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MCEER EARTHQUAKE ENGINEERING TO EXTREME EVENTS

THE DEPARTMENT OF CIVIL, STRUCTURAL AND ENVIRONMENTAL ENGINEERING

Experimental, numerical, and analytical studies on the seismic response of steel-plate concrete composite shear walls and squat RC shear walls

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1. INTRODUCTION

Different types of SC walls

1 – SC modular box units proposed by Fukumuto et al.

2 - SC shear wall composed of two corrugated steel faceplates and infill concrete proposed by Wright et al.

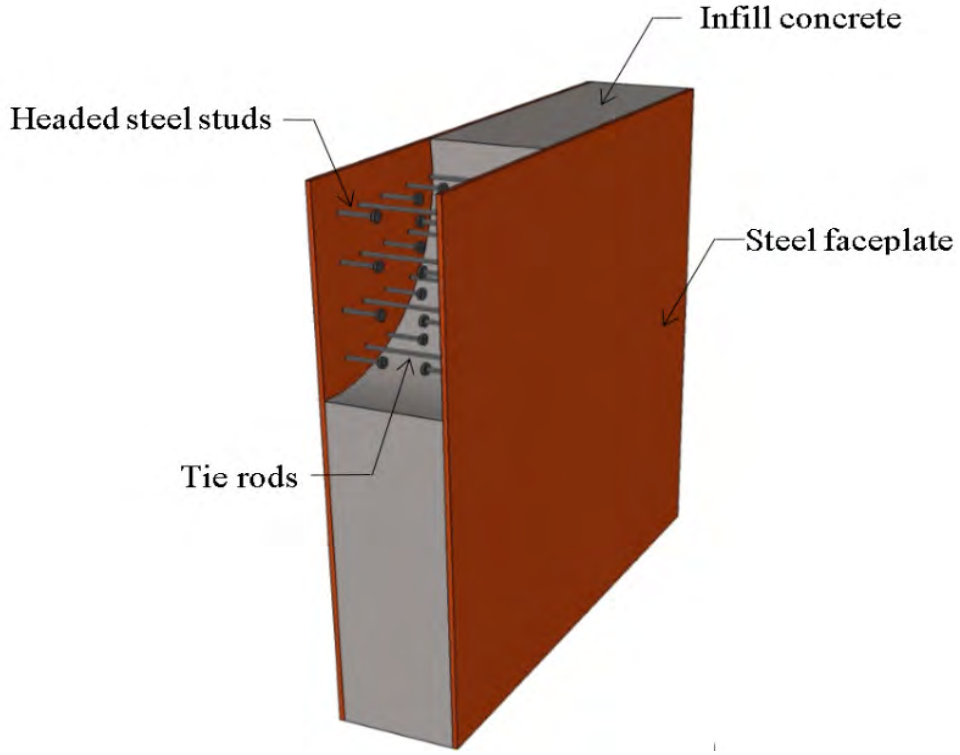
3 - SC faceplates with infill reinforced concrete proposed by Astaneh-Asl et al.

4 - Bi-Steel construction proposed by British Steel (later Corus)

(Bi-Steel)

SC walls piers

- Focus of the research is flexure- and flexure-shear critical SC wall piers.
- Only loading in the plane of the wall is considered.
- The SC wall piers studied in this research consist of:
  - Two steel faceplates
  - Infill concrete
  - Headed steel studs anchoring the faceplates to the infill
  - Tie rods connecting the two faceplates through the infill



Advantages of SC construction

- General construction
  - Elimination of formwork
  - Enables large-scale modularization
  - Penetrations easily accommodated
  - Superior strength and ductility
  - Improved quality of placed concrete (SCC)
  - Increased construction speed and economy
- Nuclear construction
  - Increased shielding capability
  - Superior missile/blast resistance

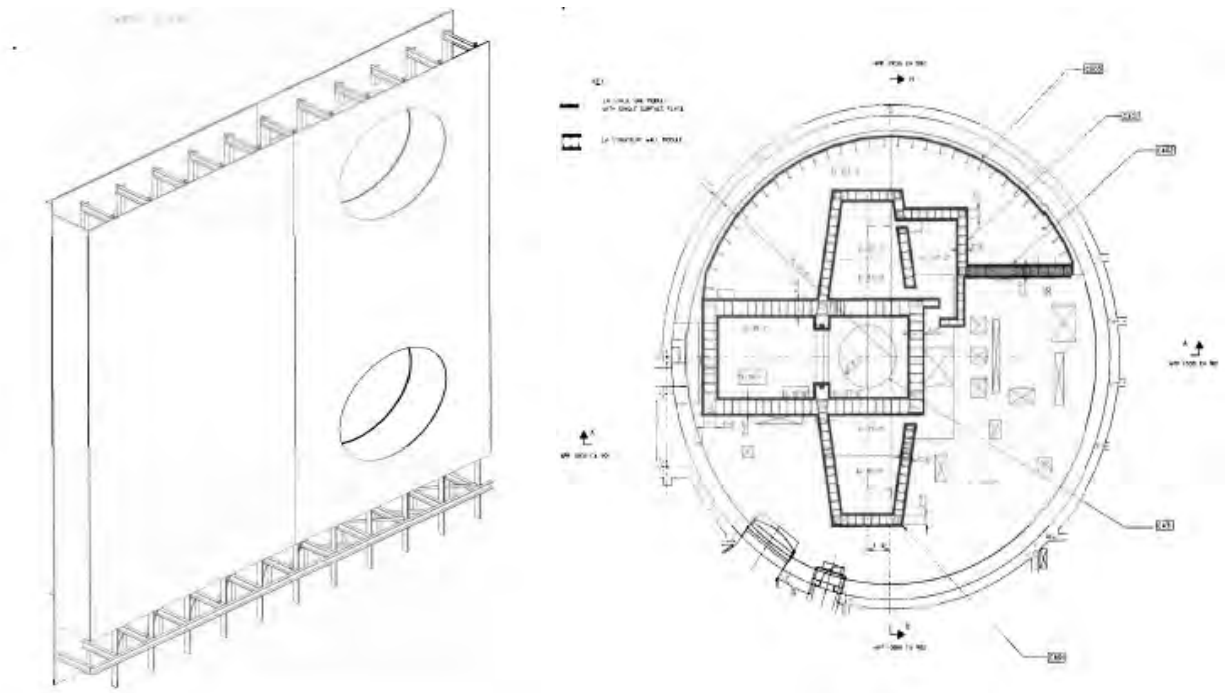
2. SC WALL APPLICATIONS

SC walls used in multi-story buildings

Forty Spring Garden Manchester's Financial District, Corus (2006)

Dundrum Cinema Lift Core, Corus (2004)

AP1000, Sanmen, China



AP1000, Sanmen, China

3. PRELIMINARY DESIGN AND ANALYSIS OF SC WALLS

Preliminary design of test specimens

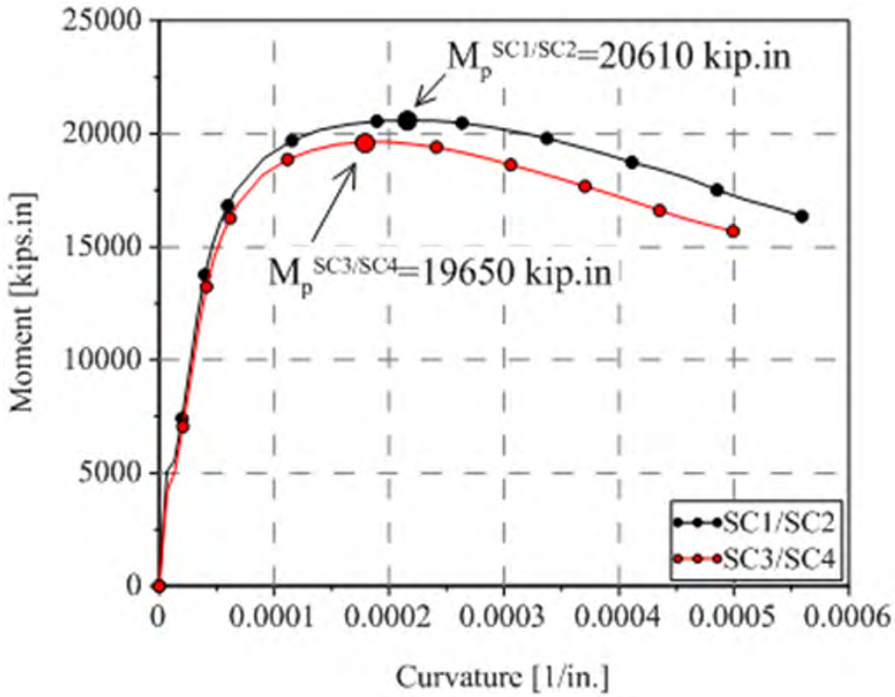
- Design of specimens based on a draft version of AISC N690s1

Specimen	Wall dimension *(H×L×T)* (in. × in. × in.)	Stud spacing (in.)	Tie rod spacing (in.)	Reinforcement ratio (%)	Faceplate slenderness ratio	Day-of-test wall concrete strength (ksi)
SC1	60×60×12	4	12	3.1	21	4.5
SC2	60×60×12	-	6	3.1	32	4.5
SC3	60×60×9	4.5	9	4.2	24	5.3
SC4	60×60×9	-	4.5	4.2	24	5.3

