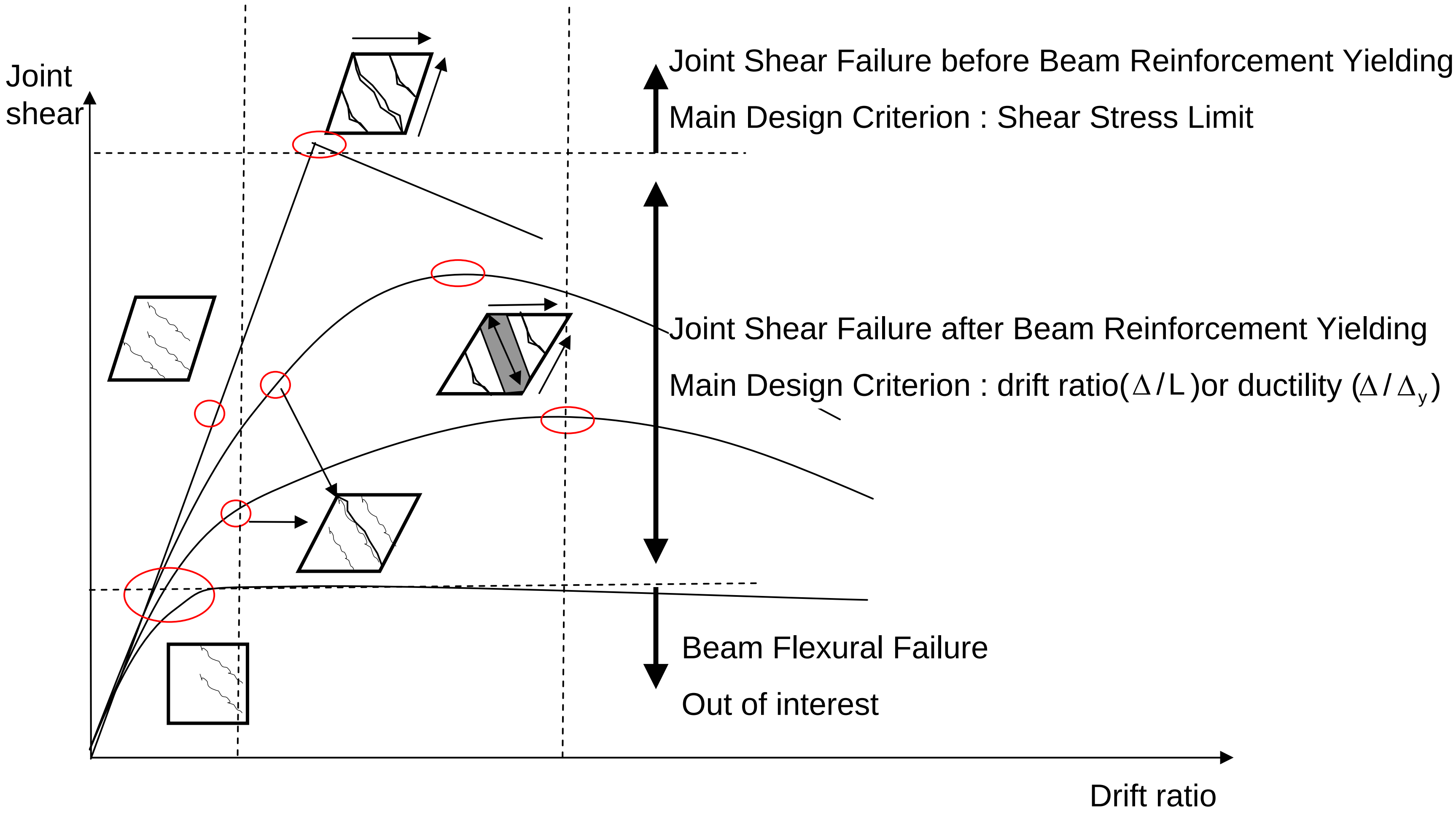
  -. $P_{total} =(0.15\ f_c\ A_g)*(1+0.6*2)=0.33f_cA_g \approx$ @ the balance point

- Joint Shear Strength and Demand

  -. Small joint shear demand due to small amount of reinforcement in beam

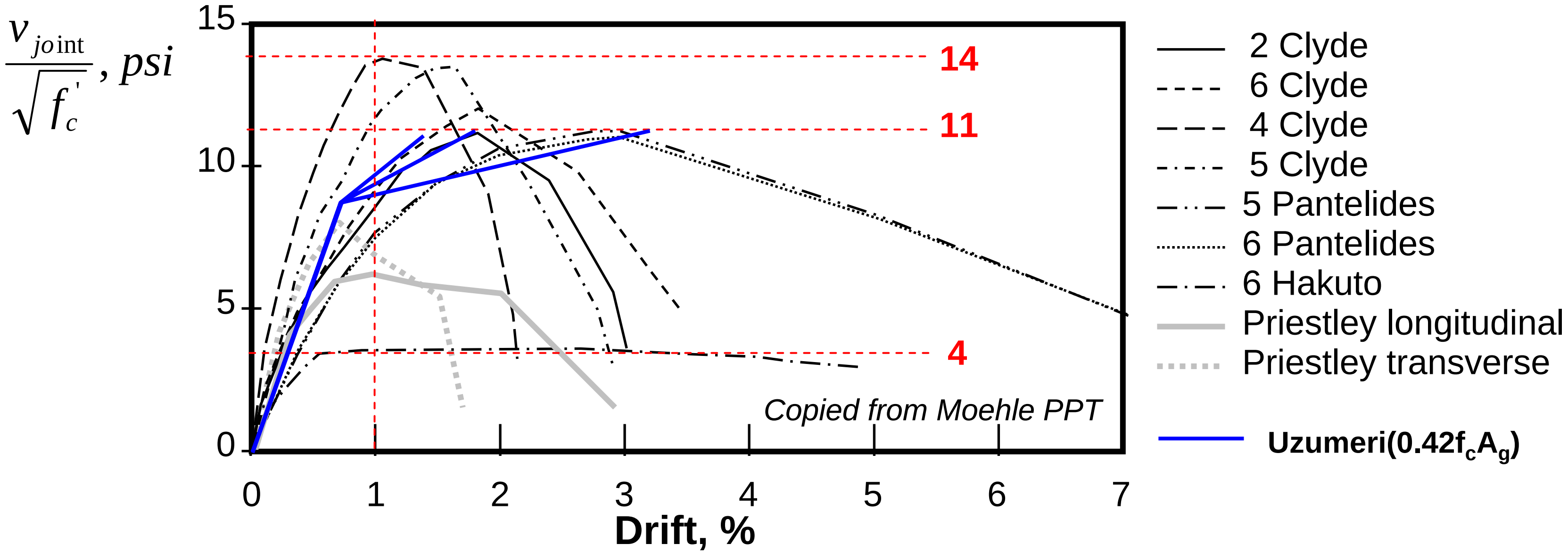
Design Criteria

Criteria per Target Failure Mode



Design Criteria

Joint Shear Strength Factor $v_{joint} / \sqrt{f'_c}$



$$\frac{v_j}{\sqrt{f'_c}} > \begin{cases} 12 \text{ for J failure} \\ 8 \text{ for BJ failure at yielding} \end{cases} \text{for aspect ratio } 1.9:1.0$$

$$\begin{cases} 14 \text{ for J failure} \\ 10 \text{ for BJ failure at yielding} \end{cases} \text{for aspect ratio } 1.0:1.0$$

Design Criteria

Drift and Ductility

Drift ratio : $\frac{\Delta}{L} > 0.010$ for J failure at yielding

Ductility : $\frac{\Delta}{L} > 0.03$, $\frac{\Delta}{\Delta_y} > 3$ for BJ failure

Principal Tensile Stress

$$\frac{\sigma_{tensile}}{\sqrt{f_c^{'}}} > \begin{cases} 5 \text{ for J failure} \\ 4 \text{ for BJ failure at yielding} \end{cases} \text{for aspect ratio } 1.9:1.0$$

$$\begin{cases} 6 \text{ for J failure} \\ 5 \text{ for BJ failure at yielding} \end{cases} \text{for aspect ratio } 1.0:1.0$$

Specimen Design

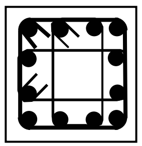
1. Specimen Matrix

Specimen	dimension	Beam Reinforcement				Aspect ratio (h_b/h_c)	Target Failure
		main rebars		stirrups	**Slab**[1]		
		Top	Bot				
SP1	16''X30''	**5-#8**	**5-#8**	#3@4''	**6-#3**	1.92 : 1	J
SP2	16''X18''	**5-#8**	**5-#8**	#3@4''	**4-#3**	1.00 : 1	J
SP3	16''X30''	**4-#7**	**4-#7**	#3@4''	**6-#3**	1.92 : 1	BJ
SP4	16''X18''	**4-#7**	**4-#7**	#3@4''	**4-#3**	1.00 : 1	BJ

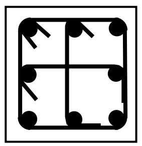
[1] : assuming effective slab width is summation of beam width(b_b) and transverse beam depth(h_{tb})

Specimen	Column			Slab	
	dimension	reinforcement	hoops[2]	thickness	reinforcement
SP1 & 3	18''X18''	**12-#9**	#3@4''	6''	#3@12''(top & bot)
SP2 & 4	18''X18''	**8-#9**	#3@4''	6''	#3@12''(top & bot)

