Seismic Performance of PT High-Strength Concrete Beam-Column Connections in part of Special Moment Frames

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Contents

Experimental Program

Experimental Program - Joints of SMF

- **Six Knee Joint Specimens / Four Exterior Joint Specimens**
- **Variables :** **1. Concrete compressive strength (35 ~ 120 MPa)**
  2. Steel fiber volumetric ratio = 1%
  3. Ratio of joint shear strength (0.58 ~ 1.54)
  4. Presence of post-tensioning

K-Joint		**E-Joint**	
K-RC-N	35 MPa V_j / V_n=0.62	E-SFRC-H	100 MPa SFRC V_j / V_n=1.28
K-PT-N-1	35 MPa PT V_j / V_n=0.69	E-PT-H-1	80 MPa PT V_j / V_n=0.98
K-PT-N-2	35 MPa PT V_j / V_n=0.98	E-PT-H-2	100 MPa PT V_j / V_n=1.29
K-PT-N-3	35 MPa PT V_j / V_n=1.24	E-PT-H-3	120 MPa PT V_j / V_n=1.54
K-RC-H	80 MPa RC V_j / V_n=0.58		
K-SFRC-H	80 MPa SFRC V_j / V_n=0.59		

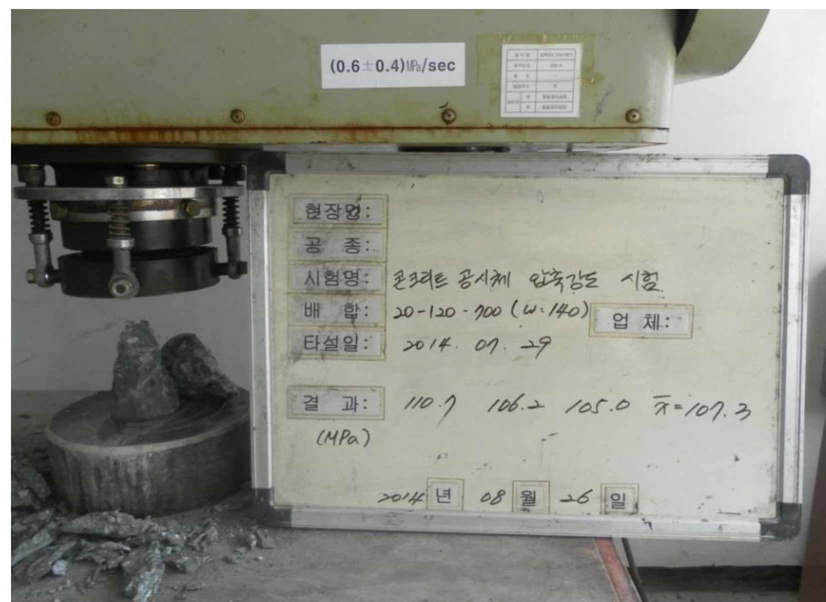
Concrete Mixture Proportion

Concrete Trial Mixture (2014. 7. 29)

- **Conducted trial mixture to find proper mixture proportion (HRWR = 10~12 kg/m^3)**
- **Target strength: 120 MPa, 120+@ MPa**
- **120 MPa: Decreased 10 kg water from the original mixture proportion**
- **120+@ MPa : Decreased 20 kg water from original mixture proportion**
- **Zirconium was used for low heat of hydration / long-term strength**

Concrete Trial Mixture Result

Strength	Date	Test piece	f_c' (3 day)	f_c' (7 day)	f_c' (28 day)
120 Mpa	2014.7.29	1	71.5	94.1	101.7
		2	77.2	92.1	101.9
		3	77.9		108.6
		Average	75.5	93.1	**104.1 MPa**
120+@ Mpa	2014.7.29	1	82.3	96.8	110.7
		2	81.7	93.8	106.2
		3	79.6	92.1	105.0
		Average	81.2	94.2	**107.3 MPa**



Mixture Proportion for Cast-In-Place

- **Mixture proportion was finalized based on trial mixture proportion & facility.**
- **Concrete curing without heat treatment**
- **Used vinyl curtain to keep heat and prevent evaporation**
- **7 day curing on the site for sufficient strength development**
- **One batch: 1.5 m^3 to prevent overload of silo**

Target Strength (MPa)	W/B (%)	S/a (%)	Unit weight (kg/m^3)					
			W	C	Slag powder	Zr	G	S
80	18.8	40	150	400	280	**120**	882	578
100	14.9	36	140	470	329	**141**	876	484
120	13.5	35	130	432	384	**144**	892	473

W/B = water to binder ratio; S/a = fine aggregate percentage; Zr = zirconium; G = coarse aggregate; S = fine aggregate

Cast-In-Place

Final Strength

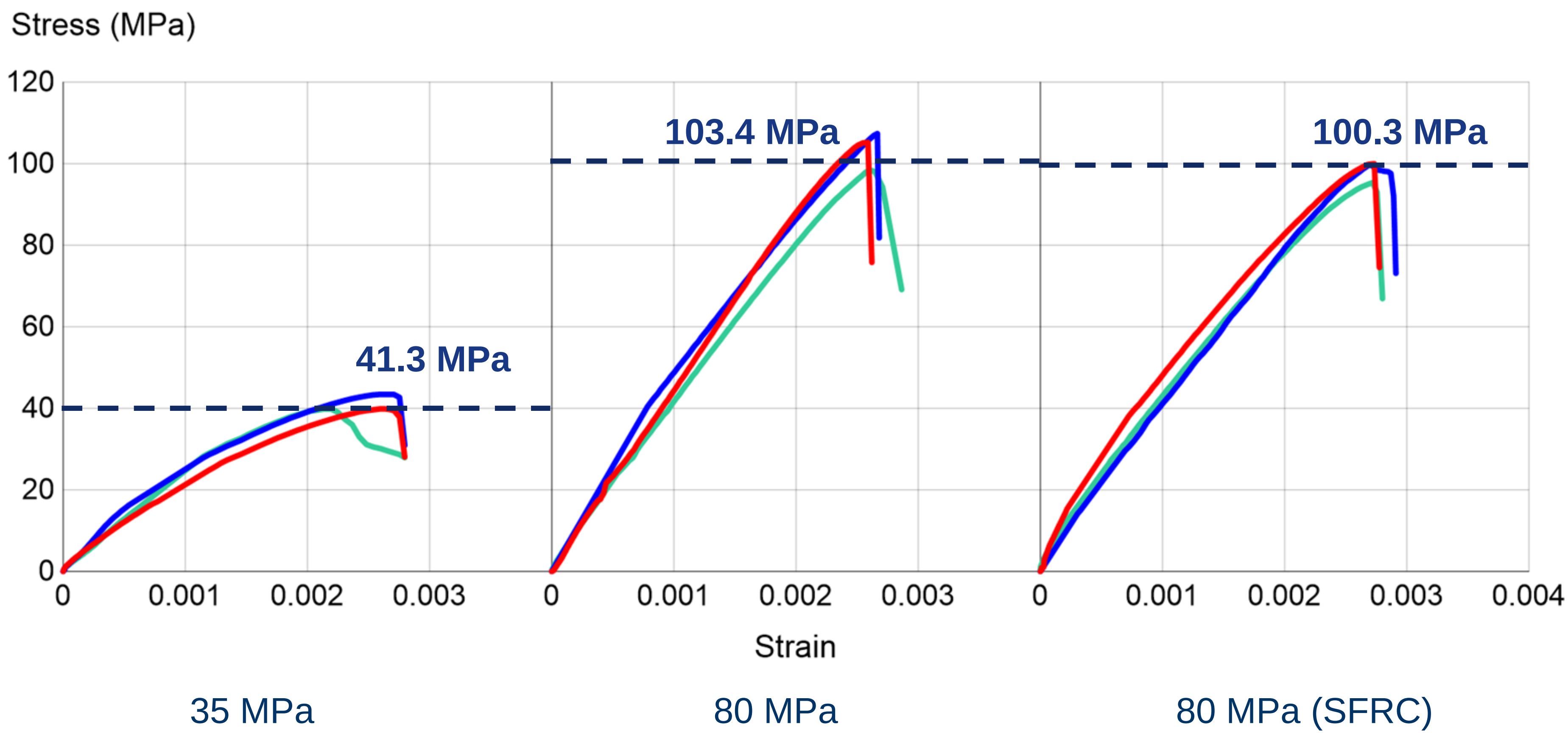
- **35, 80, 80 (SFRC), 100 (SFRC) MPa concretes**
- **100, 120 MPa concretes did not exceed the target strength.**

(MPa)

Design strength	**Date**	**f_c' (28 day)**	**f_c' (90 day)**	**f_c' (120 day)**	**f_t (120 day)**	**f_c' / f_t (120 day)**	
35	07.31	37.0	38.3	41.3	5.4	0.13	
80	09.20	87.3	85.0	103.4	9.2	0.09	
80 (SFRC)	09.23	67.3	94.7	100.3	10.6	0.11	
100	10.14	71.7	75.5	80.6	9.4	0.12	**lower**
100 (SFRC)	09.29	92.3	101.3	102.8	12.4	0.12	
120	10.02	69.7	97.0	96.0	7.6	0.08	**lower**

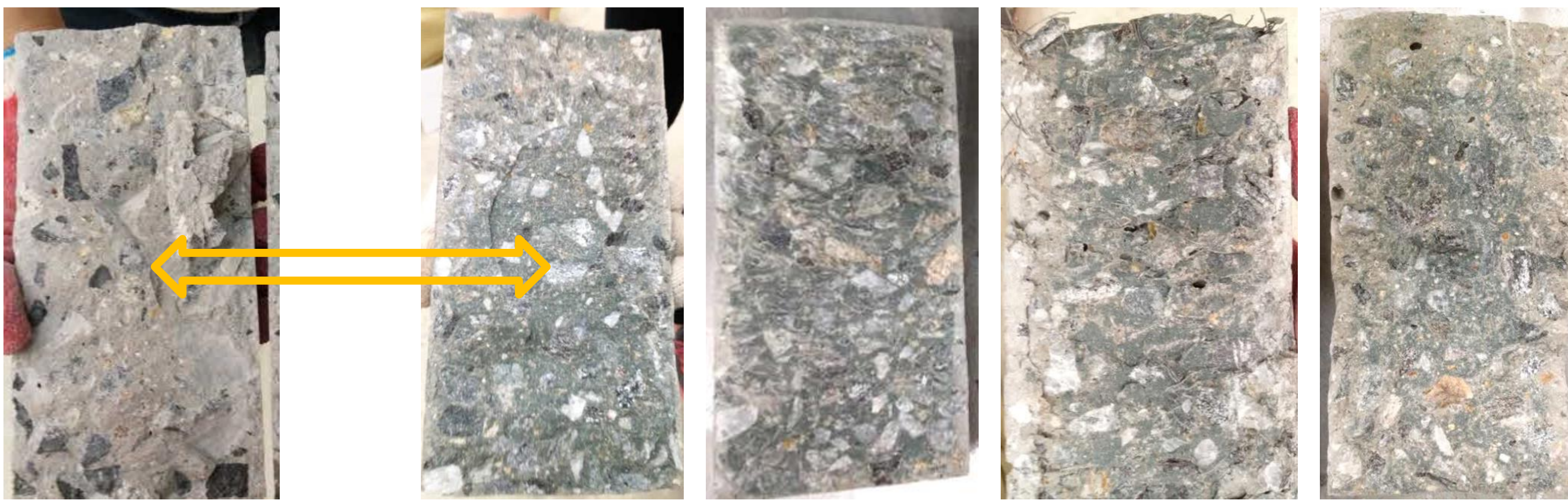
Concrete Stress-Strain Curves

- **The ultimate strain ε_{cu} for 35 MPa, 80 MPa, 80 MPa (SFRC) ~ 0.003.**



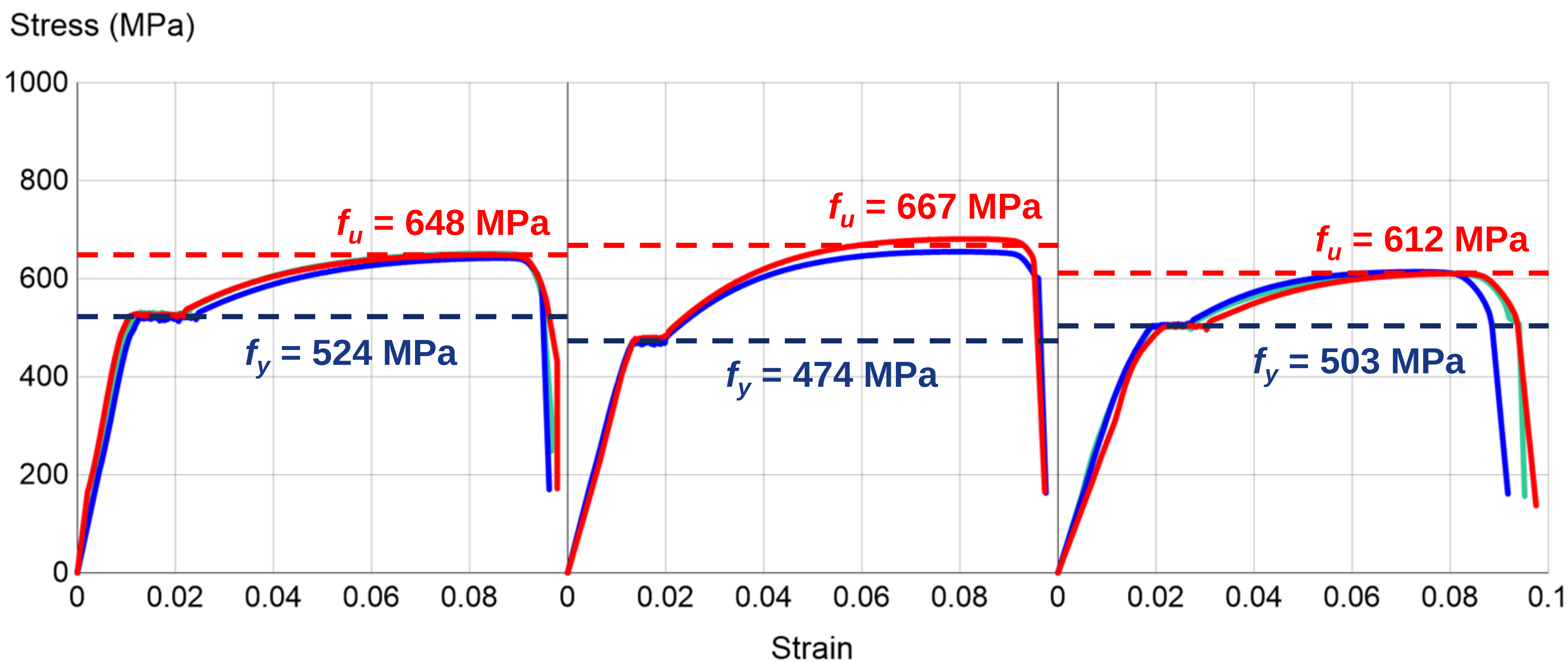
Very High-Strengh Concrete

- **35 MPa (without Zr): gray**
- **High-strength concrete (with Zr): gray (7~15 mm depth),**
  blue-green (inside)
- **After splitting tensile tests, it was found that aggregates were destructed.**
  (Typical feature of high-strength concrete)



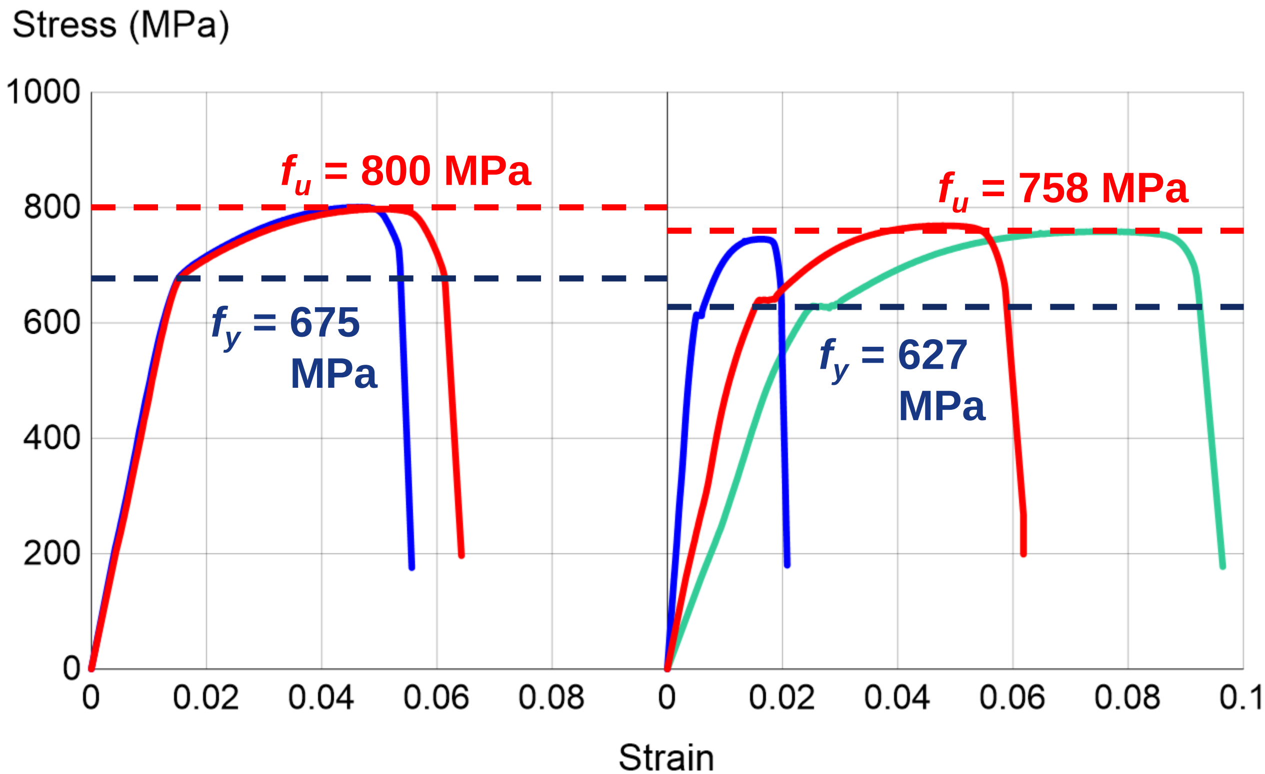
35 MPa | 80 MPa | 100 MPa | 100 MPa (SFRC) | 120 MPa