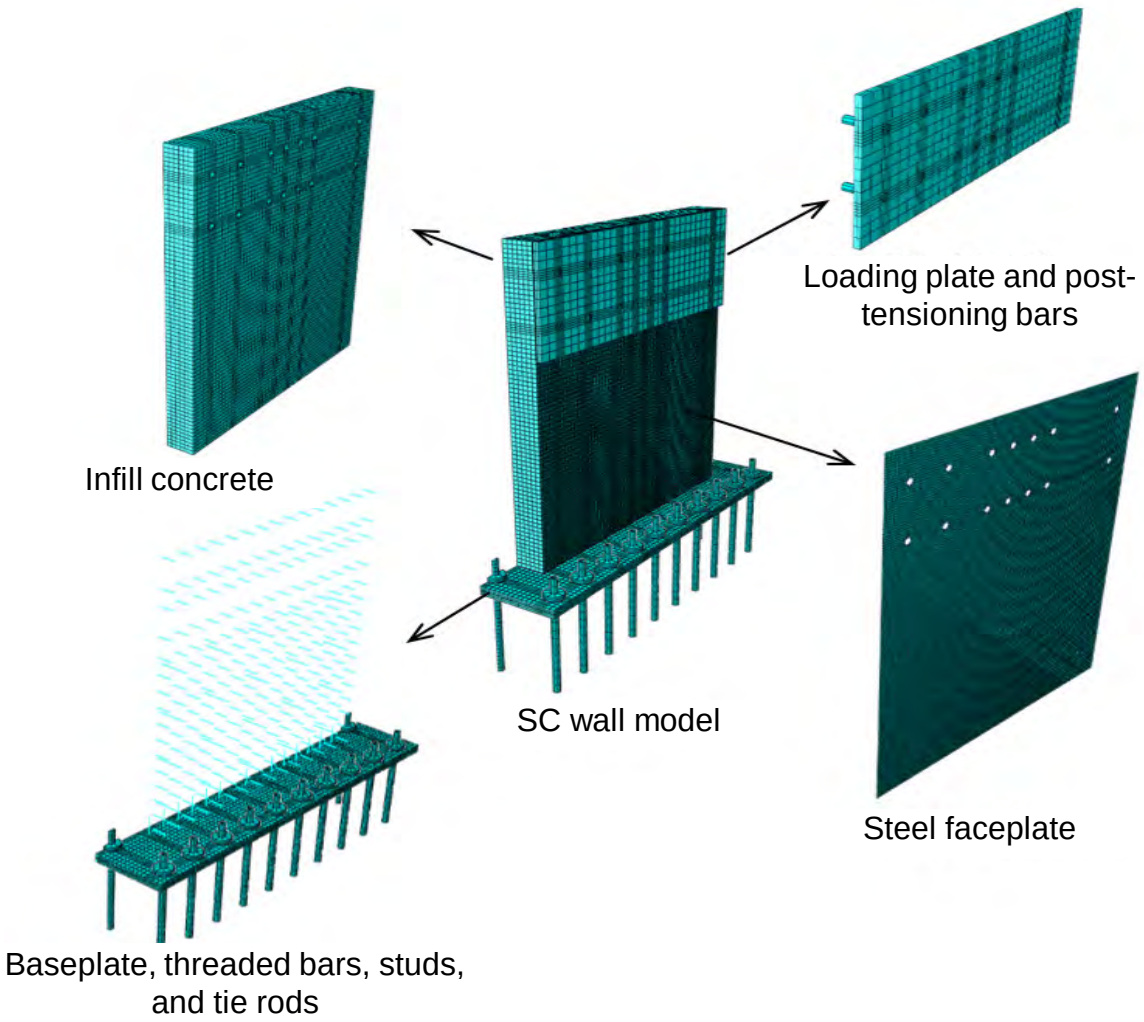
- Two 3/16-in. thick steel faceplates were used for all four SC walls.
- The diameter of the studs and tie rods was 0.375 in. for all walls.
- Reinforcement ratio: $2t_s / T$
- Slenderness ratio: S / t_s

XTRACT Analysis of SC walls

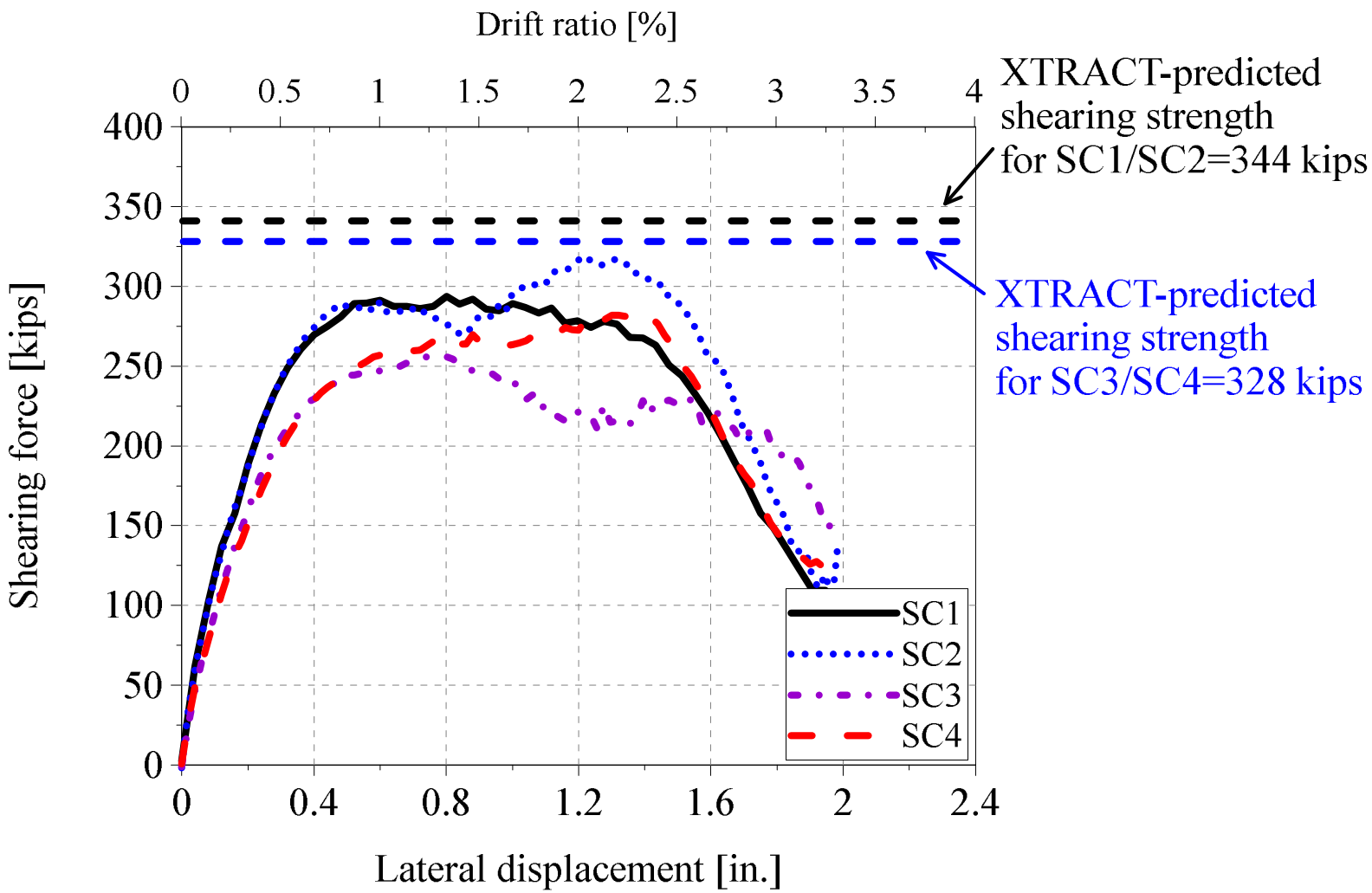
- The shear strengths of SC1 and SC3 corresponding to these flexural strengths were 344 kips and 328 kips, respectively.
- The maximum shear resistance of the walls per the draft Appendix N9 to AISC N690s1, Ozaki et al., and Varma et al. is 870/855/815 kips for SC1/SC2 and 840/855/780 kips for SC3/SC4. The SC walls were identified to be flexure-critical since the shear strength associated to the flexural strength of the walls was less than their maximum shear resistance.



