NARLabs 國家實驗研究院
國家地震工程研究中心
National Center for Research on Earthquake Engineering

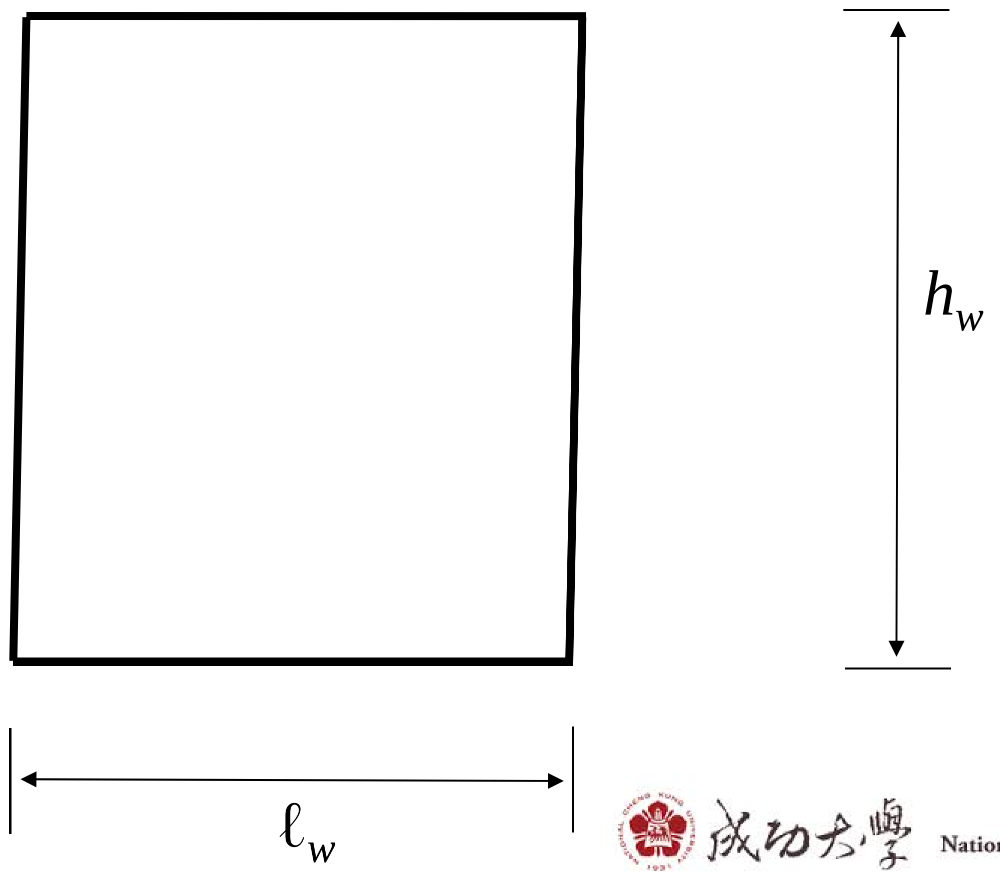
高強度鋼筋混凝土結構牆
之初步設計建議

洪崇展 副教授
國立成功大學土木工程學系

RC結構牆類別

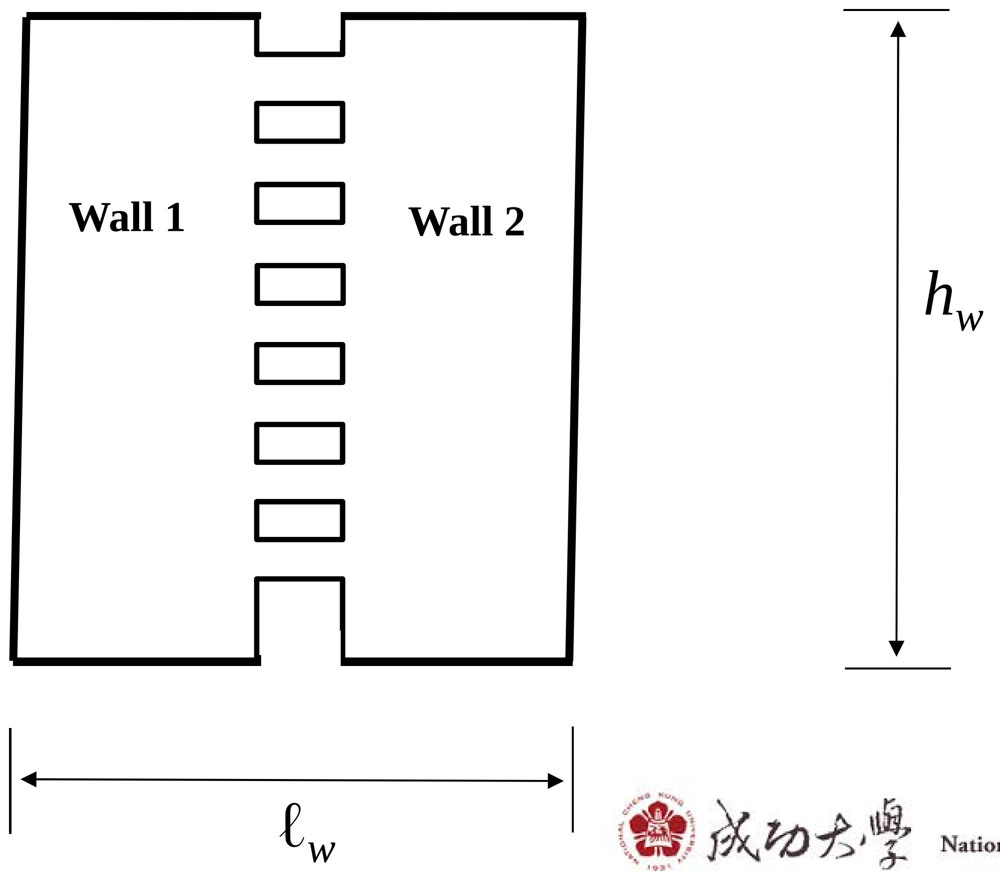
$h_w/\ell_w < 1.5$:低矮型結構牆

$h_w/\ell_w > 2.0$:中高型結構牆



RC結構牆類別

- 耦合結構牆



簡報大綱

1. 高強度鋼筋加勁高強度(纖維)混凝土低矮型結構牆
2. 中高型耦合結構牆地震行為
3. 初步設計建議

Acknowledgements

- NARLabs 國家實驗研究院
  國家地震工程研究中心
  National Center for Research on Earthquake Engineering
- 科技部 Ministry of Science and Technology

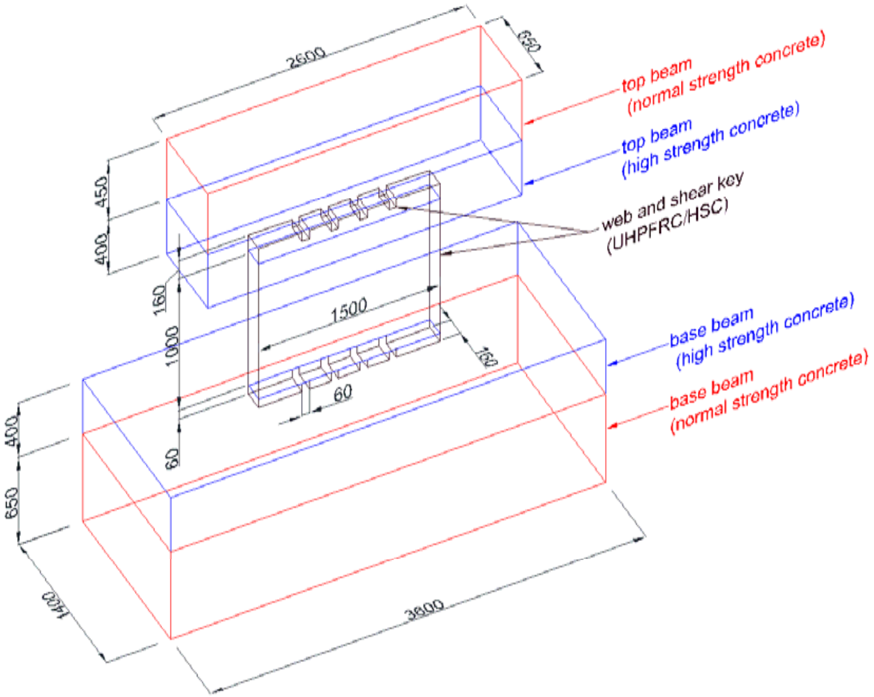
簡報大綱

1. 高強度鋼筋加勁高強度(纖維)混凝土低矮型結構牆
2. 中高型耦合結構牆地震行為
3. 初步設計建議

High Strength Concrete Squat Shear Walls

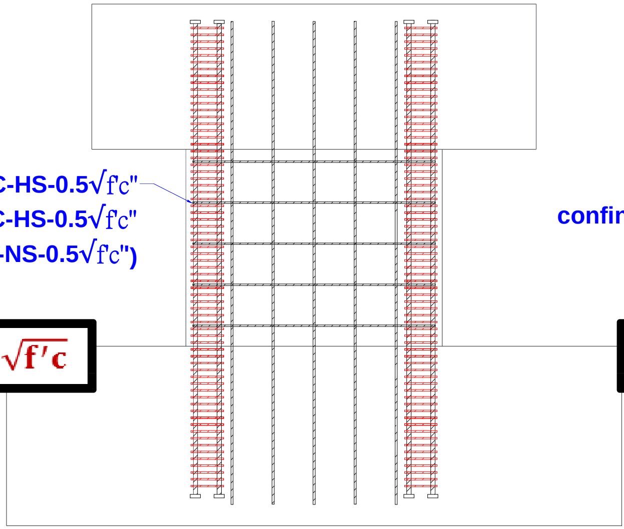
- Six high strength concrete squat walls with an aspect ratio of 0.8
- Design parameters:

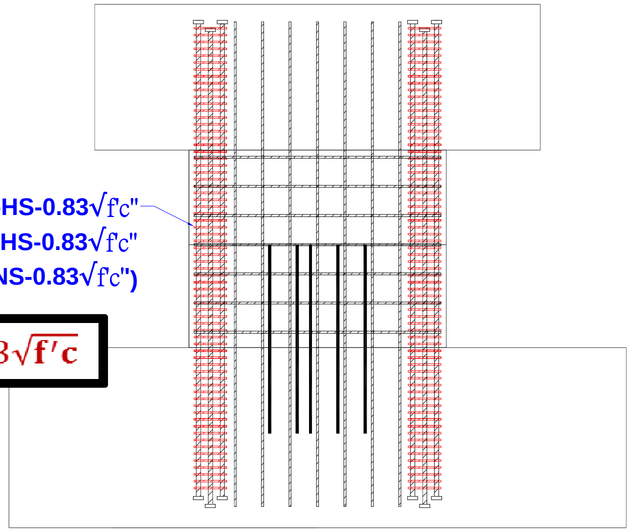
  (1)shear demand($0.5\sqrt{f'c}$ or $0.83\sqrt{f'c}$), (2)rebar strength (420MPa、785MPa) ,
  (3)steel fiber, and (4)dowel bar



Reinforcement Design

Specimen	Web		Boundary Element		Dowel Bars
	horizontal steel	vertical steel	vertical steel	confinement	
HSC-HS-0.5$\sqrt{f'c}$	10#3 (SD785)	10#3 (SD785)	4#8 (SD685)	#3@50mm (SD785)	none
UHPFRC-NS-0.5$\sqrt{f'c}$	10#4 (SD420)	10#4 (SD420)	4#8 (SD685)	#3@80 mm(SD785)	none
UHPFRC-HS-0.5$\sqrt{f'c}$	10#3 (SD785)	10#3 (SD785)	4#8 (SD685)	#3@80 mm(SD785)	none
HSC-HS-0.83$\sqrt{f'c}$	14#4 (SD785)	14#4 (SD785)	6#8 (SD685)	#3@50mm (SD785)	10#5 (SD785)
UHPFRC-HS-0.83$\sqrt{f'c}$	14#4 (SD785)	14#4 (SD785)	6#8 (SD685)	#3@80 mm(SD785)	10#5 (SD785)
UHPFRC-NS-0.83$\sqrt{f'c}$	16#5 (SD420)	16#5 (SD420)	6#8 (SD685)	#3@80 mm(SD785)	none

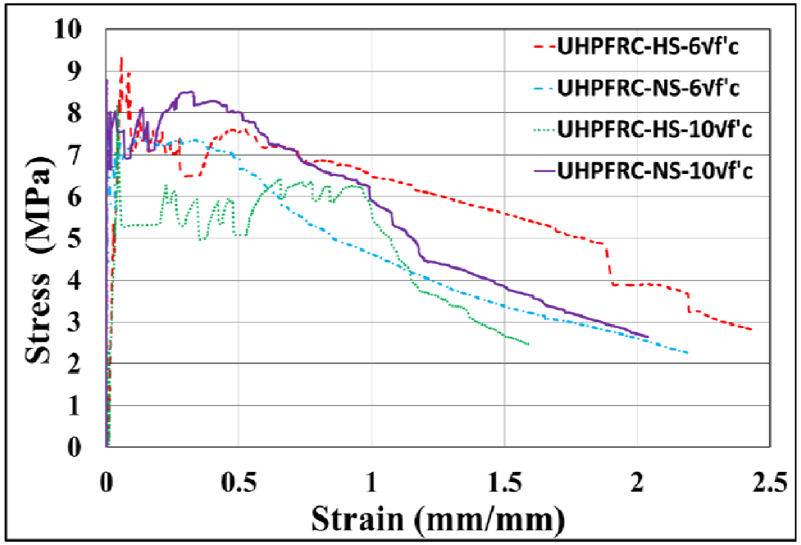


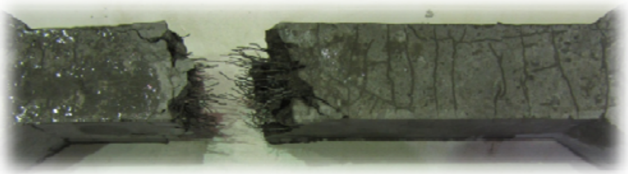


Properties of UHPC/UHPFRC

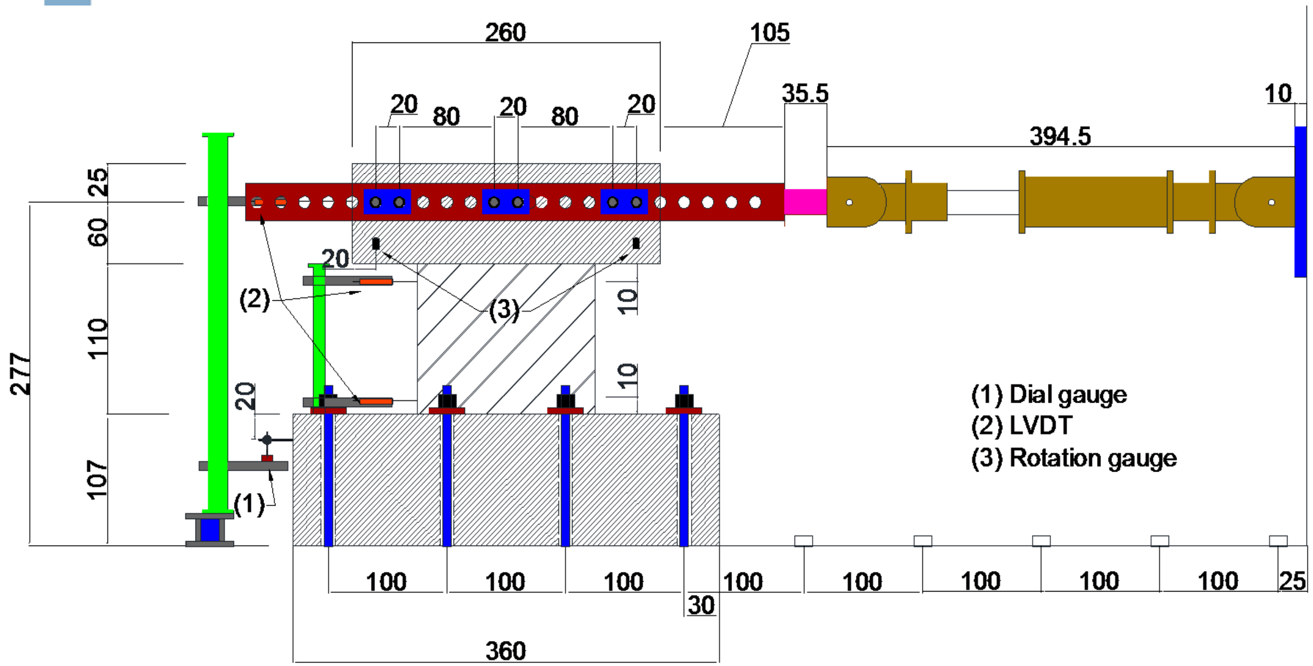
Mix proportions of UHPFRC (proportion by weight)						
	Type I Portland cement	Silica sand	Silica fume	Quartz powder	Water and superplasticizer	Steel fiber
UHPFRC	1	0.5	0.18	0.39	0.28	0.17

	fc' (MPa)	Tensile strength (MPa)	Ultimate tensile strain (%)
$HSC-HS-0.5\sqrt{f'c}$	166	5.3	0.02
$UHPFRC-HS-0.5\sqrt{f'c}$	120	7.7	2.44
$UHPFRC-NS-0.5\sqrt{f'c}$	125	5.8	2.19
$HSC-HS-0.83\sqrt{f'c}$	158	5.2	0.07
$UHPFRC-HS-0.83\sqrt{f'c}$	115	8.2	1.59
$UHPFRC-NS-0.83\sqrt{f'c}$	121	7.5	2.80