Deformed Steel Bars



SD400 D19 SD400 D22 SD400 D29

Deformed Steel Bars

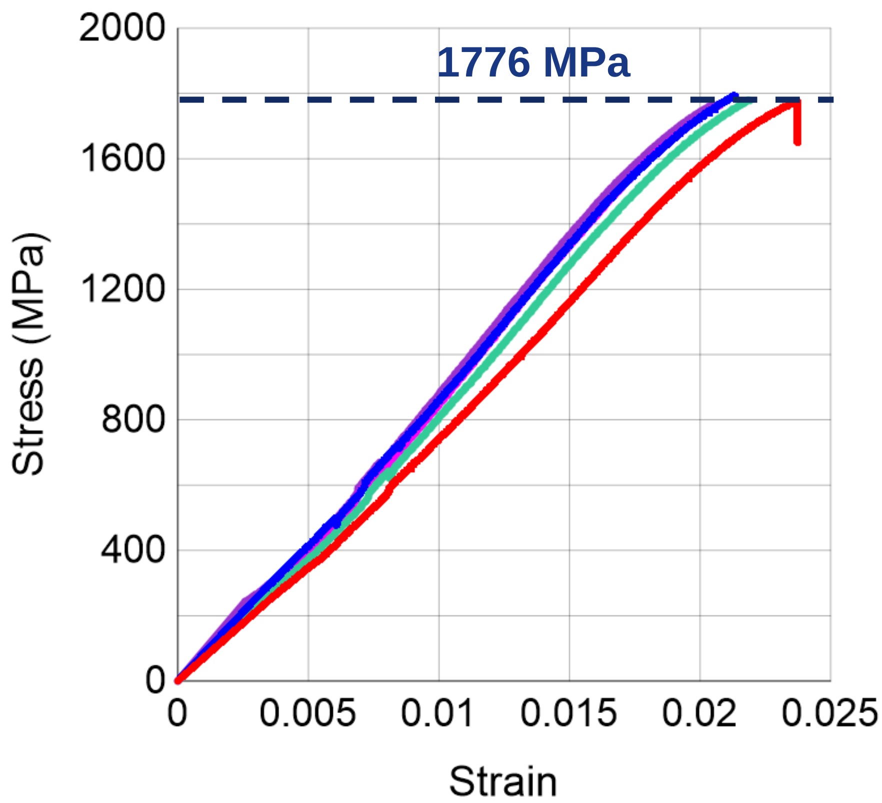


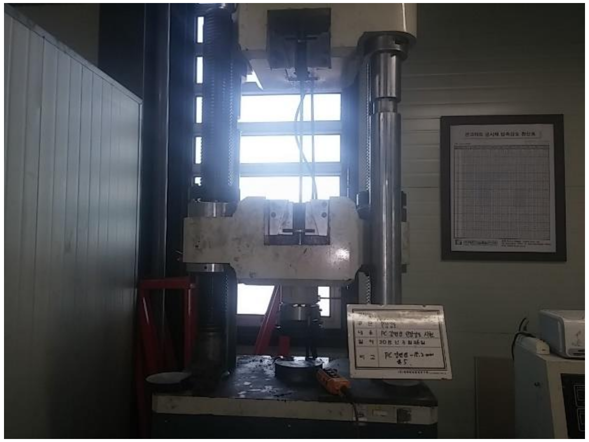
SD600 D22

SD600 D29

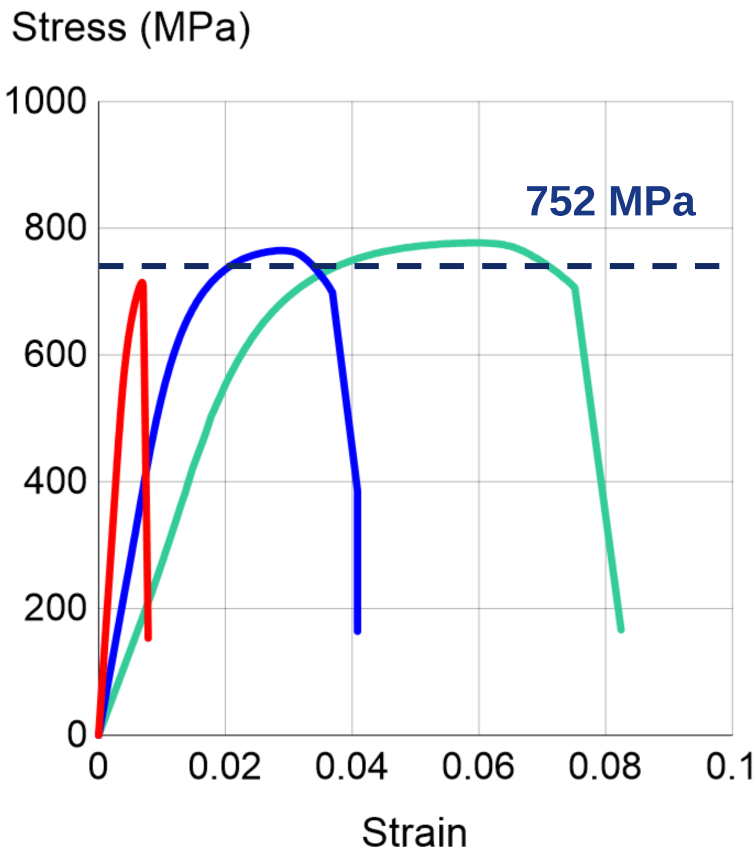
Strand Stress-Strain Curves

- **15.2 mm diameter unbonded tendons (1860 MPa)**
- **Measured 1776 < 1860 MPa (270 ksi) was likely due to grease-induced wedge slip.**





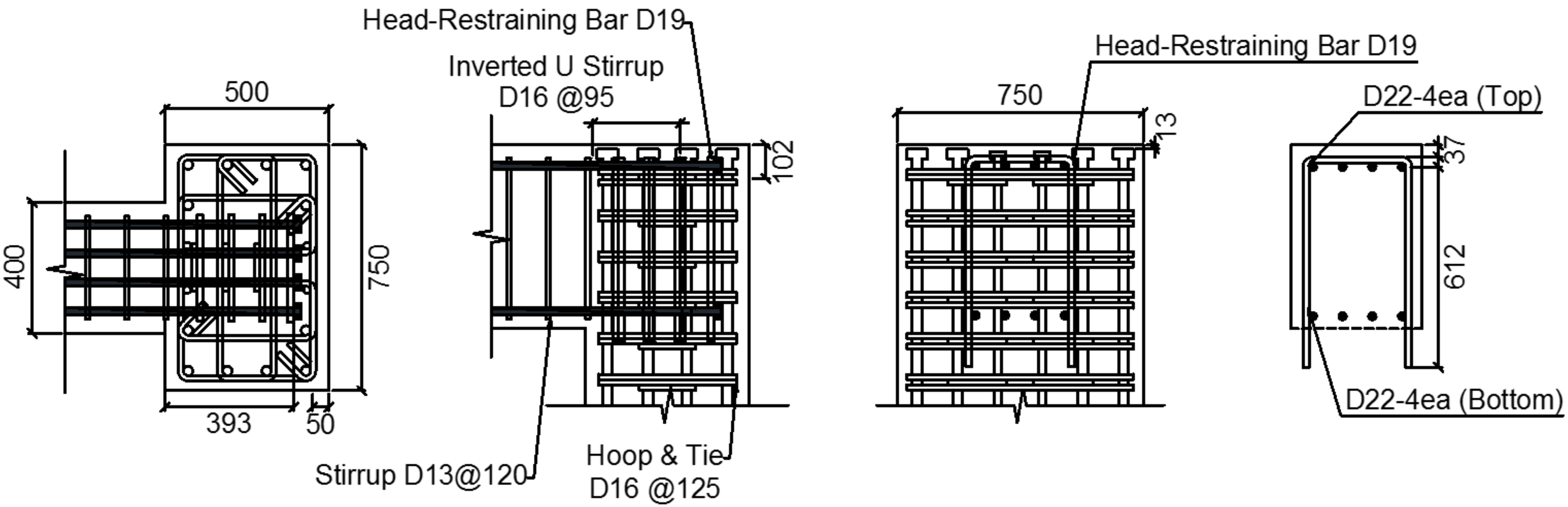
Steel for Heads of Headed Bars



Details of Specimens

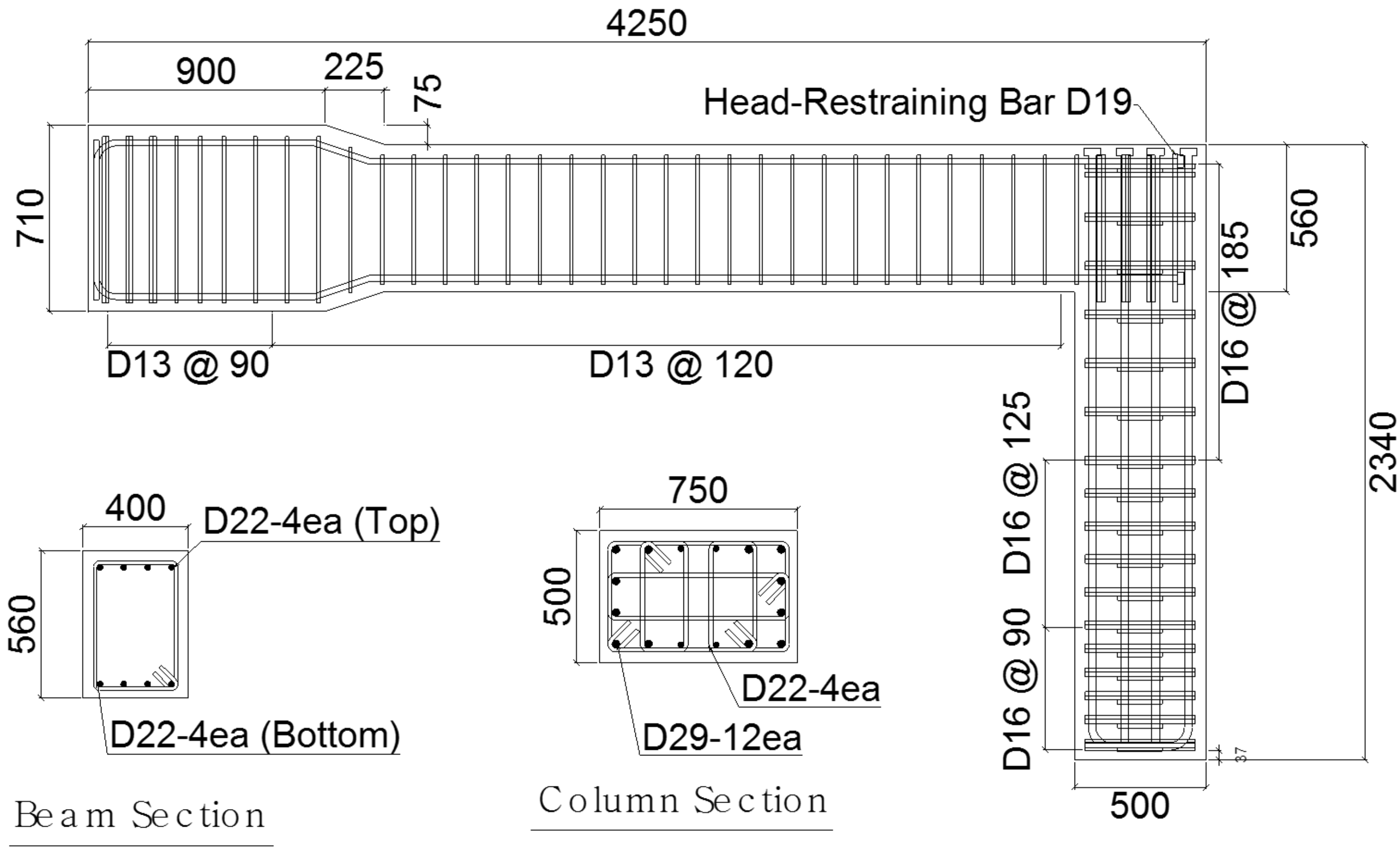
K-Joint (High-strength Concrete)

- **Head-restraining bars are placed just before the head. (2/3 of required amount)**
- **K-SFRC-H specimen w/ V_f = 1% had 150% of the spacing of hoops.**



K-RC-H (Unit: mm)

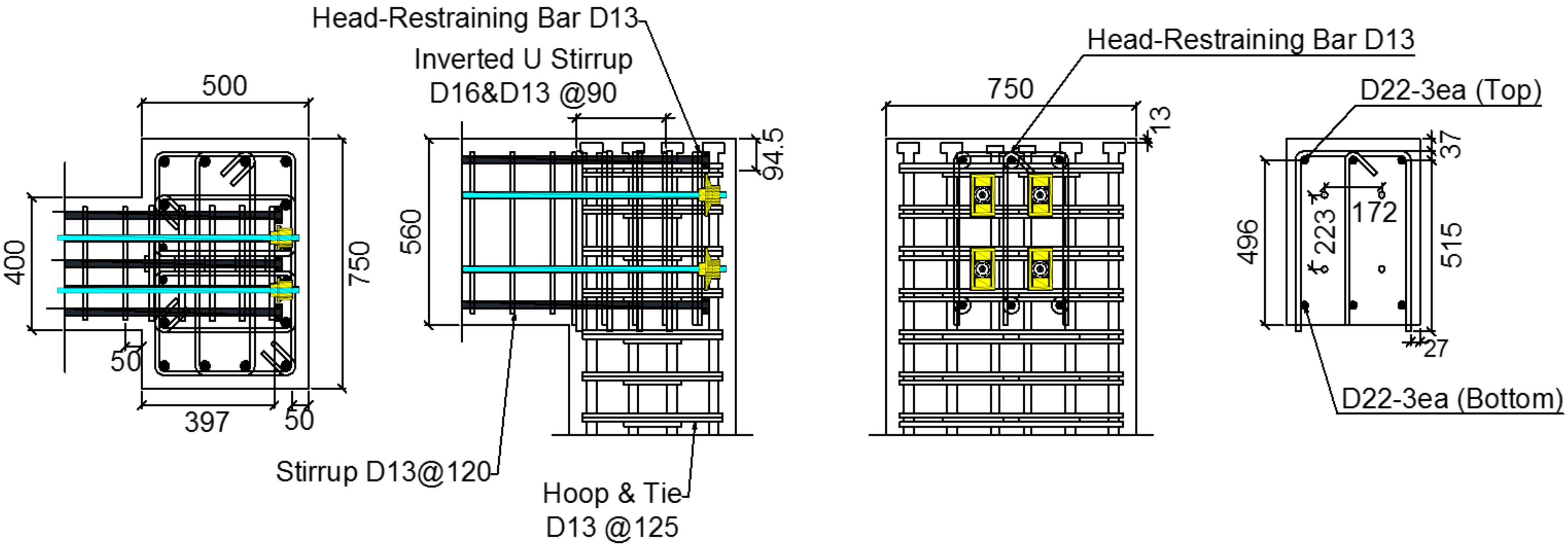
K-Joint (High-strength Concrete)



K-SFRC-H (Unit: mm)

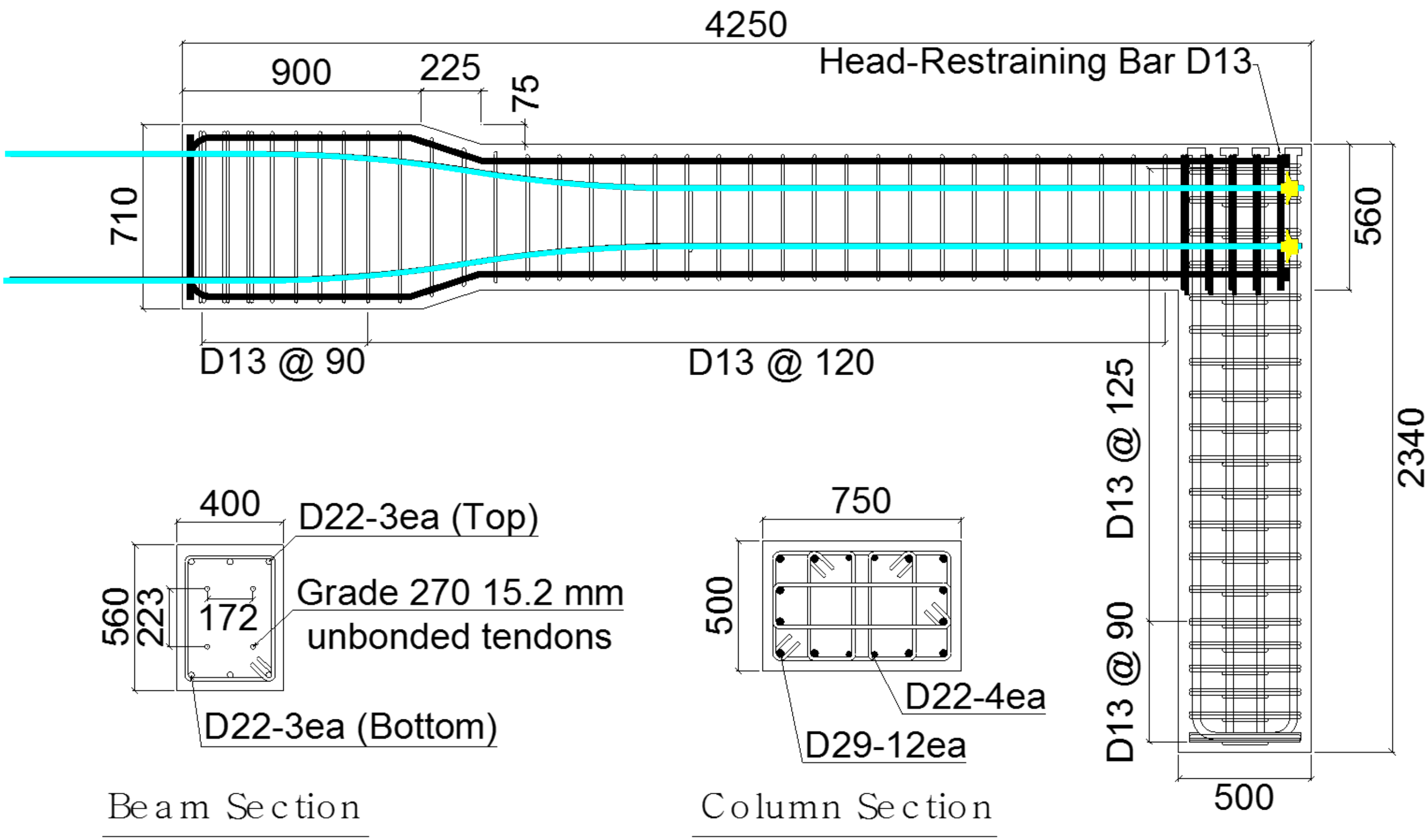
K-PT-Joints (Normal-strength Concrete)

