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

高強度鋼纖維混凝土之
連接式剪力牆抗震系統

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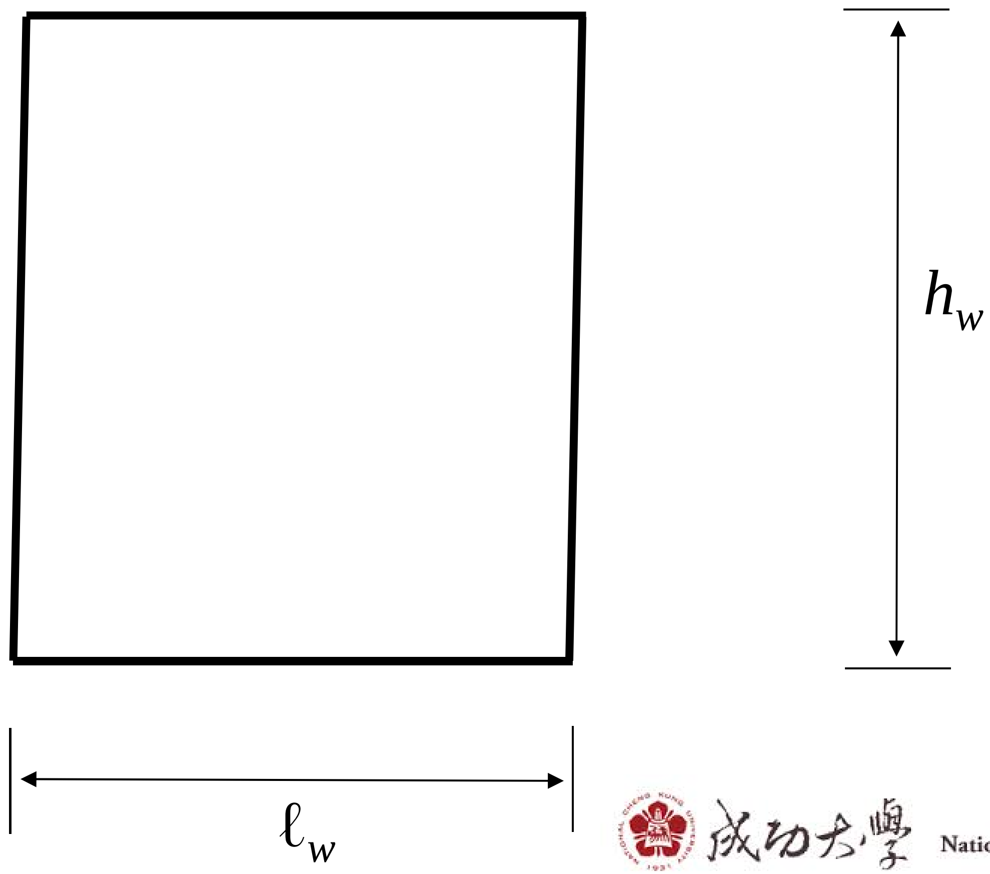
國立成功大學土木工程學系

