State-of-the-art Studies on the Behavior of Coupling Beams

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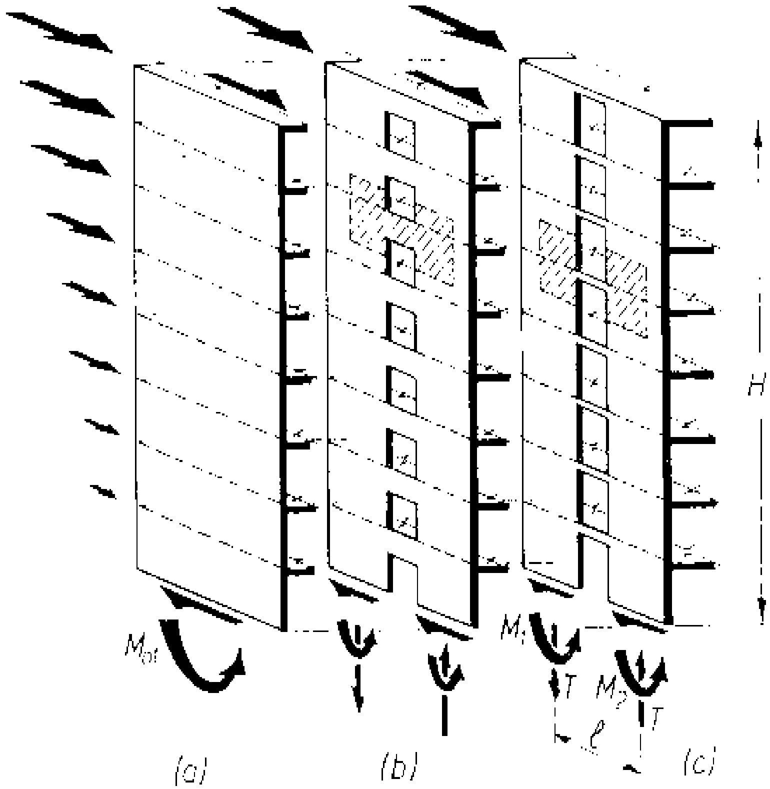
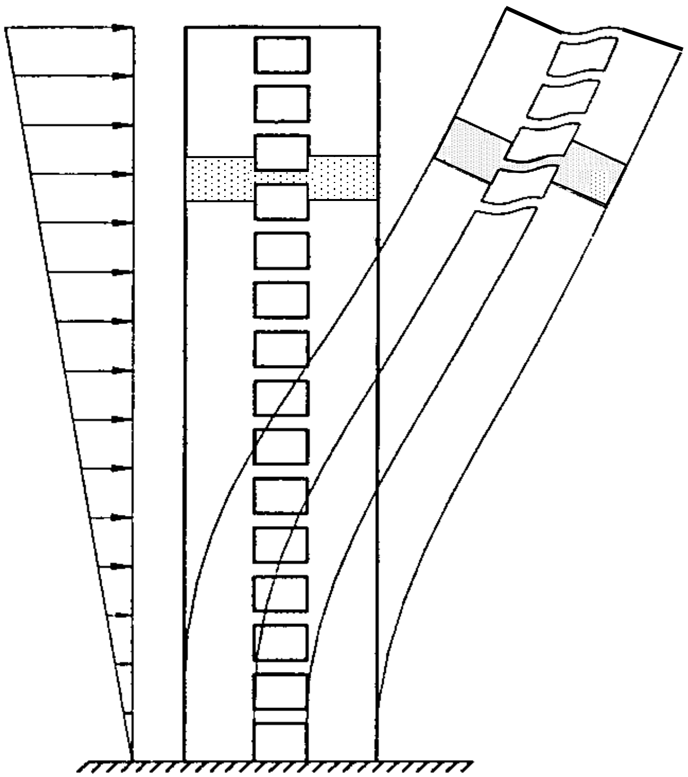
Outlines

- Background
- RC coupling beams
- Steel plate reinforced RC coupling beams
- Assembled RC coupling beams
- Replaceable steel coupling beams
- Conclusions

Background

- **Coupled shear walls(CSW)** are widely used for tall reinforced concrete (RC) buildings.
- **Overturning moment** is resisted jointly by the **bending action of the wall units** and the **couple formed** from axial forces developed in the wall units by **coupling beams(CBs).**





Background

Seismic design philosophy of CSWs

- **Strong coupling beams (CBs): shear walls may fail at their bases first. This could endanger the safety of the building and render the repair after earthquake very difficult.**

- **Weak coupling beams (CBs): coupling beams will yield before the walls yield. thereby protecting the walls from being damaged. Since the coupling beams are easier to repair than the walls, most earthquake resistant designs follow the strong wall-weak beam philosophy.**

- **Ideal failure sequence: Strong walls weak beams. Walls are the last to yield so as to maintain lateral stability of the structure and allow large deformation before collapse.**

- **Coupling beams (CBs) are required being "fuse" and possessing high rotation ductility. It is questionable whether deep RCCBs could possess such a great rotation ductility.**

Damage of deep RCCBs after strong EQ

Loma Prieta Earthquake (1989)

Wenchuan Earthquake（2008）

Kobe Earthquake (1995)

Chile Earthquake (2010)

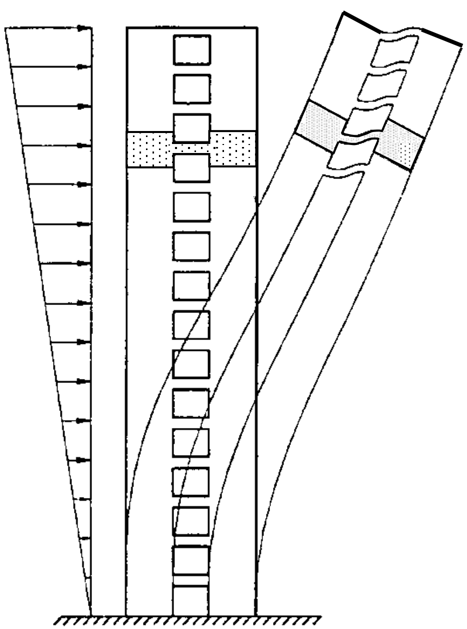
Background

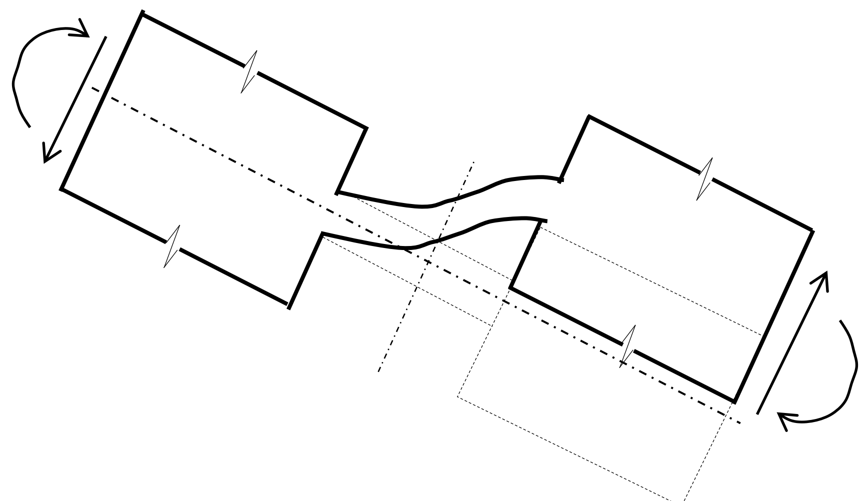
Questions:

What is the behavior of a RC coupling beam (RCCB)?

How shear force is resisted by a deep RCCB?

How to improve the seismic behavior of a deep RCCB?





Coupling beam

Outlines

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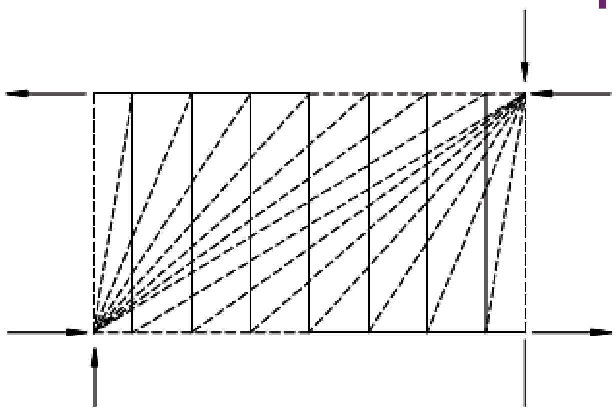
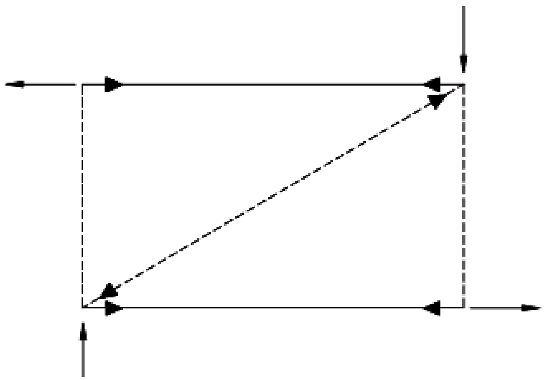
RC coupling beams(RCCBs)

Shear force transfer mechanisms in a RCCB

- **Deep RC coupling beams (RCCBs) (l/h≤2.5)**
  - Distributed truss model
  - Strut-tie model
  - Combination of the upper two models

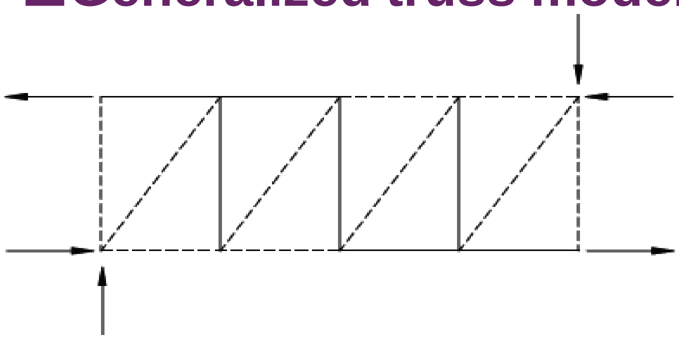


Distributed truss model



Strut-tie model

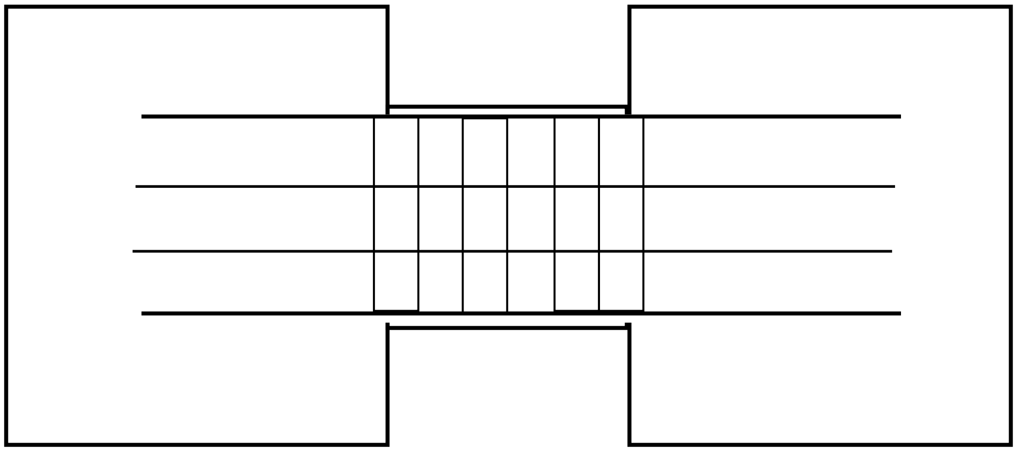
- **Slender RC coupling beams (l/h>2.5)**
  - Generalized truss model



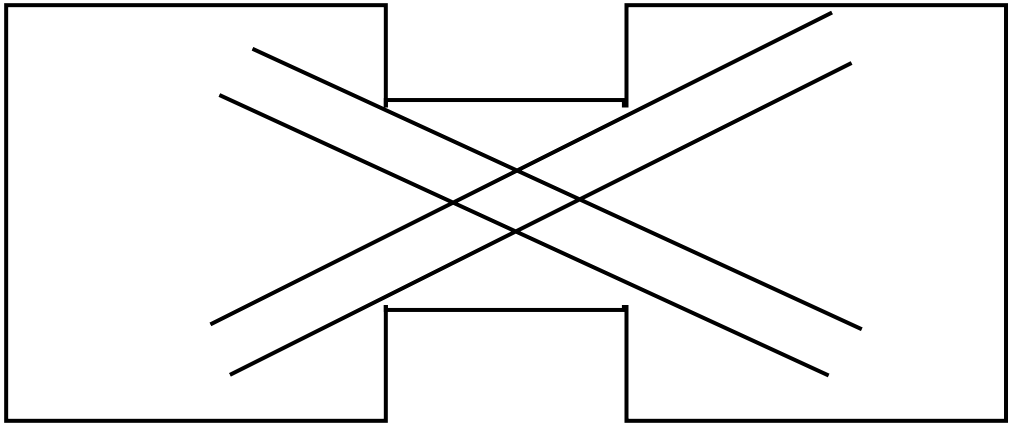
Generalized truss model

RC coupling beams(RCCBs)

Typical reinforced method of RCCBs



Conventionally reinforced



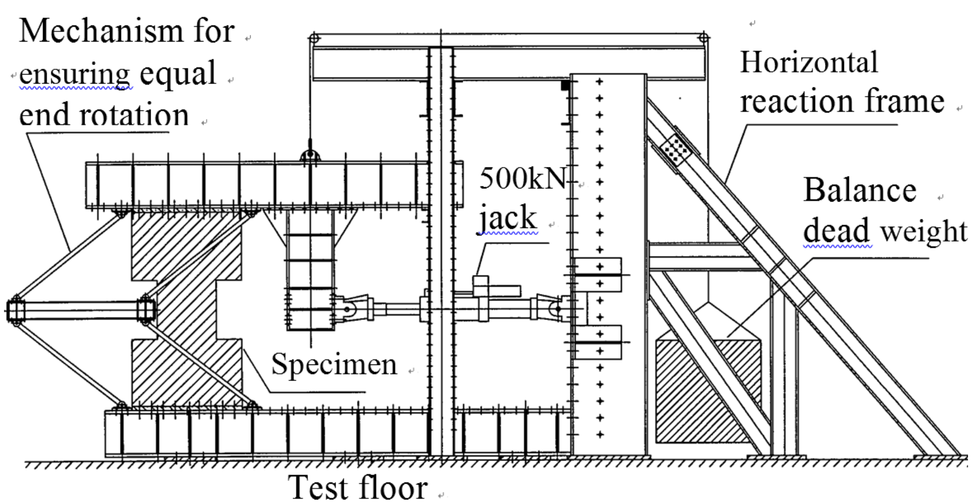
Diagonally reinforced bars

RC coupling beams(RCCBs)

Experimental study on deep RCCBs in HKU (Kwan and Zhao , 2002).

Parameters of the specimens

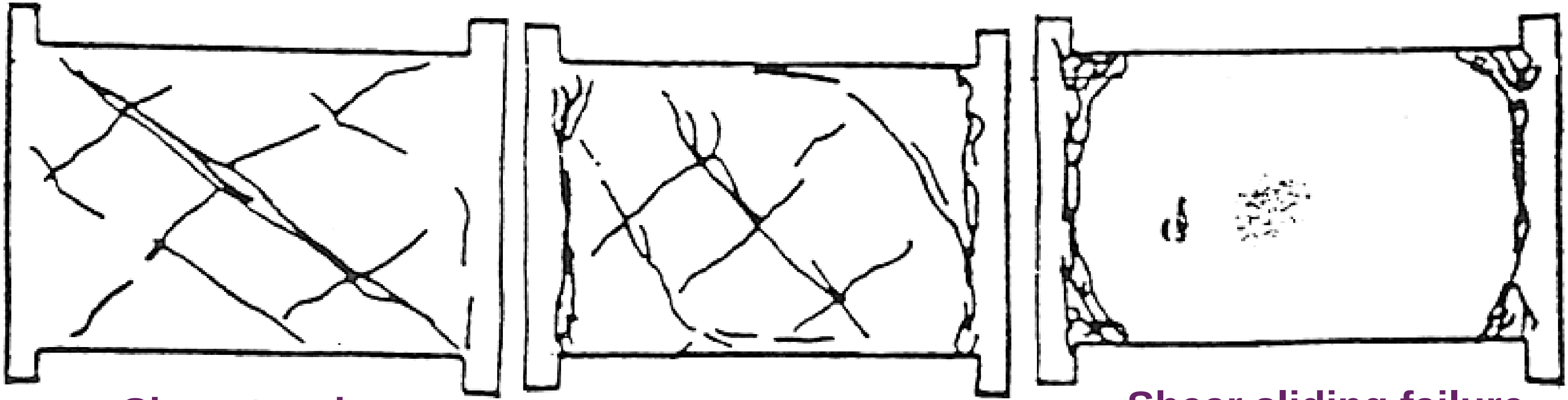
Specimen	h (mm)	L/h	f_{cu} (MPa)	f_c' (MPa)	Main longitudinal bars	ρ_s (%)	Additional longitudinal bars	Stirrups	ρ_{sv} (%)	Diagonal bars	Confining hoops
CCB1	600	1.17	58.5	42.3	3T12	0.485	4R8	R8@75	1.069	-	-
CCB11	600	1.17	50.6	34.9	2T8	0.158	4R8	R8@140	0.596	6T8	R6@60-120
CCB12	600	1.17	49.7	33.6	3T12	0.483	4R8	R8@50	1.670	-	-
CCB2	500	1.40	50.9	39.5	2T12+T8	0.486	4R8	R8@75	1.069	-	-
CCB3	400	1.75	50.3	38.9	2T12+T8	0.616	2R8	R8@75	1.069	-	-
CCB4	350	2.00	51.9	37.7	T12+2T8	0.563	2R8	R8@75	1.069	-	-



RC coupling beams(RCCBs)




MCB1(shear tension) **MCB2(flexural)** **MCB3(flexural)** **MCB4(flexural)**

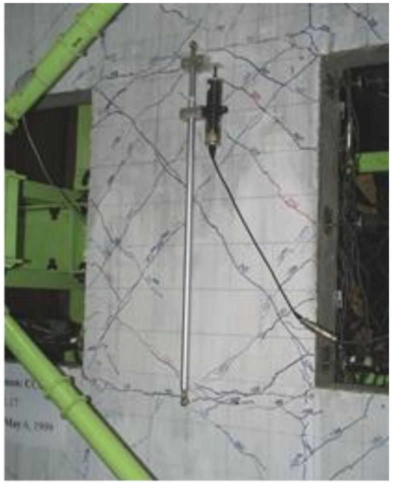


Shear tension **Flexural shear** **Shear sliding failure**

Typical failure mode of Deep RCCBs

Typical failure mode of Deep RCCBs

Peak load




Failure




CCB1 (shear tension)

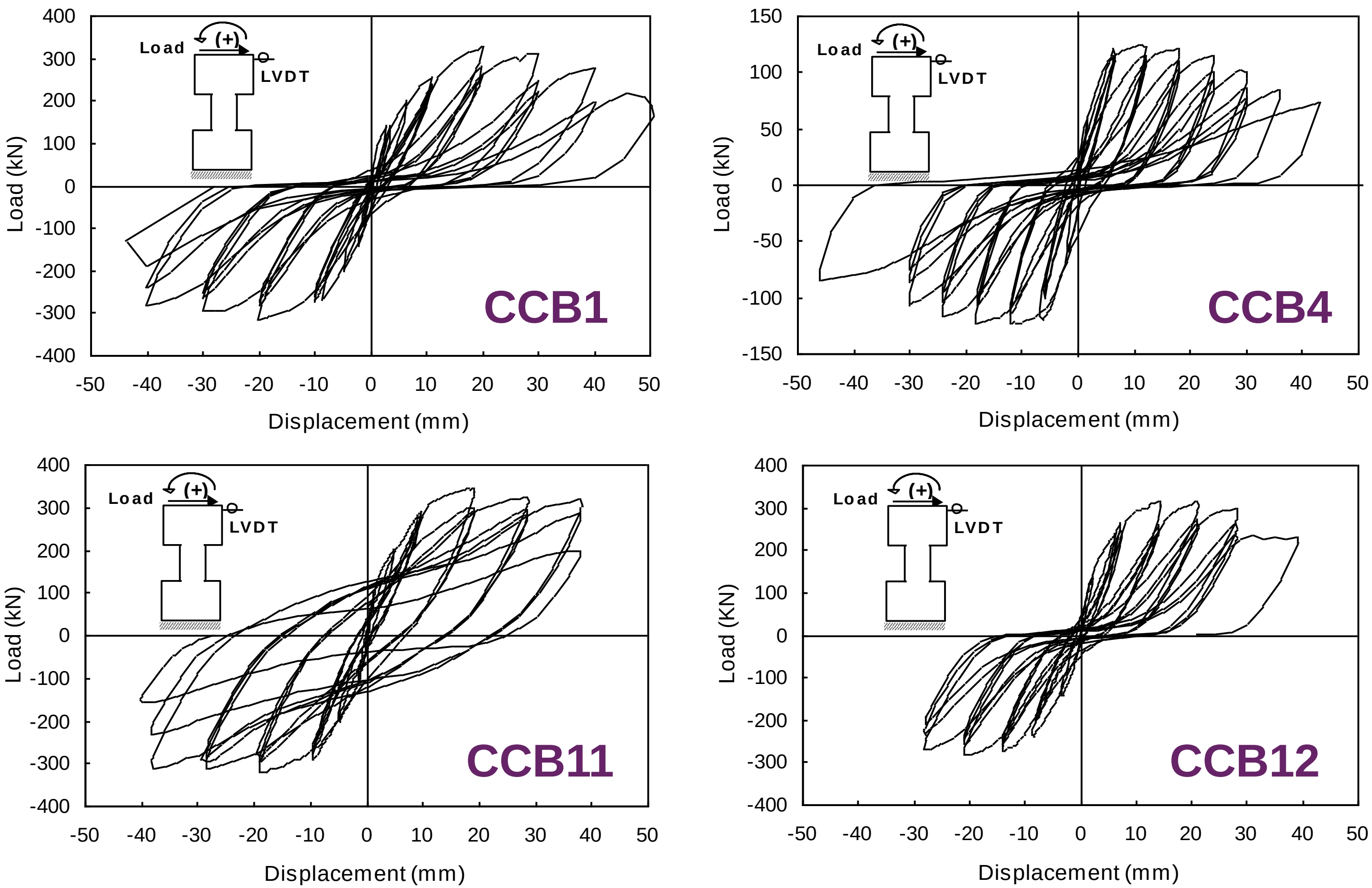
CCB11 (diag-bars buckling)

CCB12 (shear-sliding)

CCB4 (flexural)

RC coupling beams(RCCBs)

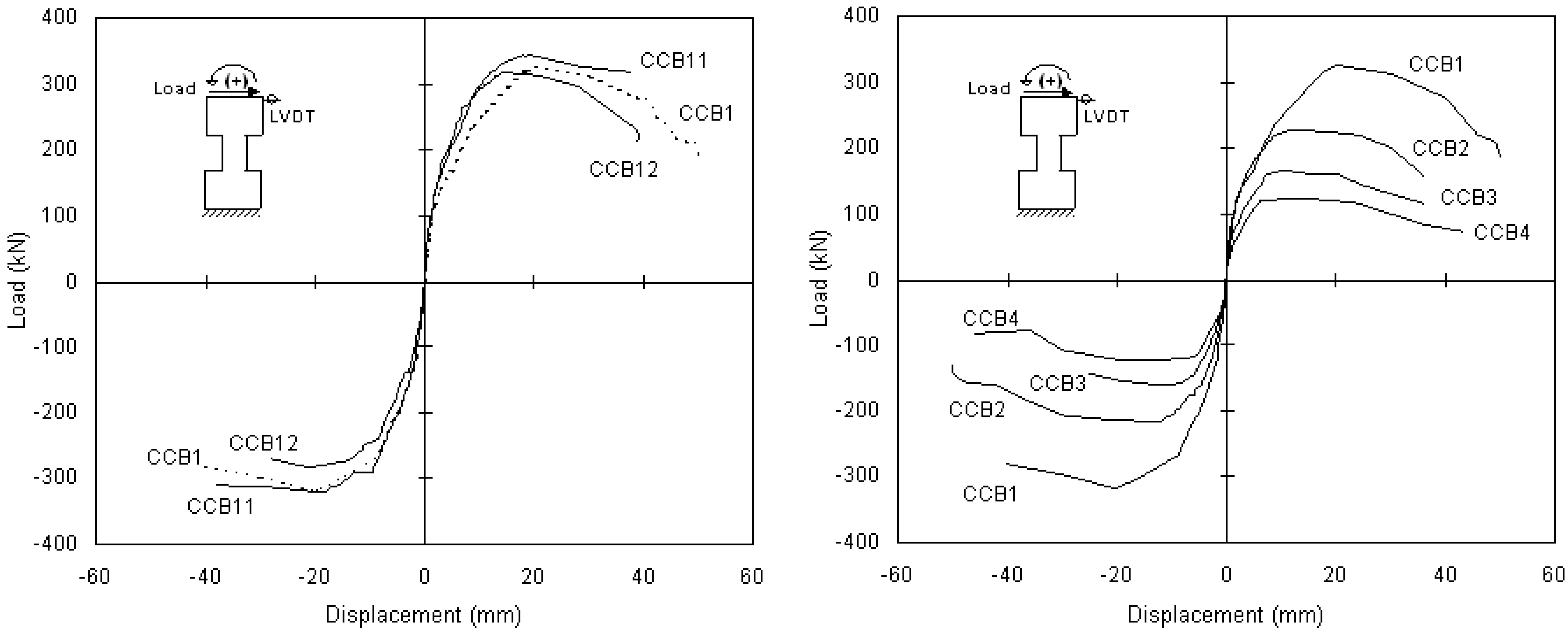
Load-displacement curves of the conventionally RCCBs exhibit substantial pinching, the curve of the diagonally reinforced RCCB exhibits no pinching and appears to be more stable.