- **Four Grade 270, 0.6 in. diameter unbonded tendons were provided.**
- **Three joint shear to joint shear strength ratios (**V_j / V_n = 0.76, 1.01, 1.36)



K-PT-N-1 (Unit: mm)

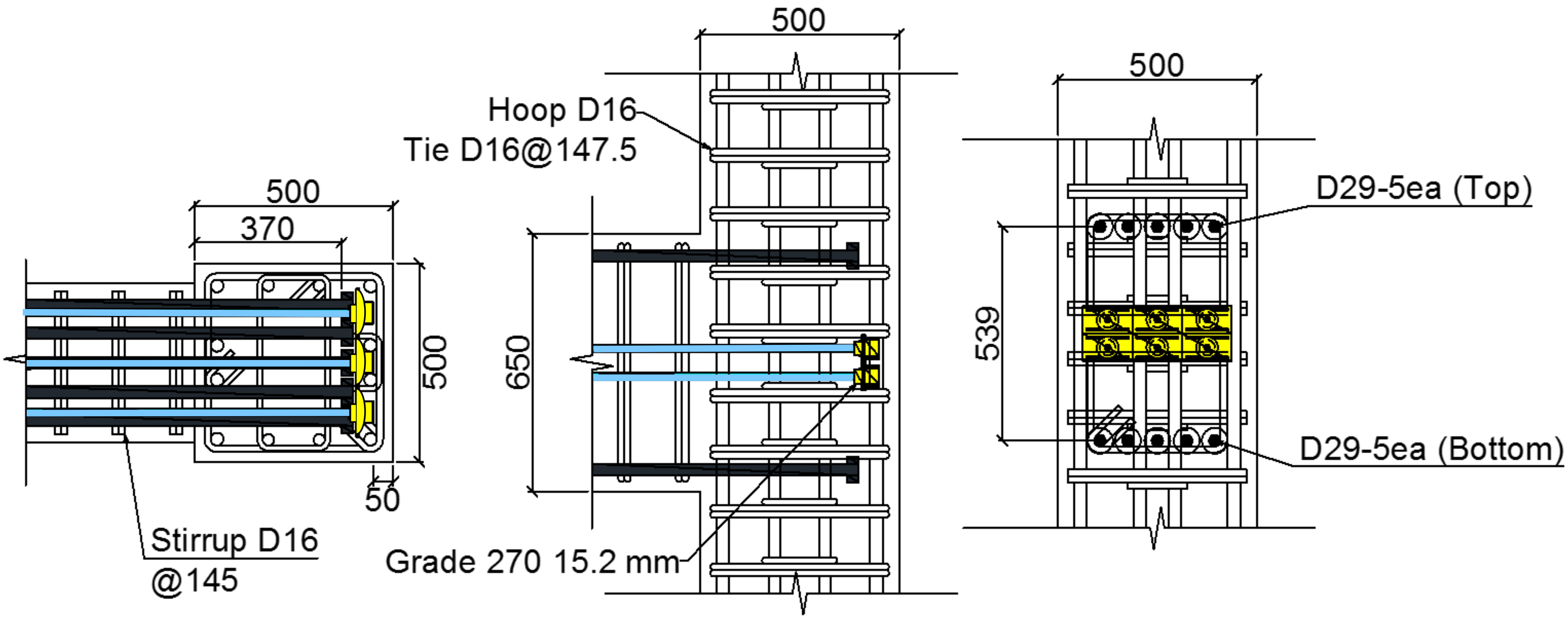
K-PT-Joints (Normal-strength Concrete)



K-PT-N-1 (Unit: mm)

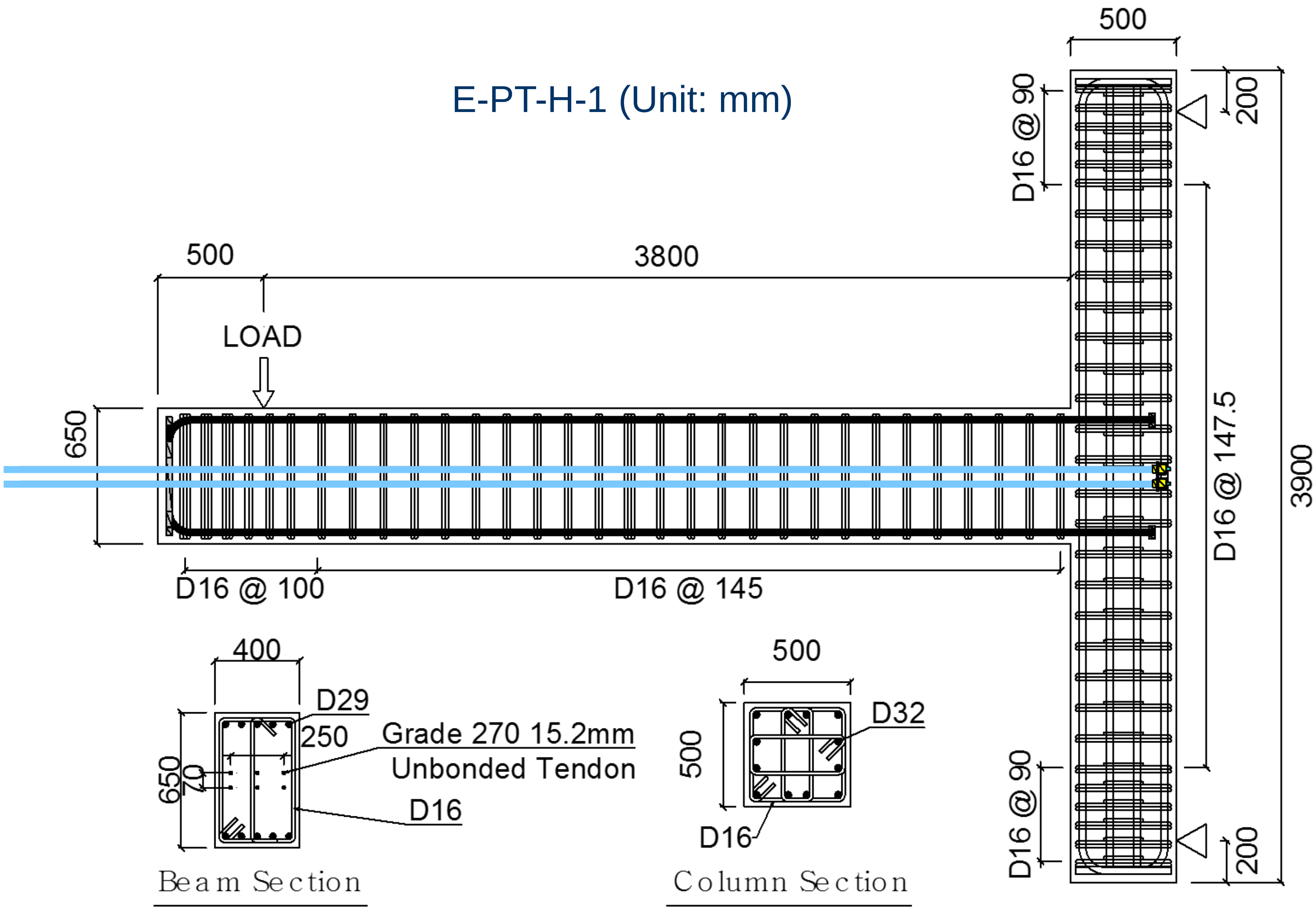
E-PT-Joints (High-strength Concrete)

- **Six Grade 270, 0.6 in. diameter unbonded tendons were provided.**
- **Three joint shear to joint shear strength ratios (**V_j / V_n = 1.22, 1.3, 1.52)



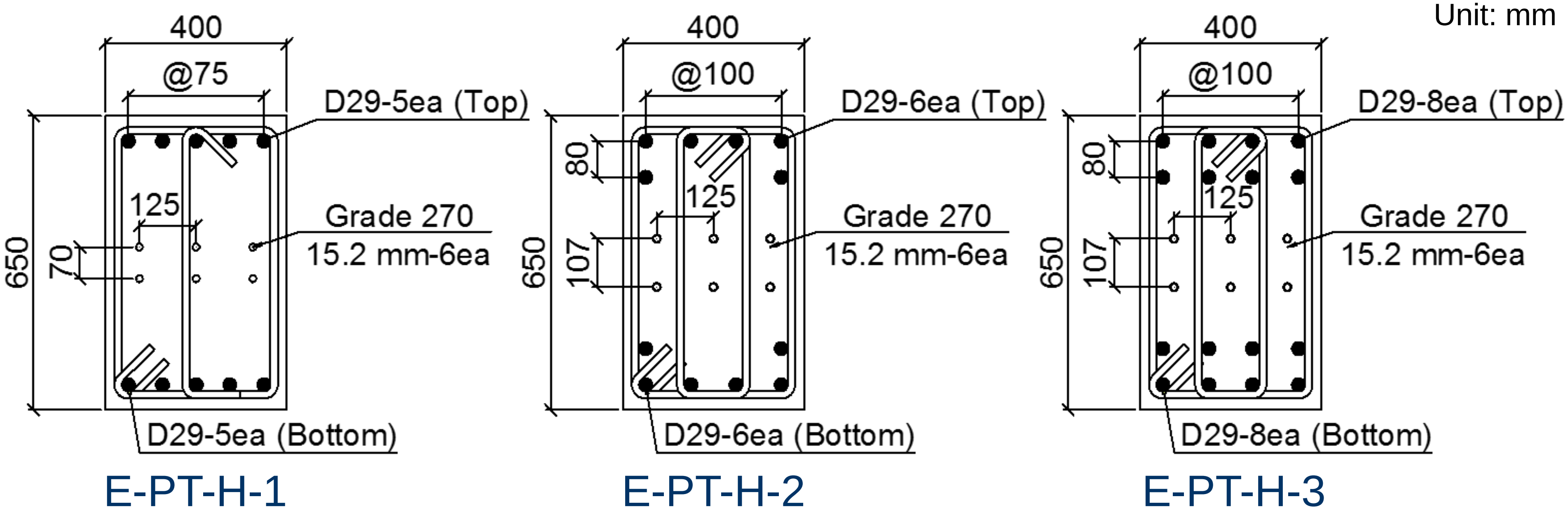
E-PT-H-1 (Unit: mm)

E-PT-Joints (High-strength Concrete)



E-PT-Joints (High-strength Concrete)

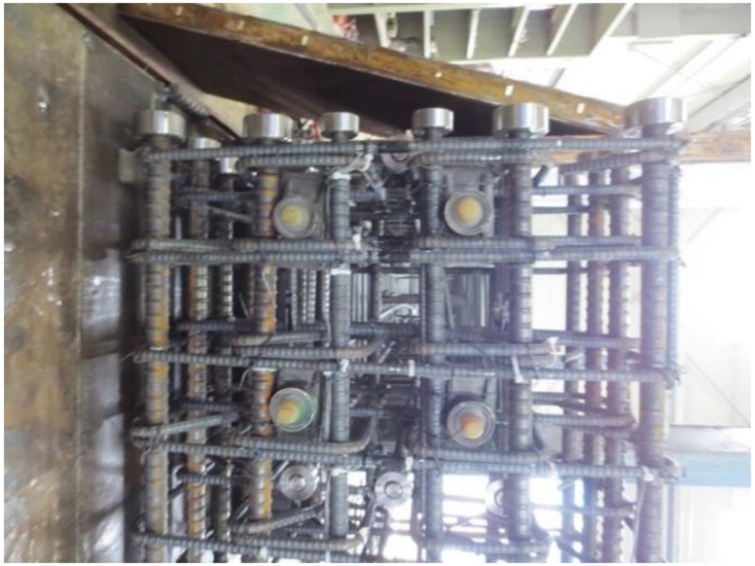
Unit: mm



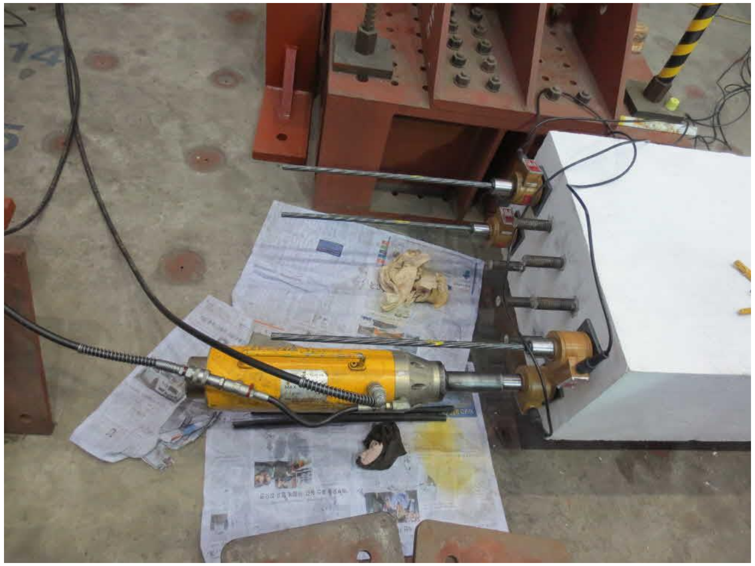
Specimens	V_j	V_n	V_j / V_n
E-PT-H-1	2443	2004	0.98
E-PT-H-2	2914	2241	1.29
E-PT-H-3	3737	2455	1.54

V_j : joint shear force demand at M_{pr} (assuming internal level arm ~ 0.9d);
V_n : joint shear strength

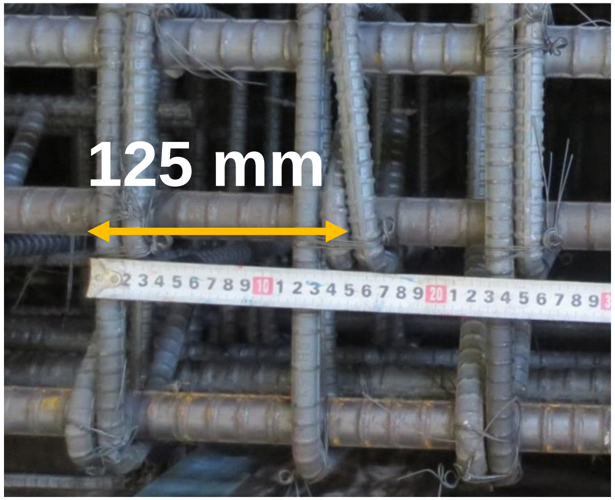
Details



Jacking

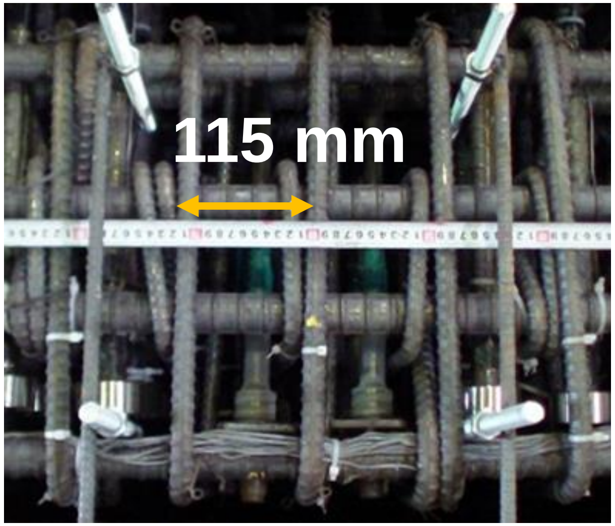


Spacing of Transverse Reinforcement (SFRC)

