國立臺灣大學 National Taiwan University

高強度鋼筋混凝土(New RC)結構設計與施工技術研討會

高流動性應變硬化鋼纖維混凝土於 New RC 結構系統之應用

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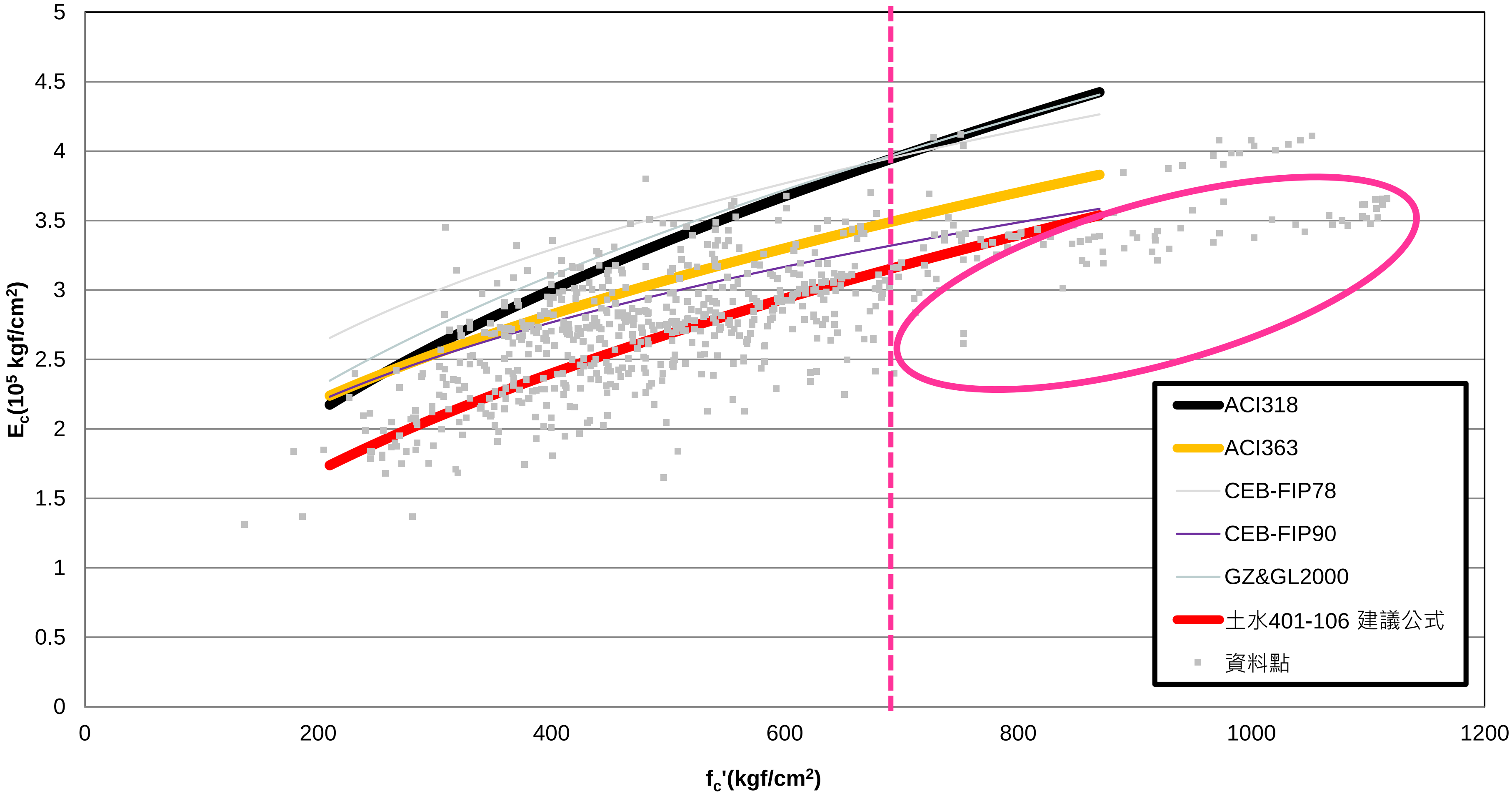
New RC 彈性模數?

$$E_C = 12000\sqrt{f_c'}\ \left(\frac{kgf}{cm^2}\right)$$

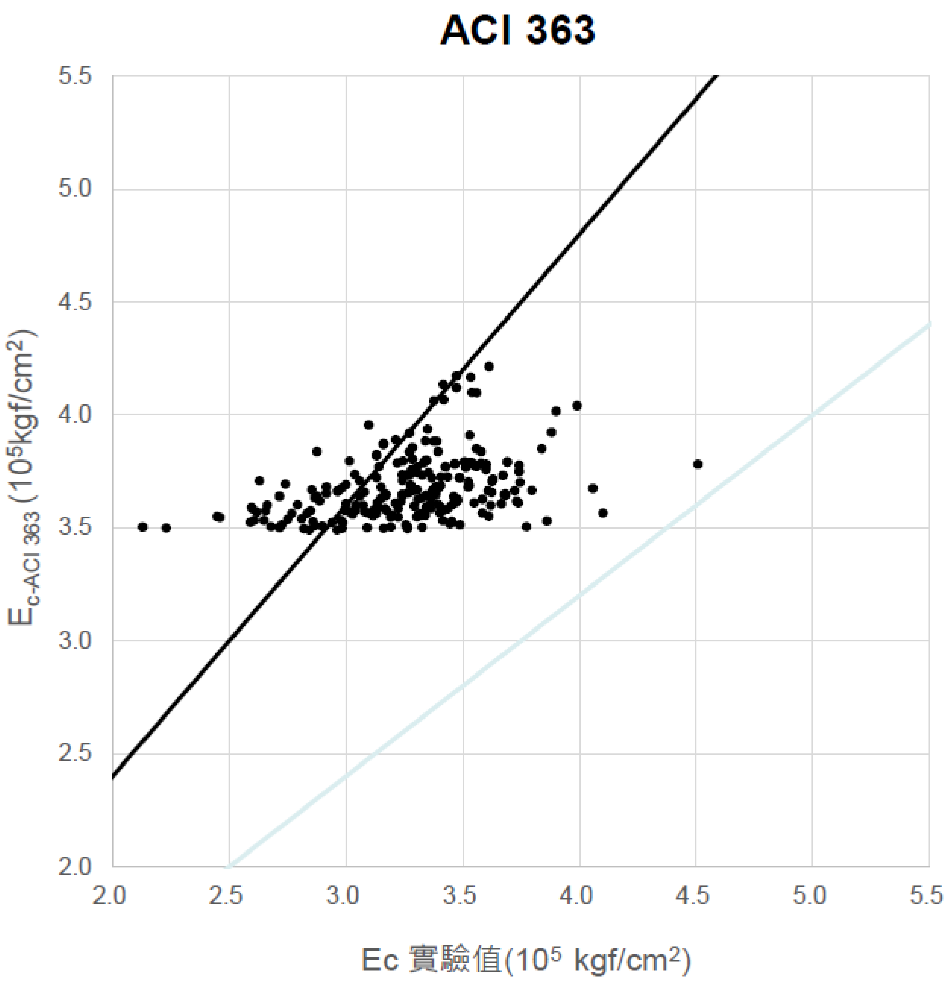
932筆資料，f'c: 210 kgf/cm²~840 kgf/cm²間，已考慮粗粒料含量、OPC SCC、卜作嵐添加量等敏感度分析

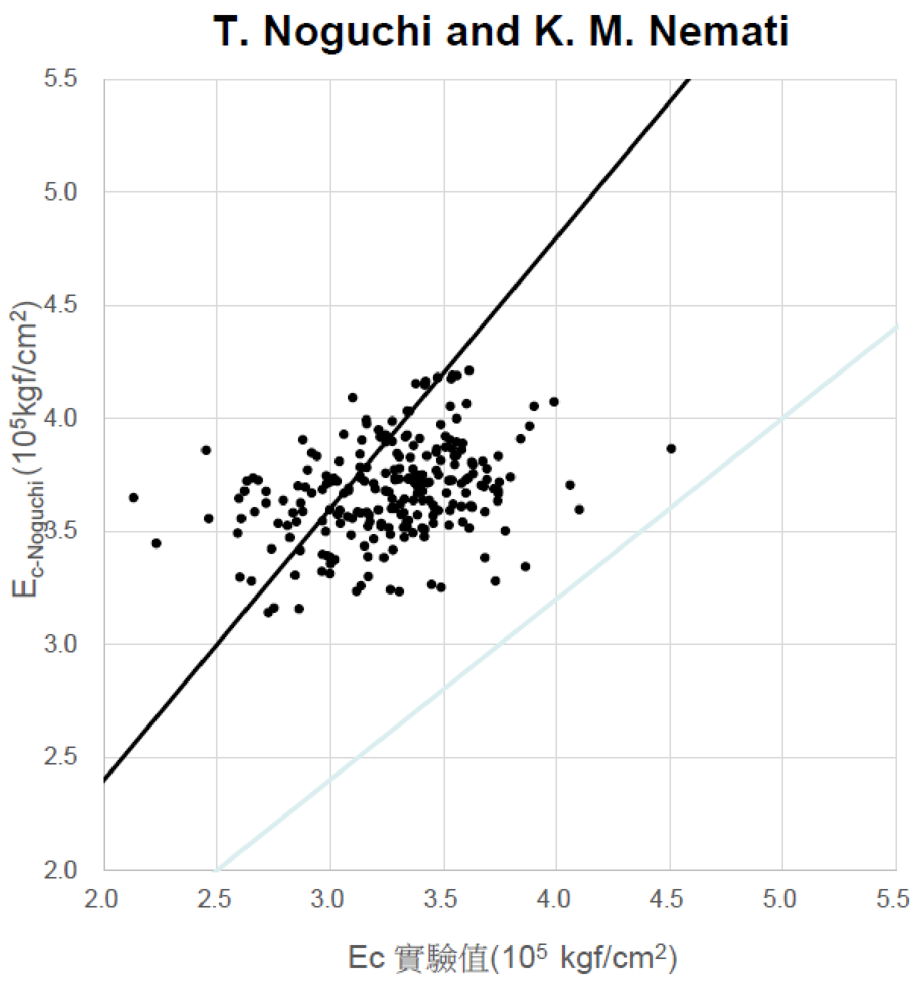


廖文正*, 林致淳, 詹穎雯 (2016年11月)。台灣混凝土彈性模數建議公式研究。結構工程期刊，31(3)。

New RC 彈性模數?

449筆資料，f'c: 650 kgf/cm²~1300 kgf/cm²間

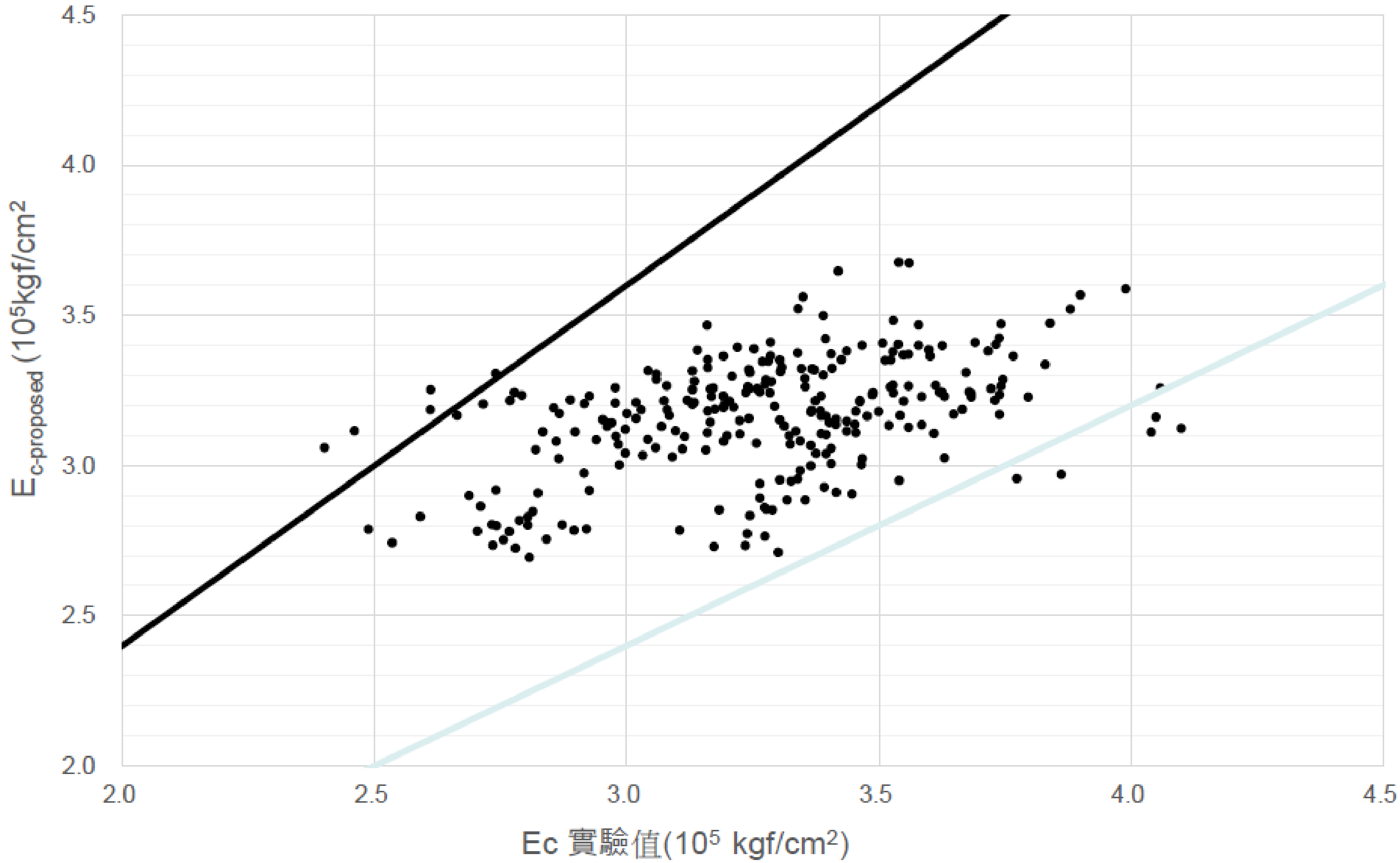




New RC 彈性模數?

$$E_c = k_1 \times \left(234000 \times \left(\frac{w}{2380}\right)^{1.5} \times \left(\frac{f'_c}{700}\right)^{0.5} + 74200\right)\left(\frac{kgf}{cm^2}\right)$$