RC coupling beams(RCCBs)

Envelopes of the cyclic load-displacement curves

Envelopes of the cyclic load-displacement curves prove that as the span/depth ratio of such conventionally reinforced RCCB decreased, the load resisting capacity increased but the ductility decreased. CCB1 series have different reinforcement layouts but had similar load resisting capacities and similar ductility.



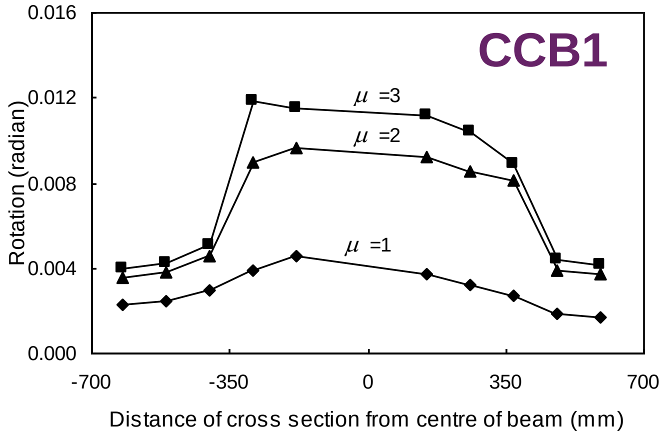
RC coupling beams(RCCBs)

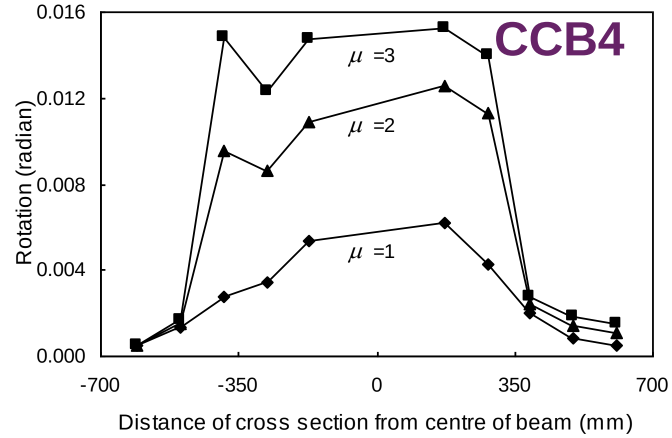
Test results of the specimens under monotonic load and reversed cyclic load

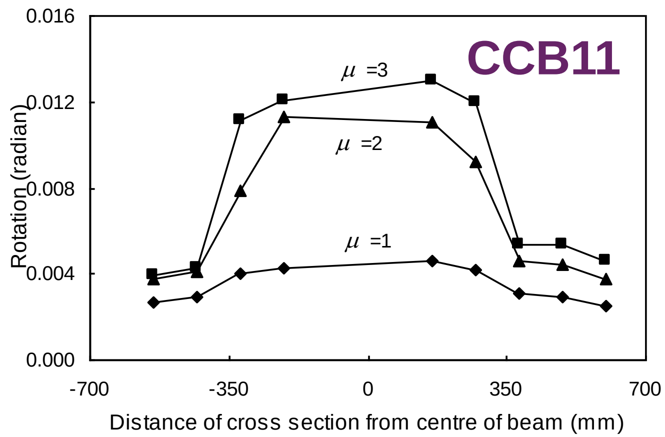
Specimen	h (mm)	L/h	f_c' (MPa)	ρ_s (%)	ρ_{sv} (%)	Applied load V (kN)				Deflection D (mm)				μ_D (= D_u/D_y)	Failure mode
						V_{sh}	V_y	V_p	V_u	D_{sh}	D_y	D_p	D_u		
MCB1	600	1.17	45.5	0.485	1.069	264	262	344	292	11.52	10.50	42.50	60.00	5.7	shear-tension
CCB1			42.3	0.485	1.069	257	260	327	278	10.96	10.00	20.00	40.00	4.0	shear-tension
MCB2	500	1.40	45.7	0.486	1.069	237	198	260	221	11.92	5.97	41.04	69.00	11.6	flexural
CCB2			39.5	0.486	1.069	184	190	227	193	5.85	6.00	12.00	30.00	5.0	shear-compression
MCB3	400	1.75	35.0	0.496	1.069	156	126	159	135	37.00	4.00	38.00	49.00	12.3	flexural
CCB3			38.9	0.616	1.069	154	135	165	140	10.00	5.00	10.00	25.00	5.0	shear-sliding
MCB4	350	2.00	37.4	0.563	1.069	133	100	140	119	46.60	4.16	48.20	70.00	16.8	flexural
CCB4			37.7	0.563	1.069	114	110	123	104	12.00	6.00	12.00	36.00	6.0	flexural

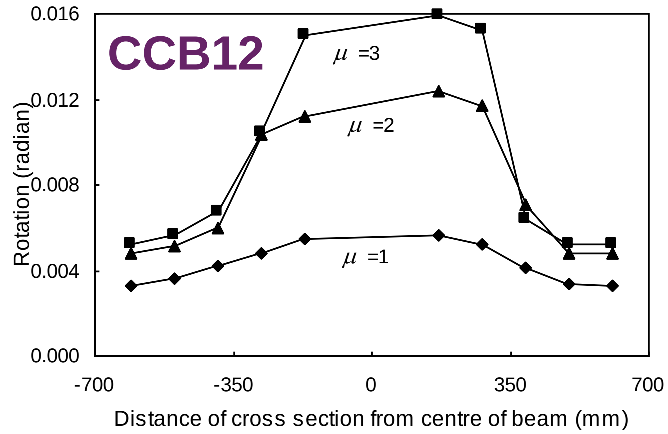
RC coupling beams(RCCBs)

Large local rotations took place at the beam-wall joints when the main or diagonal bars yielded. The additional displacements arising from the local rotations of the beam-wall joints contributed about 35 to 70 % to the total lateral displacements when μ=3.



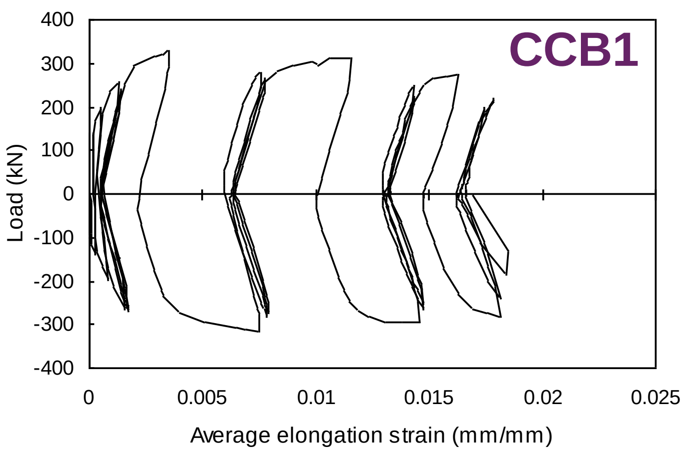


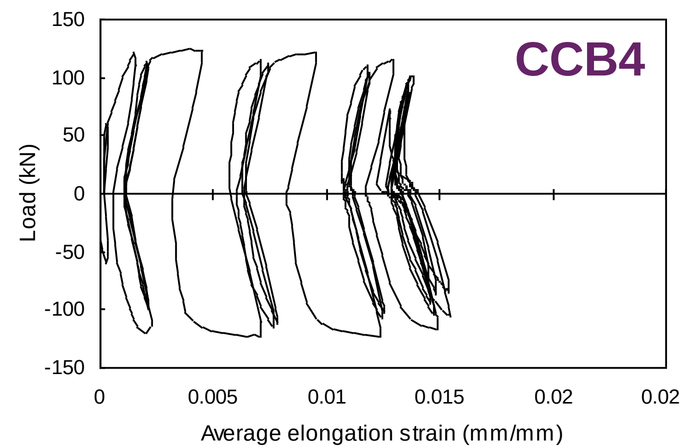


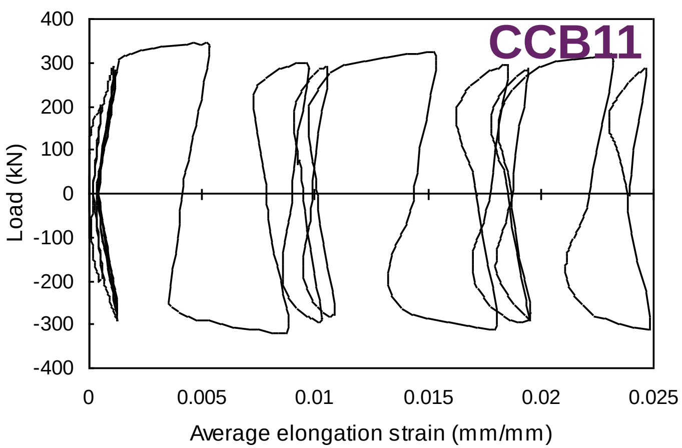


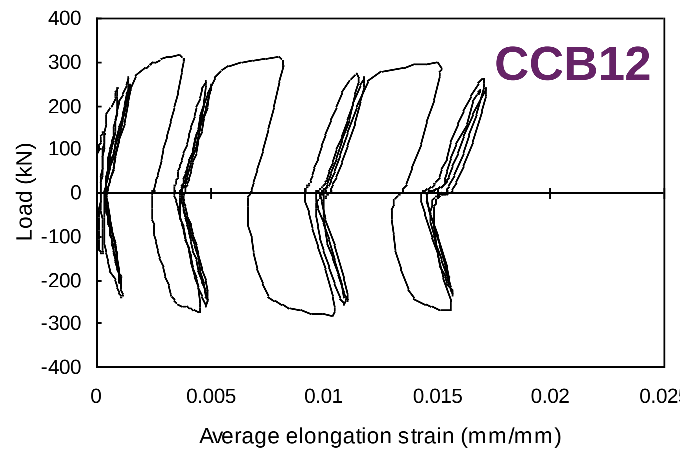
Axial elongation of a deep RCCB

- **Axial elongation increased quickly after yield load. The maximum average elongation strains recorded for the conventionally reinforced coupling beams were around 1.2 to 2.0% and that for the diagonally reinforced coupling beam was about 2.5 %.**









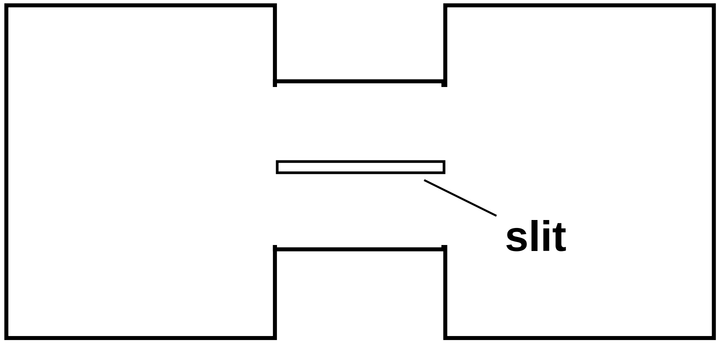
Behavior of deep RCCBs

Behavior of the deep RCCBs in shear wall system is different from frame beams in several aspects:

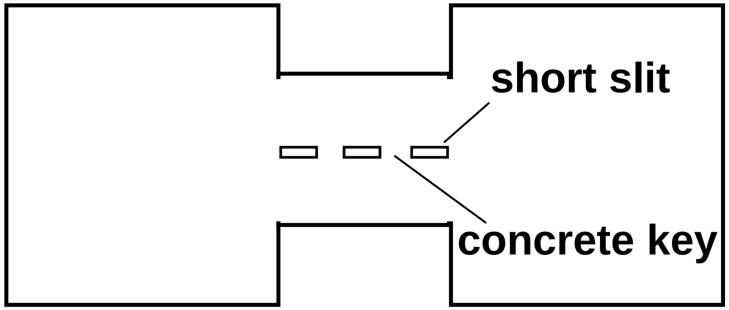
- The stress distribution in the flexural reinforcement in a coupling beam is consistent with the moment distribution before the appearance of shear crack, just like a frame beam. After shear cracking, both the top and the bottom reinforcing bars are subject to tension within most of the span, as a result, the contribution of the compression reinforcement to load resisting capacity and ductility will not exist and lead to specially failure modes .
- The local deformation at the beam-wall joint is much larger than deformation of the beam itself.
- Besides local failure such as anchorage failure and bearing failure, the failure modes of coupling beams can be classified as flexural or flexural shear failure, shear tension (diagonal splitting) failure and shear sliding failure respectively.

Behavior of deep RCCBs

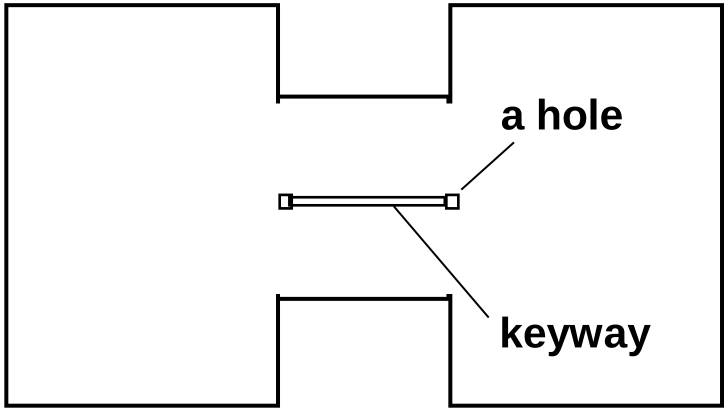
Different reinforced concrete coupling beams



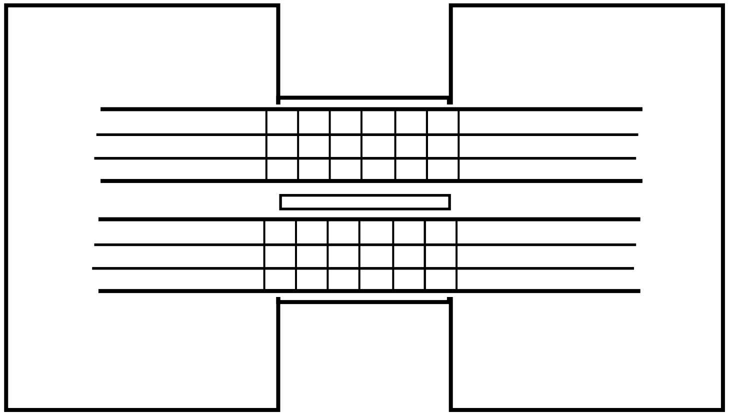
Full slit (Li and Li, 1984)



Multi-slit (Cheng et al., 1993)



Partial slit (Ding et al., 1997)



Reinforcement layout in slit coupling beam

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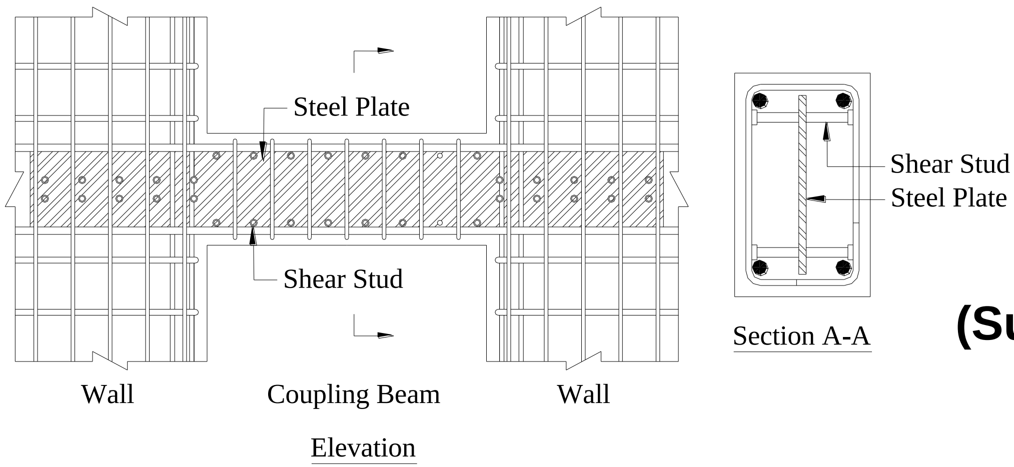
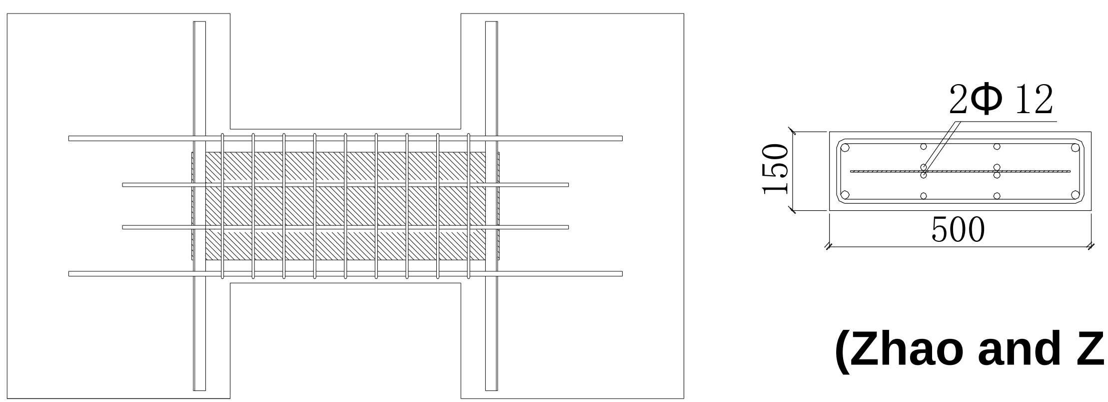
Steel plate reinforced RC coupling beam

Steel plate reinforced RC coupling beams (RCCBs) is an alternative way of RC coupling beams. Steel plate in a RC deep coupling beam can easily improve the shear resisting capacity of the RC coupling beams.



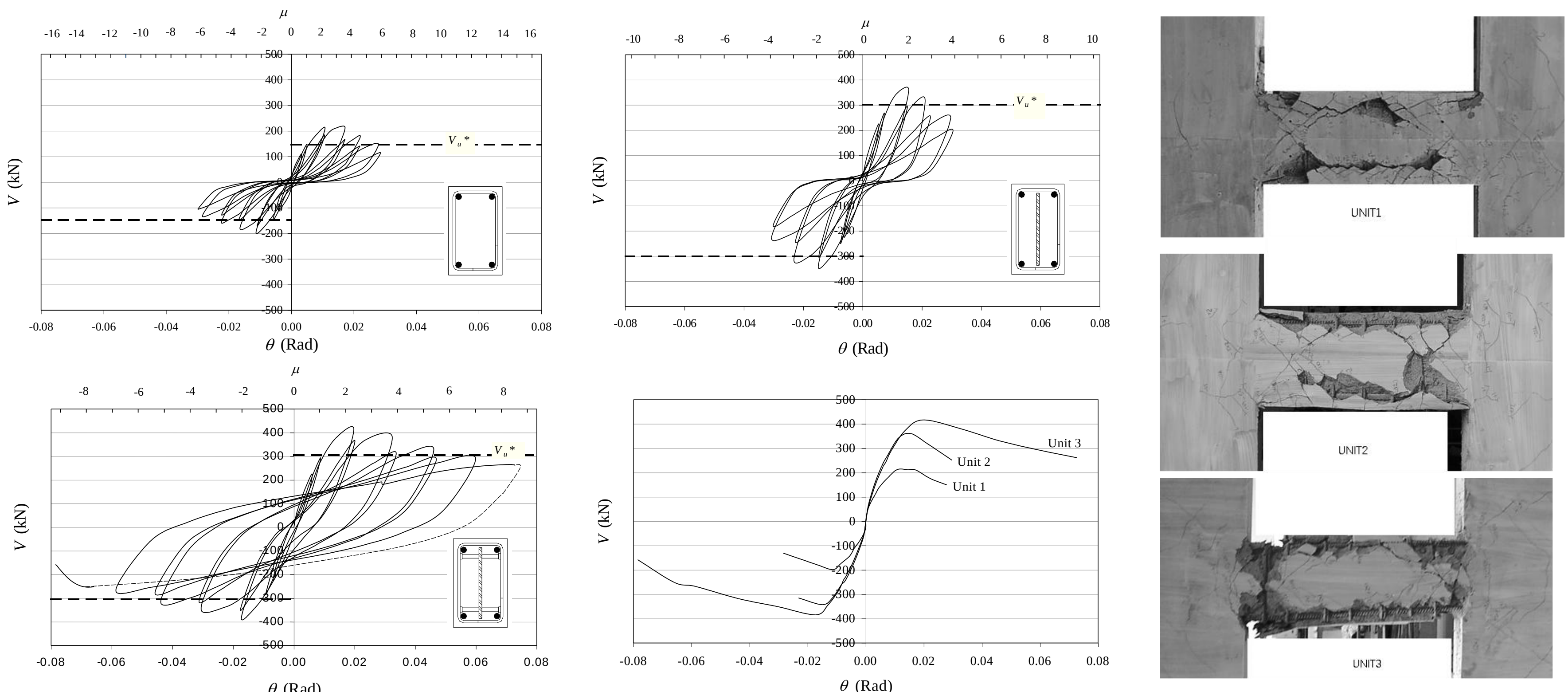
(Su and Lam, 2002)



(Zhao and Zhang, 2005)

Steel plate reinforced RC coupling beam

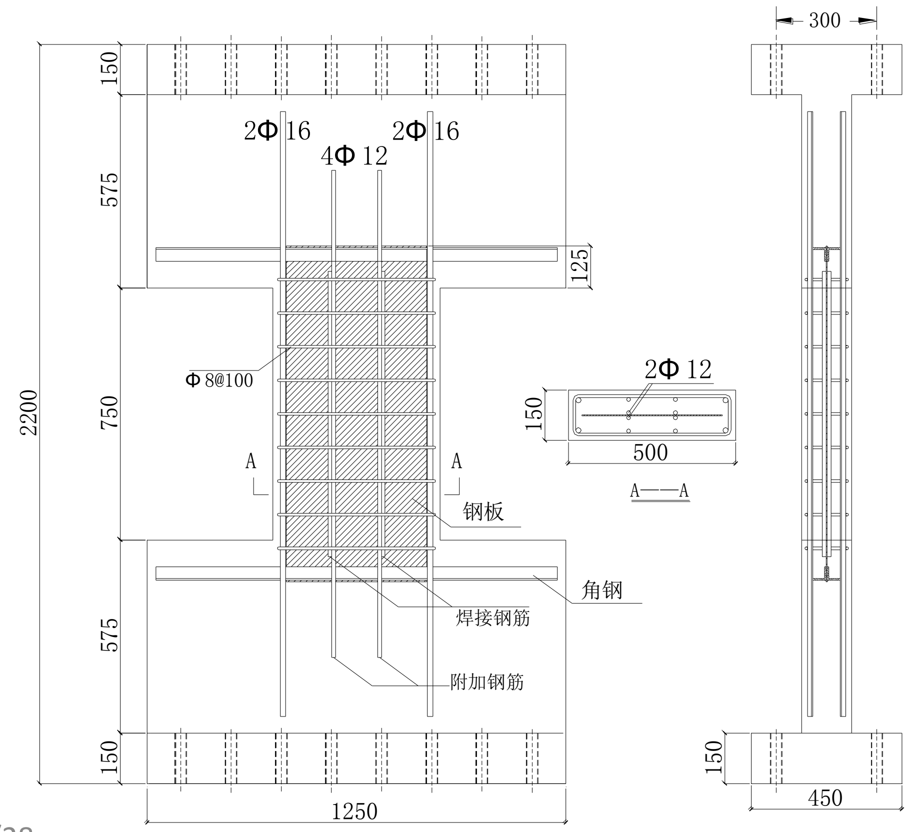
Su and Lam (2002) studied the feasibility of a new coupling beam design making use of the composite action between an embedded steel plate and its surrounding reinforced concrete via shear studs. It was proven that the use of embedded steel plates could increase the strength and stiffness of coupling beams while maintaining small sectional sizes, but shear studs are necessary to ensure desirable inelastic beam behaviours.

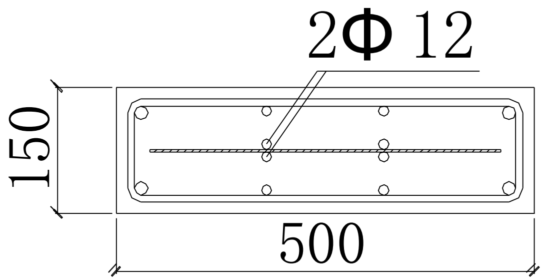


(Su and Lam 2002)

Steel plate reinforced RC coupling beam

- One **steel plate was embedded** and extended into wall blocks at both ends. **A steel angle was welded at each end** of the steel plate to ensure its anchorage in the wall blocks.
- **Two deformed bars** were welded on **each side of the plate**.





Steel plate reinforced RC coupling beam

Six coupling beams were tested. The thickness and clear span of the specimens were fixed at 150 mm and 750 mm respectively.