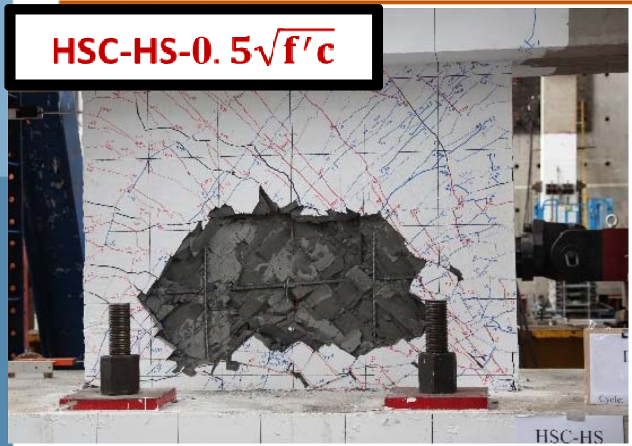
Test Setup

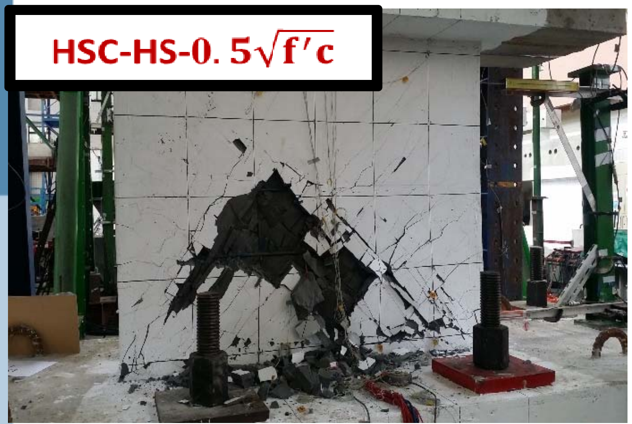


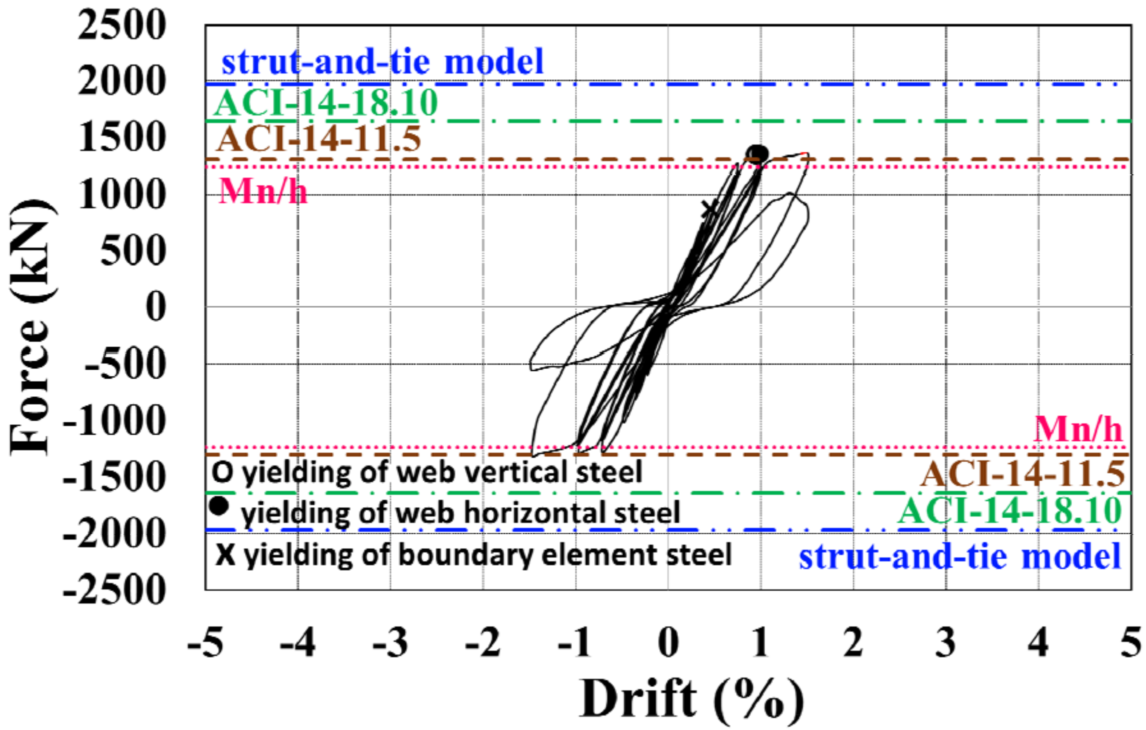
260
105
20
80
20
80
20
35.5
394.5
10
25
60
110
107
277
20
20
10
10
(1)
(2)
(3)
(1) Dial gauge
(2) LVDT
(3) Rotation gauge
100
100
100
100
100
100
100
100
25
30
360

N C R E E

Failure Modes and Load-Displacement Hysteretic Loops

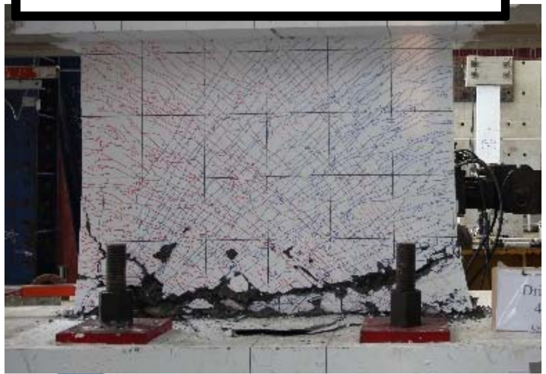


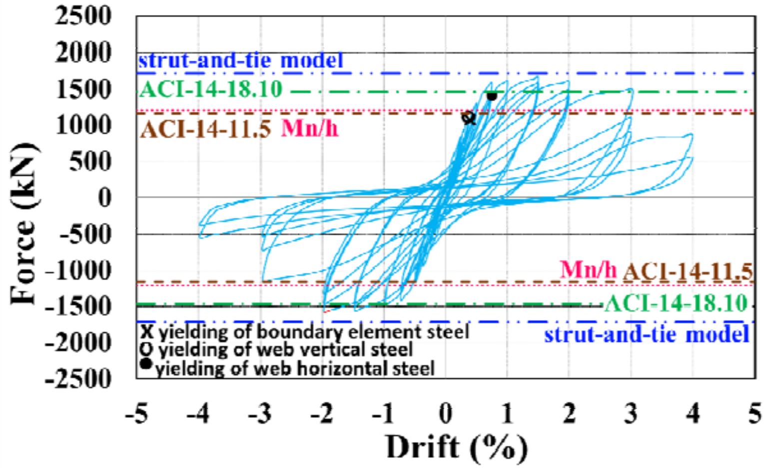




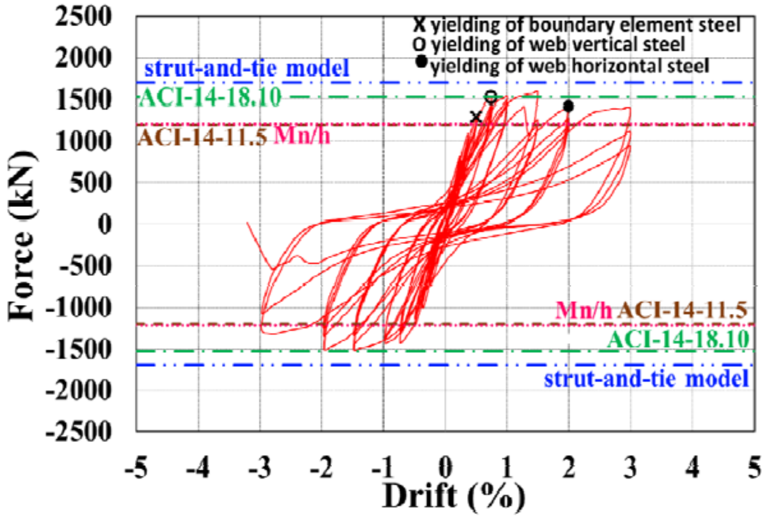
Failure Modes and Load-Displacement Hysteretic Loops