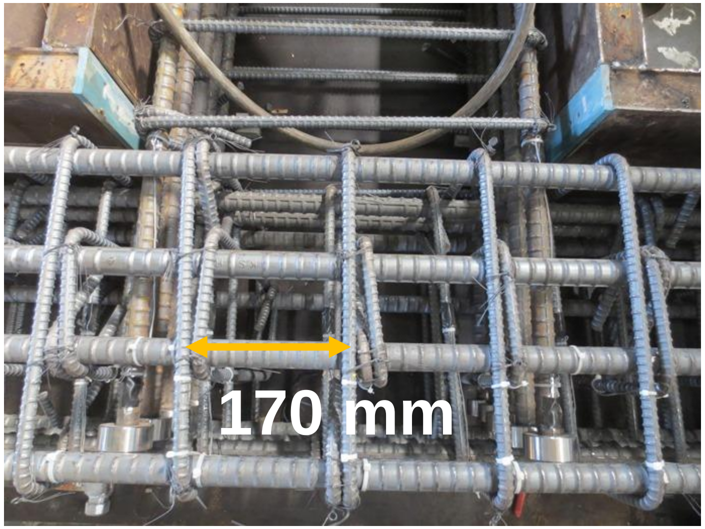


K-RC-H

K-SFRC-H



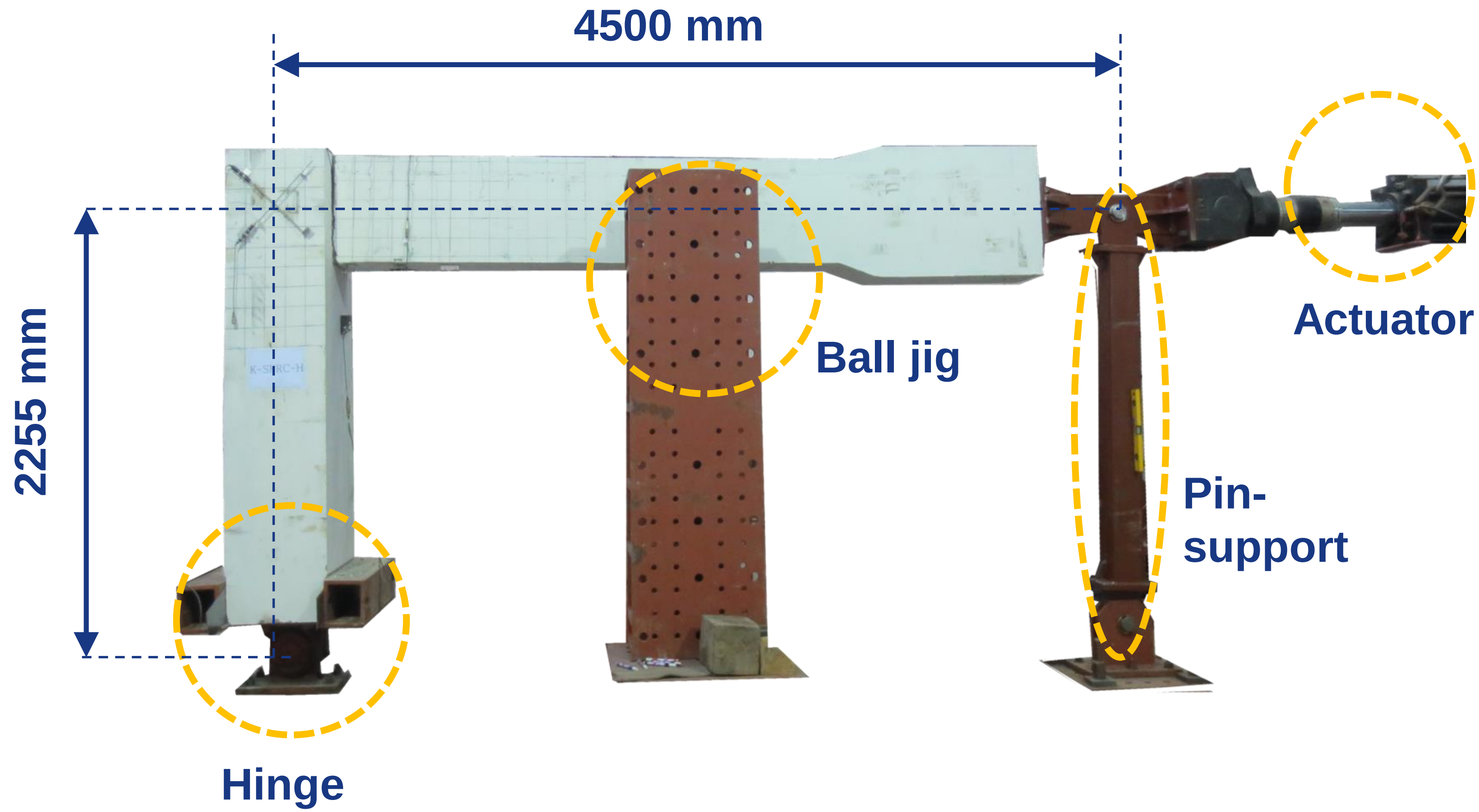
E-PT-H-2



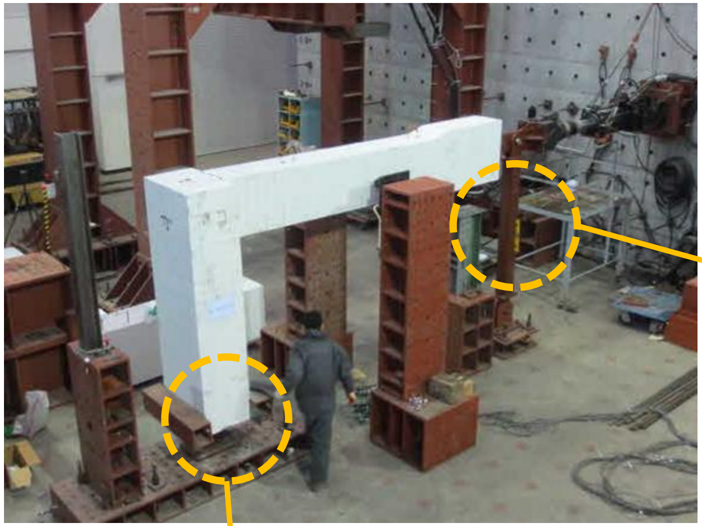
E-SFRC-H

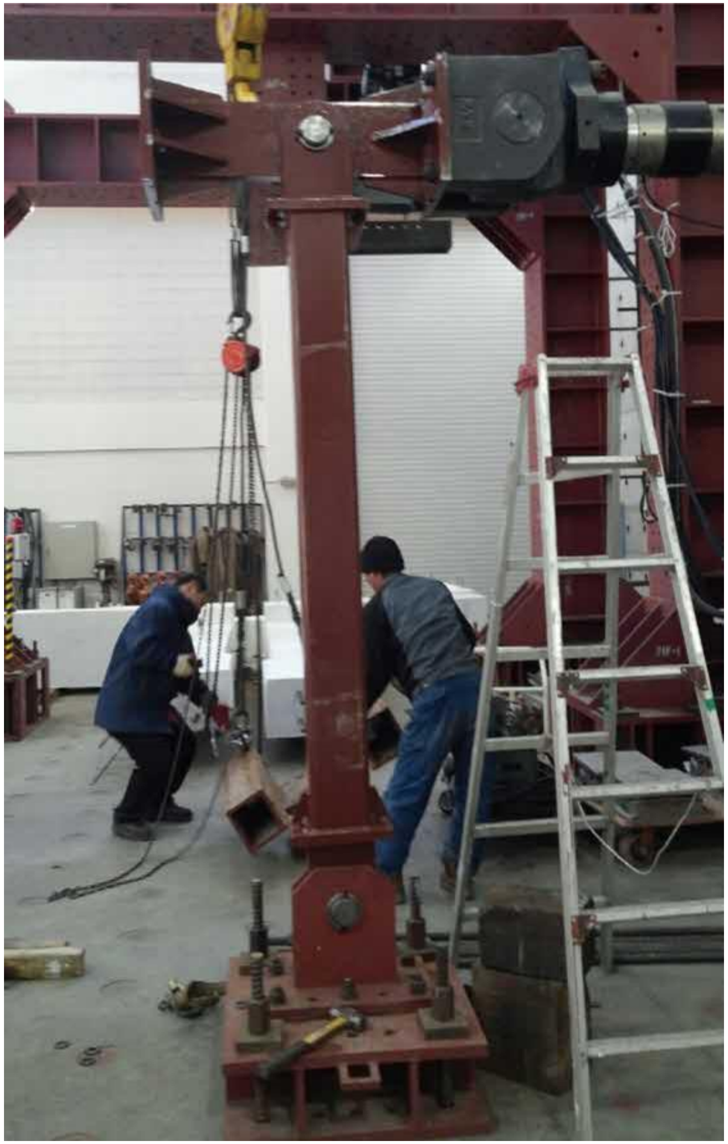
Reversed Cyclic Tests

Test Set-up (K-Joints)

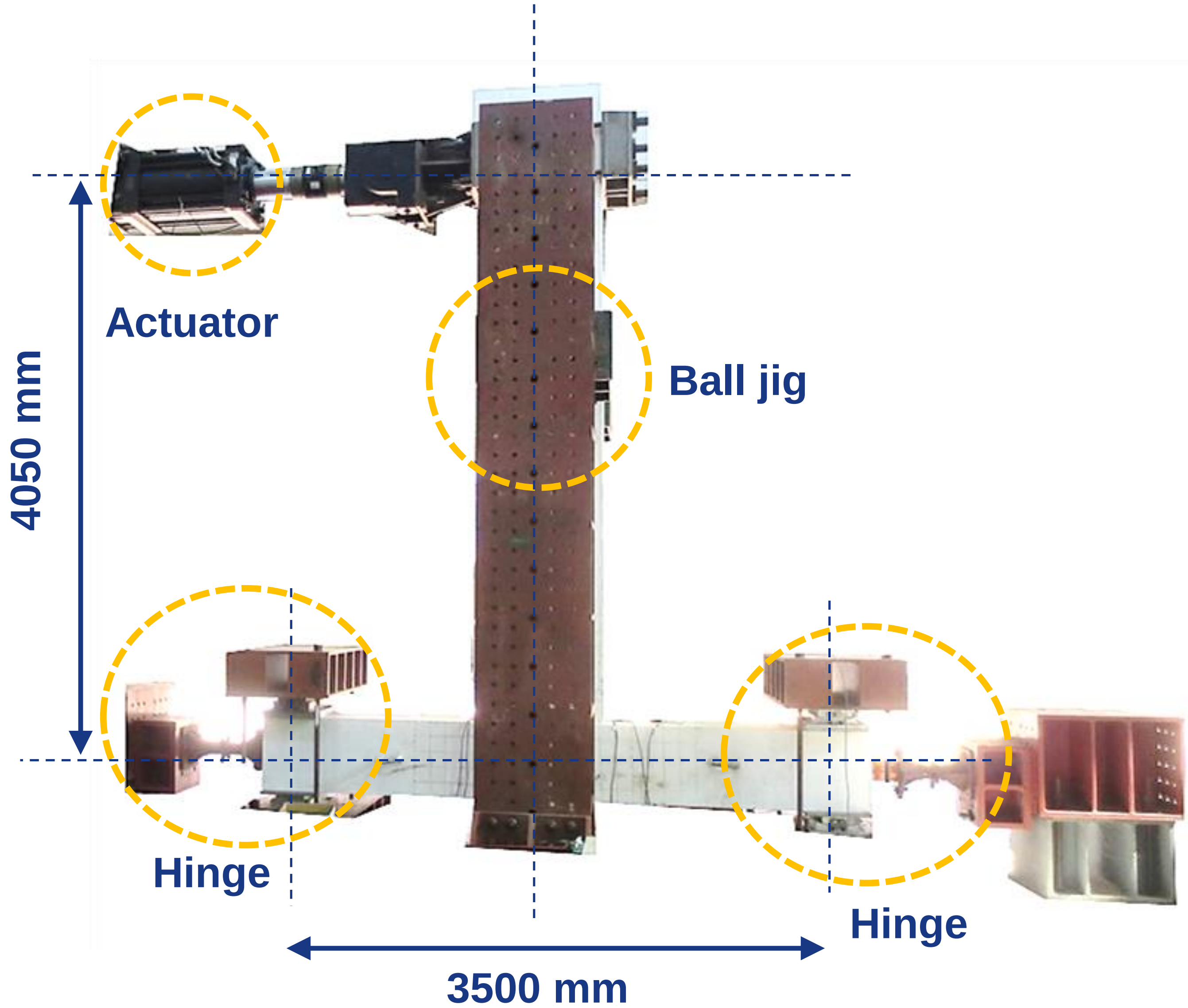


Test Set-up (K-Joints)

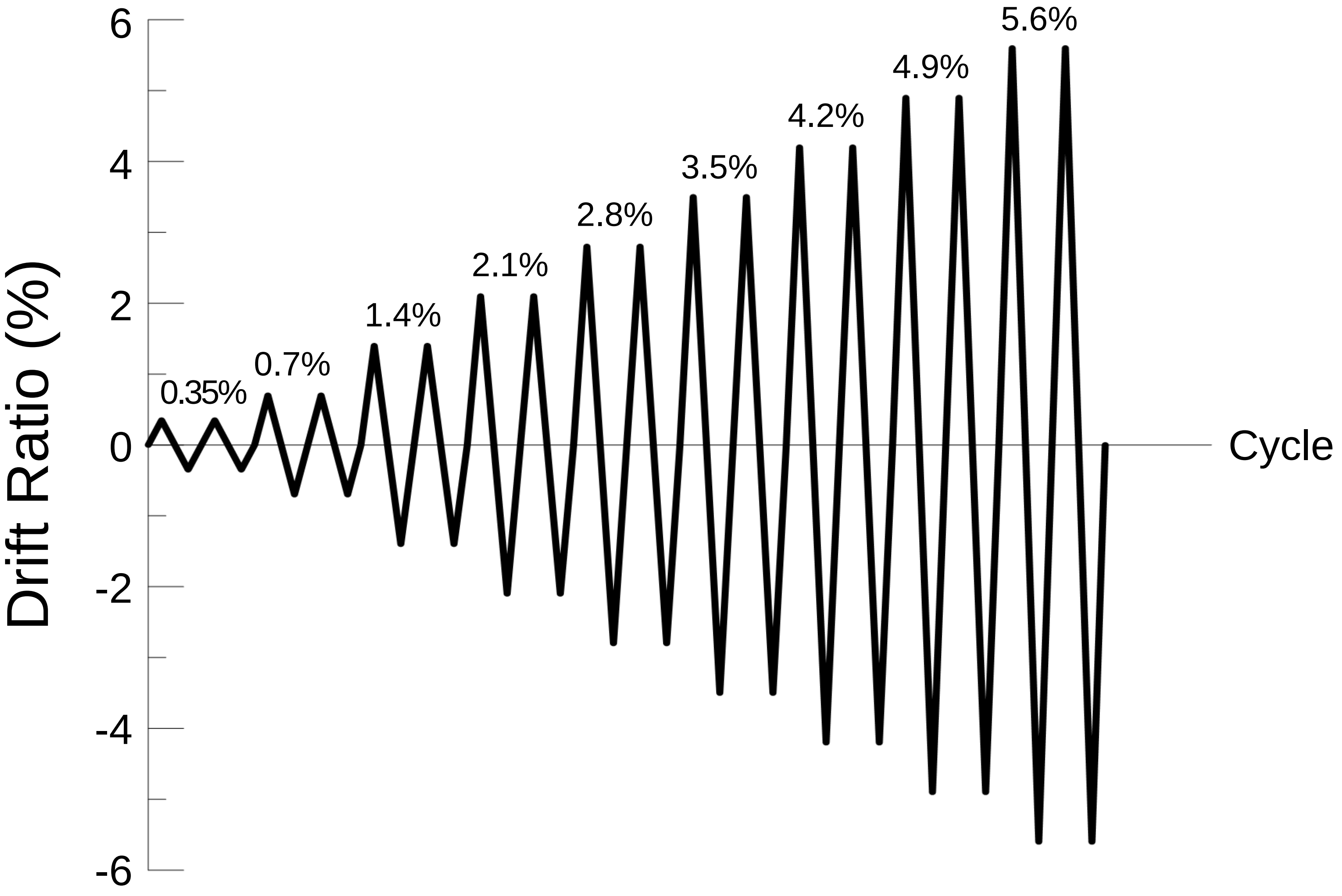




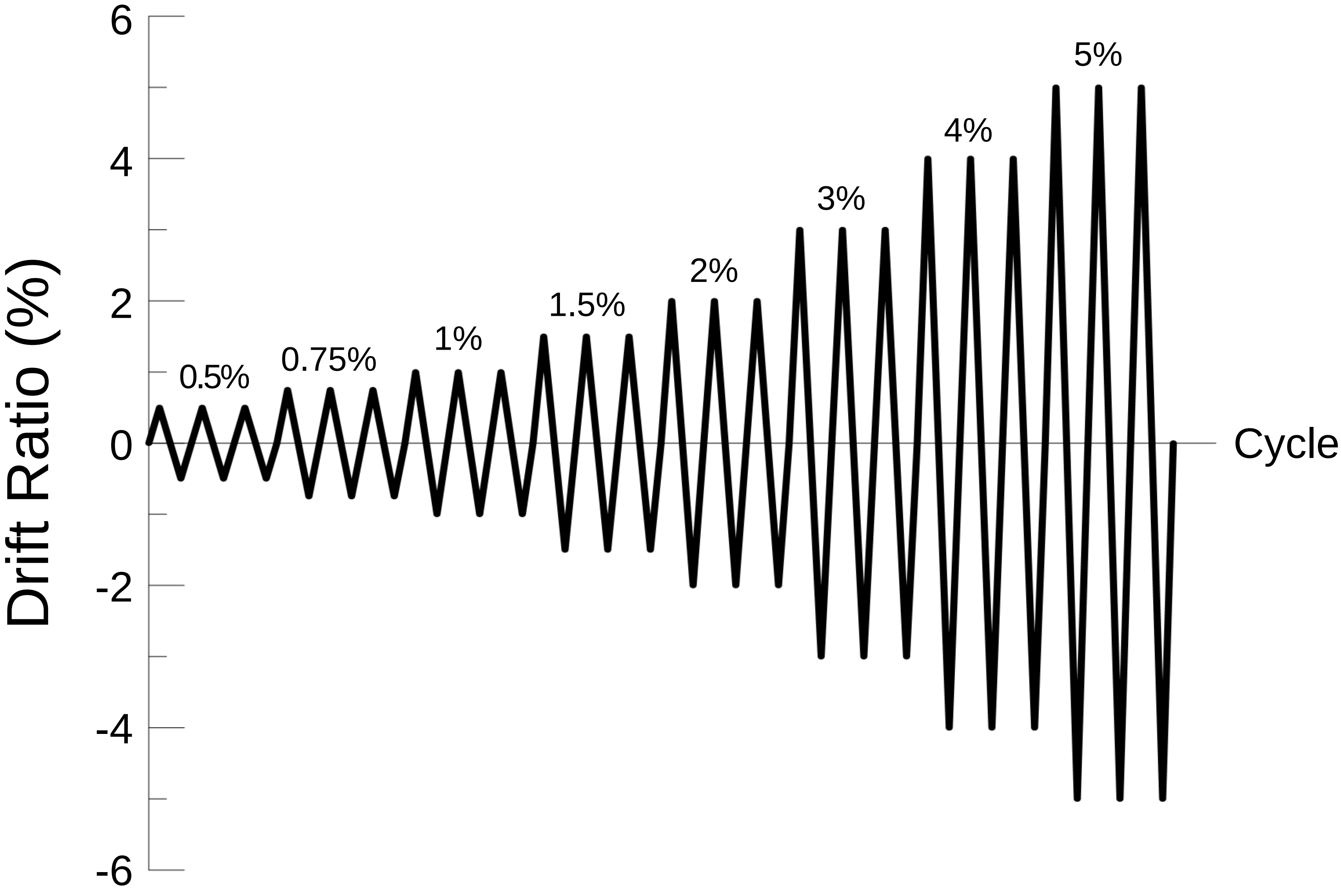
Test Set-up (E-Joints)