$k_1 = 0.24 \times S + 0.83$; **S為矽灰比**



新世代耐震水泥質材料 -

高流動性應變硬化鋼纖維混凝土

背景

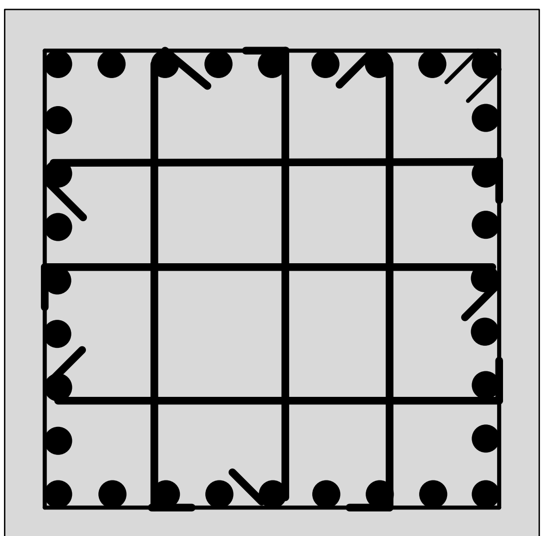
臺灣New RC Project

- ✓ 純鋼筋混凝土高樓建築（50-story）
- ✓ 高強度混凝土（>70MPa）+高強度鋼筋，減少斷面尺寸、材料用量及建物自重，增加使用空間
- x 脆性破壞，需更多箍筋圍束

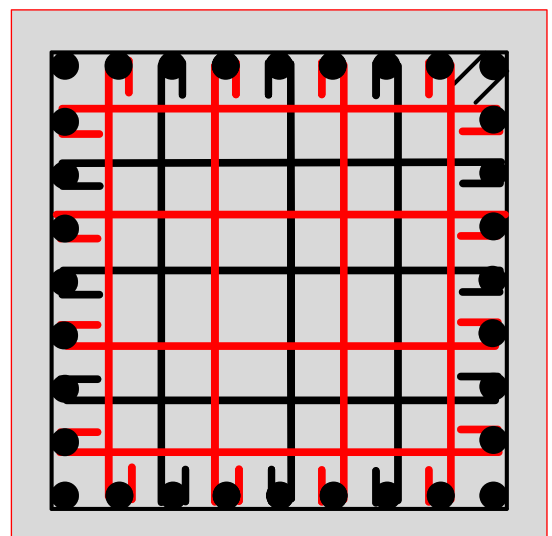
普通強度混凝土

高強度混凝土

現行規範

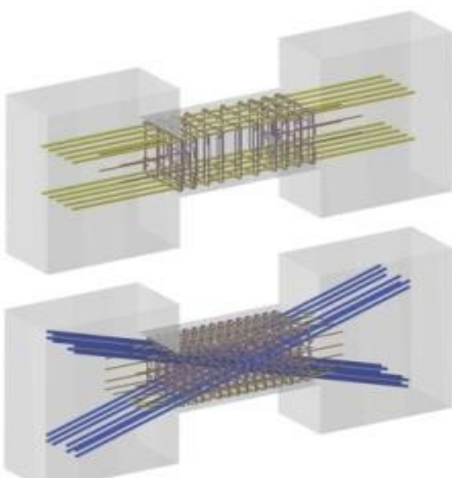


ACI 318-14



箍筋量增加70%，180°彎鉤

背景



DAILY JOURNAL OF COMMERCE
Thursday, January 31, 2013

Steel fiber concrete cuts need for rebar

■ *A new mix allowed crews to build shear wall link beams with 40 percent less rebar at The Martin apartments in Belltown.*

By LUCY BODILLY
Special to the Journal

Pouring concrete into congested rebar is difficult: Concrete is hard to place and vibrating around the tangle of rebar to remove the voids makes it even harder.

Structural engineer Cary Kopczynski, senior principal and CEO of Cary Kopczynski & Co. in Bellevue, found a solution. At his latest project, The Martin, his firm specified steel fiber concrete in the shear wall link beams, a place that is especially congested with rebar.

CONSTRUCTION INDUSTRY SPOTLIGHT

The Martin is a 24-story apartment building under construction at Fifth and Lenora in Seattle's Belltown neighborhood.

particularly during an earthquake.

"Our objective in using fiber was to reduce the quantity of rebar, making the beams easier to construct, and replace the lost strength (due to the reduction in rebar) with steel fiber mixed into the concrete," Kopczynski said.

He first heard about testing of the steel fibers while working on a national committee that reviews building codes. Also on the committee was a University of Michigan professor who was studying the steel fibers.

"The goal is to introduce modifications to the International Building Code that will make the design approach used for The Martin mainstream," Kopczynski said.

The recession and construction downturn stalled use of steel fiber concrete, adding to the hurdles the new technology faced. The first hurdle was to convince building owner Vulcan Real Estate to try the product.

"There is a wide range of

The city required two peer reviews before it would accept the new technology. Photos courtesy of Cary Kopczynski & Co.

背景

- **ACI 318-11**

11.4.6 — **Minimum shear reinforcement**

11.4.6.1 (f)

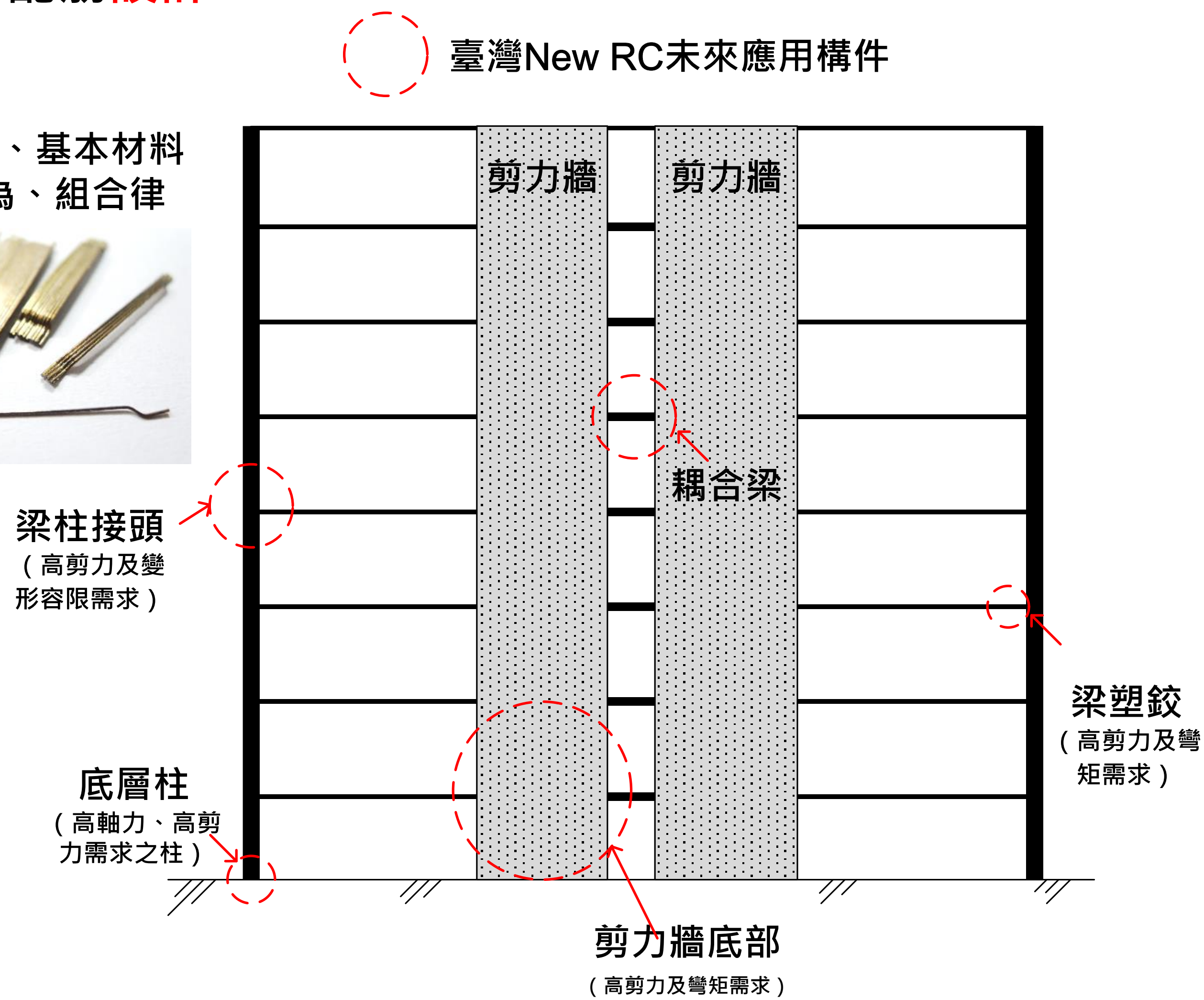
Beams constructed of steel fiber-reinforced, normalweight concrete with f_c' not exceeding 6000 psi, h not greater than 24 in., and V_u not greater than $2\sqrt{f_c'}b_wd$.

R11.4.6.1(f) — This exception is intended to provide a design alternative to the use of shear reinforcement, as defined in 11.4.1.1, for members with longitudinal flexural reinforcement in which V_u does not exceed $2\sqrt{f_c'}b_wd$. Fiber-reinforced concrete beams with hooked or crimped steel fibers in dosages as required by 5.6.6.2 have been shown, through laboratory tests, to exhibit shear strengths larger than $3.5\sqrt{f_c'}b_wd$.

背景

高流動性應變硬化鋼纖維混凝土：高剪力強度、高圍束效益，能直接取代箍筋，簡化斷面配筋設計。

配比設計、基本材料
力學行為、組合律



Wen-Cheng Liao, Wisena Perceka, En-Jui Liu (2015, Aug). Compressive Stress-Strain Relationship of High Strength Steel Fiber Reinforced Concrete. Journal of Advanced Concrete Technology, 13, pp 379-392. (SCI).

Wen-Cheng Liao, Shih-Ho Chao (2015, Mar). Crack Opening Evaluation and Sustainability Potential of Highly Flowable Strain-Hardening Fiber-Reinforced Concrete (HF-SHFRC). Journal of Testing and Evaluation, 43(2), pp 326-335. (SCI).

Main Obstacles for Fiber Reinforced Concrete

1. Workability
2. Mechanical performances is not as good as expected.

Sol:
Highly Flowable Strain Hardening Fiber Reinforced Concrete,
HF-SHFRC

3. No main advantages on usual structural applications.

Sol:
New RC project, bridge piers, beam-column joint, base columns and etc.