UHPFRC-NS-0.5$\sqrt{f'c}$



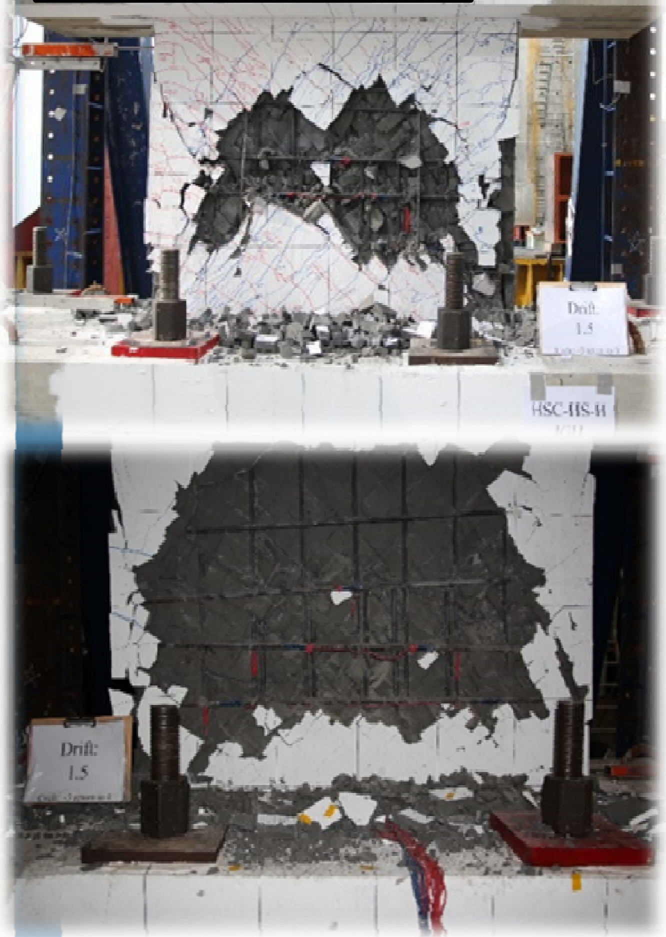


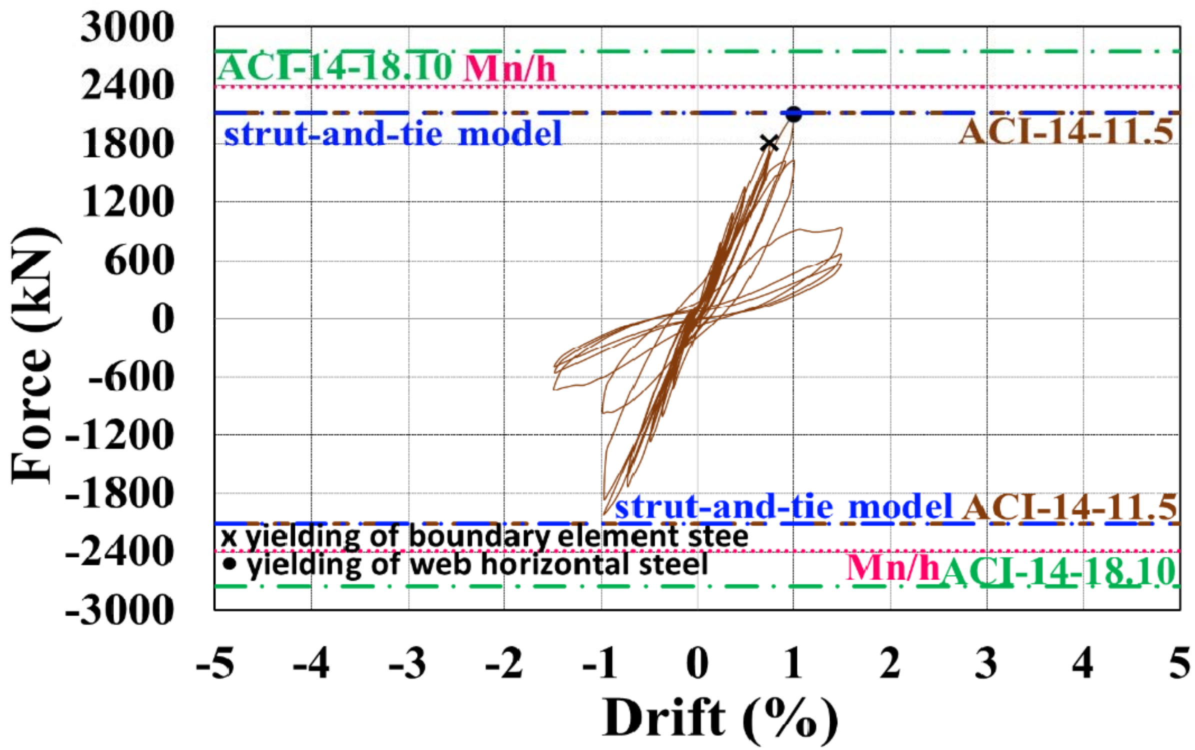
UHPFRC-HS-0.5$\sqrt{f'c}$



Failure Modes and Load-Displacement Hysteretic Loops

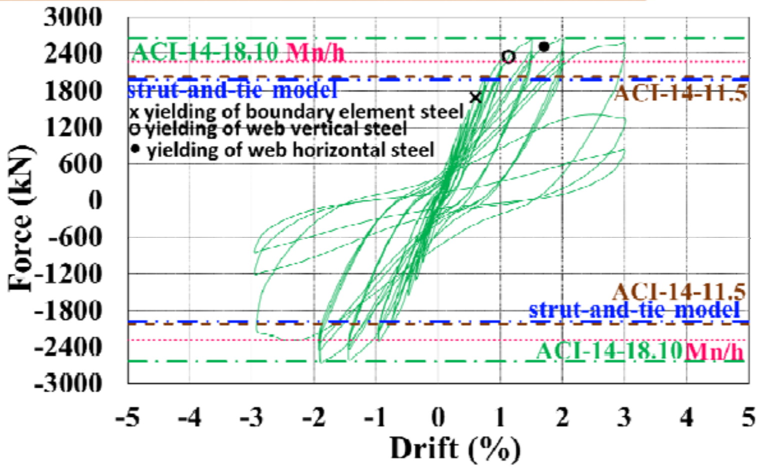
HSC-HS-$0.83\sqrt{f'c}$



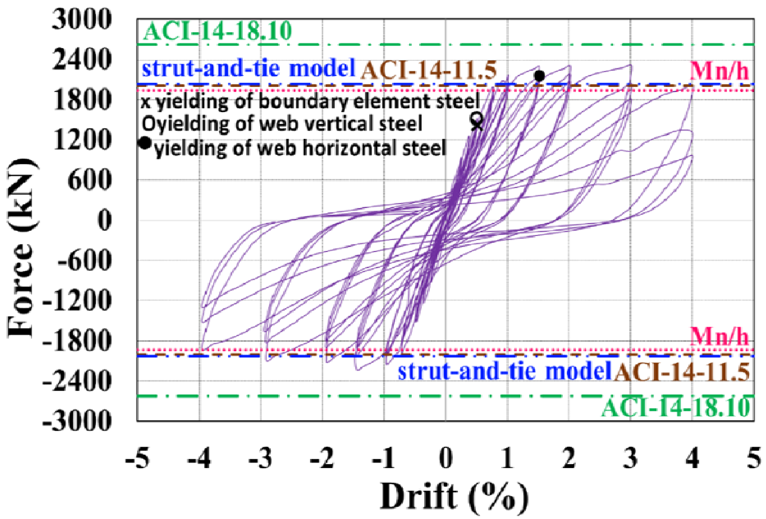


Failure Modes and Load-Displacement Hysteretic Loops

UHPFRC-HS-0. $83\sqrt{f'c}$

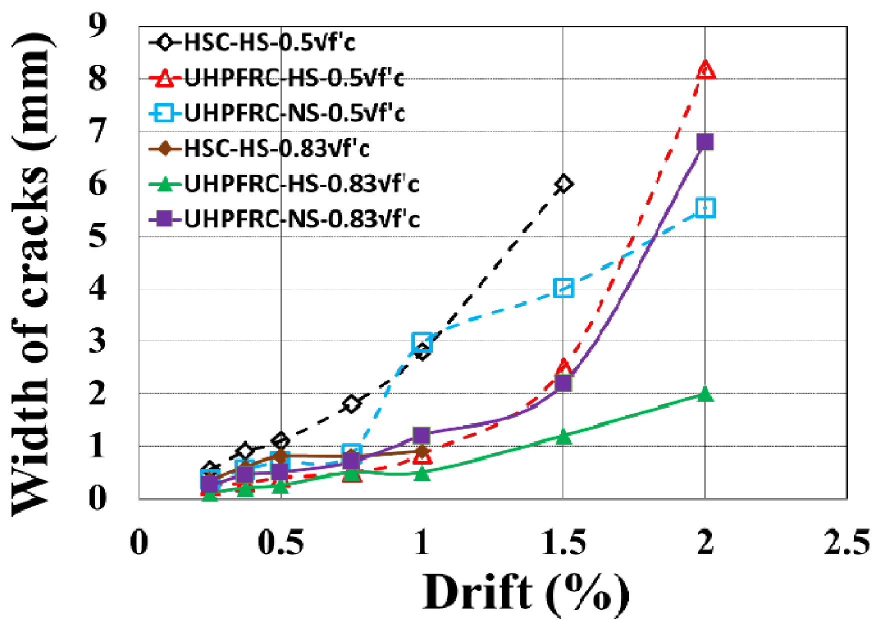


UHPFRC-NS-0. $83\sqrt{f'c}$

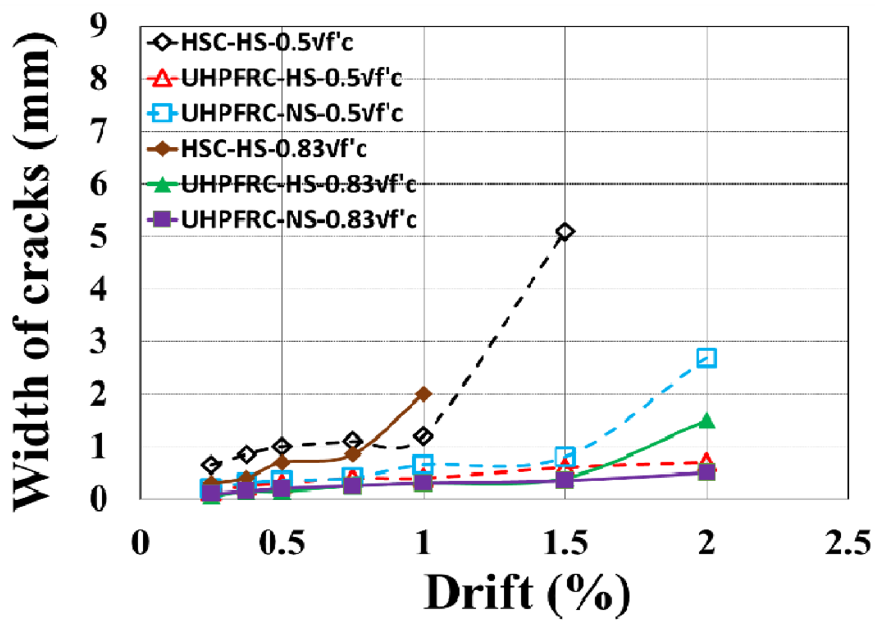


Crack Development

- Maximum flexural crack widths

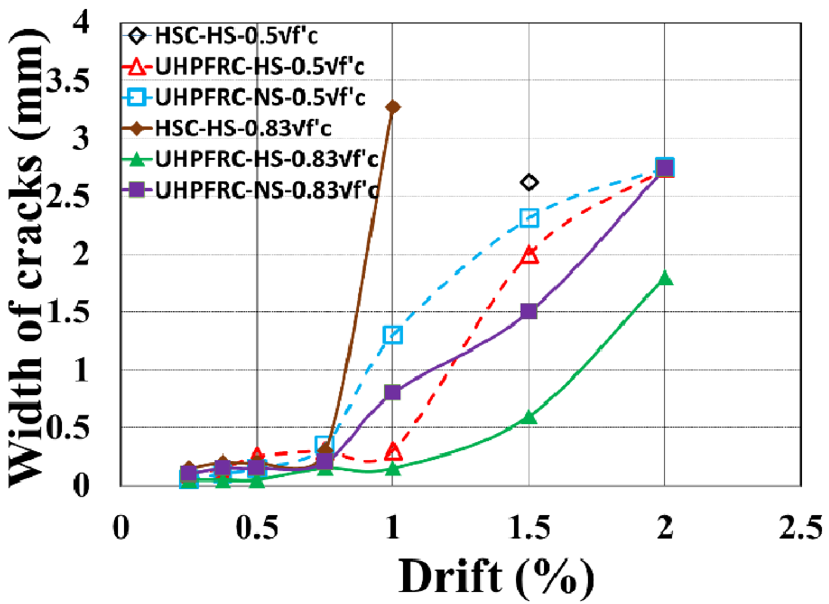


- Maximum shear crack widths

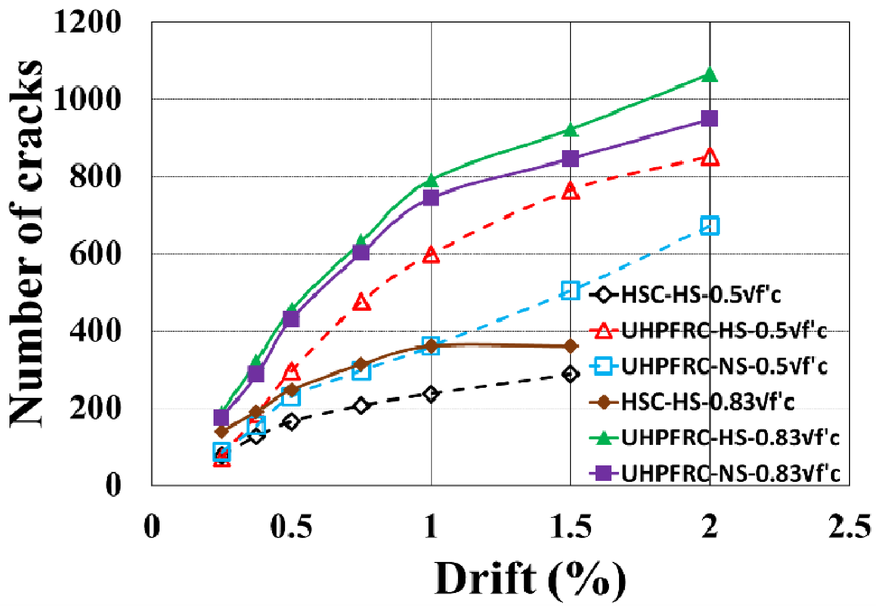


Crack Development

- Maximum crack widths after unloading

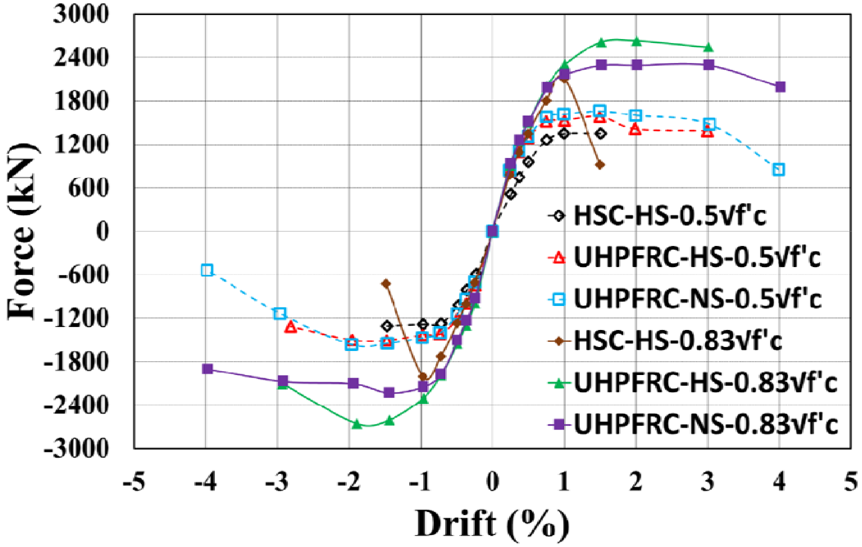


- Number of cracks

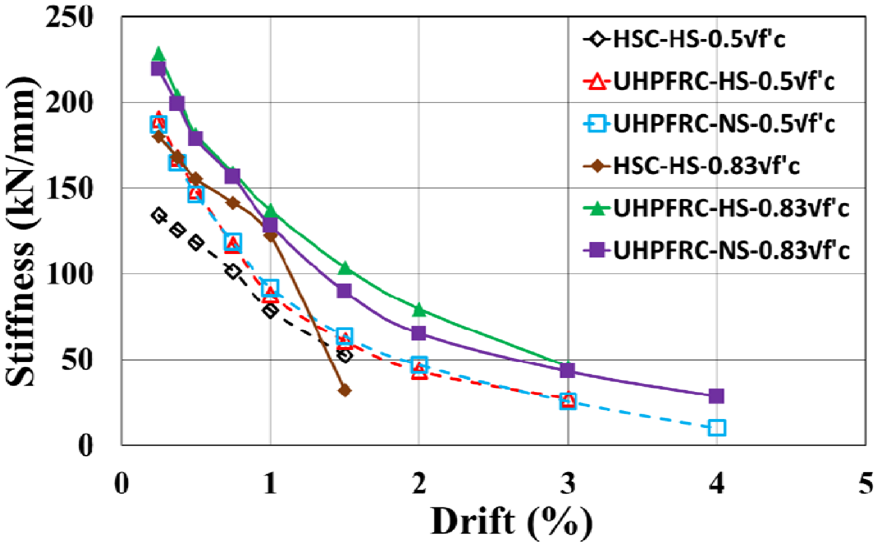


Strength and Stiffness

Strength envelopes

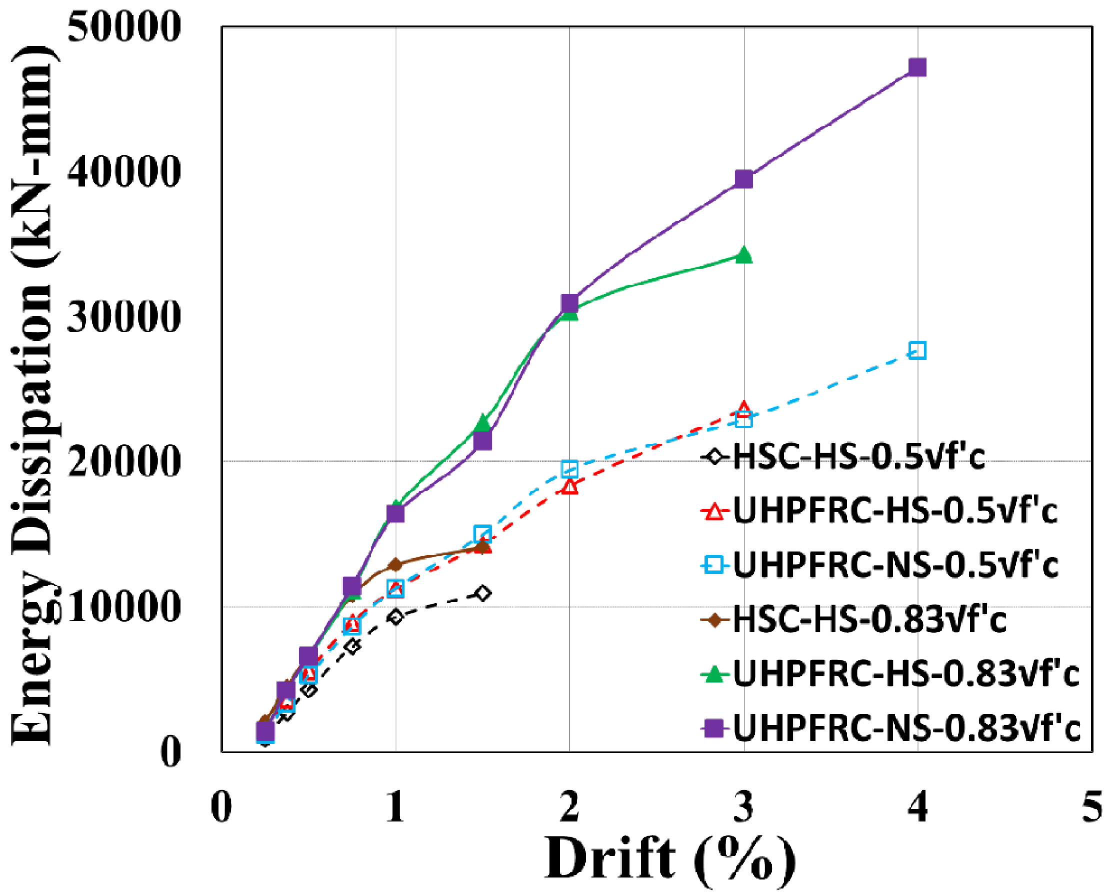


Stiffness variations

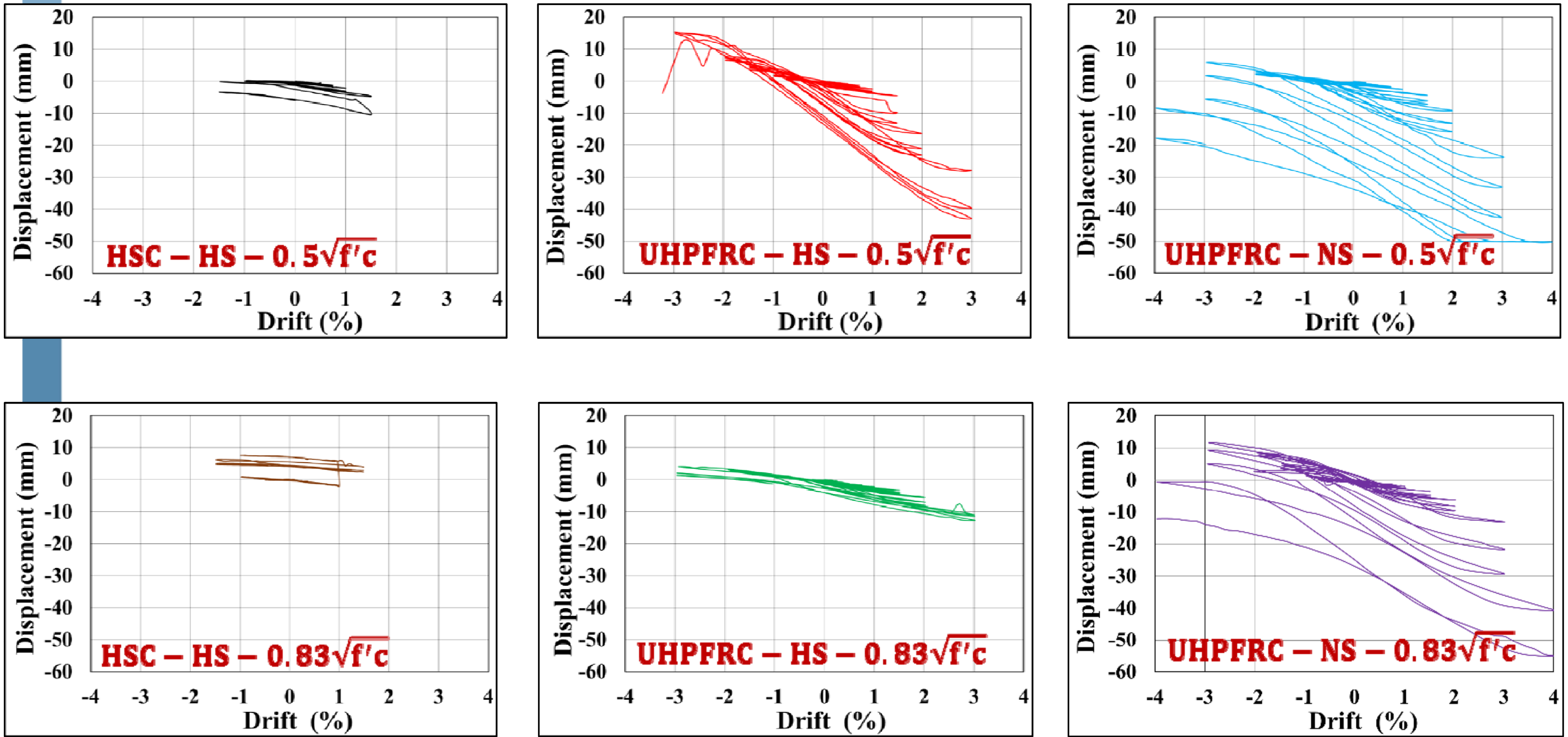


成功大學 National Cheng Kung University

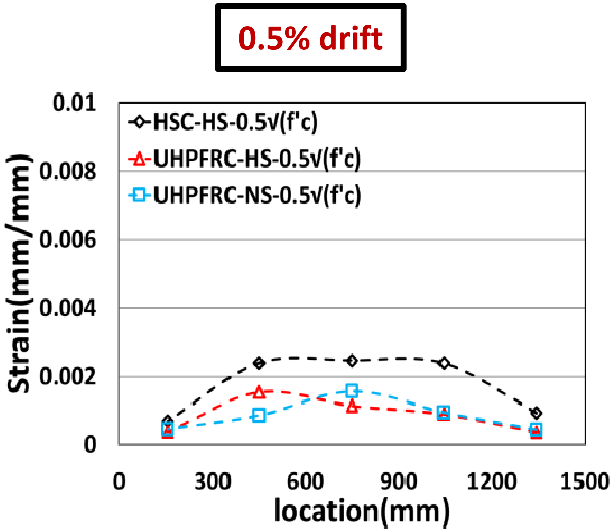
Cumulative Energy Dissipation

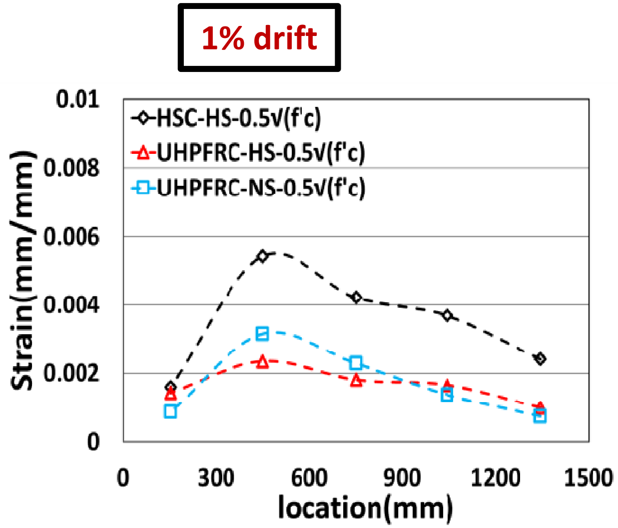


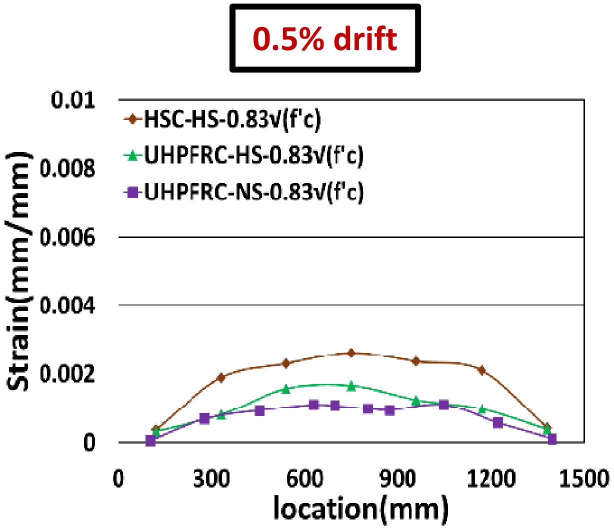
Shear Sliding

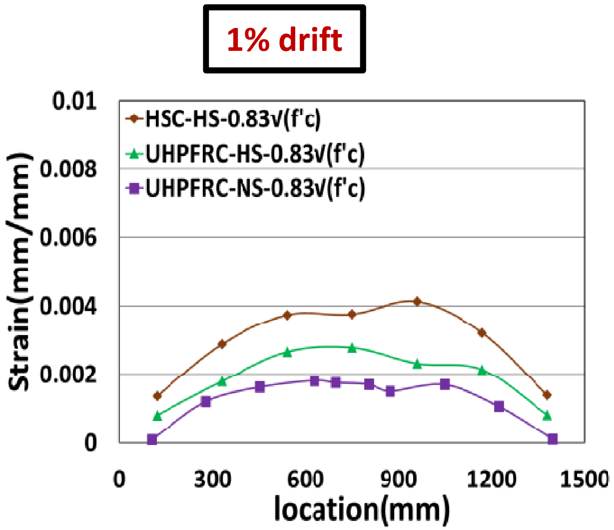


Max Strain of Web Horizontal Bars

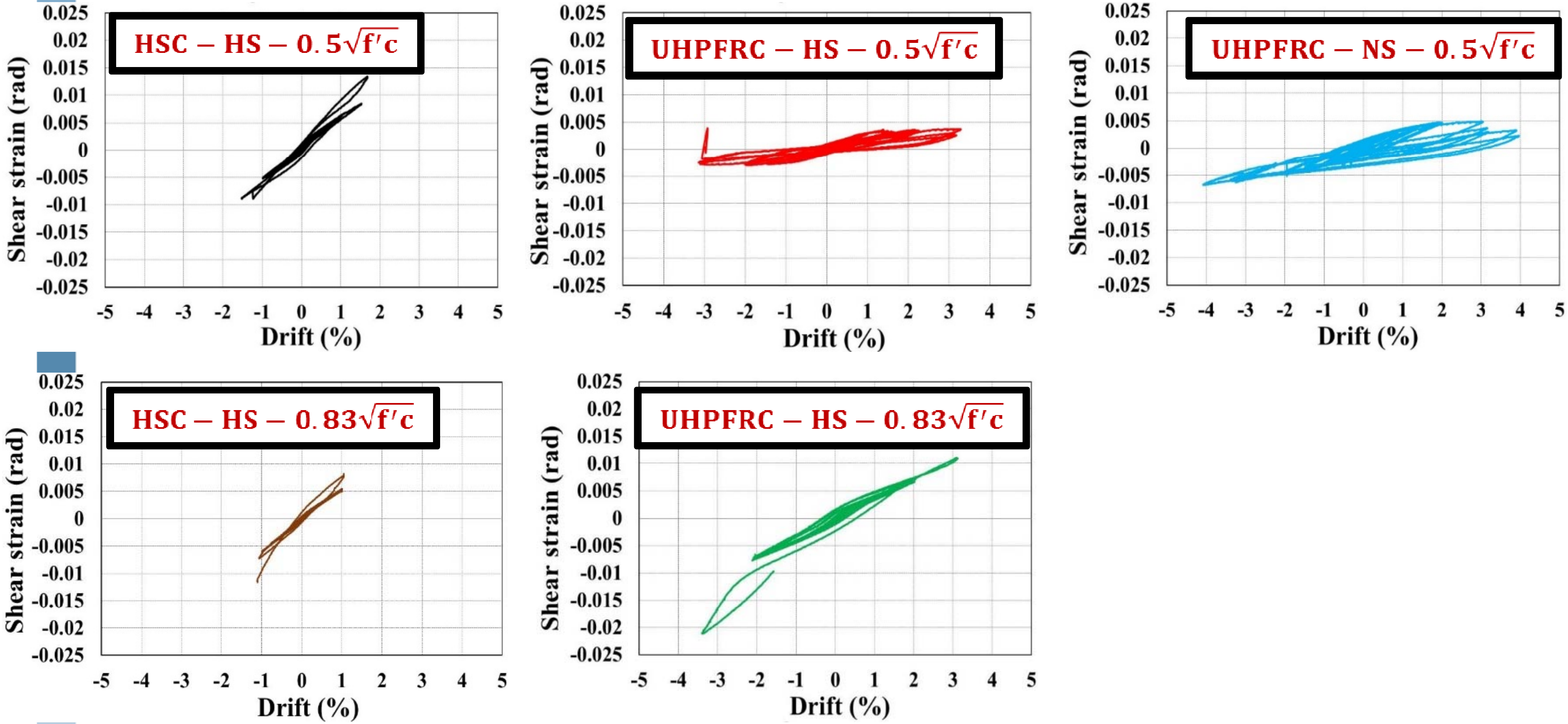








Shear Strain Versus Drift Responses



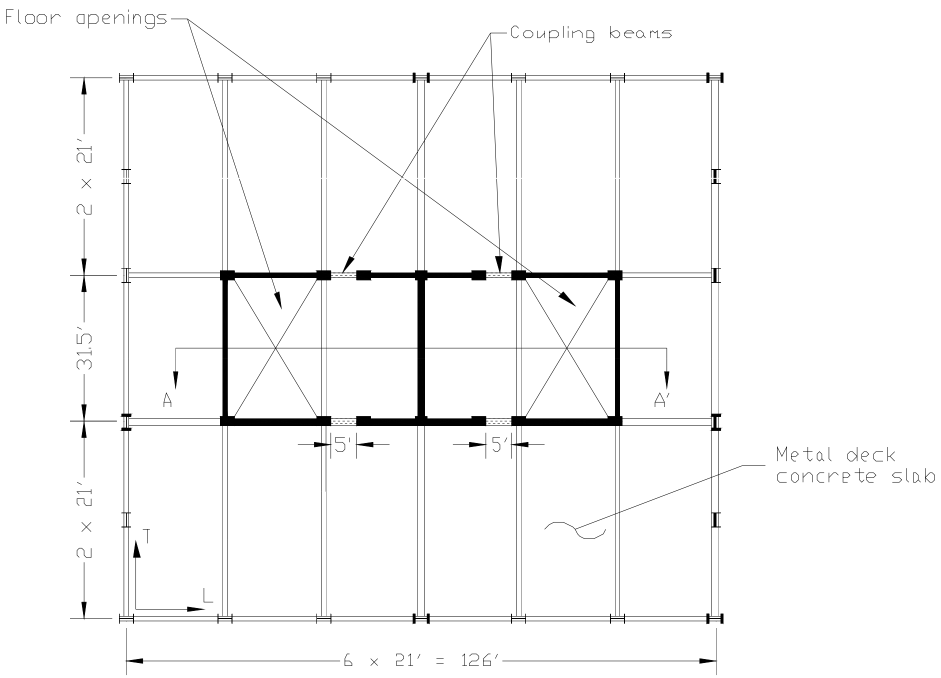
Conclusions (I)