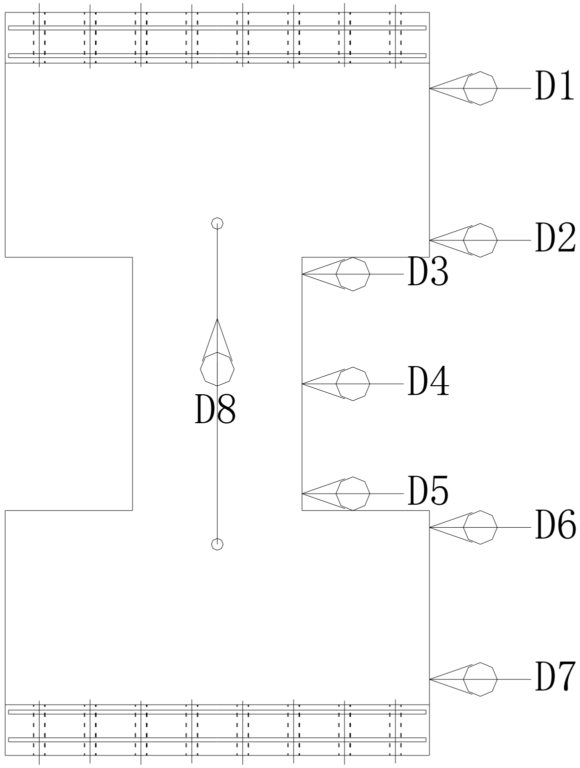
Variables: span/depth ratio; steel plate section; steel ratio

Details of the specimens

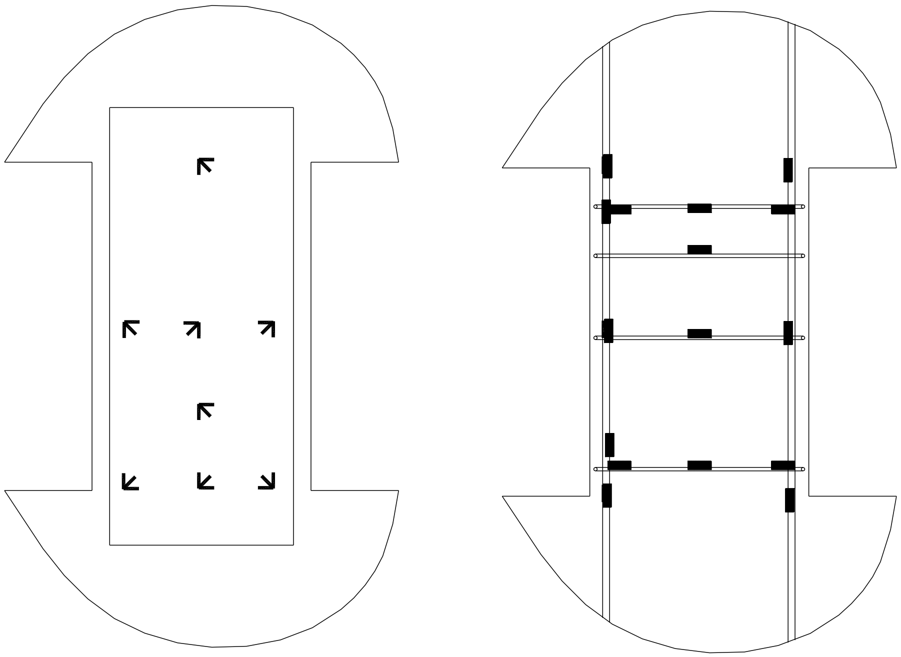
specimen	h (mm)	l/h	A_s	ρ_s (%)	$A_{s,a}$	A_{sv}	ρ_{sv} (%)	D (mm)	t (mm)	ρ_p (%)
CB15-1	500	1.5	2Φ16	0.57	4Φ12	2Φ8@100	0.57	220	6	1.87
CB15-2	500	1.5	2Φ16	0.57	4Φ12	2Φ8@100	0.57	420	3	1.79
CB15-3	500	1.5	2Φ16	0.57	4Φ12	2Φ8@100	0.57	350	6	2.98
CB15-4	500	1.5	2Φ16	0.57	4Φ12	2Φ8@100	0.57	200	10	2.84
CB25-1	300	2.5	4Φ16	1.98	—	2Φ8@120	0.56	220	3	1.63
CB25-2	300	2.5	4Φ16	1.98	—	2Φ8@120	0.56	220	6	3.26

Steel plate reinforced RC coupling beam

- **Displacements** were measured using linear variable displacement transducers (LVDTs).
- **Strains** of longitudinal bas, stirrups and steel plates were obtain by using strain gauges.



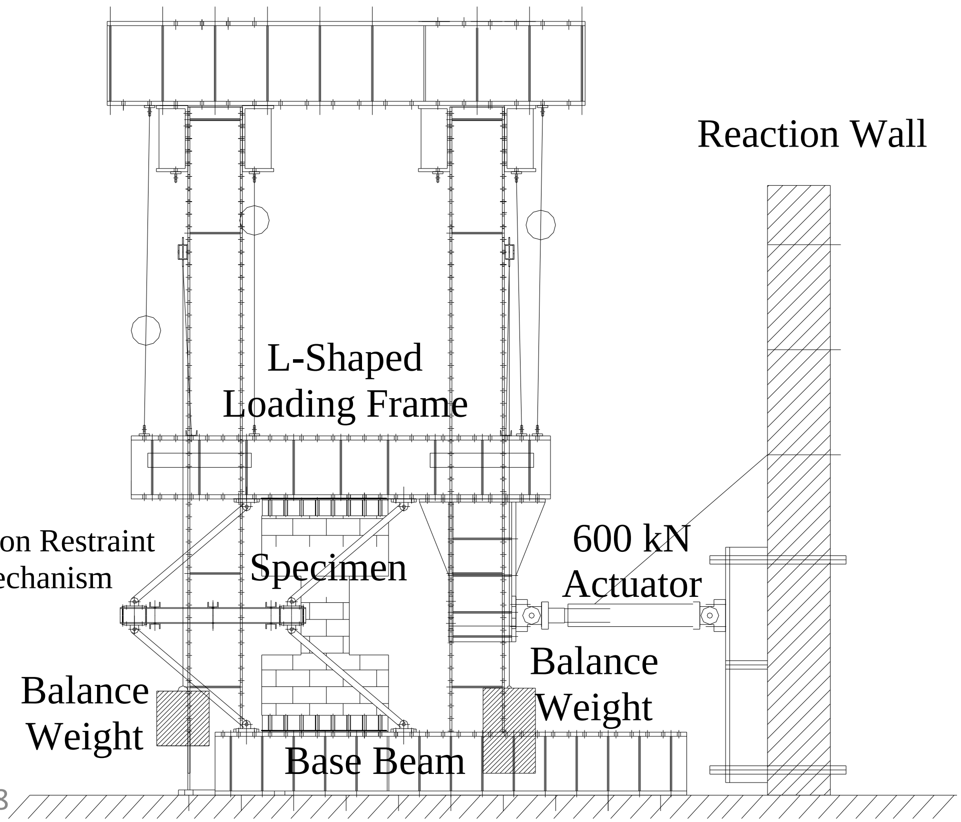
Deflection monitoring



Strain monitoring

Steel plate reinforced RC coupling beam

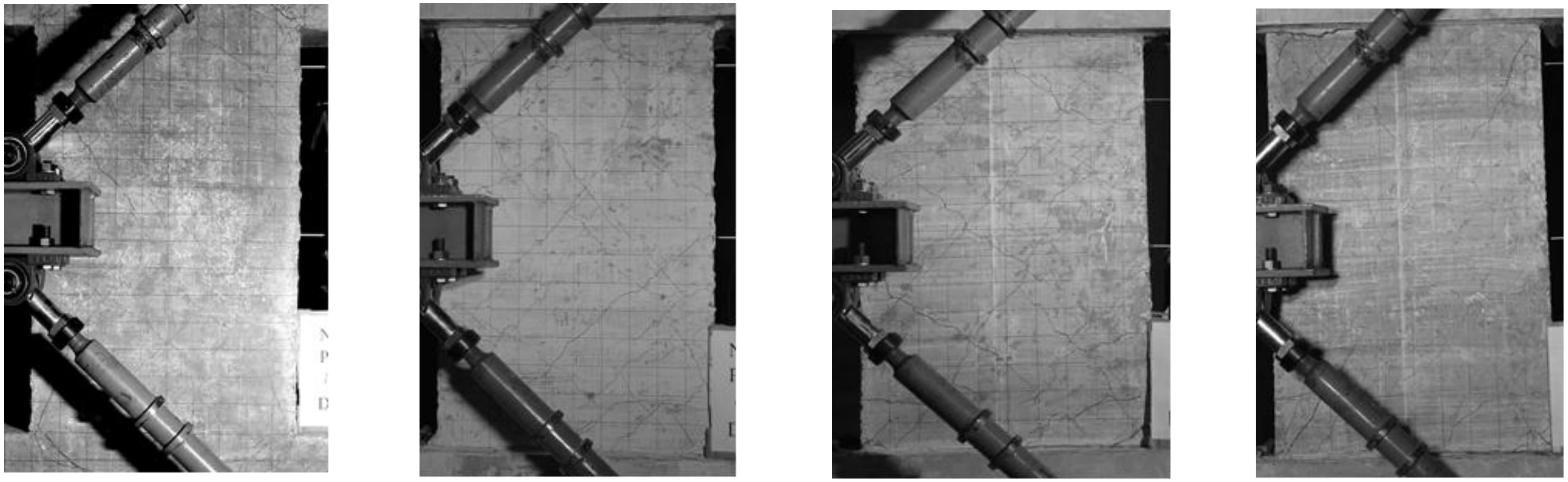
The test setup was the same as RCCBs test. The specimen was erected with beam longitudinal axis in the vertical direction. Shear load was applied to the specimen through the L-shaped loading frame. The action line of the applied load passed through the mid-span of the beam specimen. A rotation restraint mechanism was installed.



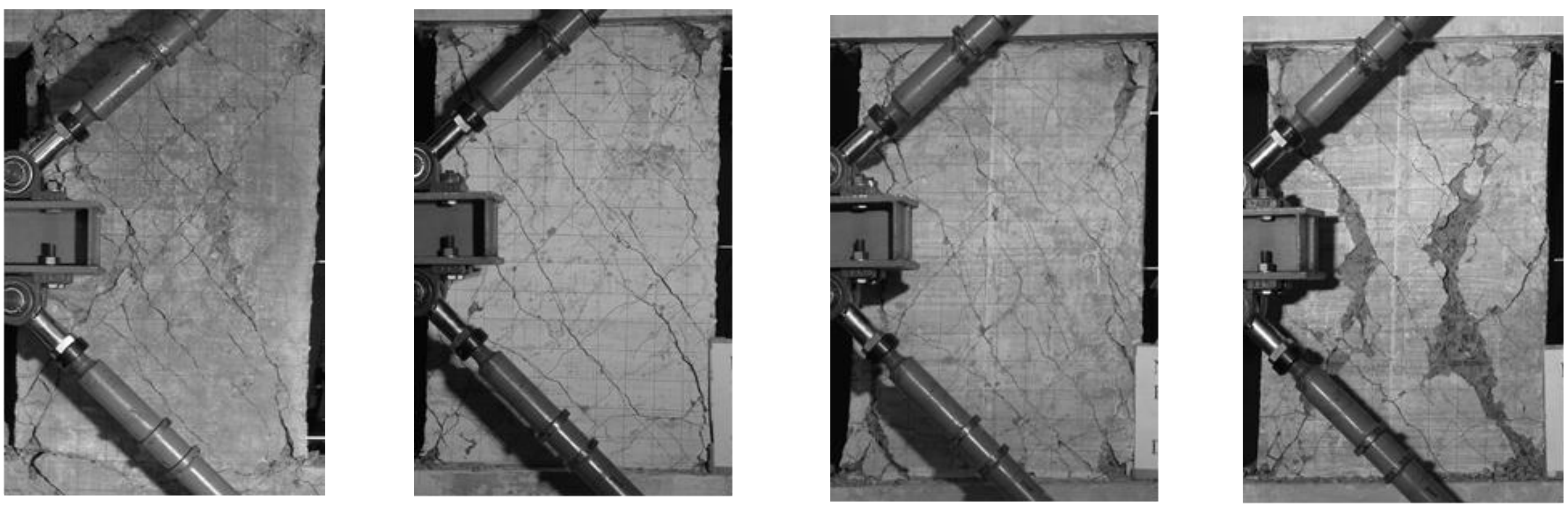
Test setup

Steel plate reinforced RC coupling beam

Peak load



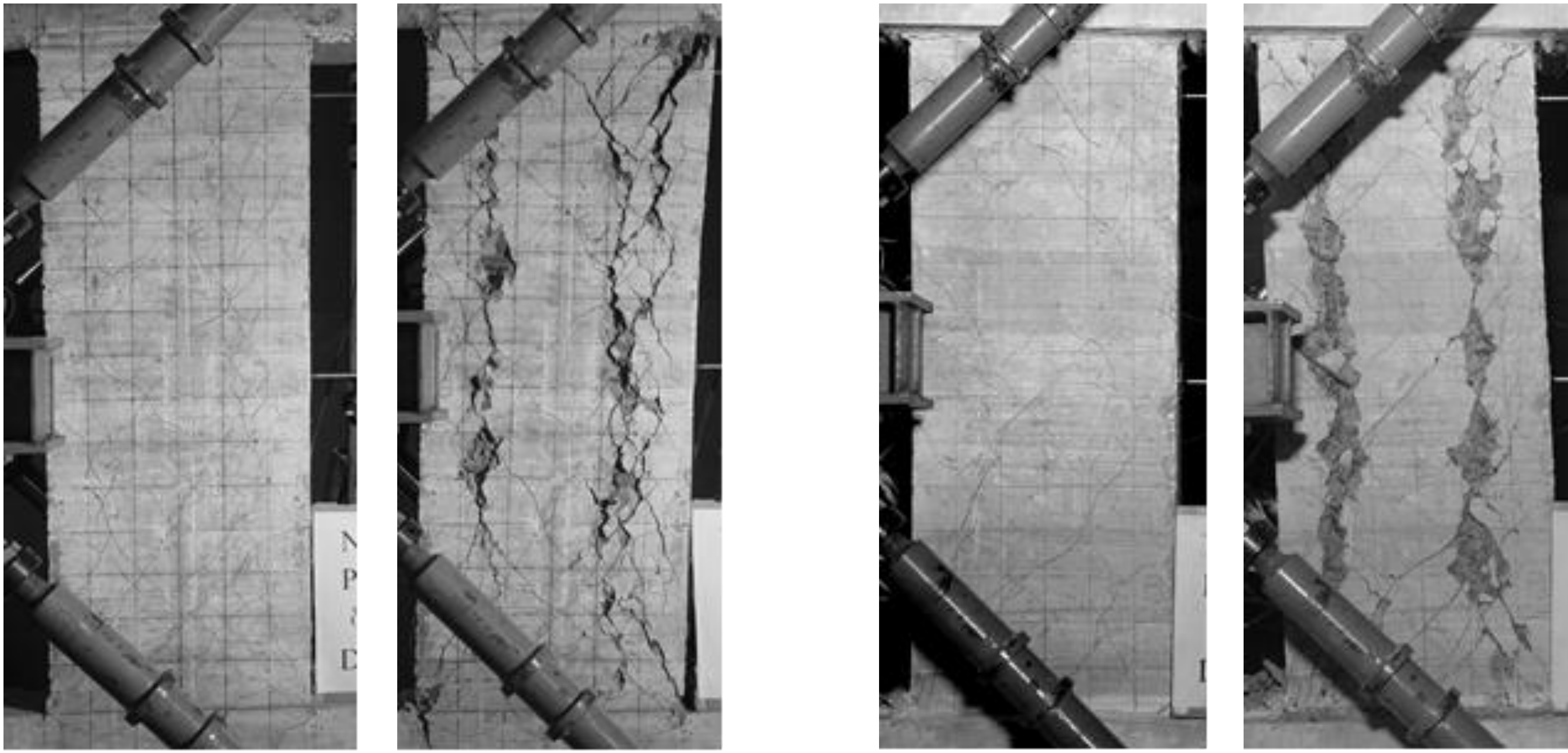
Failure



CB15-1 **CB15-2** **CB15-3** **CB15-4**

Crack pattern and failure modes

Steel plate reinforced RC coupling beam



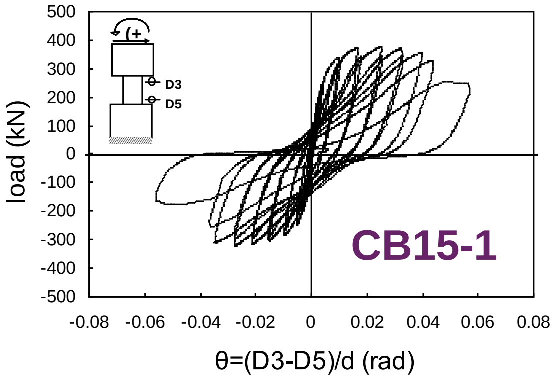
Peak load Failure Peak load Failure

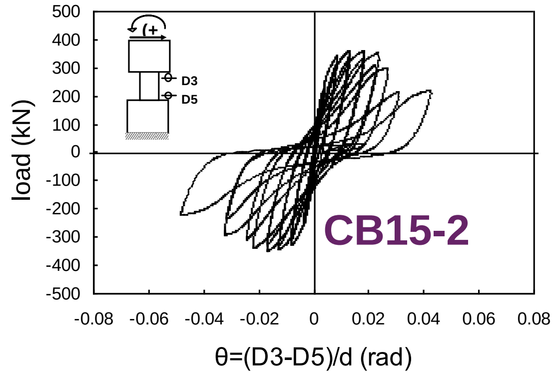
CB25-1 CB25-2

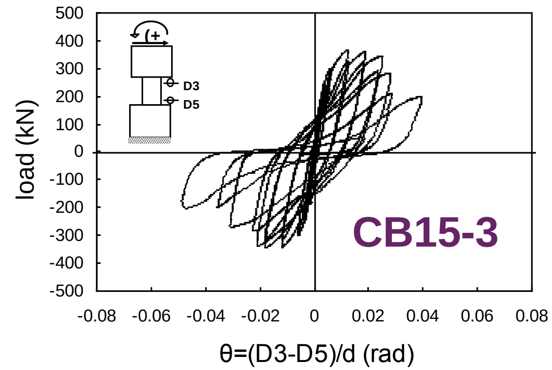
Crack pattern and failure modes

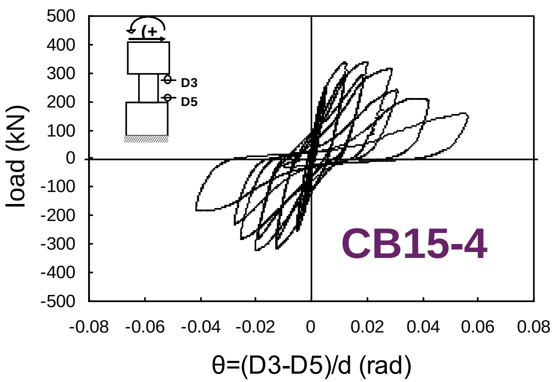
Steel plate reinforced RC coupling beam

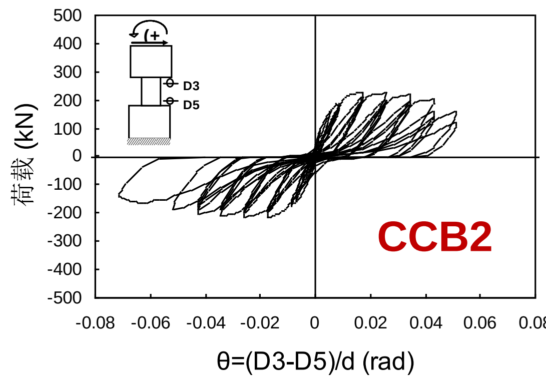
Compare the hysteretic curves of CB15 series with that of CCB2, the introduction of steel plate in a coupling beam can not only increase the strength and energy dissipation capacity, but increase the stiffness of the beam under reversed cycle loading and greatly reduce the pinching effect of the load-rotation curve.





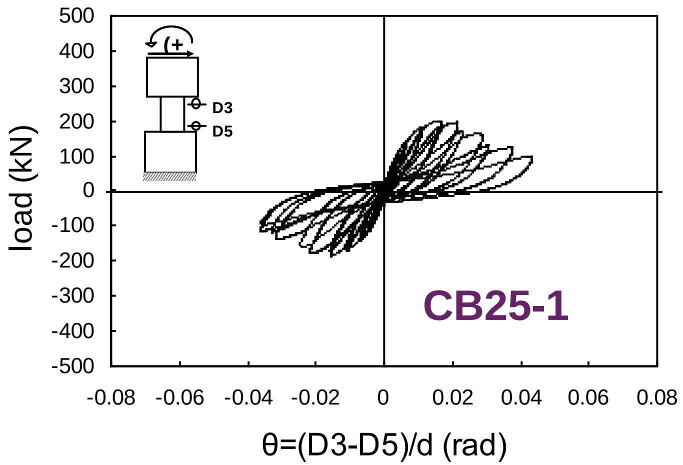


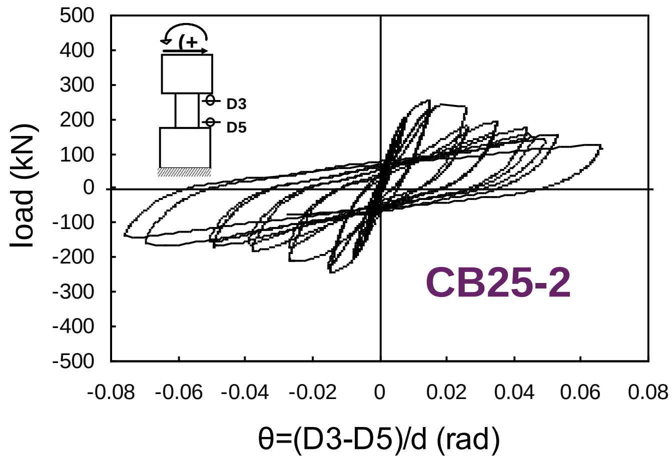


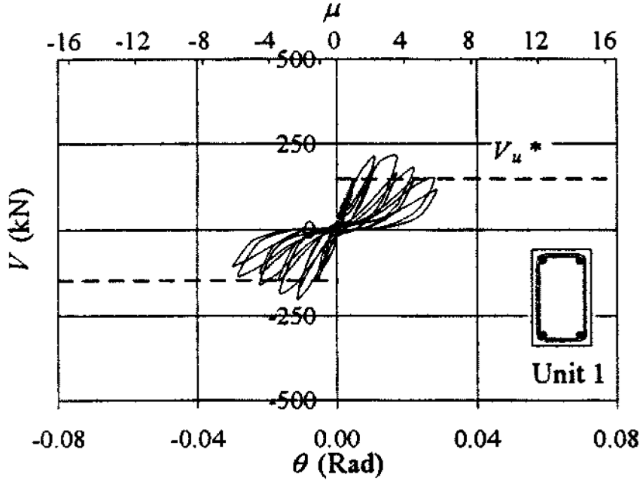


Steel plate reinforced RC coupling beam

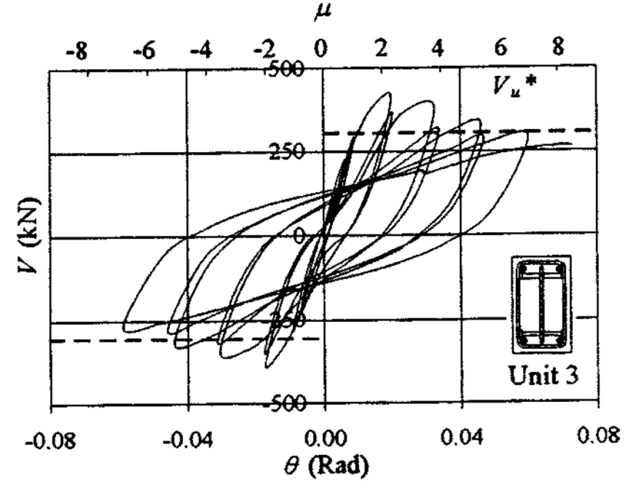
For CB25 series and Lam’s specimens, there is similar phenomenon.







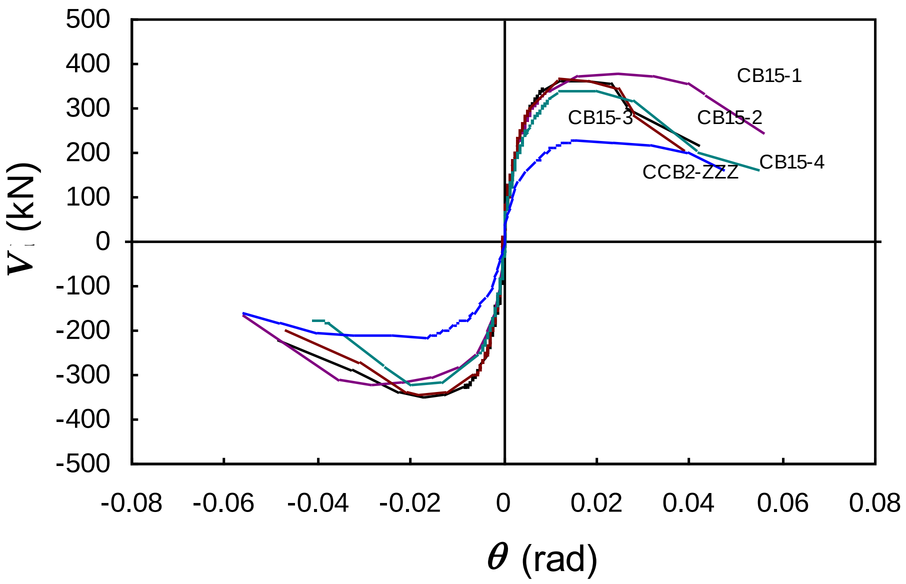
Unit 1-Lam(2005)



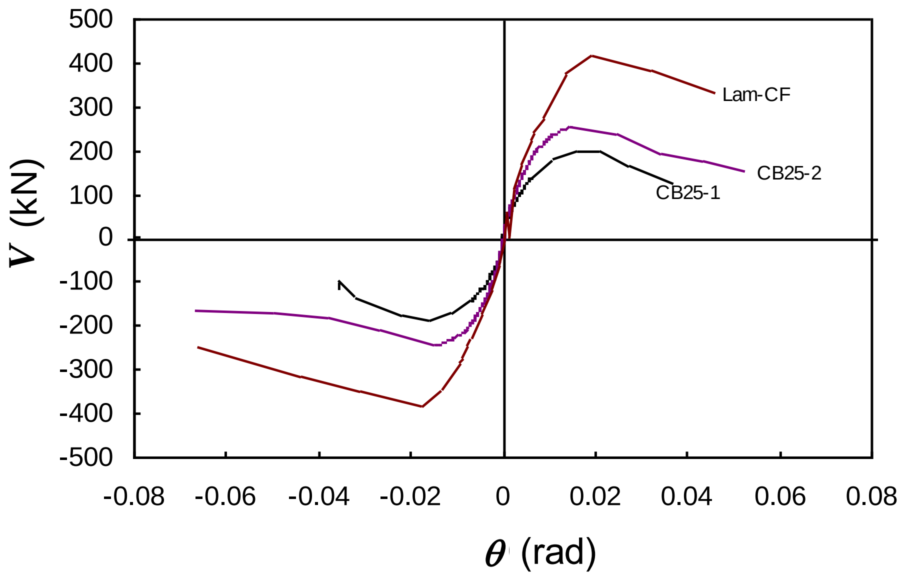
Unit 3-Lam(2005)

Steel plate reinforced RC coupling beam

Compare the skeleton curves of CB15 series with that of CCB2-ZZZ(l/h=1.4) and CB25 series and UNit3-Lam, the introduction of steel plate in a coupling beam can not only increase the strength and energy dissipation capacity, but increase the stiffness of the beam under reversed cycle loading and greatly reduce the pinching effect of the load-rotation curve.