Highly Flowable Strain Hardening Fiber Reinforced Concrete

V_f=1.5%; f'_c = 70 MPa

Highly Flowable Strain Hardening Fiber Reinforced Concrete

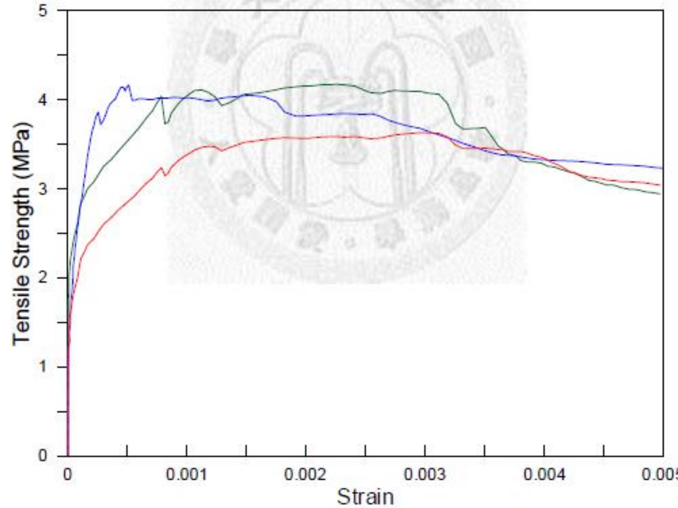


圖 5－12 C30 直接拉力應力應變圖（0.5％）

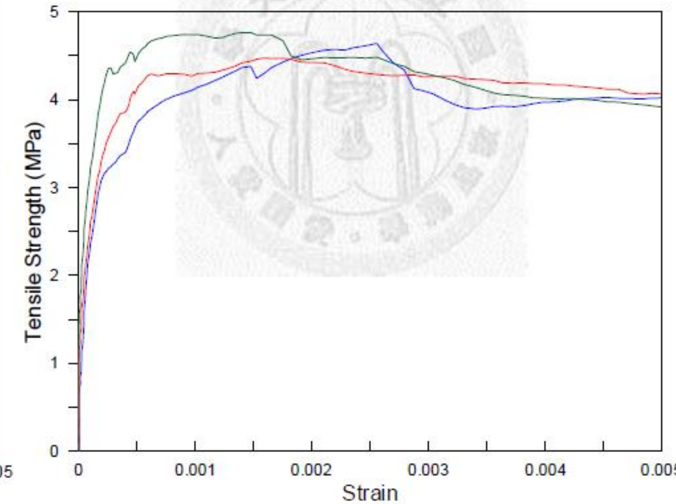


圖 5－14 C40 直接拉力應力應變圖（0.5％）

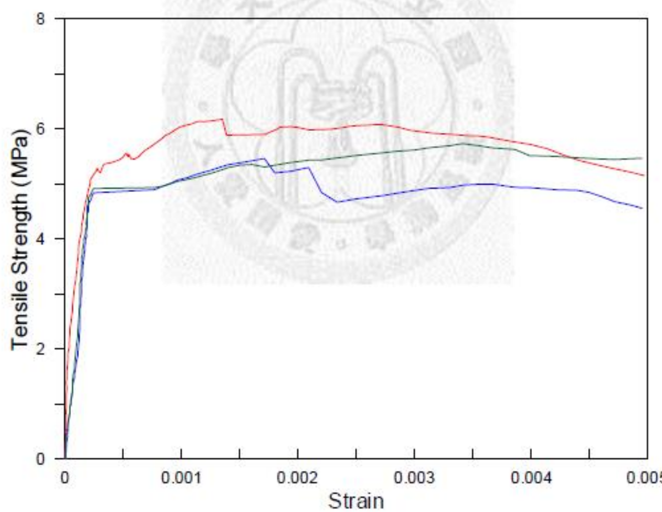


圖 5－16 C50 直接拉力應力應變圖（0.5％）

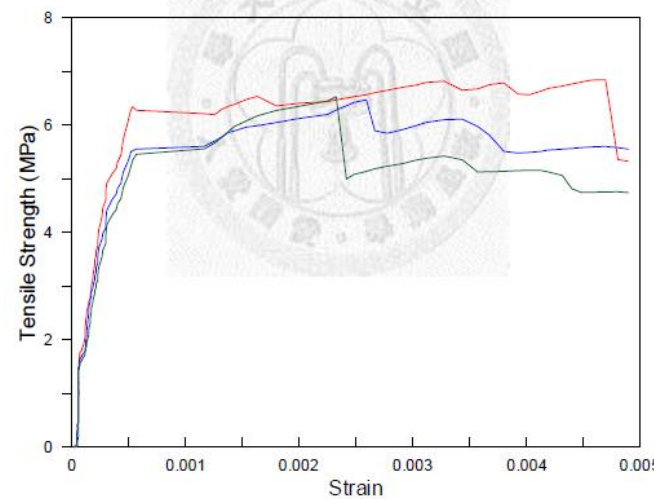
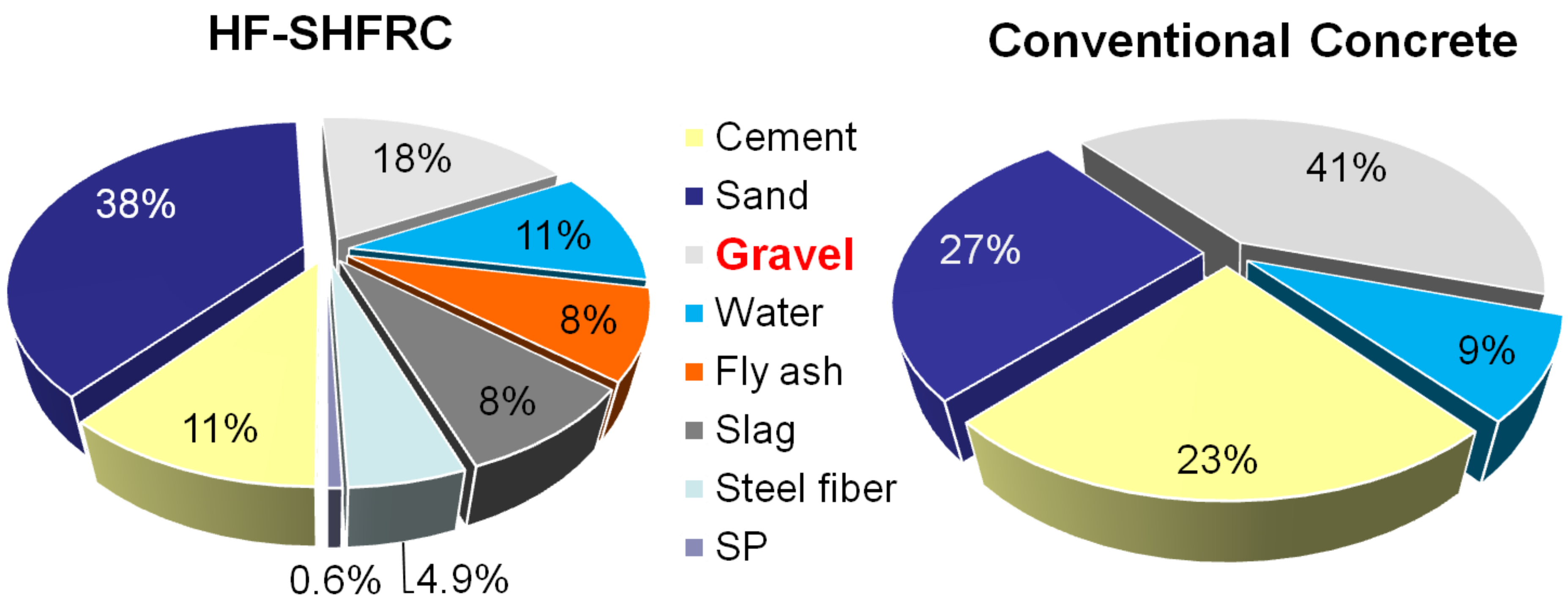


圖 5－18 C60 直接拉力應力應變圖（0.5％）

Highly Flowable Strain Hardening Fiber Reinforced Concrete



1. Unlike traditional HPFRCC, coarse aggregate is used in HF-SHFRC.
2. Slag and Fly ash (sustainable construction material) substitution of cement up to 50%.

Experimental Program

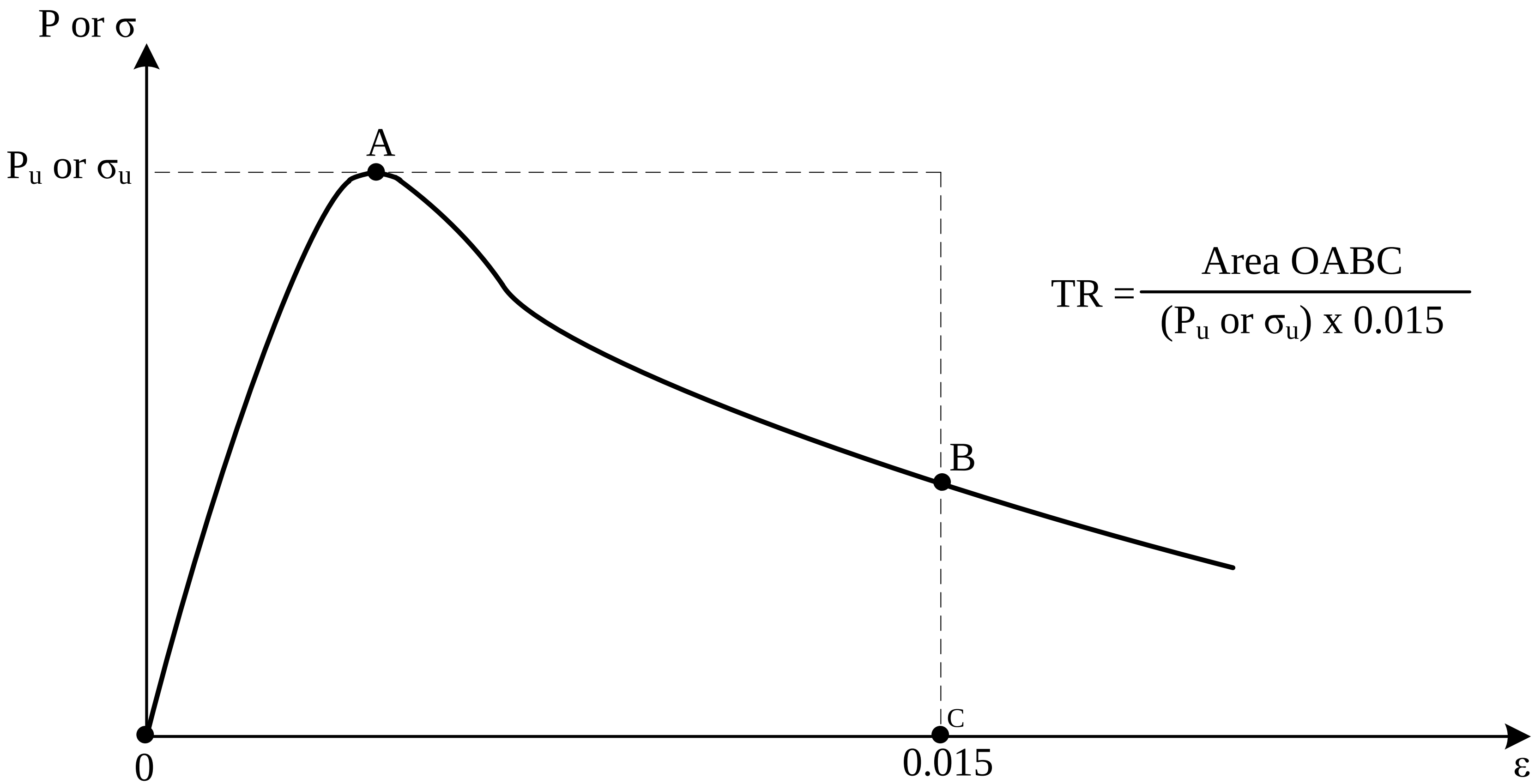
Confinement Efficiency: Proposed Toughness Ratio

Wisena Perceka, **Wen-Cheng Liao*** and Yo-de Wang (2016, Apr). High Strength Concrete Columns under Axial Compression Load: **Hybrid Confinement Efficiency** of High Strength Transverse Reinforcement and Steel Fibers. Materials, 9(4), 264; DOI:10.3390/ma9040264 (SCI)

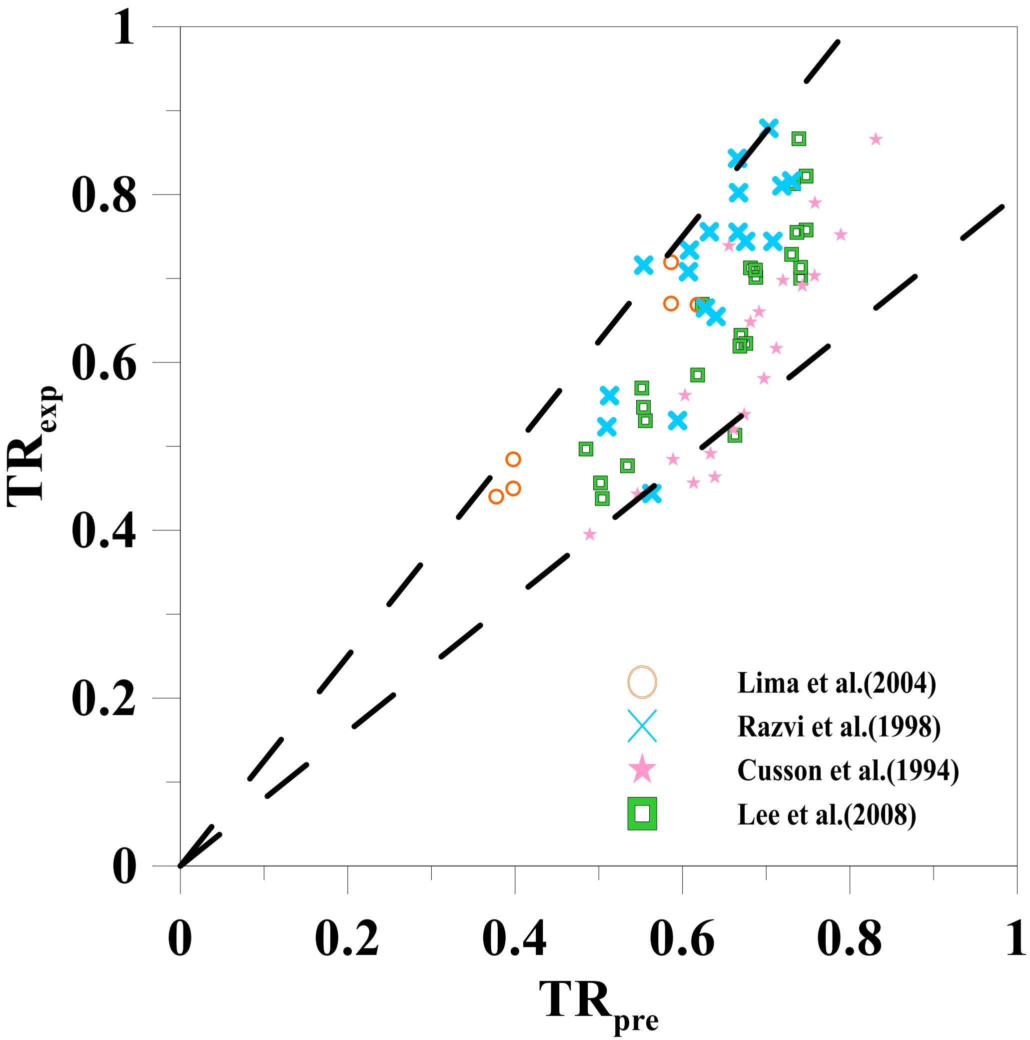
Toughness Ration, TR

Instead of P_o, TR is used for confinement design.

1. **P_o is not that well described in New RC.**
2. **Addition of fiber would not significantly affect P_o.**



Proposed Toughness Ratio Equation



$$TR = 0.45\left(\frac{k_e \rho_s f_{yt}}{f'_c}\right)^{0.19}$$

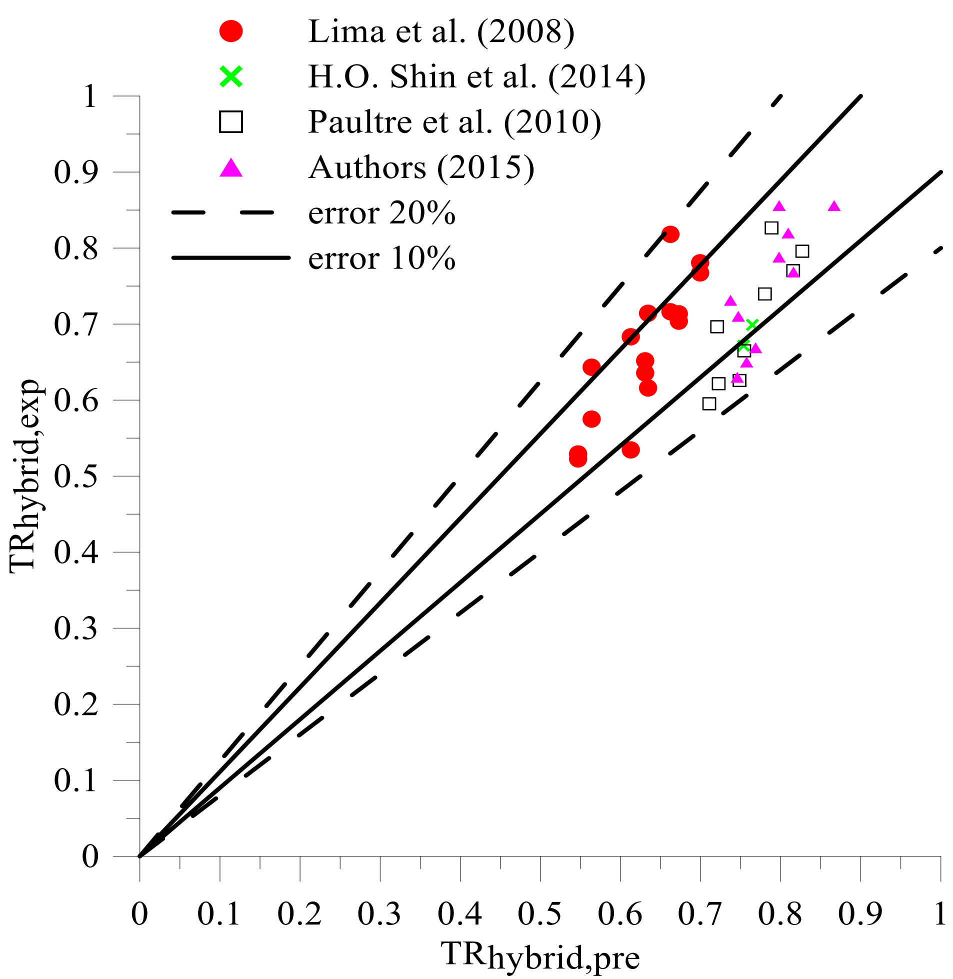
k_e = confinement effectiveness coefficient