[2] : Two types of hoops

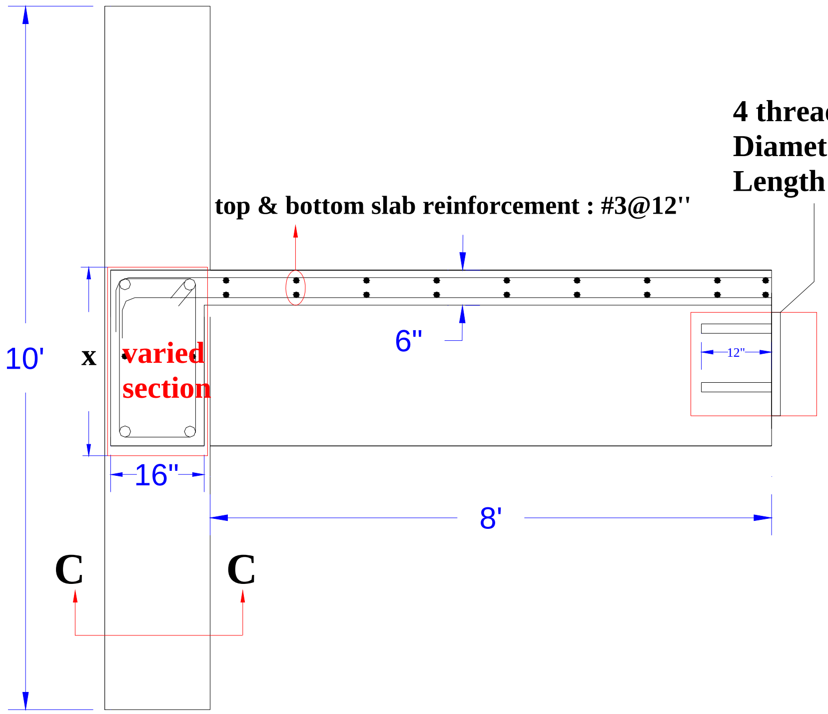


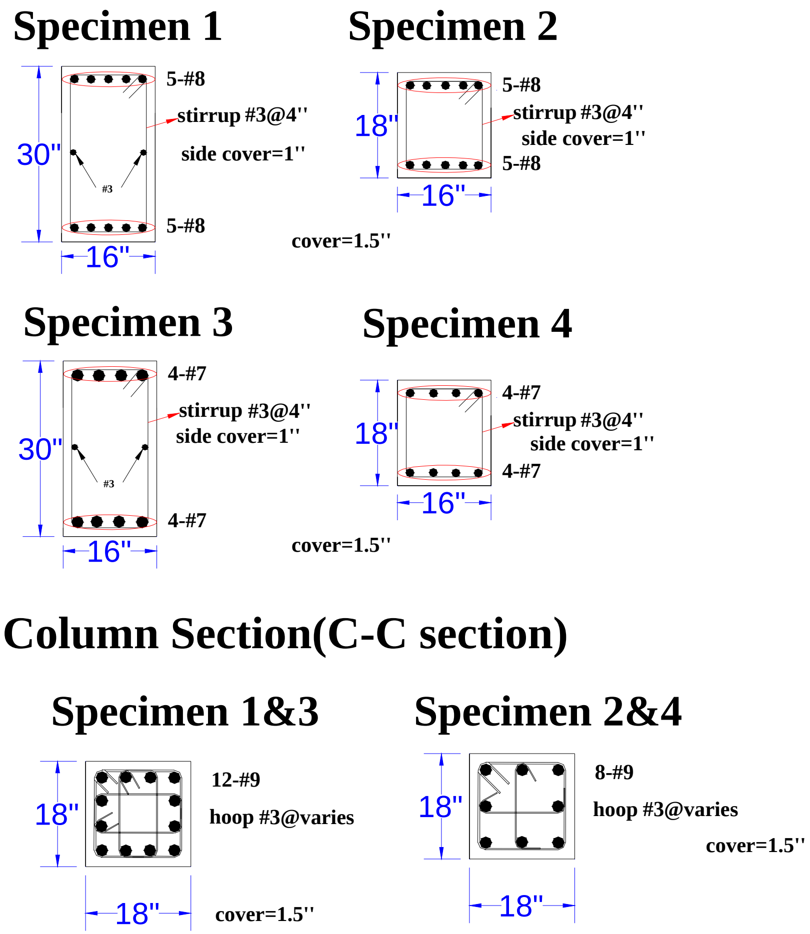
SP1&3



SP2&4

2. Specimen Geometry and Reinforcement



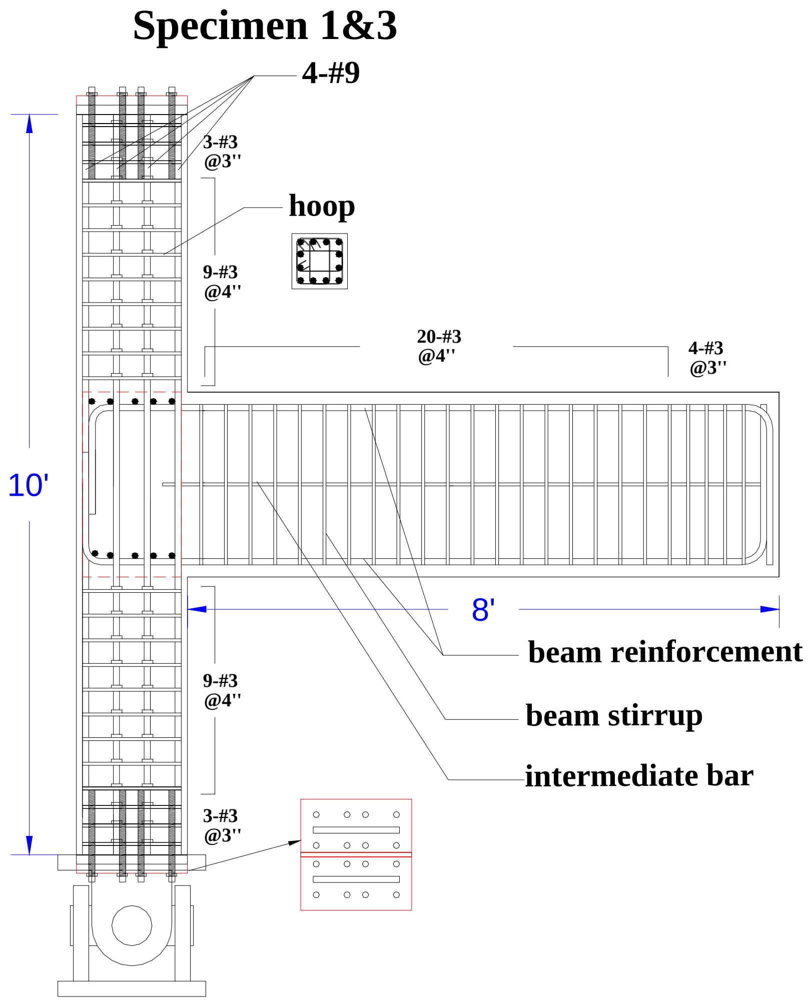


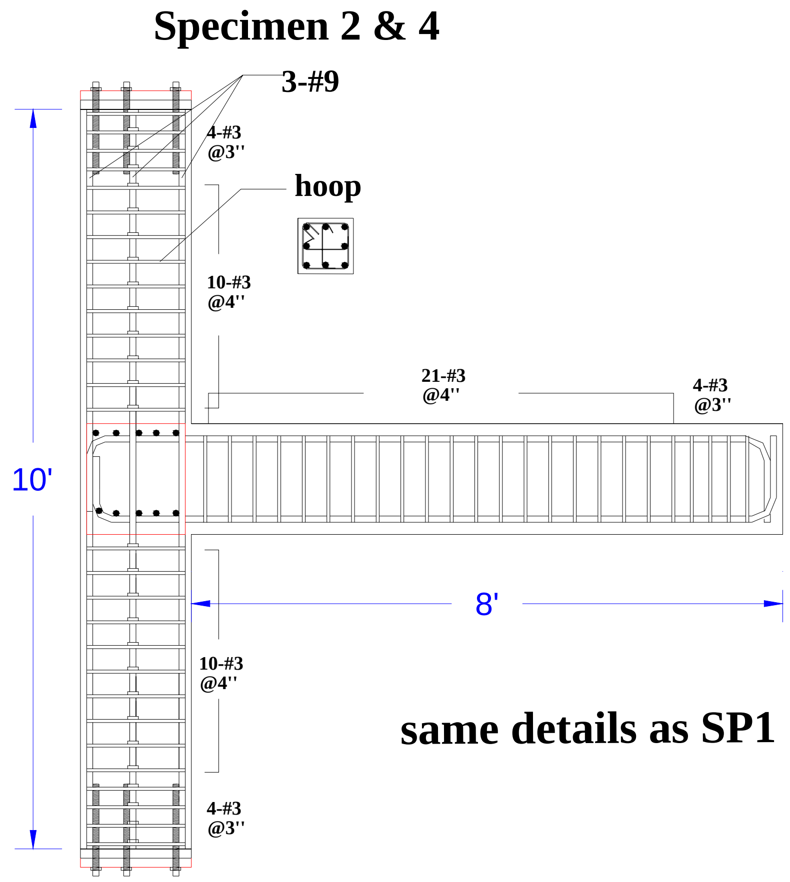
For All Specimens,

Concrete Strength : f_c = 3.5 ksi

Reinforcing bars : Grade 60

3. Specimen Geometry and Reinforcement





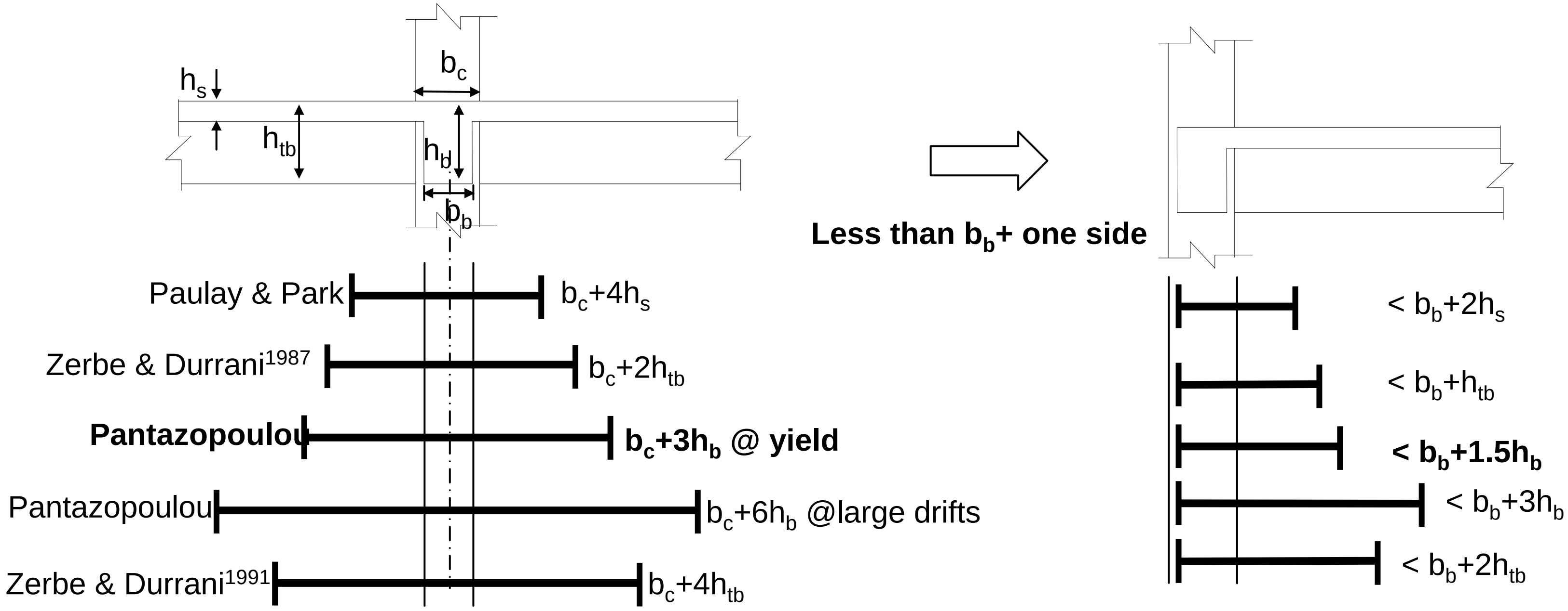
4. Effective Slab width

(1) ACI 352

b_{eff} = Min.
- a) web width + one-twelfth the span length of the beam
- b) web width + six times the slab thickness
- c) web width + one-half the clear distance to the next web

And **$b_{eff} \geq 2b_b$**

(2) Research Suggestions for Exterior Connections



Analysis of Specimen Design

Specimen 1 with $b_{eff}=b_b+h_{tb}$

SP1	Downward (Negative Moment)		Upward (Positive Moment)	
	Yield	Ultimate	Yield	Ultimate
V_b(kip)	-83	-113	73	97
M_b(kip-in)	-7922	-10812	7030	9324
f_s(ksi)	68	95	68	92
yield	Yes	Yes	Yes	Yes
$P_{col,avg}$ ($(P_{col}/(f'_cA_g))$)	**-326 (0.29)**	**-402 (0.35)**	**63**	**123**
V_{joint}(kip)	241	339	205	280
$\tau/\sqrt{f'_c}$ (psi)	**13.3**	**18.7**	**11.3**	**15.5**
$\sigma_t/\sqrt{f'_c}$ (psi)	**7.3**	**11.0**	**13.1**	**19.0**
Δ/L (in/in)	**0.005[1]+0.005[2]**	**0.007[1]+0.034[2]**	**0.004[1]+0.004[2]**	**0.006[1]+0.021[2]**
Δ/Δ_y(in/in)		**4.1**		**3.4**

( )[1] : $\theta_{col} = \frac{0.5h\,M_{col}}{3(EI)_{col}} = \frac{0.5h\,0.5M_{beam}}{3(EI)_{col}}, \quad (EI)_{col} = \frac{M_y}{\phi_y}$ at $P = -150$kips (ignoring reduced EI due to the initial crack)

( )[2] : calculated from beam tip displacement by using Principle of Virtual Work under the assumption of multi-linear curvature curve.