CB15 series & CCB2-ZZZ(l/h=1.4)



CB25 series & UNit3-Lam

Steel plate reinforced RC coupling beam

- **CB15-3 and CB15-4 have the highest and lowest yield strength respectively, which may result from the depth of the steel plate encased in the specimen.**
- **CB15-1 and CB15-2 have similar steel plate reinforcement ratio and hence have similar load capacity.**
- **CB15-4 have a large steel plate while has the lowest load capacity due to anchorage failure of steel plate in the wall piers. So enough anchorage of steel plate must be provided.**

Load and deflection characteristic parameters of the specimens

Specimen	Vy (kN)	Vu (kN)	Ratation (10^{-3}rad)			Ductility ratio		Failure mode
			θ_y(rad)	θ_u(rad)	Θ_{u1}(rad)	θ_u/θ_y	θ_{u1}/θ_y	
CB15-1	241	377	3.66	25.00	44.52	6.83	12.16	Flexural Shear
CB15-2	252	363	3.88	18.12	25.96	4.67	6.69	Flexural Shear
CB15-3	292	367	5.43	11.94	26.44	2.20	4.86	Flexural
CB15-4	223	340	3.76	12.25	31.38	3.26	8.35	Flexural Shear
CB25-1	156	198	7.71	16.23	26.81	2.10	3.48	Shear
CB25-2	191	254	6.56	14.91	29.54	2.27	4.50	Flexural Shear

Steel plate reinforced RC coupling beam

- **CB25-2 has a thicker steel plate, so its load resisting capacity and energy dissipation capacity are much higher than that of specimen CB25-1. Its yield load and peak load is increased by more than 20%. During post peak stage, yielding of the longitudinal bars and stirrups led to decreasing of load resisting capacity.**
- **Specimen with large plate section area has a stable load-deflection hysteretic curve. This proves that the minimum steel plate reinforcement ratio should be met to obtain desired performance.**

Load and deflection characteristic parameters of the specimens

Specimen	Vy (kN)	Vu (kN)	Ratation (10^{-3}rad)			Ductility ratio		Failure mode
			θ_y(rad)	θ_u(rad)	Θ_{u1}(rad)	θ_u/θ_y	θ_{u1}/θ_y	
CB15-1	241	377	3.66	25.00	44.52	6.83	12.16	Flexural Shear
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CB25-2	191	254	6.56	14.91	29.54	2.27	4.50	Flexural Shear

Steel plate reinforced RC coupling beam

Shear resisting capacity of the steel plate reinforced RCCB affected by steel plate reinforcement ratio, depth, thickness, depth/thickness ratio, using FE method.

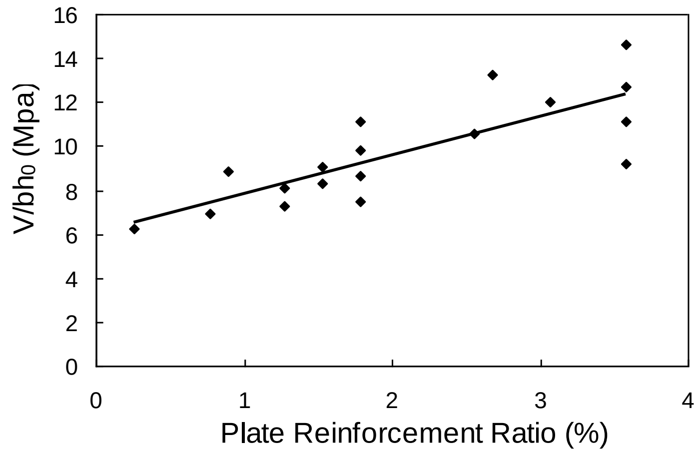


Plate Reinforcement Ratio

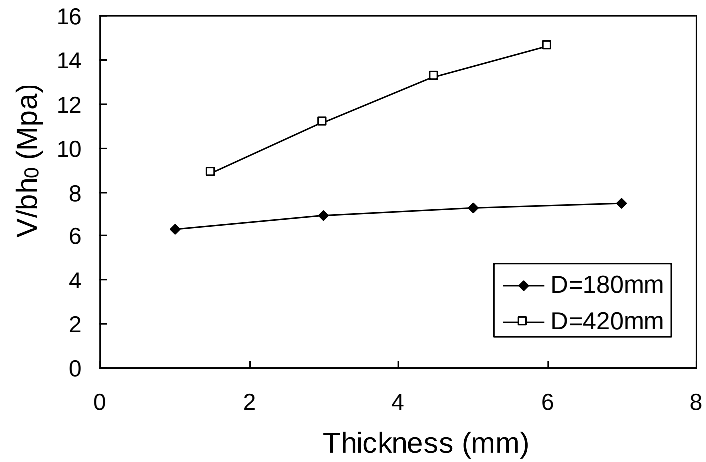
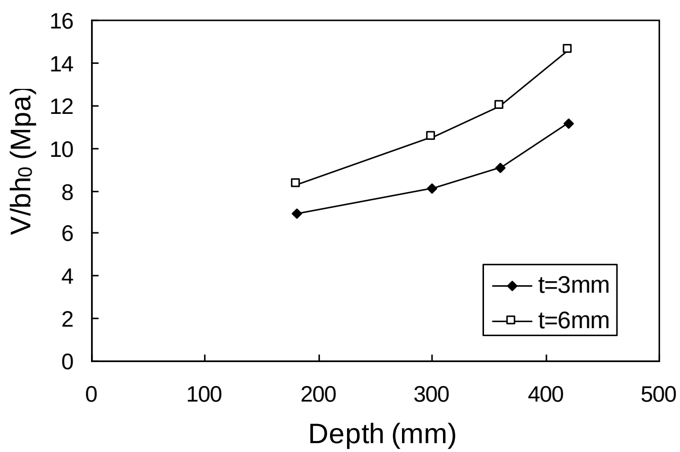
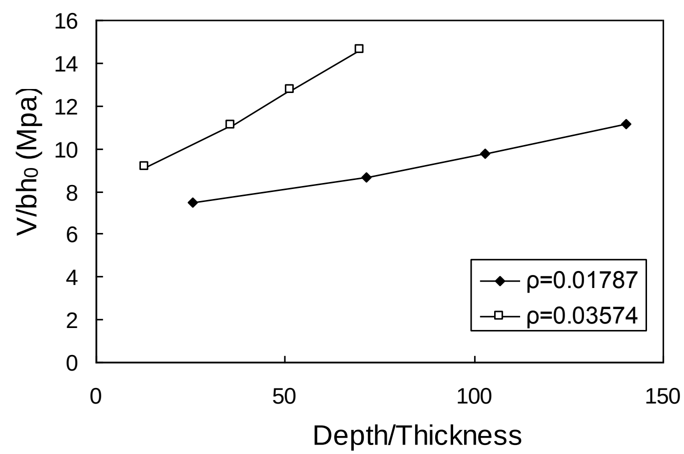


Plate Thickness



Depth



Depth/Thickness Ratio

Outlines

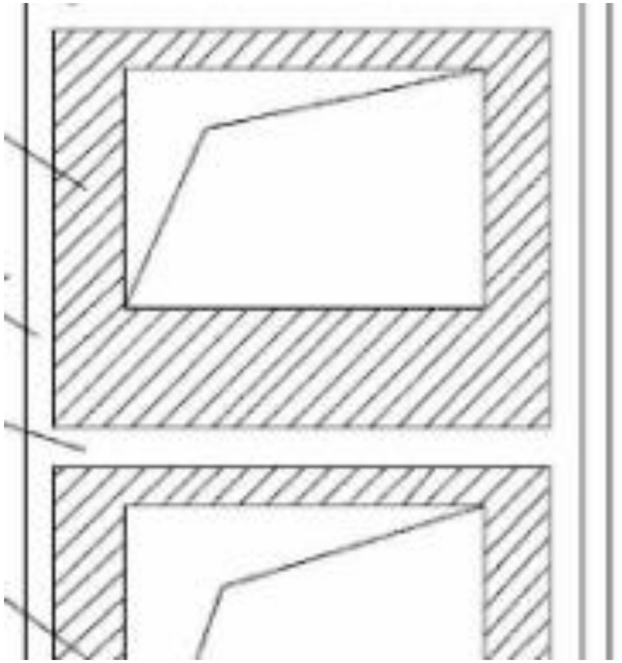
- Background
- RC coupling beams
- Steel plate reinforced RC coupling beams
- Assembled RC coupling beams
- Replaceable steel coupling beams
- Conclusions

Assembled RC coupling beam

- Advantage of Precast structures (PC VS Cast-in-site RC):
  - ✓ **Higher construction quality**
  - ✓ **Possible increased construction speed**
  - ✓ **Improved durability**
  - ✓ **Reduction in situ labor or waste**
- Seismic design are required for precast structures.
- Precast residential buildings in China are mostly designed as precast shear wall structures. Precast wall systems can be classified into two types:
  - ✓ **Jointed system: "dry" or "ductile" connections (damages concentrate on connections)**
  - ✓ **Equivalent monolithic system: "wet" or "strong" (same as cast-in-situ structures)**

Assembled RC coupling beam

- The **assembled RC coupling beam** includes the **top and the bottom precast RC segment** combined together by the center cast-in-place RC slab boundary.
- **Seismic behavior** of the assembled RC coupling beam under simulated cyclic loading have been studied carefully and some detailing methods have been proposed. Some studies conducted in Tsinghua University are briefly introduced. (Qian and Zhao,2013)



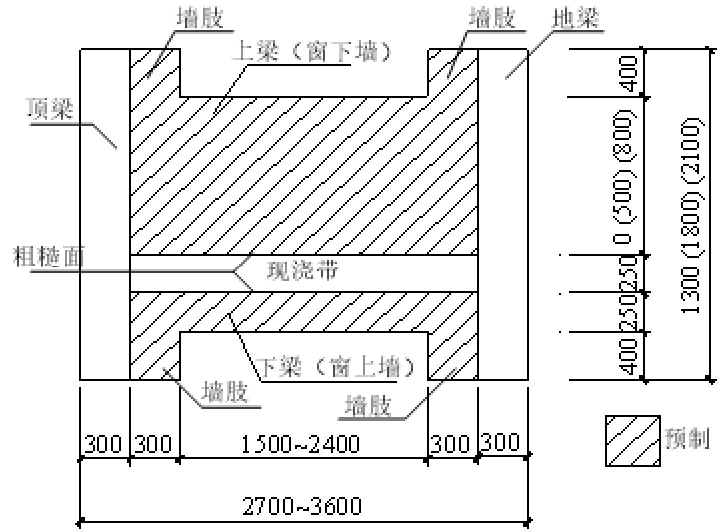
assembled RC coupling beam

Assembled RC coupling beam

Test of 9 assembled RCCB specimens with different connection methods between the upper and the lower part has been carried out in Tsinghua Univerty.

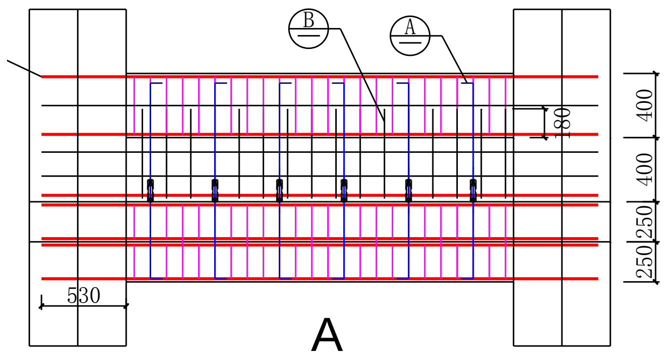
Details of the specimens

Group	Specimen	*L* (mm)	*h* (mm)	L/h	Connection method with the upper part
A	A	2400	1300	1.85	Grouted couplers
B	B	2400	1300	1.85	None
C	C1	1500	1000	1.5	Grouted couplers
	C2	2000	1000	2.0	Grouted couplers
	C3	2400	1000	2.4	Grouted couplers
D	D1	1500	1000	1.5	None
	D2	2000	1000	2.0	None
	D3	2400	1000	2.4	None
E	E	1500	500	3.0	—

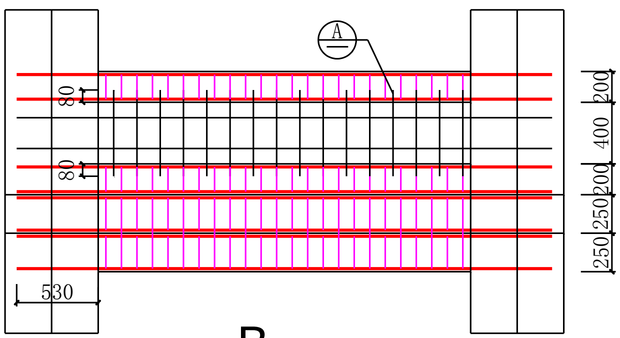


Assembled RC coupling beam

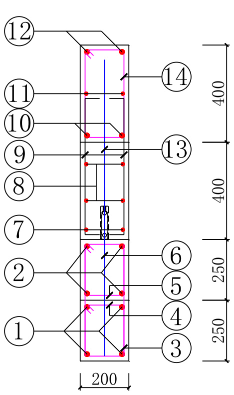
Connection detailing of the assembled RCCB specimens.



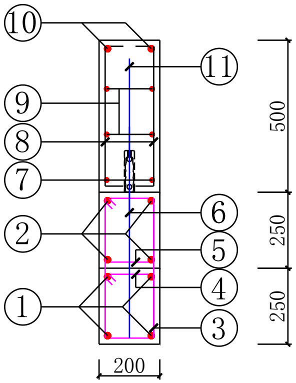
A



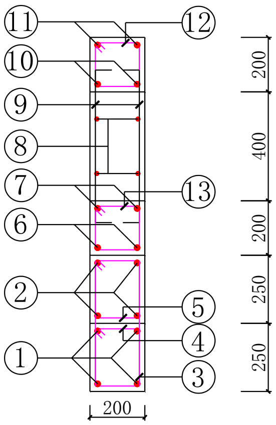
B



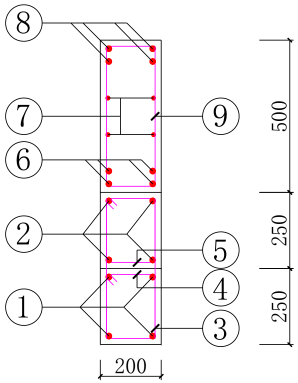
A



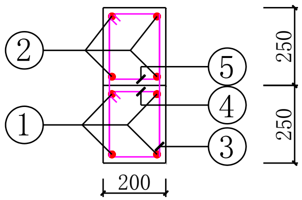
C



B



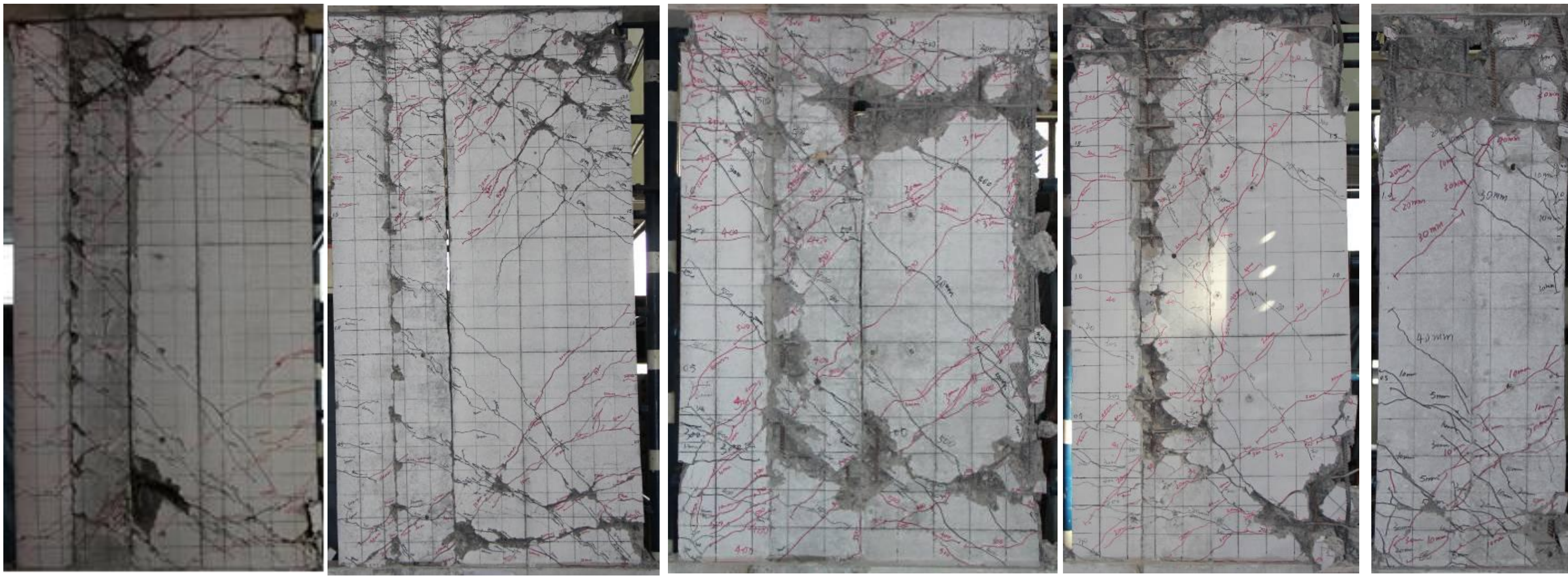
D



E

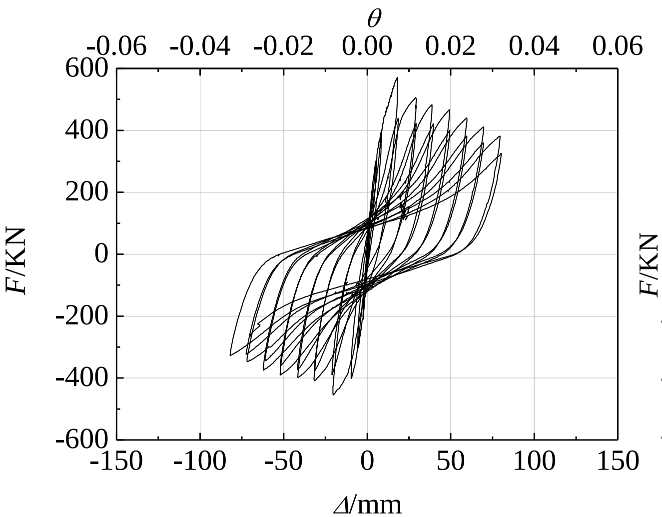
Assembled RC coupling beam

Crack pattern of the assembled RCCBs (Qian and Zhao, 2013)

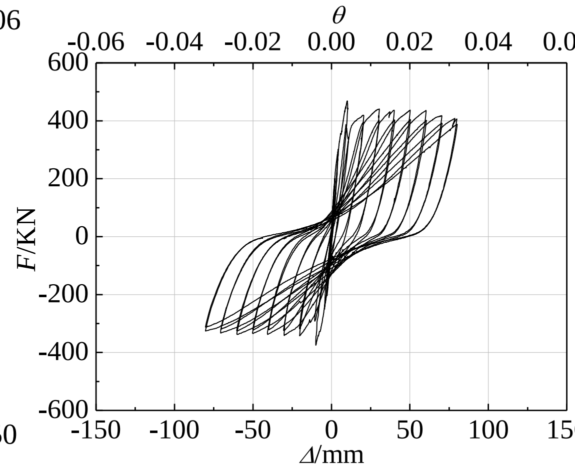


A B C1 C2 E

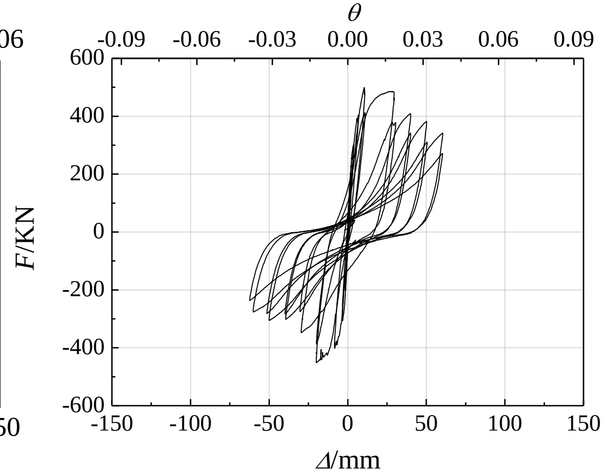
Assembled RC coupling beam



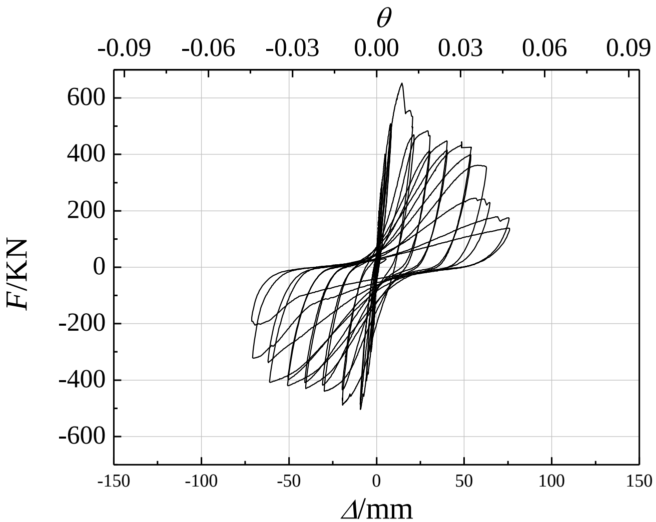
A



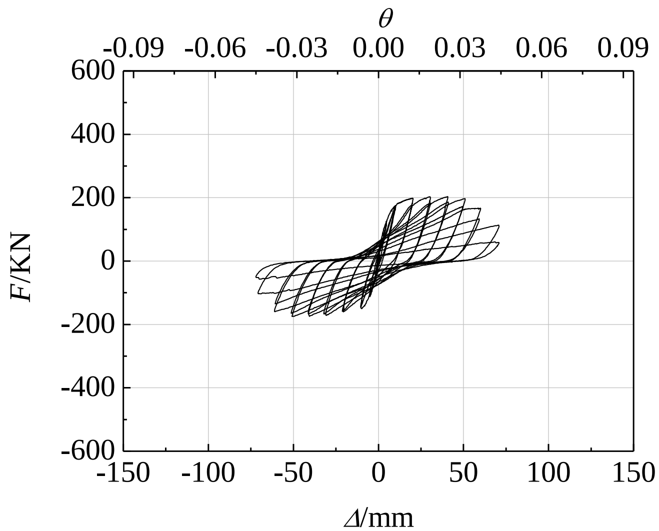
B



C1



D1



E

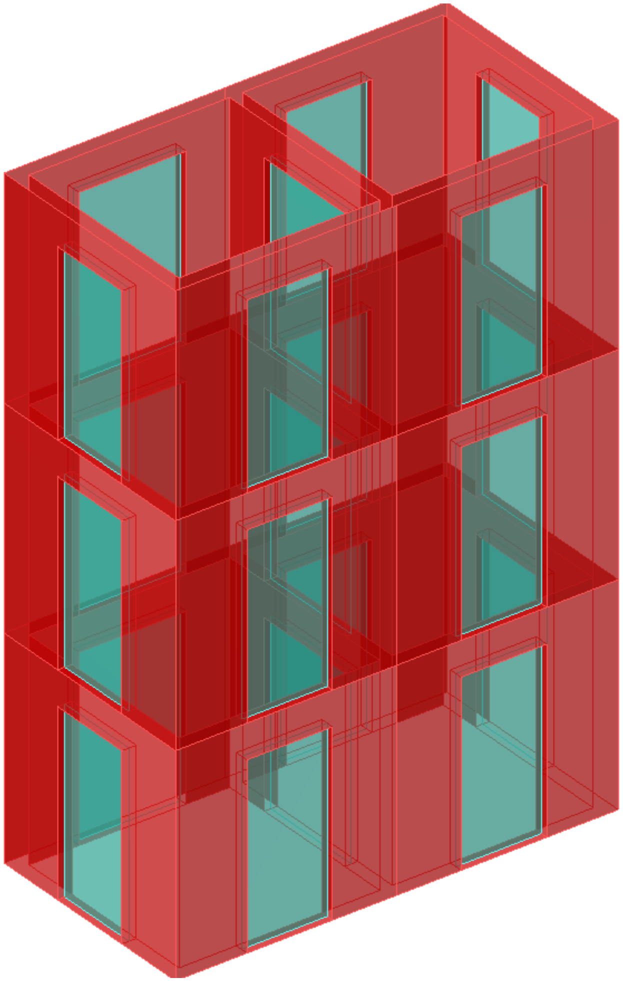
Assembled RC coupling beam

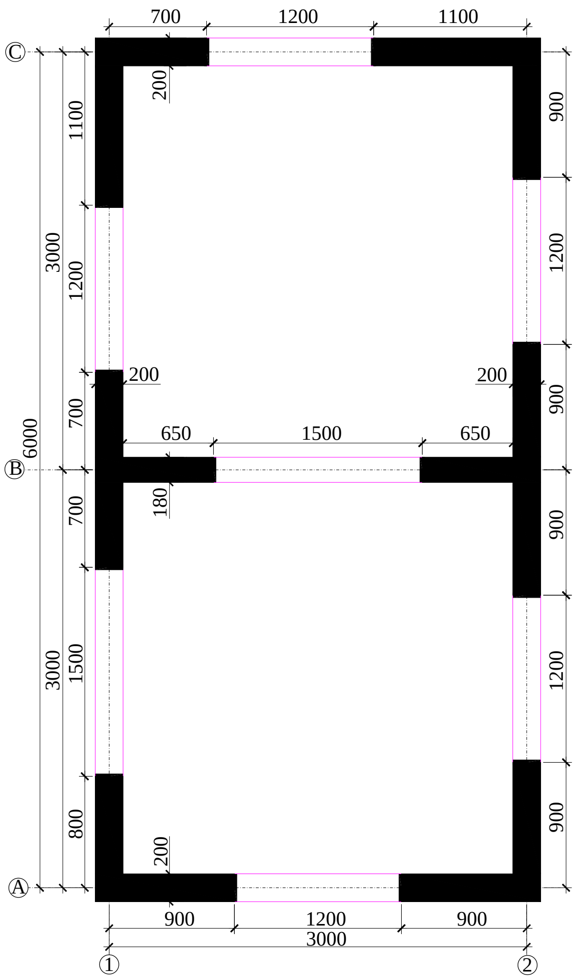
Measured and predicted capacity of assembled RCCBs