Loading Histories (K-Joints)



Loading Histories (E-Joints)



K-PT-N-1 Test Video Clip

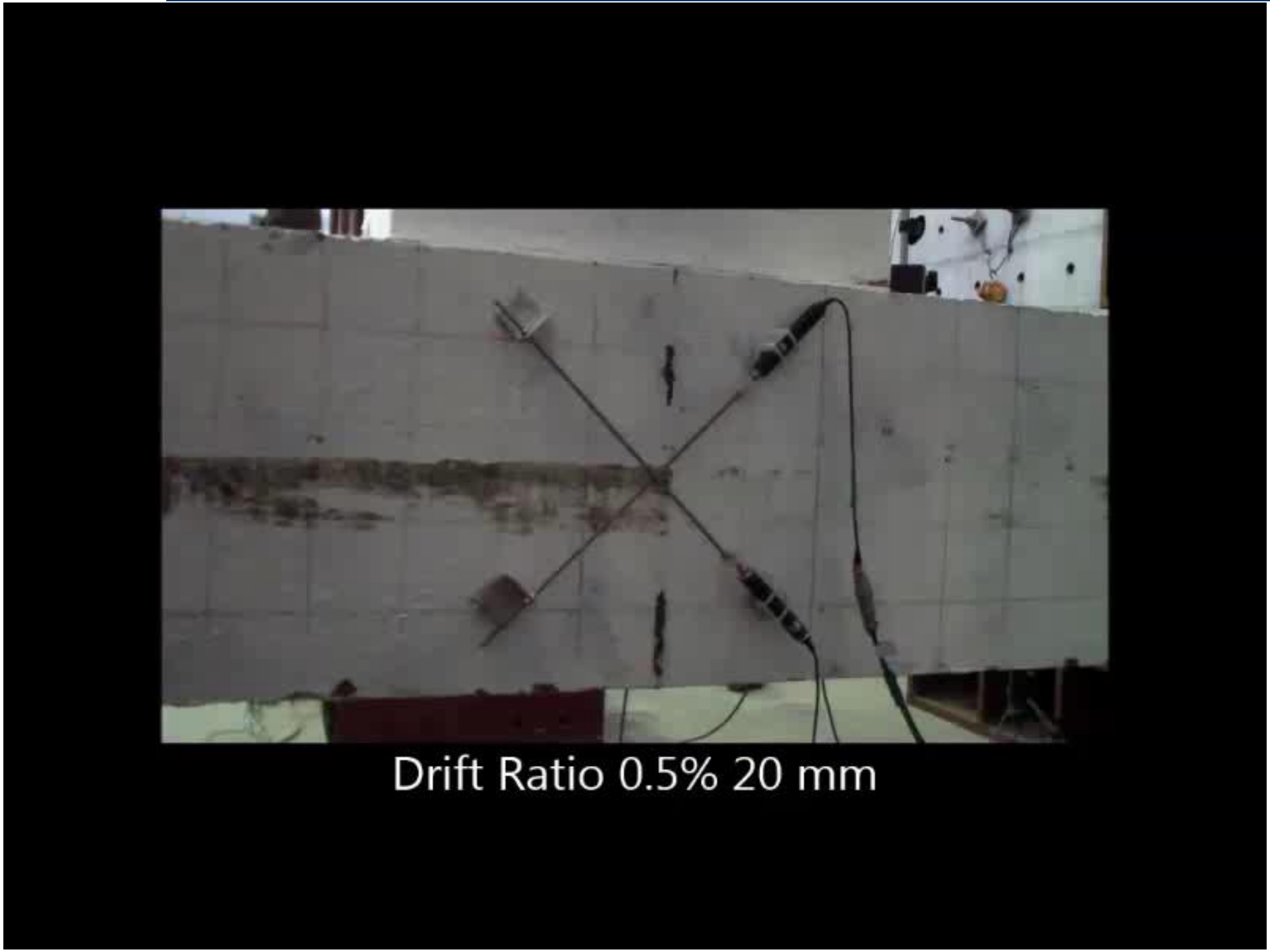
K-PT-N-3 Test Video Clip

E-PT-H-1 Test Video Clip

Drift Ratio 0.5% 20 mm

E-PT-H-2 Test Video Clip

E-PT-H-3 Test Video Clip



Test Results

Test Results (Moments of RC K-Joints)

- **For knee joints' tests, axial forces should be considered because the actuator applies lateral loading by pushing or pulling the beam longitudinally.**
- **Measured peak moments exceeded the calculated nominal moments (M_n).**

Specimen	M_n (kN-m)	M_{peak} (kN-m)	M_{peak} / M_n
K-RC-N (closing)	387	425	1.10
K-RC-N (opening)	318	328	1.03
K-RC-H (closing)	460	623	1.35
K-RC-H (opening)	381	486	1.27
K-SFRC-H (closing)	463	667	1.44
K-SFRC-H (opening)	381	487	1.28

M_n : Calculated nominal moment (based on actual material properties, measured axial force);
M_{peak} : Peak moment (measured)

Test Results (Moments of PT K-Joints)

- **For knee joints' tests, axial forces should be considered because the actuator applies lateral loading by pushing or pulling the beam longitudinally.**
- **Measured peak moments exceeded the calculated nominal moments (M_n).**

Specimen	M_n (kN-m)	M_{peak} (kN-m)	M_{peak} / M_n
K-PT-N-1 (closing)	352	469	1.33
K-PT-N-1 (opening)	275	338	1.23
K-PT-N-2 (closing)	504	613	1.22
K-PT-N-2 (opening)	405	532	1.31
K-PT-N-3 (closing)	652	715	1.10
K-PT-N-3 (opening)	541	612	1.13

M_n : Calculated nominal moment (based on actual material properties, measured axial force, ACI 318-11 Equation for f_{ps});
M_{peak} : Peak moment (measured)

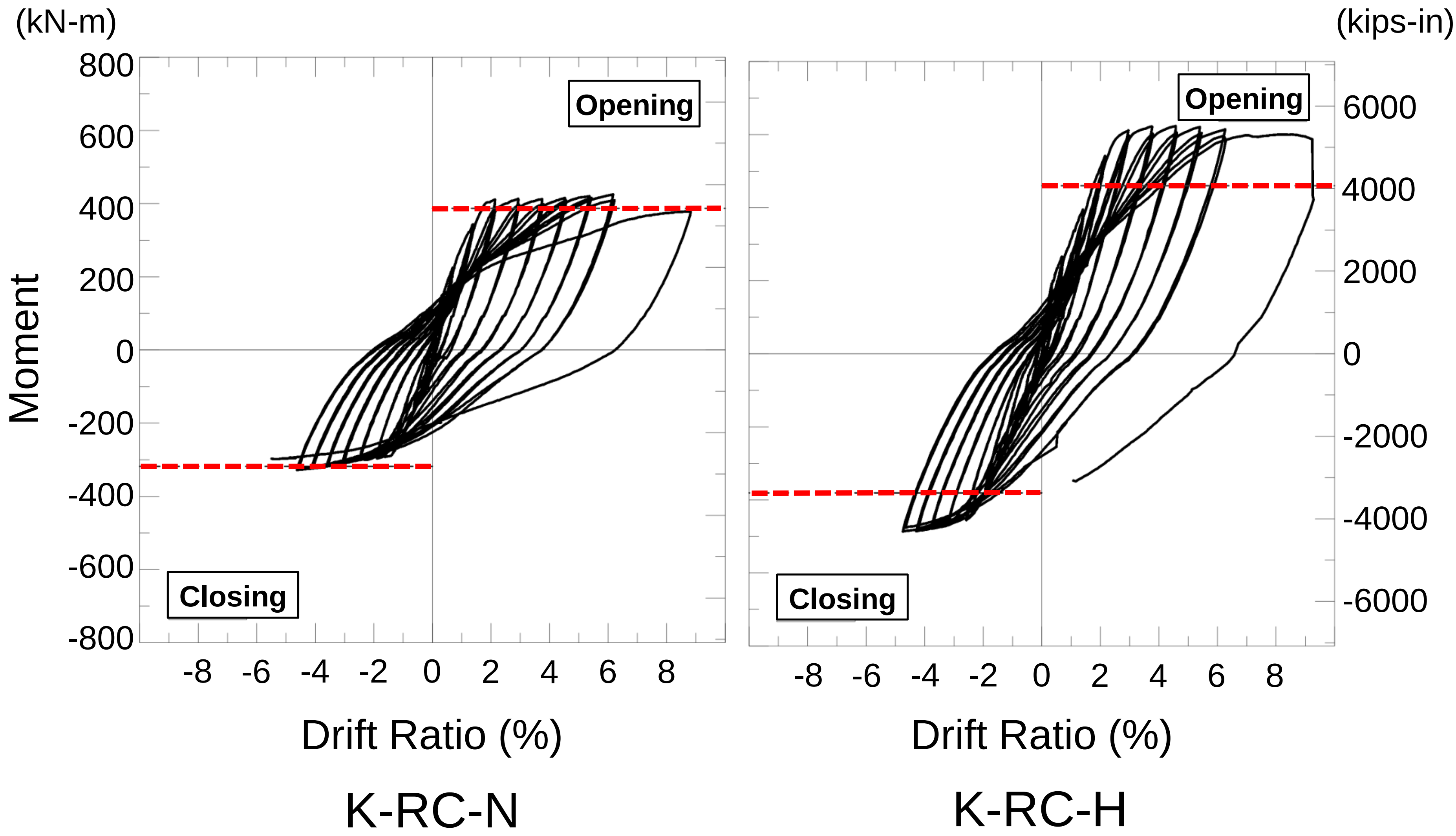
Test Results (Moments of E-Joints)

- **No axial forces (lateral loading was applied perpendicular to the beam axis)**
- **Measured peak moments exceeded the calculated nominal moments (M_n).**

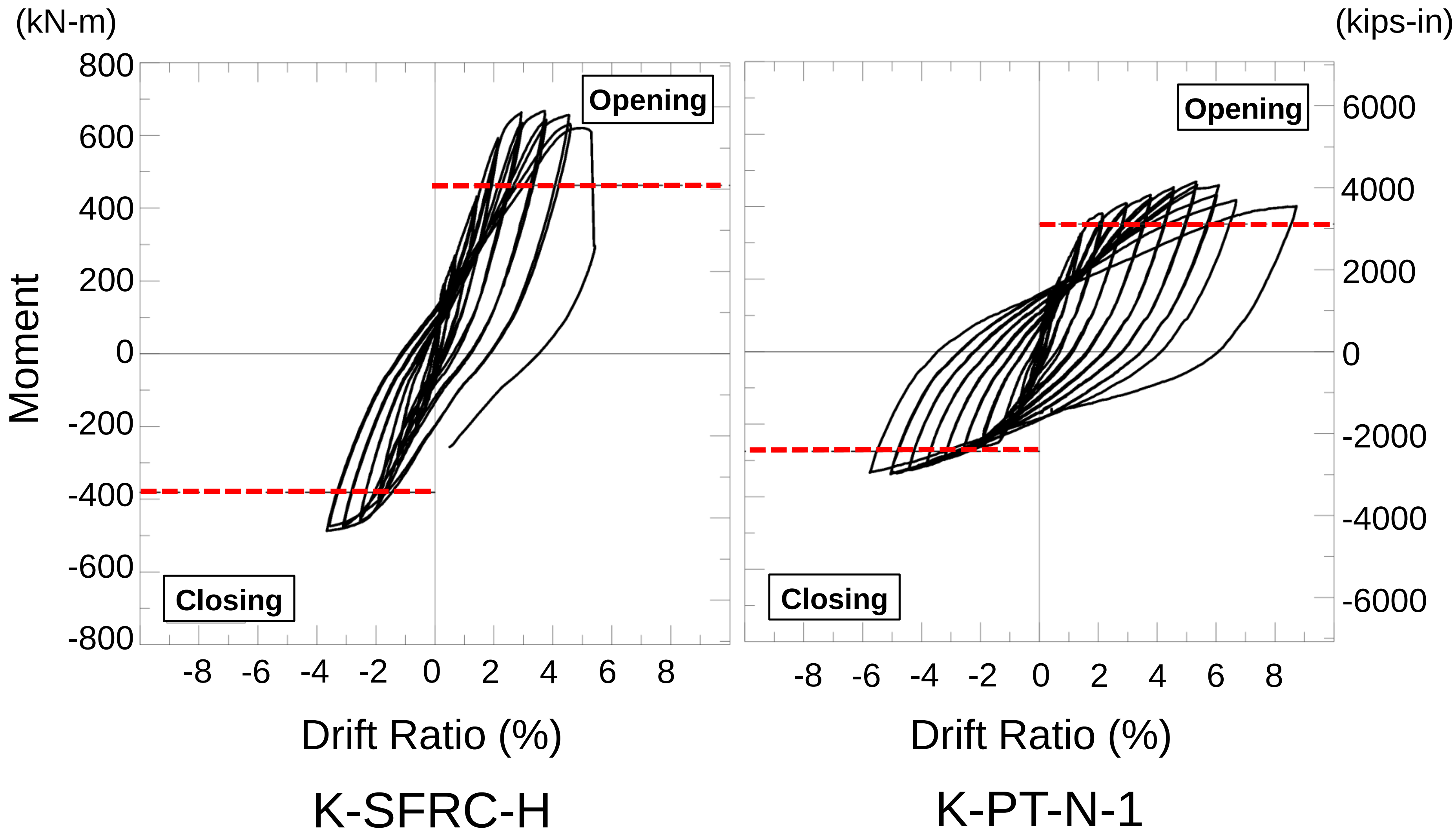
Specimen	M_n (kN-m)	M_{peak} (kN-m)	M_{peak} / M_n
E-SFRC-H (P)	1141	1431	1.25
E-SFRC-H (N)	1141	1478	1.30
E-PT-H-1 (P)	1360	1686	1.24
E-PT-H-1 (N)	1360	1775	1.31
E-PT-H-2 (P)	1485	1800	1.21
E-PT-H-2 (N)	1485	1855	1.25
E-PT-H-3 (P)	1846	2069	1.12
E-PT-H-3 (N)	1846	2197	1.19

M_n : Calculated nominal moment (based on actual material properties, ACI 318-11 Eq. for f_{ps});
M_{peak} : Peak moment (measured)

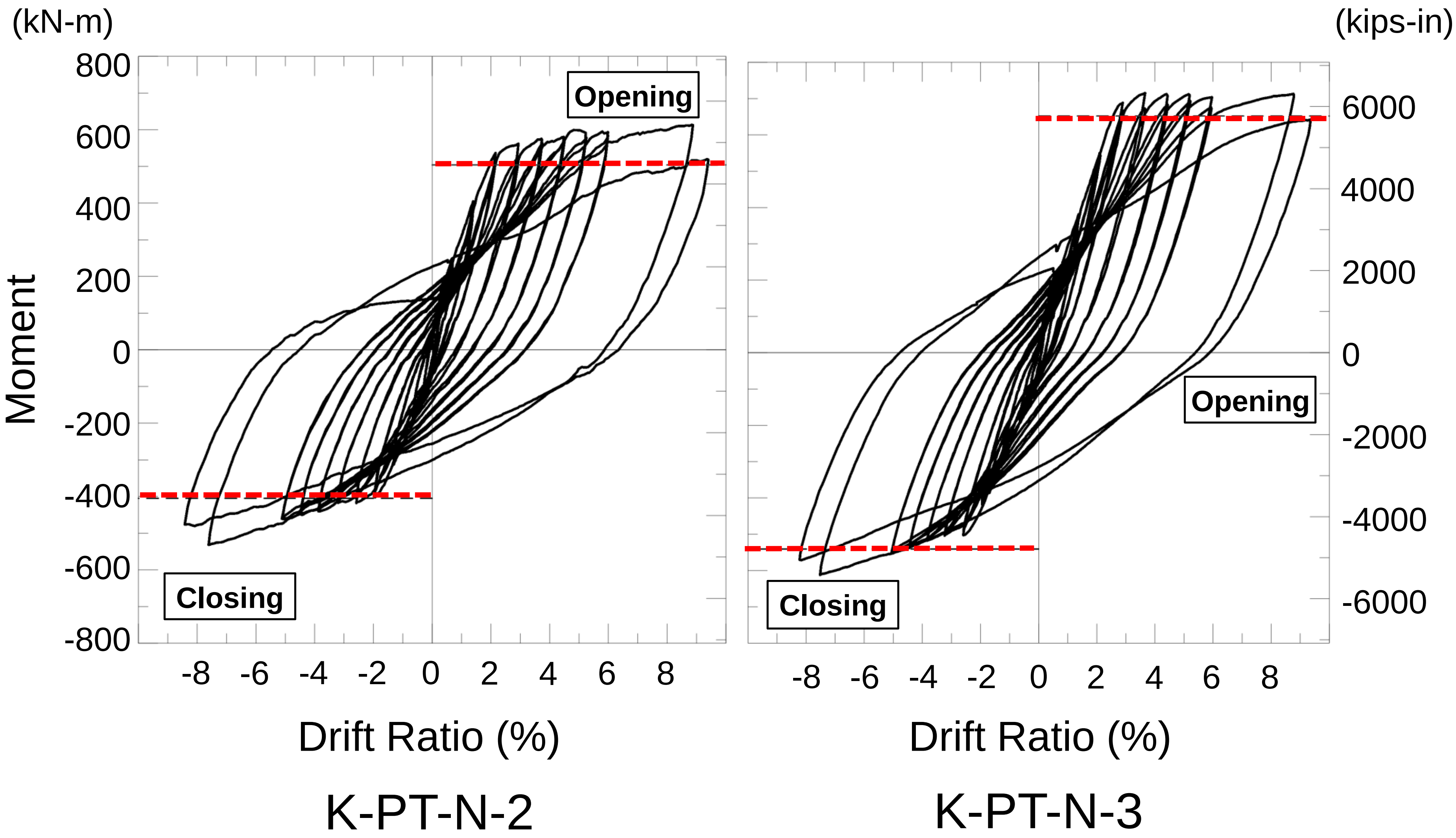
Test Results (Moment-Drift Ratio)