ABAQUS Analysis of SC walls



ABAQUS Analysis of SC walls



4. EXPERIMENTAL PROGRAM

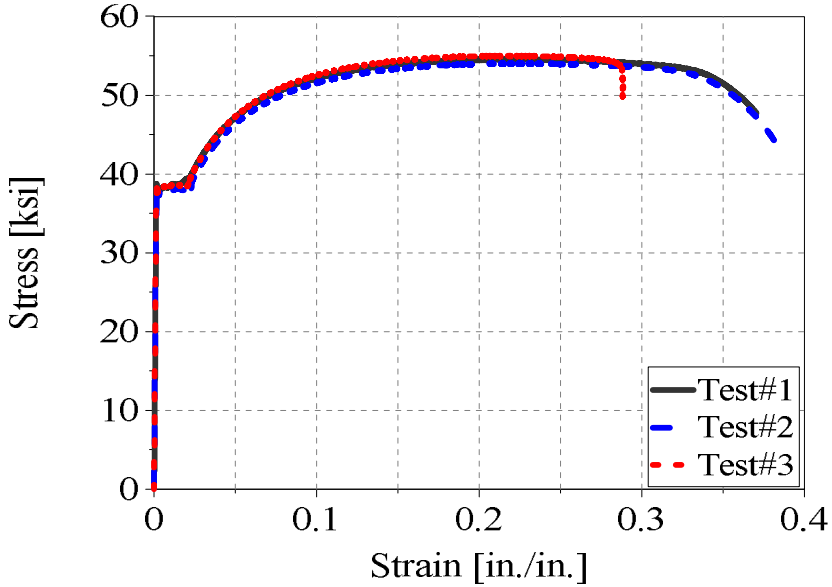
Construction of the steel shells

Foundation construction

Constructed SC walls

Material testing

- **Studs and tie rods:**
  - The 3/8-in. and 5/8-in. diameter Nelson studs and tie rods were fabricated from carbon steel
  - Nominal yield and ultimate stresses were 50 and 75 ksi, respectively.
- **Steel faceplates:**
  - Three coupons were tested per ASTM A370.
- **Infill concrete and foundation:**
  - Concrete cylinder were tested per ASTM C39-02 at 7, 14, 21, 28 days after concrete casting and on the days of the SC wall tests



Stress-strain relationships of the faceplate coupons

$f_c' = 4.4$ ksi for SC1/SC2

$f_c' = 5.3$ ksi for SC3/SC4

Test setup and loading protocol

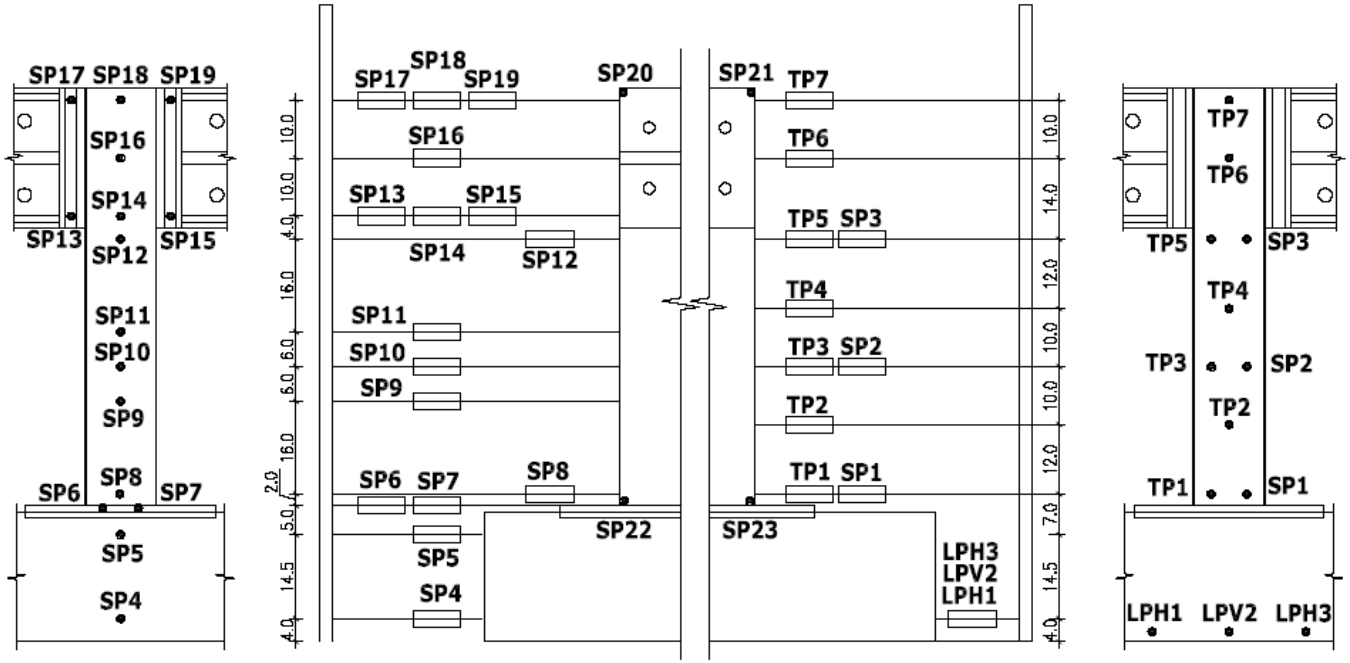
Load step	Peak displacement (in.)	Drift ratio (%)	Number of cycles	Description
LS1	±0.014	0.02	2	$0.1\delta_y$
LS2	±0.070	0.12	2	$0.5\delta_y$
LS3	±0.105	0.18	2	$0.75\delta_y$
LS4	±0.142	0.23	2	δ_y
LS5	±0.283	0.47	2	$2\delta_y$
LS6	±0.425	0.70	2	$3\delta_y$
LS7	±0.567	0.93	2	$4\delta_y$
LS8	±0.709	1.17	2	$5\delta_y$
LS9	±0.850	1.40	2	$6\delta_y$
LS10	±0.992	1.63	2	$7\delta_y$
LS11	±1.134	1.87	2	$8\delta_y$
LS12	±1.276	2.10	2	$9\delta_y$
LS13	±1.417	2.33	2	$10\delta_y$
LS14	±1.701	2.80	2	$11\delta_y$
LS15	±1.984	3.27	2	$12\delta_y$

Loading protocol

Instrumentation of test specimens

LVDTs, Temposonic Displacement Transducers, and String Potentiometers

Potentiometers and Temposonics were attached to the ends of the walls to measure in-plane displacement. Potentiometers measured also the out-of-plane displacements of the walls. The movement of the foundation block relative to the strong floor was monitored using potentiometers.



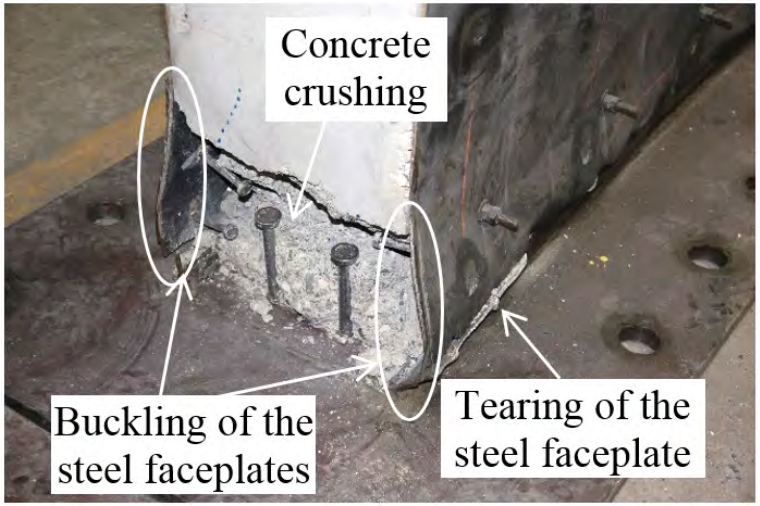
Layout of the string potentiometers (SP), Temposonic displacement transducers (TP), and linear variable displacement transducers (LPH and LPV)