Specimen	Model	Predicted		Measured F_p（kN）			Measured/Predicted	
		V_u（kN）	$2M_u/L$（kN）	Positive	Negative	Average	F_p/V_u	$F_p/(2M_u/L)$
A	1 beam	584	300	571	455	513	0.89	1.71
	2 beam	639	182				0.80	2.82
B	1 beam	584	294	468	375	422	0.72	1.44
	2 beam	646	224				0.65	1.88
C1	1 beam	491	359	500	451	475	0.97	1.32
	2 beam	543	191				0.87	2.49
C2	1 beam	496	269	446	376	411	0.83	1.53
	2 beam	548	143				0.75	2.87
C3	1 beam	494	224	381	330	356	0.72	1.59
	2 beam	545	119				0.65	2.99
D1	1 beam	574	361	653	504	578	1.00	1.60
	2 beam	636	271				0.91	2.13
D2	1 beam	604	271	352	357	354	0.59	1.31
	2 beam	669	204				0.53	1.74
D3	1 beam	573	226	302	293	298	0.52	1.32
	2 beam	631	170				0.47	1.75
E	—	348	109	204	175	189	0.54	1.73

3-story full-scale PC shear wall structure model

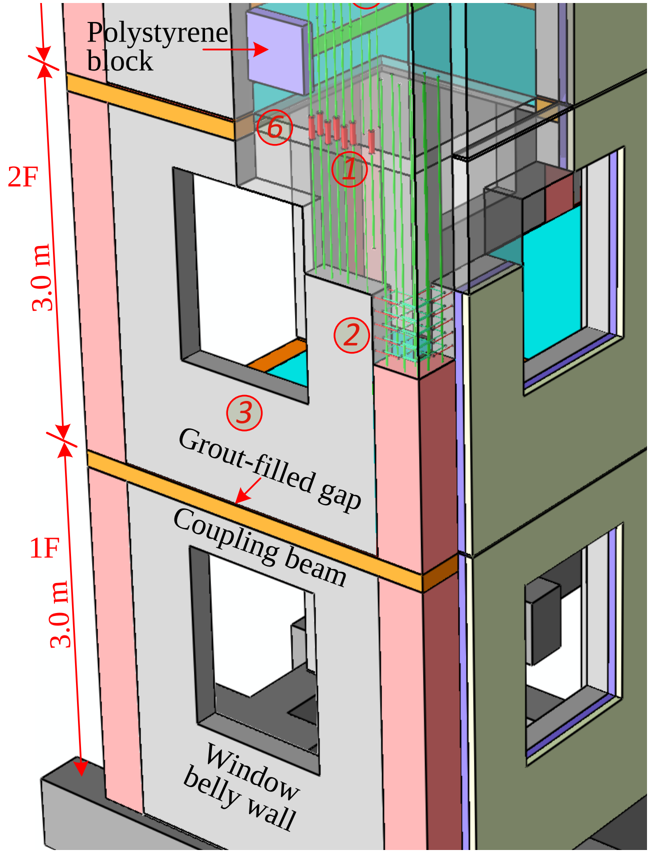
Global experimental study on a 3-story full-scale precast concrete shear wall structure with rebars spliced by grouted couplers in Tsinghua University.

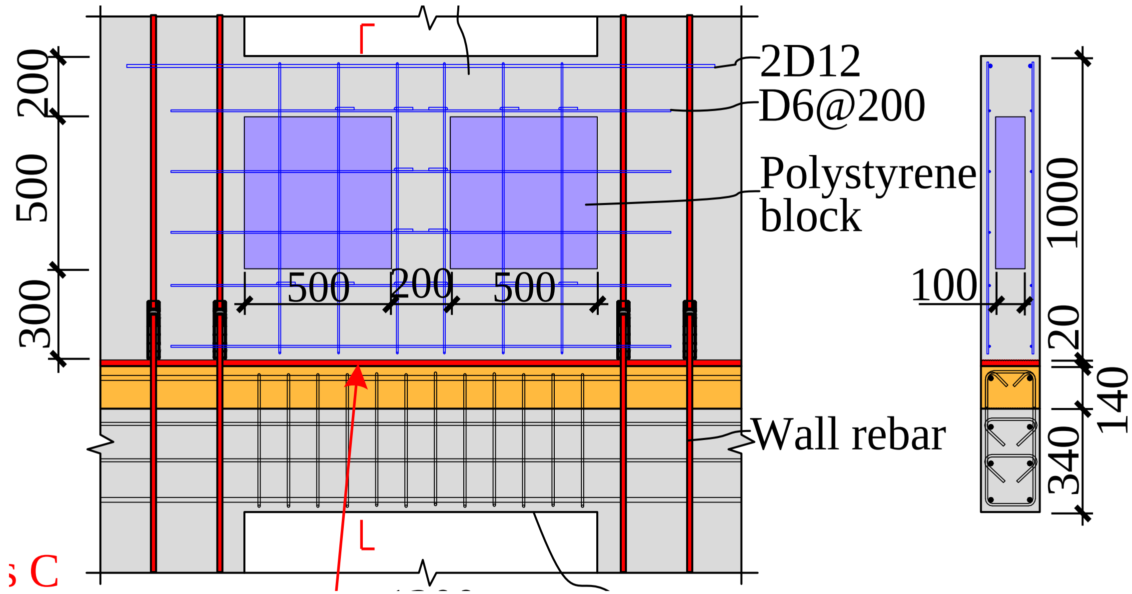




3-story full-scale PC shear wall structure model

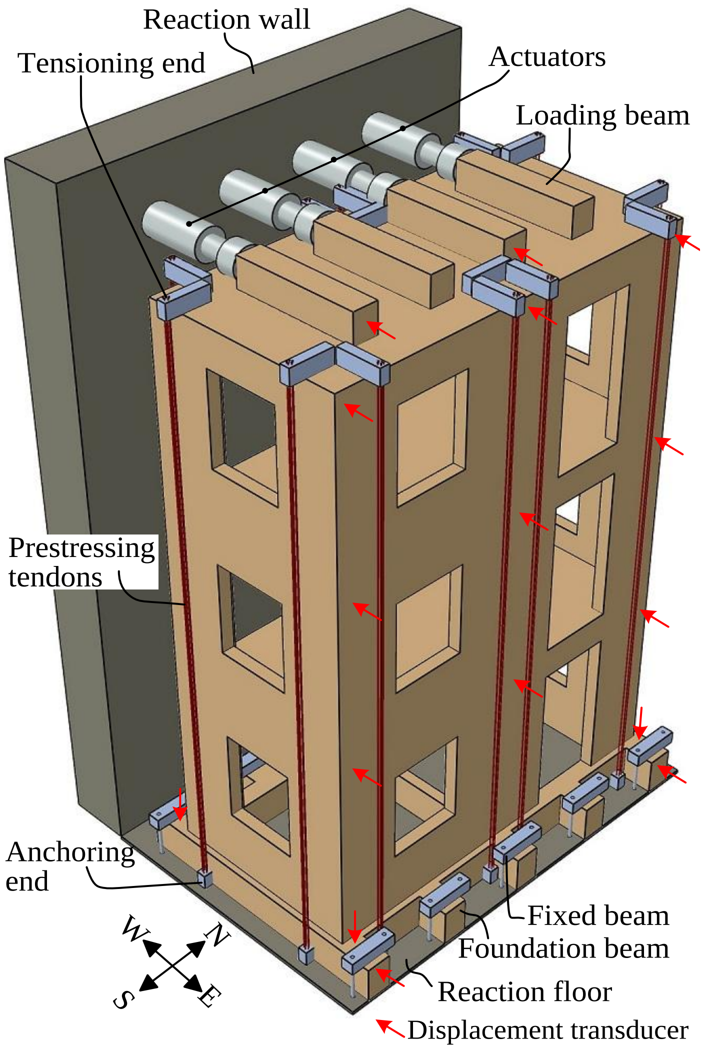
Detailing of the assembled RC coupling beams: upper belly wall (non structure element) + grout-filled gap + bottom coupling beam. All window belly walls and the lower segments were connected by a 20 mm thick high-strength grout-filled construction gap, no rebar spliced.



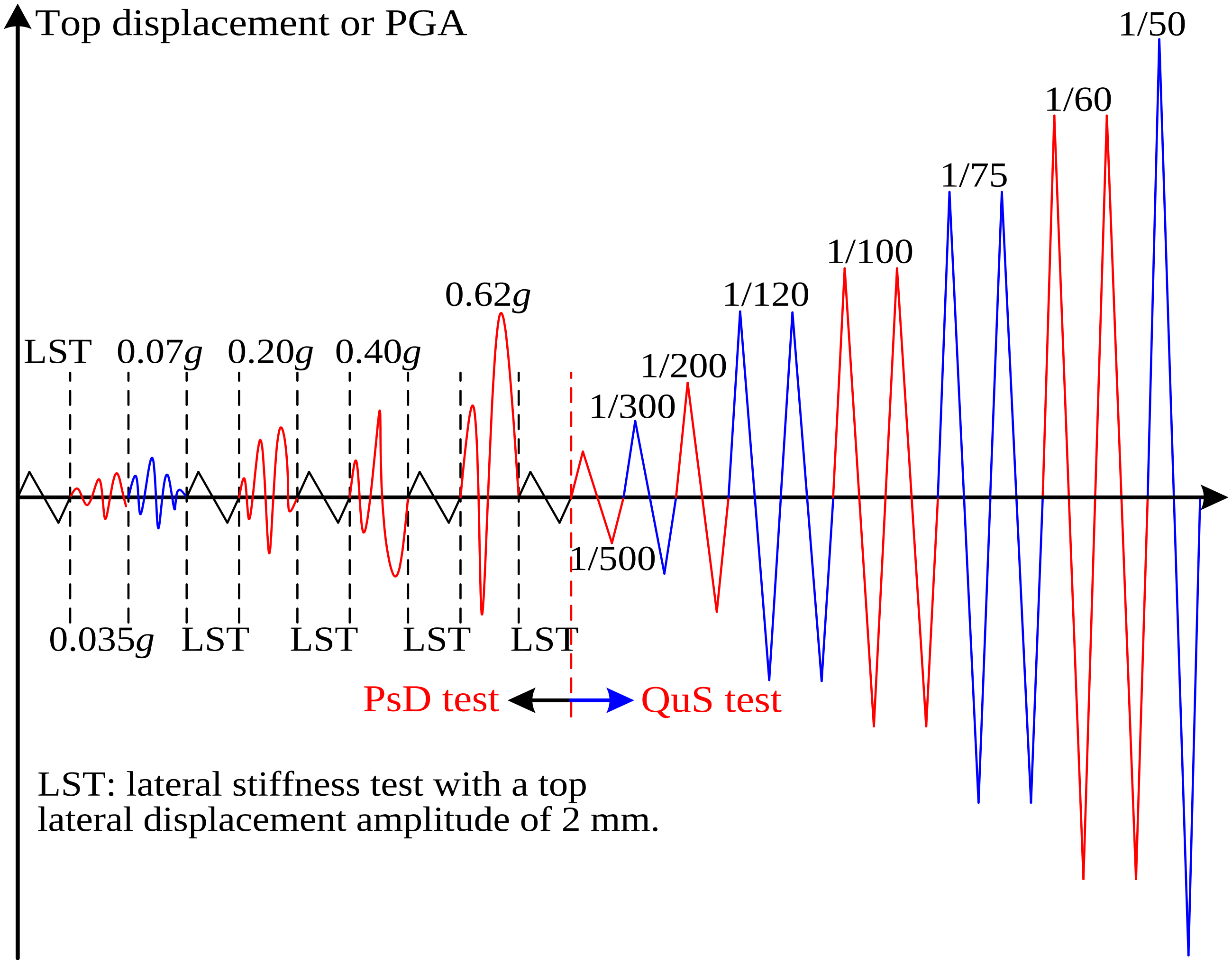


3-story full-scale PC shear wall structure model

The 3-story full-scale precast concrete shear wall structure model.



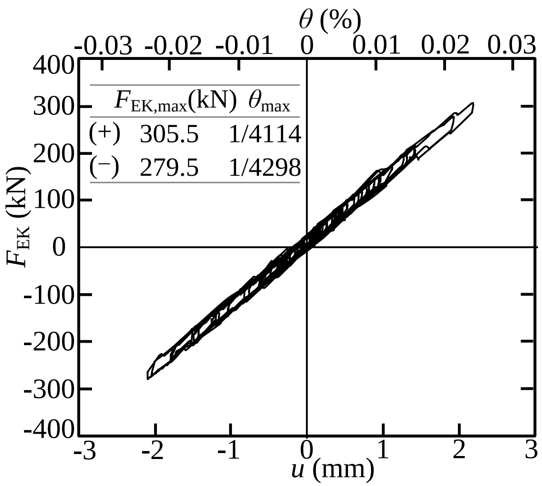
3-story full-scale PC shear wall structure model



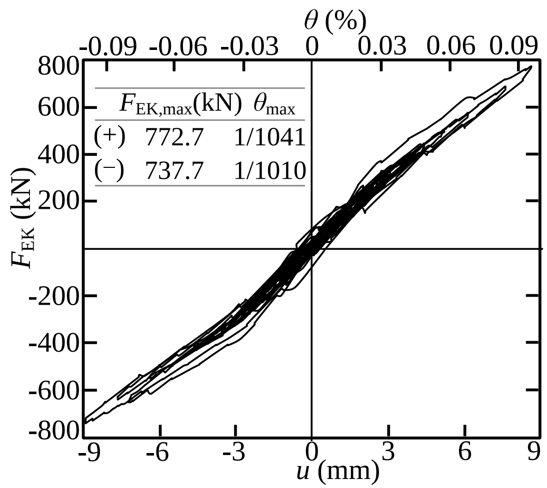
Loading protocol

3-story full-scale PC shear wall structure model

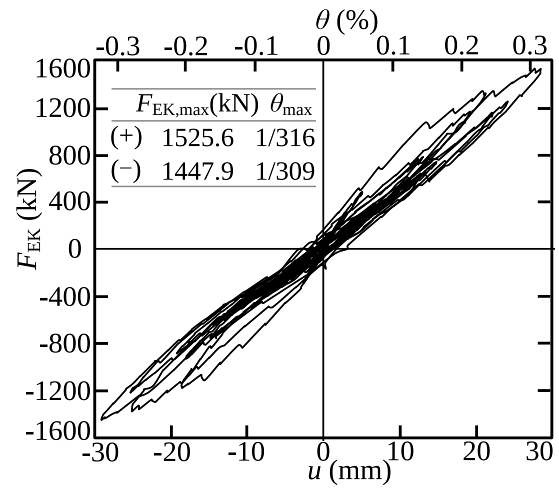
Hysteretic loops or skeleton curves under different load conditions



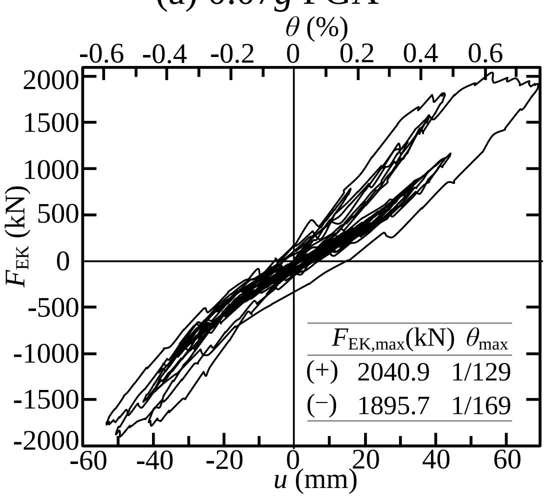
(a) 0.07*g* PGA



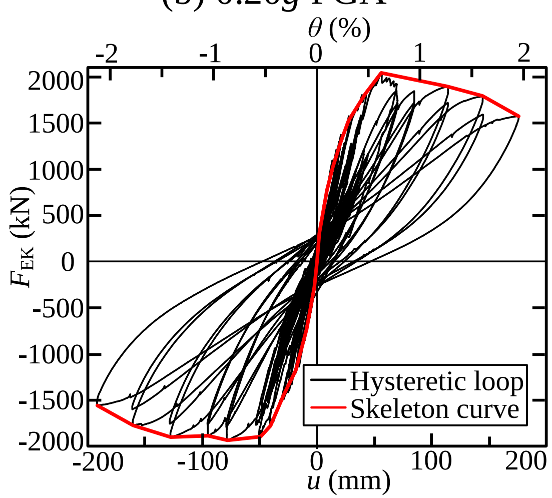
(b) 0.20*g* PGA



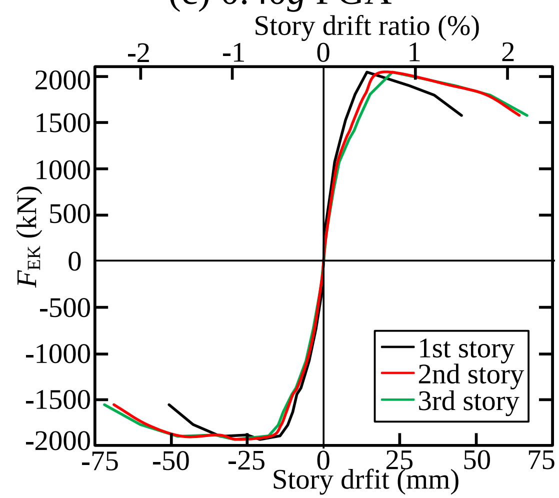
(c) 0.40*g* PGA



(d) 0.62*g* PGA



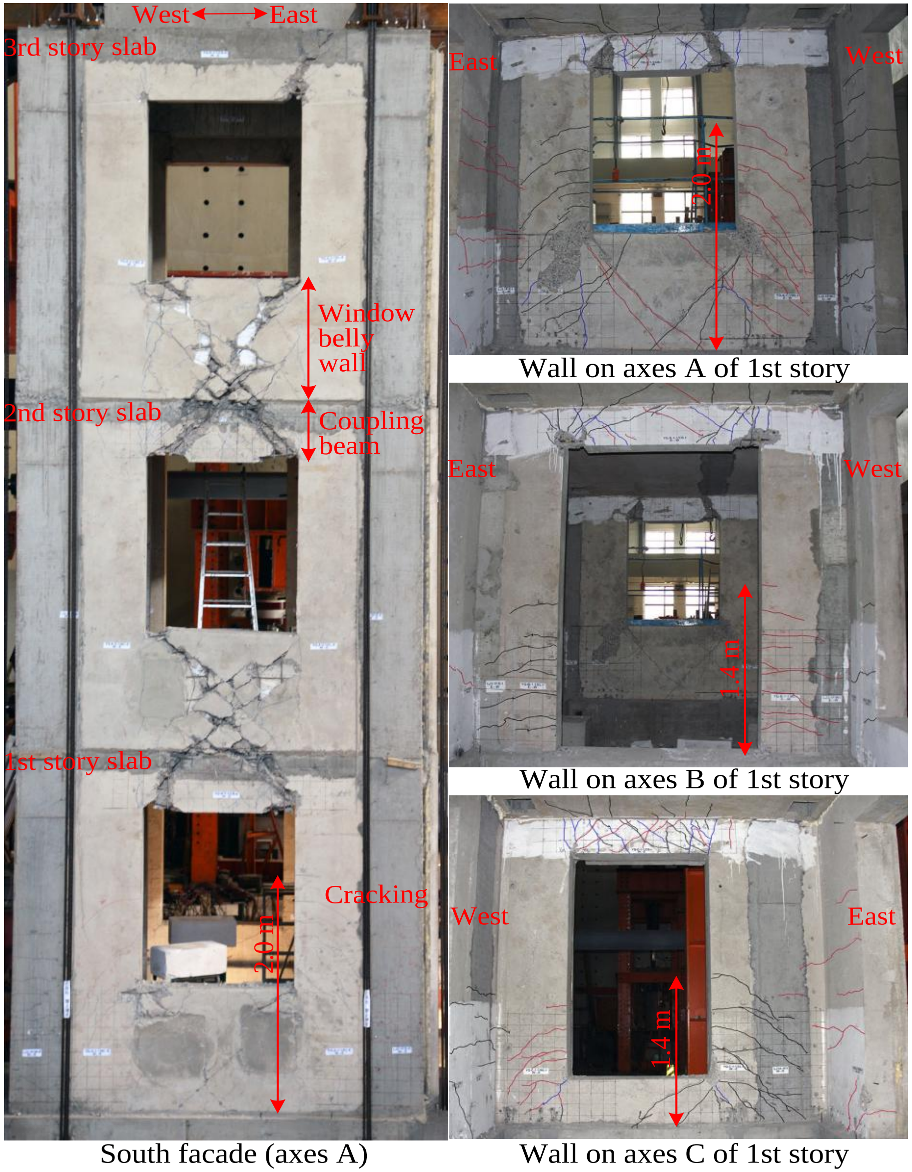
(e) PsD and QuS tests



(f) story drift

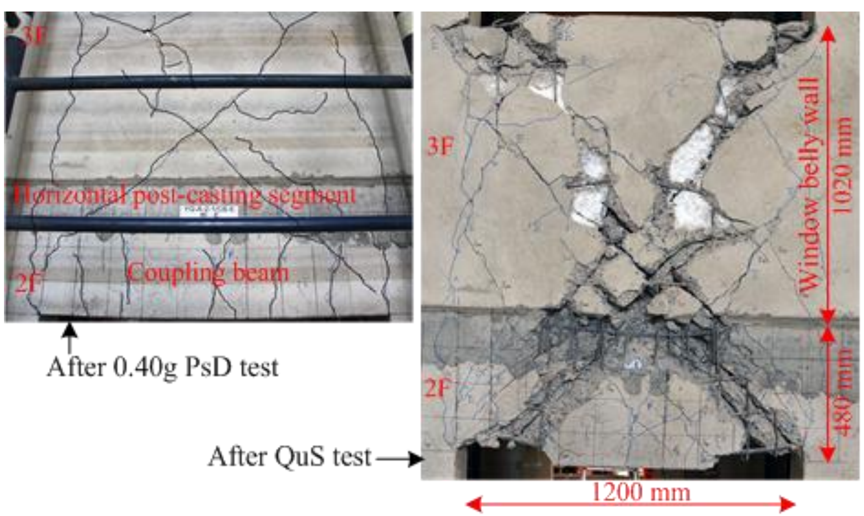
Failure modes of the test model after QuS test

- After the 1st cycle of 1/50 drift, the QuS test was terminated for safety reasons.
- Cracks and damages of the test model concentered on the coupling beams and window belly walls in loading direction.
- Cracks of walls distributed at a height of 0 ~ 2.0 m from the foundation, with a maximum width of 2 mm.
- No crack was observed at wall limbs of the 2nd and 3rd story.
- The test model exhibited the desired "strong wall limb and weak coupling beam" failure mode.

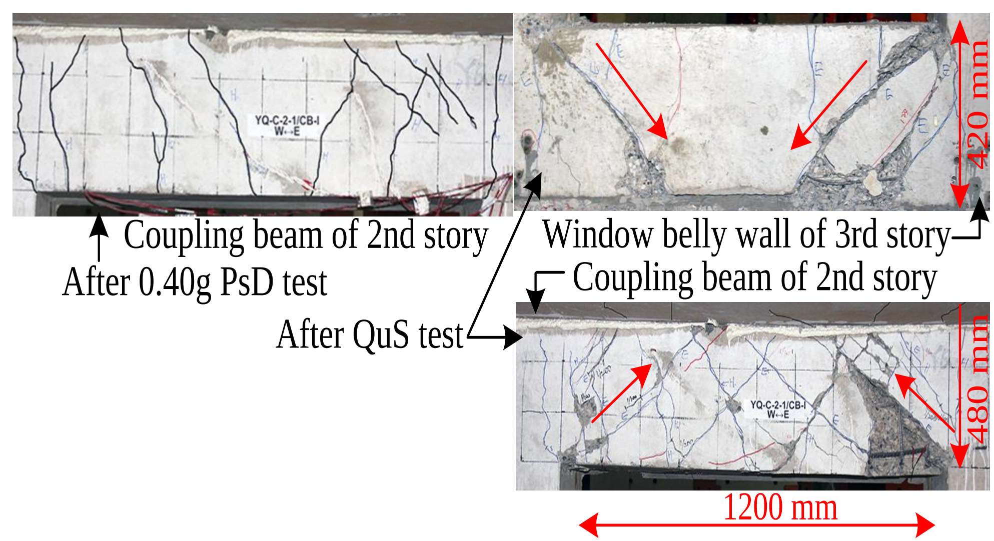


Failure modes of coupling beams and window belly walls

- After 0.40*g* PsD test, **all coupling beams were dominated by flexural cracks**, while shear cracks developed at the window belly walls located on axes A and C at the 2nd and 3rd story.
- After QuS test, the window belly walls on **axes A and C failed in shear mode**. Influenced by the upper window belly walls, **coupling beams** located on axes A and C at the 1st and 2nd story **with aspect ratios of 2.5** were dominated by **shear inclined cracks**.