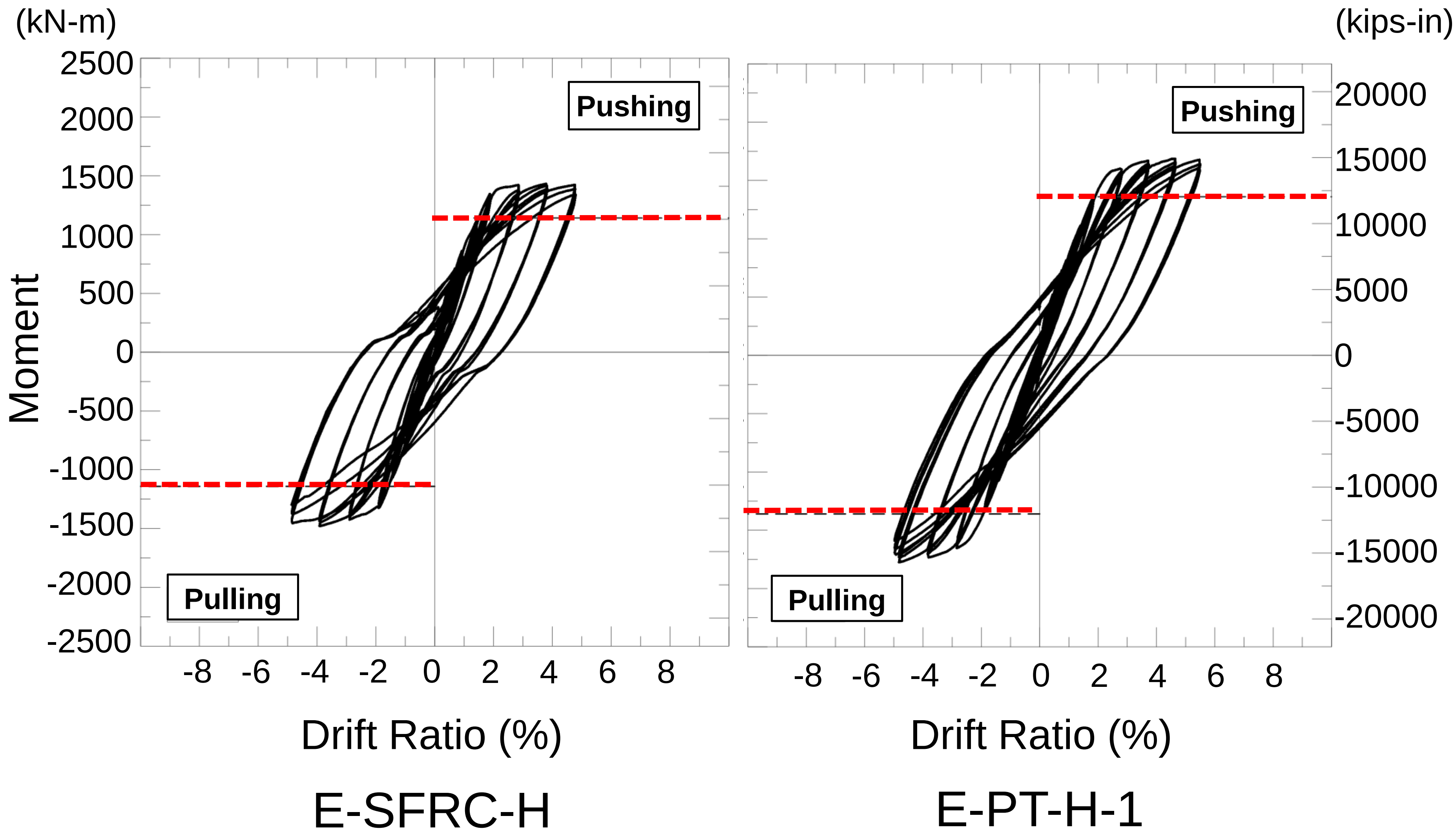
Test Results (Moment-Drift Ratio)



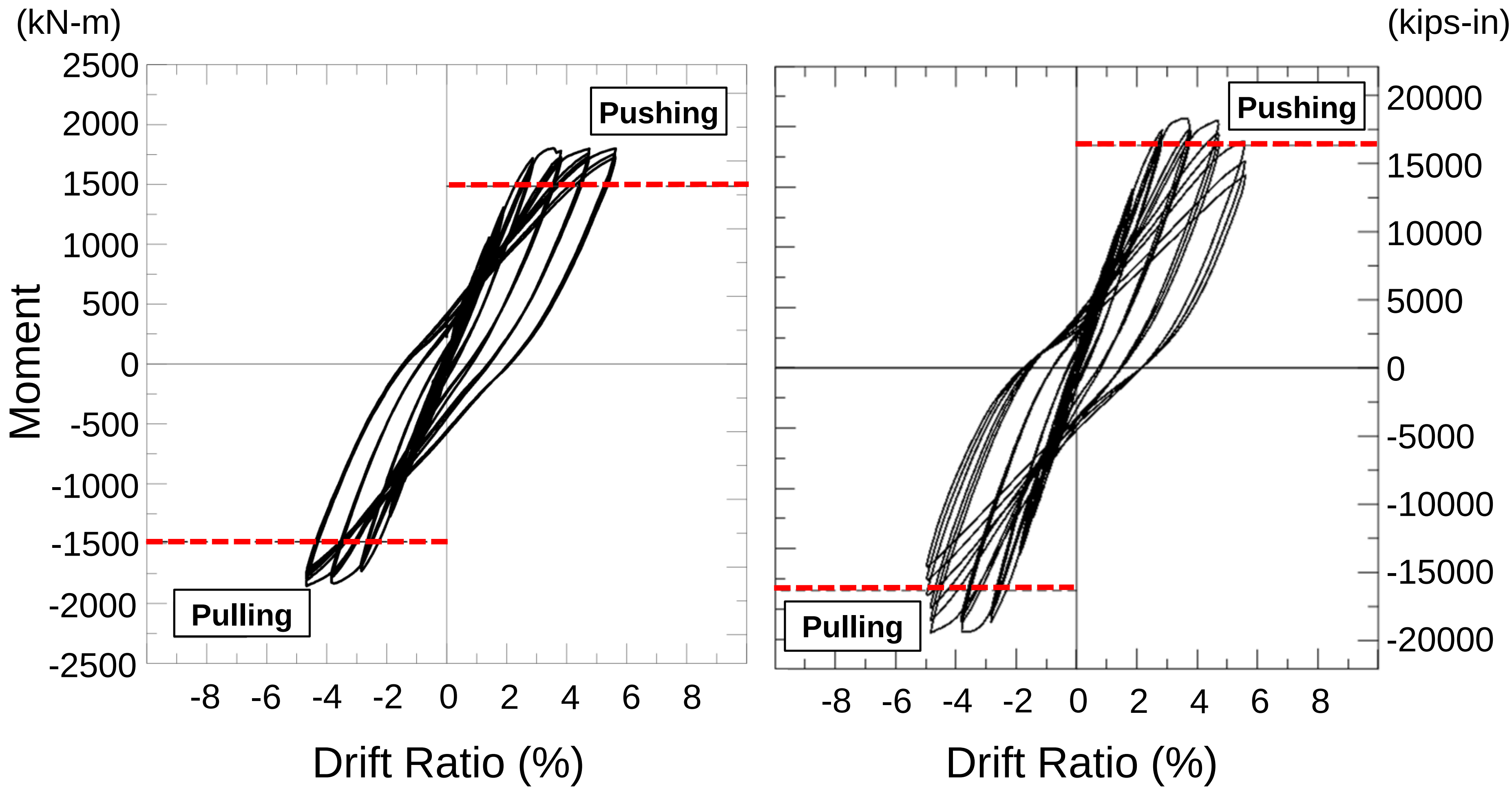
Test Results (Moment-Drift Ratio)



Test Results (Moment-Drift Ratio)

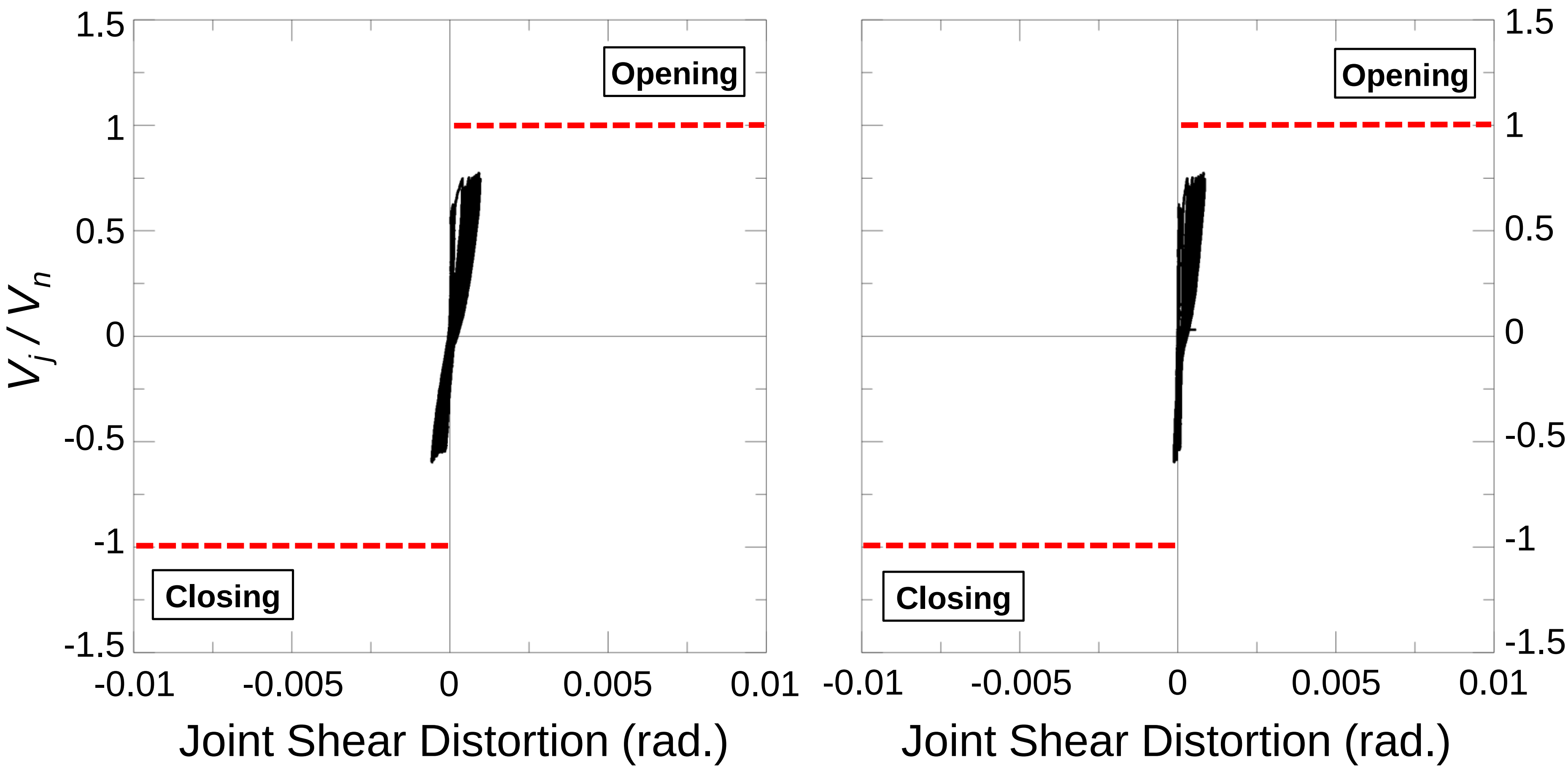


Test Results (Moment-Drift Ratio)



E-PT-H-2 E-PT-H-3

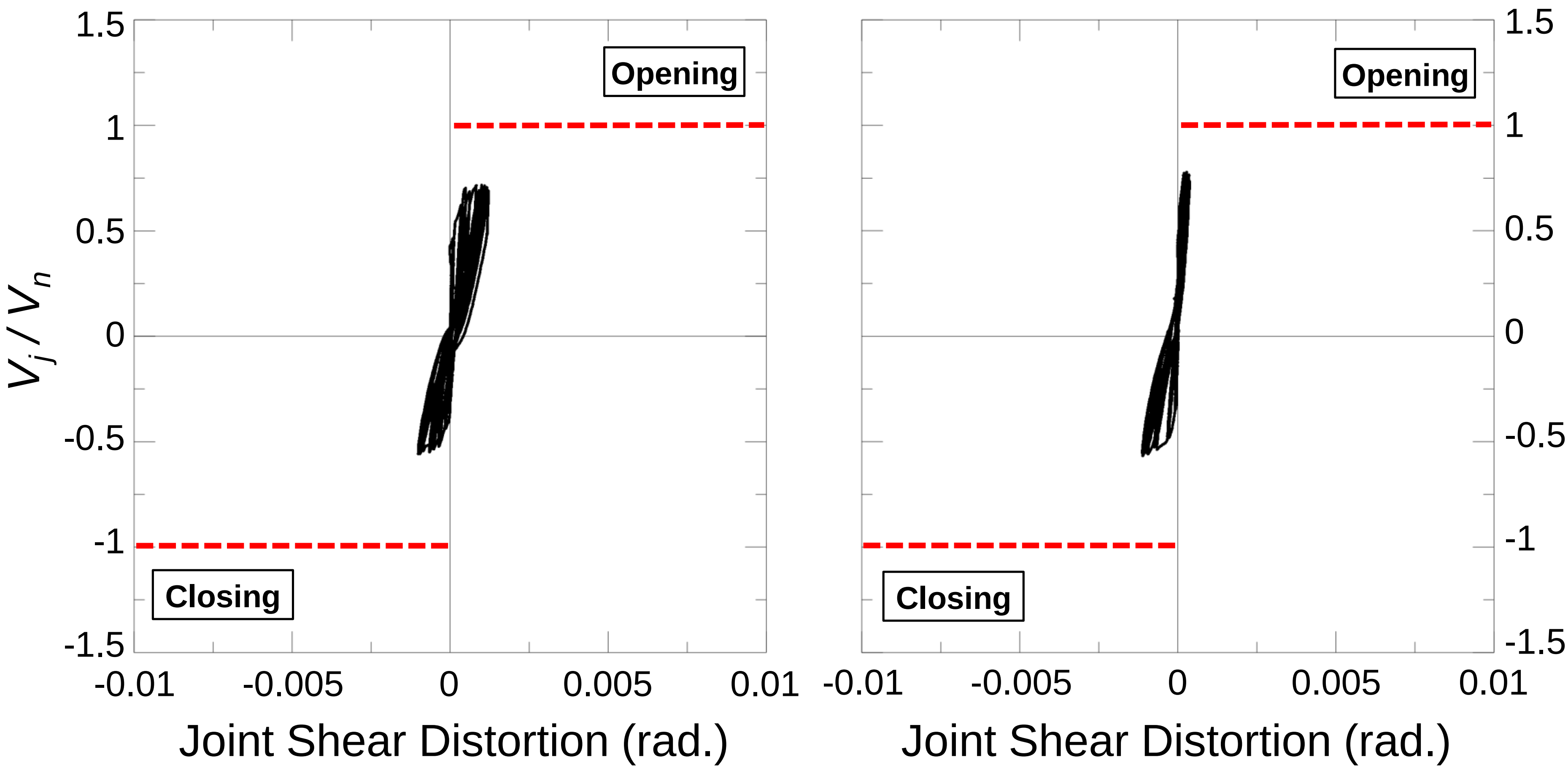
Test Results (Joint Shear Distortion)



K-RC-N (Front)

K-RC-N (Back)

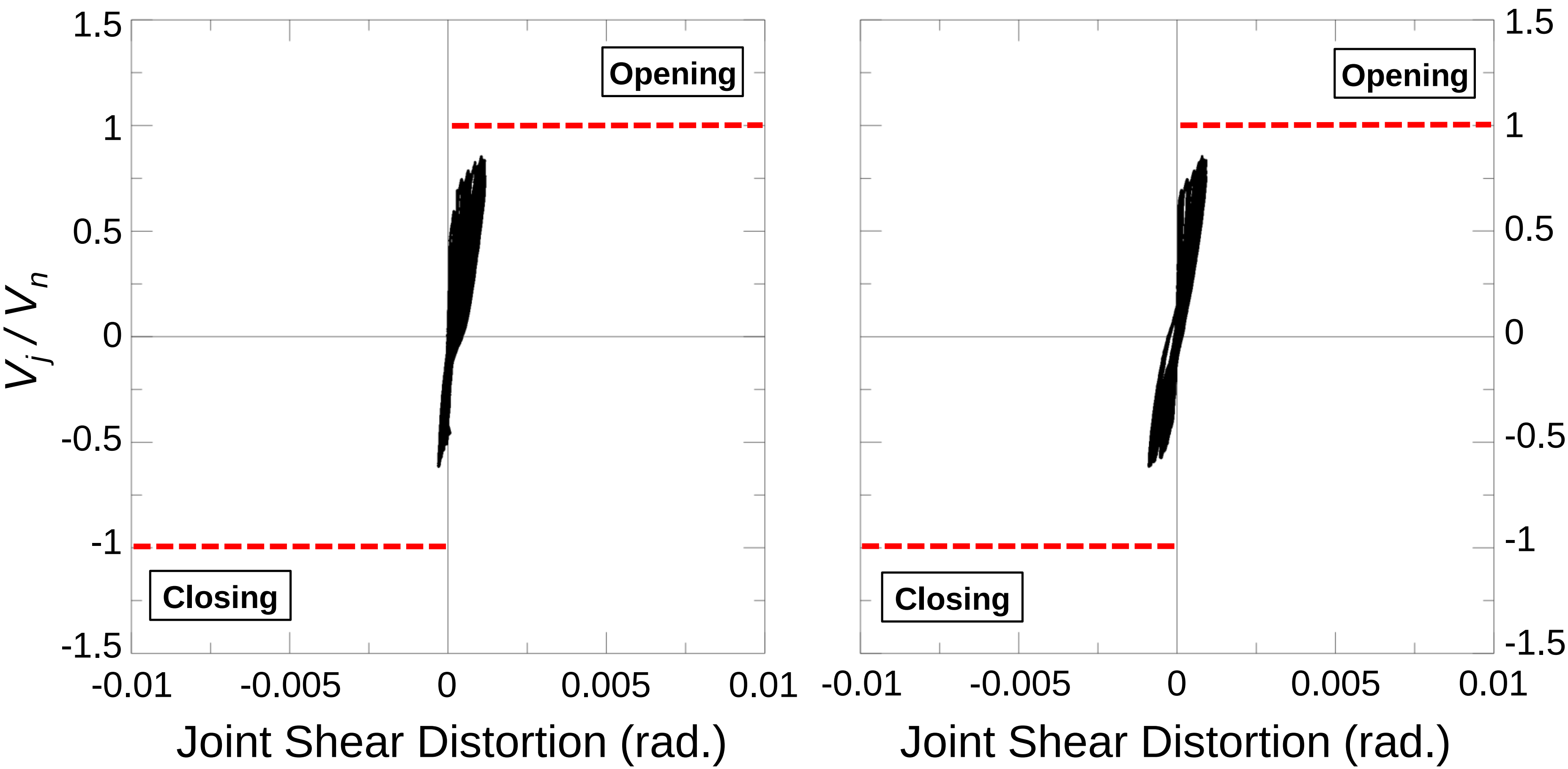
Test Results (Joint Shear Distortion)