Specimen 2 with $b_{eff}=b_b+h_{tb}$

SP2	Downward (Negative Moment)		Upward (Positive Moment)	
	Yield	Ultimate	Yield	Ultimate
V_b(kip)	-42	-57	40	51
M_b(kip-in)	-4075	-5425	3831	4870
f_s(ksi)	68	95	68	92.9
yield	Yes	Yes	Yes	Yes
$P_{col,avg}$ ($P_{col}/(f'_c A_g)$)	**-331 (0.29)**	**-394 (0.35)**	**40**	**88**
V_{joint}(kip)	261	367	234	323
$\tau/\sqrt{f'_c}$ (psi)	**14.4**	**20.3**	**12.9**	**17.8**
$\sigma_t/\sqrt{f'_c}$ (psi)	**8.2**	**12.5**	**14.0**	**20.3**
Δ/L (in/in)	**0.005+0.009**	**0.007+0.068**	**0.005+0.007**	**0.006+0.042**
Δ/Δ_y(in/in)		**5.4**		**4.0**

Specimen 3 with $b_{eff}=b_b+h_{tb}$

SP3	Downward (Negative Moment)		Upward (Positive Moment)	
	Yield	Ultimate	Yield	Ultimate
V_b(kip)	-55	-75	45	60
M_b(kip-in)	-5299	-7187	4323	5794
f_s(ksi)	68	95	68	94
yield	Yes	Yes	Yes	Yes
$P_{col,avg}$ ($P_{col}/(f'_c A_g)$)	**-258 (0.22)**	**-307 (0.27)**	**-7 (0.0)**	**31**
V_{joint}(kip)	160	225	124	173
$\tau / \sqrt{f'_c}$ (psi)	**8.8**	**12.4**	**6.8**	**9.6**
$\sigma_t / \sqrt{f'_c}$ (psi)	**4.4**	**6.8**	**6.6**	**10.4**
Δ / L (in/in)	**0.003+0.004**	**0.005+0.030**	**0.003+0.004**	**0.004+0.020**
Δ / Δ_y(in/in)		**5.0**		**3.4**

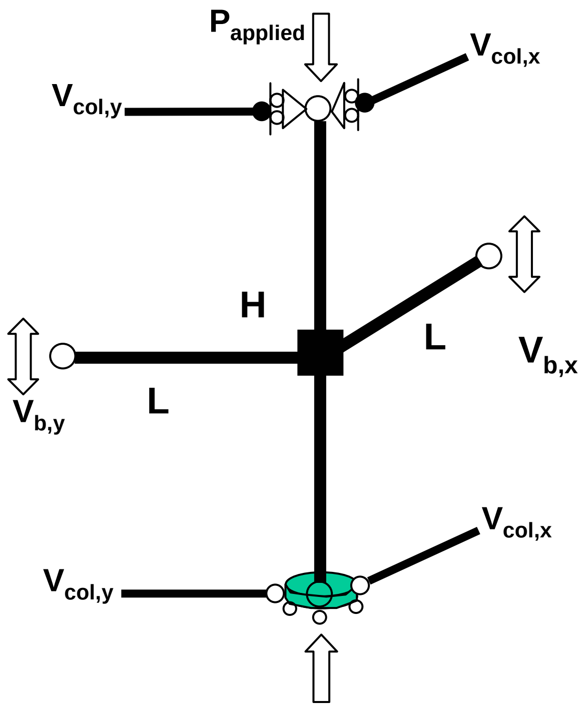
Specimen 4 with $b_{eff}=b_b+h_{tb}$

SP4	Downward (Negative Moment)		Upward (Positive Moment)	
	Yield	Ultimate	Yield	Ultimate
V_b(kip)	-28	-36	25	31
M_b(kip-in)	-2679	-3492	2383	2999
f_s(ksi)	68	95	68	93
yield	Yes	Yes	Yes	Yes
$P_{col,avg}$ ($P_{col}/(f'_c A_g)$)	**-266 (0.23)**	**-304 (0.27)**	**-28 (0.02)**	**1 (0.0)**
V_{joint}(kip)	169	238	141	197
$\tau / \sqrt{f'_c}$ (psi)	**9.3**	**13.1**	**7.8**	**10.9**
$\sigma_t / \sqrt{f'_c}$ (psi)	**4.7**	**7.4**	**7.1**	**10.9**
Δ / L (in/in)	**0.004+0.008**	**0.005+0.065**	**0.003+0.007**	**0.004+0.036**
Δ / Δ_y(in/in)	**-**	**5.8**		**4.0**

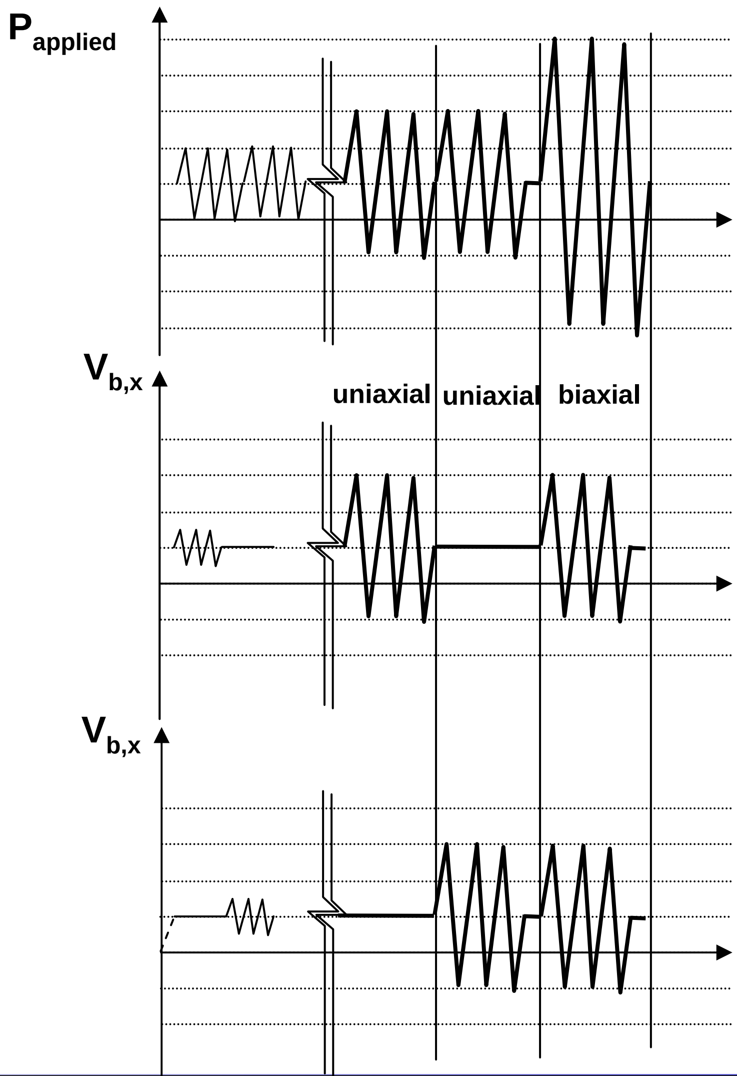
Axial Loading Sequence

SP1&3
- $P_{applied} = 135 + 2(V_{b,x} - 10) + 2(V_{b,y} - 10)$
- $P_{average} = 145 + 2.5(V_{b,x} - 10) + 2.5(V_{b,y} - 10)$

SP2&4
- $P_{applied} = 175 + 4(V_{b,x} - 10) + 4(V_{b,y} - 10)$
- $P_{average} = 185 + 4.5(V_{b,x} - 10) + 4.5(V_{b,y} - 10)$



$P_{react} = P_{applied} \pm V_{b,x} \pm V_{b,y}$



Comparison of Axial Loads

SP1 vs SP2 : Joint Shear Failure before beam reinforcement yielding

J failure		$P_{joint,avg}$ @yield			$P_{joint,avg}$ @ult.		
		Beam Shear	Column Axial		Beam Shear	Column Axial	
			uniaxial	biaxial		uniaxial	biaxial
Neg.	SP1	-83	**-326**	**-510**	-113	-402	-660
	SP2	-42	**-331**	**-473**	-57	-394	-608
Pos.	SP1	73	**63**	**270**	97	123	390
	SP2	40	**40**	**265**	51	88	364

SP3 vs SP4 : Joint Shear Failure after beam reinforcement yielding

BJ failure		$P_{joint,avg}$ @yield			$P_{joint,avg}$ @ult.		
		Beam Shear	Column Axial		Beam Shear	Column Axial	
			uniaxial	biaxial		uniaxial	Biaxial
Neg.	SP3	-55	**-258**	**-370**	-75	**-307**	**-470**
	SP4	-28	**-266**	**-347**	-36	**-304**	**-419**
Pos.	SP3	45	**-7**	**130**	60	**31**	**205**
	SP4	25	**-28**	**157**	31	**1**	**184**

Expected Axial Loading Range

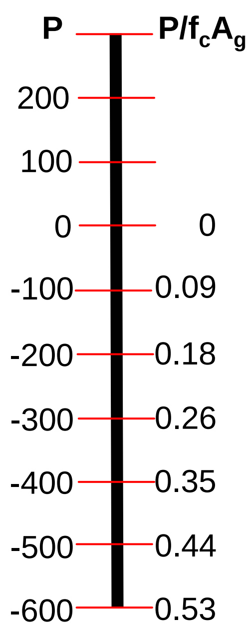
-. SP1 & SP3

$$P_{applied} = 135 + 2(V_{b,x}-10) + 2(V_{b,y}-10)$$

$$P_{average} = 145 + 2.5(V_{b,x}-10) + 2.5(V_{b,y}-10)$$

$$P_{react} = 155 + 3(V_{b,x}-10) + 3(V_{b,y}-10)$$

Beam Shear Force (Actuator), kip	Uniaxial Loading			Biaxial Loading		
	$P_{applied}$	$P_{average}$	$\mathbf{P_{react}}$	$P_{applied}$	$P_{average}$	$\mathbf{P_{react}}$
60	5	30	55	145	205	265
40	-35	-20	-5	65	105	145
20	-75	-70	-65	-15	5	25
0	-135	-120	-125	-95	-95	-95
-20	-155	-170	-185	-175	-195	-215
-40	-195	-220	-245	-255	-295	-335
-60	-235	-270	-305	-335	-395	-455
-80	-275	-320	-365	-415	-495	-575