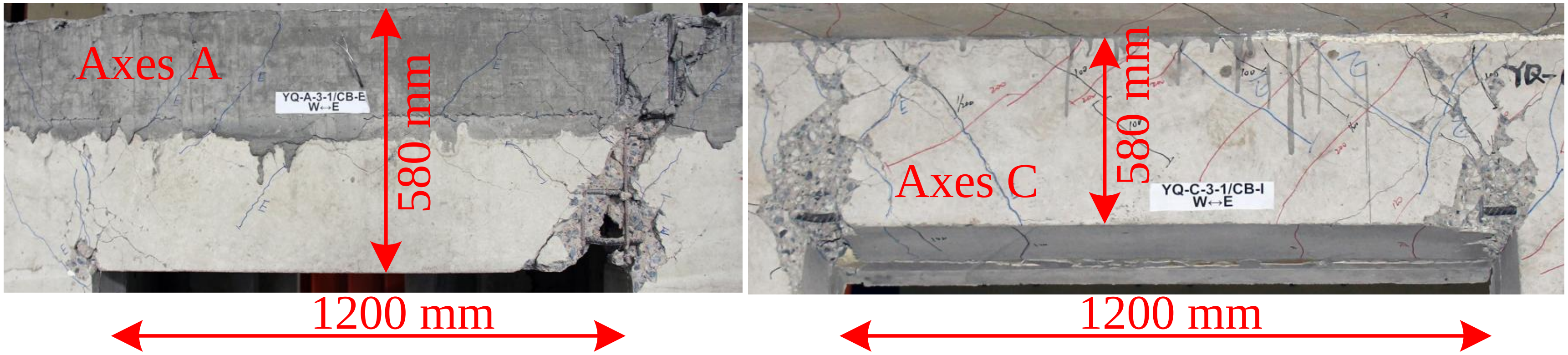
Axes A



Axes C

Failure modes of coupling beams and window belly walls

- Note that coupling beams located on axes A and C at the 3rd story, with aspect ratios of 2.1 and **no upper window belly wall, failed in flexural mode**, characterized by concentrated plastic hinges at both ends and slight shear cracks.

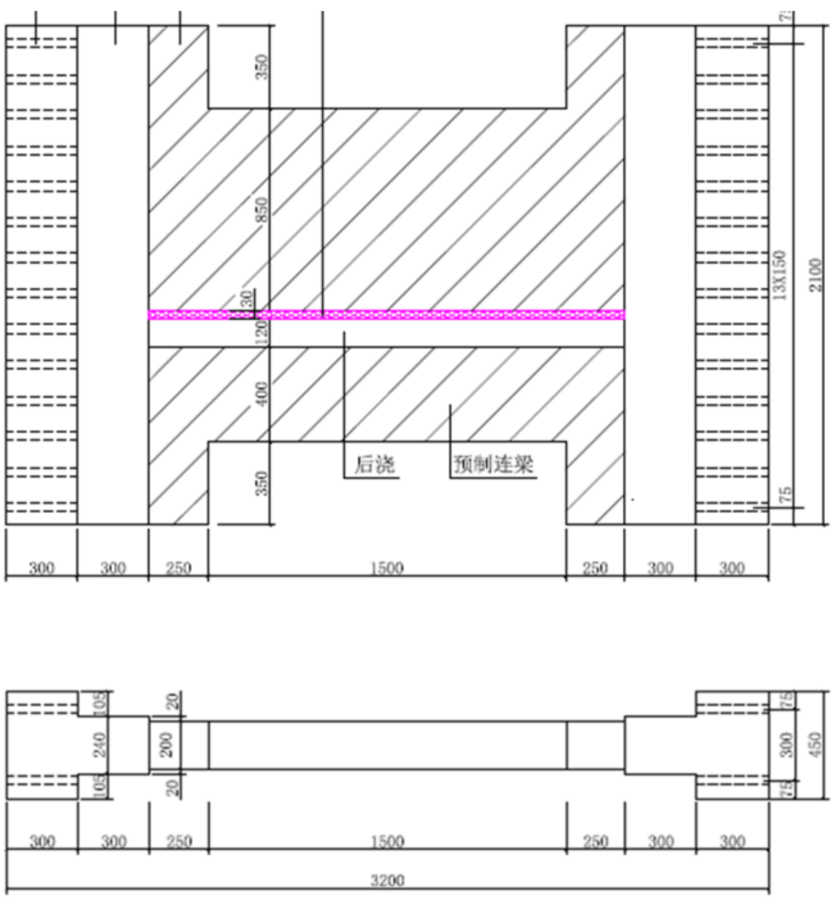


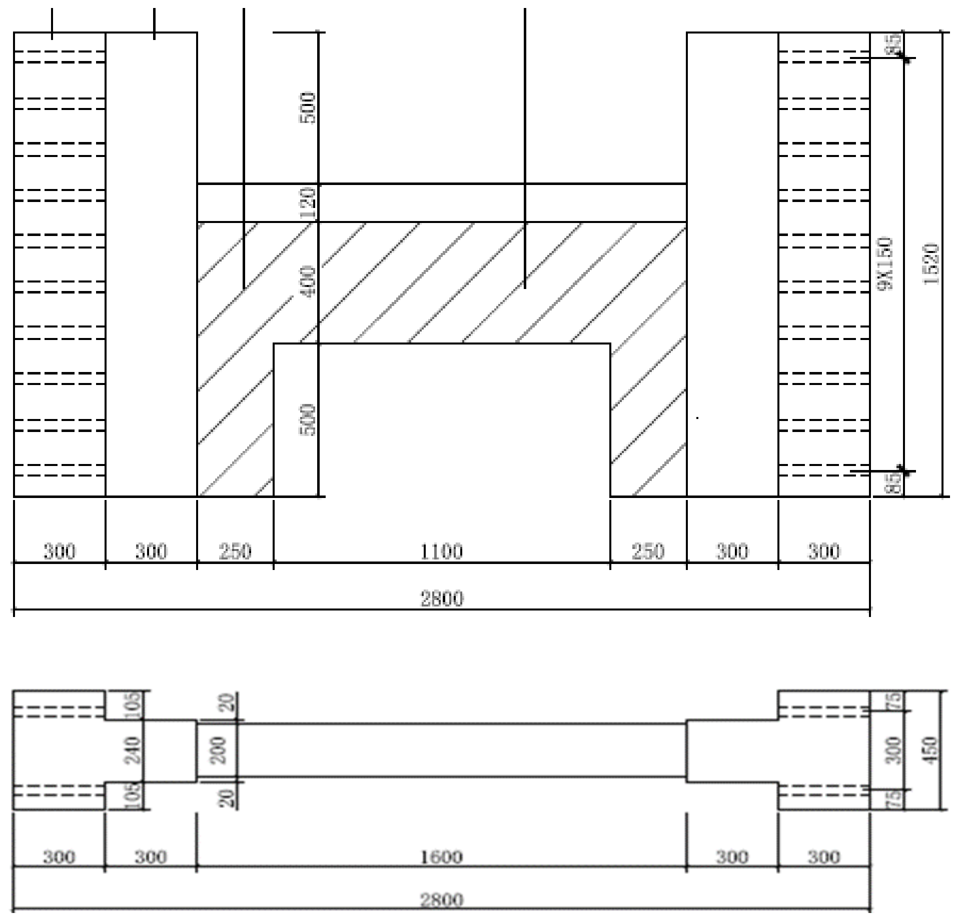
Coupling beams at the 3rd story, after QuS test

- It can be concluded that **upper window belly walls significantly influenced the failure modes of coupling beams.** A composite effect existed in the lower coupling beam and upper window belly wall. Designing the window belly wall as **a upper coupling beam** to form **double coupling beams** may be a feasible alternative.

3-story full-scale PC shear wall structure model

A new research program on assembled RCCBs, especially composite effect between the window belly wall and the lower coupling beams are carried out in Tsinghua University.





LB1

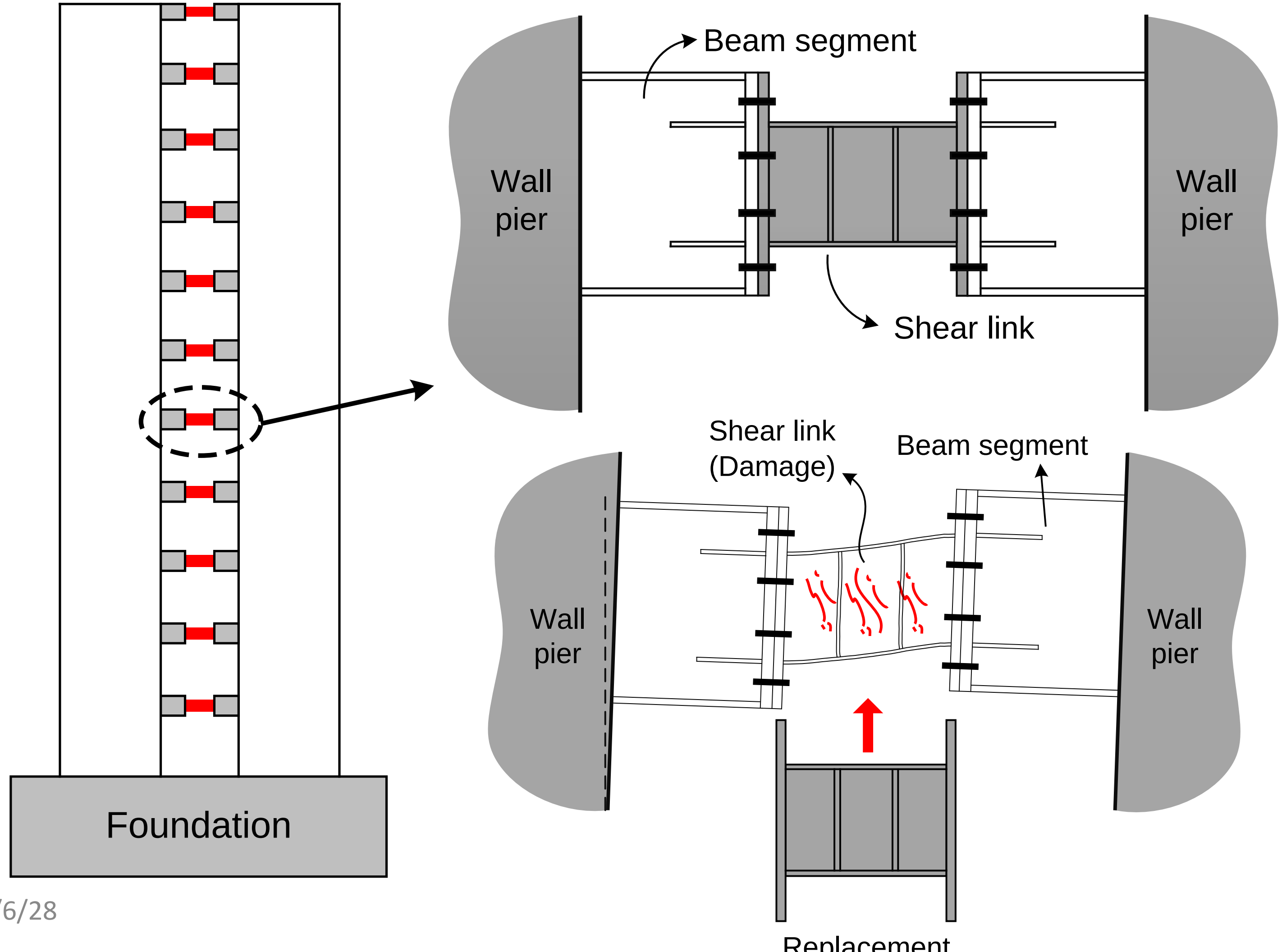
LB4

Outlines

- Background
- RC coupling beams
- Steel plate reinforced RC coupling beams
- Assembled RC coupling beams
- Replaceable steel coupling beams
- Conclusions

Replaceable steel coupling beam (RSCB)

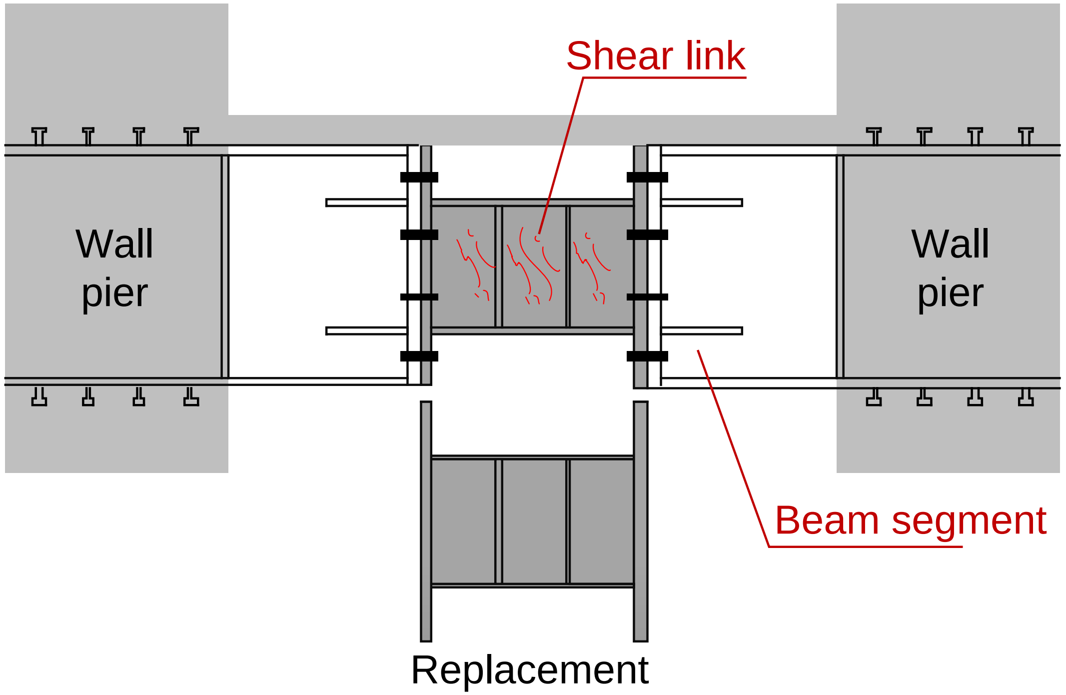
A type of replaceable steel coupling beam, with a central fuse shear link connecting with normal steel beam segment at its two ends, has been proposed and studied in Tsinghua Univ. (Ji and Wang 2016)



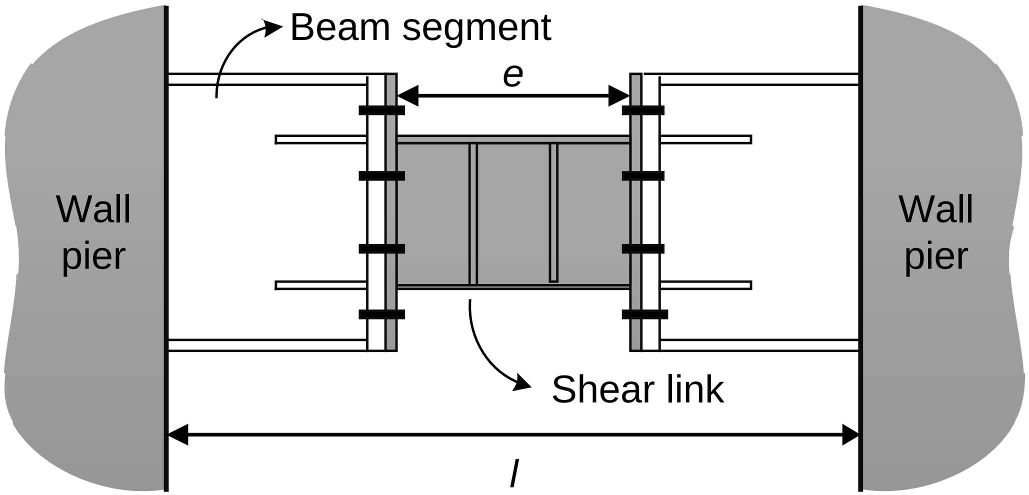
Replaceable steel coupling beam (RSCB)

3 Key issues should be considered.

- **Very short shear links**
- **Link-to-beam connections**
- **RC slab design**

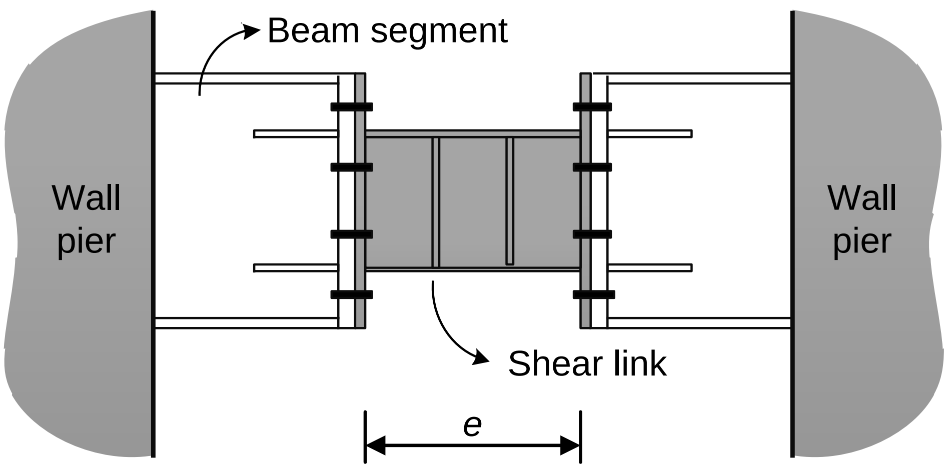


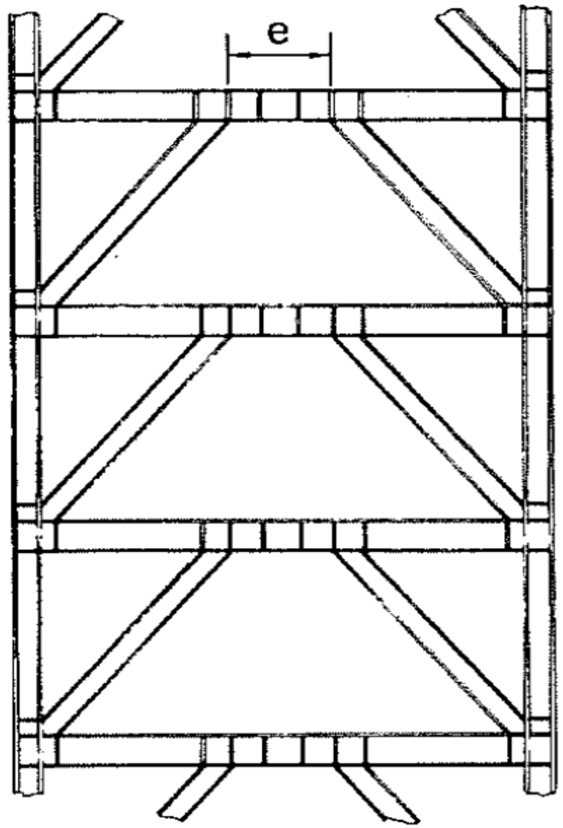
Capacity design philosophy of RSCBs



Shear link	Yield in shear	$e/(M_p/V_p)<1.6$
	Yield strength	$V_p=0.6f_yA_w$
Beam segment	Flexural strength	$M_{bp}>0.5l\cdot(\Omega V_p)$
	Shear strength	$V_{bp}>\Omega V_p$
Link-to-beam connection	Flexural strength	$M_{cp}>0.5e'\cdot(\Omega V_p)$
	Shear strength	$V_{cp}>\Omega V_p$

Shear links （per AISC 341 & GB 50011）





RSCBs

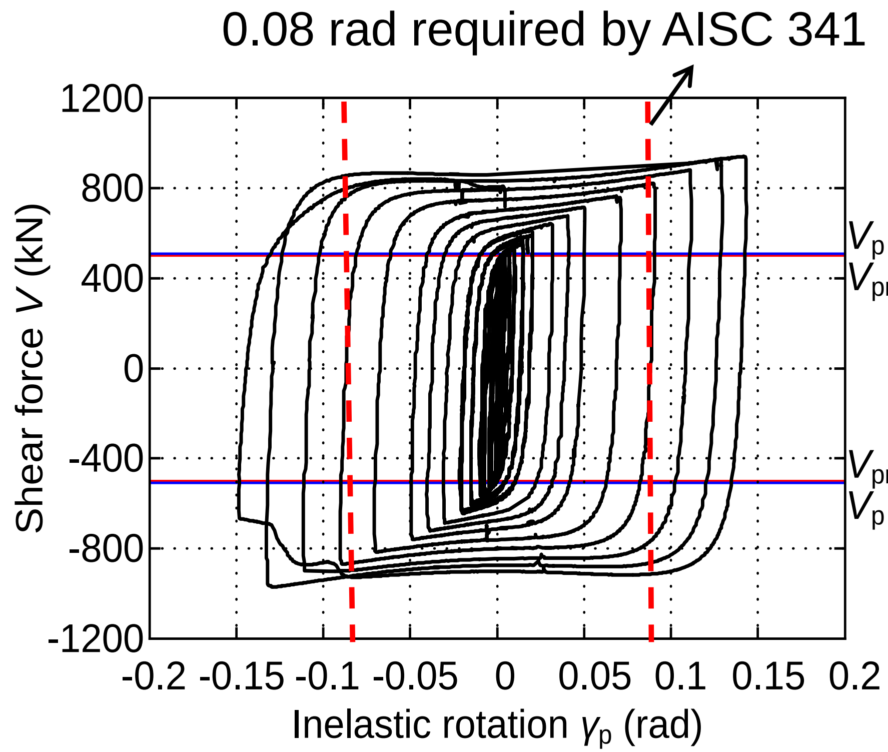
EBFs

Length ratio

$e/(M_p/V_p) < 1.0$

$e/(M_p/V_p) \approx 1.5$

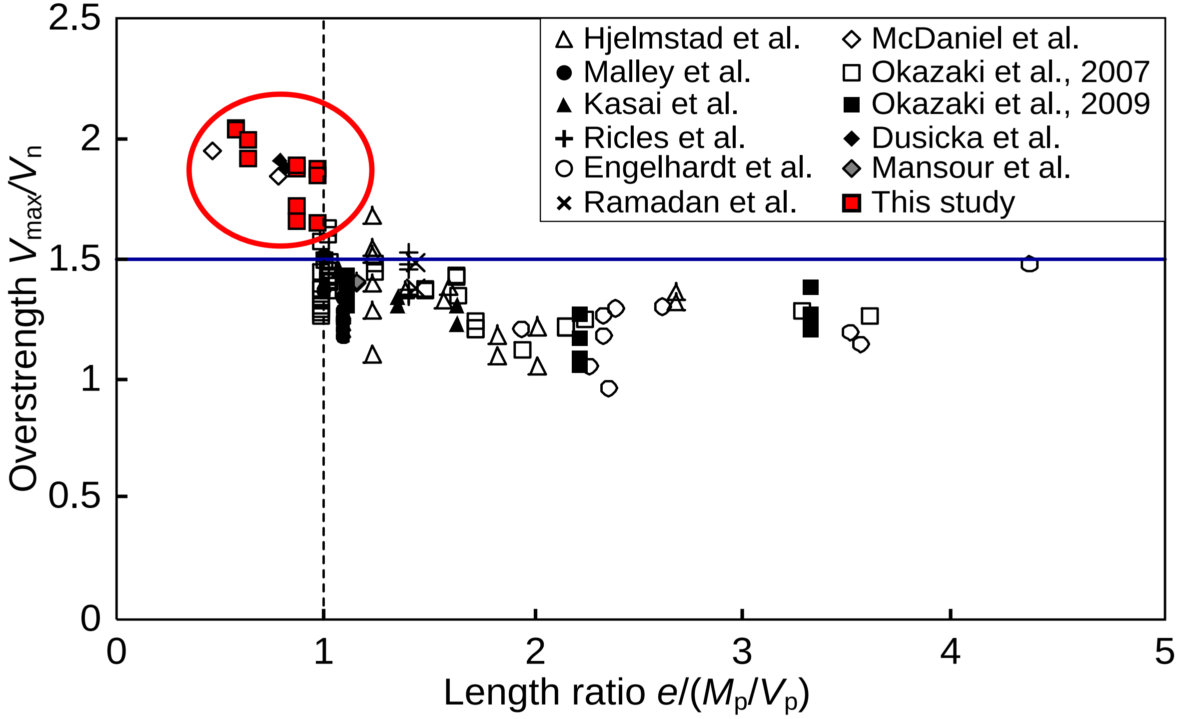
Test of very short shear links

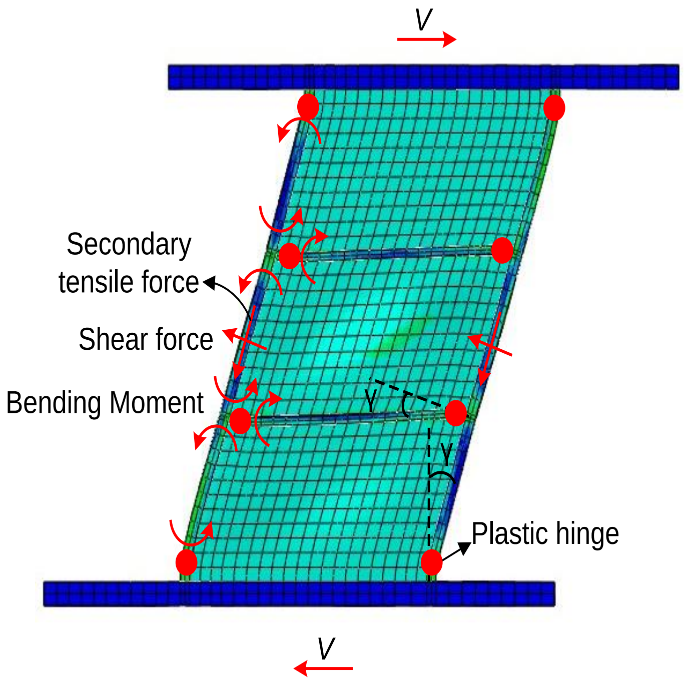


Length ratio: $e/(M_p/V_p) = 0.87$

Hybrid section: LY 225/Q235 for link web and Q345 for flanges

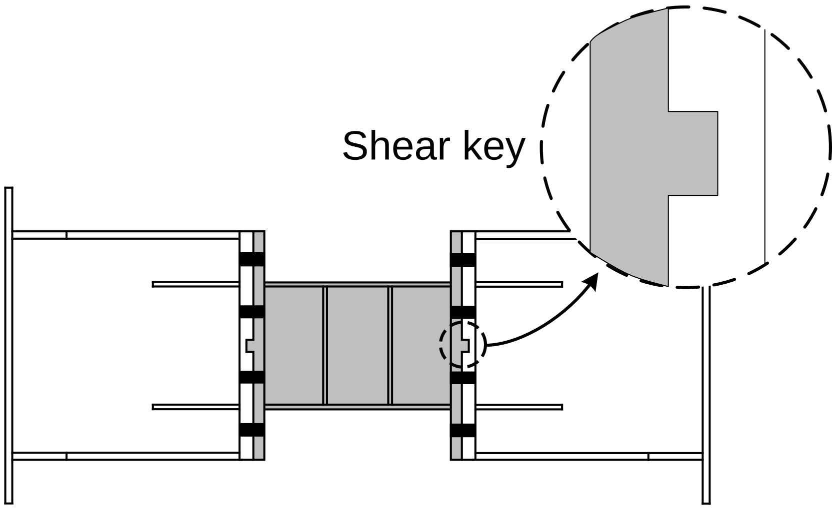
Overstrength $\Omega = V_{max}/V_n$

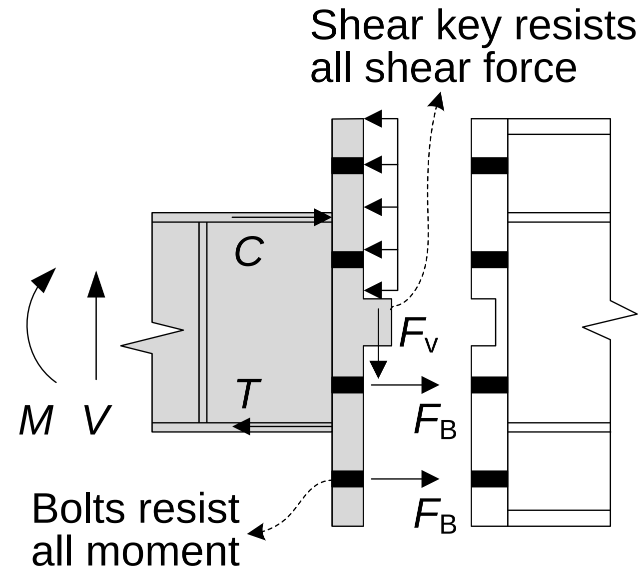




- The very short shear links generated an overstrength factor of approximately 1.9, significantly exceeding the value of 1.5 assumed for EBF links in the AISC 341-10 provisions.