RC結構牆類別

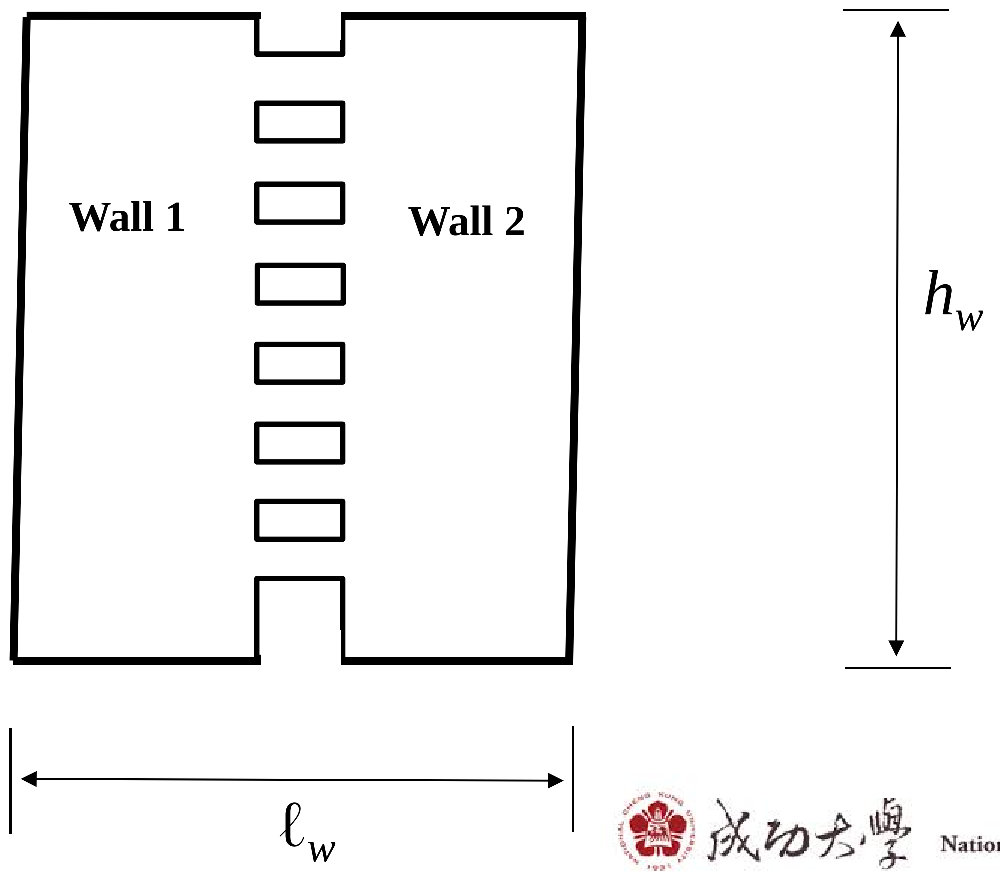
$h_w/\ell_w < 1.5$:低矮型結構牆

$h_w/\ell_w > 2.0$:中高型結構牆

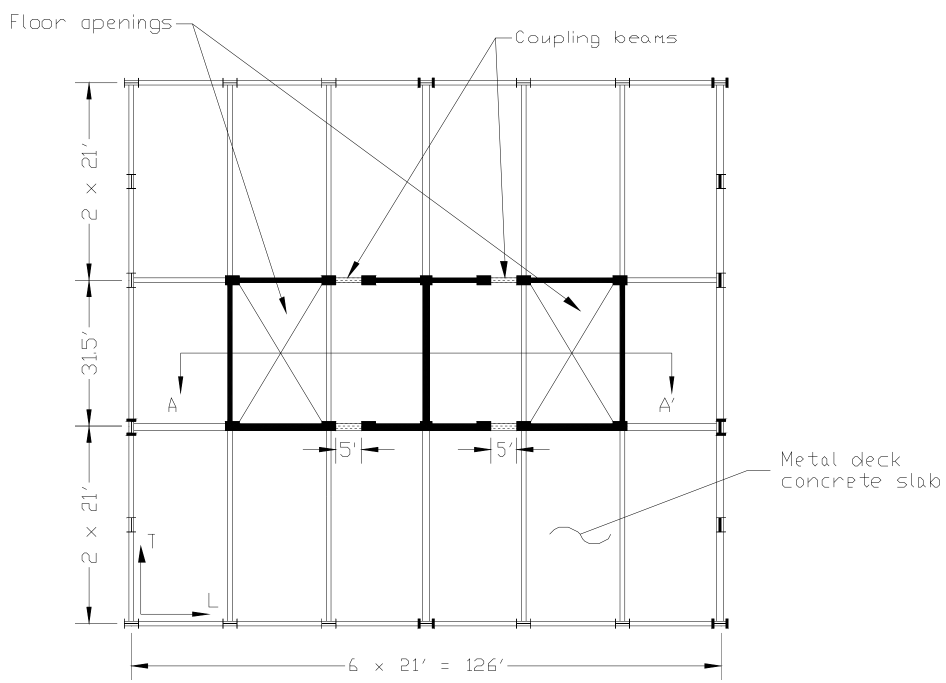


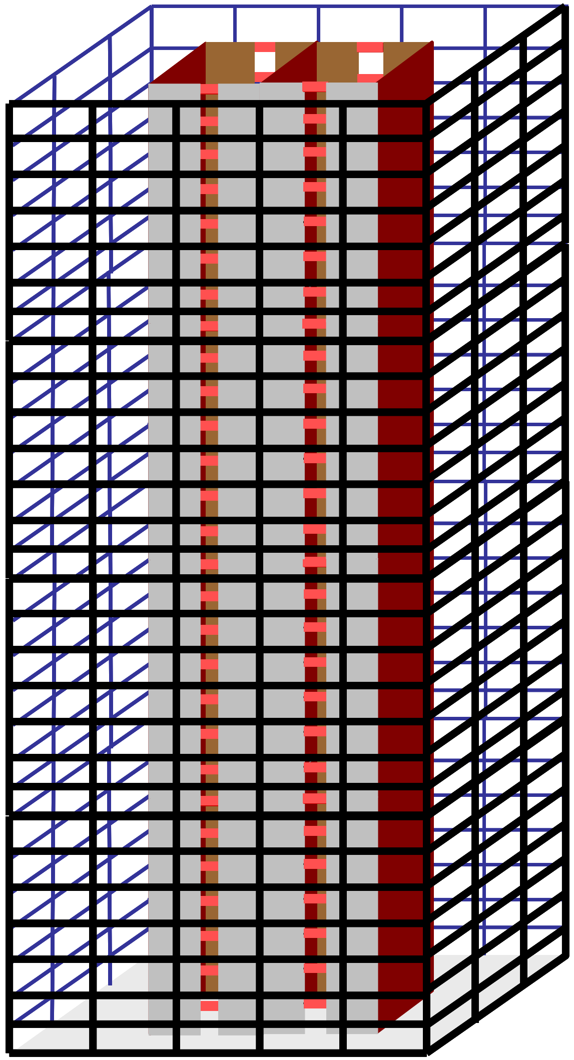
RC結構牆類別

- 耦合結構牆

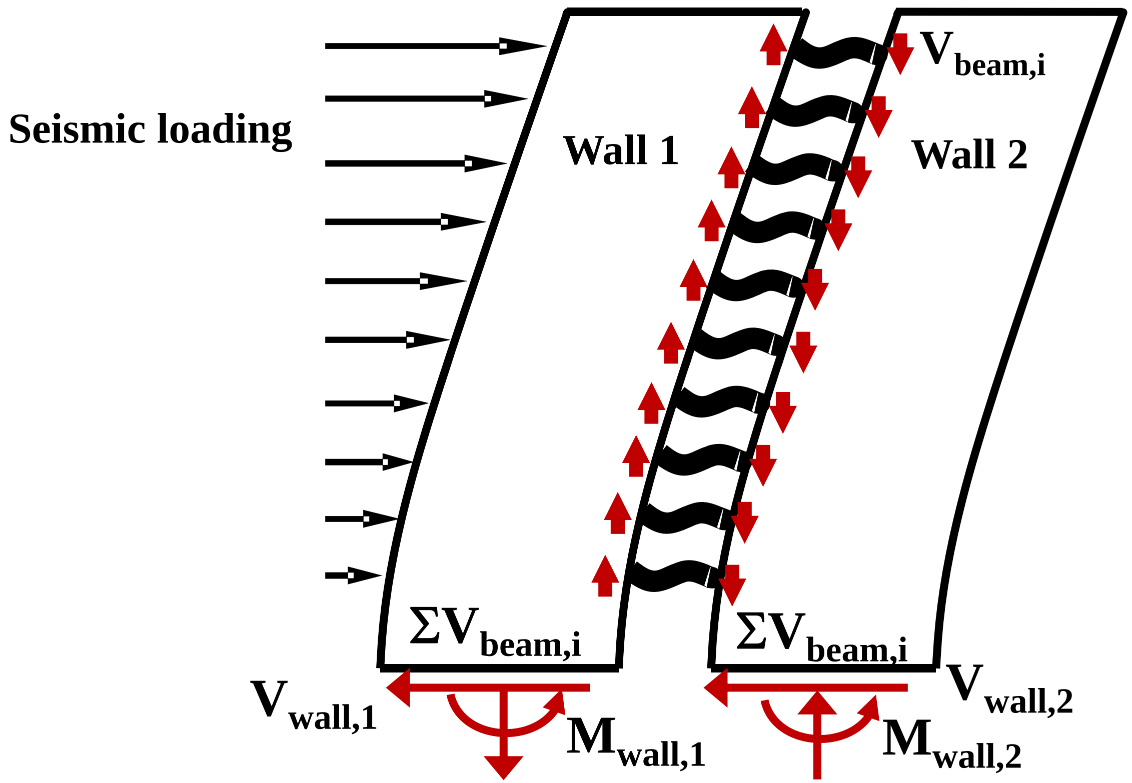


耦合結構牆 Coupled Structural Walls





耦合結構牆 Coupled Structural Walls



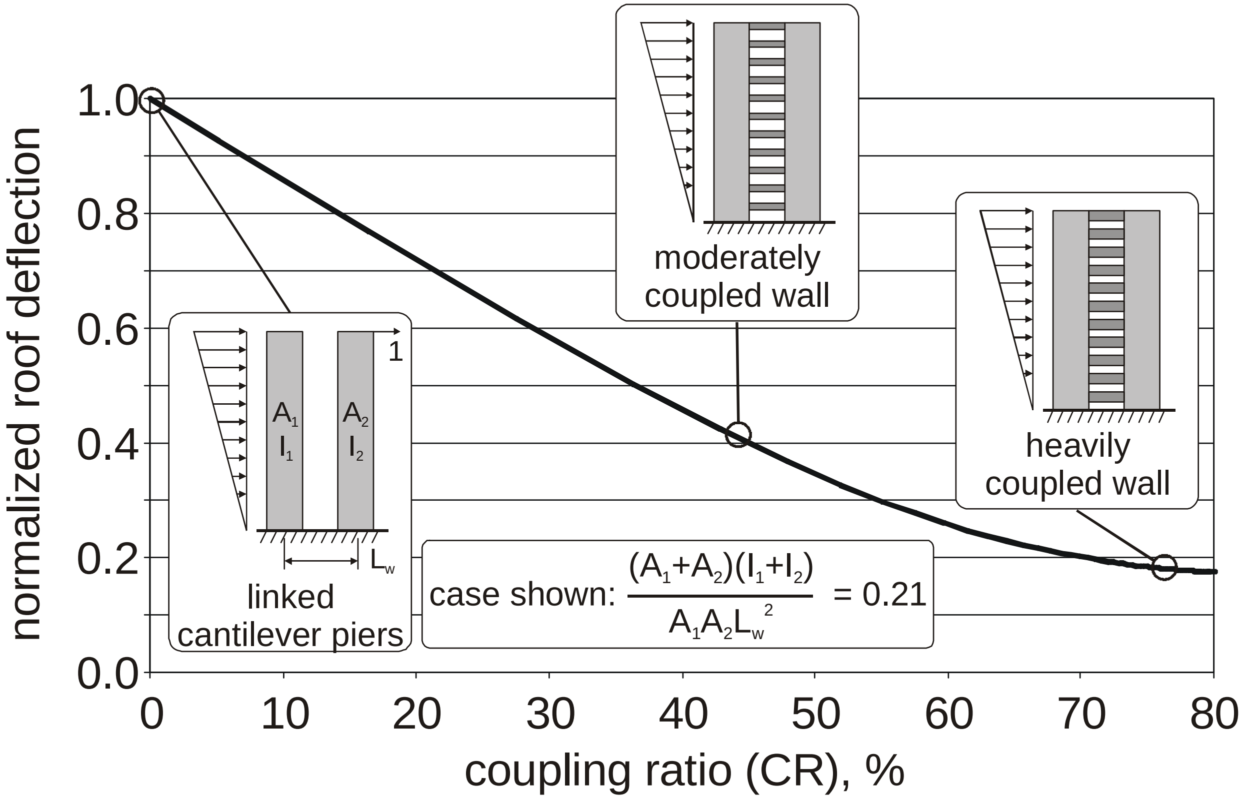
- 耦合率 (coupling ratio)

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

簡介:

耦合率 (Coupling Ratio/CR)

- 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

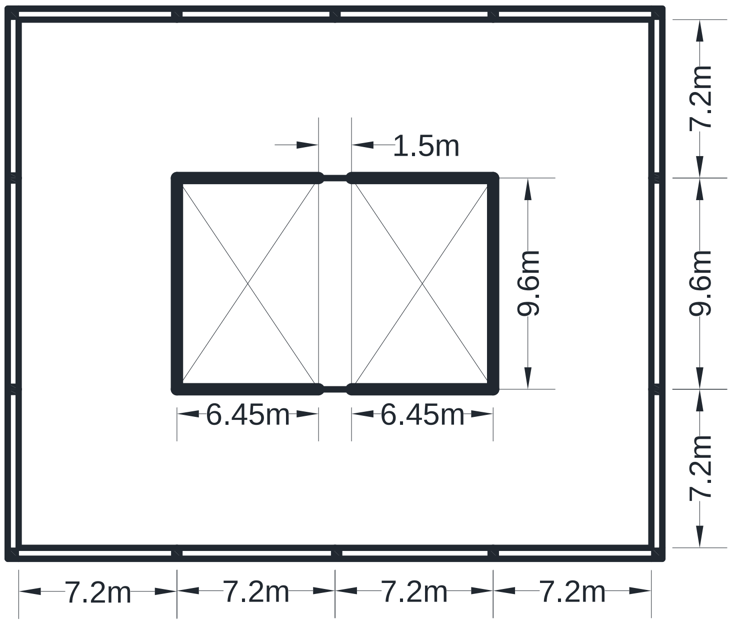


(Harries 等人 2004)

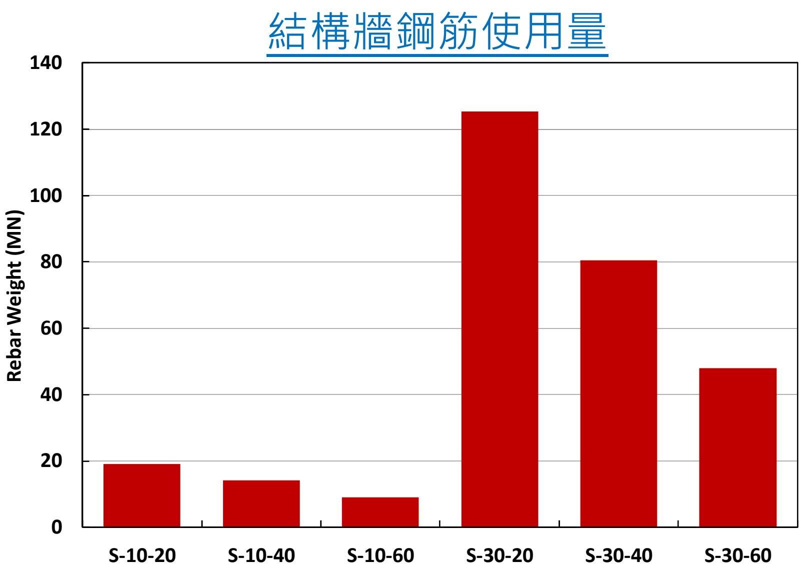
耦合率對於使用鋼筋量之影響

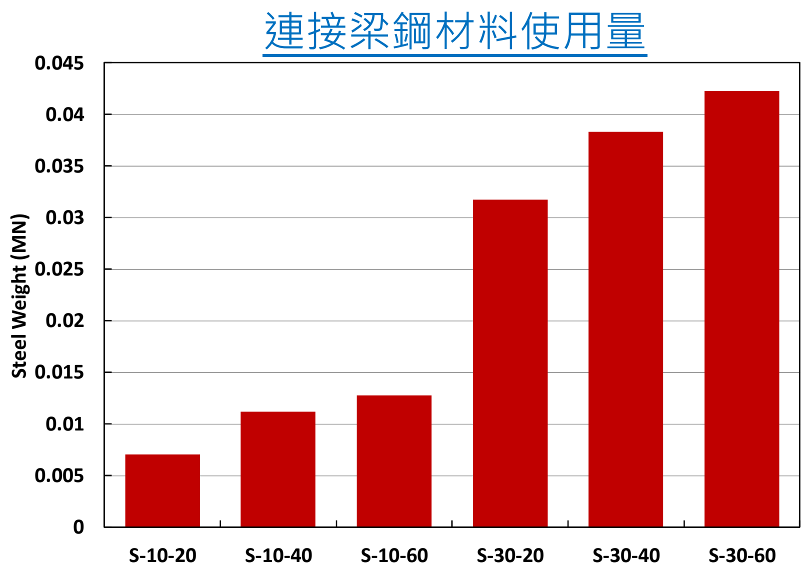
系統代號	樓層高度	耦合率(%)	系統重量
S-樓層數-CR	10 (37.5 m)	20、40、60	47 MN
	30 (92.0 m)		161 MN

系統平面圖



耦合率對於使用鋼筋量之影響





RC連接梁

- RC coupling beams, particularly those in mid-rise or shorter coupled walls, have to be designed with high shear demands in order to provide **adequate coupling action**, which could likely exceed the acceptance value stipulated in design codes.

$$V_n = 2A_{vd}f_y\sin\alpha \leq 0.83\sqrt{f_c'}\,A_{cw}$$

- In order to provide stable hysteretic behavior, RC coupling beams with small aspect ratios often requires diagonal reinforcement with dense arrays of steel confinement. This results in the difficulty of construction.


From [2]

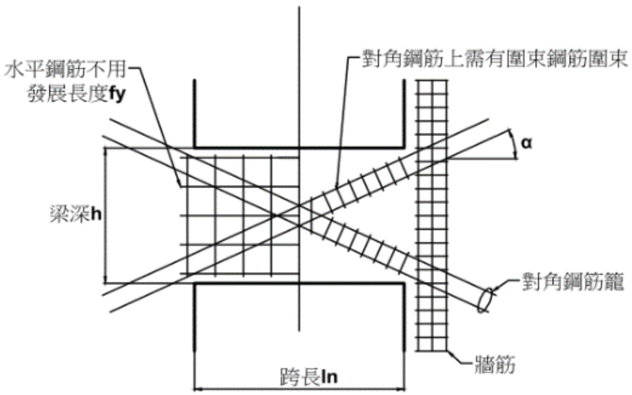

From [1]

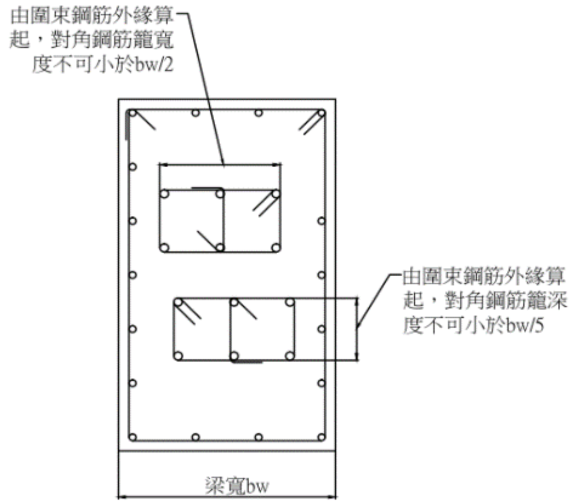

From [1]

[1] Moehle, J. P., Ghodsi, T., Hooper, J. D., Fields, D. C., & Gedhada, R. (2011). Seismic Design of Cast-in-Place Concrete Special Structural Walls and Coupling Beams. *NEHRP Seismic Design Technical Brief No, 6*.
[2] Lequesne, Remy D. *Behavior and design of high-performance fiber-reinforced concrete coupling beams and coupled-wall systems*. Diss. The University of Michigan, 2011.