Expected Axial Loading Range

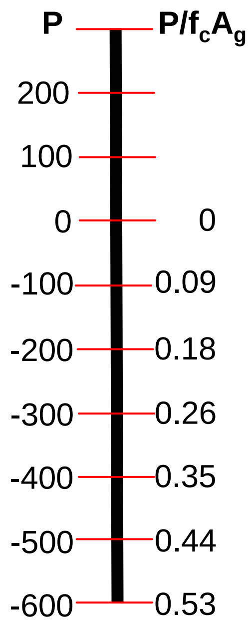
-. SP2 & SP4

$$P_{applied} = 175 + 4(V_{b,x}-10) + 4(V_{b,y}-10)$$

$$P_{average} = 185 + 4.5(V_{b,x}-10) + 4.5(V_{b,y}-10)$$

$$P_{react} = 195 + 5(V_{b,x}-10) + 5(V_{b,y}-10)$$

Beam Shear Force (Actuator), kip	Uniaxial Loading			Biaxial Loading		
	$P_{applied}$	$P_{average}$	**P_{react}**	$P_{applied}$	$P_{average}$	**P_{react}**
30	-15	-5	5	145	175	205
20	-55	-50	-45	65	85	105
10	-95	-95	-95	-25	-5	5
0	-135	-140	-145	-105	-95	-95
-10	-175	-185	-195	-185	-185	-195
-20	-215	-230	-245	-265	-275	-295
-30	-255	-275	-295	-345	-365	-395
-40	-295	-320	-345	-425	-455	-495
-50	-335	-365	-395	-505	-545	-595



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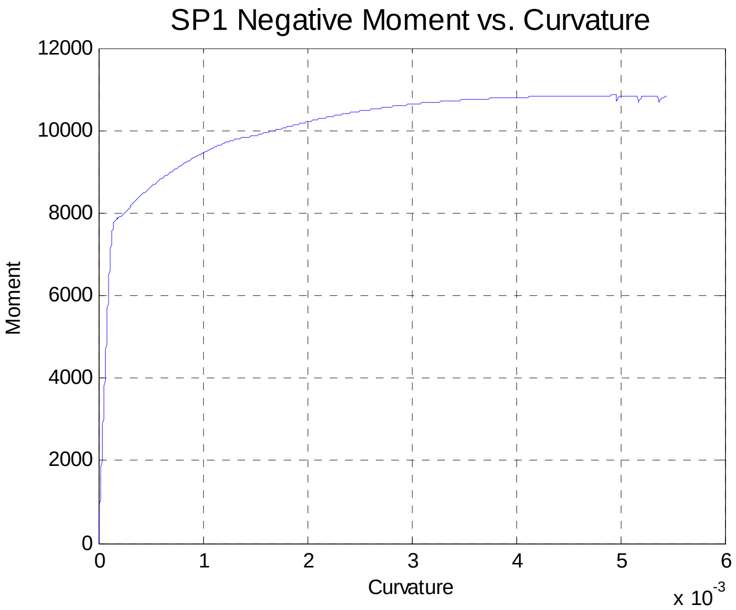

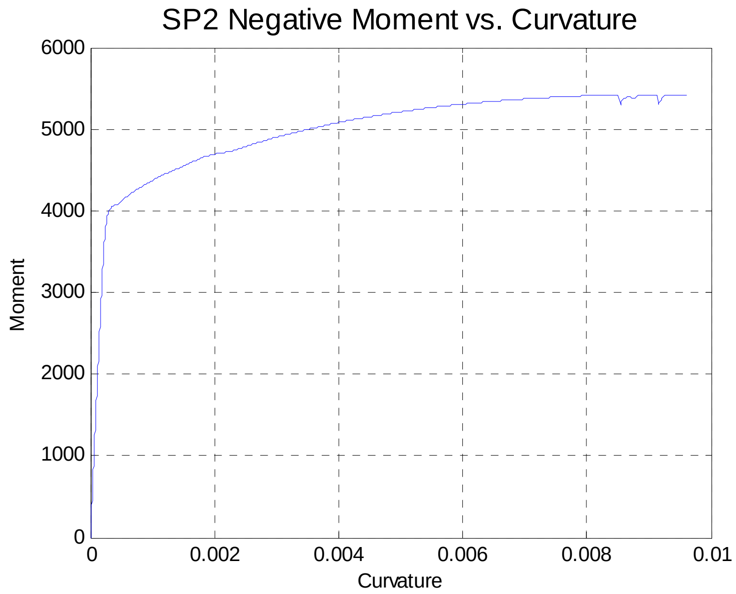

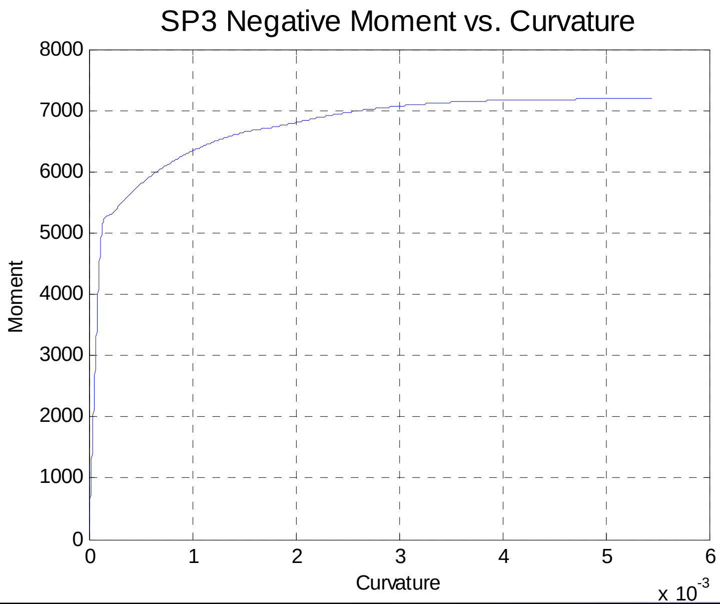

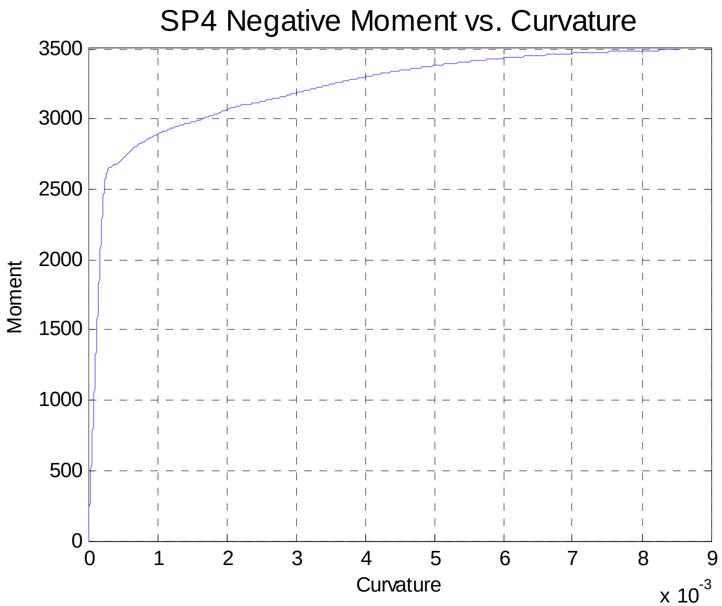

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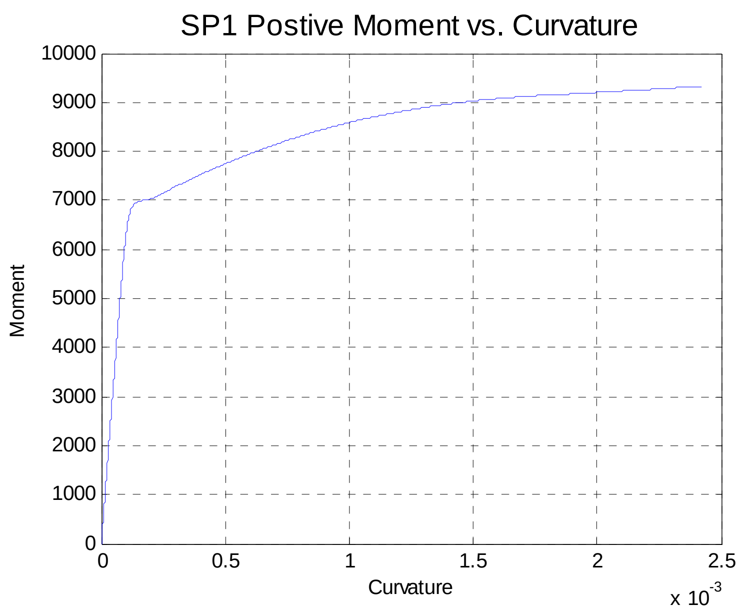