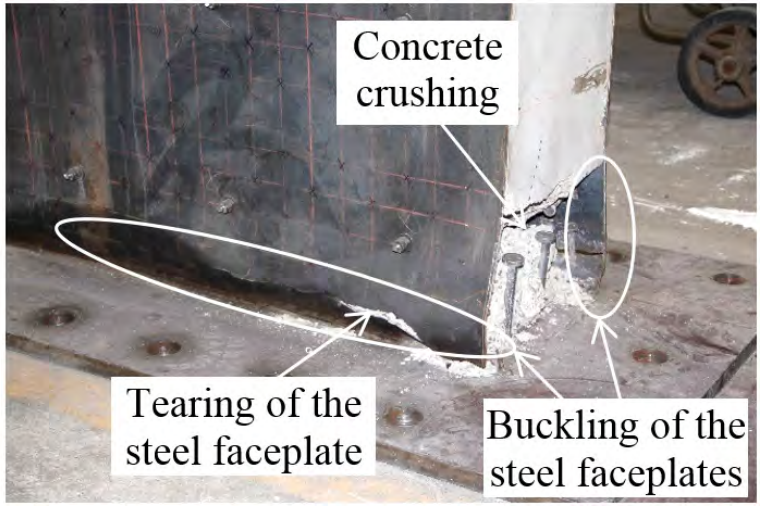
5. EXPERIMENTAL RESULTS

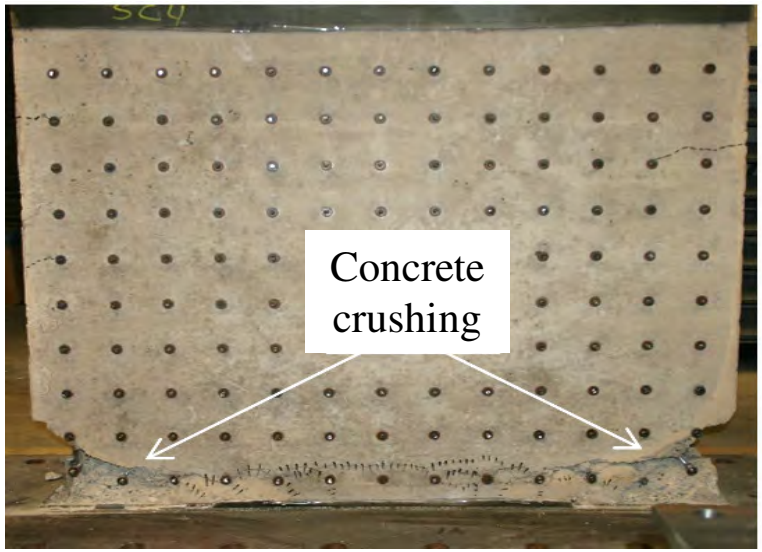
Test results

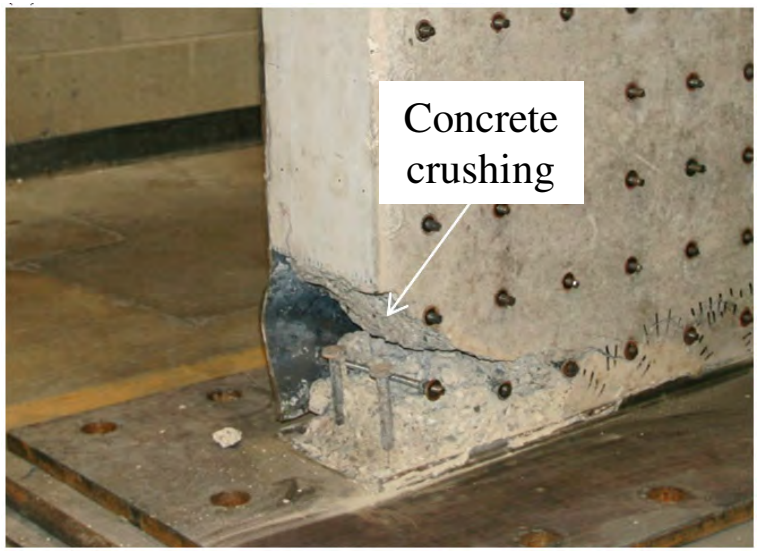
Specimen	Initial stiffness (kips/in.)	Data point						
		Onset of steel plate buckling		Onset of steel plate yielding		Peak load		Test termination at 3.3% drift ratio
	(kip/in.)	Load (kips)	Drift ratio (%)	Load (kips)	Drift ratio (%)	Load (kips) WL+/EL-	Drift ratio (%) WL+/EL-	Load (kips) WL+/EL-
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SC1	1680	245	0.48	240	0.48	317/320	1.18/1.18	130/144
SC2	1420	200	0.48	200	0.48	314/319	1.18/1.18	134/126
SC3	1380	240	0.70	185	0.48	265/275	1.40/1.18	112/126
SC4	1310	240	0.70	200	0.48	270/275	1.18/1.18	120/141