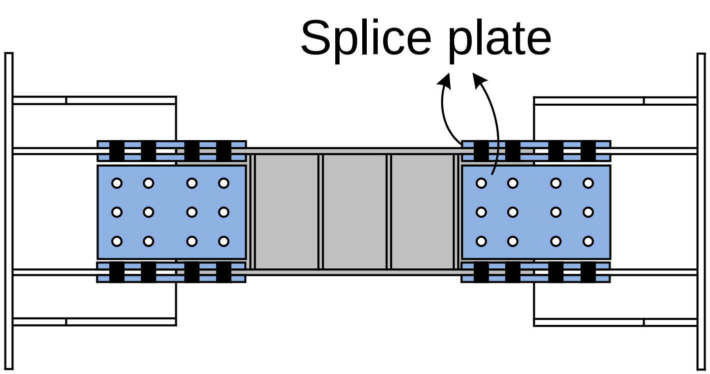
Test of link-to-beam connection

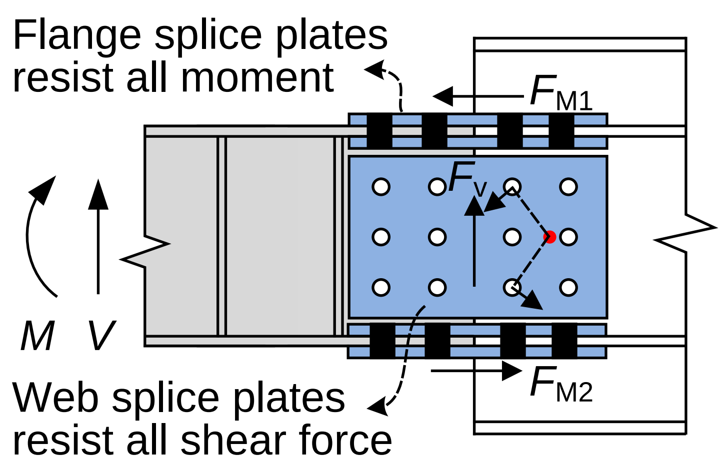




I-shaped section link

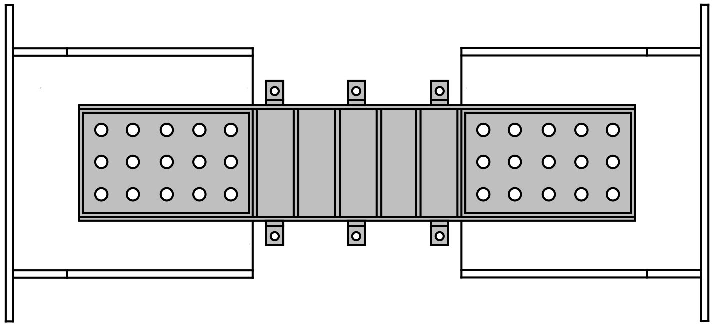
CB1: End plate connection

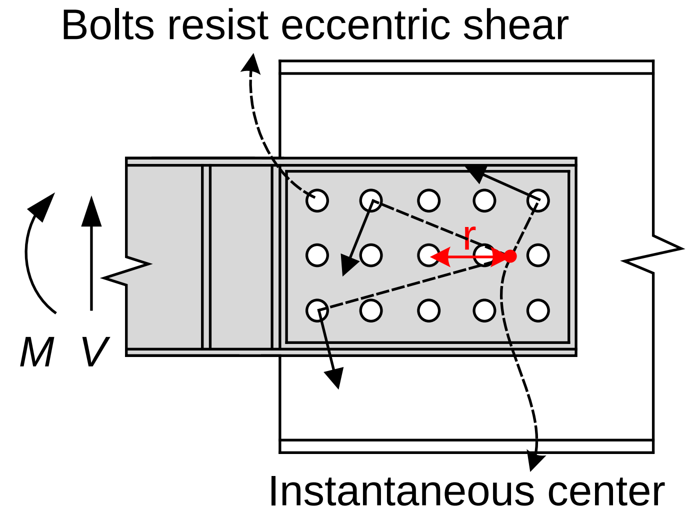




I-shaped section link

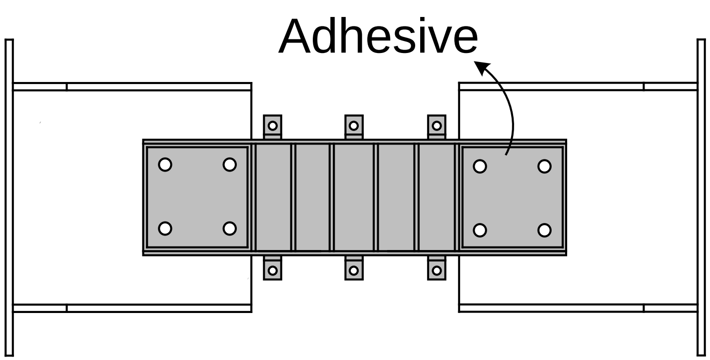
CB2: Splice plate connection

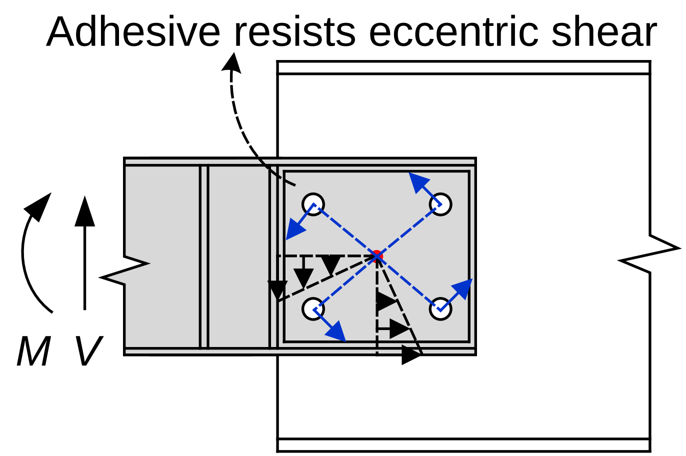




Double channel section link

CB3: Bolted web connection





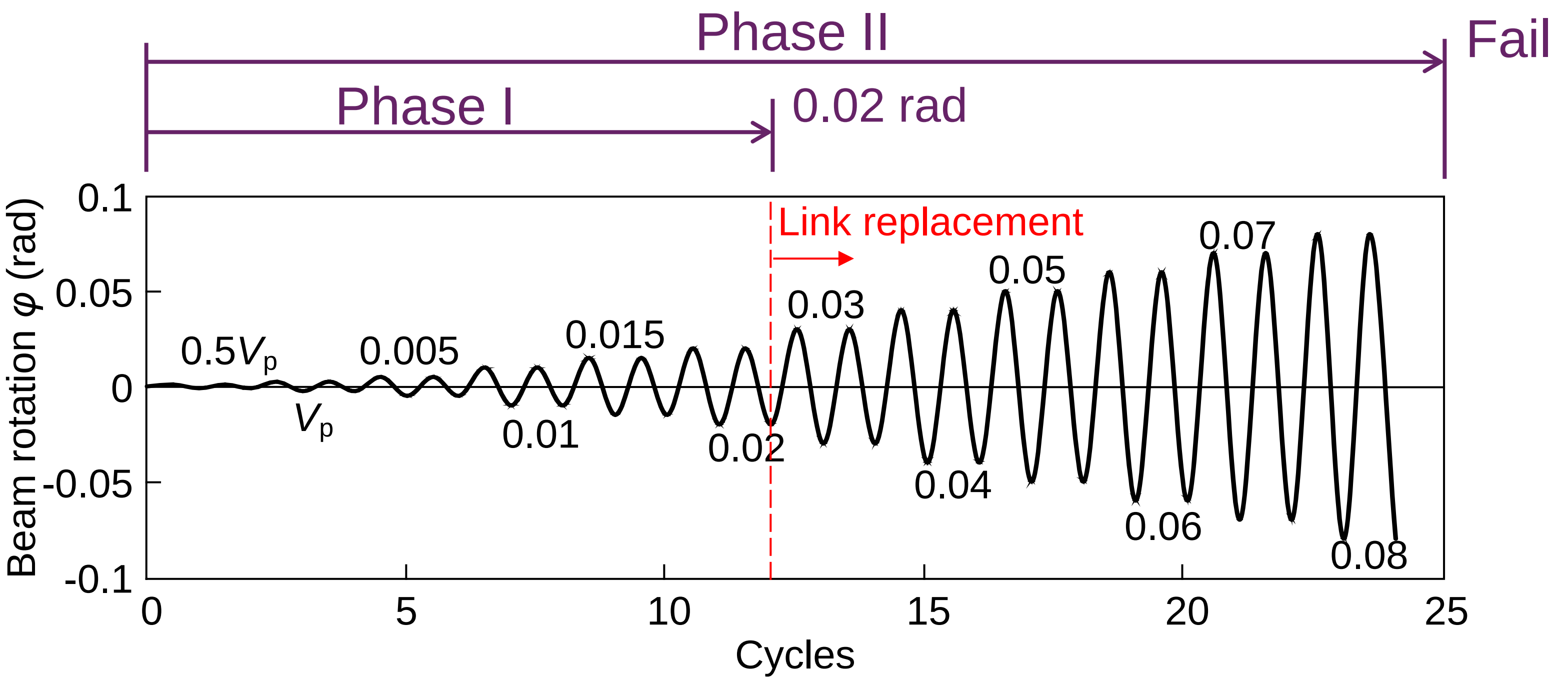
Double channel section link

CB4: Adhesive web connection

Epoxy adhesive f_v = 15 MPa

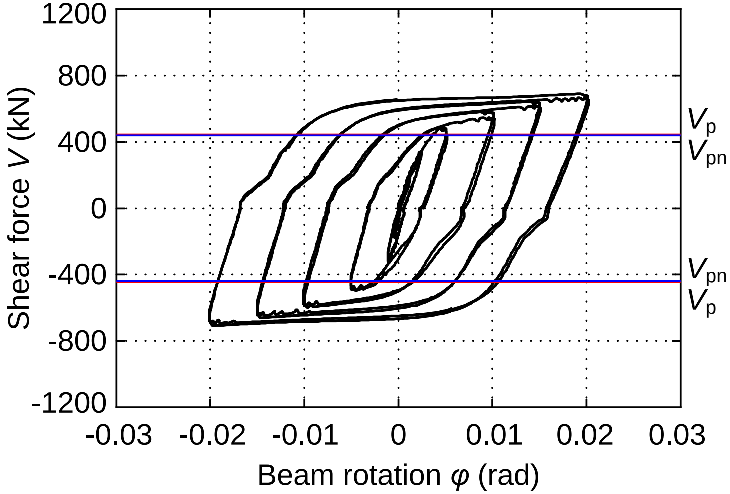
Test setup

Loading protocol

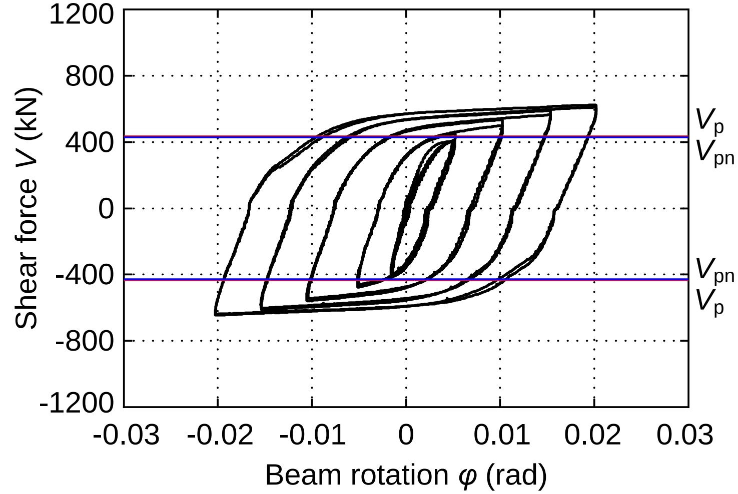


- Phase I: load to 0.02 rad rotation
- Replacement of the shear link
- Phase II: load till failure

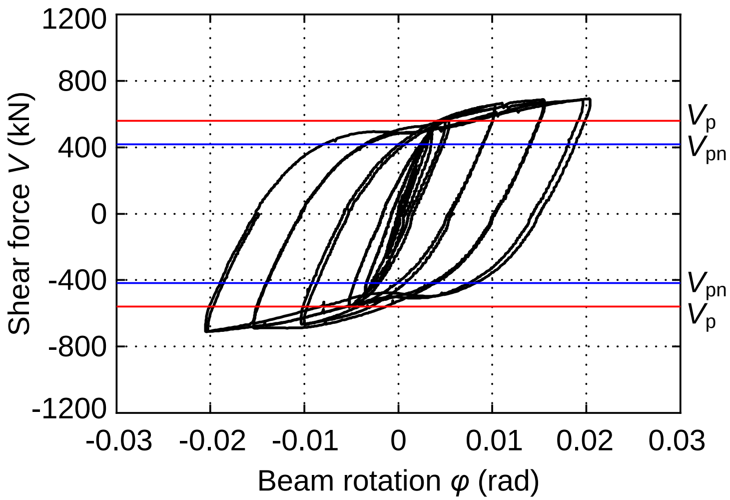
Phase I test



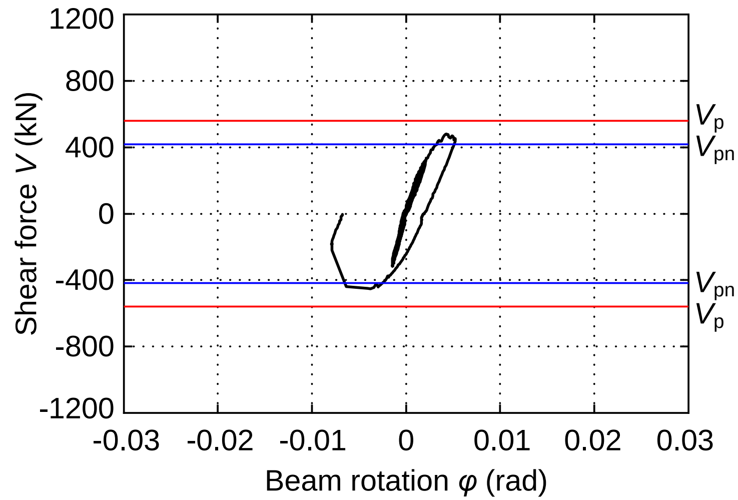
CB1



CB2

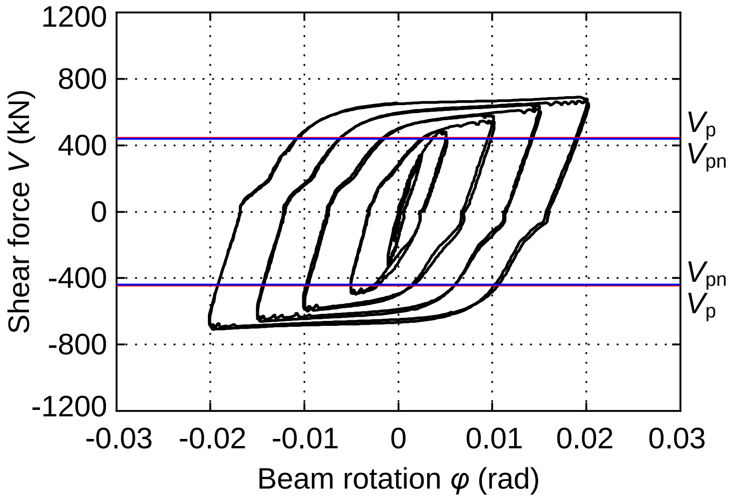


CB3

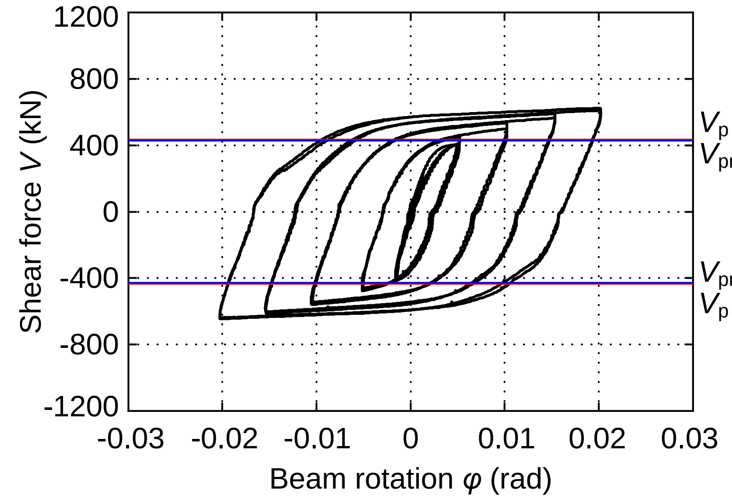


CB4

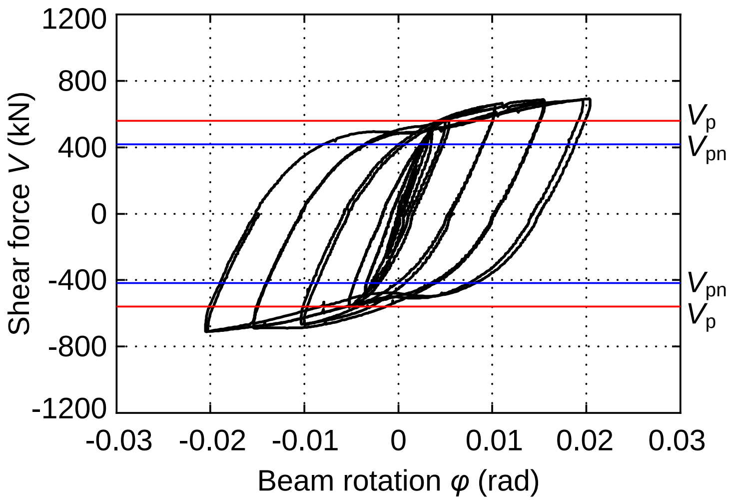
Phase I test



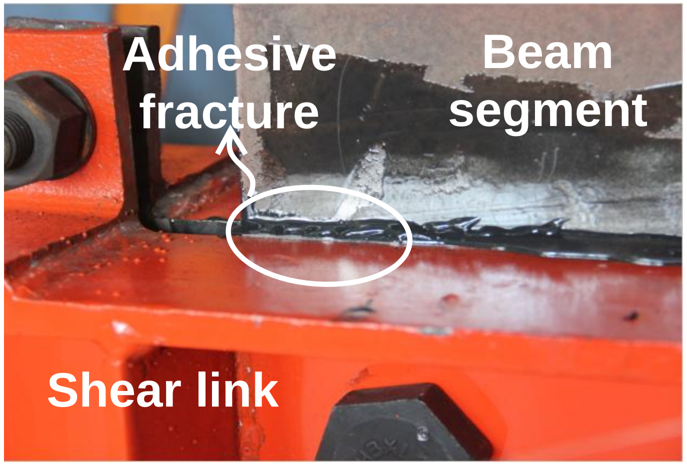
CB1



CB2



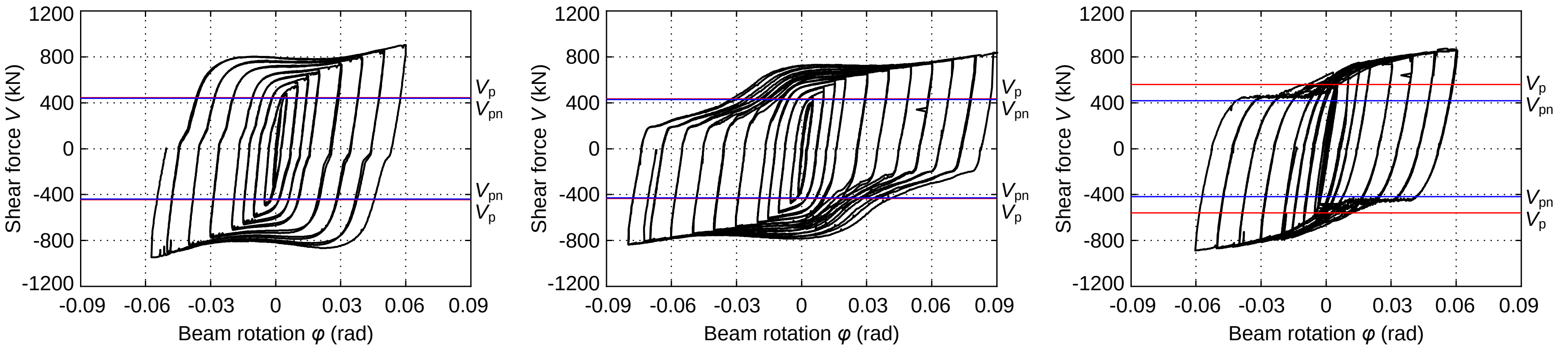
CB3



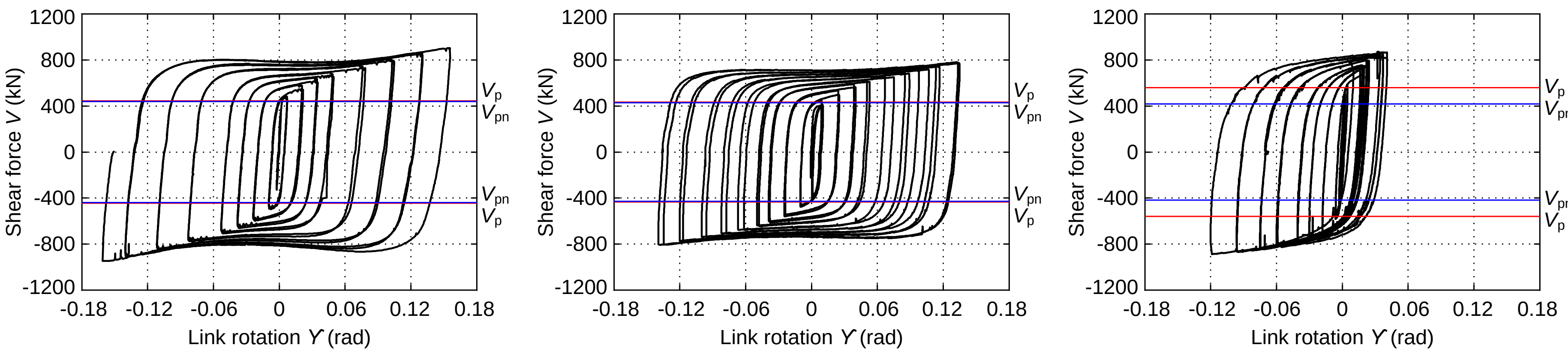
CB4: Adhesive fracture

Phase II test

■ Coupling beam



■ Shear link



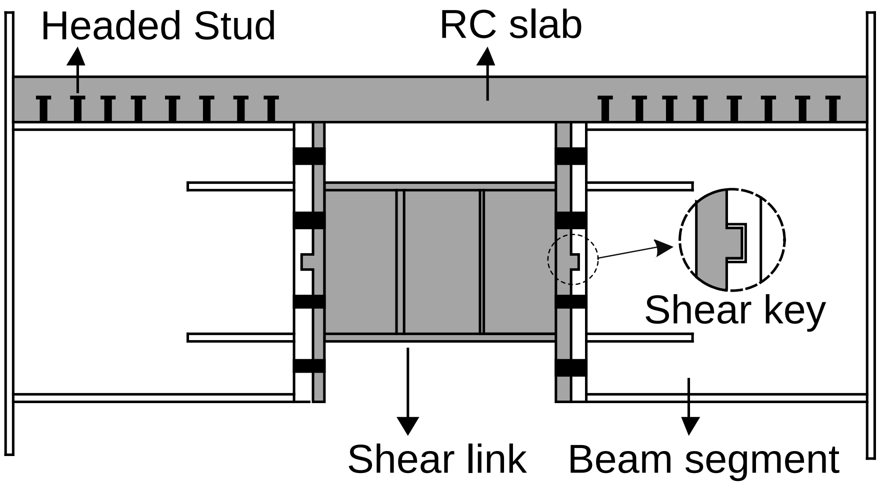
CB1 CB2 CB3

Replaceability

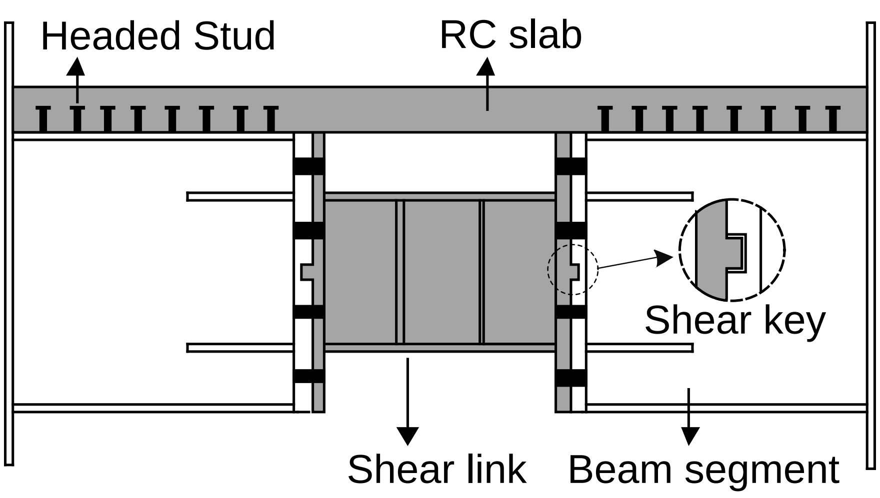
Spec. No.	Connection type	Ultimate rotation (rad)	Residual rotation for replacement (rad)	Replacement time (hour)
CB1	End plate connection	0.06	0.0045	0.4
CB2	Splice plate connection	0.09	0.0045	2.6
CB3	Bolted web connection	0.06	0.0065	2.2
CB4	Adhesive web connection	0.003	——	——