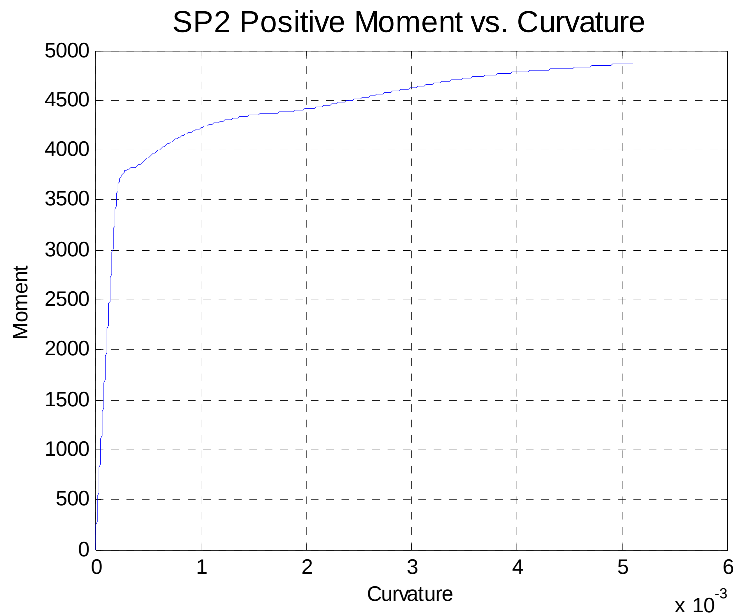

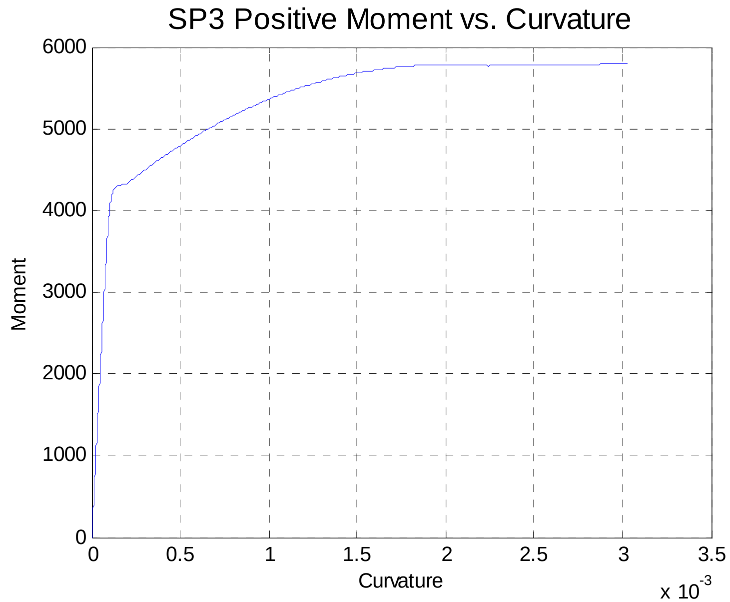

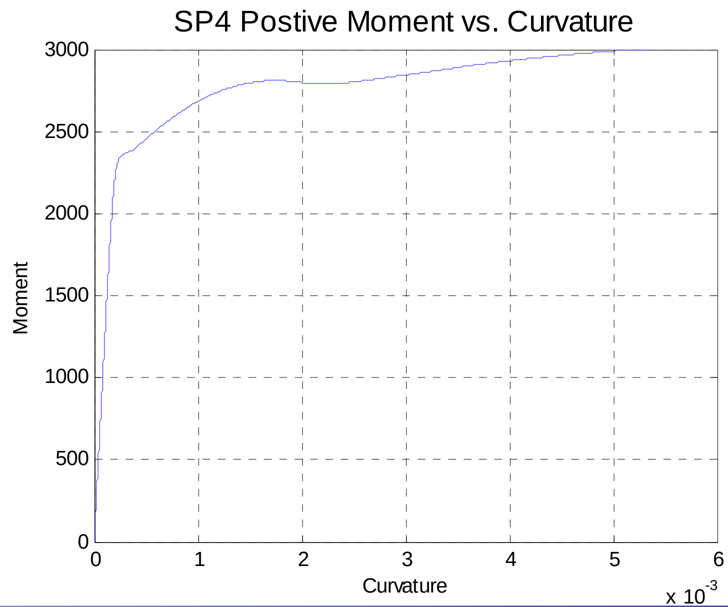

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Check Specimen Design

1. Joint Shear Demand by Section Analysis and ACI (A_s are estimated with $b_{eff}=b_b+1.0h_{tb}$)

-. Section Analysis

	$v_j/\sqrt{f'_c}$ (psi)			
	SP1	**SP2**	**SP3**	**SP4**
Yield	**13.3**	**14.4**	**8.8**	**9.3**
Ult.	18.7	20.3	**12.4**	**13.1**

-. ACE352

Specimen	V_{joint}(kip)	$\gamma(\upsilon_j/\sqrt{f_c})$
SP1	275	15.2
SP2	295	16.2
SP3	181	10.0
SP4	189	10.4

$$V_{demand} = T_{beam} - V_{col} \quad ,$$

$$T_{beam} = \alpha A_s f_y, \alpha = 1.25$$

$$V_{col} = \frac{M_b}{(h_{below} + h_{above})/2}$$

2. Joint Shear Strength by SST model and ACI

-. SST Model

$N/A_g f_c$	SP1 & SP3		SP2 & SP4	
	V_{joint}(kip)	$\gamma(\upsilon_j/\sqrt{f_c})$	V_{joint}(kip)	$\gamma(\upsilon_j/\sqrt{f_c})$
0.0	102	5.6	163	9.0
0.1	122	6.7	190	10.5
0.20	**142**	**7.8**	**216**	**11.9**
0.25	**152**	**8.4**	**229**	**12.6**
0.30	**162**	**8.9**	**242**	**13.4**
0.35	172	9.5	254	14.0

-. ACI352

exterior joint : $V_n = \gamma \times \sqrt{f_c} \times b_j \times h_c$(psi), $\gamma = 12$

$$= 12 \times \sqrt{3500} \times 17 \times 18 / 10^3 = 217 \text{ kips}$$

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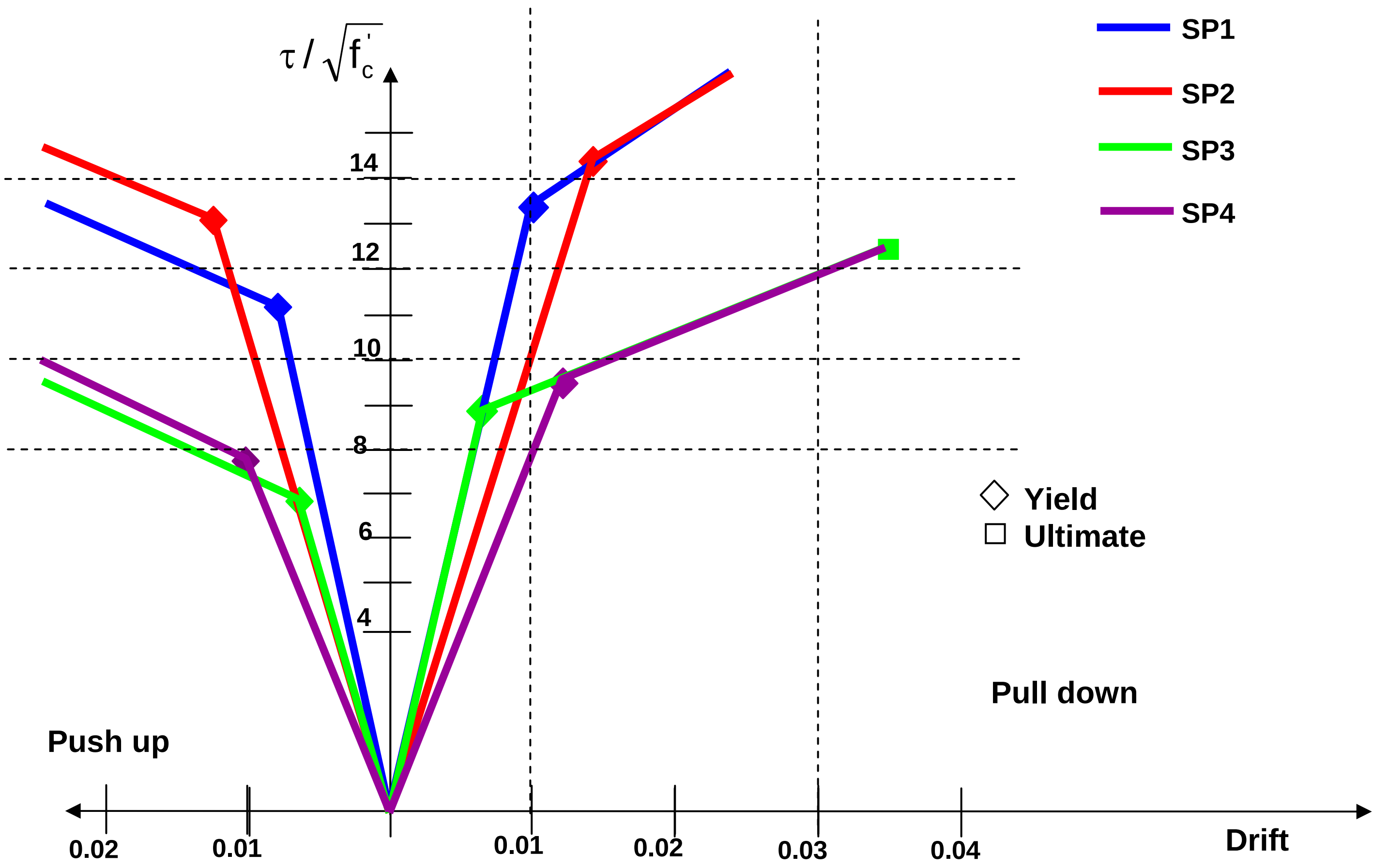
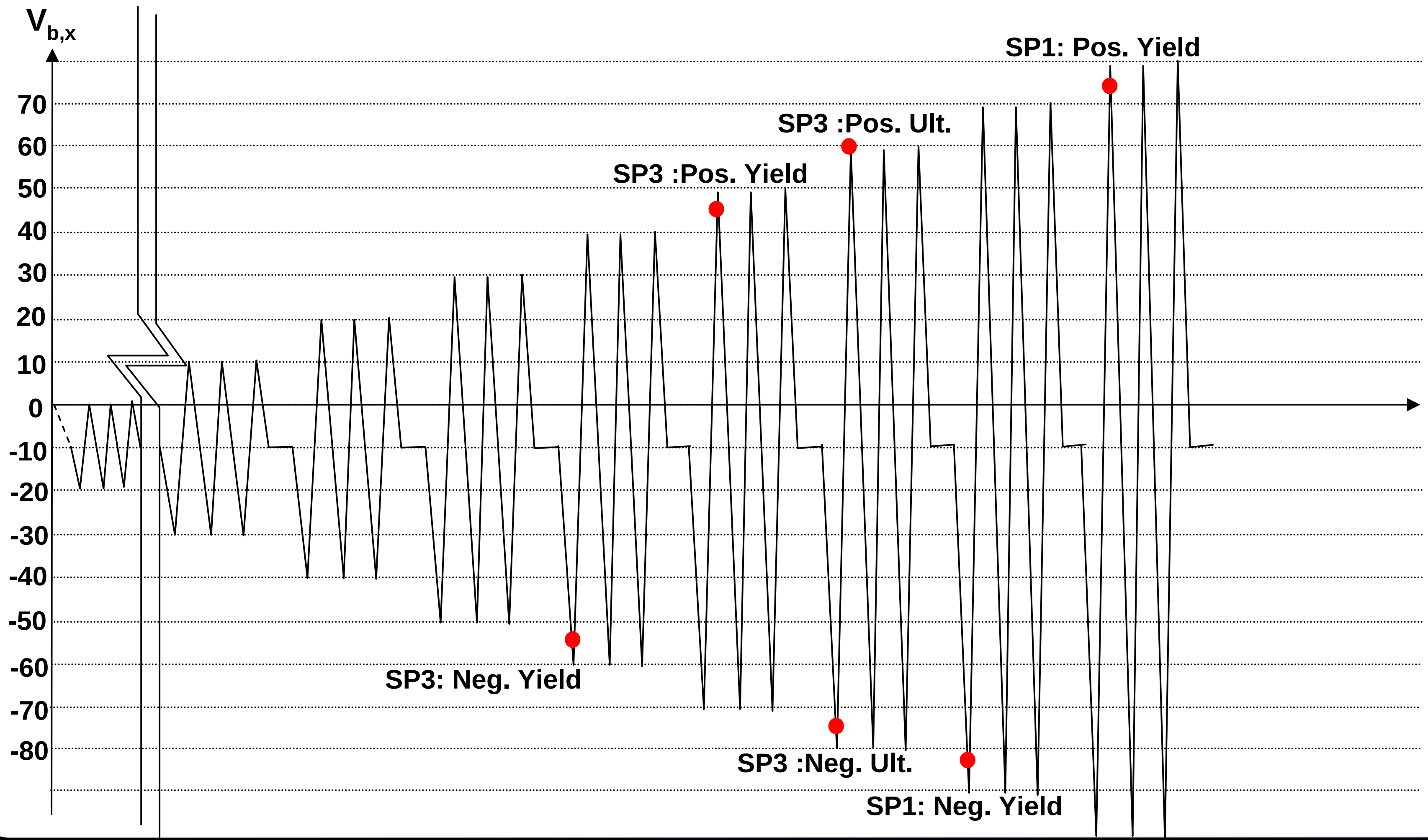
Check Specimen Design