Damage to SC walls

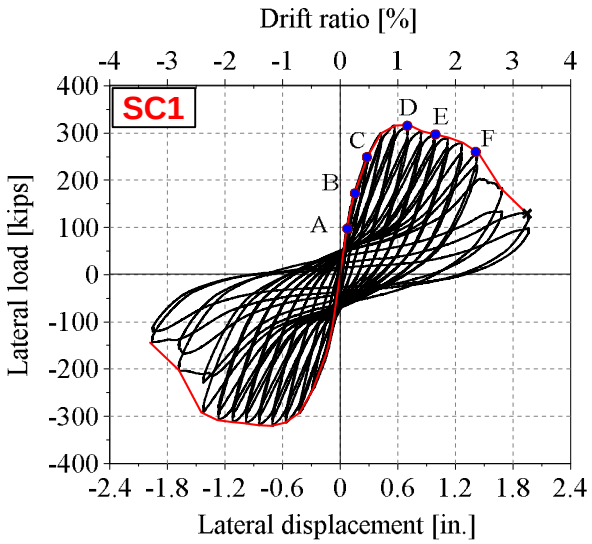


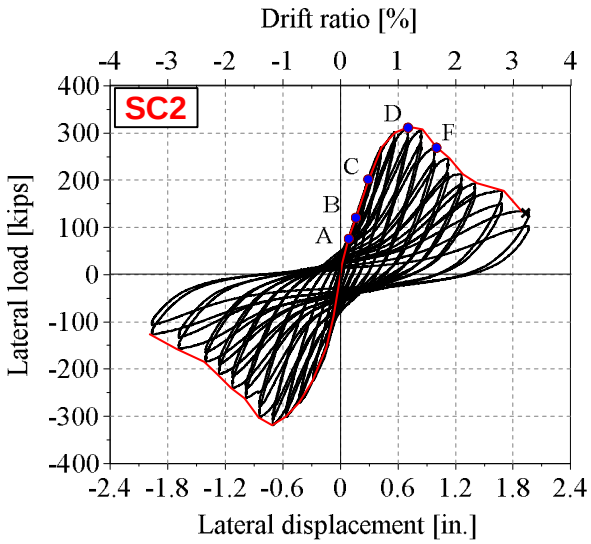


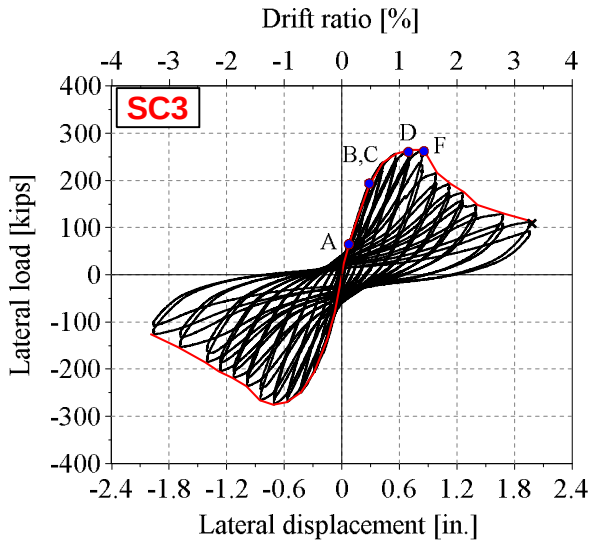


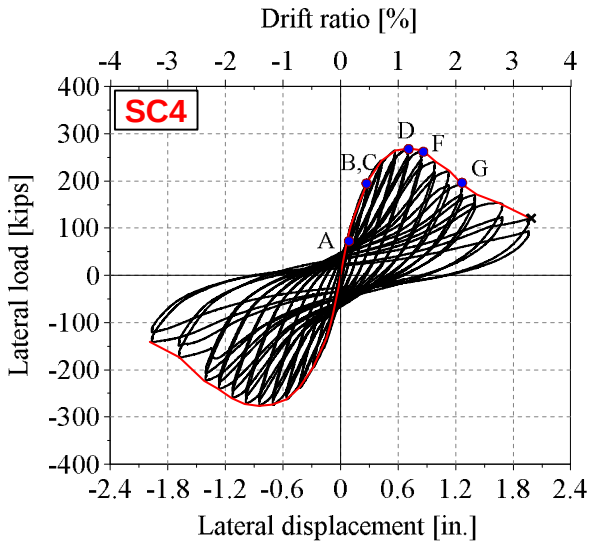


Load-displacement cyclic response









A: Concrete cracking

B: Yielding of the steel faceplates

C: Buckling of the steel faceplates

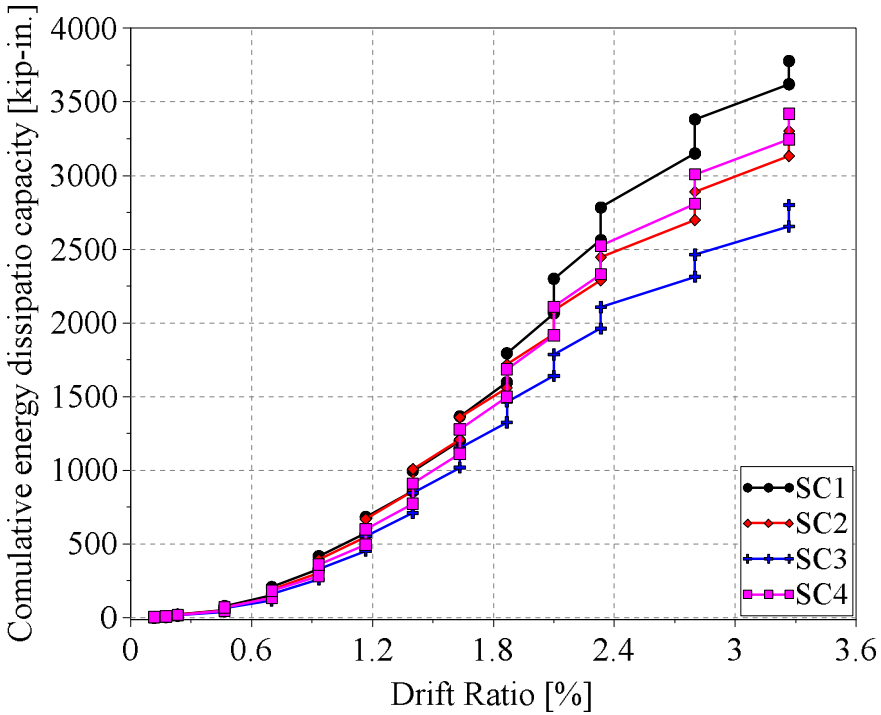
D: Concrete crushing

E: Fracture of the steel faceplates at their connection to the headed studs

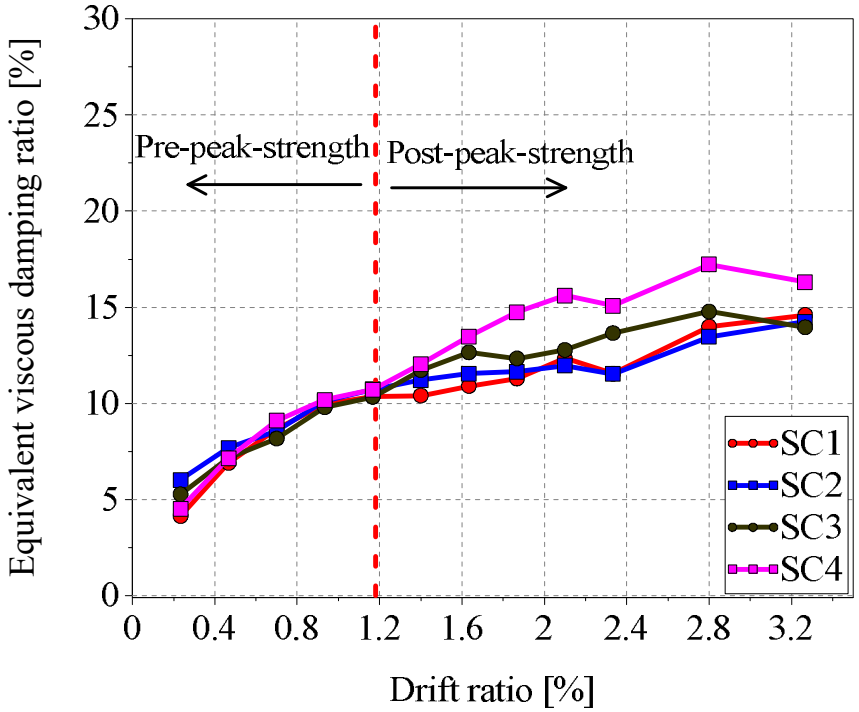
F: Tearing of the steel faceplate above the welded connection of the faceplates to the baseplate

G: Fracture of tie rod

Energy dissipation and viscous damping



Cumulative energy dissipation capacities of SC walls

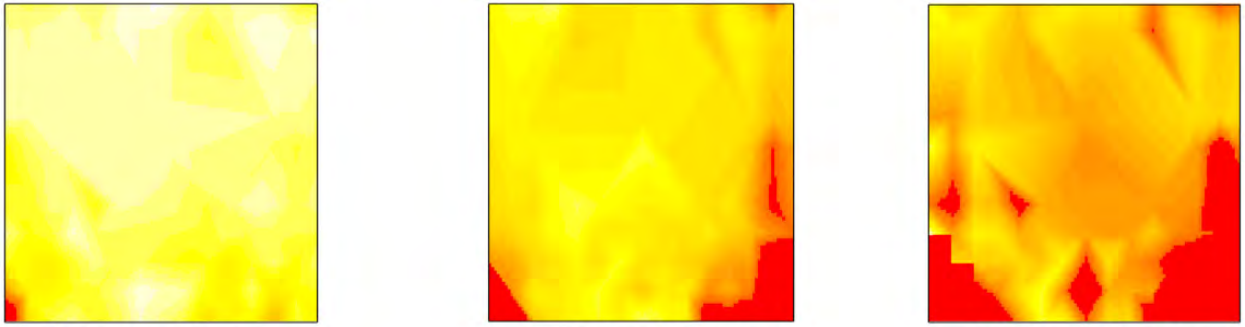


Equivalent viscous damping ratios

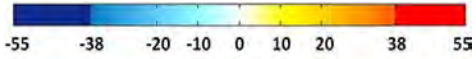
- The energy dissipated in each cycle was calculated as the area enclosed by the hysteresis loop in that cycle.
- the equivalent viscous damping in the SC walls was calculated using: $\xi_{eq} = \frac{1}{4\pi}\frac{E_D}{E_S}$

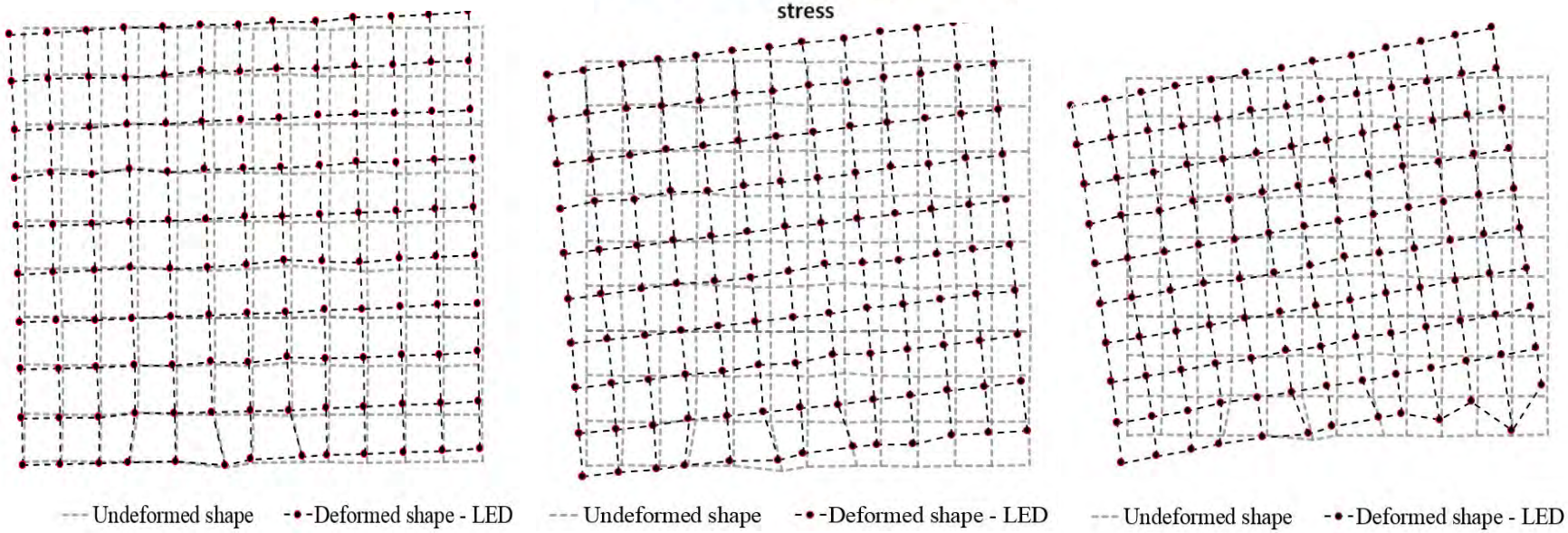
Strain and stress fields in steel faceplates

Von-Mises stress



0.12% drift ratio | 0.47% drift ratio | 1.17% drift ratio

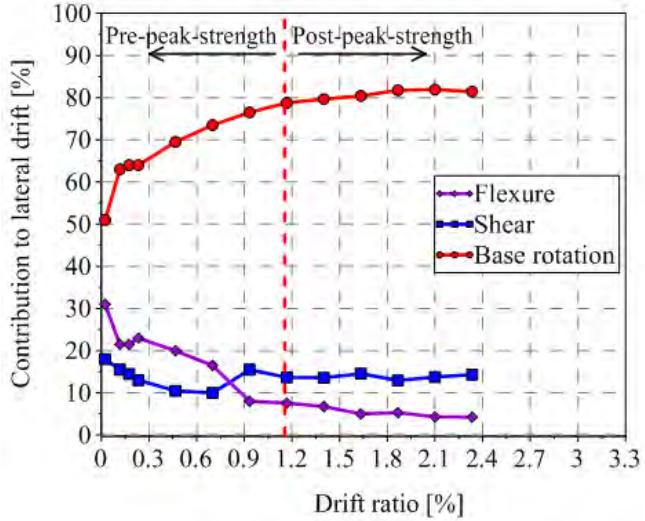




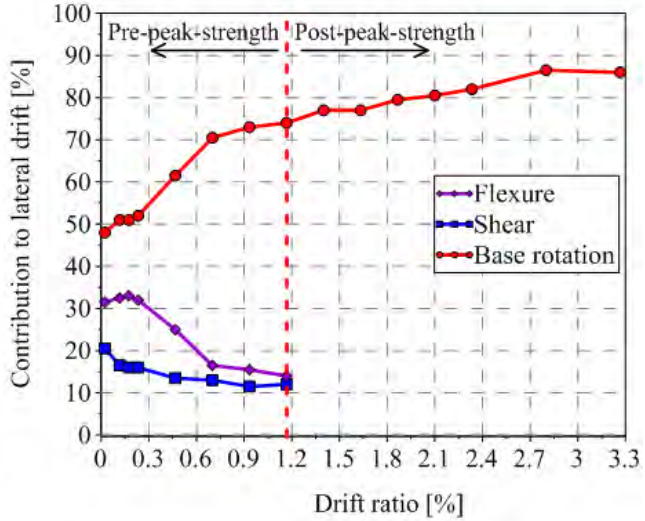
0.47% Drift ratio | 1.17% Drift ratio | 1.87% Drift ratio