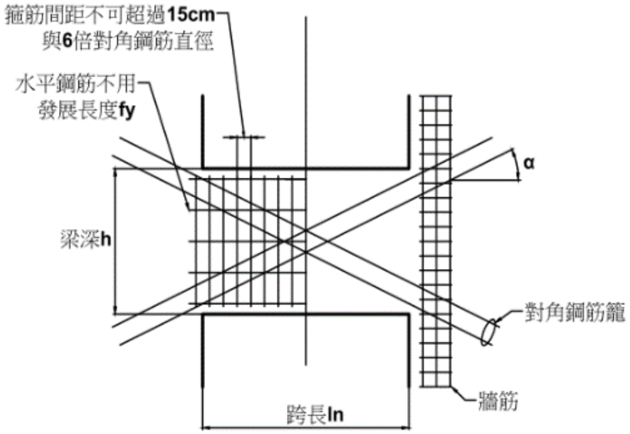
RC連接梁

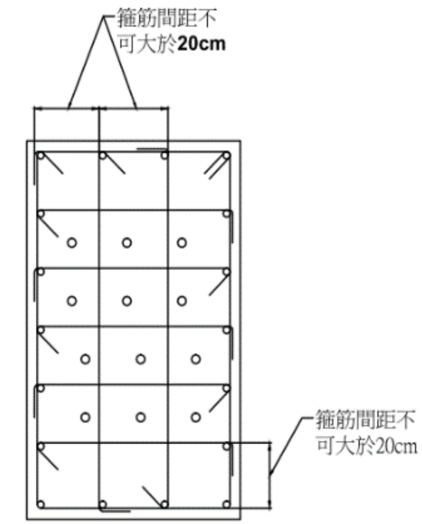
- ACI 318-14
  - Type-A confinement





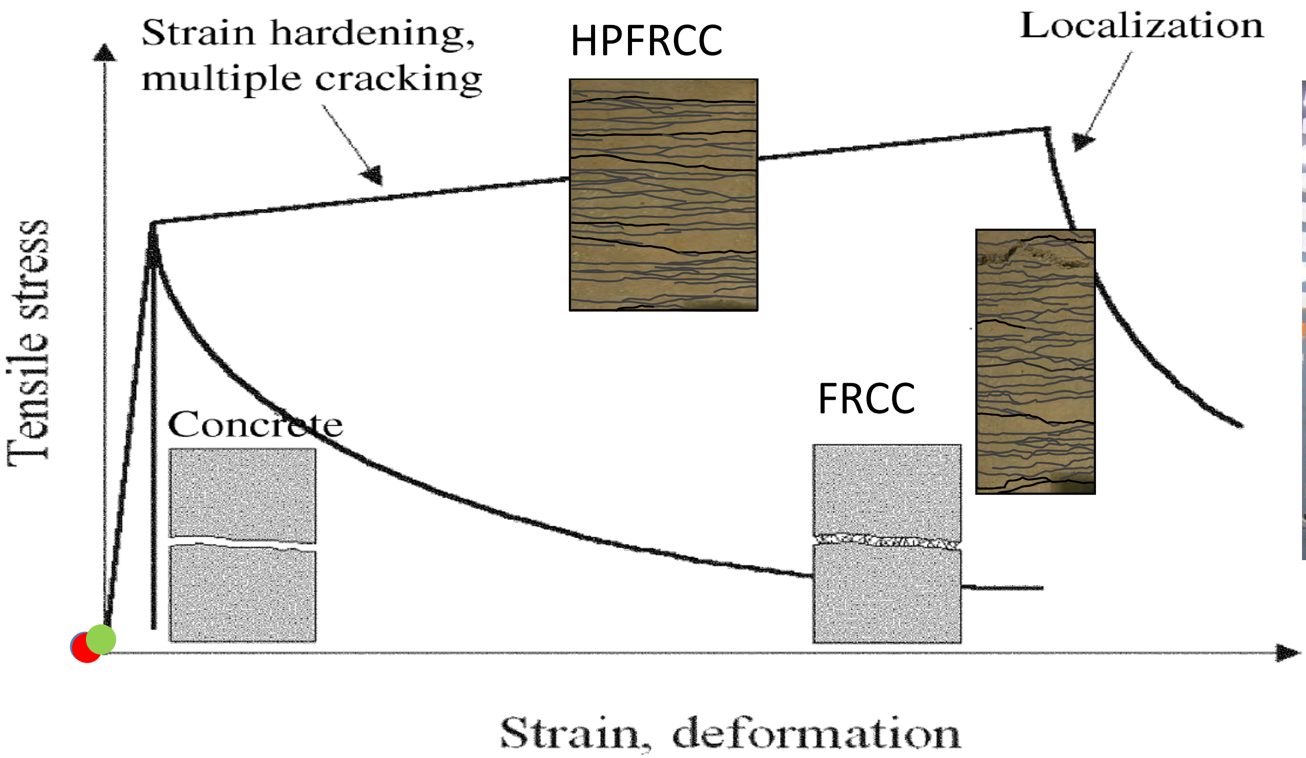
  - Type-B confinement





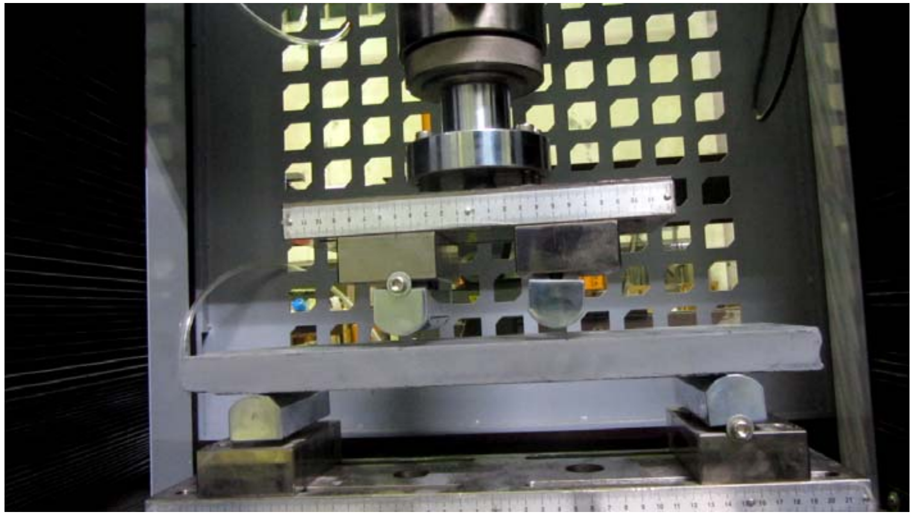
簡介:高性能纖維混凝土

- ***<u>高性能纖維混凝土</u>***
  <u>High Performance Fiber Reinforced Cementitious Composites (HPFRCCs) :</u>
  - a class of cement composites exhibits strain hardening behavior in tension, accompanied by multiple cracking

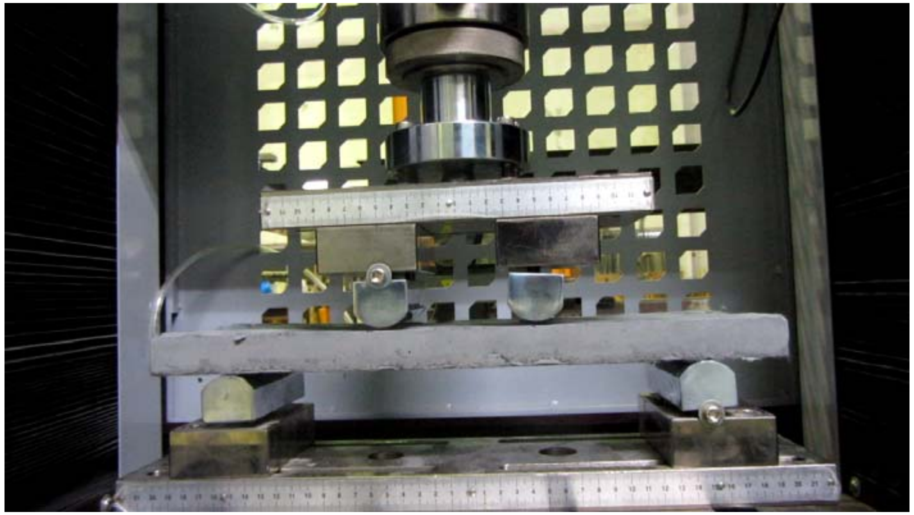


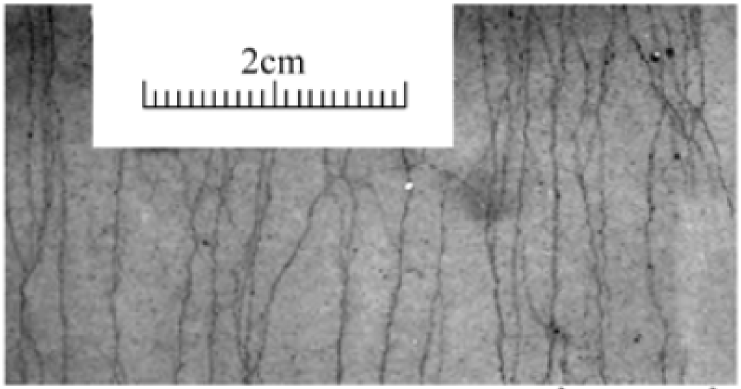
高性能纖維混凝土之韌性行為

- *傳統混凝土材料*



- *高性能纖維混凝土*

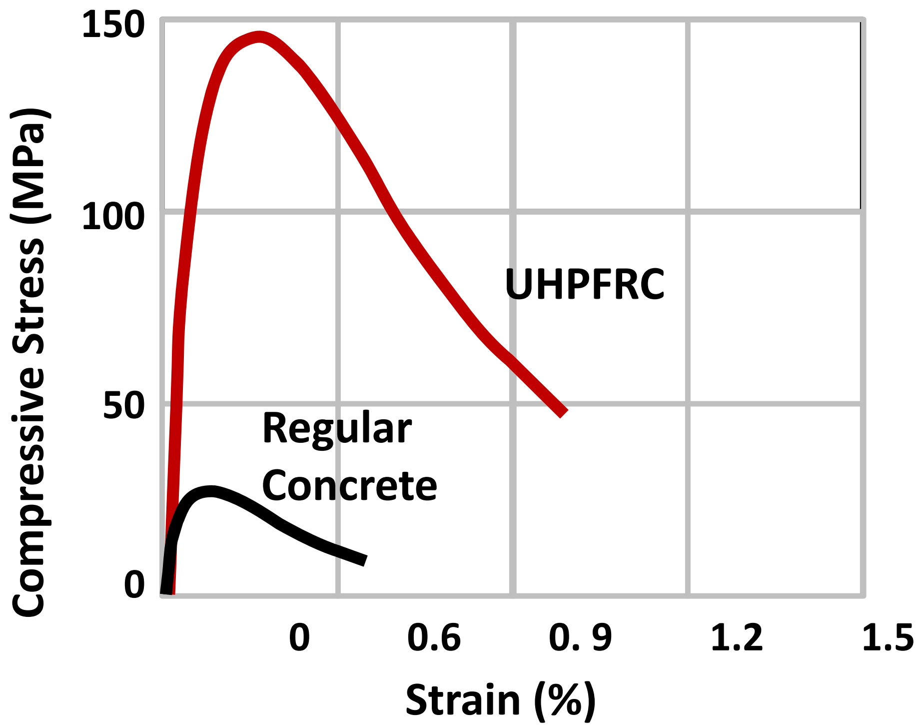


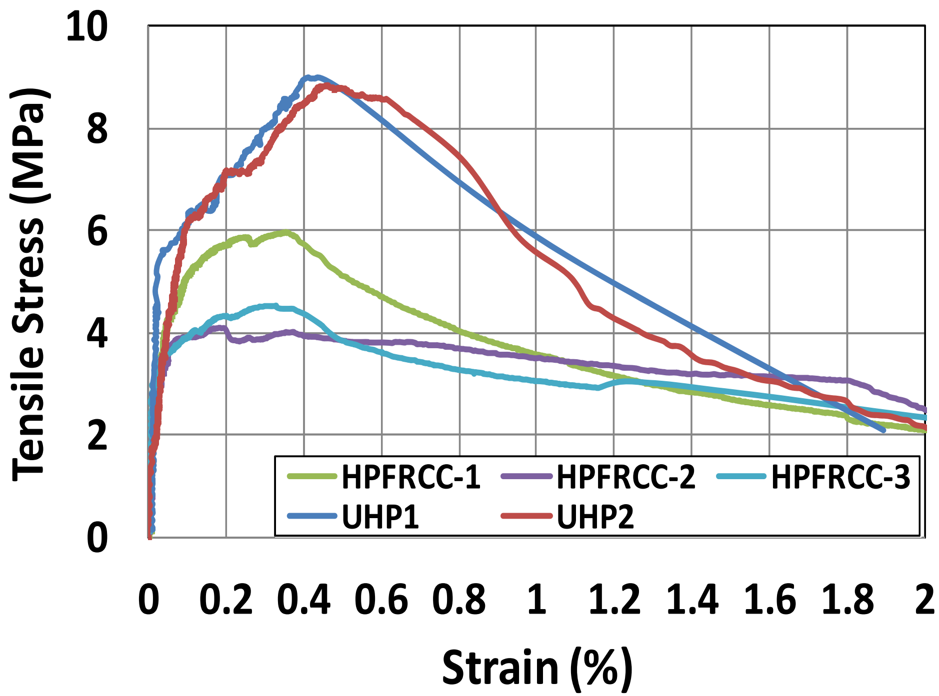


28d: crack width 30 ~ 60 μm (1.18×10^{-3}~2.36×10^{-3} in.)

超高性能纖維混凝土
Ultra High Performance Fiber Reinforced Concrete (UHPFRC)

- possessing ultra high strength and ductility





纖維類型

- **_PVA fibers_**

- **_Torex steel fibers_**

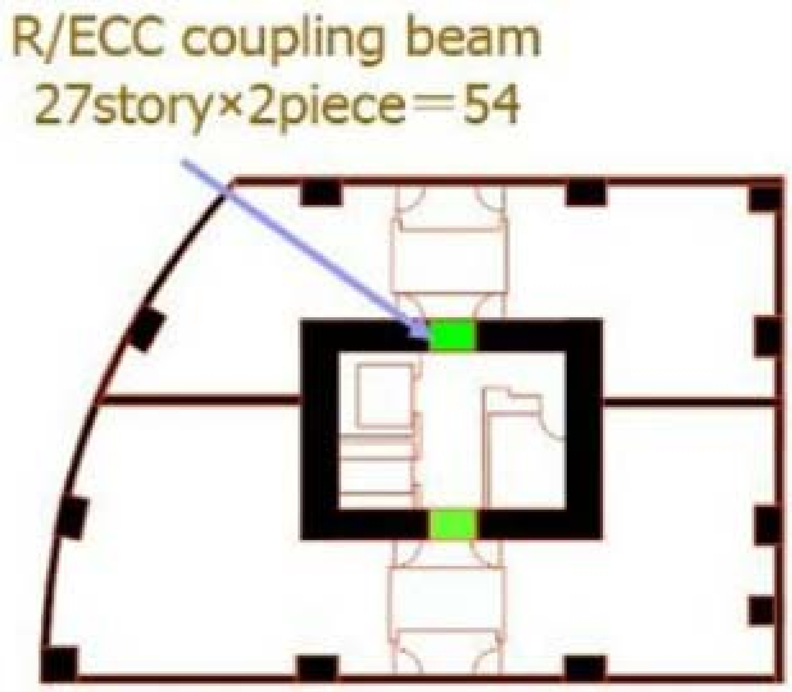
- **_Spectra fibers_**

- **_Hooked steel fibers_**

Fiber Type	Diameter (mm)	Length (mm)	Density (g/cc)	Tensile Strength (MPa)	Elastic Modulus (MPa)
PVA	0.19	12	1.31	900	29000
Spectra	0.038	38	0.97	2585	117000
Hooked (Regular Strength)	0.3	30	7.9	1050	200000
Hooked (High Strength)	0.4	30	7.9	2100	200000
Torex (Regular Strength)	0.3	30	7.9	1380	200000
Torex (High Strength)	0.3	30	7.9	2760	200000