ρ_s = transverse reinforcement ratio

f_{yt} = yield strength of transverse reinforcement

f_c' = compressive strength of concrete

Proposed Toughness Ratio Equation



$$TR = 0.45\left(\frac{k_e \rho_s f_{yt}}{f'_c}\right)^{0.19} + \chi_f \left(V_f \times \frac{L}{\varphi} \times \tau_{eq}/f'_c\right)$$

k_e = confinement effectiveness coefficient

ρ_s = transverse reinforcement ratio

f_{yt} = yield strength of transverse reinforcement

f_c' = compressive strength of concrete

V_f = steel fiber volume fraction

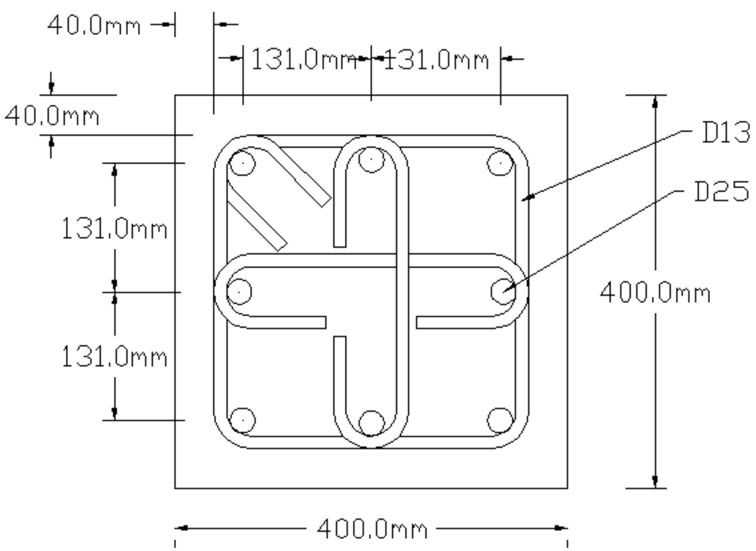
L/φ = aspect ratio of steel fiber

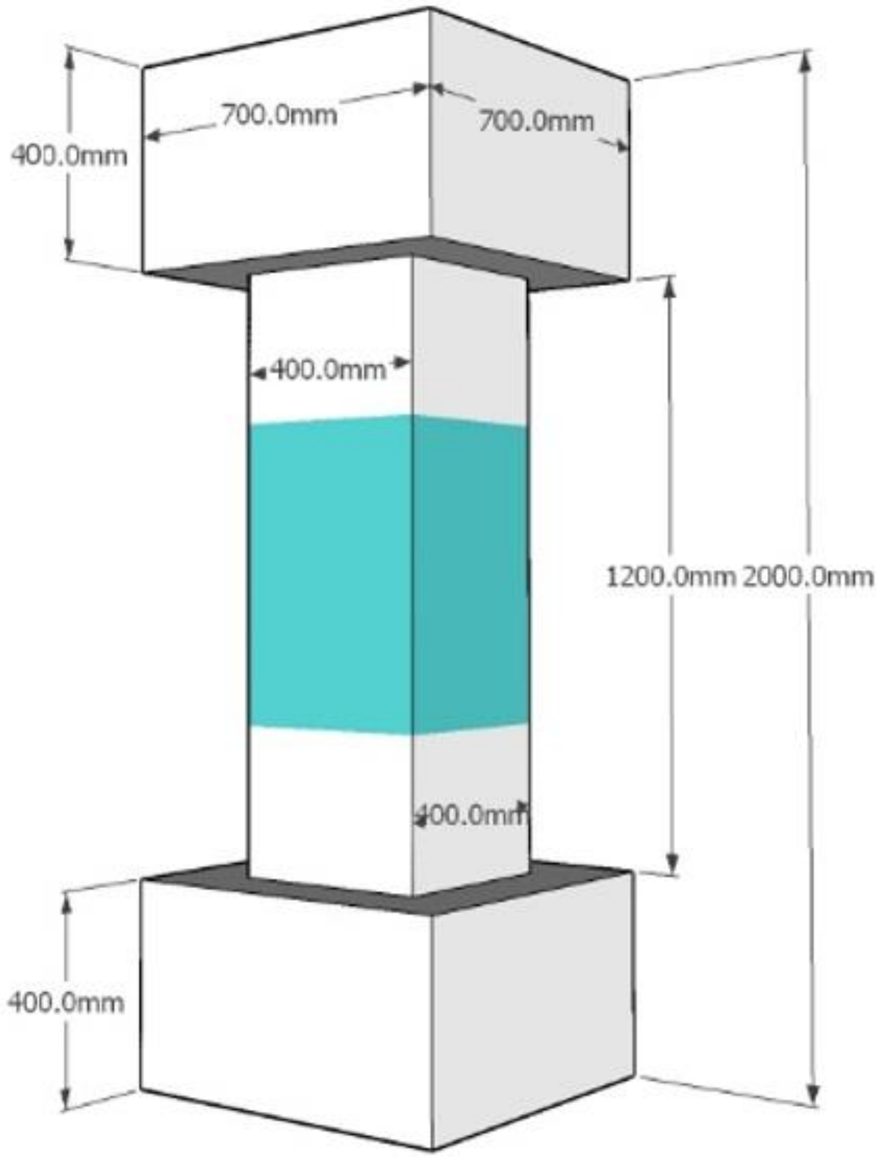
X_f = fiber efficiency factor in terms of stirrups spacing

τ_{eq} = equivalent bond strength

Specimen design

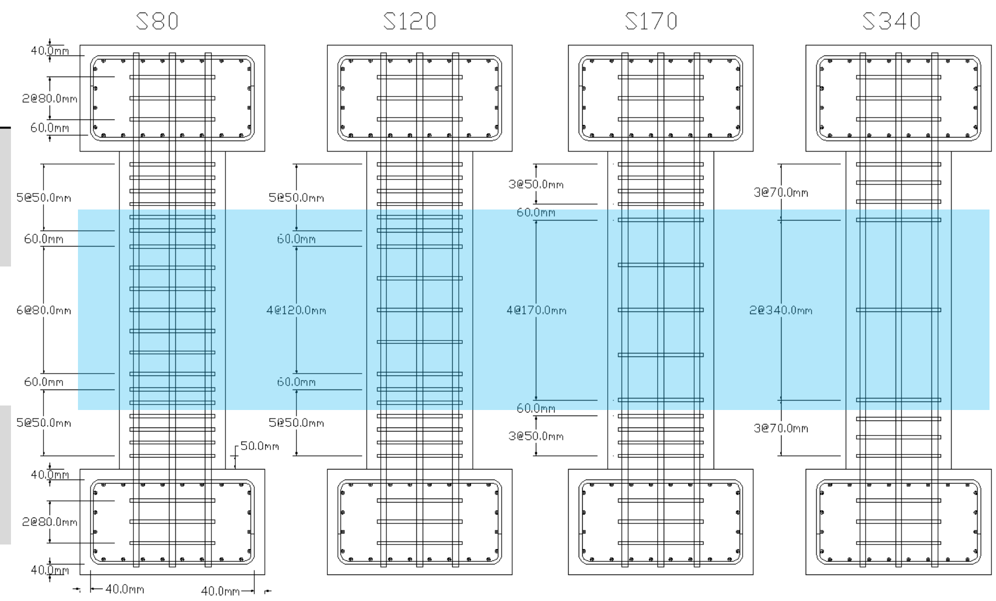
- Column size：40×40×120 (cm)
- Section：





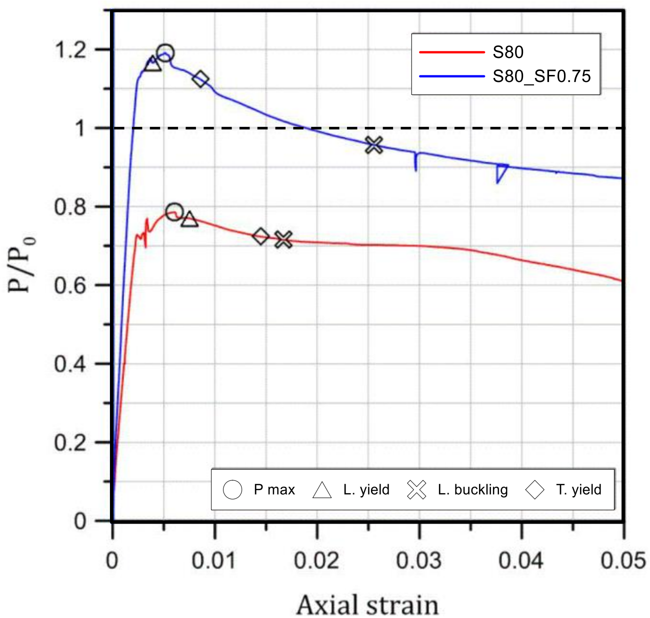
Specimen design

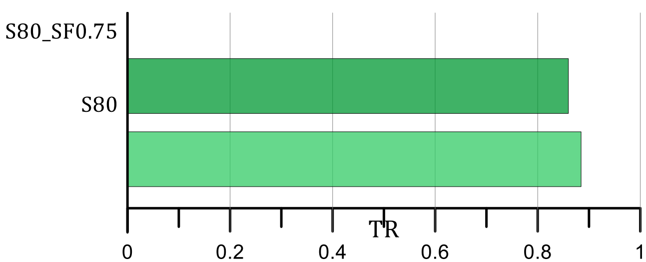
Specimen ID	Stirrups spacing (mm)	Stirrups spacing / Effective depth	V_f
S80	80	0.24	0 %
S80_SF0.75	80	0.24	0.75 %
S120	120	0.36	0 %
S120_SF1.0	120	0.36	1 %
S170	170	0.51	0 %
S170_SF1.5	170	0.51	1.5 %
S340	340	1.01	0 %
S340_SF1.5	340	1.01	1.5 %