Displacement components

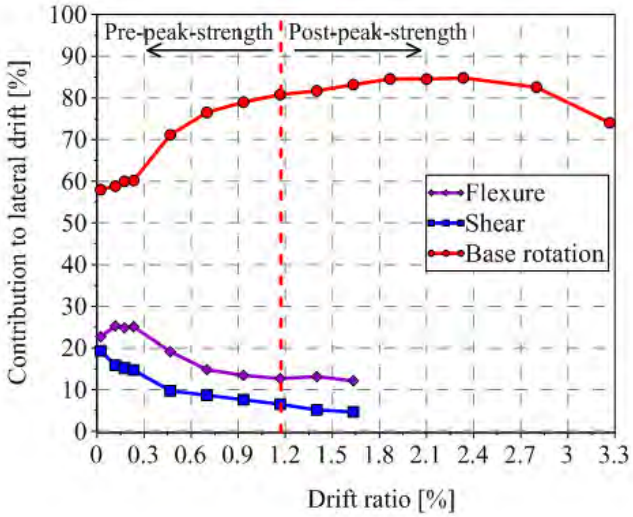
SC1



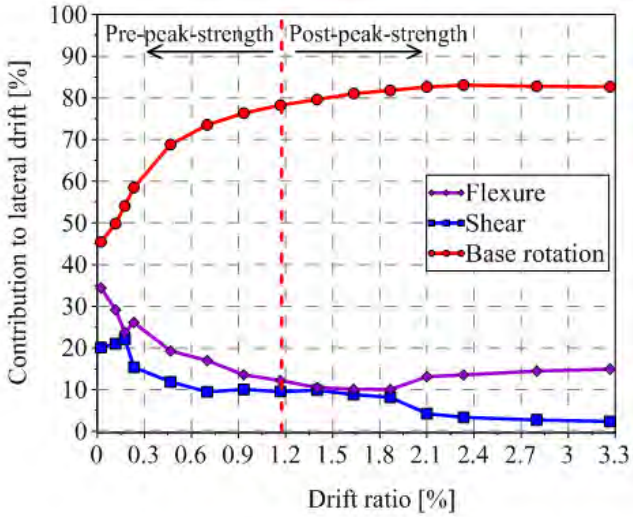
SC2



SC3

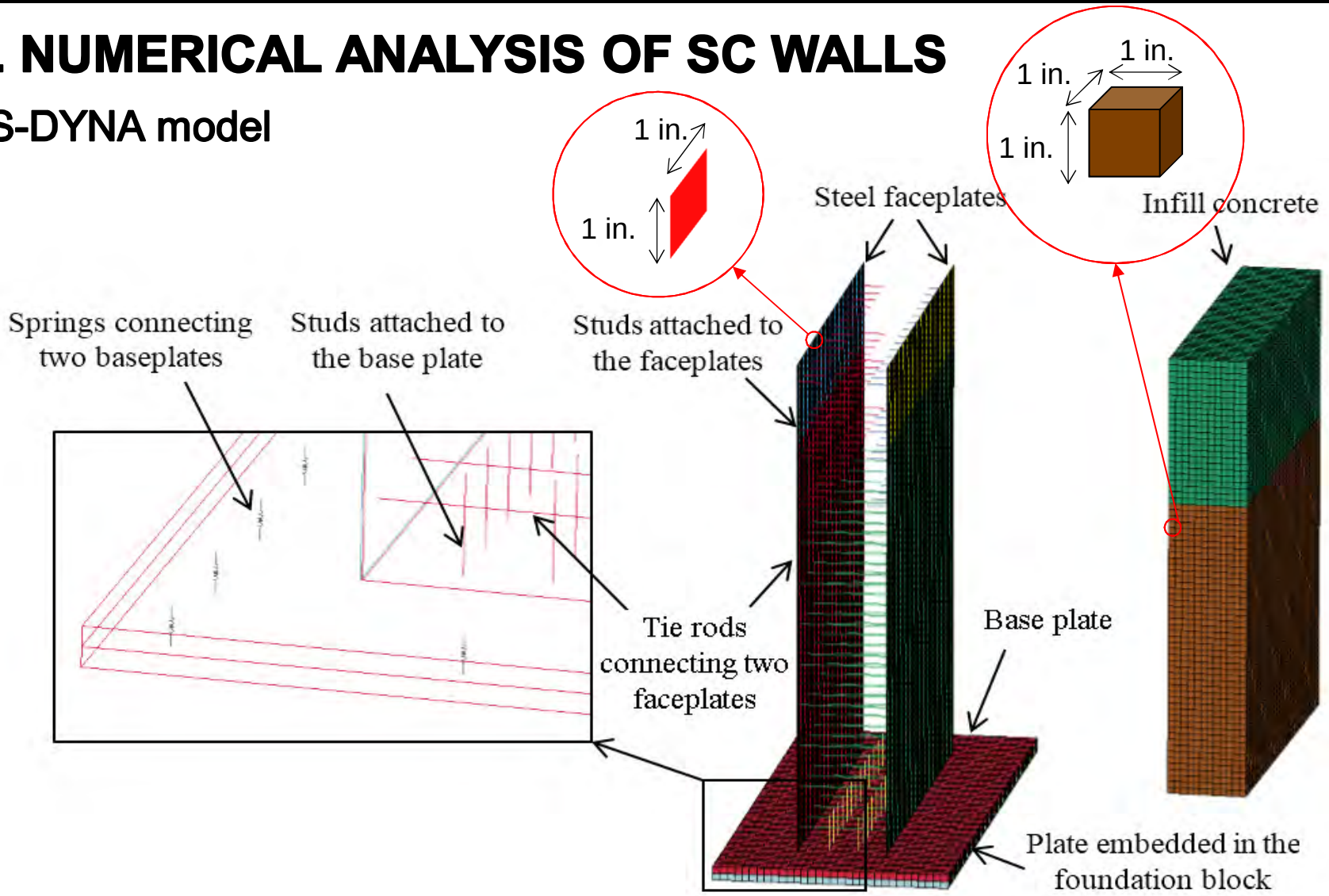


SC4



6. NUMERICAL ANALYSIS OF SC WALLS

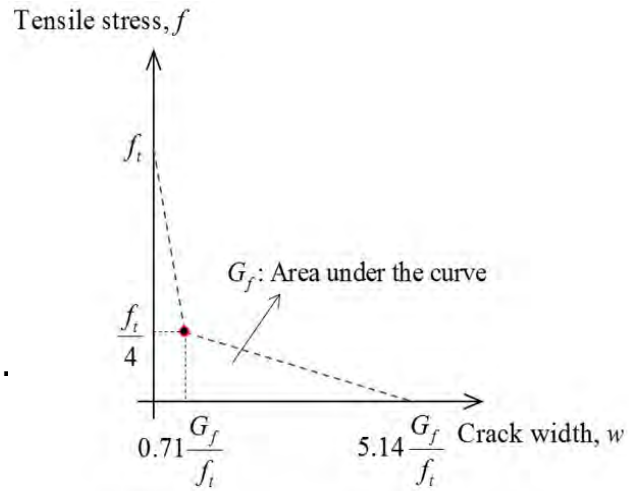
LS-DYNA model



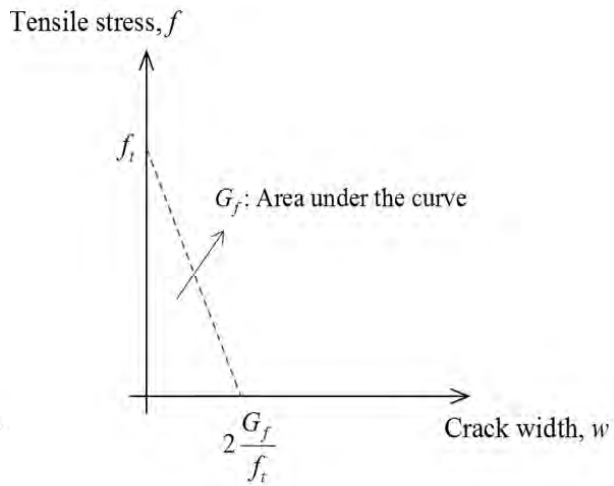
Concrete material model

Crack Analysis in the Winfrith Model

The cracking formulation used in the Winfrith model is based on Wittmann et al.



with the strain-rate effect



without the strain-rate effect

Model	Mass density $\left(\frac{lbf.sec^2}{in^4}\right)$	Young's modulus (ksi)	Poisson's ratio	Uniaxial compressive strength (ksi)	Uniaxial tensile strength (ksi)	Crack width (in.)	Agg. Size (in.)
SC1/SC2	2.25×10^{-4}	3000	0.18	4.40	0.35	0.0025	0.75
SC3/SC4	2.25×10^{-4}	3300	0.18	5.30	0.40	0.0025	0.75

Steel material model

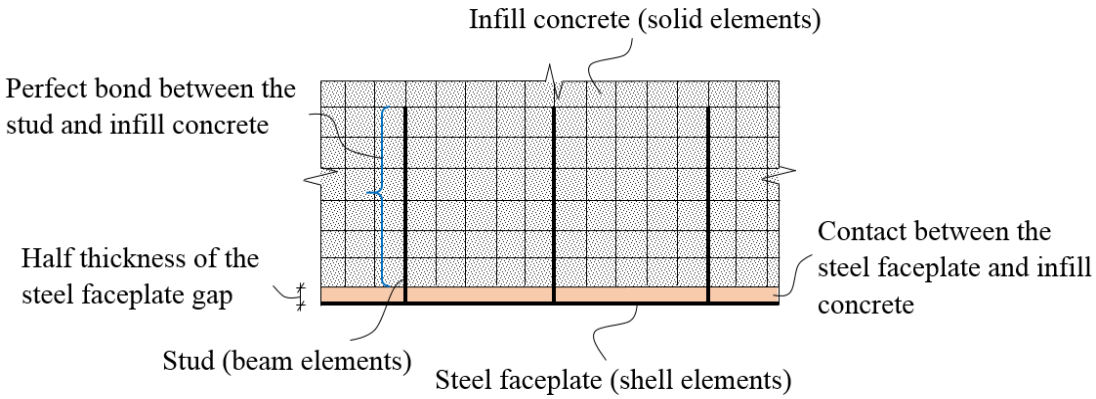
- A plastic-damage model, Mat-Plasticity-With-Damage (MAT081) with isotropic hardening, was used to simulate the nonlinear behavior of the steel faceplates and the connectors.
- The average stress-strain relationship, derived from coupon tests, was used to model the steel faceplates.