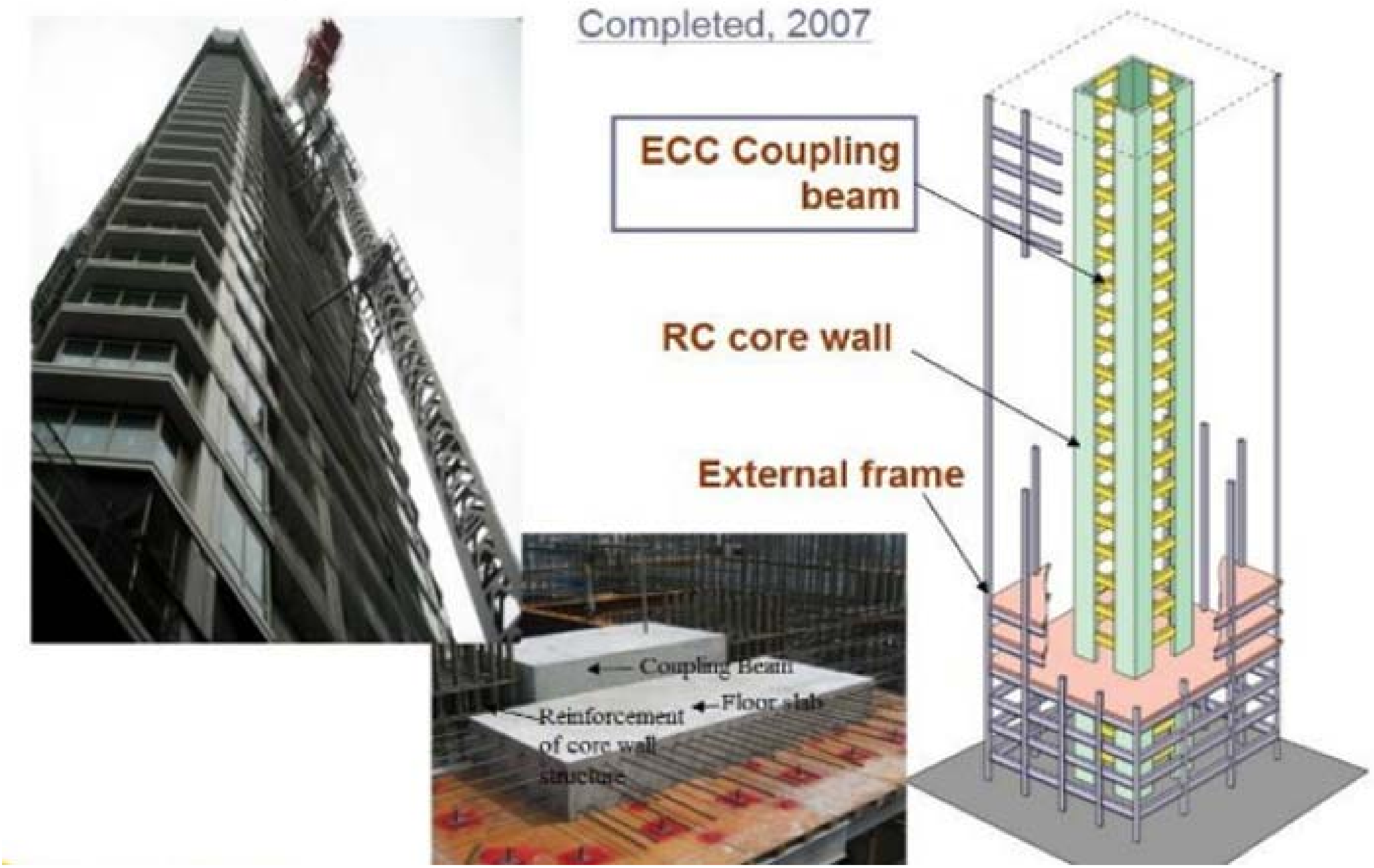
高性能纖維混凝土-耦合結構牆之應用

- 2004 Glorio Roppongi High Rise Residential Building, central Tokyo,



高性能纖維混凝土-耦合結構牆之應用

- 2007 41-story Nabeaure Tower, Yokohama



2017 41&31-story Buildings, WA

LINCOLN SQUARE EXPANSION

STEEL FIBER REINFORCED CONCRETE SOLVES SEISMIC DESIGN CHALLENGES

By Cary Kopczynski, P.E., S.E., FACI and Mark Whiteley, P.E., S.E.

Lincoln Square Expansion (LSE) in Bellevue, WA.

Bellevue, Washington continues to blossom into a vibrant, world class city. The Lincoln Square Expansion (LSE) broke ground in downtown Bellevue in June 2014 and, when complete in 2017, will add two 450-foot towers, a four level retail podium, and six levels of subterranean parking to Bellevue's urban core. LSE is an excellent example of how innovative structural design can respond to high seismic requirements and still meet demanding architectural programs.

The 41-story hotel/residential tower will feature a W Hotel and upscale apartments. The 31-story office tower will feature Class-A office space with unparalleled views. Both towers integrate with a podium structure with retail shops and restaurants. The subterranean parking will include 2,200 new parking spaces and connect to adjacent existing underground parking via tunnels.

The hotel/residential tower is cast-in-place concrete with a mix of one-way and two-way post-tensioned slabs, with the office tower and retail podium framed in structural steel. Concrete shear walls resist seismic loads for both towers and the retail podium. The subterranean parking structure utilizes one-way post-tensioned slabs with wide-shallow beams to create large open space and user-friendly parking.

Performance-Based Design

Performance-Based Design (PBD) was key to the structural design of LSE. Essentially, PBD is a methodology for creating acceptable alternates to prescriptive building code requirements, contingent upon demonstrating that the proposed design meets code required seismic performance levels. This is generally accomplished through rigorous non-linear analysis and by checking the stiffness, ductility, and strength of critical elements.

Steel fiber reinforced concrete shear wall coupling beam under construction.

Since LSE consists of two towers and a common podium, careful attention was given to the seismic interaction between these structures. A combined nonlinear model consisting of both towers, the retail podium, and below grade parking was created. The stiffness assumptions for backstay effects between slabs and basement walls were important considerations, since they determined the effective fixity at the base of the towers. Two different sets of assumptions were made for these elements in the nonlinear analysis in order to effectively evaluate an upper and lower bound solution.

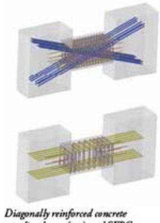
Steel Fiber Reinforced Concrete

Reinforcing congestion has long been the bane of concrete construction in high seismic regions. Some of the most difficult and congested reinforcing is often in shear wall coupling beams. Traditionally, diagonal bars are used to reinforce these coupling beams, combined with tightly spaced stirrups and ties. This creates significant constructability problems since the diagonal bars clash with adjacent shear wall reinforcing.

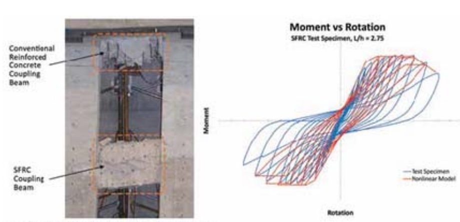
For the LSE seismic system, PBD provided a means to implement steel fiber reinforced concrete (SFRC) in 341 of 392 total coupling beams. This is significant, since the use of SFRC for seismic design has heretofore been limited. The only prior use of SFRC in seismic coupling beams was in a 24-story tower in Seattle, for which CKC was also the structural engineer.

Modeling of key elements is critical to reliably predicting seismic behavior. The SFRC coupling beams in LSE were of particular importance. Both the initial stiffness and cyclic degradation used in the model were carefully calibrated against the hysteresis loops derived from dynamic lab testing. This hysteretic behavior was then used in the non-linear analytical models.

Dramix© steel fibers manufactured by Bekaert, with a fiber dosage of 200 lb/yd^3 (120 kg/m^3) of concrete, were used in LSE. The fibers are 0.015-inch (0.38mm) diameter by 1.18-inch (30mm) cold-drawn steel wire with hooked ends for anchorage. Fibers were delivered to the producer in subsets of thirty. The subsets were bonded with water-soluble glue that dissolved when mixed into the concrete, allowing the fibers to separate and disperse throughout the mix. After workability was confirmed at the site, a bucket was used to place coupling beam



Diagonally reinforced concrete coupling beam (top) and SFRC coupling beam (bottom).



Analytical model calibration with physical testing.

concrete. A piece of "Stayform" at each end of the coupling beam restrained the SFRC from flowing into the adjacent core walls, which were pumped with high-strength concrete.

The study of SFRC started at the University of Michigan, with financial support from the National Science Foundation. Further research was funded by the National Science Foundation Network for Earthquake Engineering Simulation, and Bekaert, a Belgium based global supplier of steel fibers. The studies concluded that SFRC coupling beams without diagonal bars achieve similar or better performance, compared to prescriptively designed beams. With SFRC, the stiffness, strength and ductility of coupling beams is maintained, even though a significant quantity of reinforcing steel – including the diagonal bars – is eliminated. Use of SFRC in coupling beams can result in up to a 40 percent reduction in reinforcing and 30 percent net cost savings, compared to traditional coupling beam construction.

SFRC provides the structural engineering profession with a valuable tool for improving the constructability of reinforced concrete buildings in high seismic regions. The use of SFRC in LSE resulted in a coupling beam design that eased reinforcing congestion, facilitated faster construction, and reduced rebar tonnage.

Additional SFRC research is currently underway at the University of Wisconsin, funded by the Charles Pankow Foundation. The results of this testing are expected to broaden the range of fiber types, dosage rates, and aspect ratios available for use by designers of concrete buildings in high seismic regions.

above, creating column-free 50-foot spans throughout. The use of PT in both the beams and slabs lowered the floor-to-floor heights, resulting in reduced excavation and shoring depth. The garage layout partially carries through to the structures above, creating column-free space of 40 by 50 feet in the office tower. The hotel/residential tower was framed with a two-way flat plate system with spans of 25 to 34 feet. Parking columns and columns in the lower levels of the hotel/residential Tower utilized 14,000 psi concrete, specified with a test age of 90 days.

Office Tower

In the office tower, high-strength ASTM A913 Grade 65 structural steel was specified for the columns. This eliminated the need for custom fabricated shapes at the lowest levels where load demands exceeded the capacity of standard Grade 50 column shapes.

Mechanical, electrical, and plumbing (MEP) in the office tower was integrated with the structural steel framing. Penetrations in the steel framing allowed the mechanical systems to feed through the floor framing, which increased the floor-to-ceiling height and allowed for an additional leasable floor in the tower.

The office core was constructed of high-strength concrete, utilizing a high-production climbing form and scaffold system. Prior to starting structural steel erection, the core construction was advanced well ahead to allow simultaneous topping out of both the core and structural steel frame.

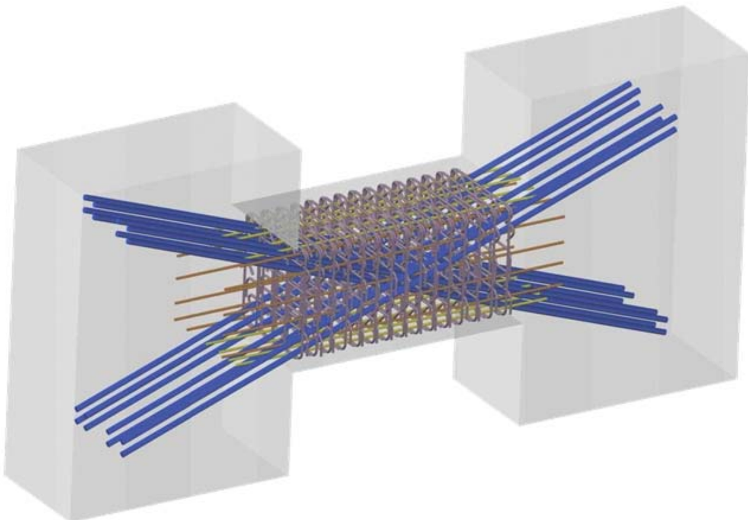
Conclusion

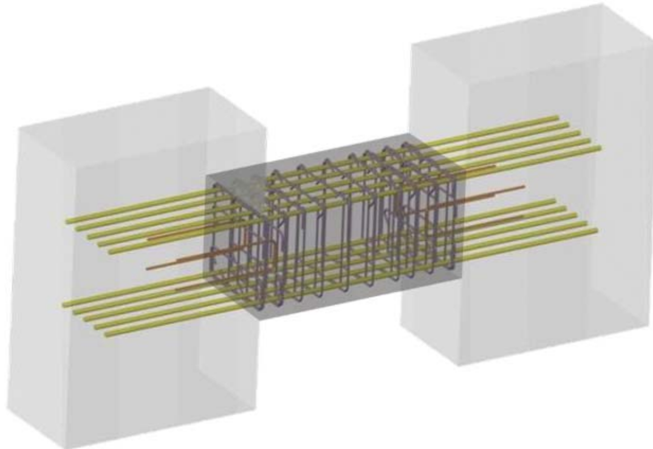
The Lincoln Square Expansion in Bellevue, Washington is as an excellent example of how innovative structural design can add value to a multi-use project. LSE both enhances the Bellevue urban landscape and advances the structural engineering profession. Through careful coordination among all parties, CKC's unique solutions to the design challenges resulted in an efficient structural system, and use of SFRC created a new approach to high-rise building design and construction in high seismic regions.▪

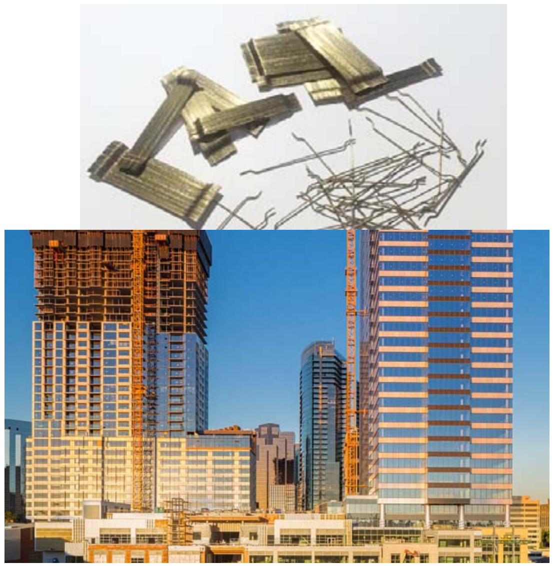
Cary Kopczynski, P.E., S.E., FACI, is Senior Principal and CEO of Cary Kopczynski & Company (CKC). Mr. Kopczynski serves on the Board of Directors of both the American Concrete Institute (ACI) and Post-Tensioning Institute (PTI), Chaired the PTI's Technical Advisory Board for six years, and served on ACI Committee 318 for several building code cycles. Mr. Kopczynski can be reached at ***caryk@ckcps.com****.*