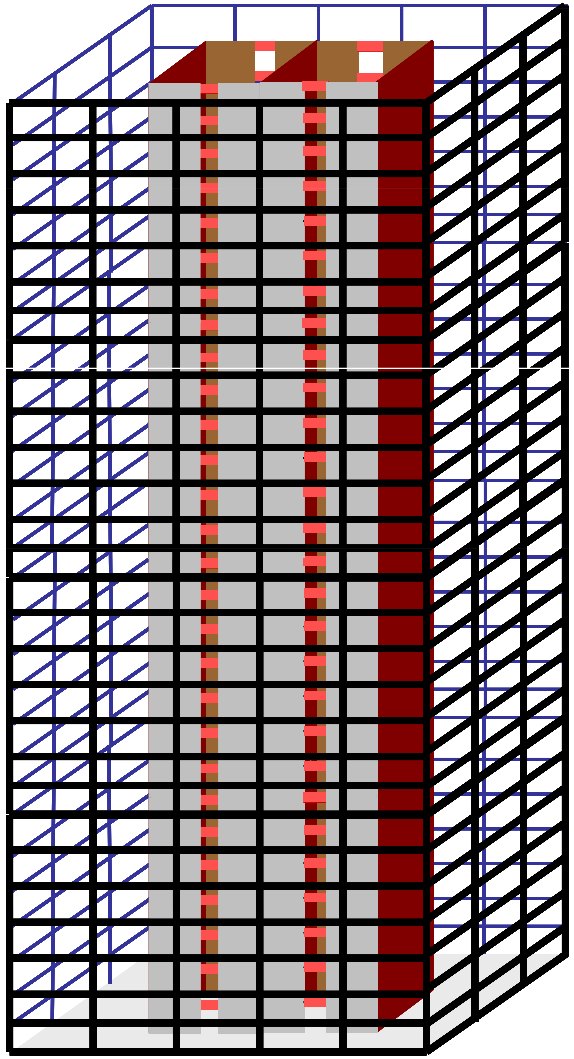
- Adding steel fibers in high strength concrete squat shear walls is able to enhance the shear resistance, which delays/prevents the occurrences of diagonal tension and compression failure modes and facilitates the flexural-controlled behavior.
- Although the addition of fibers in squat shear walls leads to advantageous earthquake-resistance ability and crack width control ability, it cannot prevent the shear sliding failure mode as the drift demand increases to more than 2%.
- The addition of dowel bars in squat walls can effectively prevent the shear sliding failure mode even when the shear demand is as large as $\mathbf{0.83\sqrt{f'c}}$ (MPa).
- The use of high strength steel to replace the regular one in RC squat walls can reach the same good cyclic performance while alleviating the steel congestion.

簡報大綱

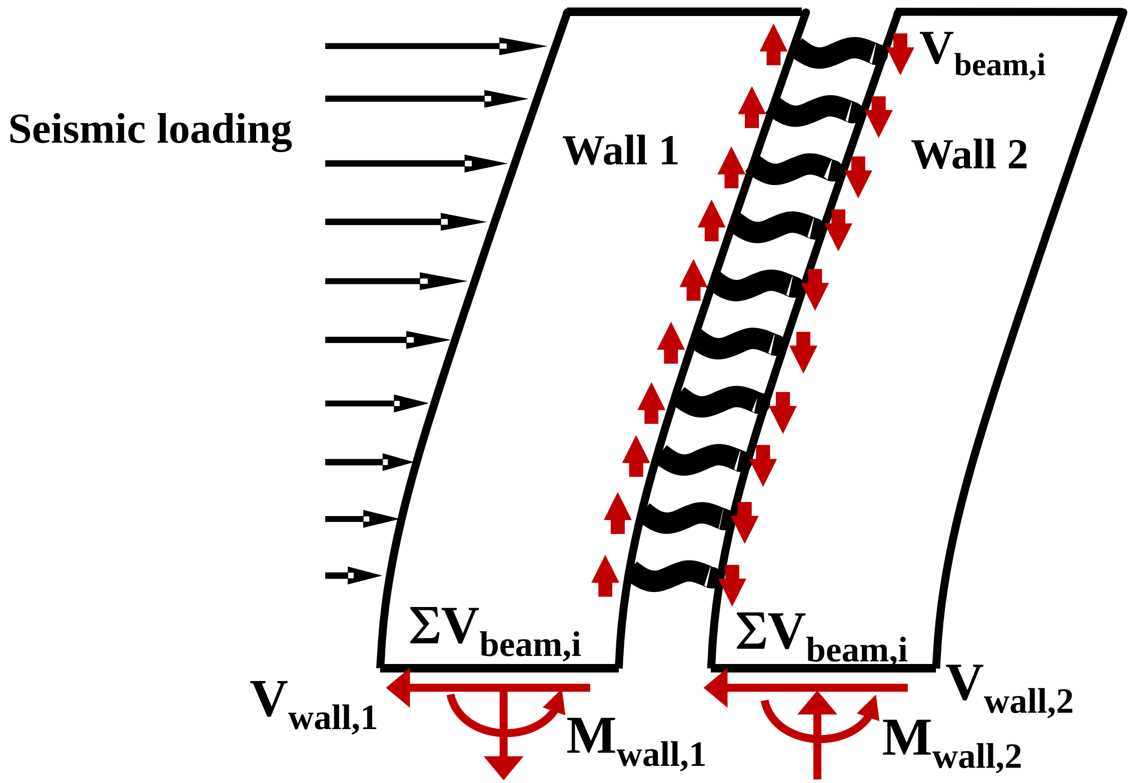
1. 高強度鋼筋加勁高強度(纖維)混凝土低矮型結構牆
2. 中高型耦合結構牆地震行為
3. 初步設計建議

2. 中高型耦合結構牆地震行為





耦合牆系統 (Coupled Wall Systems)

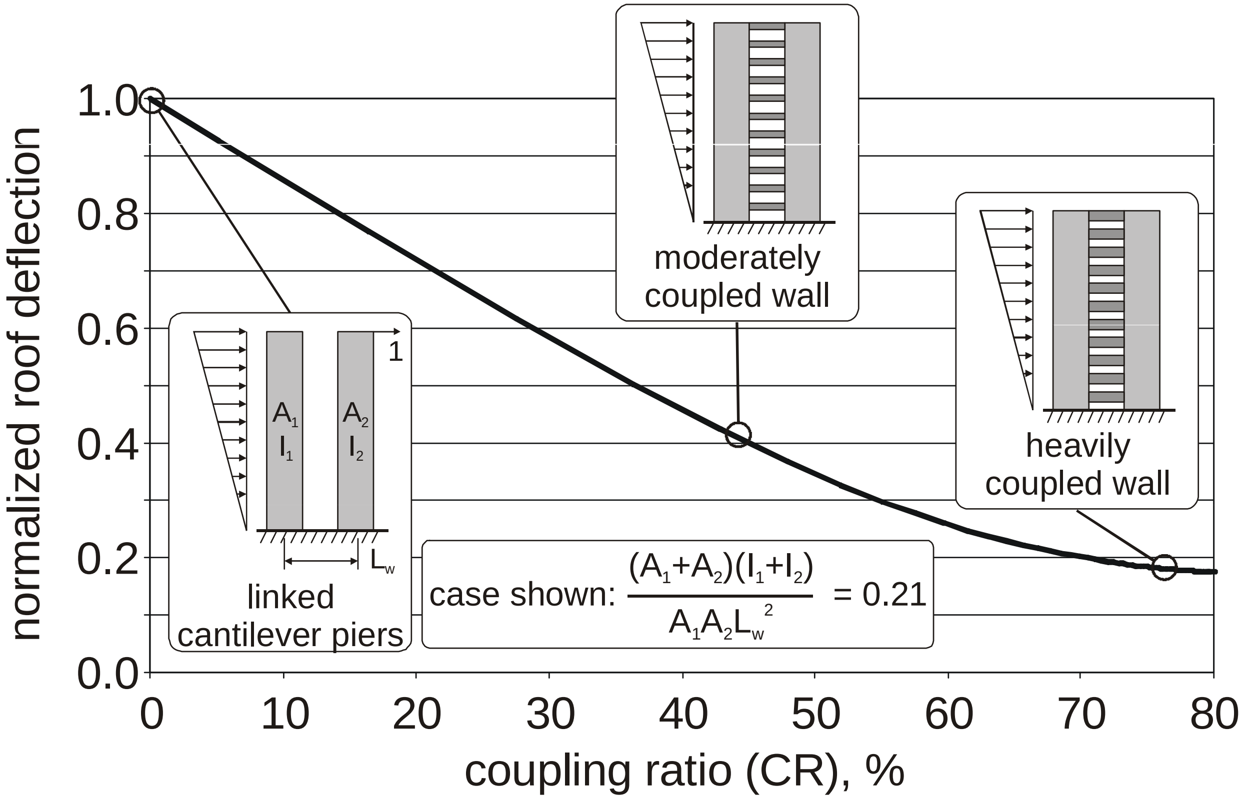


- 耦合率 (coupling ratio)

$$CR = \frac{L\sum V_{beam.i}}{L\sum V_{beam.i} + \sum m_i} = \frac{L\sum V_{beam.i}}{OTM}$$

簡介:
耦合率 (Coupling Ratio/CR)[2/2]

- 耦合效果的優點
  - 增加側向勁度、提高消能容量、減少結構牆縱向鋼筋量

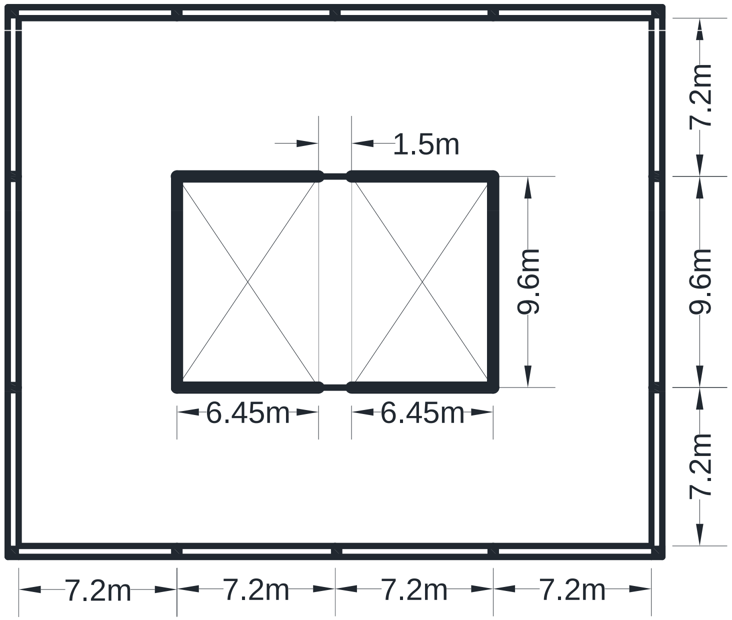


(Harries 等人 2004)

耦合率對於耦合結構牆地震行為的影響

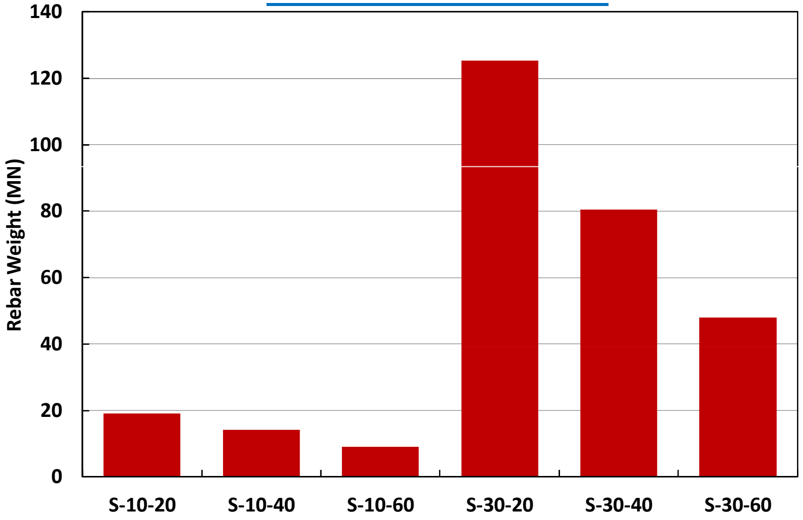
系統代號	樓層高度	耦合率(%)	系統重量
S-樓層數-CR	10 (37.5 m)	20、40、60	47 MN
	30 (92.0 m)		161 MN