3. Analysis Results



Check Specimen Design

-. Expected crucial points of SP1 & SP3



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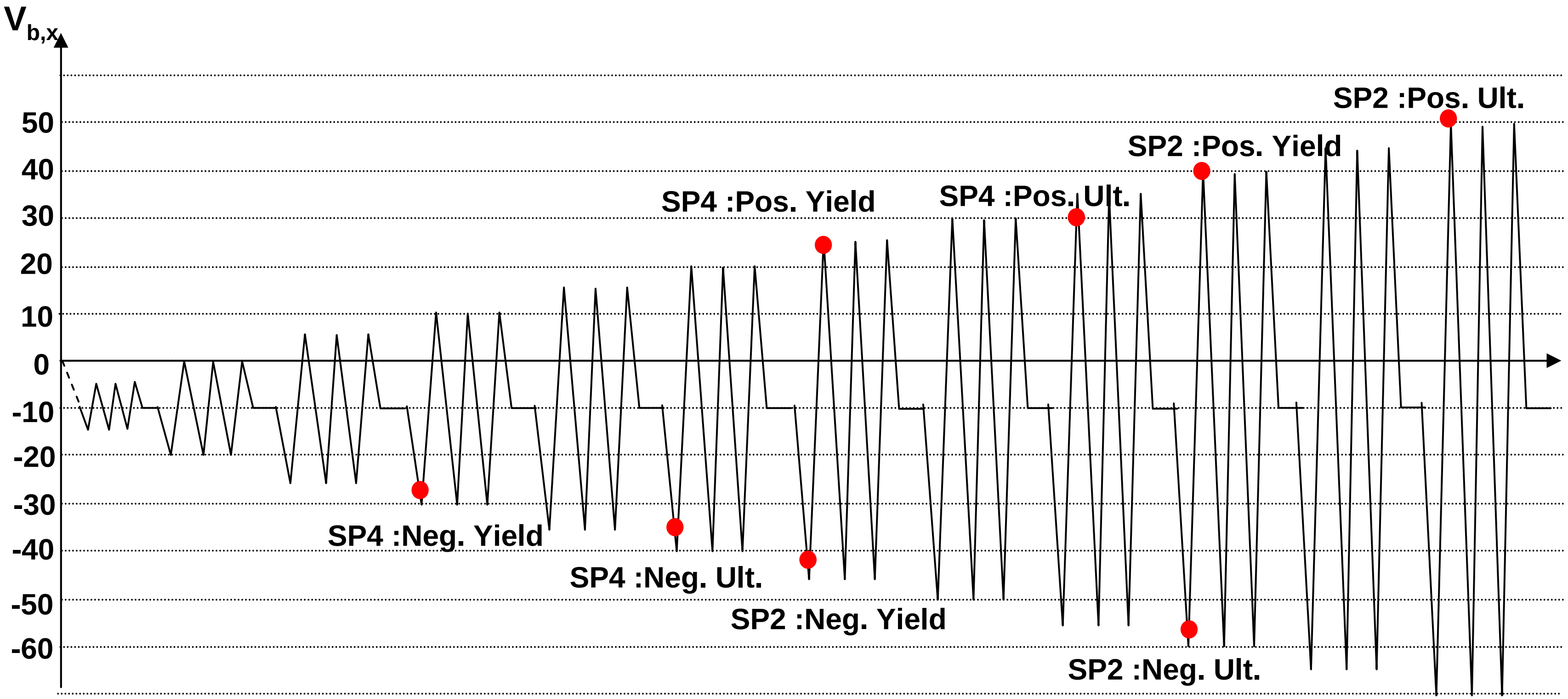
Check Specimen Design

-. Expected crucial points of SP2 & SP4



Check Specimen Design

-. Comparison with different b_{eff}

SP1 (1.9:1.0 &JF)	Yield			Ultimate		
	b_b	b_b+h_{tb}	$b_b+1.5h_{tb}$	b_b	b_b+h_{tb}	$b_b+1.5h_{tb}$
V_b(kip)	-71	-83	-86	-98	-113	-117
$P_{col}/(f'_c A_g)$	**0.26**	**0.29**	**0.30**	**0.32**	**0.35**	**0.36**
V_{joint}(kip)	206	241	253	288	339	353
$\tau/\sqrt{f'_c}$ (psi)	**11.4**	**13.3**	**14.0**	**15.9**	**18.7**	**19.5**
$\sigma_t/\sqrt{f'_c}$ (psi)	**6.0**	**7.3**	**7.7**	**9.0**	**11.0**	**11.5**

SP2 (1.0:1.0 &JF)	Yield			Ultimate		
	b_b	b_b+h_{tb}	$b_b+1.5h_{tb}$	b_b	b_b+h_{tb}	$b_b+1.5h_{tb}$
V_b(kip)	-39	-42	-44	-51	-57	-58
$P_{col}/(f'_c A_g)$	**0.28**	**0.29**	**0.30**	**0.33**	**0.35**	**0.35**
V_{joint}(kip)	235	261	275	329	367	380
$\tau/\sqrt{f'_c}$ (psi)	**13.0**	**14.4**	**15.2**	**18.2**	**20.3**	**21.0**
$\sigma_t/\sqrt{f'_c}$ (psi)	**7.2**	**8.2**	**8.7**	**10.9**	**12.5**	**13.0**

Check Specimen Design

SP3 (1.9:1.0 &BJ)	Yield			Ultimate		
	b_b	b_b+h_{tb}	$b_b+1.5h_{tb}$	b_b	b_b+h_{tb}	$b_b+1.5h_{tb}$
V_b(kip)	-44	-55	-59	-60	-75	-79
$P_{col}/(f'_c A_g)$	**0.20**	**0.22**	**0.24**	**0.24**	**0.27**	**0.28**
V_{joint}(kip)	125	160	171	175	225	240
$\tau/\sqrt{f'_c}$ (psi)	**6.9**	**8.8**	**9.5**	**9.7**	**12.4**	**13.3**
$\sigma_t/\sqrt{f'_c}$ (psi)	**3.1**	**4.4**	**4.8**	**4.9**	**6.8**	**7.4**

SP4 (1.0:1.0 &BJ)	Yield			Ultimate		
	b_b	b_b+h_{tb}	$b_b+1.5h_{tb}$	b_b	b_b+h_{tb}	$b_b+1.5h_{tb}$
V_b(kip)	-24	-28	-30	-31	-36	-38
$P_{col}/(f'_c A_g)$	**0.22**	**0.23**	**0.24**	**0.25**	**0.27**	**0.28**
V_{joint}(kip)	142	169	182	200	238	255
$\tau/\sqrt{f'_c}$ (psi)	**7.9**	**9.3**	**10.1**	**11.0**	**13.1**	**14.1**
$\sigma_t/\sqrt{f'_c}$ (psi)	**3.7**	**4.7**	**5.2**	**5.9**	**7.4**	**8.1**

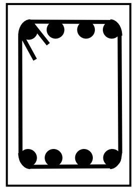
Check Specimen Design

-. Check Shear in Beam ($b_{eff}=b_b+h_{tb}$)

	$V_{b,max}$ (kip)	Con'c		Stirrup[1]		$\frac{V_{b,max}}{(V_c+V_s)}$
		dim.	V_c(kip)	spac.	V_s(kip)	
SP1	83(113)	16x30	52	#3@4"	91	**0.58(0.79)**
SP2	42(57)	16x18	29	#3@4"	51	**0.53(071)**
SP3	75	16x30	52	#3@4"	91	**0.52**
SP4	36	16x18	29	#3@4"	51	**0.45**

( ) : at ultimate moment stage

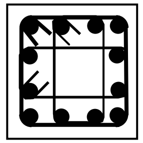
Stirrup[1]



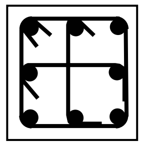
-. Check Shear in Column without Axial Load

	$V_{col,max}$(kip)	Con'c		Hoop[2]		$\frac{V_{col,max}}{(V_c+V_s)}$
		dim.	V_c(kip)	spac.	V_s(kip)	
SP1	73(99)	18x18	35	#3@4"	102	**0.66(0.89)**
SP2	37(50)	18x18	35	#3@4"	77	**0.43(0.58)**
SP3	66	18x18	35	#3@4"	102	**0.59**
SP4	32	18x18	35	#3@4"	77	**0.37**

hoop[2]



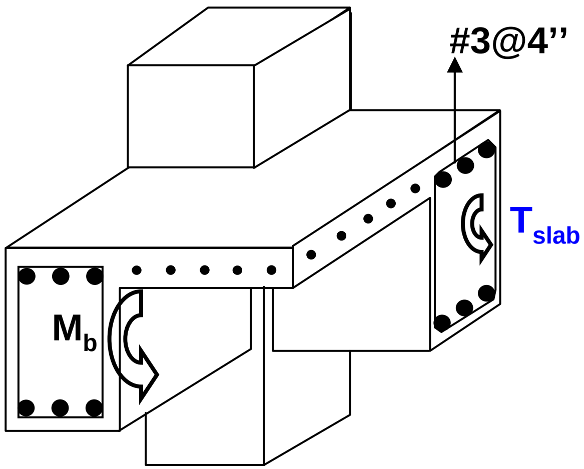
SP1&3

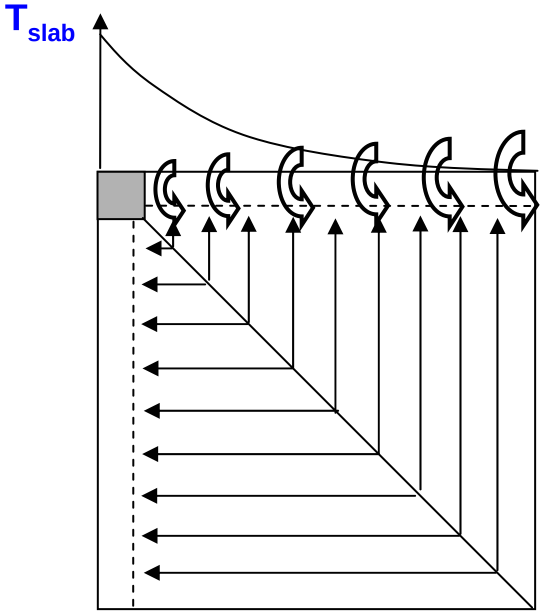


SP2&4

Check Specimen Design

-. Torsion in Transverse Beam



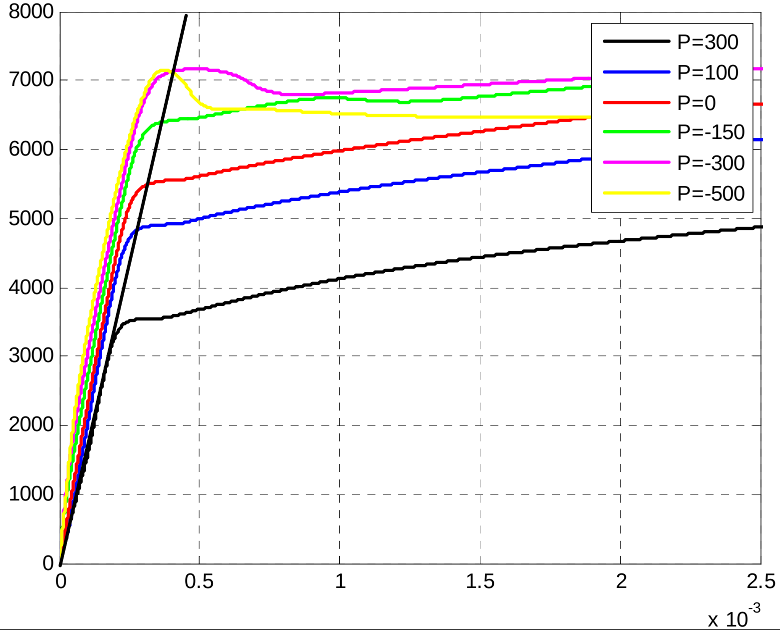


Slab thk.	T_{slab} (kip-in)	stirrup	
		spac.	T_S (kip-in)
6''	76.8	#3@4''	1077

$$T_S = \frac{A_t(2A_O f_{yt} \cot 45)}{S}$$

-. Moment Capacity Ratio between Column and Beam (SP1 & SP3)