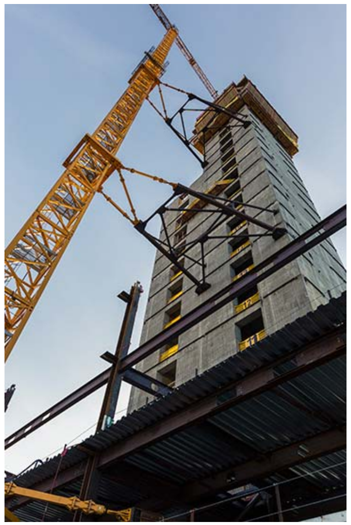
Mark Whiteley, P.E., S.E., is a Principal at Cary Kopczynski & Company (CKC), located in Bellevue, Washington, and the Senior Project Manager for Lincoln Square Expansion. Mr. Whiteley can be reached at ***markw@ckcps.com****.*

高性能纖維混凝土-耦合結構牆之應用







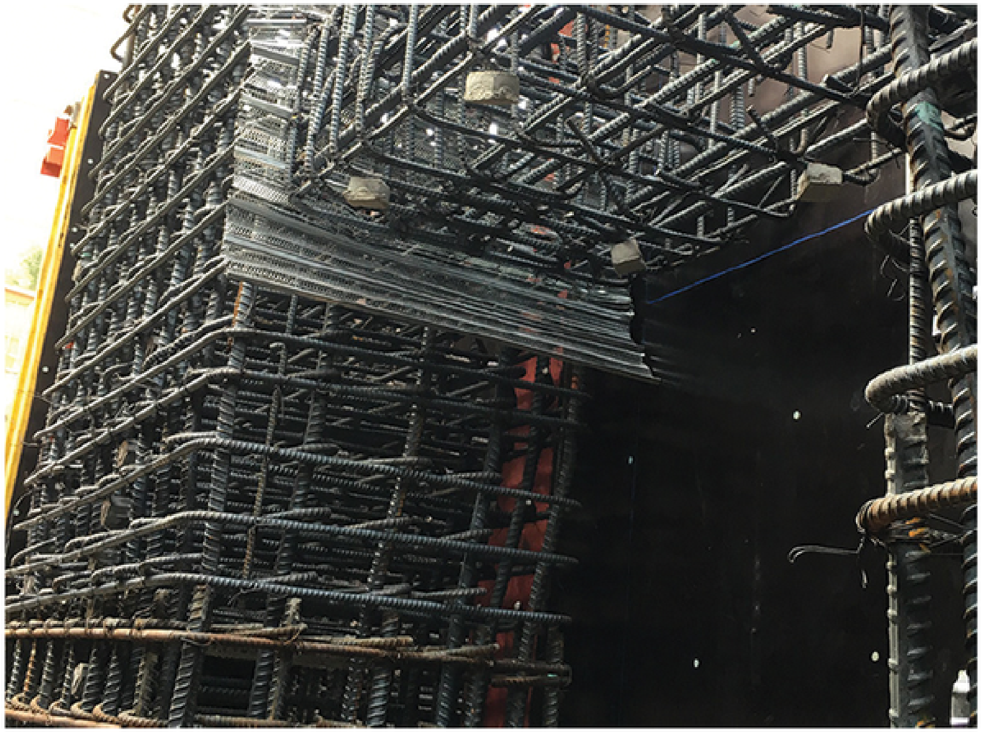


ENR
Engineering News-Record

Building Materials

Making Better Connections

Northwest teams improve steel-fiber-concrete link beams to reduce rebar congestion in seismic-zone shear walls



At the 40-story 970 Denny project, the team learned, after recent trial runs in the below-grade core, tl
to-install steel mesh at the link-beam ends was not needed to keep the fibrous mix out of the wall sec

PHOTO BY JOE FERZIL/CARY KOPCZYNSKI & CO.

Code Change Proposal

For the code change proposal, the aim is to create a chart with different classes of SFRC, based on bending performance and linked to a given drift capacity in link beams. The chart will be wire-brand blind, to keep it generic for the code, says Parra-Montesinos.

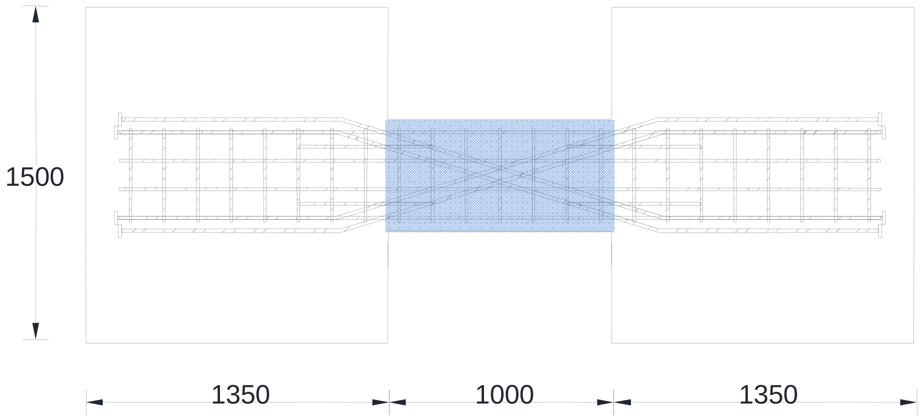
Andrew W. Taylor, an associate with KPFF Consulting Engineers who is involved with the Pankow research, chairs the seismic subcommittee of the "ACI 318 Building Code: Requirements for Structural Concrete," published by the American Concrete Institute. "We would like to formulate provisions for SFRC link beams for the 2019 edition," but this will depend on deliberations of both the seismic subcommittee and the main ACI 318 committee, says Taylor.

高強度鋼纖維混凝土連接梁實驗 -高剪力需求

- Four high strength steel reinforced concrete coupling beams, with cross-sectional dimensions of 300mm*500mm and an aspect ratio of 2, are prepared.
- They are designed to have high shear demands over the code-specified limit.
- Design parameters:

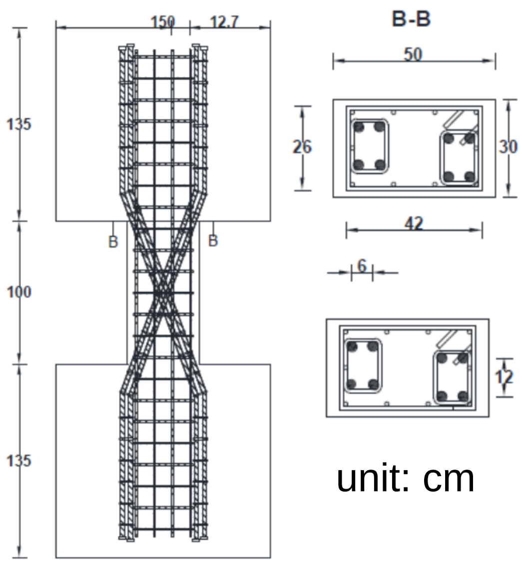
(1) Concrete strength (40MPa, 80MPa, or 80MPa with steel fibers)

(2) Steel confinement (Type-A or Type-B)

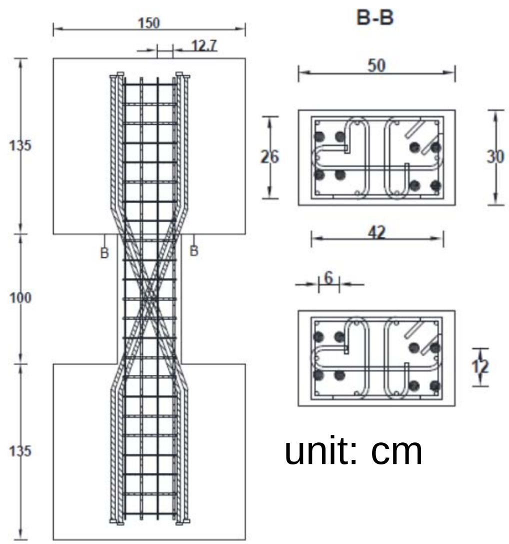


Specimen	Concerte strength (MPa)	Reinforcement design				Design shear stress/(f'c)^0.5 (in MPa)					Test results
		Diagonal steel	longitudinal steel	transverse steel (SD785)	**confinement type**	concrete (Vc)	transverse steel (Vts)	**diagonal steel (Vds)**	total	flexural shear stress demand	Vmax
CB-40-B	**45**	8#9 (SD685)	10#4 (SD420)	#4@15mm	**B**	0.17	0.78	**1.24**	2.18	-	1.52
CB-70-A	**72**	8#9 (SD685)	10#4 (SD420)	#4@15mm	**A**	0.17	0.41	**0.98**	1.56	-	1.29
CB-70-B	**72**	8#9 (SD685)	10#4 (SD420)	#4@15mm	**B**	0.17	0.61	**0.98**	1.76	-	1.29
CB-70F-B	**77+fibers**	8#9 (SD685)	10#4 (SD420)	#4@15mm	**B**	0.17	0.59	**0.95**	1.71	-	1.35