K-RC-H (Front)

K-SFRC-H (Front)

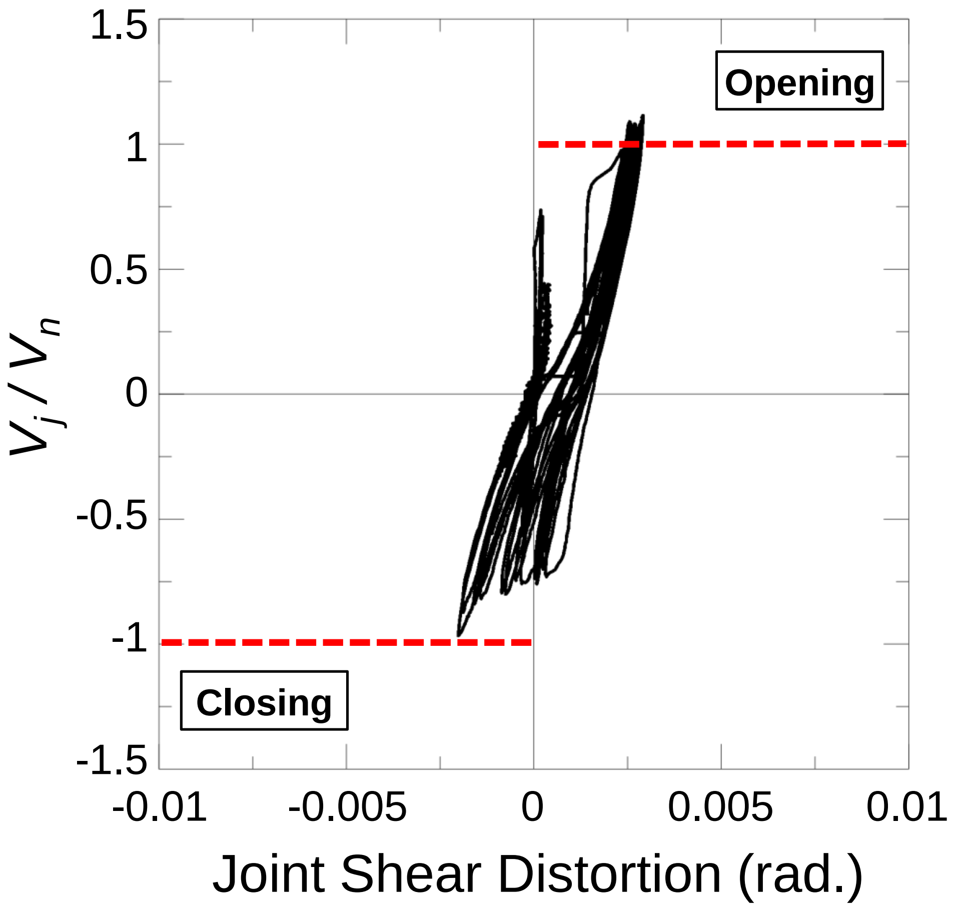
Test Results (Joint Shear Distortion)



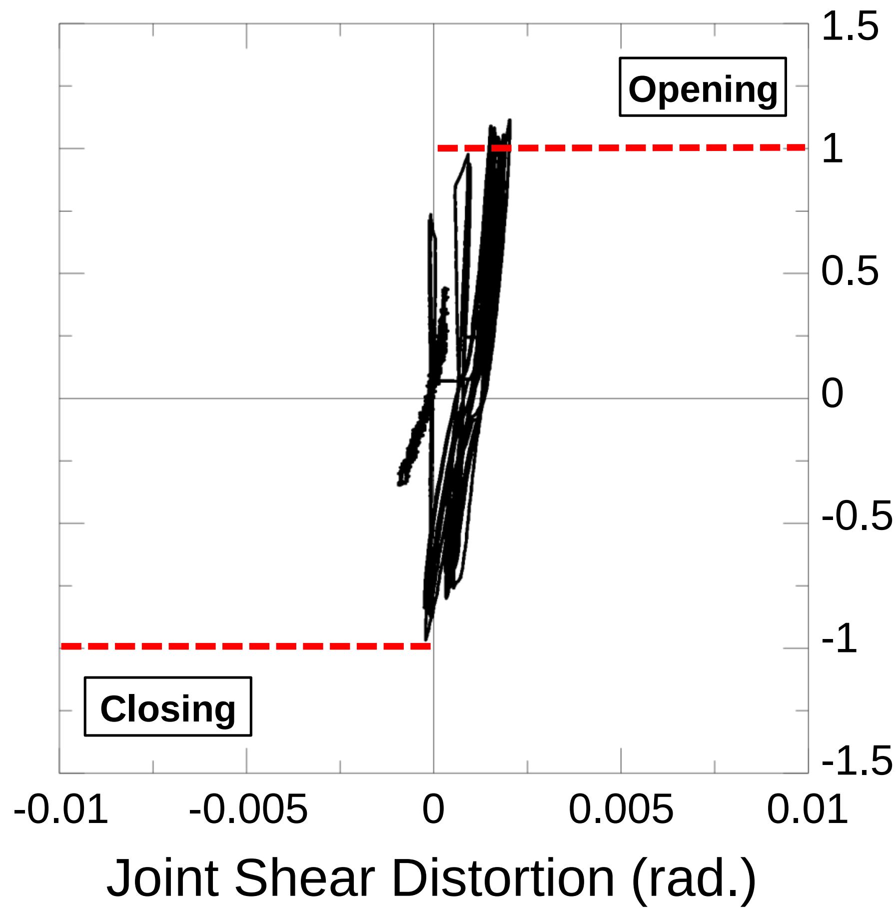
K-PT-N-1 (Front)

K-PT-N-1 (Back)

Test Results (Joint Shear Distortion)

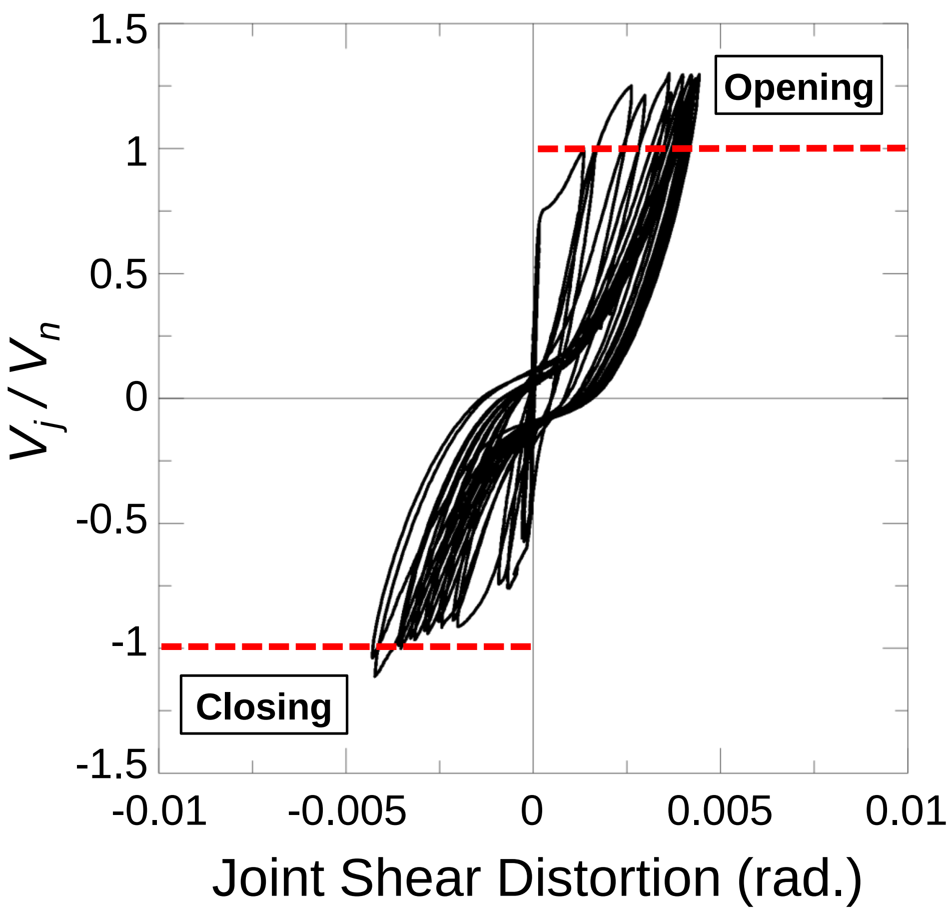


K-PT-N-2 (Front)

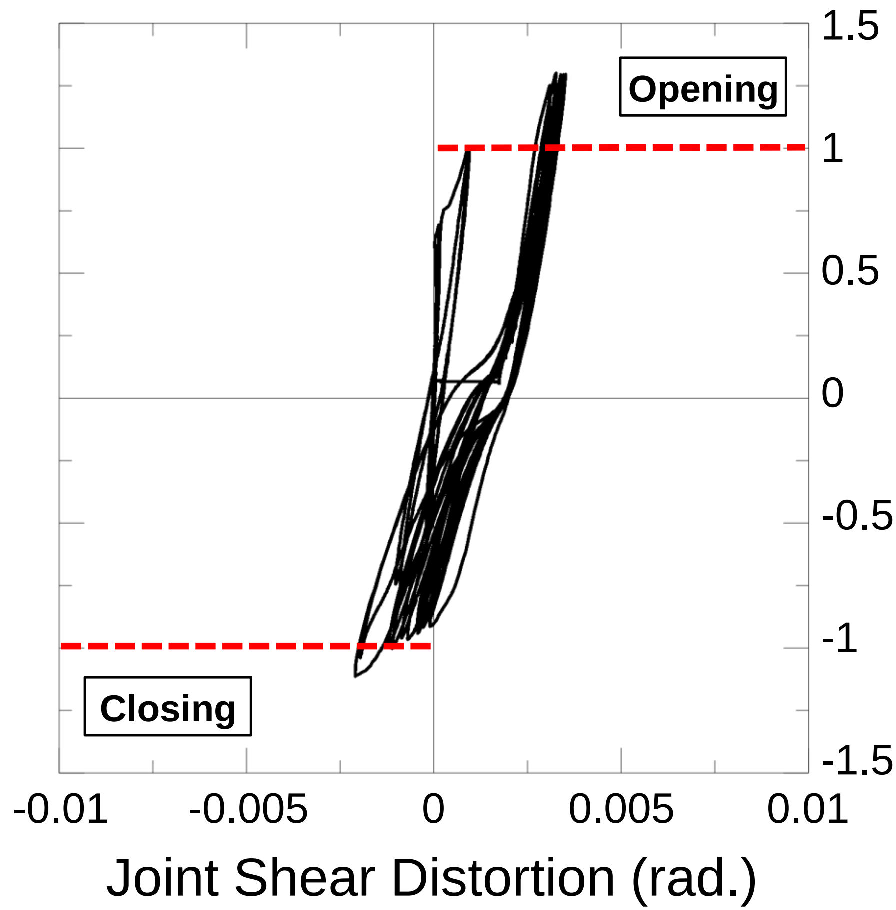


K-PT-N-2 (Back)

Test Results (Joint Shear Distortion)

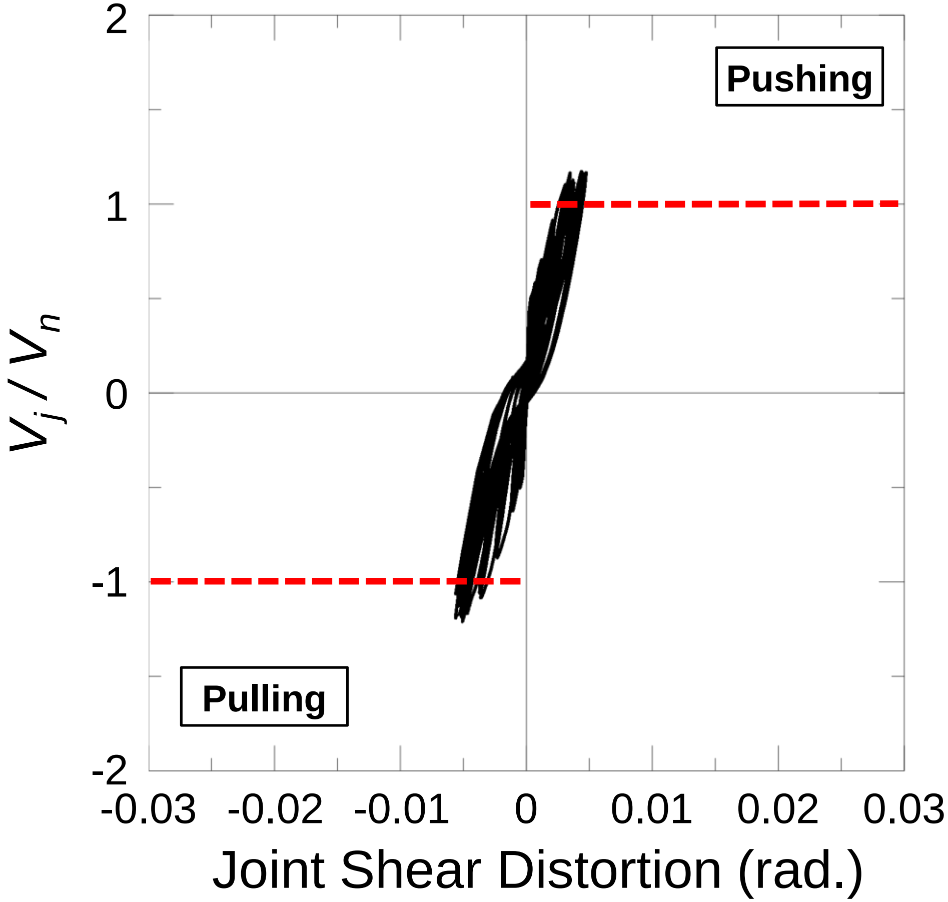


K-PT-N-3 (Front)

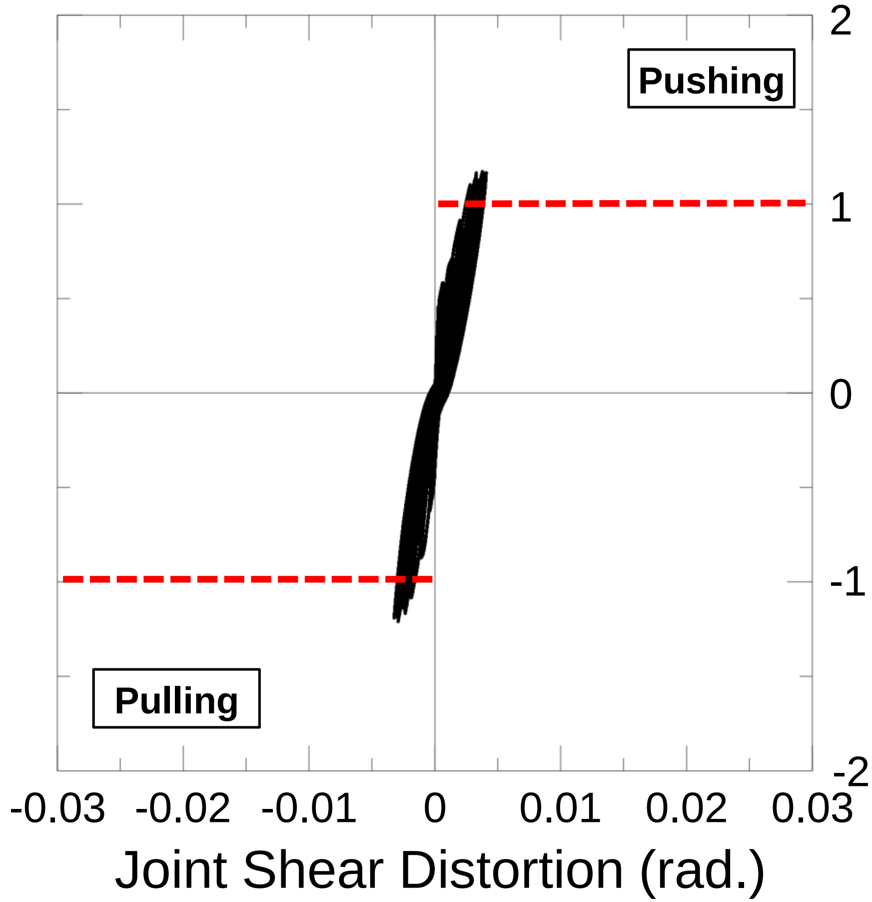


K-PT-N-3 (Back)

Test Result (Joint Shear Distortion)

