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Reinforced Concrete Columns with High-Strength Concrete and Steel Reinforcement, Part 2

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WEB SESSIONS

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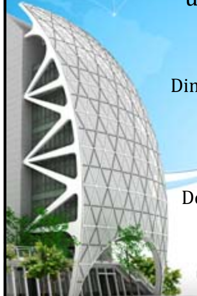
Shear Behavior of Reinforced Concrete Columns with High Strength Steel and Concrete under Low Axial Load



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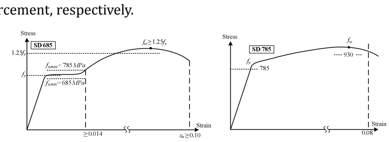
INTRODUCTION

- High strength steel and concrete has gained increasing attention recently in reinforced concrete (RC) buildings due to the need to limit the size of structural members in high-rise buildings.
- Some benefit of using high strength steel and concrete:
  a. Increasing available floor area
  b. Reducing reinforcement congestion in beam-column joints and plastic hinge regions of columns and beams
  c. Column section along the height of the building can be uniformly designed by using higher material strength in the lower stories
- Limitation of current ACI 318M-11 of specified yield strength of transverse reinforcement and concrete compressive strength for shear design of 60 ksi (420 MPa) and 10 ksi (70 MPa) respectively.

INTRODUCTION

- Recent advancement in material technology in Taiwan: Concrete with compressive strength of 100 MPa, deformed reinforcement with yield strength of 685 MPa and 785 MPa for longitudinal reinforcement and transverse reinforcement, respectively.



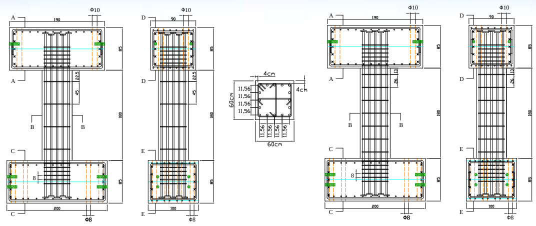
- Taiwan launched an integrated research project named as "Taiwan New RC Project". The objective of this research is to investigate shear behavior of RC columns with such high strength materials. Shear design requirement of current ACI 318M-11 provision may not be applicable of columns with high strength steel and concrete.

SPECIMEN DESIGN

- Eight large-scale column specimens were constructed and tested in double bending under uni-directional lateral load.
- The columns were designed to have elastic shear failure in which shear failure occurs without any yielding of column longitudinal bars.

Column	Axial load Ratio (f'_cA_g)	Stirrup spacing (mm)	Concrete f'_c (MPa)		Longitudinal Rebar D32 f_y (MPa)		Stirrup D13 f_{yt} (MPa)	
			Design	Actual	Design	Actual	Design	Actual
A-1	10%	450	70	92.5	685	735	785	862
A-2			100	103.15				
A-3		260	70	96.9				
A-4			100	107.1				
B-1	20%	450	70	80.6				
B-2			100	114.1				
B-3		260	70	112.9				
B-4			100	121.0				

SPECIMEN DESIGN



(a) Specimen with 450 mm spacing (b) Specimen with 260 mm spacing

SPECIMEN DESIGN

(a) Construction of specimen

(b) Testing setup

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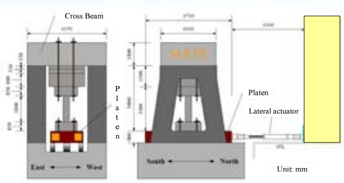
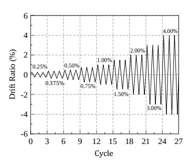
TEST SETUP



(a) Testing Setup



(b) Loading Protocol

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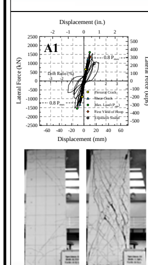
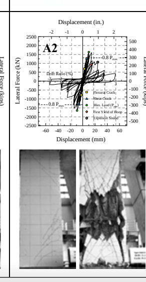
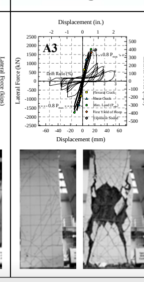
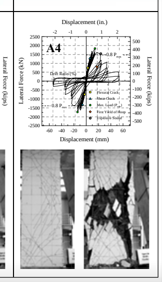
TEST RESULTS