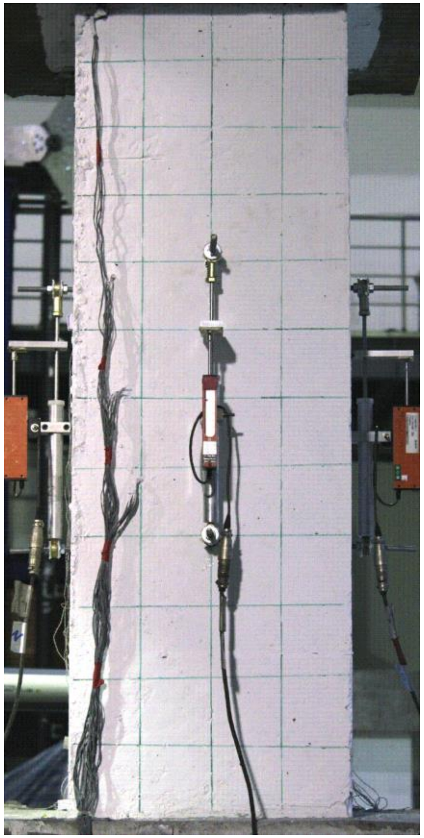
Test results

- S80 & S80_SF0.75

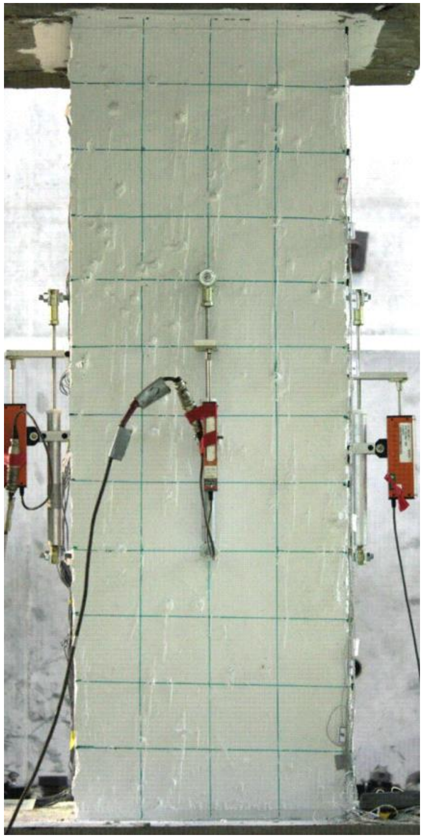




S80

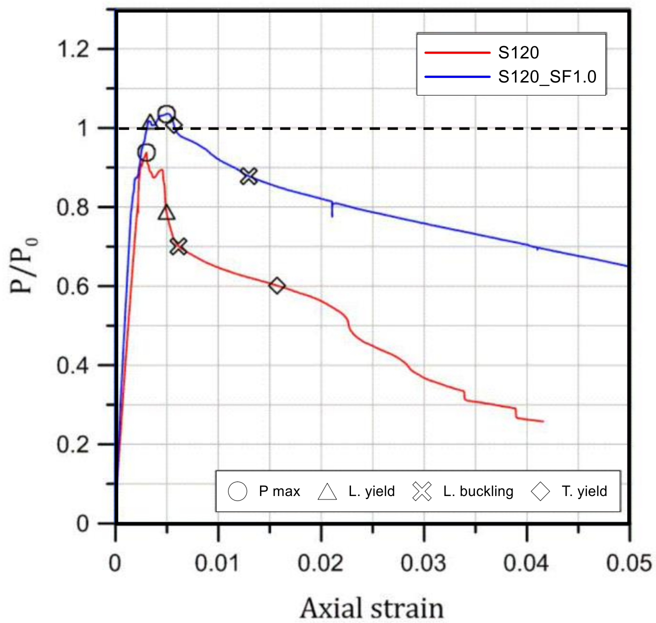


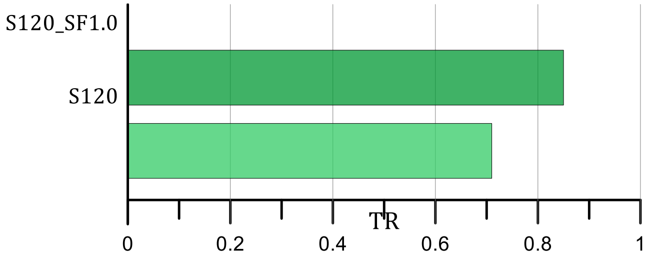
S80_SF0.75



Test results

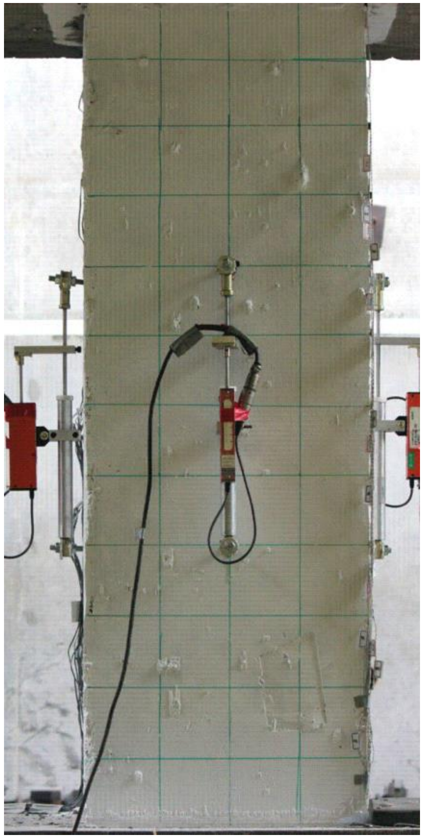
- S120 & S120_SF1.0

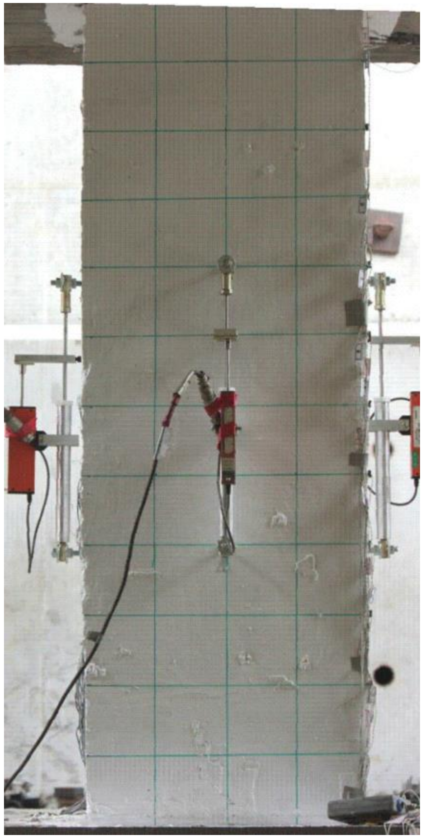




S120

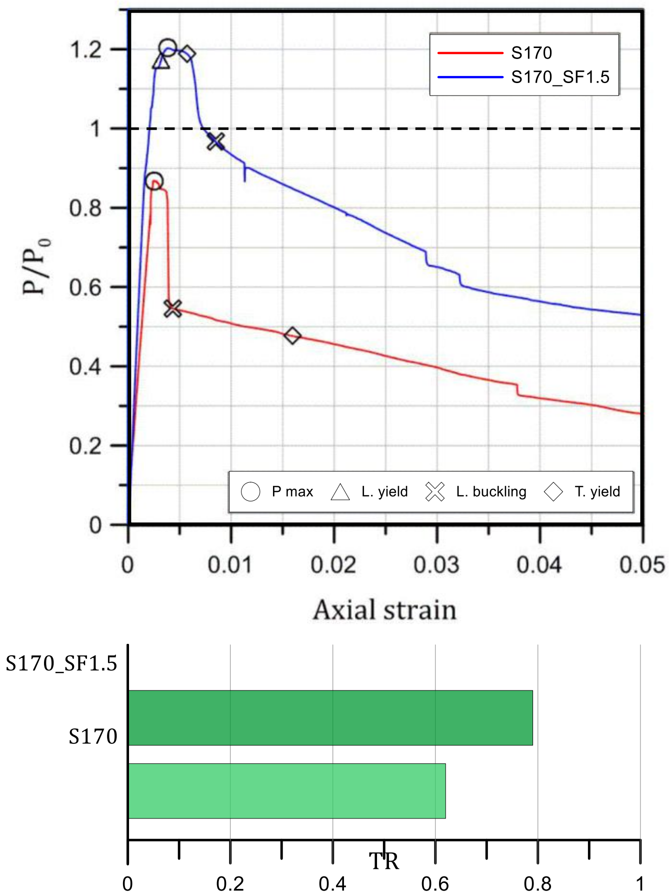
S120_SF1.0



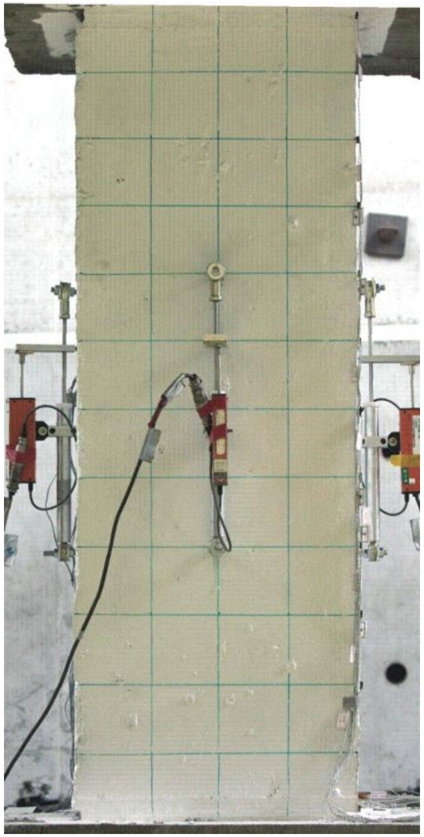


Test results

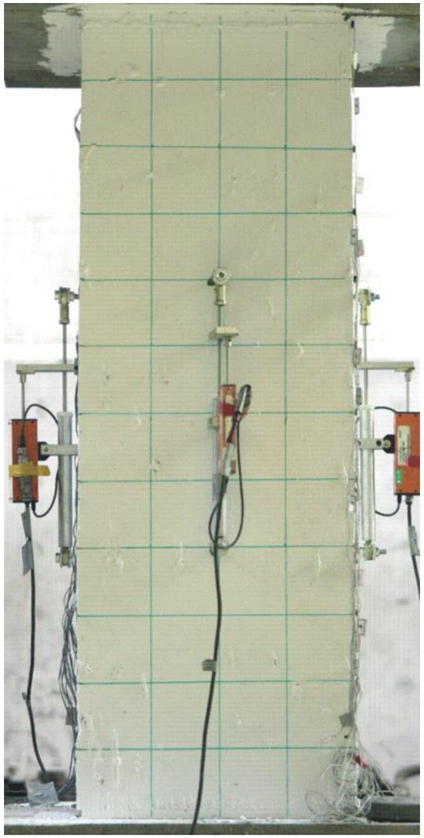
- S170 & S170_SF1.5



S170

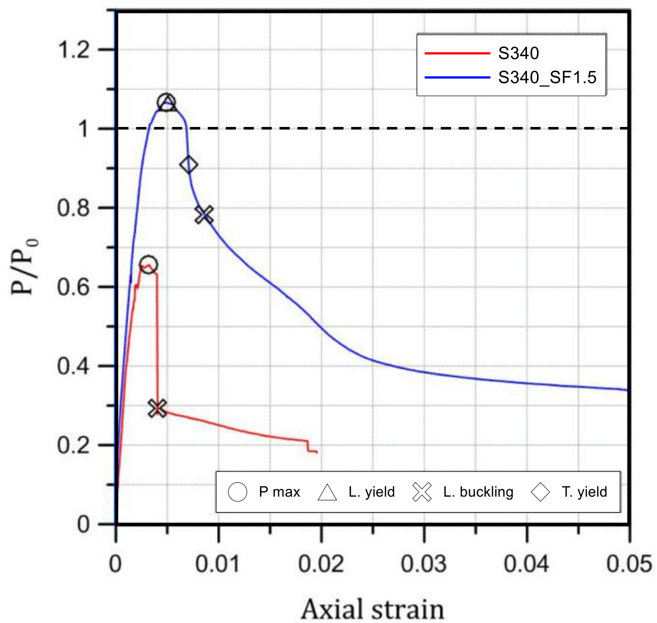


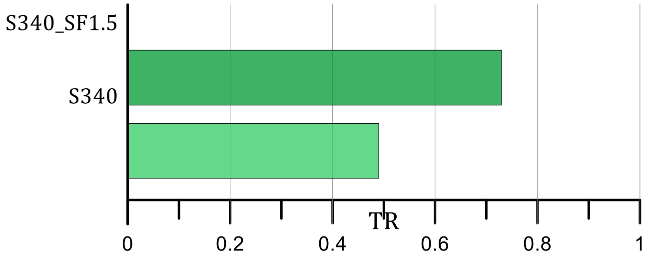
S170_SF1.5



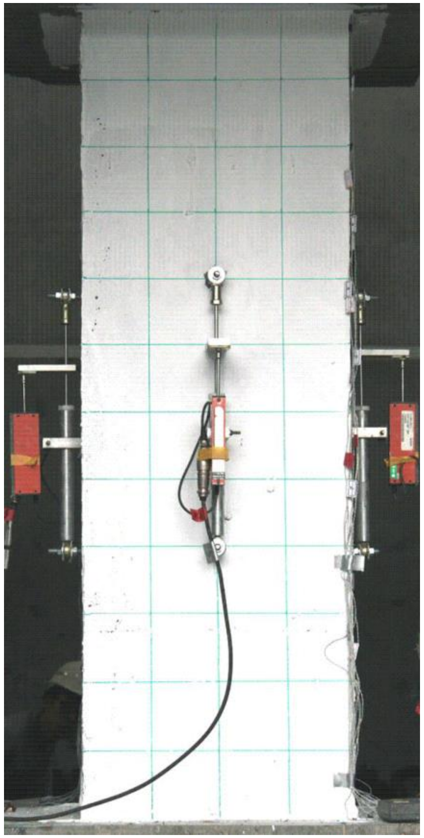
Test results

- S340 & S340_SF0.75

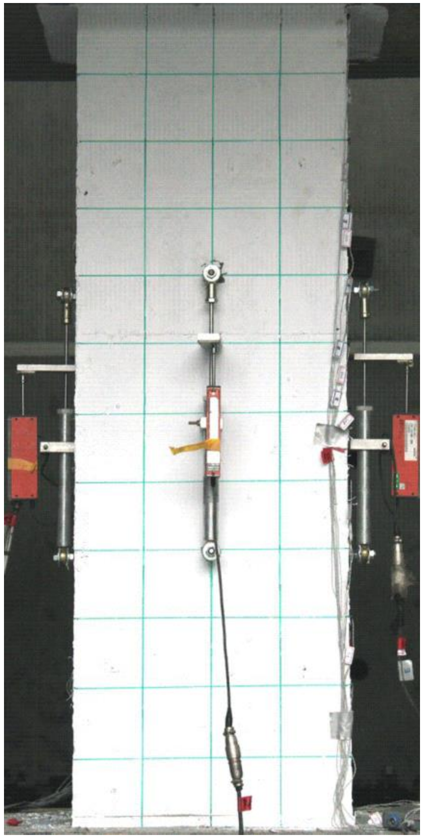




S340



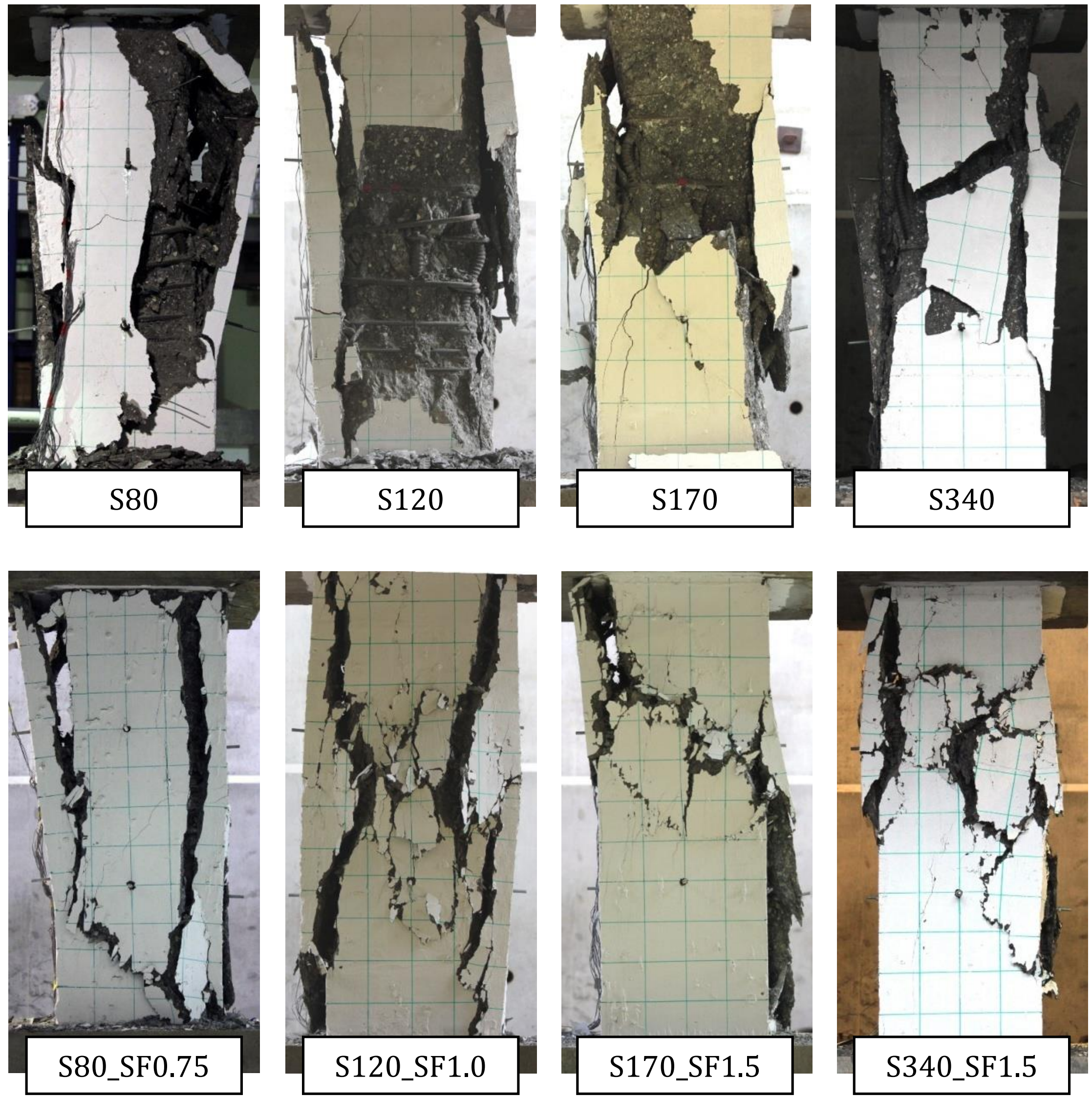
S340_SF1.5



Failure modes

w/o fibers

w/ fibers



TR verification

Specimen ID	f'_c (MPa)	TR	TR_{pre}	Error
S80	68.6	0.88	0.80	-8.6 %
S80_SF0.75	67.6	0.86	0.85	-1.5 %
S120	70.5	0.71	0.73	2.7 %
S120_SF1.0	75.0	0.84	0.78	-6.3 %
S170	70.5	0.62	0.66	6.4 %
S170_S1.5	65.4	0.78	0.79	0.9 %
S340	70.8	0.48	0.49	3.0 %
S340_SF1.5	65.1	0.73	0.74	1.5 %

Experimental Program

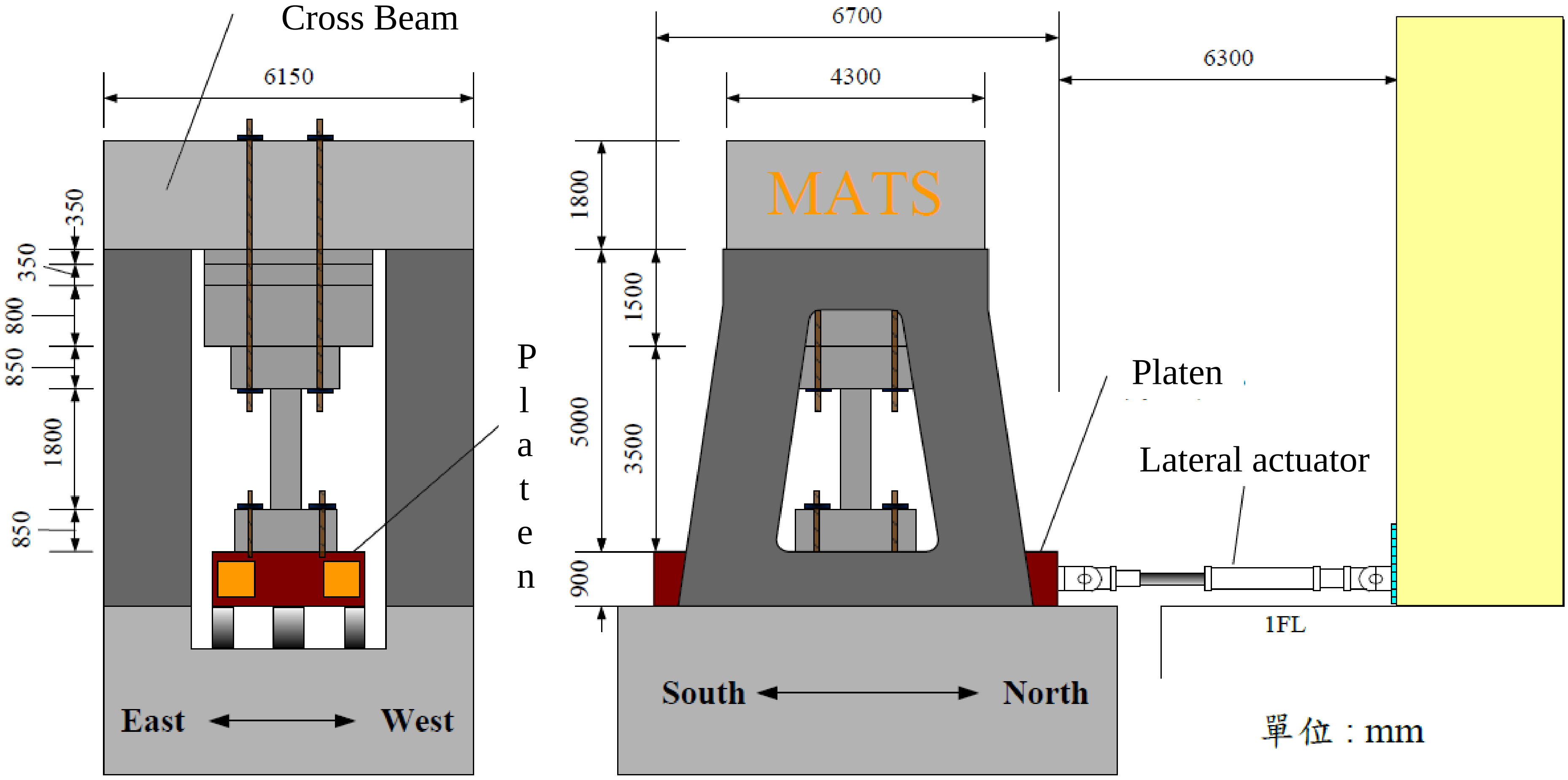
Lateral cyclic behavior of HF-SHFRC Columns