系統平面圖

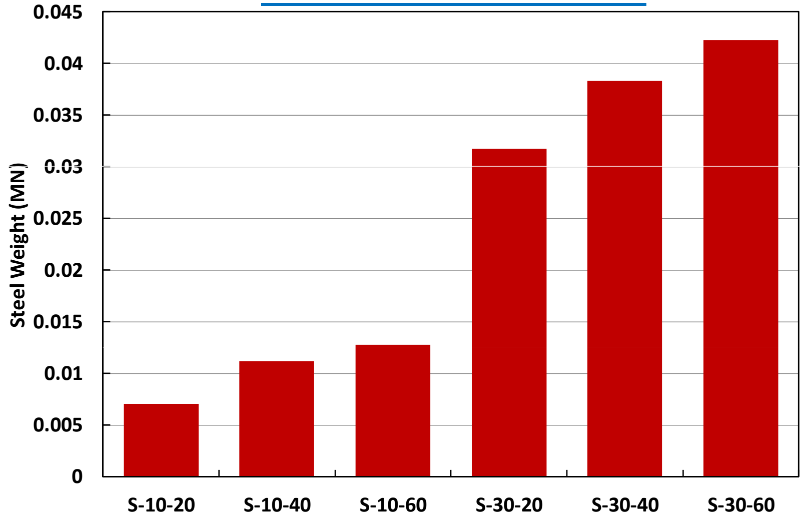


耦合牆的規範設計法
系統設計結果

結構牆鋼筋使用量

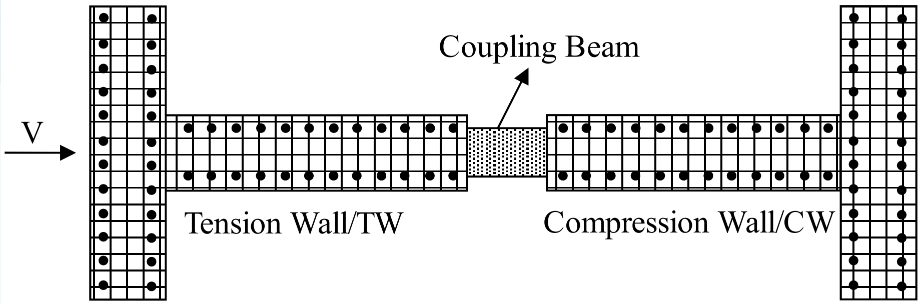


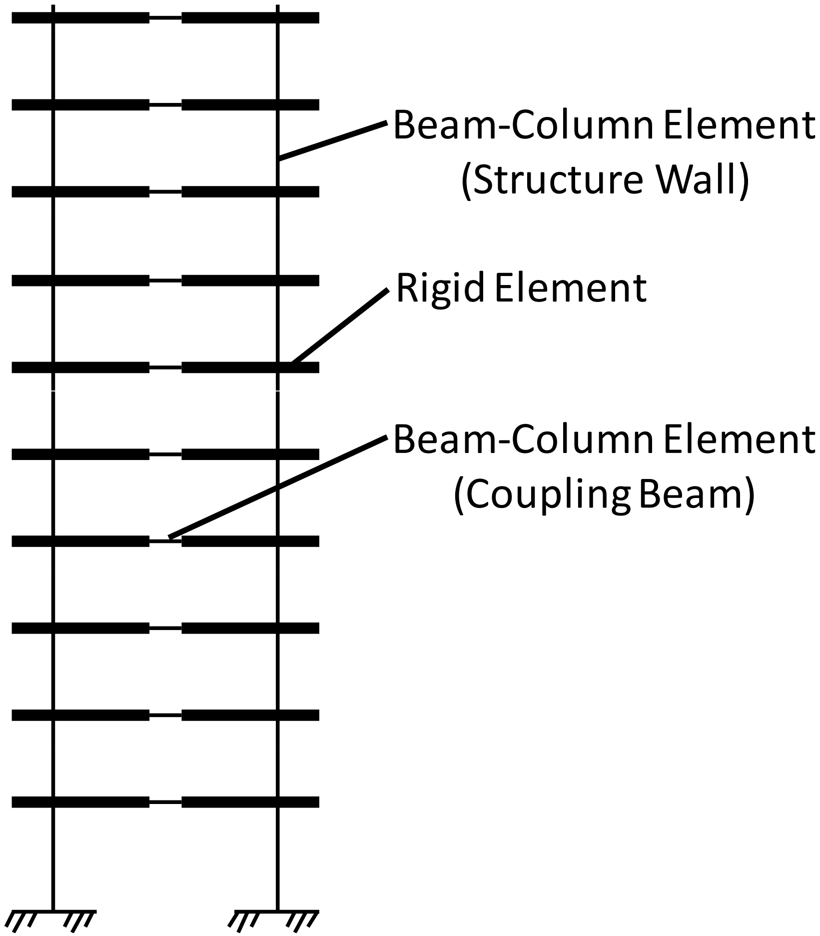
連接梁鋼材料使用量



分析程序

- 分析軟體: OpenSees
- 分析方法
  - NSP
  - NDP





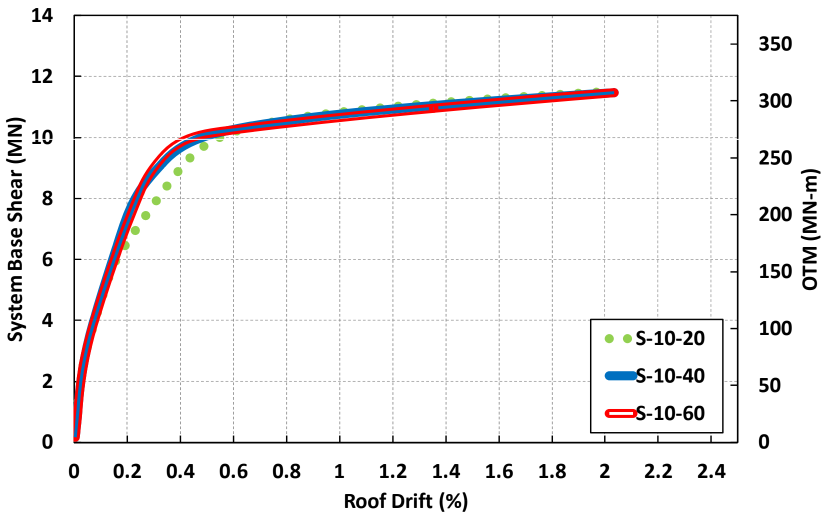
分析程序
地震歷時資料

SAC 地震資料

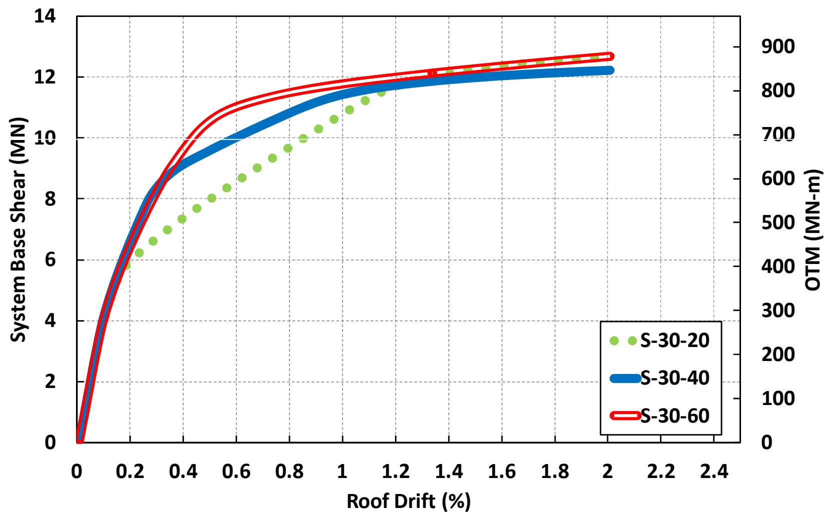
50/50		10/50		2/50	
EQ	PGA (cm/sec^2)	EQ	PGA (cm/sec^2)	EQ	PGA (cm/sec^2)
LA41	578.34	LA04	478.65	LA23	409.95
LA43	140.67	LA05	295.69	LA24	463.76
LA45	141.49	LA08	417.49	LA30	972.58
LA47	331.22	LA11	652.49	LA33	767.26
LA49	312.41	LA16	568.58	LA34	667.59
LA51	765.65	LA18	801.44	LA37	697.84
LA53	680.01	LA20	967.61	LA38	761.31

耦合牆系統的性能表現
側推曲線

10 層樓系統

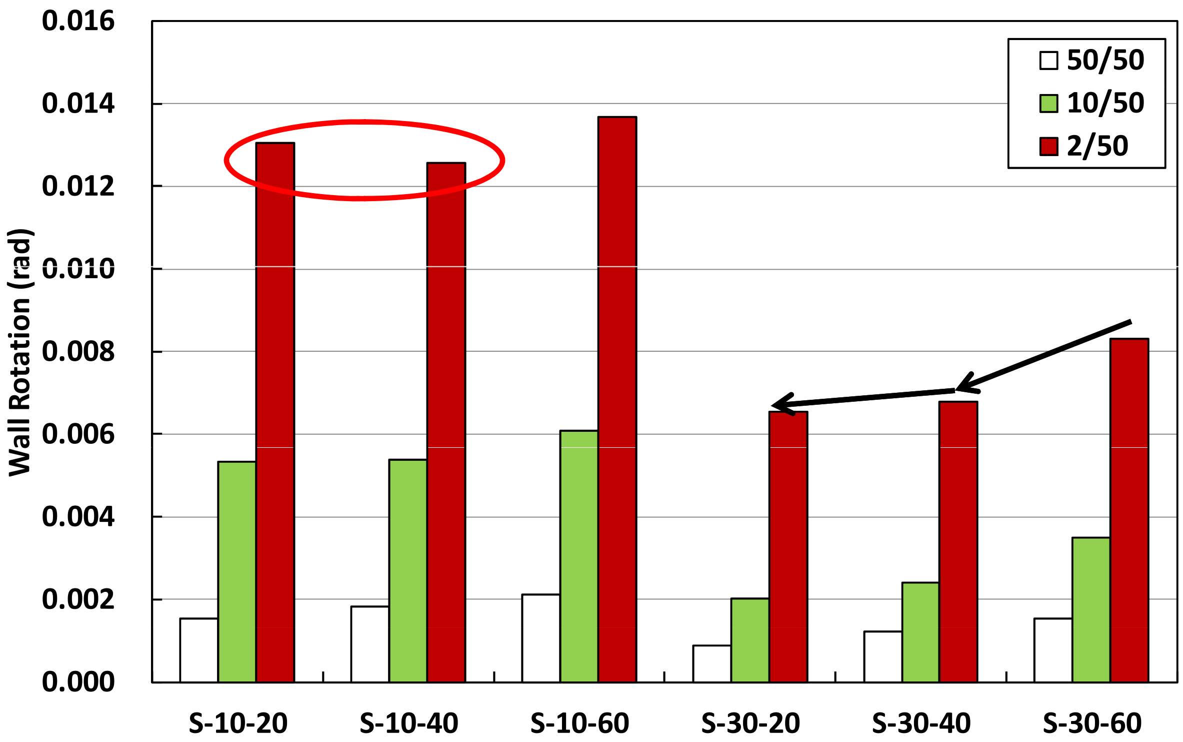


30 層樓系統



耦合牆系統的性能表現

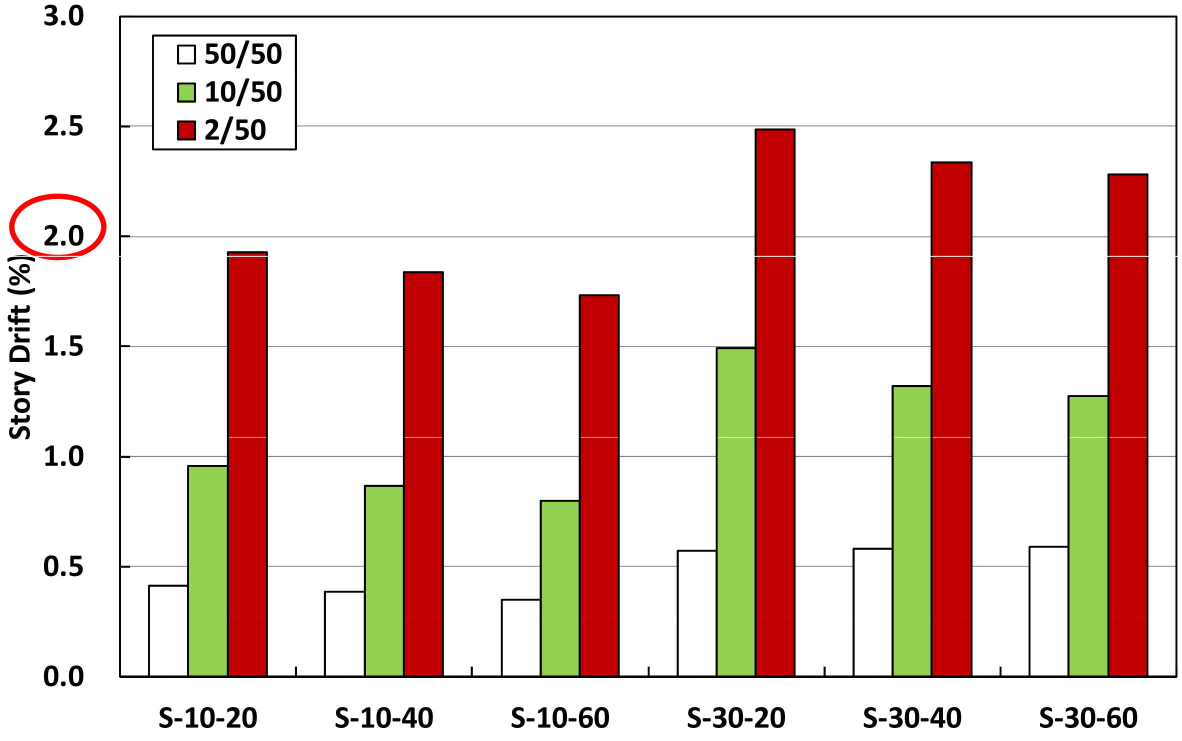
結構牆旋轉角



National Cheng Kung University

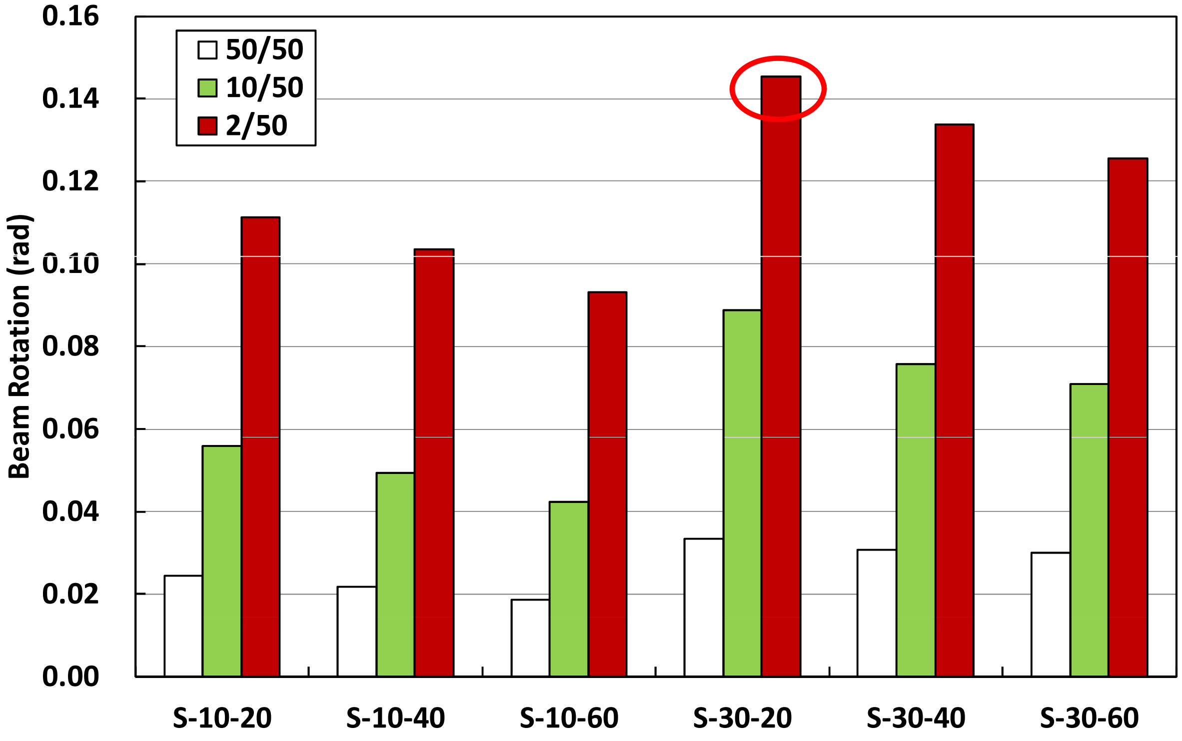
耦合牆系統的性能表現

層間側移



耦合牆系統的性能表現

連接梁旋轉角

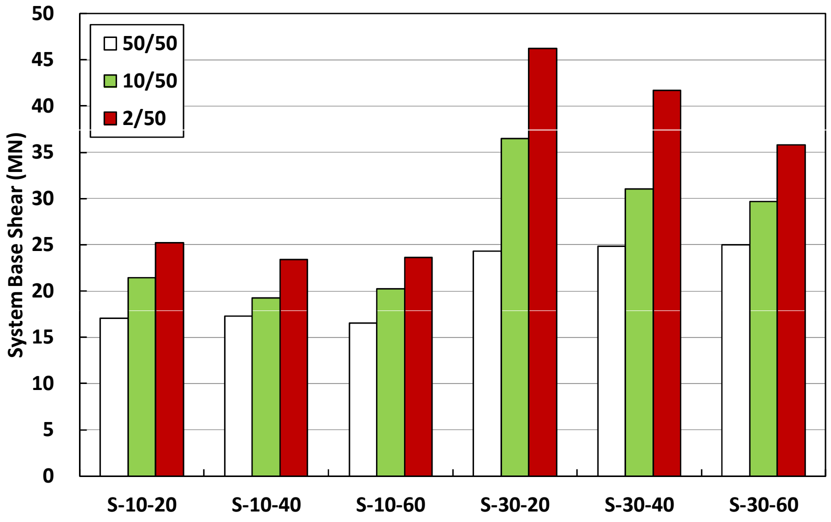


耦合牆系統的性能表現
結論 (1)