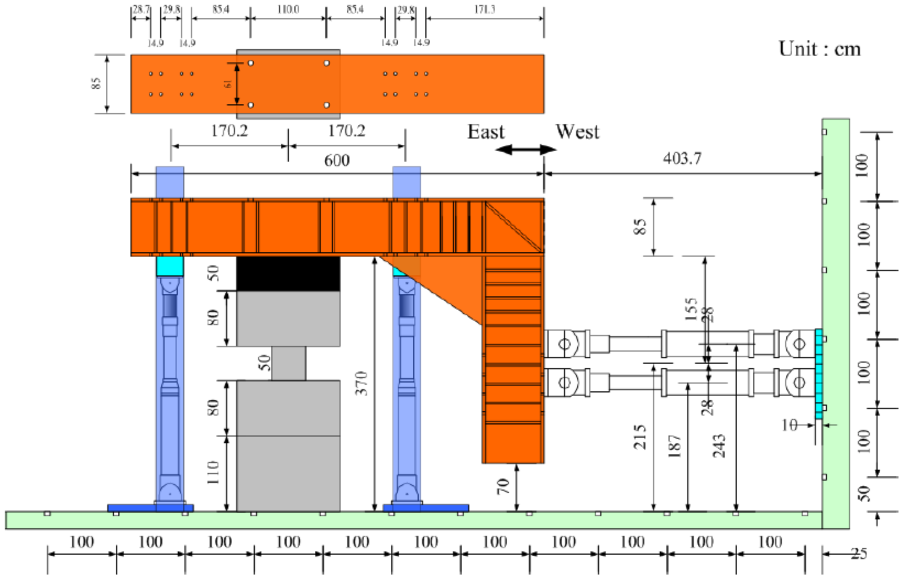
TYPE-A



TYPE-B



實驗架設


Unit : cm
East
West
170.2
170.2
600
403.7
85
155
28
28
370
215
187
243
70
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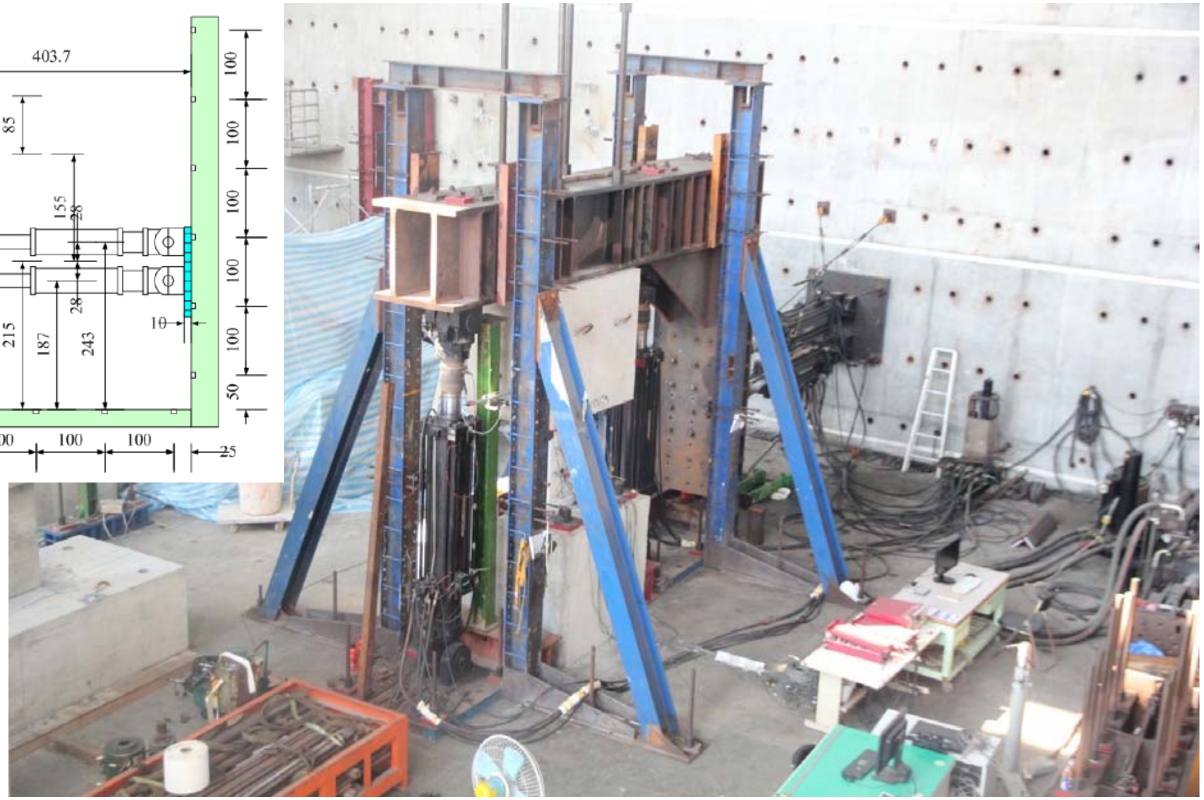
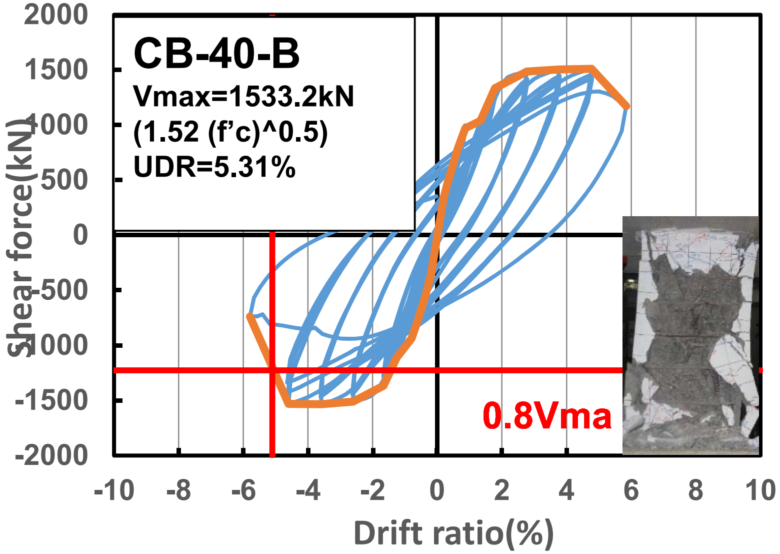
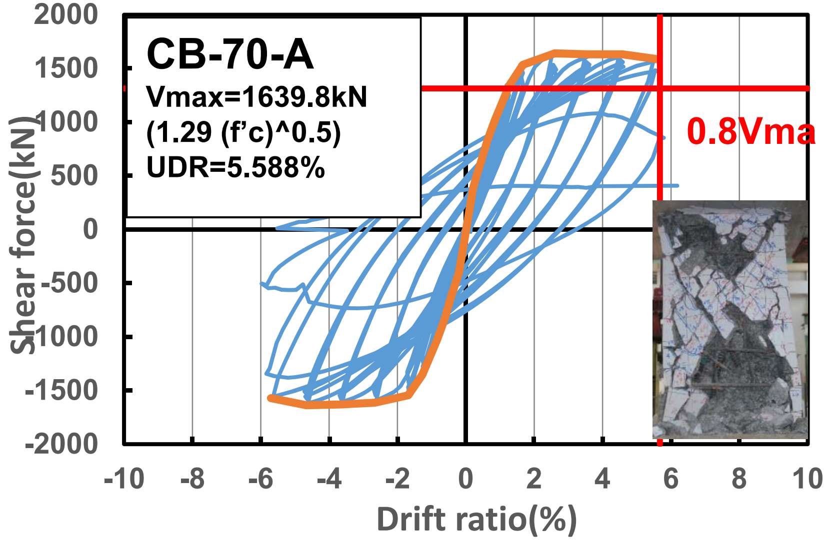
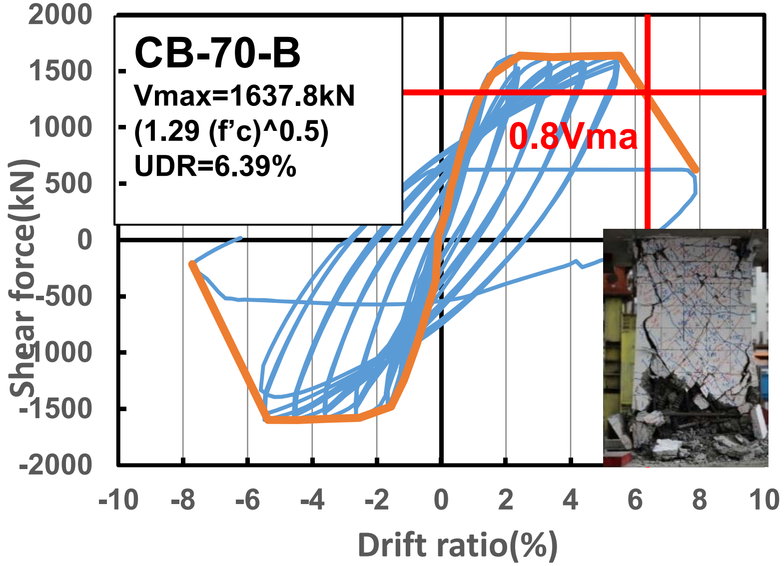
100
100
100
25
50

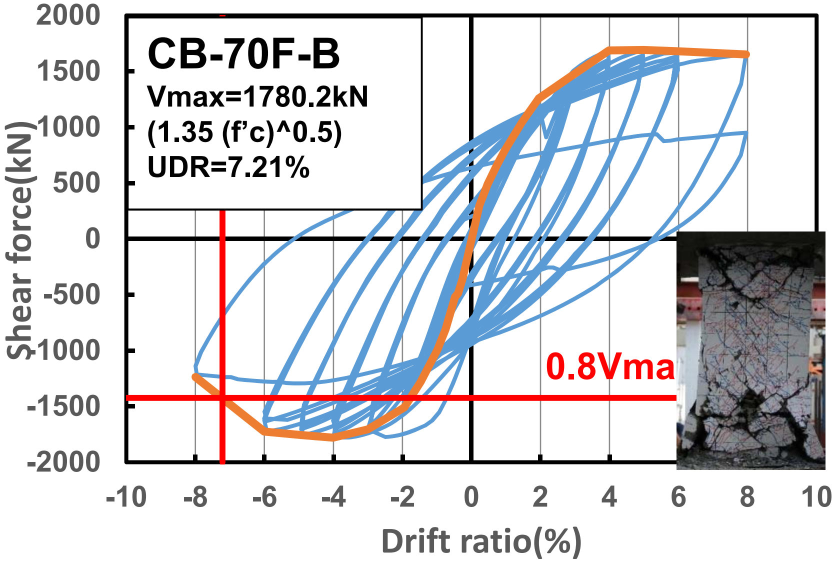


往復載重行為

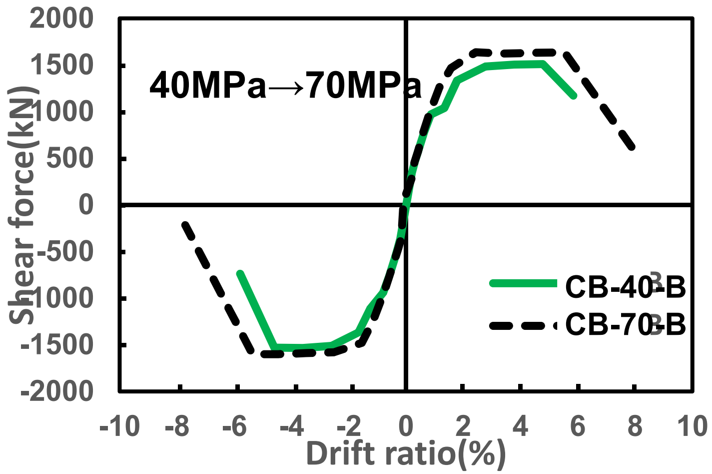

CB-40-B
Vmax=1533.2kN
(1.52 (f'c)^0.5)
UDR=5.31%
0.8Vma
Shear force(kN)
Drift ratio(%)


CB-70-A
Vmax=1639.8kN
(1.29 (f'c)^0.5)
UDR=5.588%
0.8Vma
Shear force(kN)
Drift ratio(%)

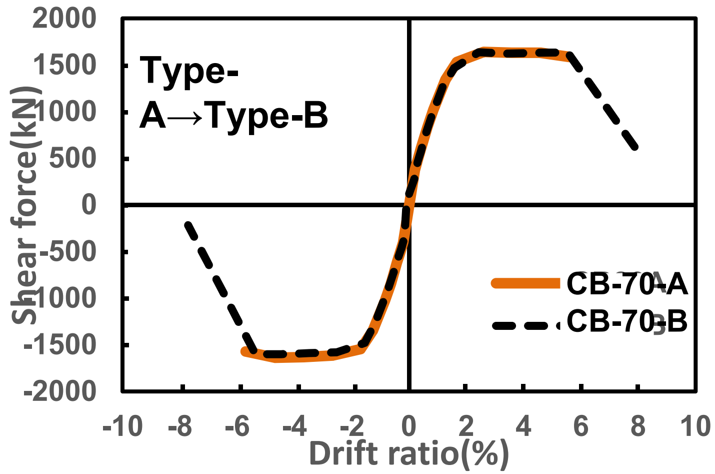

CB-70-B
Vmax=1637.8kN
(1.29 (f'c)^0.5)
UDR=6.39%
0.8Vma
Shear force(kN)
Drift ratio(%)


CB-70F-B
Vmax=1780.2kN
(1.35 (f'c)^0.5)
UDR=7.21%
0.8Vma
Shear force(kN)
Drift ratio(%)

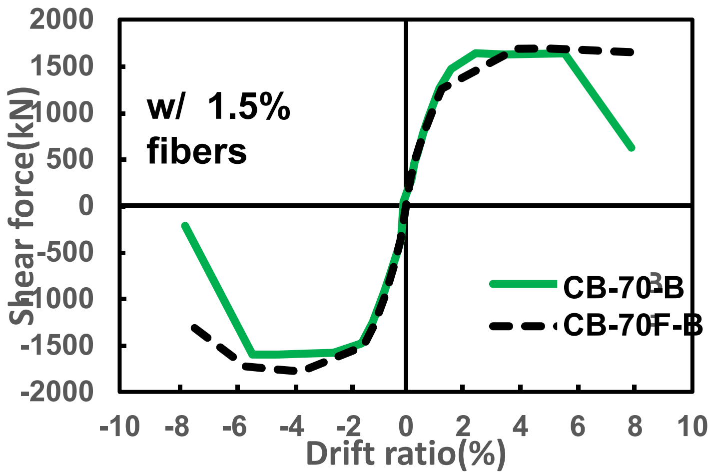
強度包絡線



40MPa→70MPa
CB-40-B
CB-70-B
Shear force(kN)
Drift ratio(%)

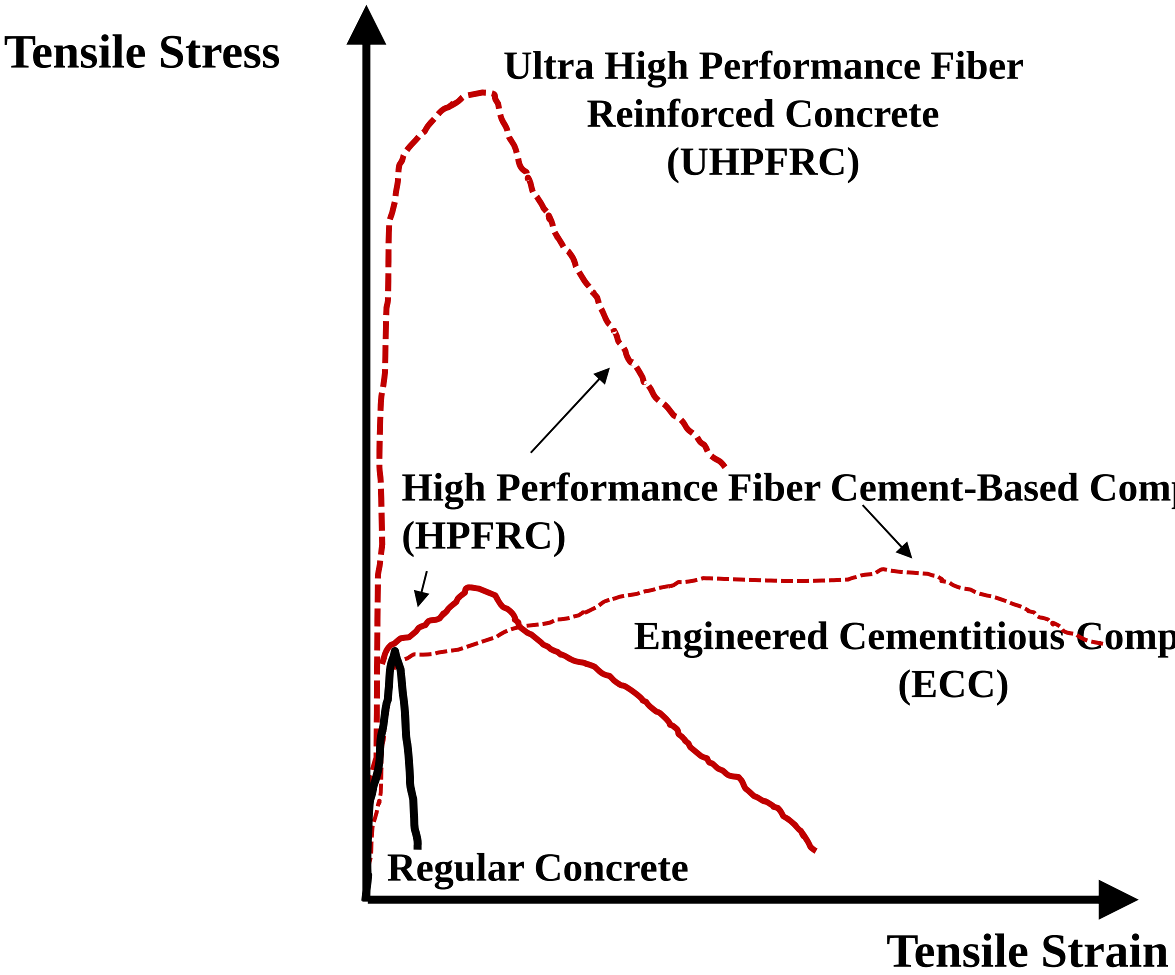


Type-
A→Type-B
CB-70-A
CB-70-B
Shear force(kN)
Drift ratio(%)



w/ 1.5%
fibers
CB-70-B
CB-70F-B
Shear force(kN)
Drift ratio(%)