Experimental Program

Multi-Axial Resting System (MATS)

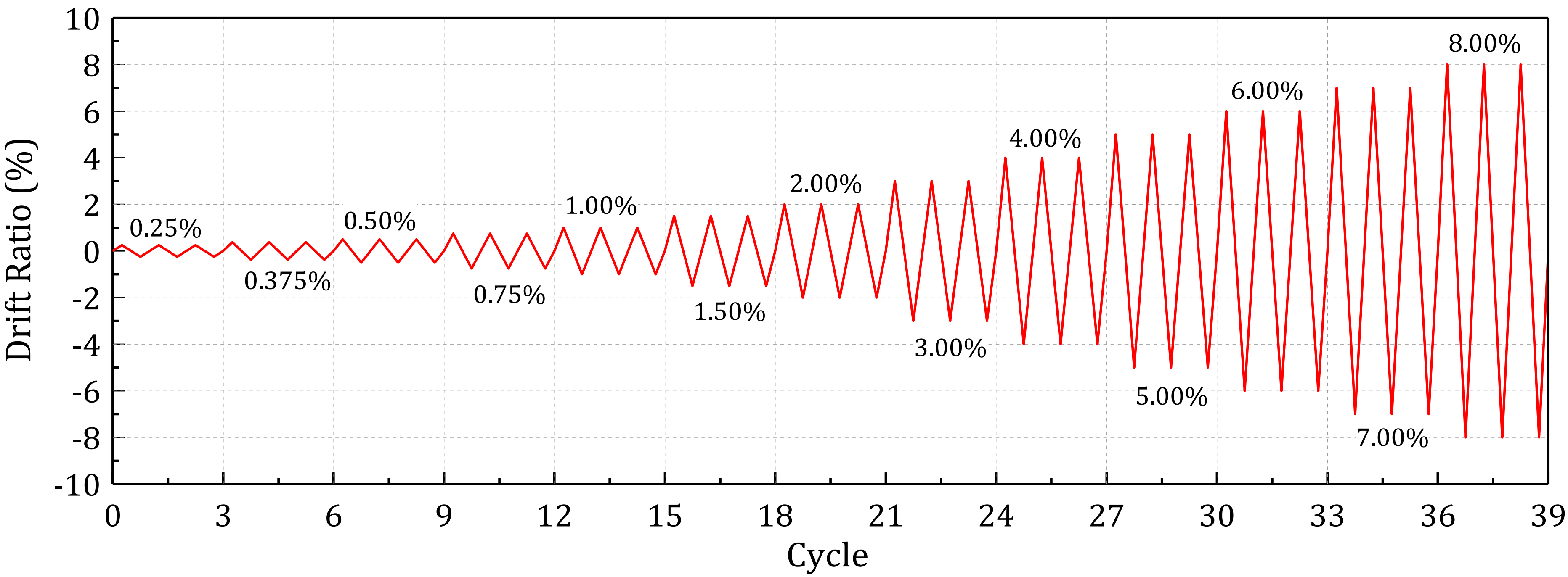
Axial loading capacity: up to 60 MN

National Center for Research on Earthquake Engineering (NCREE)



Experimental Program

Loading Protocol

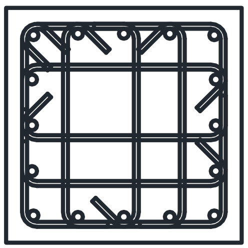
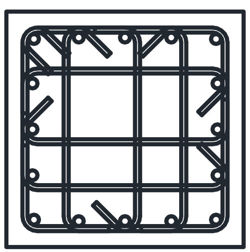
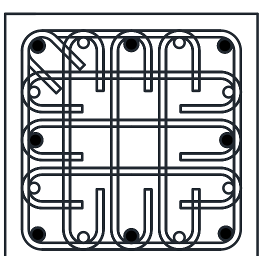


Ref： ACI Committee 374, “Acceptance Criteria for Moment Frames Based on Structural Testing and Commentary(ACI 374.1-05),” American Concrete Institute, 2006.

Passing Criteria:

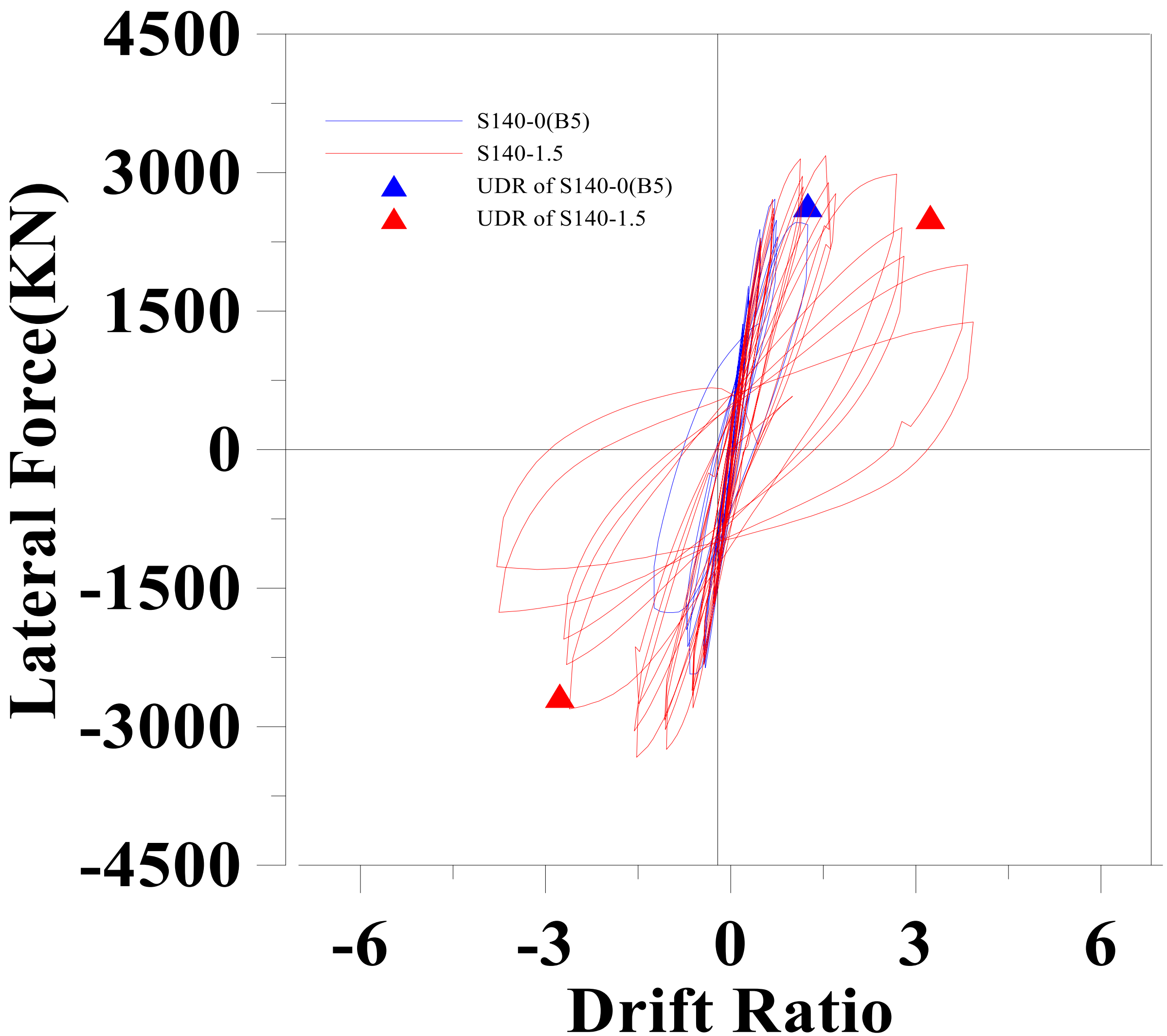
Ultimate drift ratio, UDR (drift ratio corresponding to 80% Max lateral capacity) > 3.0%

Experimental Program

No.	Section	ρ_s (%)	f'_c (MPa)	f_{yl} (MPa)	f_{yt} (MPa)	s (mm)	$\frac{P}{A_g f'_c}$	TR
S140-0 (ACI 318-11)		1.74	83.4	#8, SD685	#4, SD785	140	0.57	0.68
S140-1.5		1.74	73 (V_f= 1.5%)	#8, SD685	#4, SD785	140	0.57	0.75
S260-1.5		1.46	72 (V_f= 1.5%)	#8, #10, SD685	785 (#5, SD785)	260 (d/2)	0.43	0.75

Test Results

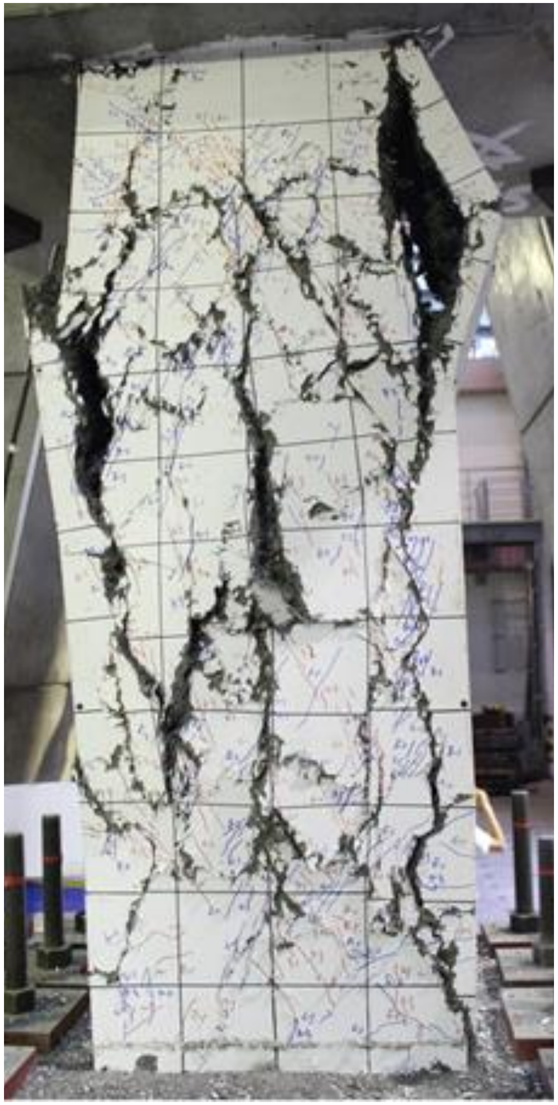
S140-0 (UDR: 1.25%) VS. S140-1.5 (UDR: 3.23%)



Test Results

Failure

S140-0 (2^{nd} cycle of 1.5%)

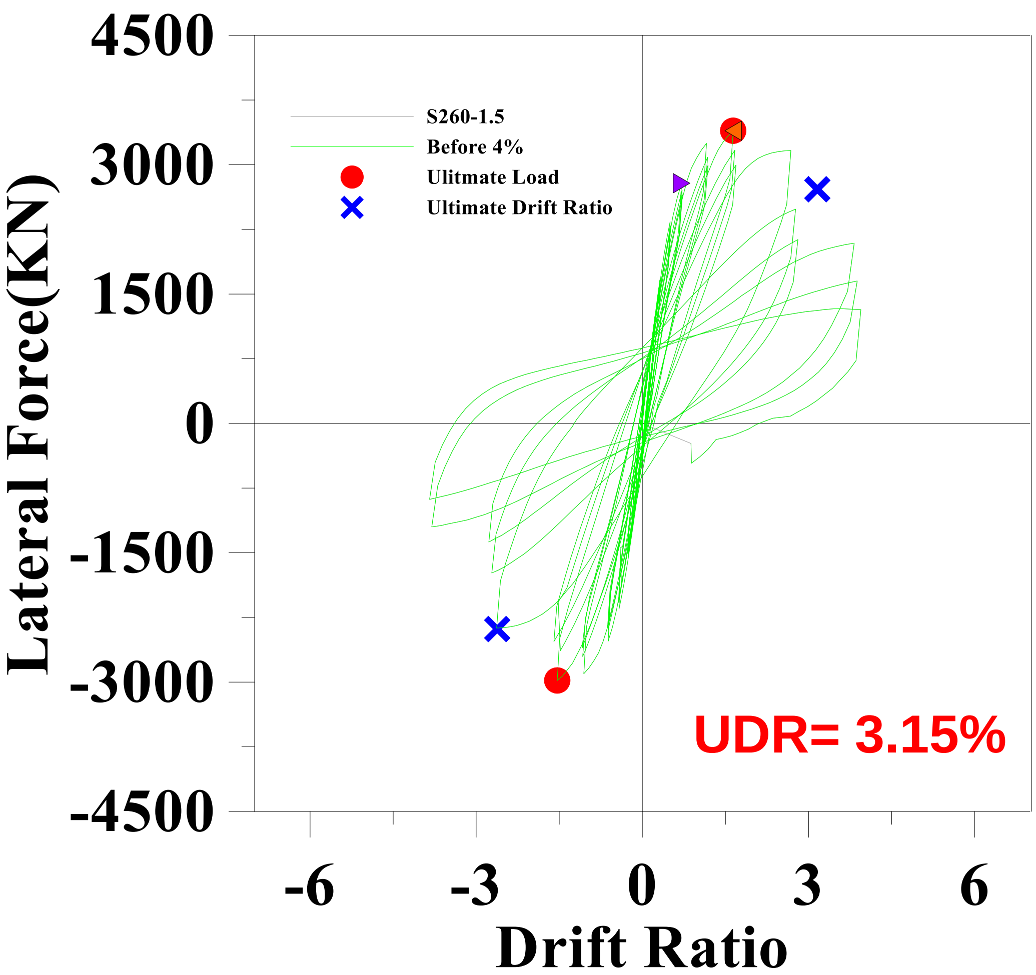


S140-1.5 (4.0%)