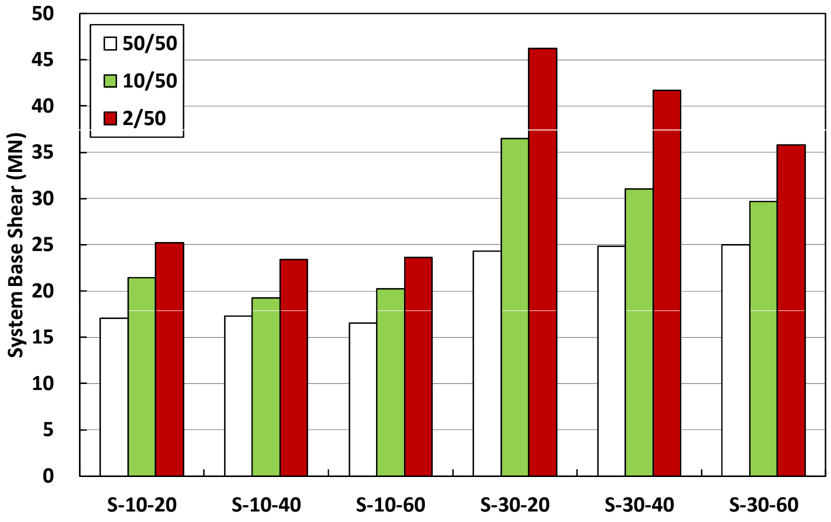
- 20%不適合耦合牆系統
- 耦合率對位移反應的控制性

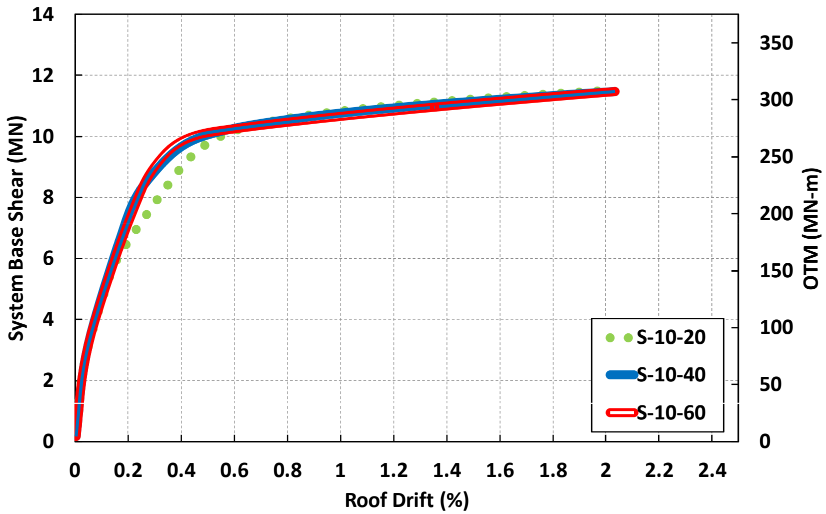
耦合牆系統的性能表現

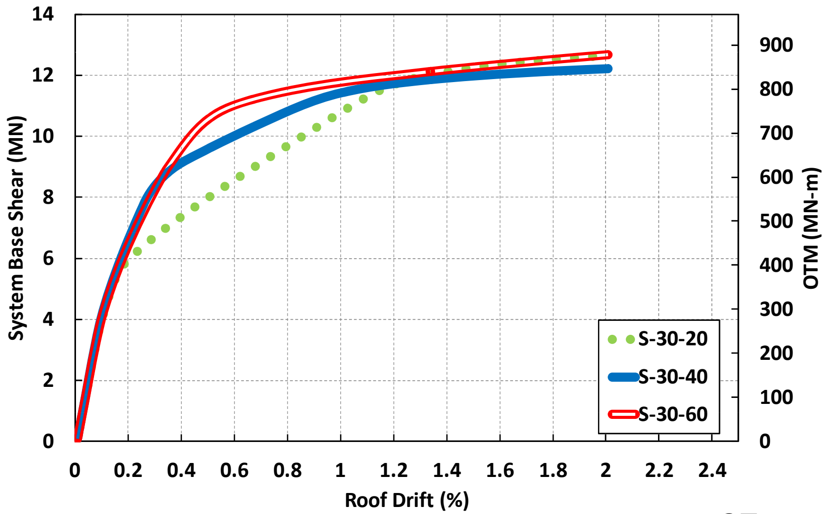
基底剪力



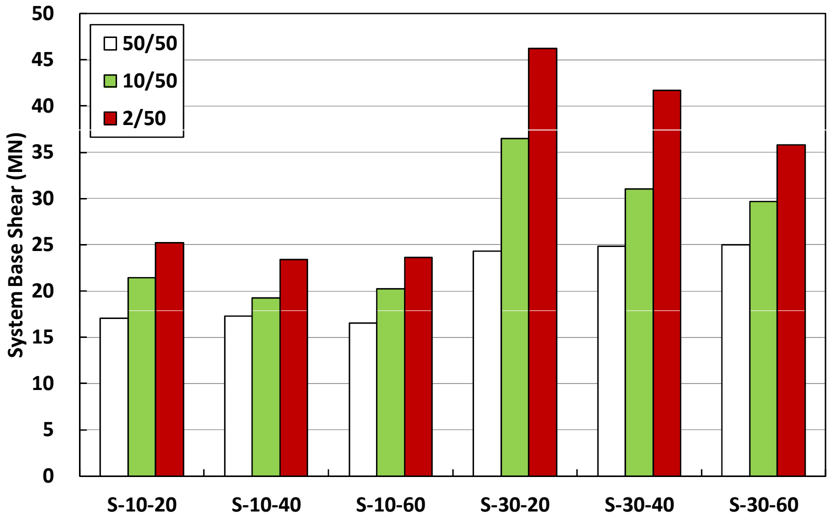
耦合牆系統的性能表現
基底剪力

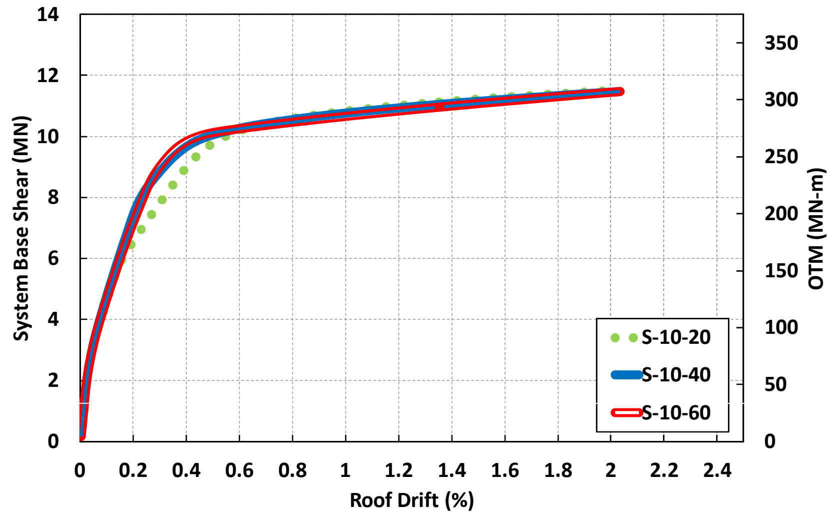


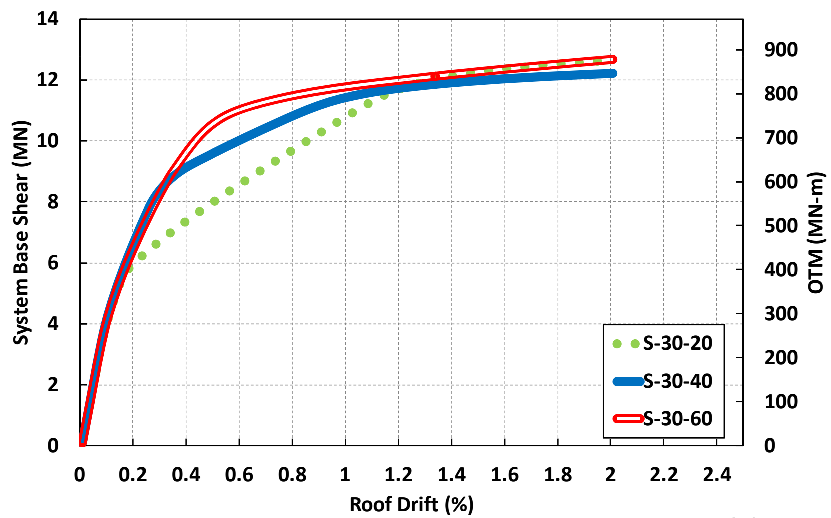




耦合牆系統的性能表現
基底剪力





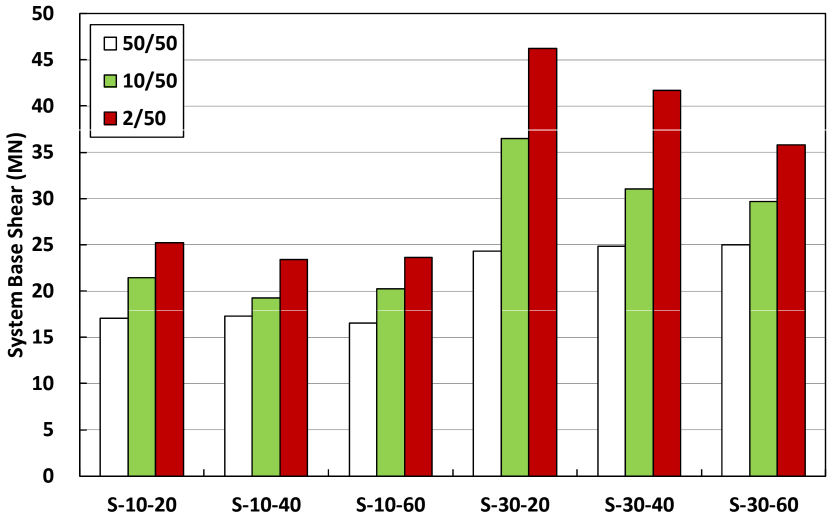


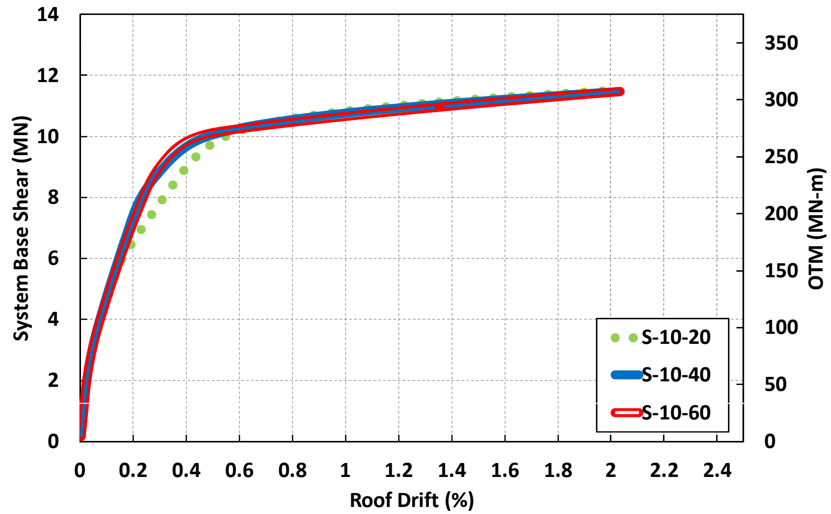
動態剪力放大因子

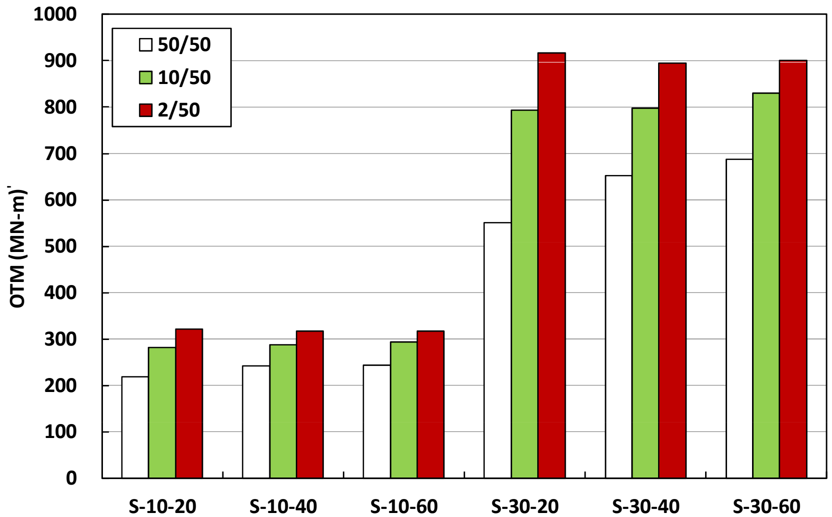
	ω_v	NDP/NSP
10 層樓系統	1.6	1.9
30 層樓系統	1.8	2.7