Steel material properties input to the DYNA model

Material	Mass density $(\frac{lbf.sec^2}{in^4})$	Young's modulus (ksi)	Poisson's ratio	Yield strength (ksi)	Ultimate strength (ksi)	Failure strain (%)	Fracture strain (%)
Faceplate	7.34×10^{-4}	29000	0.30	38	55	30	40
Connectors	7.34×10^{-4}	29000	0.30	50	75	-	-

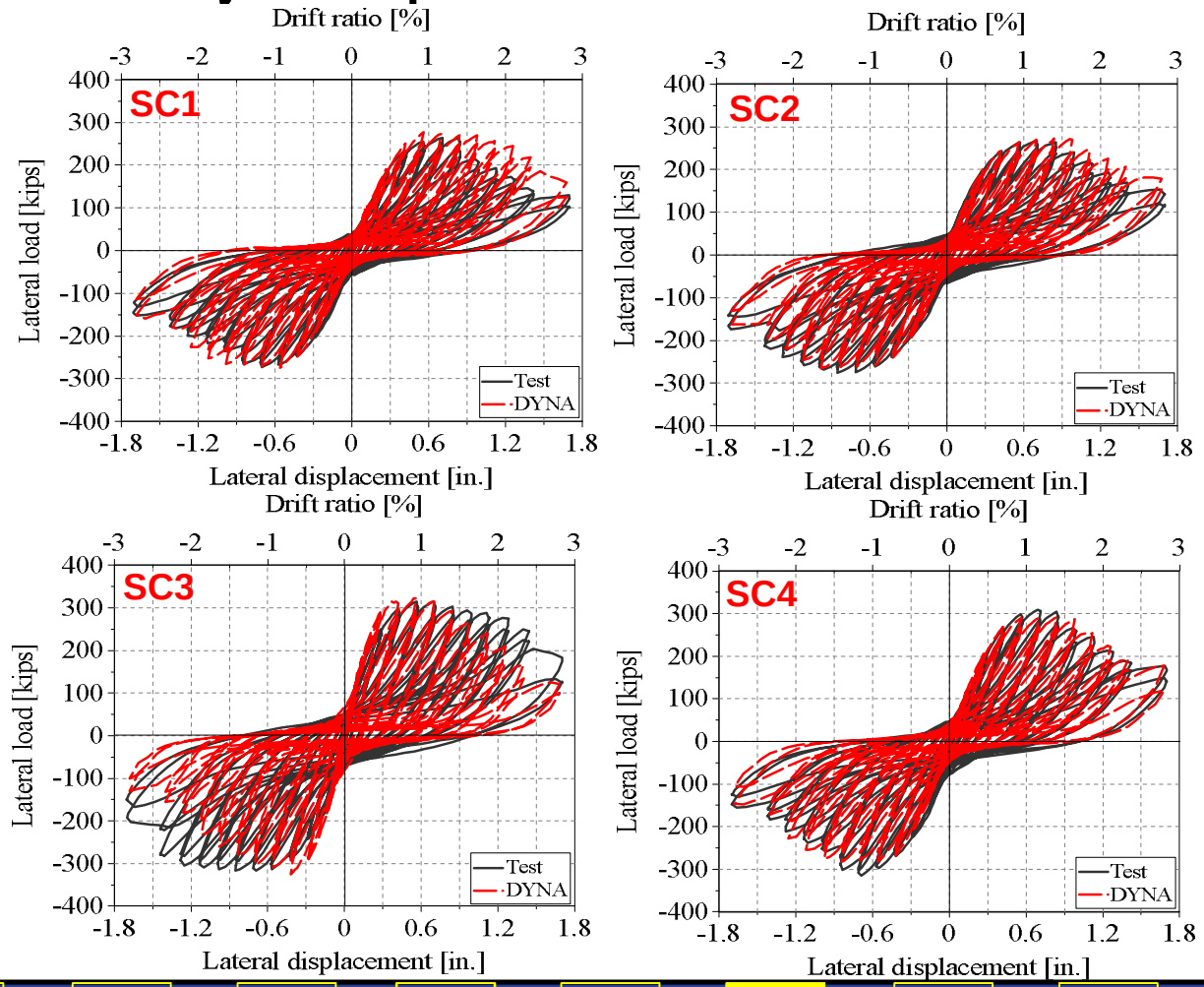
Contact and constraint modeling

- Contact-Automatic-Surface-To-Surface formulation was used to model friction between:
  - the infill concrete and the steel faceplates,
  - the infill concrete and the baseplate, and
  - the baseplate and the steel plate embedded in the foundation block
- The coefficient of friction for steel on concrete = 0.5
  - Rabbat et al. showed that the coefficient of friction between a steel plate and cast-in-place concrete varied between 0.57 and 0.7.
- The steel faceplates were tied to the baseplate using the kinematic constraint Contact-Tied-Shell-Edge-To-Surface.
- The studs and tie rods were coupled to the infill concrete elements using the Constrained-Lagrange-In-Solid formulation.