Test Results

Test Results (S260 – 1.5)

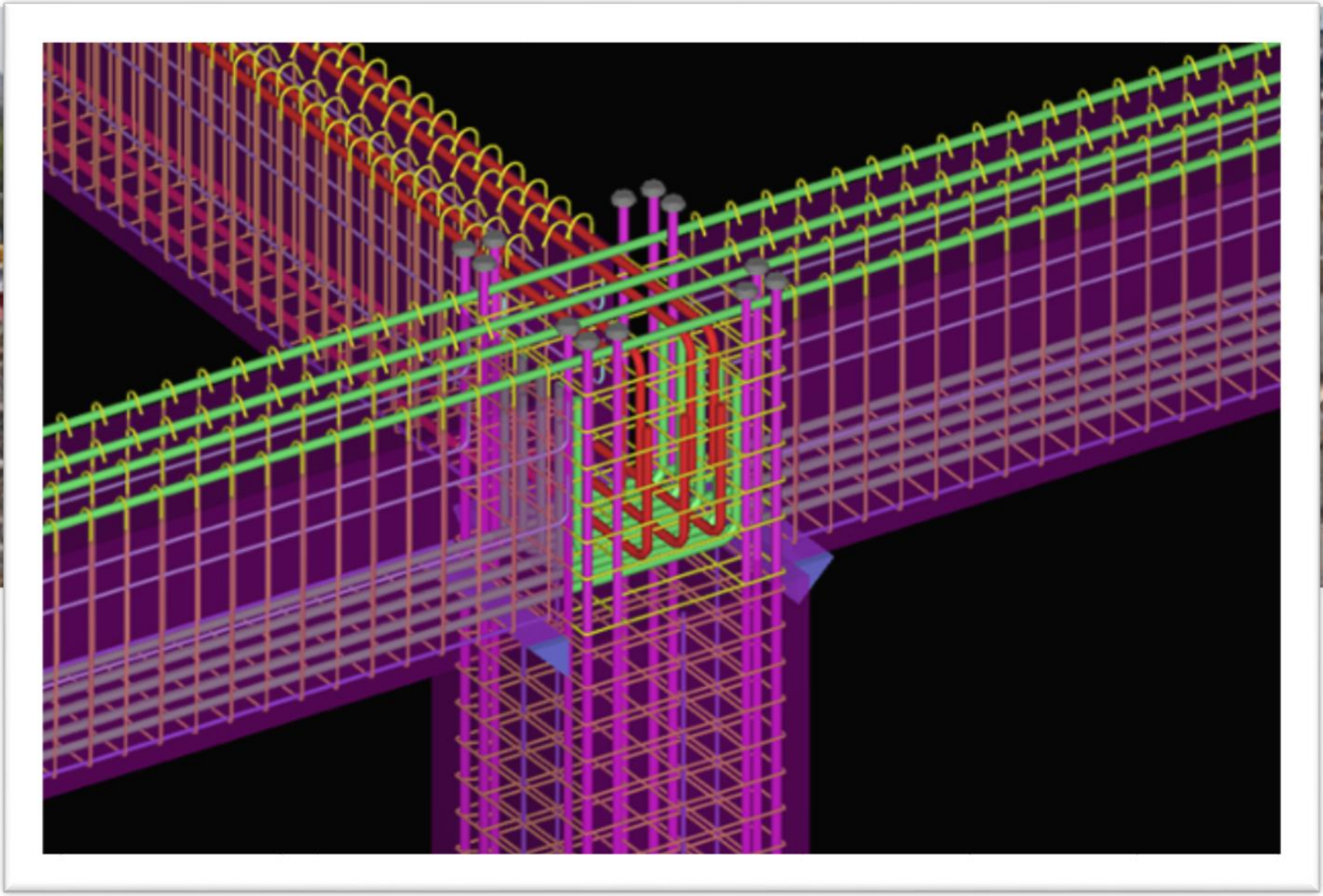
failure



Experimental Program

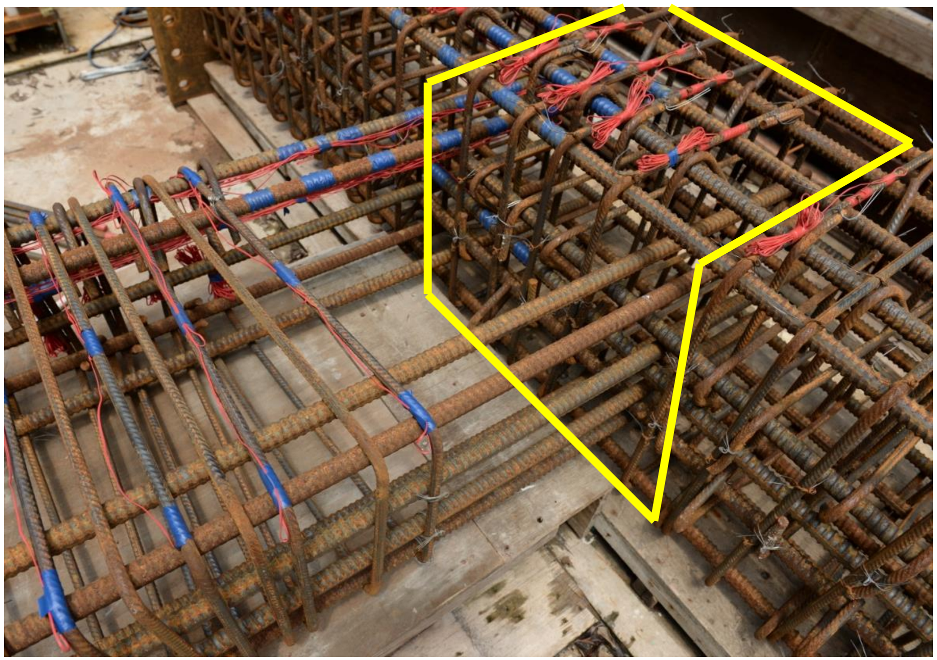
External Beam Column Joint

Precast Technology



梁柱接頭（鋼筋量極高：柱主筋＋柱箍筋＋梁主筋）

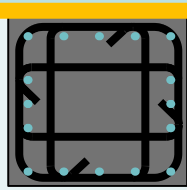
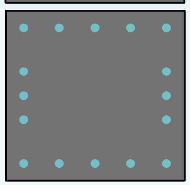
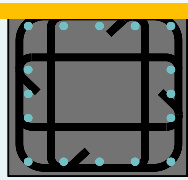
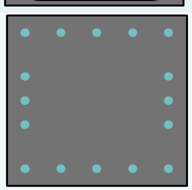
現行規範



完全移除梁柱接頭箍筋，以高流動性應變硬化鋼纖維混凝土澆置

Experimental Program

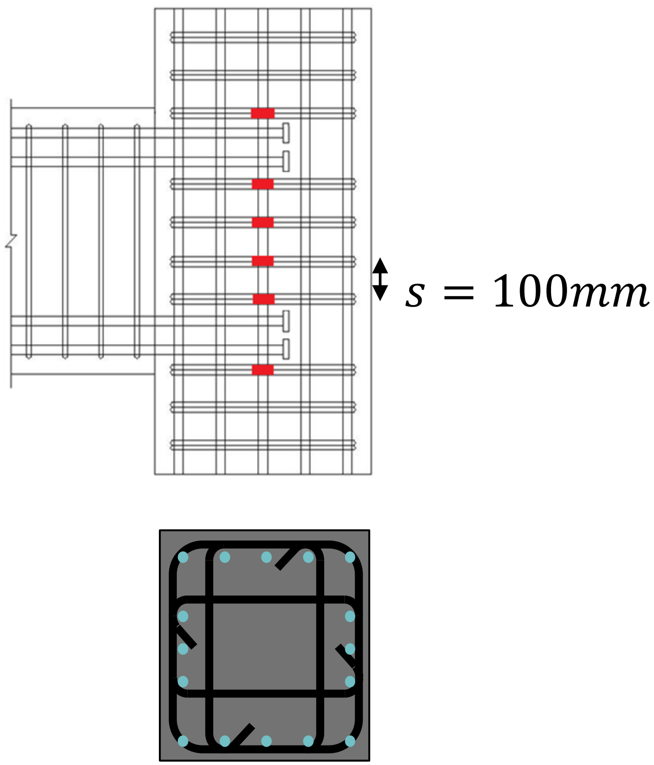
Design Parameters

Specimen	Section	ρ (%)	ρ_s (%)	l_{dt} (cm)	M_r ratio	$V_{jh}/V_{n,ACI}$	$P/A_g f'_c$
LAMV*		2.25 (16-#8)	2.08	40	2.2	0.7	0.1
LAMV_SF		2.25 (16-#8)	0	40	2.2	0.7	0.1
HAMV*		2.25 (16-#8)	2.08	40	2.2	0.7	0.45
HAMV_SF		2.25 (16-#8)	0	40	2.2	0.7	0.45

*趙偉帆，「使用擴頭鋼筋錨定之高強度鋼筋混凝土梁柱接頭在P-δ效應下耐震行為研究」，國立台灣科技大學營建工程系，2016

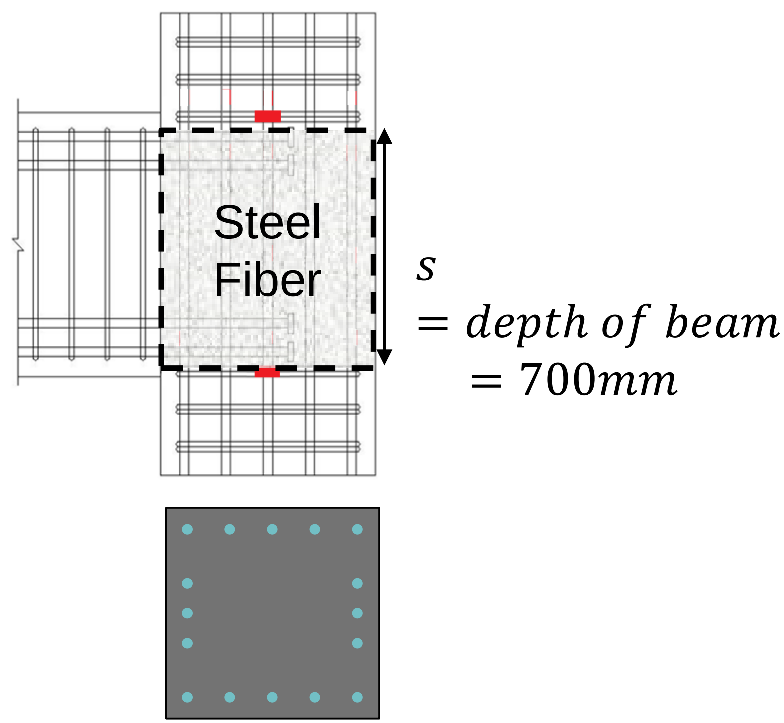
Specimen layout

LAMV、HAMV



Moderate shear ratio
Low axial load
1.5% Volume fraction of steel fiber

LAMV_SF、HAMV_SF

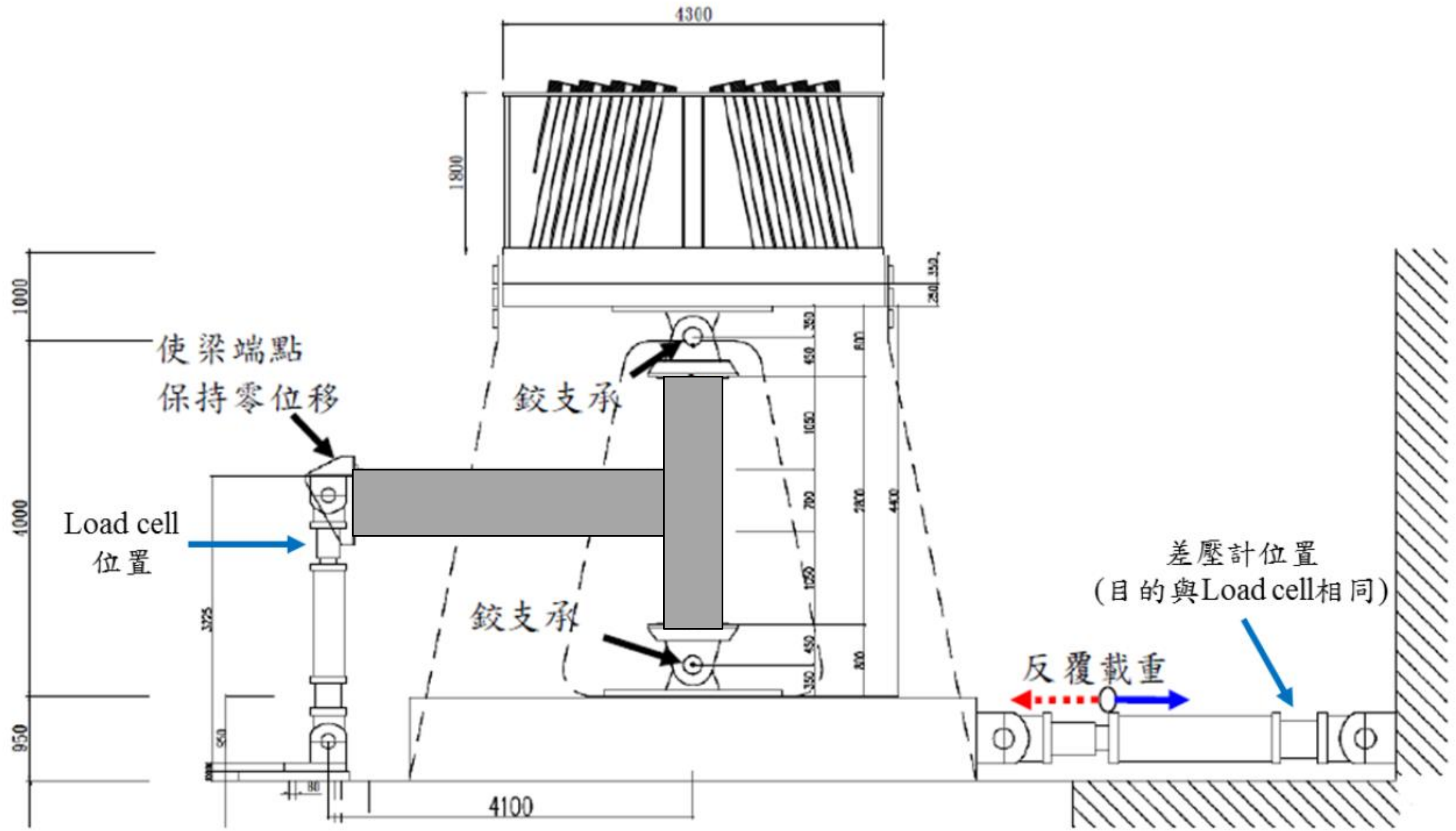


Casting

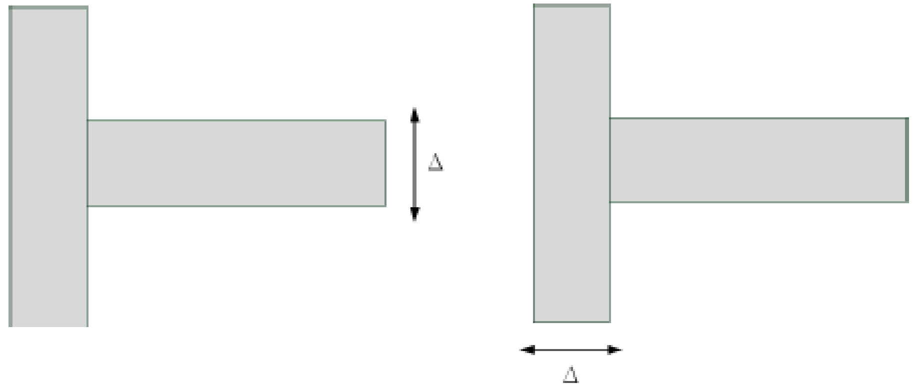





Experiment Setup

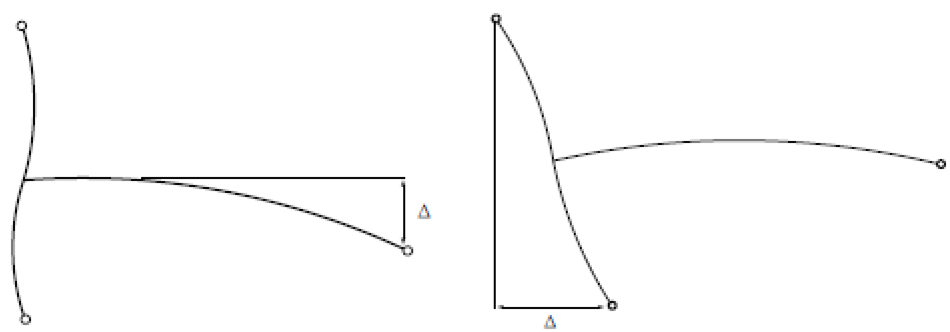


P-delta effect



(a) (b)