A-1	A-2	A-3	A-4
			

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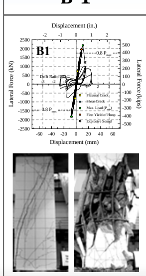
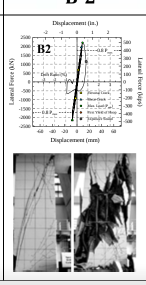
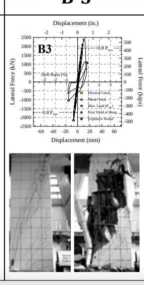
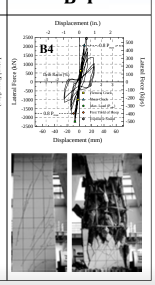
TEST RESULTS

B-1	B-2	B-3	B-4
			

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Calculation of Vs_test and Vc_test

Shear strength from reinforcement $V_{s\_test} = \frac{A_v f_y d}{s} \cot\theta$

Shear strength from concrete $V_{c\_test} = V_{n\_test} - V_{s\_test}$

where:

f'_c is concrete compressive strength
d is effective depth
A_v is cross-sectional area of shear reinforcement
f_y is yield stress of shear reinforcement
s is spacing of shear reinforcement
θ is angle of shear crack

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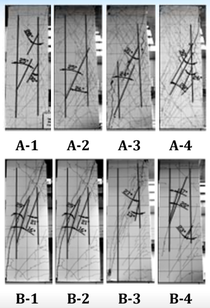
Shear Crack Angle



Specimen	Axial Load Ratio	Shear Crack Angle (°)				
		Test Results			AASHTO LRFD	Elwood & Moehle
		Min	Average	Max		
A-1	10%	24	26.75	30	43.9	31.84
A-2		24	25	26	43.9	31.75
A-3		22	24.6	31	43.9	31.8
A-4		26	28.6	30	43.9	31.72
B-1	20%	16	23	29	43.1	28.57
B-2		14	18.5	21	43.9	28.35
B-3		13	21.4	27	43.1	28.36
B-4		17	20	23	43.9	28.26

- The crack angle was measured by observing the dominant diagonal shear crack that developed during the test.
- Crack angle varies from 13^o to 31^o.
- Higher axial load showed smaller critical crack angle.
- Most critical crack angles are smaller than 30^o.

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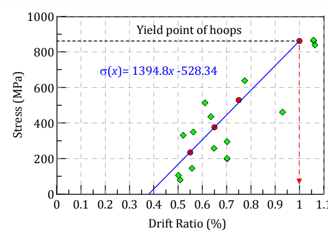
Stress of shear reinforcement at the shear crack



f'_c: 80.6 MPa to 121 MPa

Axial Load ratio: 10% and 20%

Specimen	Drift ratio at max shear (%)
A-1	0.57
A-2	0.53
A-3	0.75
A-4	0.79
B-1	0.59
B-2	0.50
B-3	0.54
B-4	0.64

Yielding of transverse reinforcement is reached at a drift of 1%.

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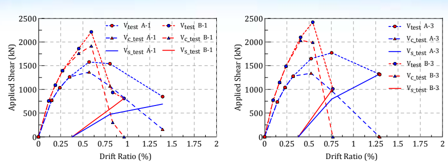
EFFECT OF AXIAL LOAD



- The peak of Vn was reached before yielding of transverse reinforcement
- Increasing axial load increases Vc and causes a more rapidly drop of Vc after the peak of Vc; decreases the shear angle and hence increases Vs for a given drift; does not affect the drift at the peak of Vc.

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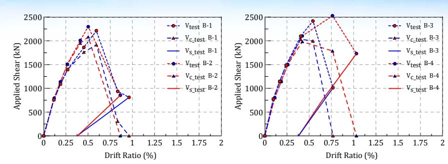
EFFECT OF f'_c

Column	Concrete f'_c (MPa)
	Actual
A-1	92.5
A-2	103.15
A-3	96.9
A-4	107.1
B-1	80.6
B-2	114.1
B-3	112.9
B-4	121.0



Increasing f'c seems to decrease the drift at the peak of Vc, thus reducing the corresponding stress in the transverse reinforcement.

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Aggregate Interlock

- Concrete shear strength contribution consists of three important terms: compression zone mechanism, aggregate interlock and dowel action.
- In high strength concrete, the strength of mortar is typically higher than that of aggregate so cracks typically cut through the aggregate (shown on the right), possibly reducing the aggregate interlock mechanism.