12-#9 Column Moment Curvature Relations



For biaxial loading, if slab effect is included,

$$\frac{\sum M_{n,col}}{M_{n,beam}} > 1.5 \sim 1.8 \quad \text{to avoid column hinging}$$

[from 'Towards New Bond and Anchorage Provisions for Interior Joints by R.T. Leon]

For biaxial loading, $\left(\frac{M_{n,beam}}{\sum M_{n,col}}\right)^{1.5} \times 2$

ex) $P = 0 \Rightarrow \left(\frac{1}{1.7}\right)^{1.5} \times 2 = 0.9 < 1.0$

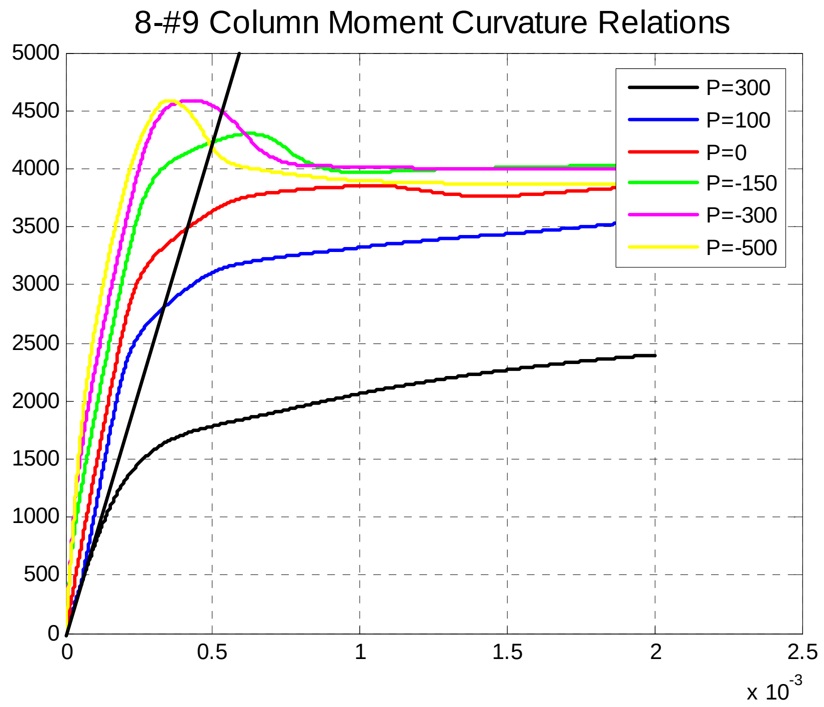
dimension	Specimen	$\sum M_{n,col} / M_{n,beam}$							
		M_b=M_y				M_b=M_{ult}			
		Positive		Negative		Positive		Negative	
		P≈0	P≈P_{biaxia}	P≈0	P≈P_{biaxia}	P≈0	P≈P_{biaxia}	P≈0	P≈P_{biaxia}
16''X30''	SP1	**1.8**	**1.3**	**1.6**	**1.8**	1.3	0.91	1.2	1.2
	SP3	2.9	2.7	2.4	2.8	**2.2**	**1.8**	**1.7**	**2.0**

Note : $M_{n,col}$ is taken at outermost concrete strain = 0.005

Advisor : Professor Mosalam

Student Researcher : SANGJOON PARK

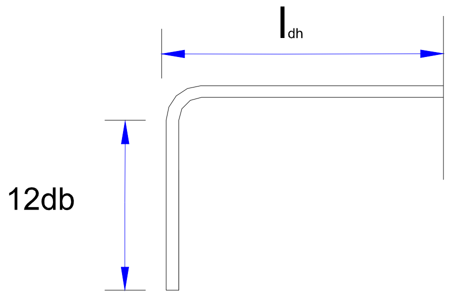
-. Moment Capacity Ratio between Column and Beam (SP2 & SP4)

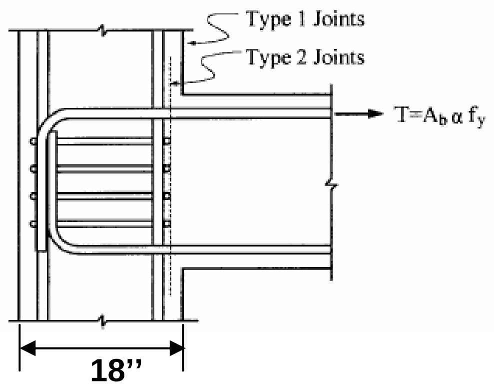


dimension	Specimen	$\sum M_{n,col} / M_{n,beam}$							
		$M_b=M_y$				$M_b=M_{ult}$			
		Positive		Negative		Positive		Negative	
		P≈0	$P \approx P_{biaxia}$	P≈0	$P \approx P_{biaxia}$	P≈0	$P \approx P_{biaxia}$	P≈0	$P \approx P_{biaxia}$
16''X18''	SP2	**2.0**	**1.4**	**1.9**	**2.3**	1.6	0.88	1.4	1.6
	SP4	**3.2**	**2.7**	**2.9**	**3.5**	**2.6**	**2.0**	**2.2**	**2.7**

Some Details to be discussed

1. Hook Detail





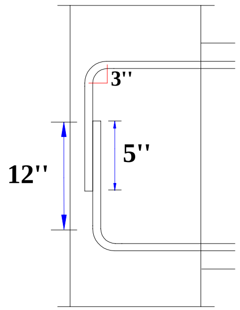
For #8 bar,

$$\text{type 1 } l_{dh} = \frac{f_y d_b (\text{psi})}{50\sqrt{f_c^{'}}(\text{psi})} = 20''$$

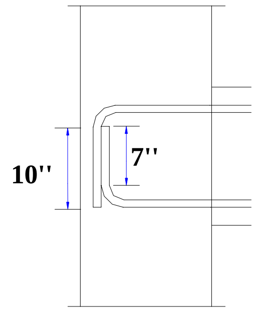
$$\text{type 2 } l_{dh} = \frac{\alpha f_y d_b (\text{psi})}{75\sqrt{f_c^{'}}(\text{psi})} = 17''$$

$12d_b$=12''