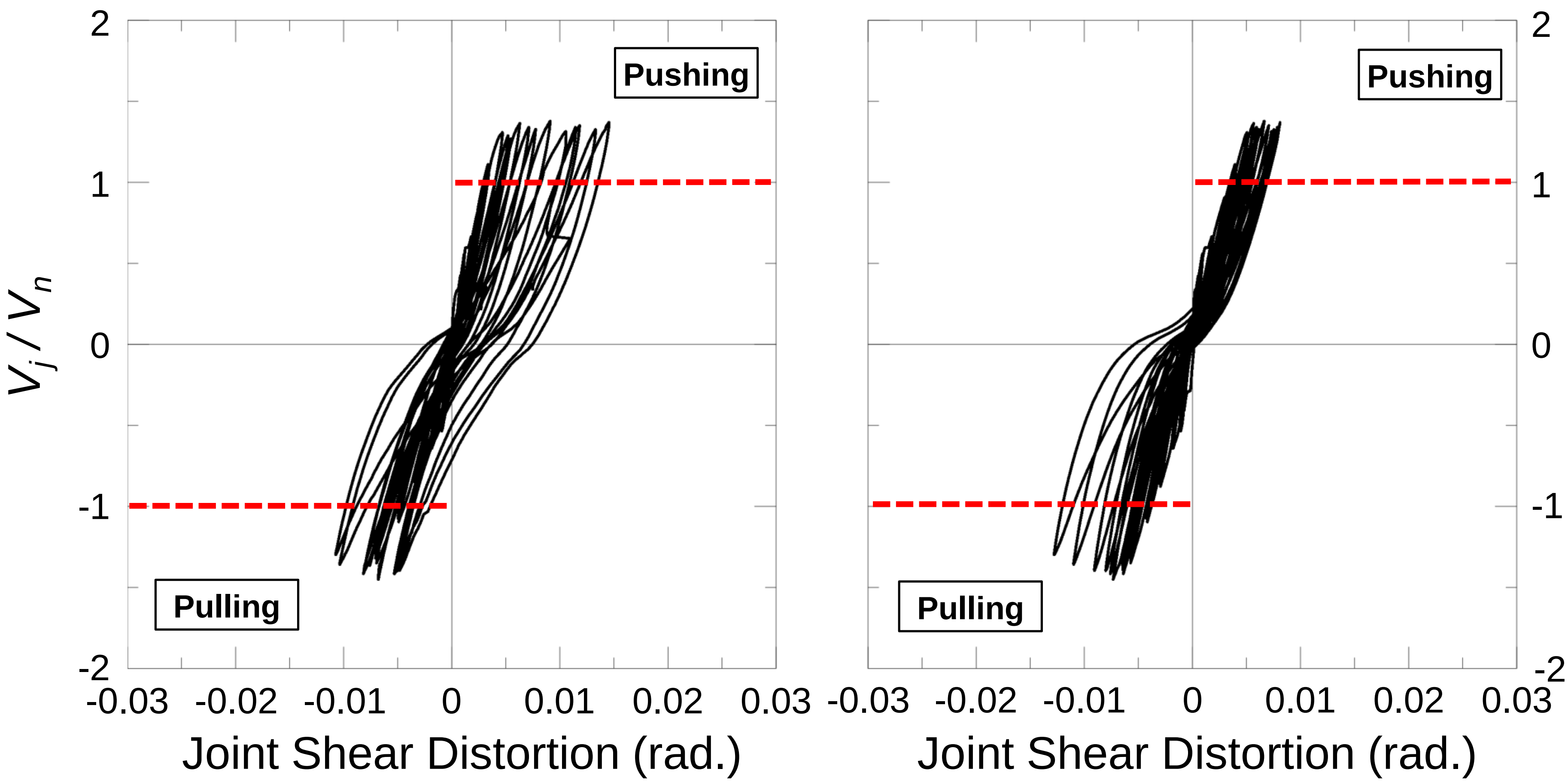


E-SFRC-H (Front)



E-SFRC-H (Back)

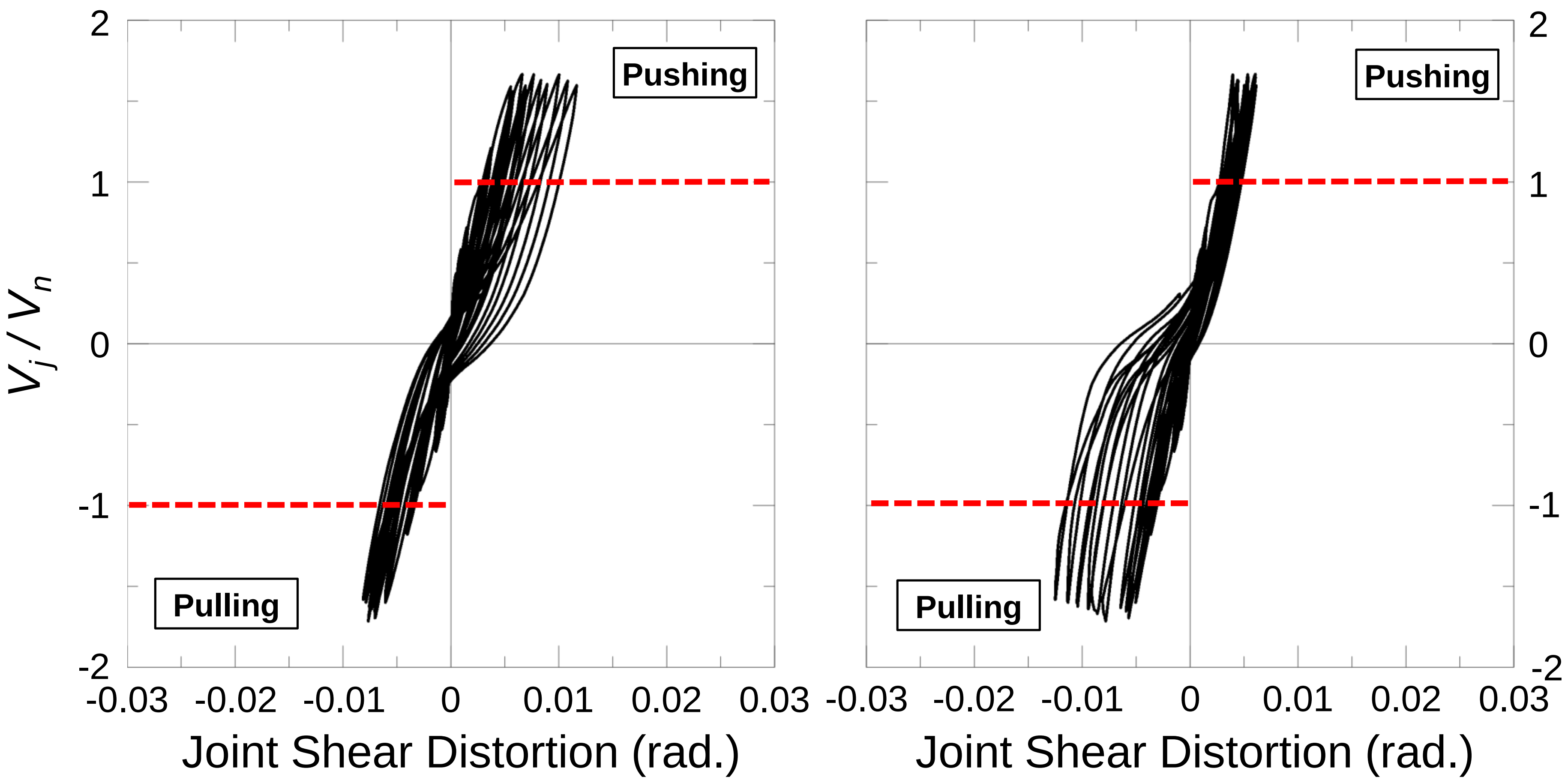
Test Result (Joint Shear Distortion)



E-PT-H-1 (Front)

E-PT-H-1 (Back)

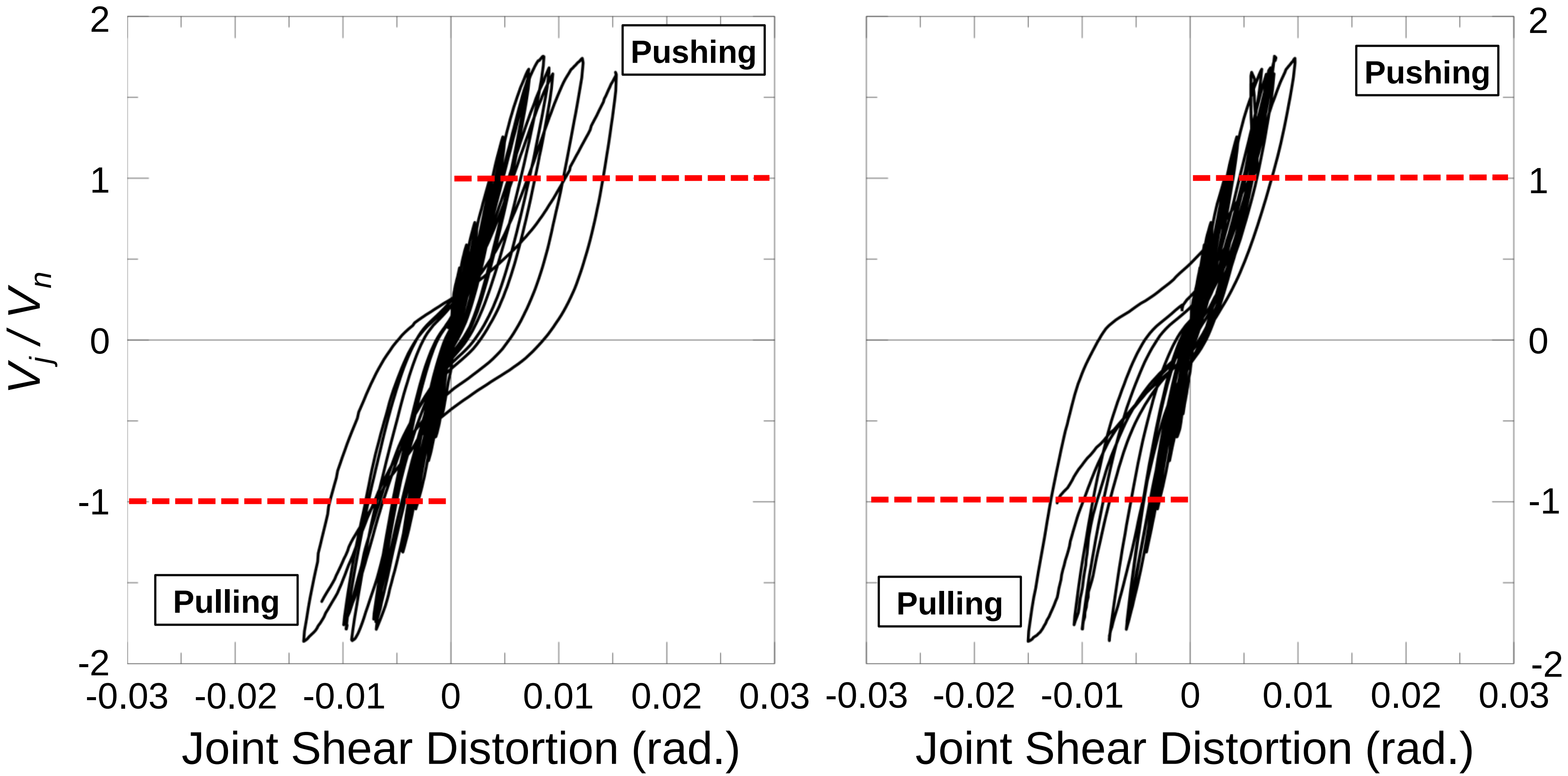
Test Result (Joint Shear Distortion)



E-PT-H-2 (Front)

E-PT-H-2 (Back)

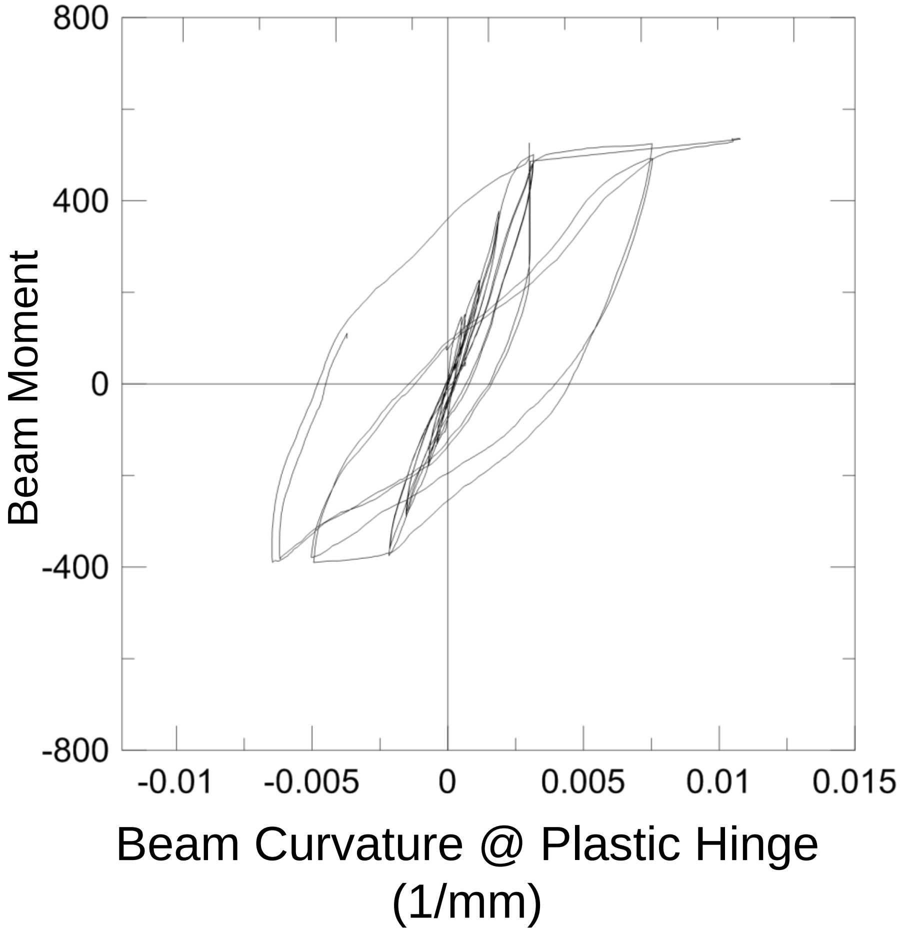
Test Result (Joint Shear Distortion)



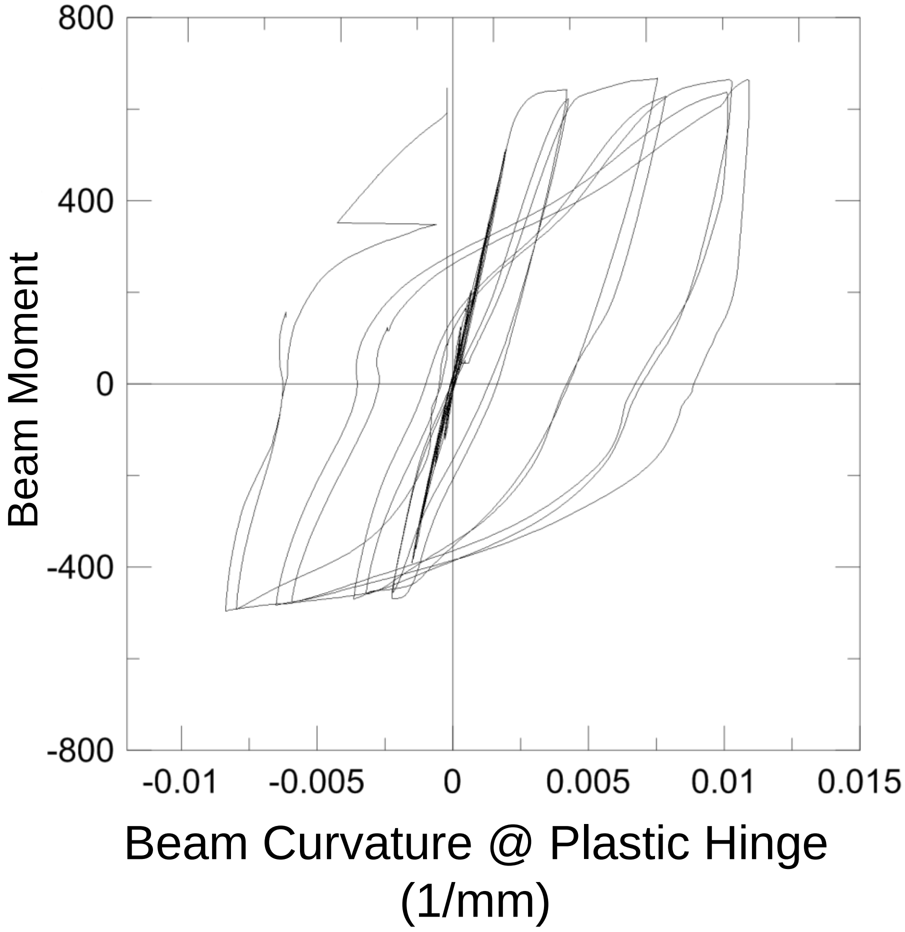
E-PT-H-3 (Front)

E-PT-H-3 (Back)

Test Results (Beam Moment-Curvature)



K-PT-N-2



K-PT-N-3

Conclusions

Conclusions

PT Beam-Column Joints of Special Moment Frames

- All PT specimens showed excellent seismic performance for every performance indicators (essentially did not completely fail until the end of testing, except for E-PT-H3 which failed at a drift ratio of 4%).
- Very high-strength concrete and SD 600 (Grade 90) steel bars can be promoted for tall buildings (joints, coupling beams, boundary elements of core walls, transfer slabs/girders) and mega infrastructures.
- Joint shear strengths of PT beam-column joints were turned out to be much larger than those for conventional RC beam-column joints.
- Applications of post-tensioning, high-strength materials, steel fibers (1% volume fraction ratio) are promising.
- Test program & data are of great value for PT / seismic / materials societies.

Thank you

Further development of the data will be made and shared with the PT industry.

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