(Ji and Wang 2016)

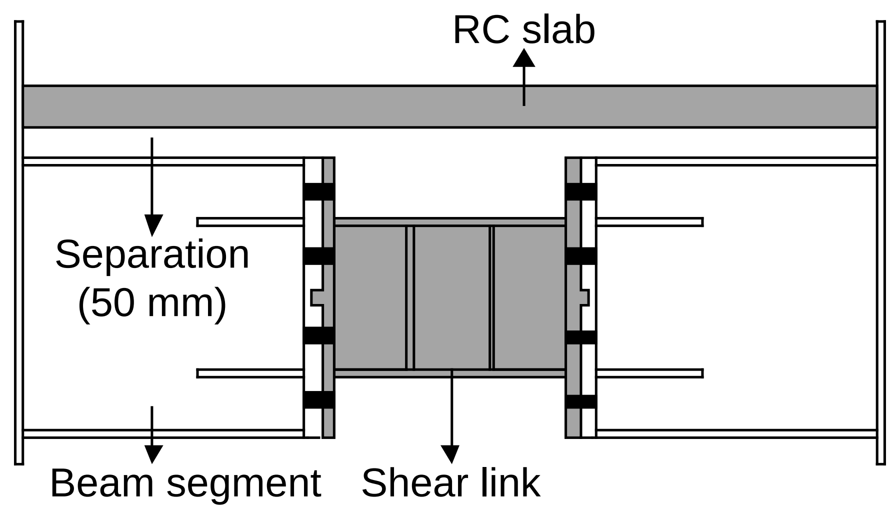
RC slab design



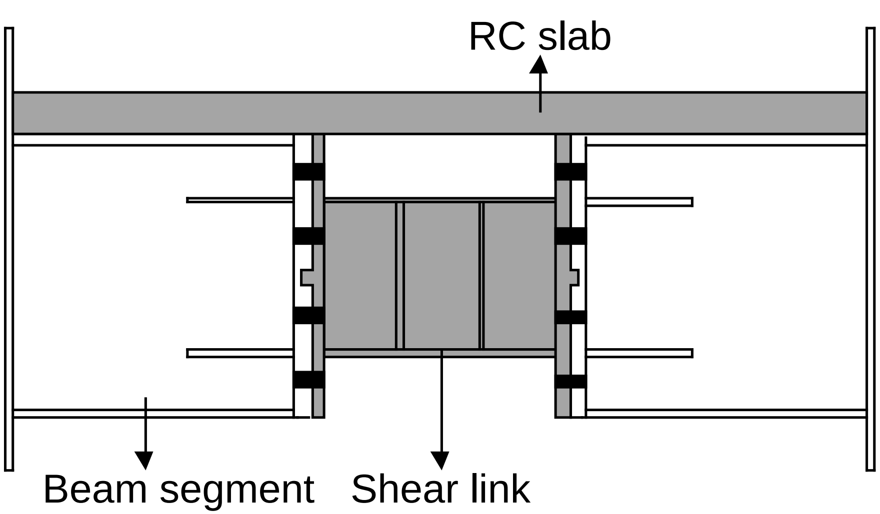
CBS1: Composite slab



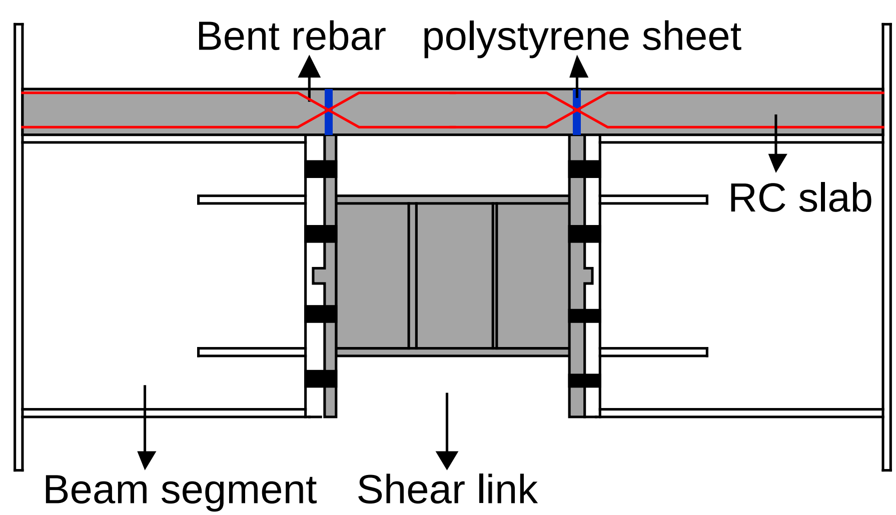
CBS1: Composite slab



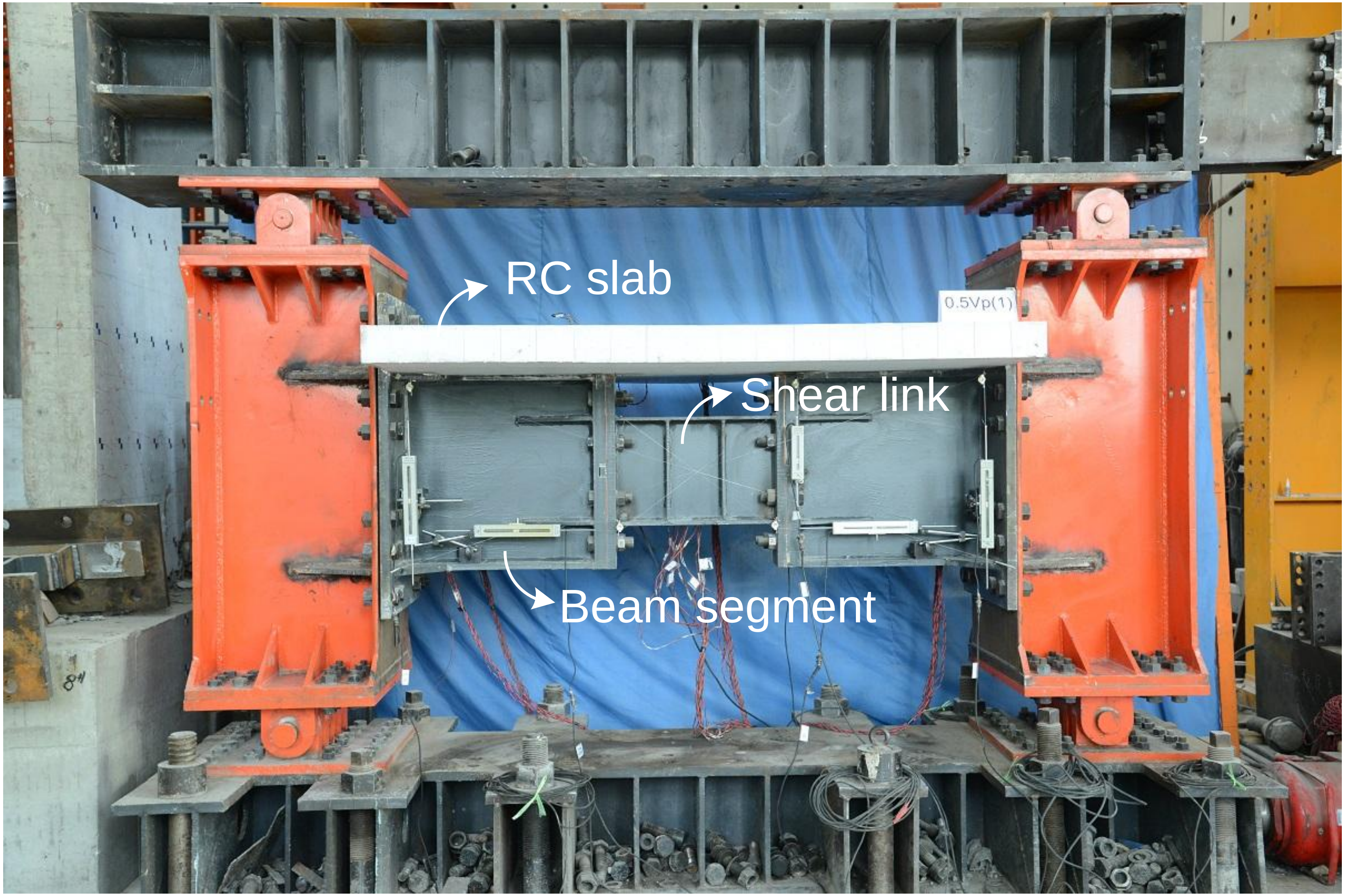
CBS2: Isolated slab



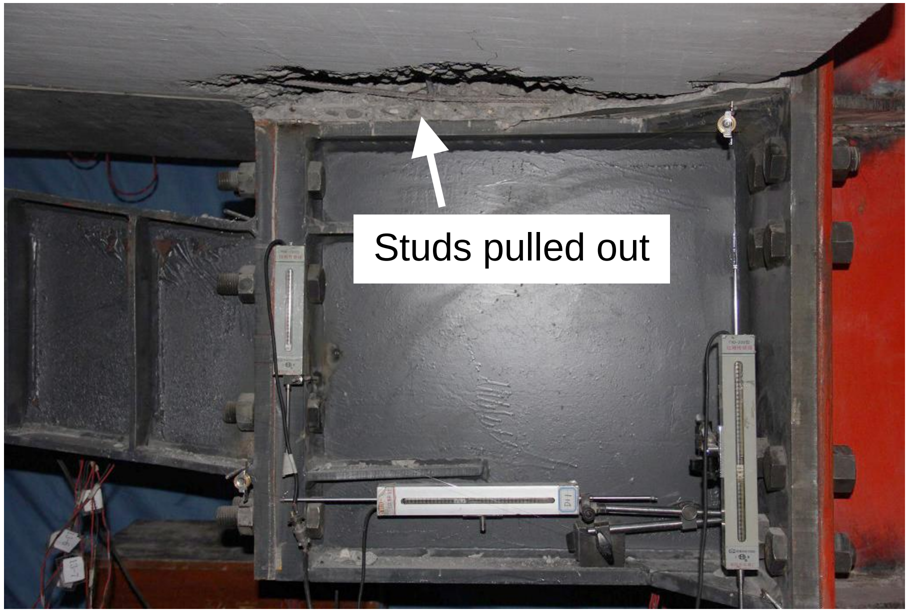
CBS3: Bearing slab

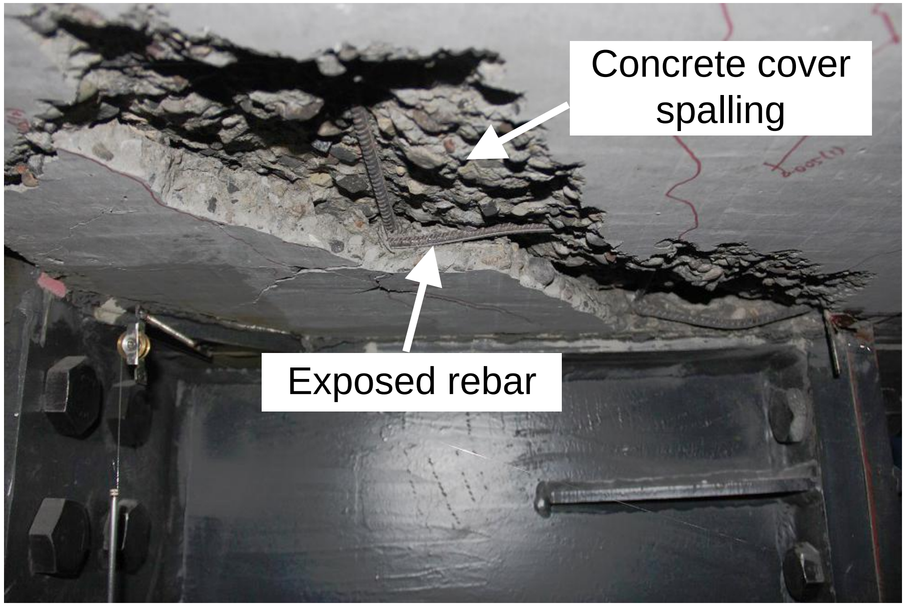


CBS4: Slotted slab

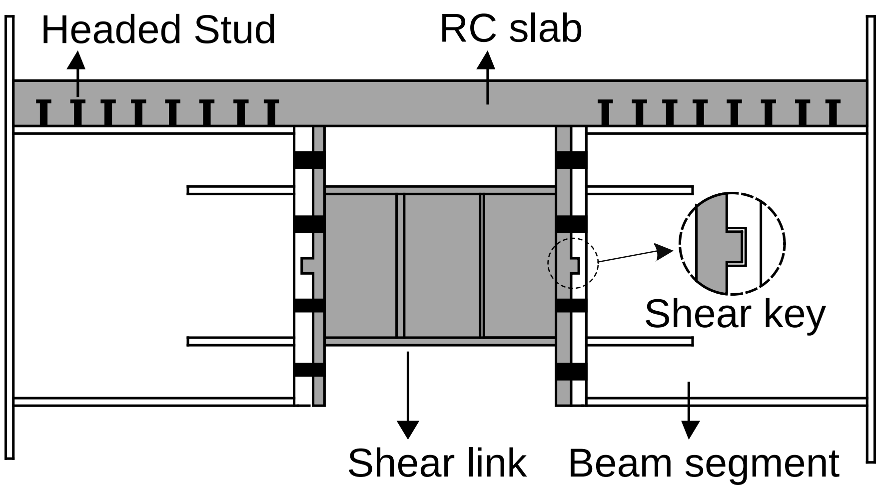

RC slab
0.5Vp(1)
Shear link
Beam segment

Slab damage

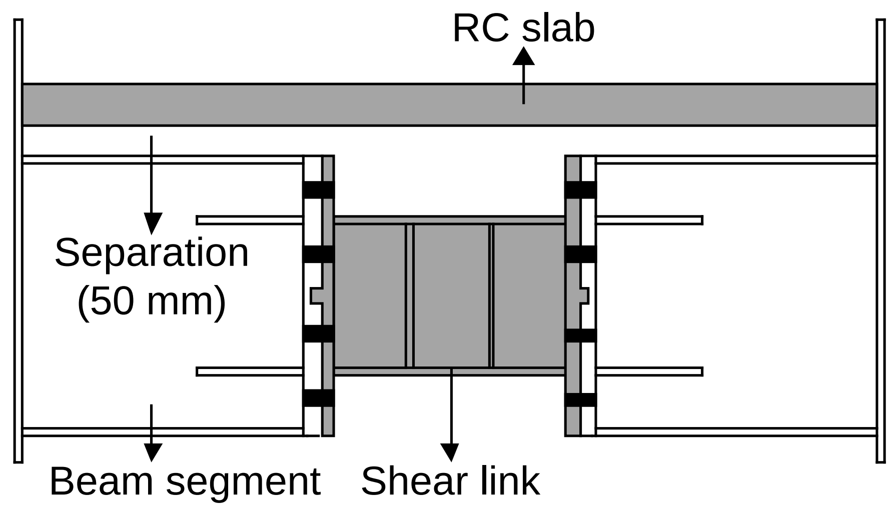




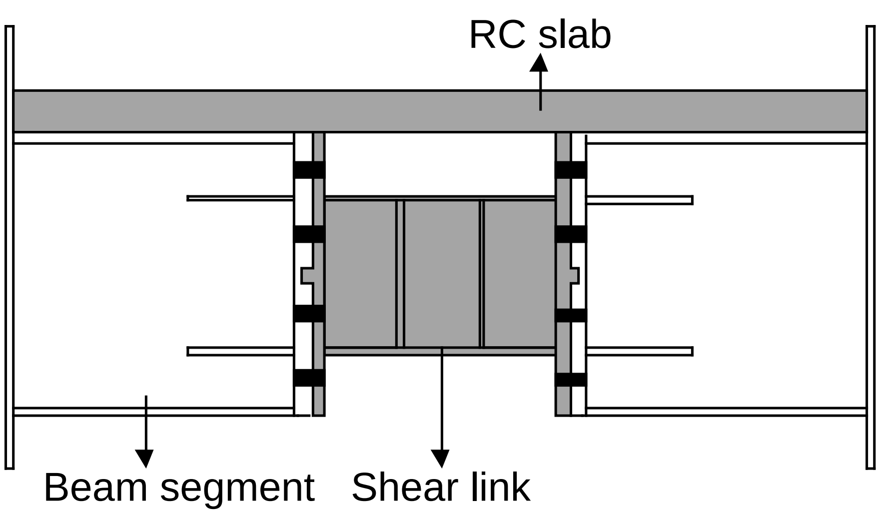
- At 0.04 rad beam rotation, most of shear studs pulled out from the RC slab, and the rebars were exposed and buckled.
- Shear studs are NOT recommended for use between the RSCBs and their above slabs.



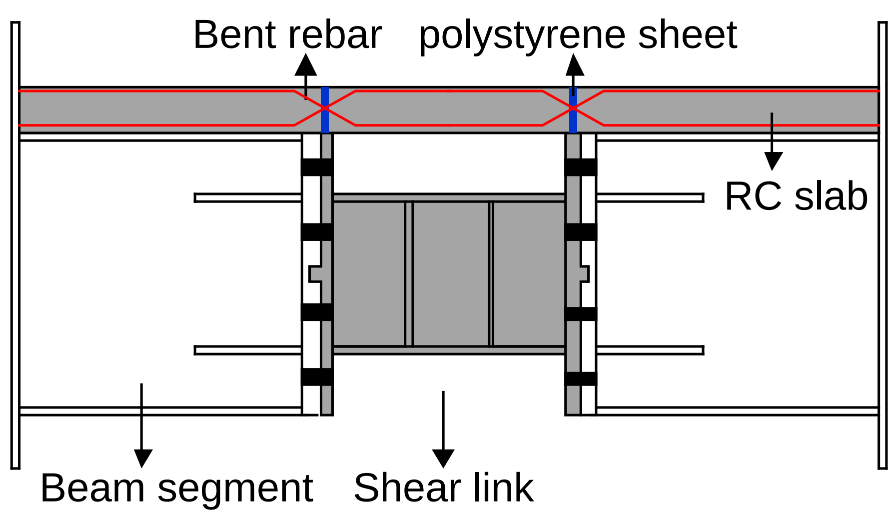
CBS1: Composite slab (BAD)



CBS2: Isolated slab (GOOD)

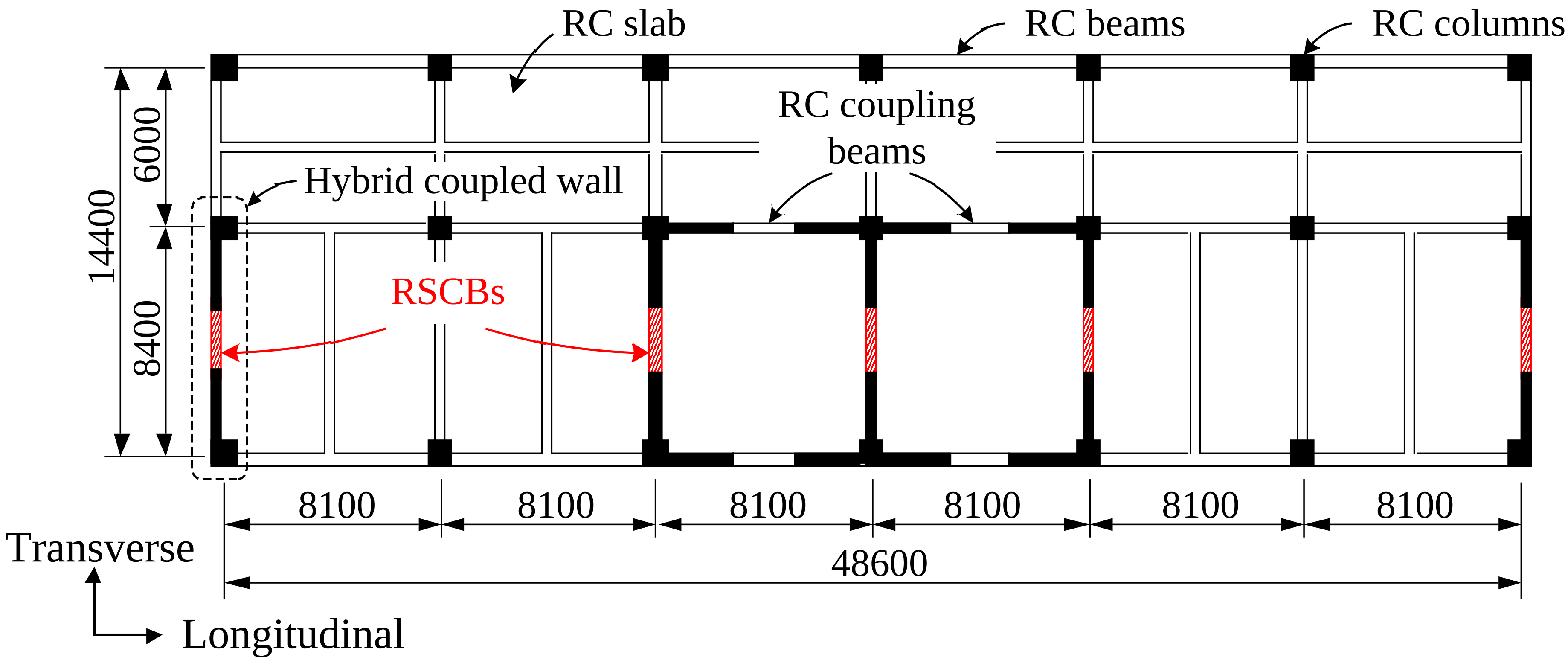


CBS3: Bearing slab (FAIR)



CBS4: Slotted slab (FAIR)

Beijing Sancai Building (11 story, 48.5 m)



- Design basis earthquake (DBE) PGA 0.2g
- Period：1.57 s (Y)、1.53 s (X)、1.26 s (Torsion)
- Seismic design: linear spectrum analysis under SLE
- Interstory drift ratio (SLE) < 1/800

Outlines

- Background
- RC coupling beams
- Steel plate reinforced RC coupling beams
- Assembled RC coupling beams
- Replaceable steel coupling beams
- Conclusions

Conclusions

■ Deep RCCBs behaved quite differently from ordinary frame beams after the appearance of inclined shear cracks. All the longitudinal reinforcement bars becoming in tension and the beams starting to elongate. The elongation strains of the beams were of the order of 1.5 to 2.5 %.

■High nominal shear stresses had led to the tendency of the deep RCCBs to fail in shear. Additional displacement due to the local rotations at the beam-wall joints had contributed about half to the total lateral displacement and resulted in the above relatively high drift ratios. Diagonally reinforced deep RCCB had a more stable hysteretic load-displacement curve and a much better energy dissipation capacity. Sufficient lateral hoops should be provided along the diagonal reinforcement.

■Steel plate RCCB can improve the behavior of Deep RCCB. Steel plate can resist more shear force with the displacement increasing. Stirrups also plays an important role in resisting the shear loads. The spacing of the stirrups should be limited to prevent the spalling of the concrete cover around the longitudinal reinforcement.

Conclusions

■ The precast shear wall structure with rebars spliced by grouted couplers(PSWGC) exhibited excellent seismic performance. No visible damage concentrated on the joints connecting precast members. The window belly wall, which was precast with wall limbs as a whole, significantly affected crack patterns of the lower coupling beams under large drift. The composite effect between the window belly wall and the lower coupling beams should be carefully considered in structure design.

■ Replaceable steel coupling beam is a feasible way for improving seismic performance of deep RCCBs in a CSW structure. Design philosophy and detailing method have been proposed.

Thanks much for your attention!