耦合牆系統的性能表現

基底剪力



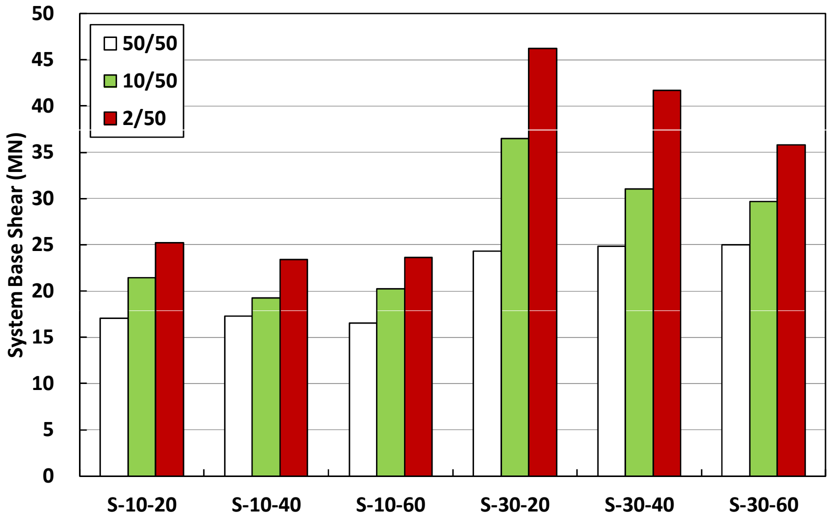


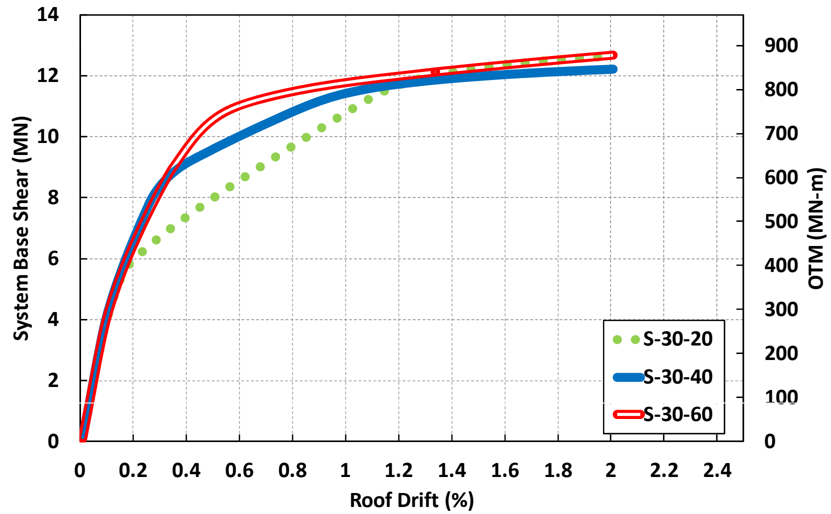


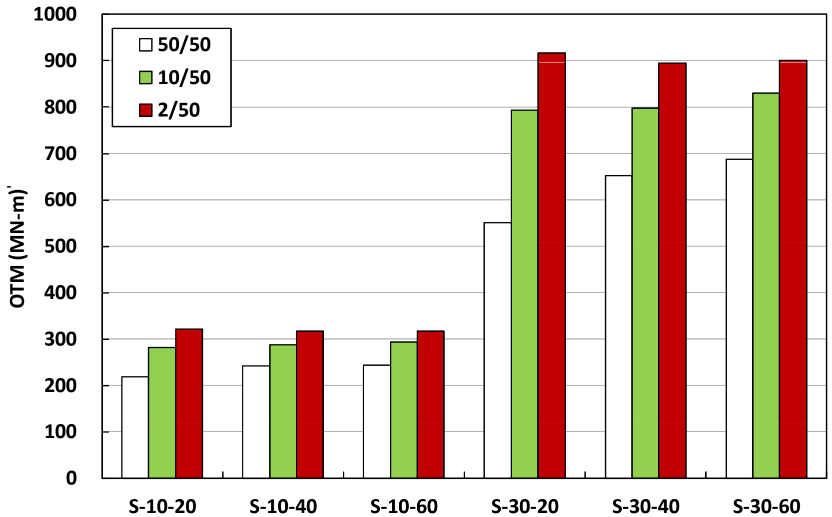
動態剪力放大因子

	ω_v	NDP/NSP
10 層樓系統	1.6	1.9
30 層樓系統	1.8	2.7

耦合牆系統的性能表現
基底剪力



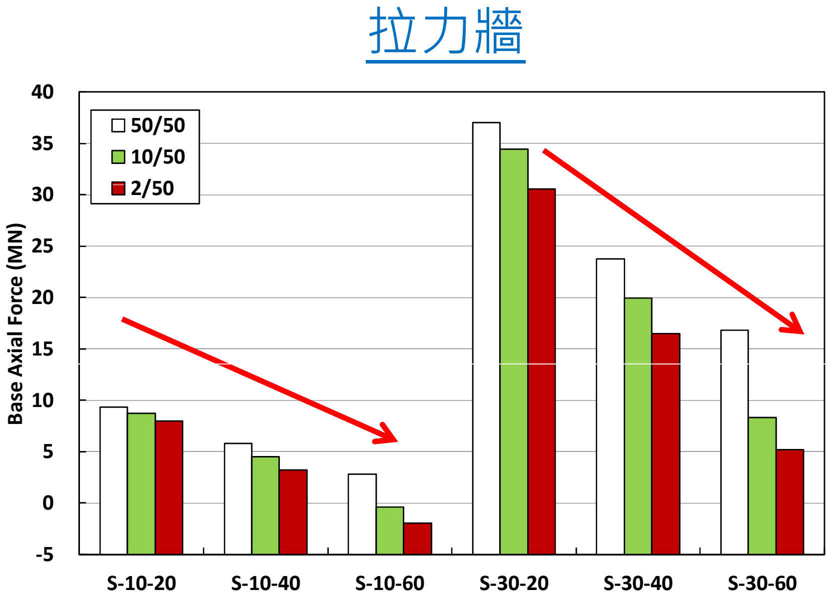


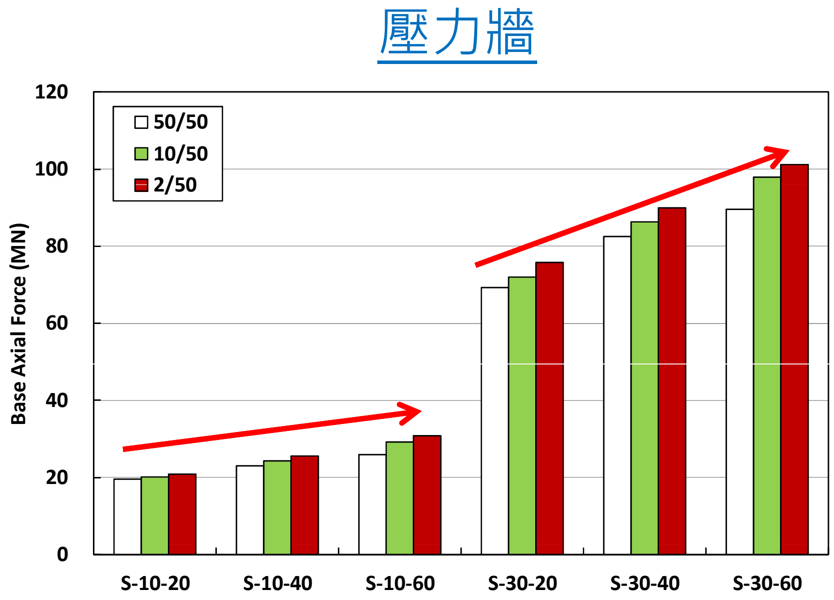


動態剪力放大因子

	ω_v	NDP/NSP
10 層樓系統	1.6	1.9
30 層樓系統	1.8	2.7

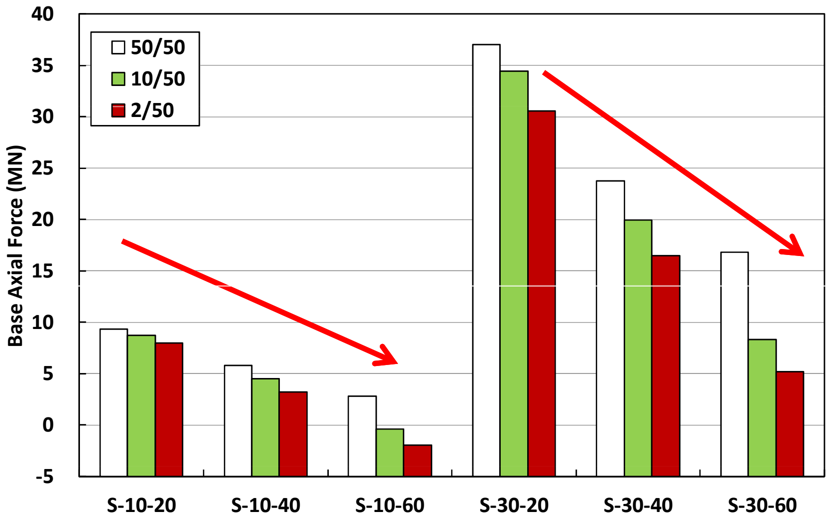
耦合牆系統的性能表現
牆底軸力



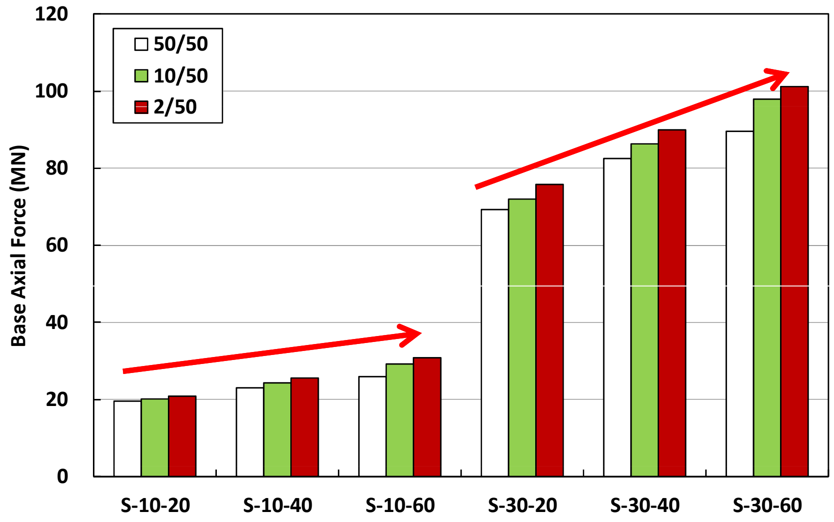


耦合牆系統的性能表現
牆底軸力

拉力牆



壓力牆

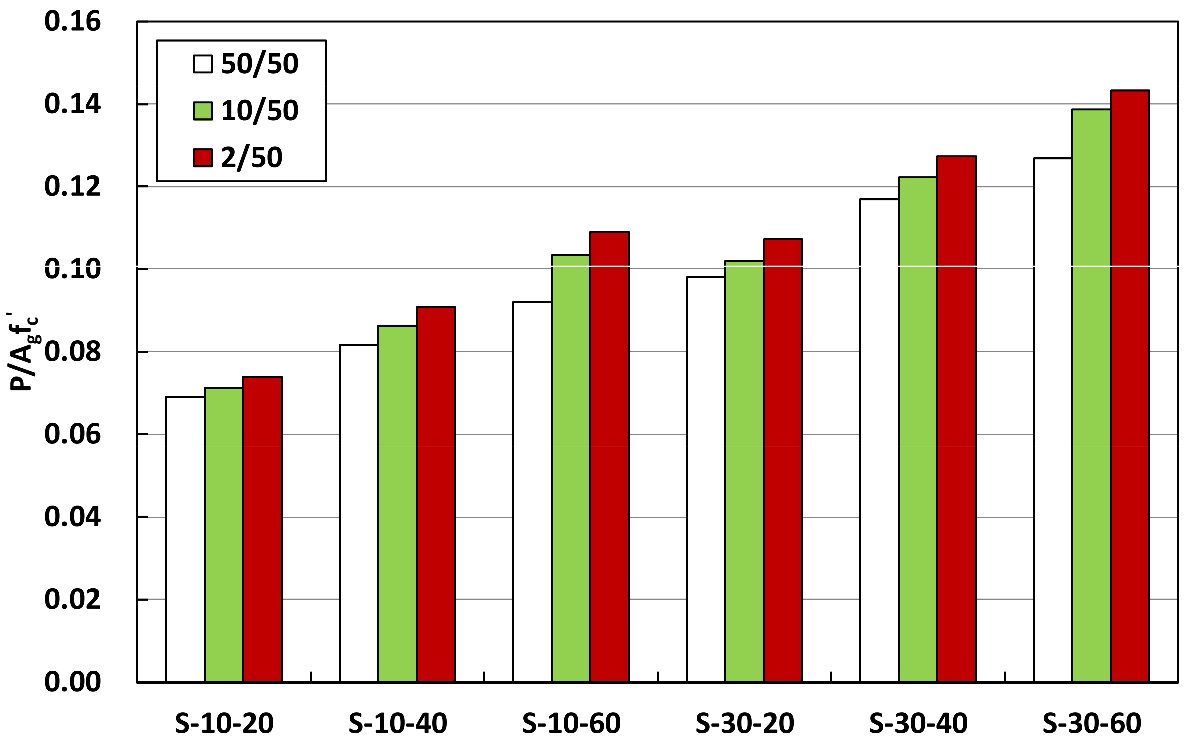


系統牆底設計軸力

	S-10-20	S-10-40	S-10-60	S-30-20	S-30-40	S-30-60
設計拉力(MN)	1.3	-3.8	-9.5	7.7	-9.3	-24.2
設計壓力(MN)	24.4	27.6	33.2	82.3	99.3	114.3

耦合牆系統的性能表現

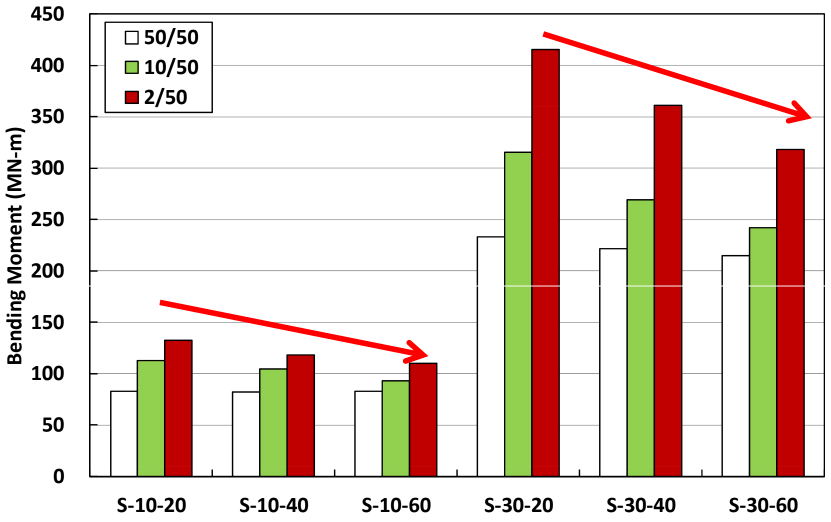
牆底軸力



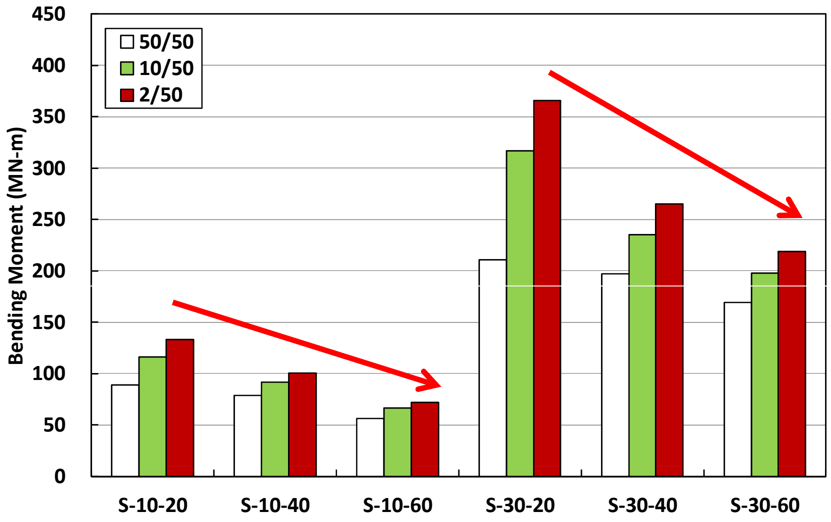
National Cheng Kung University

耦合牆系統的性能表現
牆底彎矩

拉力牆

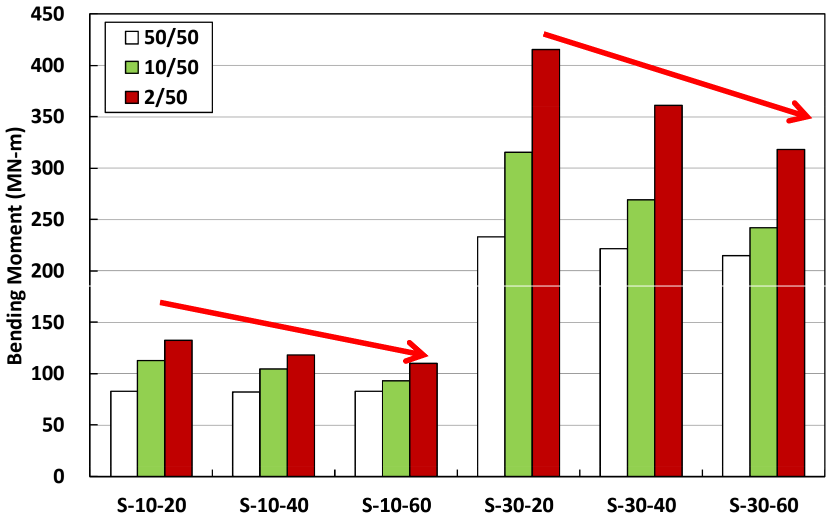


壓力牆

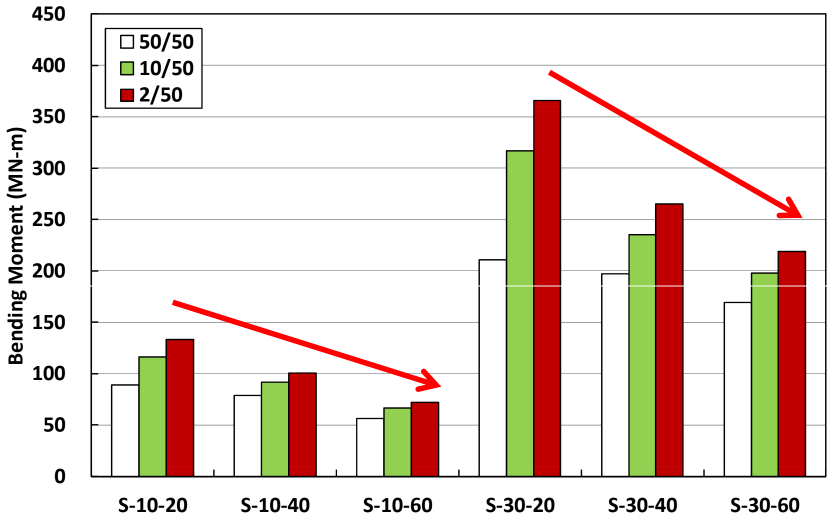


耦合牆系統的性能表現
牆底彎矩

拉力牆



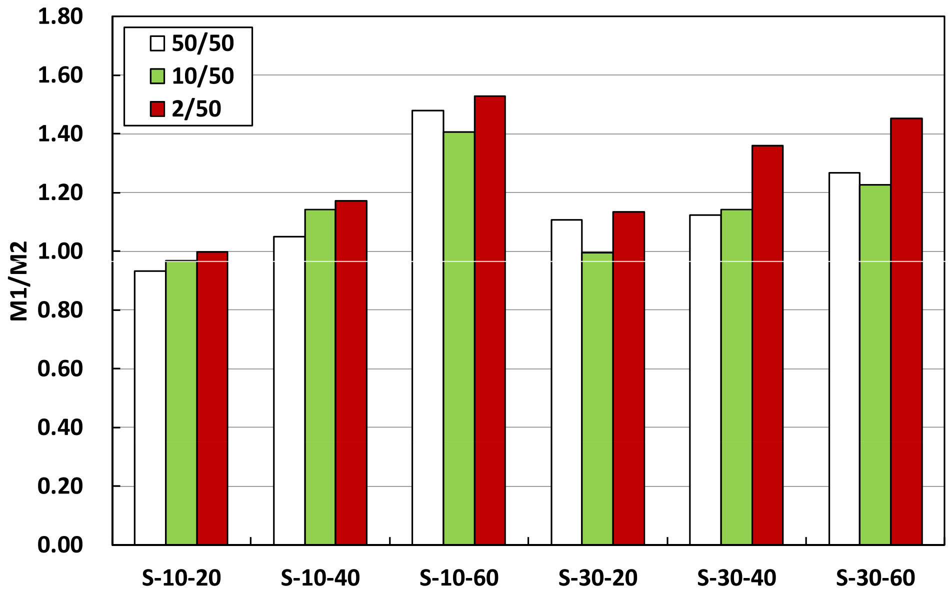
壓力牆



系統牆底設計彎矩

	S-10-20	S-10-40	S-10-60	S-30-20	S-30-40	S-30-60
拉力牆(MN-m)	60	44	30	225	154	108
壓力牆(MN-m)	106	84	58	312	236	178
拉力牆/壓力牆	0.56	0.52	0.52	0.72	0.65	0.60