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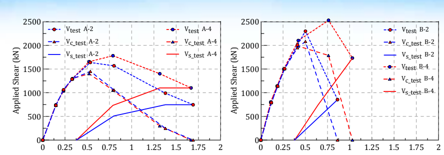
EFFECT OF SPACING OF HOOPS



Decreasing vertical spacing of transverse reinforcement seems not affecting the degradation pattern of Vc. However, due to the increase of Vs for a given drift, Vn is still able to increase after the peak of Vc, thus increasing Vn and the stress in transverse reinforcement at the peak of Vn.

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EXAMINATION OF CURRENT ACI 318 SHEAR EQUATION

Specimen	Drift ratio at max shear (%)	$\sigma_{prediction}$ (MPa)	V_{s_test} (kN)	V_{c_test} (kN)	V_{c_test} from the peak of V_c (kN)	V_{test} (kN)
A-1	0.57	265.15	212.36	1365.92	1365.92	1578.27
A-2	0.53	216.72	187.20	1451.16	1451.16	1638.36
A-3	0.75	522.41	796.80	975.74	1341.88	1772.54
A-4	0.79	572.43	730.79	1050.21	1401.17	1780.99
B-1	0.59	299.24	298.05	1915.34	1915.34	2213.38
B-2	0.50	171.38	216.44	2081.83	2081.83	2298.27
B-3	0.54	226.40	422.54	1995.39	2032.96	2417.93
B-4	0.64	368.98	741.17	1786.80	1982.70	2527.98

Assumption:

- Actual f'_c
- Actual critical crack angle
- Stress prediction of shear reinforcement

EXAMINATION OF CURRENT ACI 318 SHEAR EQUATION

$$V_n = V_c + V_s$$

$$V_c = 0.166\sqrt{f'_c}\, b_w d\left(1 + \frac{N_u}{13.8A_g}\right)$$

More detailed calculation:

$$V_c = 0.16\sqrt{f'_c} + 17\rho_w \frac{V_u d}{M_m} b_w d$$

$$M_m = M_u - N_u \frac{(4h - d)}{8}$$

Shall not be taken greater than:

$$V_c = 0.29\sqrt{f'_c}\, b_w d\sqrt{1 + \frac{0.29N_u}{A_g}}$$

$$V_s = \frac{A_v f_y d}{s}\cot\theta$$

Where:

- f'_c is concrete compressive strength
- b_w is effective web width
- d is effective depth
- h is height of the section area
- N_u is factored axial compression load
- V_u is factored shear due to the total factored loads
- M_u is factored moment due to the total factored loads
- A_v is cross-sectional area of shear reinforcement
- f_y is yield stress of shear reinforcement
- s is spacing of shear reinforcement

EXAMINATION OF CURRENT ACI 318 SHEAR EQUATION

Specimen	Drift ratio at max shear (%)	V_{ns} (kN)	$V_{nc\_simplified}$ (kN)	$V_{nc\_detailed}$ (kN)	$V_{n\_simplified}$ (kN)	$V_{n\_detailed}$ (kN)
A-1	0.57	169.55	600.39	585.53	769.94	755.08
A-2	0.53	169.18	599.08	582.84	768.26	752.02
A-3	0.75	293.29	600.06	572.14	893.35	865.43
A-4	0.79	292.34	598.12	567.77	890.46	860.11
B-1	0.59	177.57	840.40	716.82	1017.97	894.39
B-2	0.50	177.48	839.96	712.65	1017.44	890.13
B-3	0.54	307.19	840.02	681.87	1147.21	989.06
B-4	0.64	307.07	839.67	671.90	1146.74	978.97

Assumption:

- ACI 318 concrete compressive strength limitation of 70 MPa
- ACI 318 Stress limitation of shear reinforcement of 420 MPa
- Critical crack angle of 45 degrees