圖5-1 反覆推梁及柱之示意圖

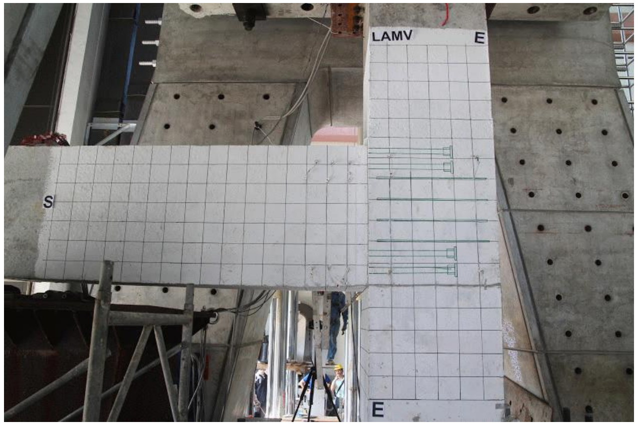


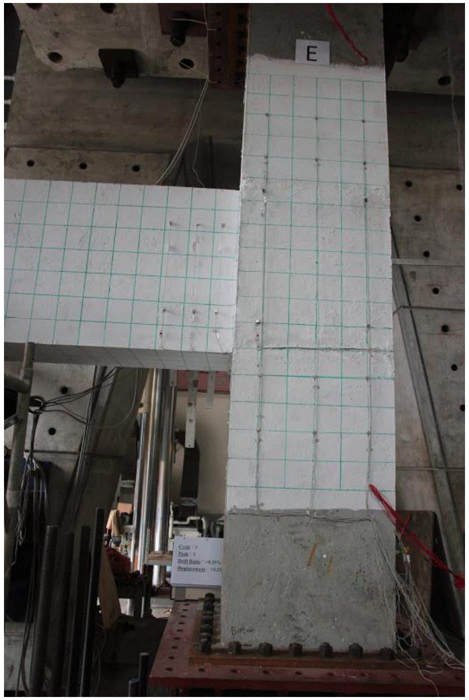
(a) (b)

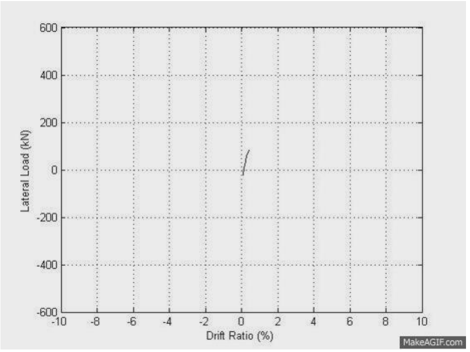
圖5-2 反覆推梁及柱之 Deform shape 示意圖

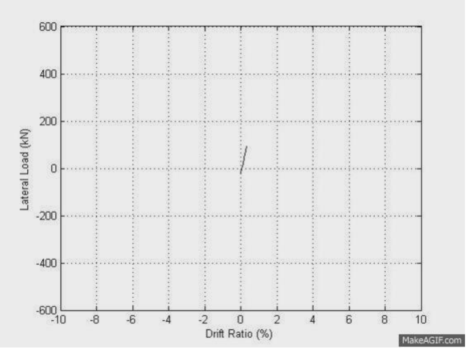
Result and discussion

- LAMV v.s LAMV_SF



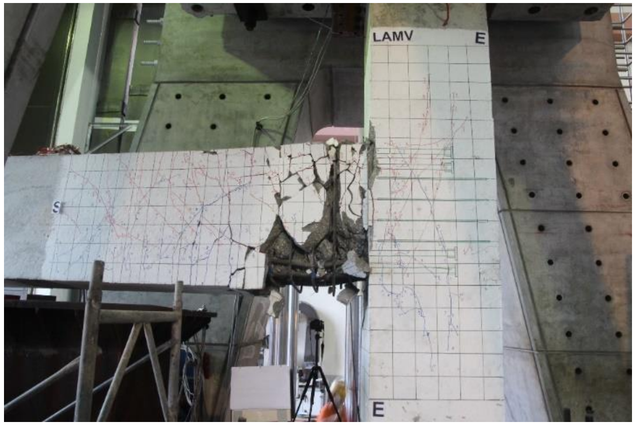




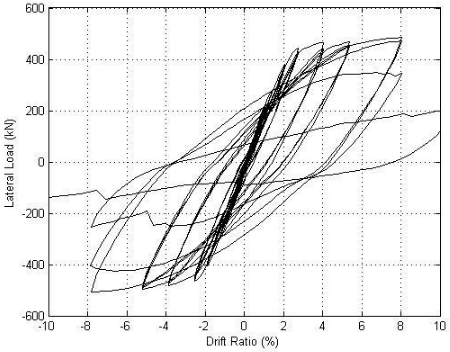


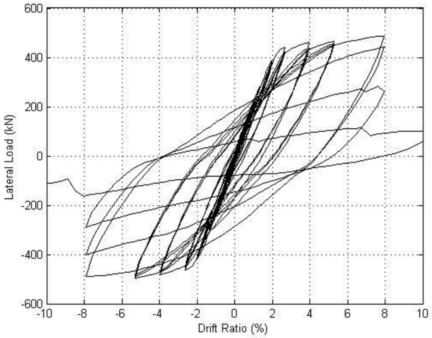
Result and discussion

- LAMV v.s LAMV_SF



B type

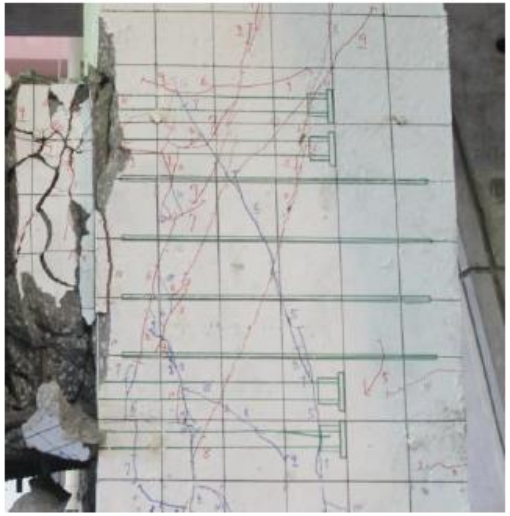




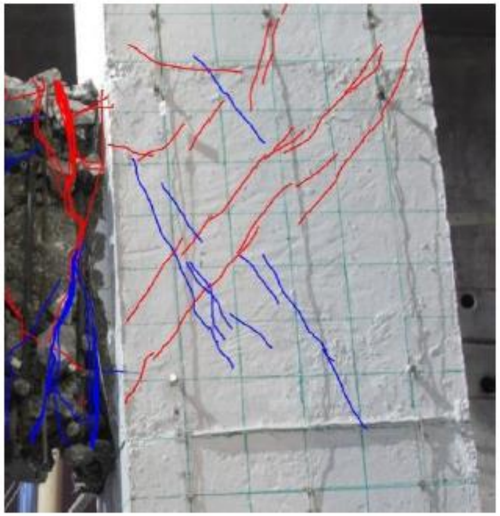
B type

Result and discussion

Specimen	Failure mode	$V_{c,max}$	$Drift_{max}$
LAMV	B	486.0 kN	8 %
LAMV_SF	B	487.5 kN	8 %

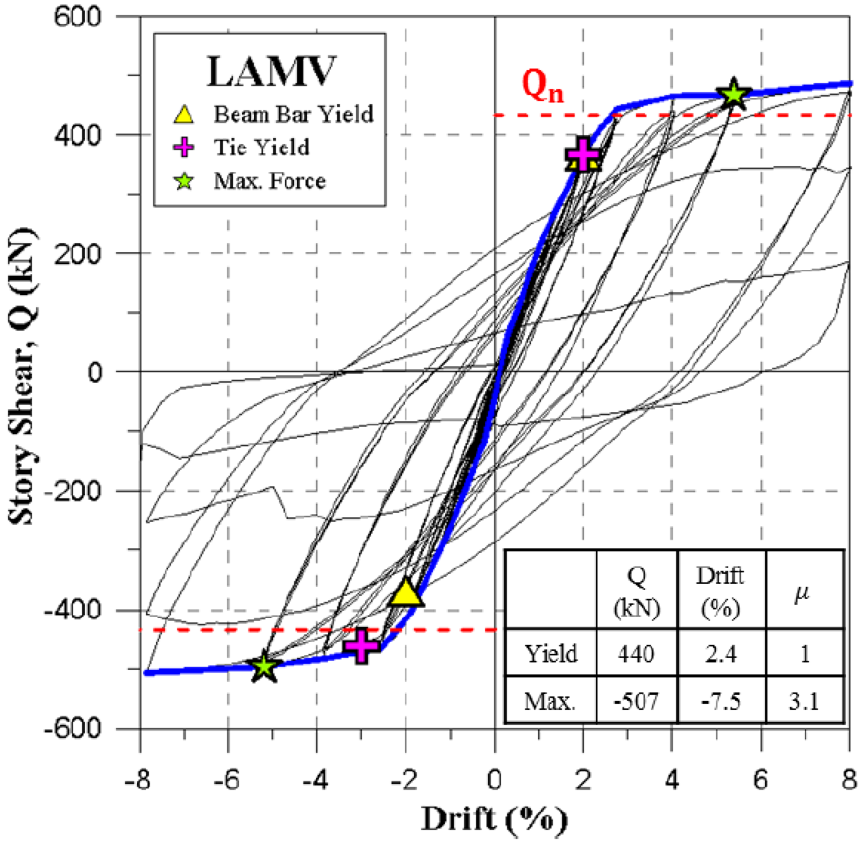


LAMV 破壞時接頭處裂縫分布

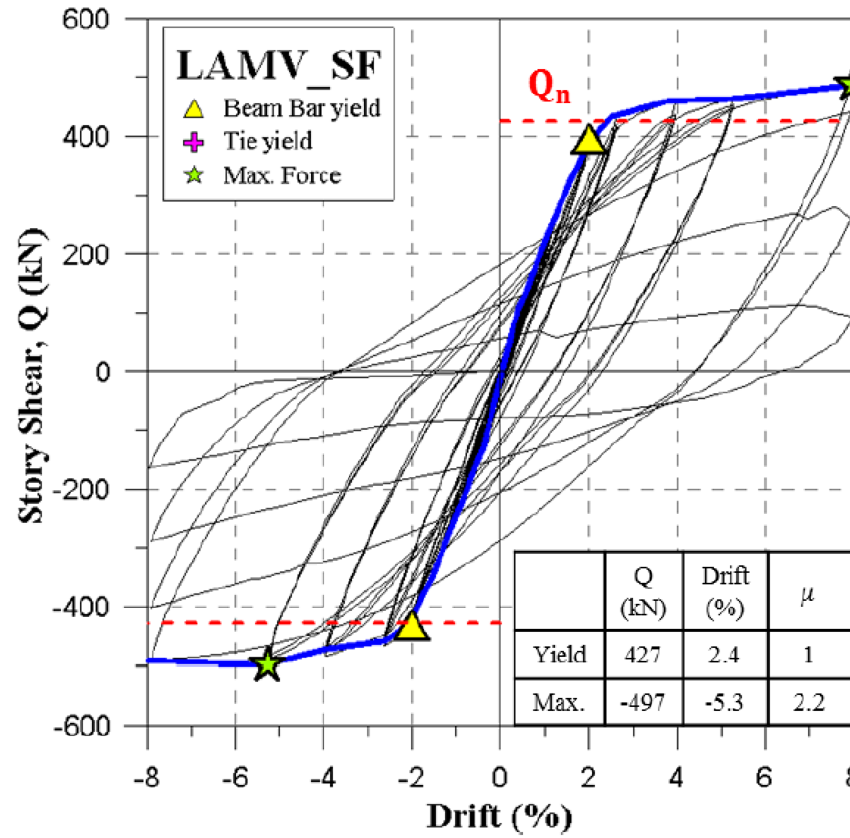


LAMV_SF 破壞時接頭處裂縫分布

Result and discussion



	Q (kN)	Drift (%)	μ
Yield	440	2.4	1
Max.	-507	-7.5	3.1



	Q (kN)	Drift (%)	μ
Yield	427	2.4	1
Max.	-497	-5.3	2.2

Conclusions

1) Addition of fibers provides **high ductility** to brittle concrete, particularly for high strength concrete (NEW RC).

2) Compared to HSC, HF-SHFRC presents **high toughness, damage tolerance and excellent shear capacity** while allowing **good workability**.

3) The experimental results shows that addition of **fibers can be an effective alternative** for transverse reinforcement in NEW RC buildings.

4) By **increasing the spacing to d/2** and under 0.43 $A_g f'_c$ axial loading level, excellent performance and damage tolerance can be still observed in S260-1.5. It shows the great potential to apply HF-SHFRC to NEW RC columns.

Conclusions

5) By using HF-SHFRC, **the lateral reinforcement can be completely eliminated** in NEW RC external beam-column joints under 0.1 $A_g f'_c$ axial loading.

6) To Implement HF-SHFRC in NEW RC Precast systems, **its excellent mechanical properties** also offer the opportunity to significantly **simplify the design and construction** and **push the practice achieving higher levels of performance and safety.**

Thank you ☺

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