耦合牆系統的性能表現
牆底彎矩

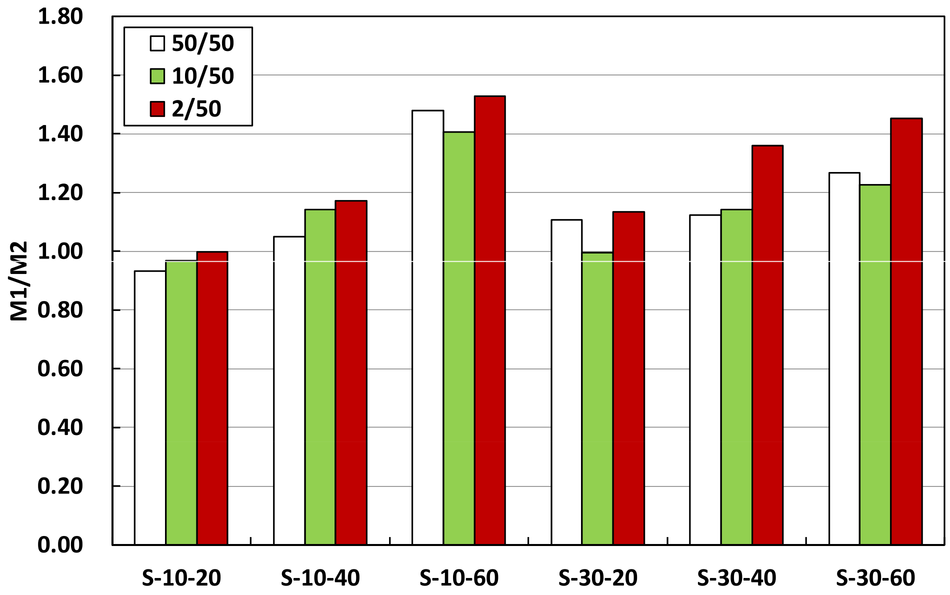


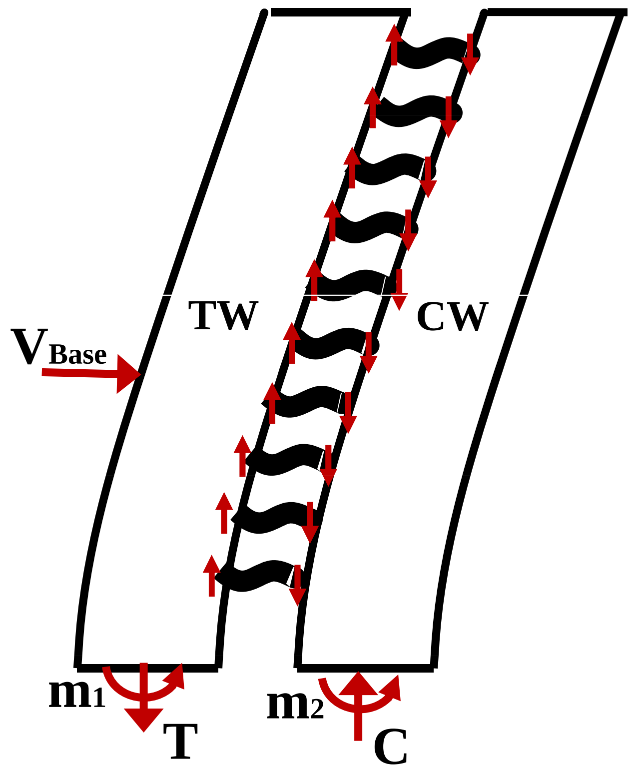
系統牆底設計彎矩

	S-10-20	S-10-40	S-10-60	S-30-20	S-30-40	S-30-60
拉力牆/壓力牆	0.56	0.52	0.52	0.72	0.65	0.60

耦合牆系統的性能表現

牆底彎矩





系統牆底設計彎矩

	S-10-20	S-10-40	S-10-60	S-30-20	S-30-40	S-30-60
拉力牆/壓力牆	0.56	0.52	0.52	0.72	0.65	0.60

耦合牆系統的性能表現
結論 (2)

- 耦合率提高雖然可減少牆底彎矩，但也會增加牆底軸力
- 設計結構牆時需要考慮動態剪力放大的效果

簡報大綱

1. 高強度鋼筋加勁高強度(纖維)混凝土低矮型結構牆
2. 中高型耦合結構牆地震行為
3. 中高型高強度鋼筋混凝土結構牆 - 初步設計建議

結構牆強度需求

- 等值側向力法 (Equivalent Lateral Force Analysis)
  - $T < 3.5\,Ts = 3.5\,SD_1/SD_s$ (FEMA 450，2003)

- 反應譜分析法 (Modal Response Spectrum Analysis)
  - 所考量振態之有效質量和，超過建物90%以上之振態數 (ASCE/SEI 7-10，2010)。

結構牆強度需求 - 有效勁度

- 有效勁度 (0.2EI~0.9EI)
  - 因反覆載重所造成之裂縫與勁度損失，結構牆之撓曲與軸向勁度均需折減
  - 決定構件設計強度
  - 評估彈性模型位移表現

Member	ACI 318	CSA A23.3	NZS 3101[1]
compression wall in flexure	$0.70EI_g$ (uncracked)	$0.80EI_g$	$0.45EI_g$
tension wall in flexure	$0.35EI_g$ (cracked)	$0.50EI_g$	$0.25EI_g$
compression wall axial	$1.00EA_g$	$1.00EA_g$[2]	$0.80EA_g$
tension wall axial	$0.35EA_g$ (inferred)	$0.50EA_g$[2]	$0.50EA_g$

Note: NZS 3101 has different recommendations for different limit states. The values corresponding to the most critical limit state are shown.

結構牆強度需求 - 有效勁度

- 有效勁度 (0.2EI~0.9EI)
  - 因反覆載重所造成之裂縫與勁度損失，結構牆之撓曲與軸向勁度均需折減
  - 決定構件設計強度
  - 評估彈性模型位移表現

Ibrahim (2000)

$$I_e = \left(0.6 + \frac{P}{f_c' A_g}\right) I_g \le I_g$$

$$I_e = \left(0.2 + 2.5\frac{P}{f_c' A_g}\right) I_g \le 0.7 I_g$$

where P = applied axial compression

f_c' = specified concrete strength

A_g = gross cross-sectional area of wall

結構牆強度需求 - 有效勁度

- 建議高強度鋼筋混凝土結構牆塑鉸區以上之有效彎曲與軸向勁度分別為$0.7EI_g$ 與 $0.7EA_g$，塑鉸區則為$0.35EI_g$與$0.35EA_g$，塑鉸長度可取為牆長度。

Member	ACI 318	CSA A23.3	NZS 3101[1]
compression wall in flexure	$0.70EI_g$ (uncracked)	$0.80EI_g$	$0.45EI_g$
tension wall in flexure	$0.35EI_g$ (cracked)	$0.50EI_g$	$0.25EI_g$
compression wall axial	$1.00EA_g$	$1.00EA_g$[2]	$0.80EA_g$
tension wall axial	$0.35EA_g$ (inferred)	$0.50EA_g$[2]	$0.50EA_g$

Note: NZS 3101 has different recommendations for different limit states. The values corresponding to the most critical limit state are shown.

結構牆強度需求 - 軸壓比限制

- 採用FEMA-356 (2000)軸壓比之建議，避免早期非韌性破壞 (Zhang 與 Wang，2000)。
  - 限制結構牆牆底之斷面最大軸壓力$P_{u,w}$小於$0.35(P_0)$

$$P_{u,w} = 1.2D + 1.0E + L$$

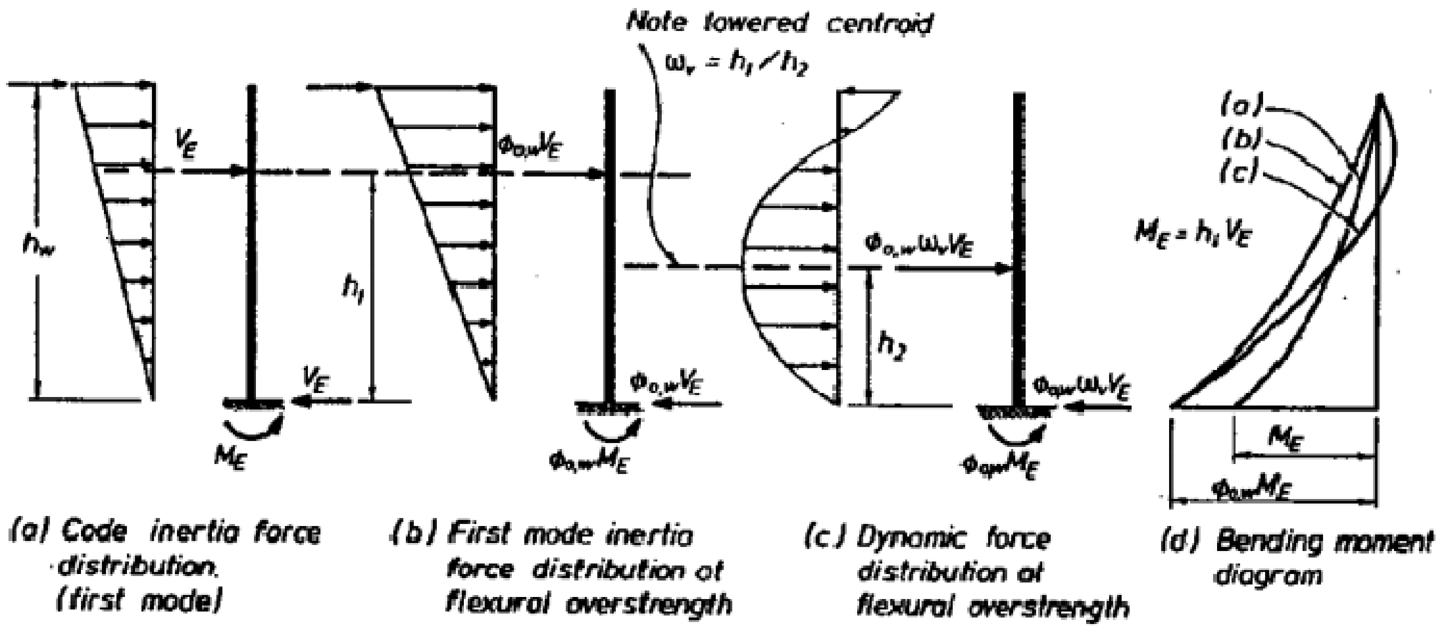
$$P_0 = \phi P_{n,w} = \phi\left(0.85(0.85 f_c^{'} A_g)\right)$$

結構牆強度需求 – 剪力需求

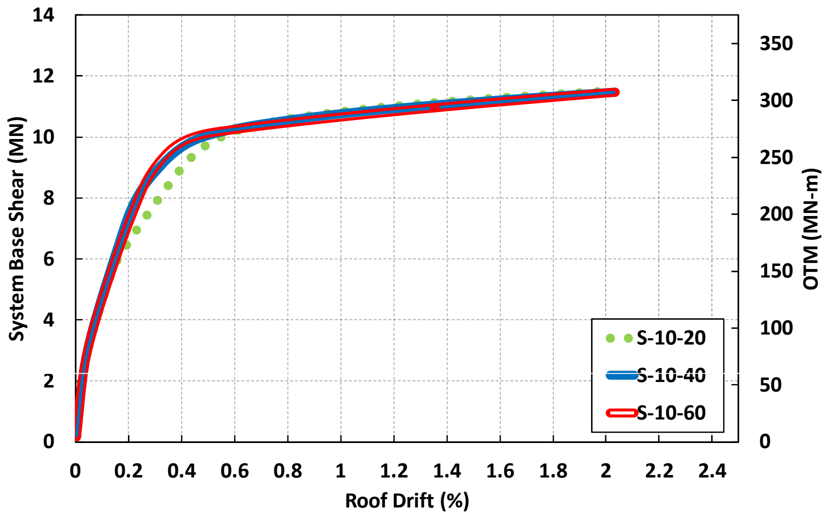
- 設計基底剪力採用*Paulay與Priestley(1992)*建議：

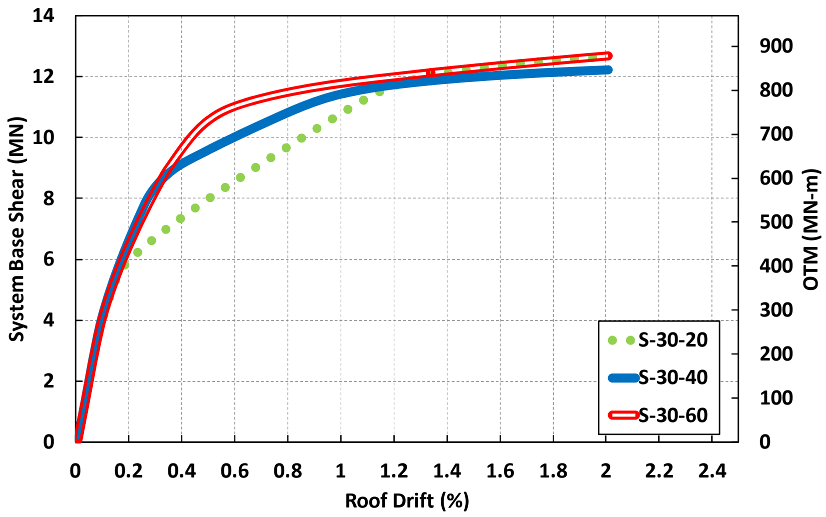
$$V_u = \omega_v \phi_{o,w} V_E \qquad \omega_v = 1.3 + \frac{n}{30} \le 1.8$$

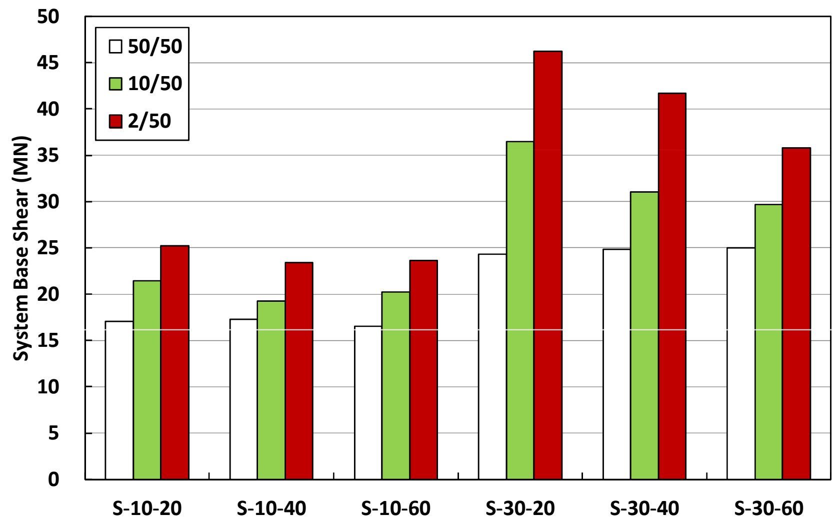
V_u 為系統設計基底剪力；ω_v 為動態剪力修正係數；$\phi_{o,w}$ 為撓曲超額因子1.25；V_E 為經由分析所得之基底剪力需求。其中，動態剪力修正係數與結構牆之樓層數*n* 相關。



耦合牆系統的性能表現
基底剪力







動態剪力放大因子

	ω_v	NDP/NSP
10 層樓系統	1.6	1.9
30 層樓系統	1.8	2.7

結構牆剪力設計

- 結構牆斷面之標稱剪力強度折減後須大於設計剪力，剪力強度分別由混凝土與鋼筋所提供，

$$\emptyset V_n \geq V_u$$

$$V_n = V_c + V_s$$

V_u為設計剪力強度；V_n為標稱剪力強度；為強度折減因數；V_c為混凝土提供之標稱剪力強度；V_s為鋼筋提供之標稱剪力強度。

結構牆剪力設計

- 剪力強度上限，採用*ACI-318 (2014)建議*

$$V_n = 0.83\lambda\sqrt{f_c'}\,b_w d \text{ (MPa)}$$
$$V_n = 2.59\lambda\sqrt{f_c'}\,b_w d \text{ (kgf/cm}^2\text{)}$$

d為斷面最外受壓處至縱向拉力鋼筋中心之距離與0.8倍牆寬之大者

結構牆剪力設計–混凝土標稱剪力強度

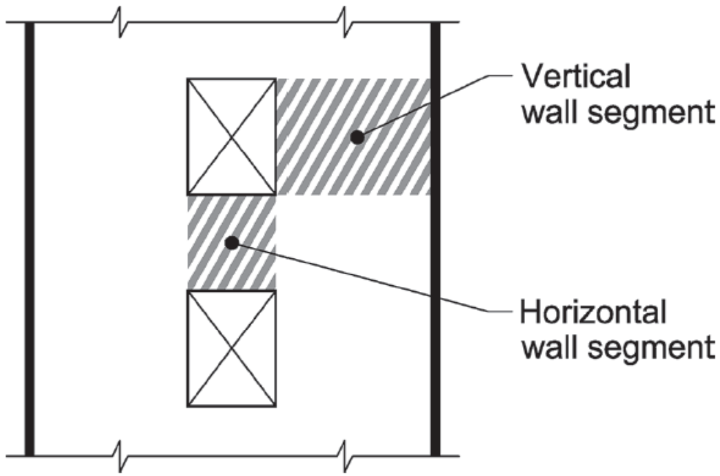
- 沿用*ACI 318-14*，結構牆在抵抗設計地震力時，其標稱剪力強度Vn 不得大於式(7-10)之計算值，

$$V_n = A_{cv}(\alpha_c \lambda \sqrt{f_c'} + \rho_t f_y)$$

α_c為用以描述高寬比(h_w/ℓ_w)對混凝土所提供之標稱剪力強度之影響參數。其中，在考量高寬比時，應採整體牆或牆段(wall segment)之大者。

表7-3 高寬比係數表

	α_c	
	$\sqrt{f_c'}$(MPa)	$\sqrt{f_c'}$(kgf/cm²)
$h_w/\ell_w \le 1.5$	0.25	0.80
$1.5 \le h_w/\ell_w \le 2$	線性內插	線性內插
$h_w/\ell_w \ge 2$	0.17	0.53



結構牆剪力設計–混凝土標稱剪力強度

- *採用ACI 318-14規定*，總牆或總垂直牆段橫斷面面積所提供之平均剪力強度不超過

$$0.67\sqrt{f_c'}\,(\mathrm{MPa})\text{或}2.08\sqrt{f_c'}\,(\mathrm{kgf/cm^2})$$

- 任一垂直牆段之平均剪力強度不超過

$$0.83\sqrt{f_c'\,(MPa)}\text{或}2.59\sqrt{f_c'\,(kgf/cm^2)}$$

，

結構牆剪力設計–鋼筋設計

- 水平鋼筋提供之剪力強度Vs應按式(7-11)計算，f_y應不大於600MPa。
- 最小鋼筋量、鋼筋配置細節(Sections 18.10.2)、及特殊邊界構材規定(Sections 18.10.6.2 - 18.10.6.5)，則沿用ACI318-14建議。