超高性能纖維混凝土
Ultra High Performance Fiber Reinforced Concrete (UHPFRC)



高強度低矮型RC剪力牆

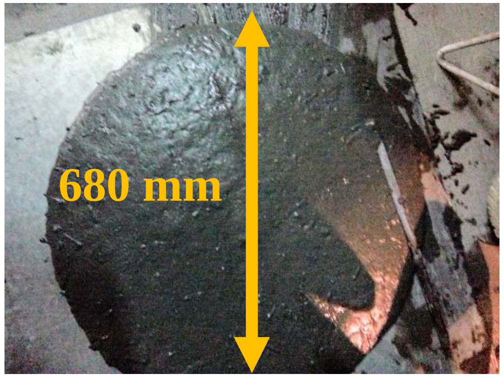
- **Ten high strength squat RC walls with an aspect ratio (h/l) of 1.13**
- **Design parameters:**

(1) concrete types (HSC、UHPC、UHPFRC)

(2) shear demand($0.53\sqrt{f'c}$ or $0.83\sqrt{f'c}$), (3) failure pattern (M_n/hV_n > or < 1)

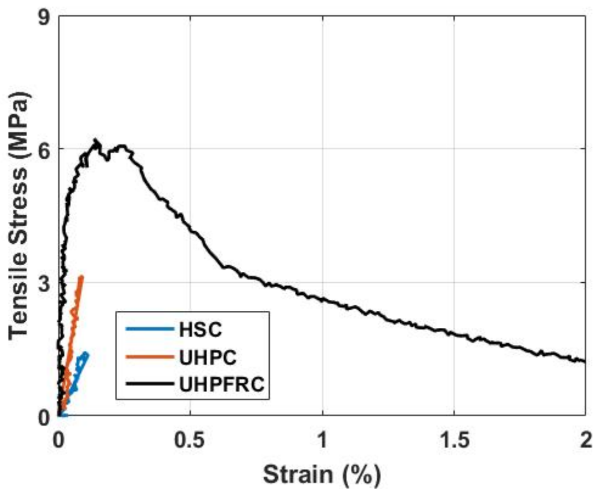
(4) rebar strength (SD420、SD685/SD785),

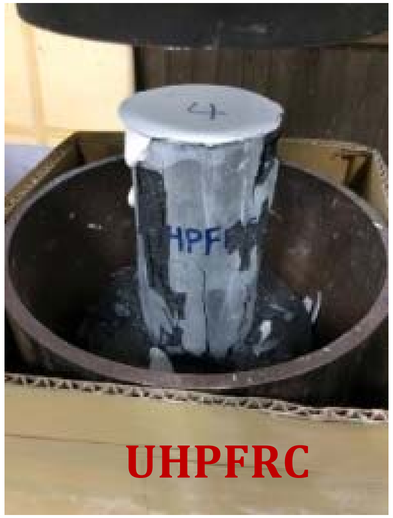
(5) steel fiber (0、0.75%、1.5%、2%), and (6)dowel bar



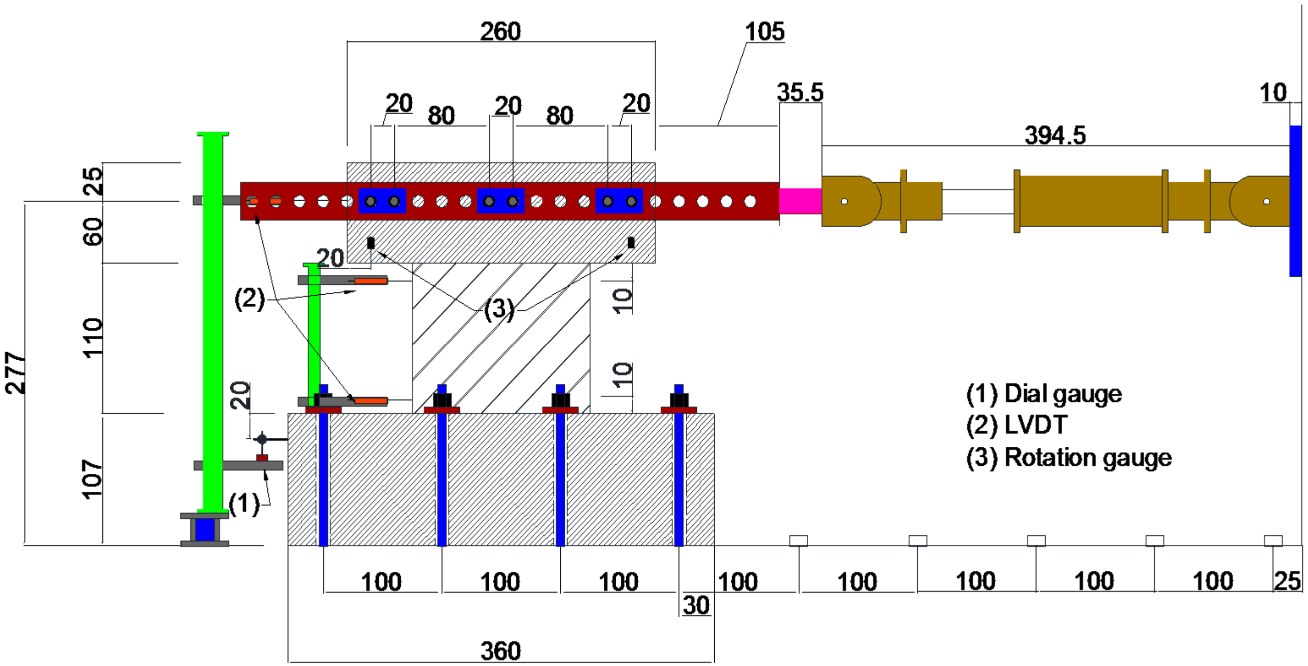
混凝土材料性質

	fc' (MPa)	Tensile strength (MPa)	Ultimate tensile strain (%)
$HSC - HS$	87	2.08	0.09
$UHPC - HS$	120	3.15	0.09
$UHPFRC - NS$	94	5.57	1.87
$UHPFRC - HS$	94	5.57	1.87
$\mathrm{UHPC - HS - 0.5\sqrt{f'c}}$	166	5.3	0.02
$\mathrm{UHPFRC - HS - 0.5\sqrt{f'c}}$	120	7.7	2.44
$\mathrm{UHPFRC - NS - 0.5\sqrt{f'c}}$	125	5.8	2.19
$\mathrm{UHPC - HS - 0.83\sqrt{f'c}}$	158	5.2	0.07
$\mathrm{UHPFRC - HS - 0.83\sqrt{f'c}}$	115	8.2	1.59
$\mathrm{UHPFRC - NS - 0.83\sqrt{f'c}}$	121	7.5	2.80