Specimen 1&3

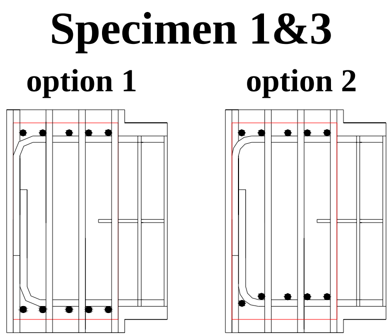


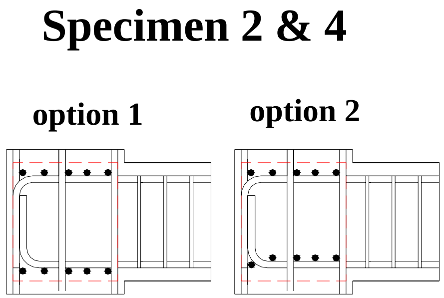
Specimen 2 &



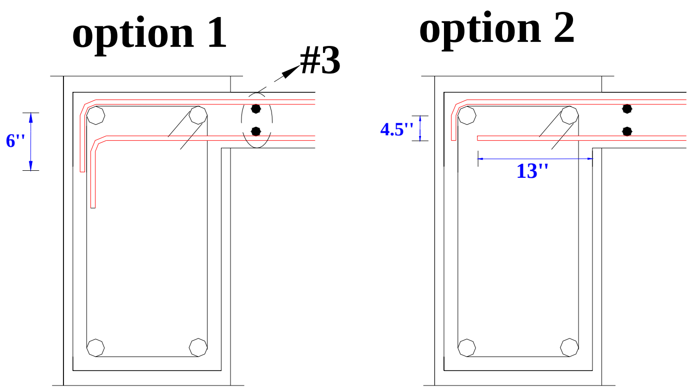
Some Details to be discussed

2. Crossed Beam Reinforcement Layers



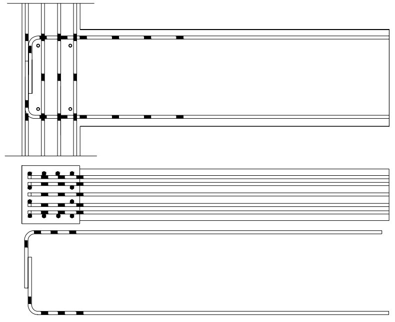


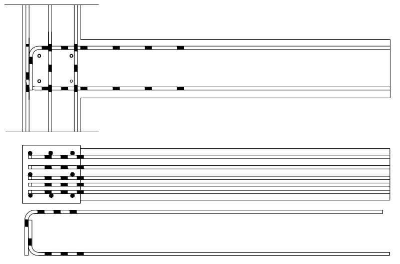
3. Slab Reinforcement Detail

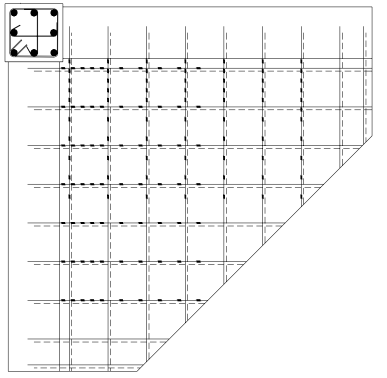


Instrumentation

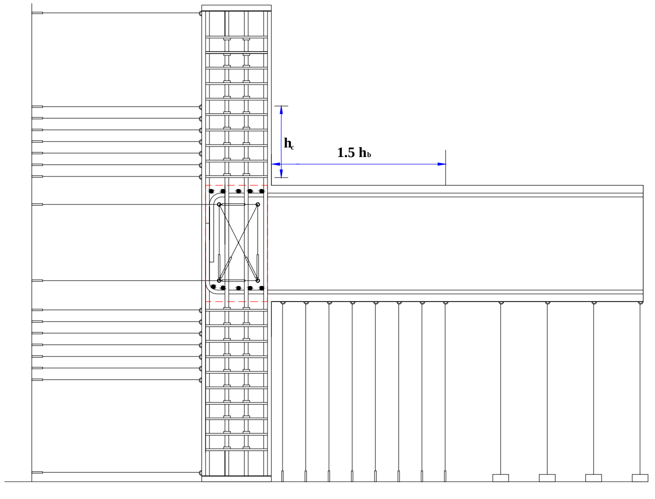
Strain gage location



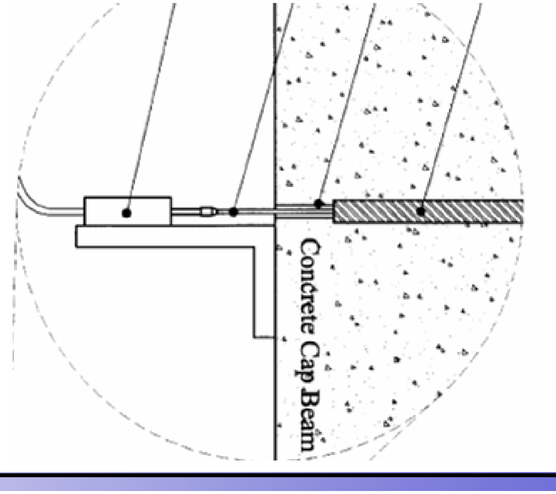




Displacement Measurement

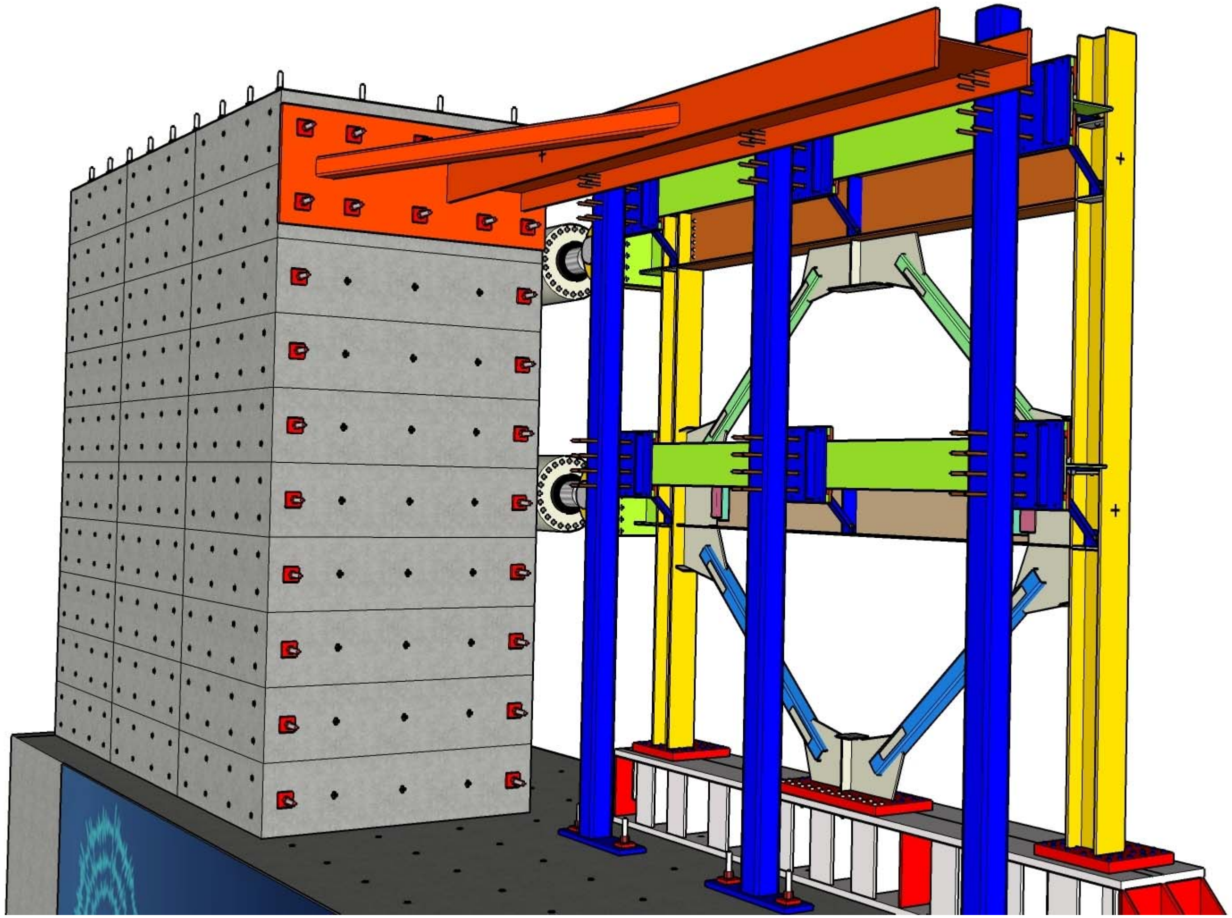


Slip measurement of slab reinforcement



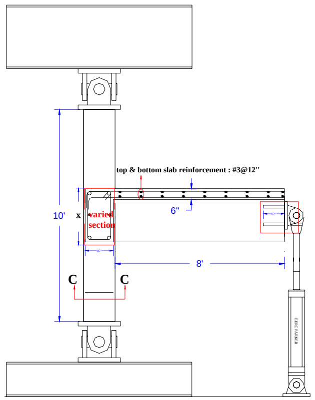
Test Setup

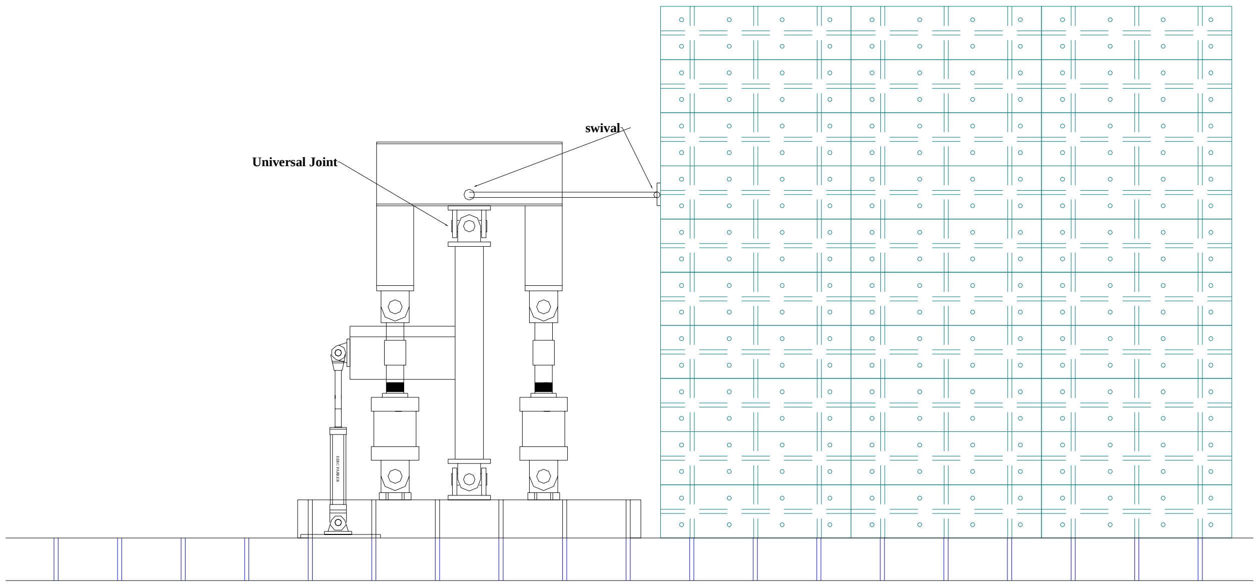
1. Lab Condition

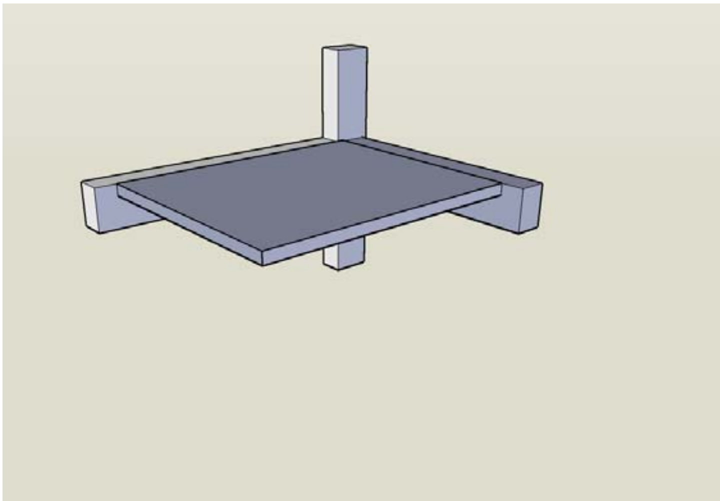


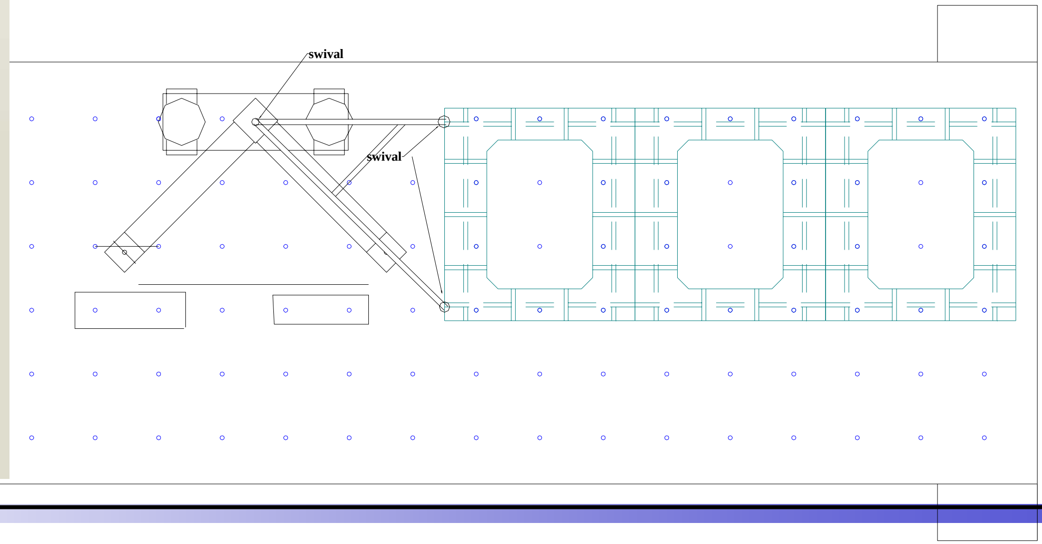
Test Setup

2. Setup









Test Setup

3. Setup