EXAMINATION OF CURRENT ACI 318 SHEAR EQUATION

Specimen	Drift ratio at max shear (%)	V_{ns} (kN)	$V_{nc\_simplified}$ (kN)	$V_{nc\_detailed}$ (kN)	$V_{n\_simplified}$ (kN)	$V_{n\_detailed}$ (kN)
A-1	0.57	347.98	764.58	702.74	1112.56	1050.72
A-2	0.53	347.22	843.13	764.17	1190.35	1111.39
A-3	0.75	601.94	797.06	696.47	1399.00	1298.42
A-4	0.79	599.99	871.79	740.82	1471.79	1340.82
B-1	0.59	364.44	970.56	843.07	1335.00	1207.51
B-2	0.50	364.25	1412.56	2566.70	1776.81	2930.95
B-3	0.54	630.47	1395.35	1779.51	2025.82	2409.99
B-4	0.64	630.22	1509.63	2622.81	2139.84	3253.03

Assumption:

- Actual concrete compressive strength
- Actual yield strength of shear reinforcement
- Critical crack angle of 45 degrees

EXAMINATION OF CURRENT ACI 318 SHEAR EQUATION

ACI 318 with material strength limitation

Specimen	Drift ratio at max shear (%)	$\frac{V_{ns}}{V_{s\_test}}$	At maximum strength		At peak V_c		At maximum strength	
			$\frac{V_{nc\_simplified}}{V_{c\_test}}$	$\frac{V_{nc\_detailed}}{V_{c\_test}}$	$\frac{V_{nc\_simplified}}{V_{c\_test}}$	$\frac{V_{nc\_detailed}}{V_{c\_test}}$	$\frac{V_{n\_simlified}}{V_{n\_test}}$	$\frac{V_{n\_detailed}}{V_{n\_test}}$
A-1	0.57	0.80	0.44	0.43	0.44	0.43	0.49	0.48
A-2	0.53	0.90	0.41	0.40	0.41	0.40	0.47	0.46
A-3	0.75	0.37	0.61	0.59	0.45	0.43	0.50	0.49
A-4	0.79	0.40	0.57	0.54	0.43	0.41	0.50	0.48
B-1	0.59	0.60	0.44	0.37	0.44	0.37	0.46	0.40
B-2	0.50	0.82	0.40	0.34	0.40	0.34	0.44	0.39
B-3	0.54	0.73	0.42	0.34	0.41	0.34	0.47	0.41
B-4	0.64	0.41	0.47	0.38	0.42	0.34	0.45	0.39

- V_c, V_s, and V_n calculated by shear strength equation of ACI 318 with its material strength limitation are conservative.

EXAMINATION OF CURRENT ACI 318 SHEAR EQUATION

ACI 318 with actual material strength

Specimen	Drift ratio at max shear (%)	$\frac{V_{ns}}{V_{s\_test}}$	At maximum strength		At peak V_c		At maximum strength	
			$\frac{V_{nc\_simplified}}{V_{c\_test}}$	$\frac{V_{nc\_detailed}}{V_{c\_test}}$	$\frac{V_{nc\_simplified}}{V_{c\_test}}$	$\frac{V_{nc\_detailed}}{V_{c\_test}}$	$\frac{V_{n\_simlified}}{V_{n\_test}}$	$\frac{V_{n\_detailed}}{V_{n\_test}}$
A-1	0.57	1.64	0.56	0.51	0.56	0.51	0.70	0.67
A-2	0.53	1.85	0.58	0.53	0.58	0.53	0.73	0.68
A-3	0.75	0.76	0.82	0.71	0.59	0.52	0.79	0.73
A-4	0.79	0.82	0.83	0.71	0.62	0.53	0.83	0.75
B-1	0.59	1.22	0.51	0.44	0.51	0.44	0.60	0.55
B-2	0.50	1.68	0.68	1.23	0.68	1.23	0.77	1.28
B-3	0.54	1.49	0.70	0.89	0.69	0.88	0.84	1.00
B-4	0.64	0.85	0.84	1.47	0.76	1.32	0.85	1.29

- V_c calculated by simplified shear strength equation of ACI 318 with actual material strength is conservative.
- V_s is unconservative for 5 specimens (total 8 specimens).

CONCLUSION

1. The peaks of Vn and Vc were reached before yielding of transverse reinforcement for the specimens examined in this research. Adding more transverse reinforcement increases the stress in the transverse reinforcement. Maximum stress of transverse reinforcement was found to be around 600 MPa (specimen A4)
2. The Vs, Vc, and Vn equations of the ACI 318 code with material strength limitations are conservative for high strength columns examined in this research.
3. With actual concrete compressive strength, the simplified Vc equation of the ACI 318 code is still conservative.

THANK YOU