實驗設置


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

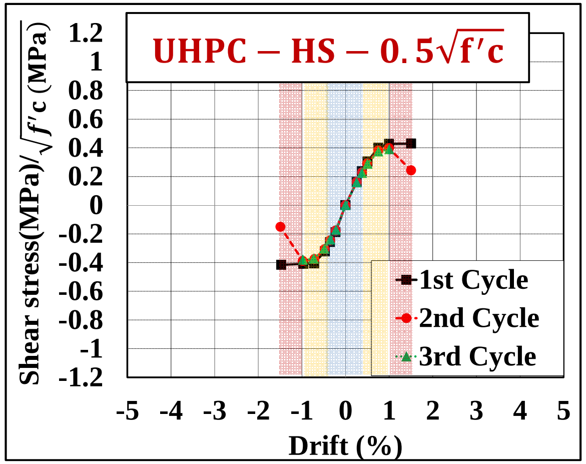
鋼筋設計: $M_n/(hV_n) < 1$

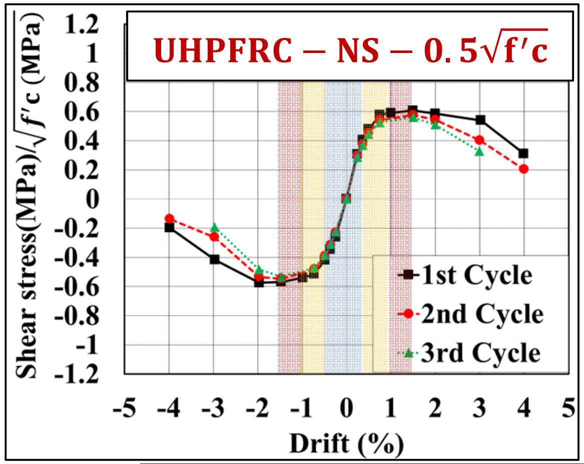
- ASCE 41 (2013): acceptance criteria

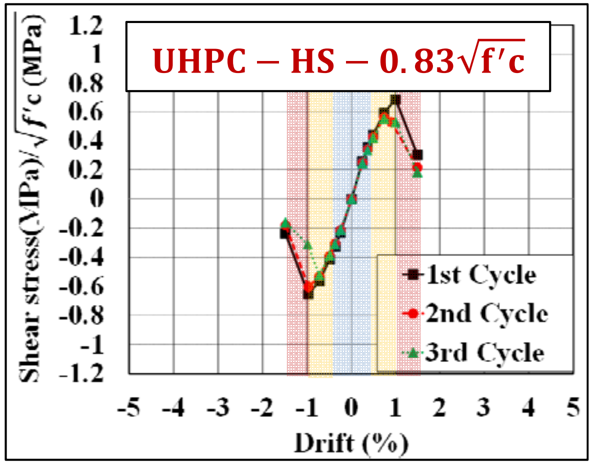
IO

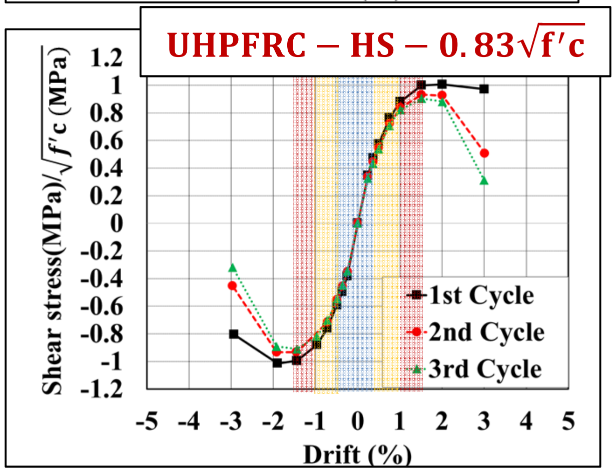
LS

CP



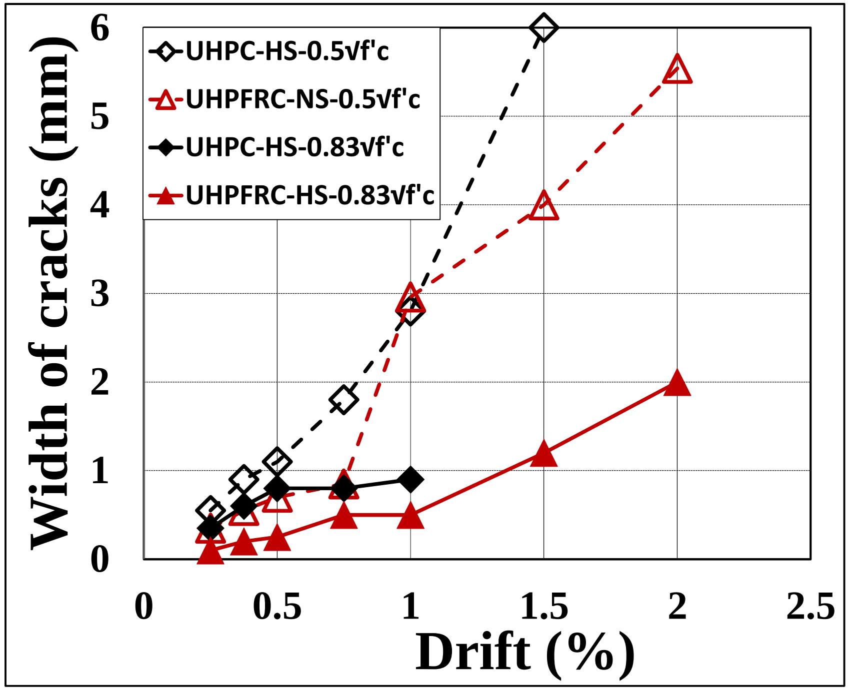




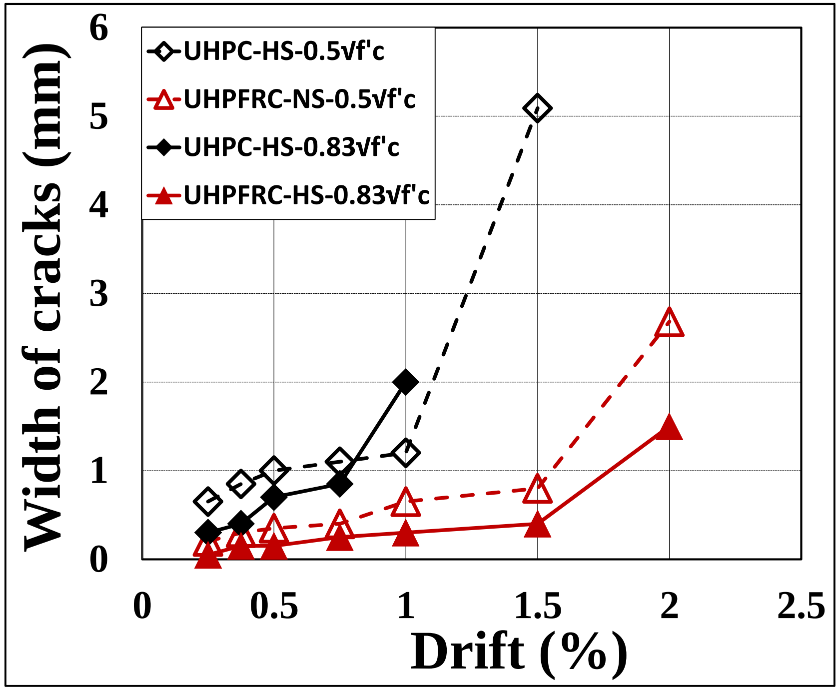


裂縫寬度

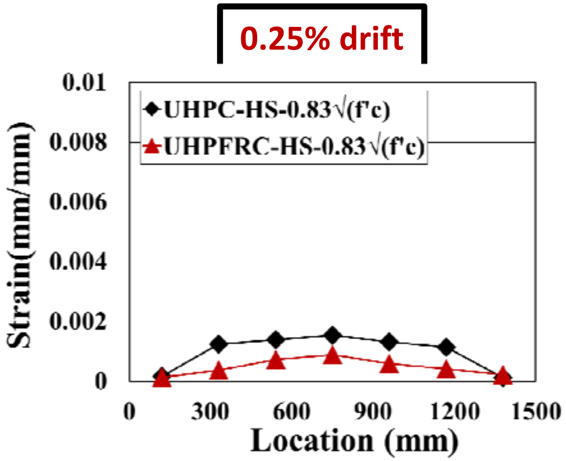
- **Maximum flexural crack widths**

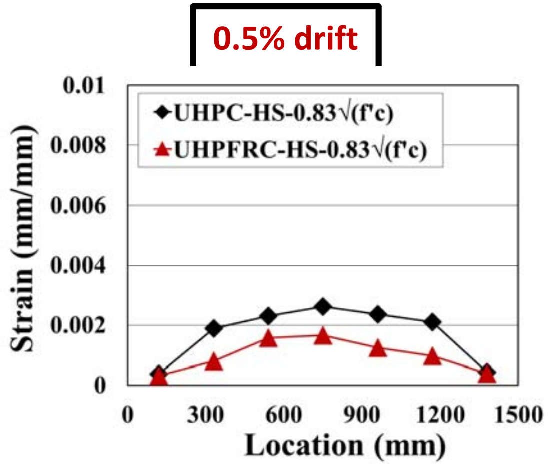


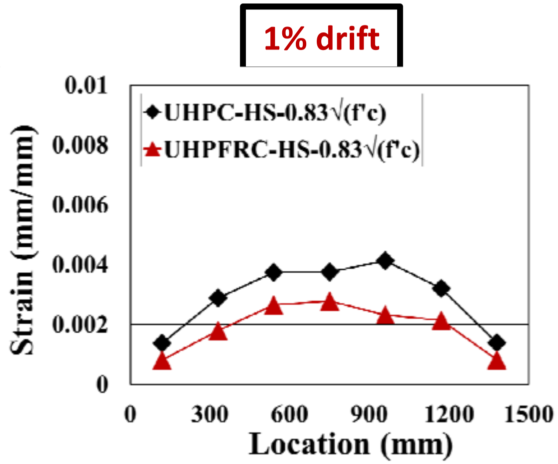
- **Maximum shear crack widths**



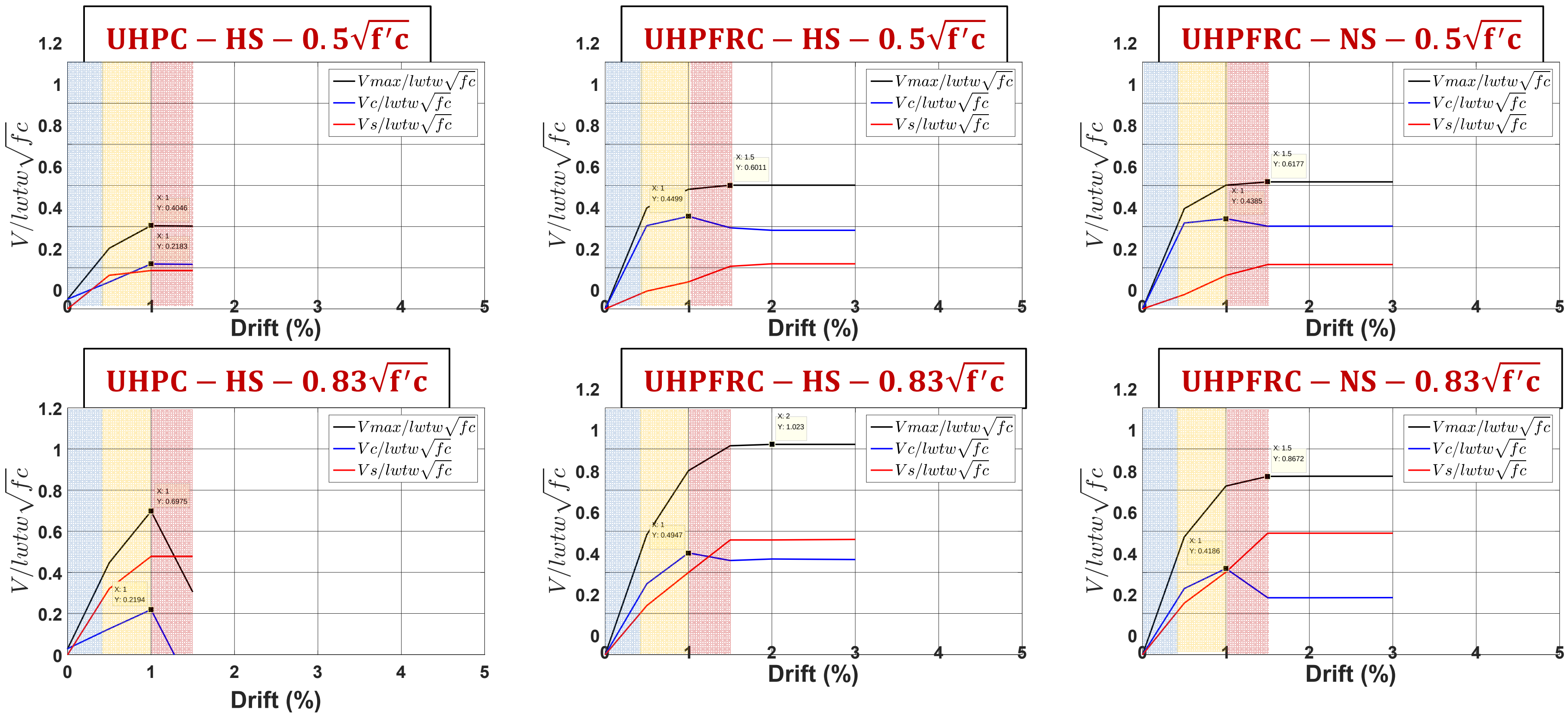
橫向鋼筋最大應變


0.25% drift
Strain(mm/mm)
Location (mm)
UHPC-HS-0.83√(f'c)
UHPFRC-HS-0.83√(f'c)
0
0.002
0.004
0.006
0.008
0.01
0
300
600
900
1200
1500


0.5% drift
Strain (mm/mm)
Location (mm)
UHPC-HS-0.83√(f'c)
UHPFRC-HS-0.83√(f'c)
0
0.002
0.004
0.006
0.008
0.01
0
300
600
900
1200
1500


1% drift
Strain (mm/mm)
Location (mm)
UHPC-HS-0.83√(f'c)
UHPFRC-HS-0.83√(f'c)
0
0.002
0.004
0.006
0.008
0.01
0
300
600
900
1200
1500

剪力抵抗機制



- While the high-strength transverse reinforcement had a nominal yield strength of 785 MPa, which was substantially greater than the maximum permitted value of 420 MPa by ACI-318, its capacity could be fully exploited for providing shear in the squat UHPC and UHPFRC shear walls.

結論

September 28, 2016

Nadine M. Post

Structural engineer Cary Kopczynski once penned a prediction: “There may come a day in the not-too-distant future when concrete building structures will commonly be reinforced with a combination of steel fibers and steel reinforcing bar. Rebar requirements could be reduced, perhaps significantly.” He wrote “Beyond Rebar: A Revolution in Concrete” for the Seattle Daily Journal of Commerce in April 1994.

But the not-too-distant future came and went without a concrete revolution. And the 40-year veteran of earthquake engineering, who practices mostly on the West Coast, still is making the same prediction about reinforced concrete dosed with steel fibers as rebar decongestants. “Looking downstream, there are applications for steel fiber throughout the shear wall,” says Kopczynski, CEO of the 30-year-old Bellevue, Wash., firm that bears his name. “That’s still a way off.”

In quake-prone areas, rebar congestion has long bedeviled contractors. Kopczynski’s solution—adding high-strength wire reinforcement—enhances ductility and shear strength, allowing for less rebar. That, in turn, increases constructibility, productivity and material performance.

Thanks for your attention

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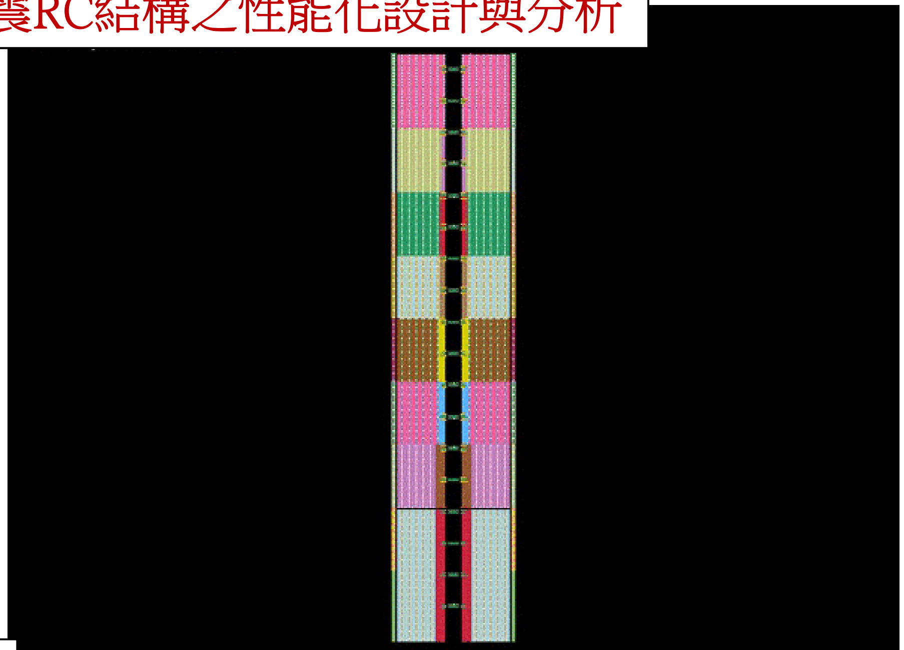
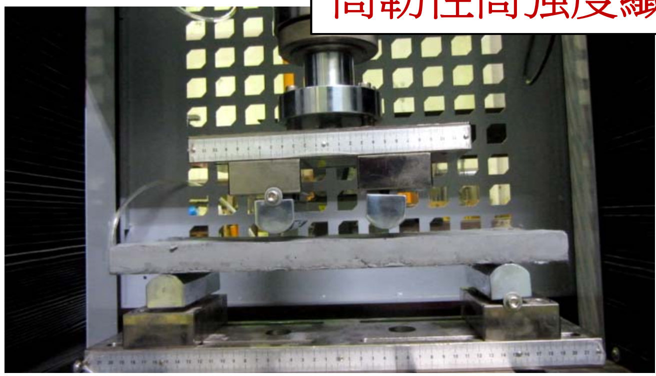
國立成功大學
土木工程學系

抗震RC結構之性能化設計與分析



高韌性高強度纖維混凝土



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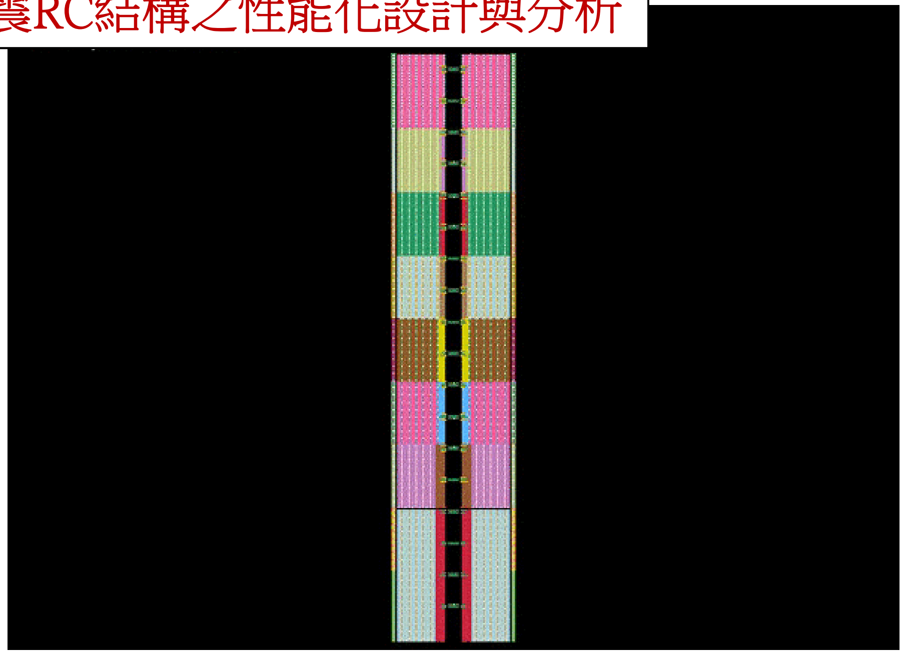

高韌性高強度纖維混凝土