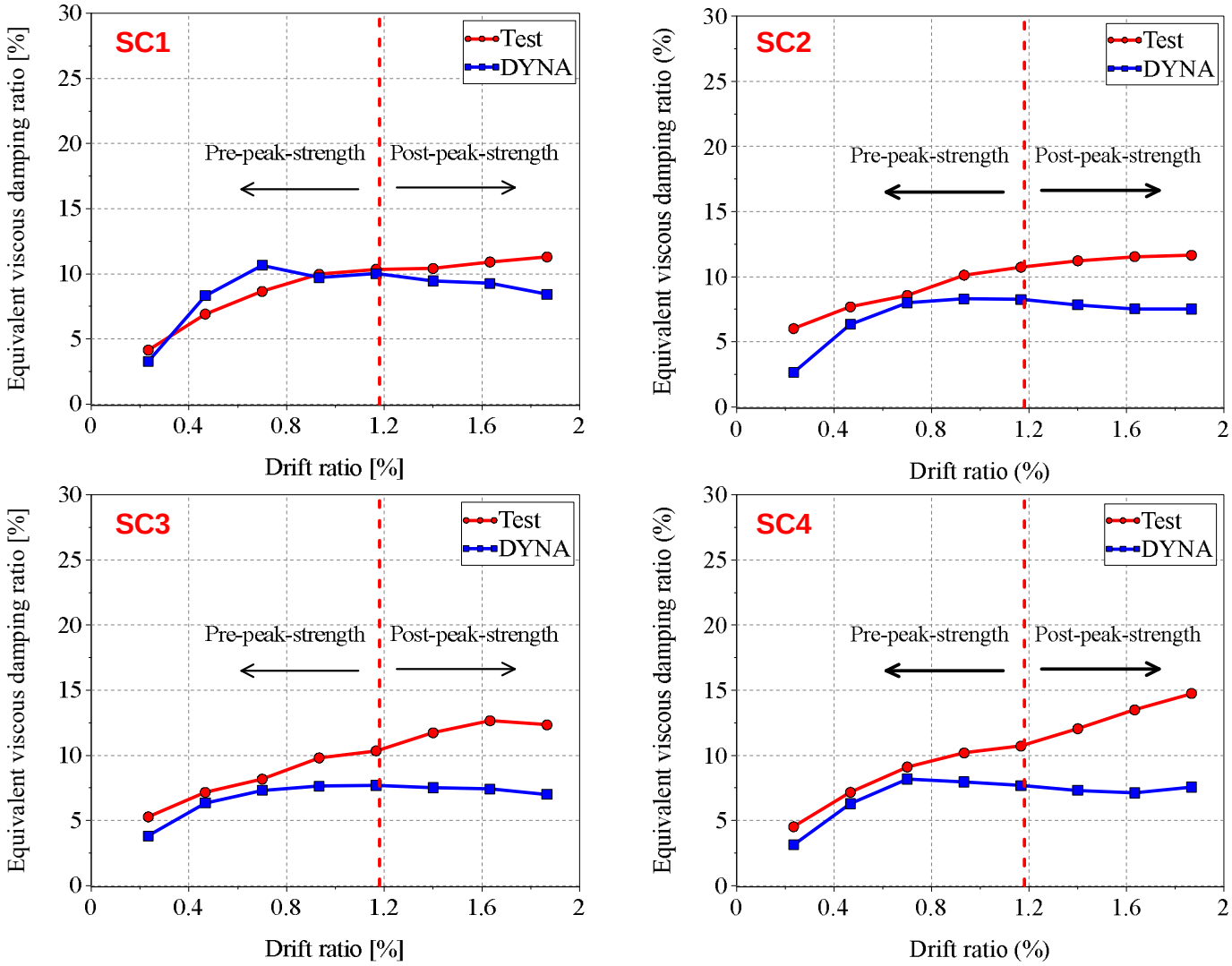


7. LS-DYNA ANALYSIS RESULTS

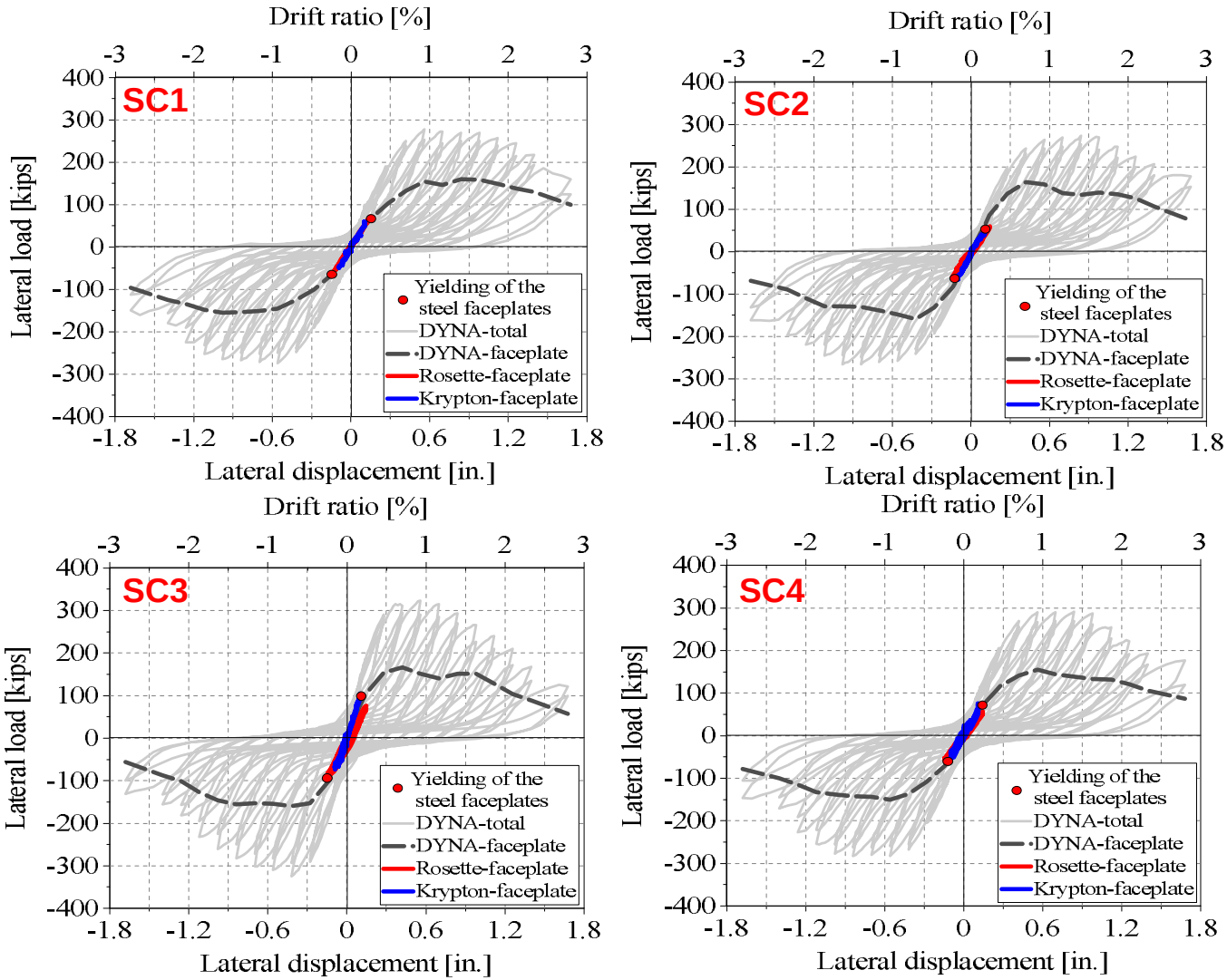
Load-displacement cyclic response



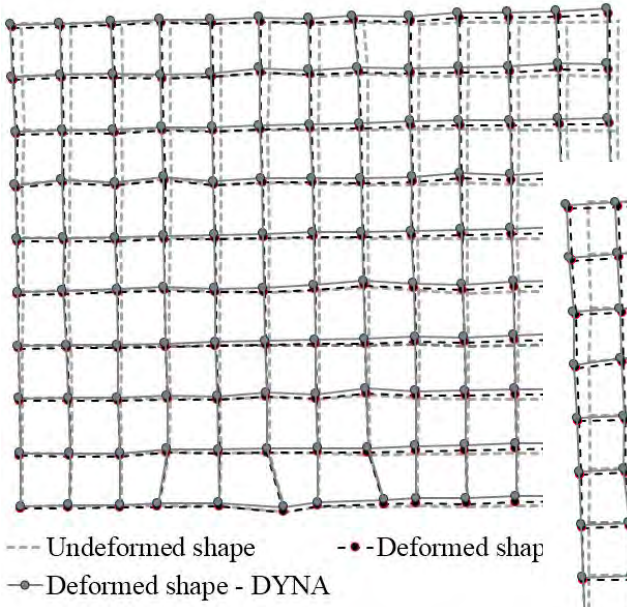
Hysteretic damping



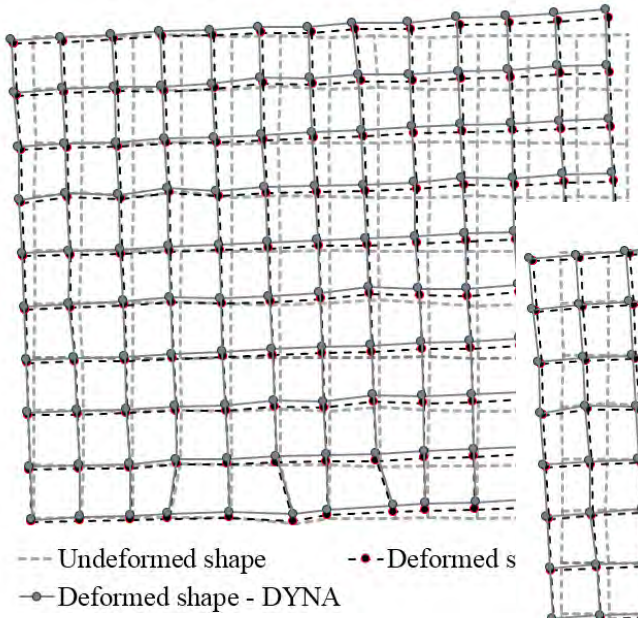
Steel faceplate contribution to the total load



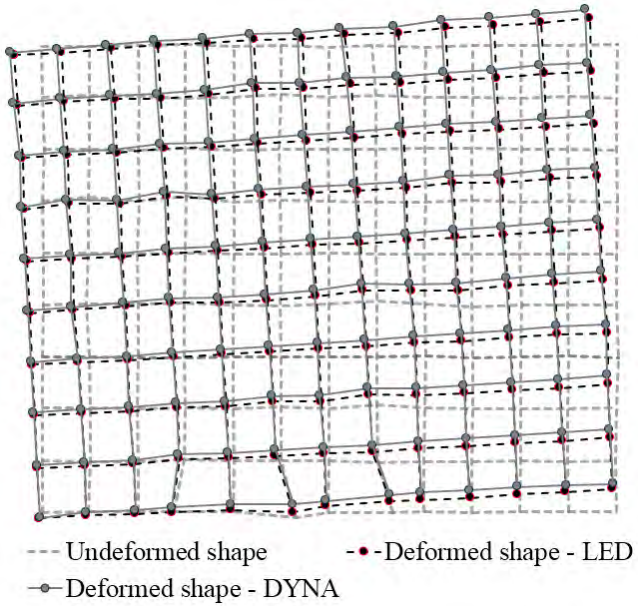
Steel faceplate contribution to the total load



0.23% drift ratio

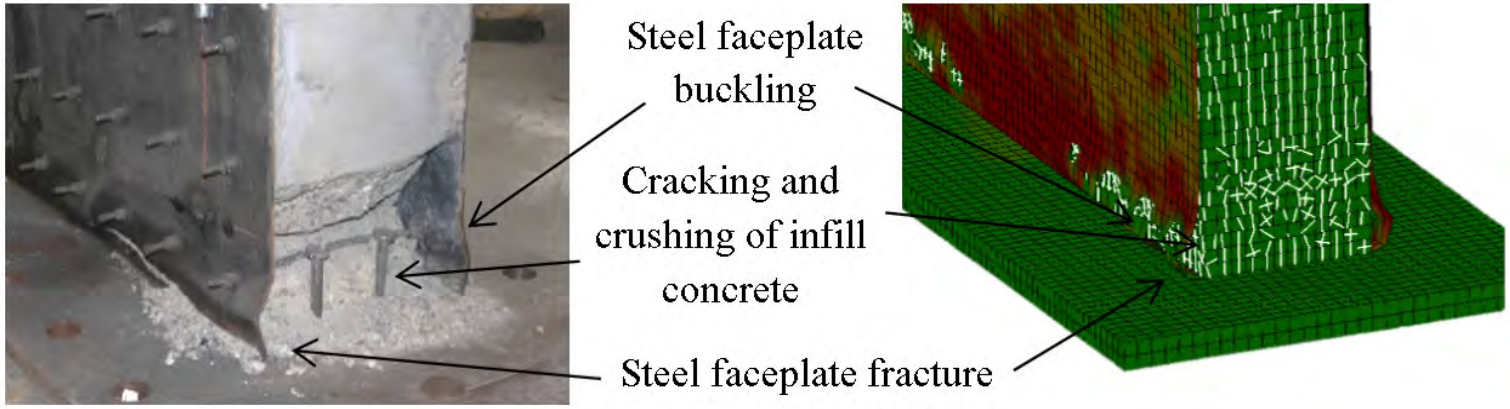


0.47% drift ratio

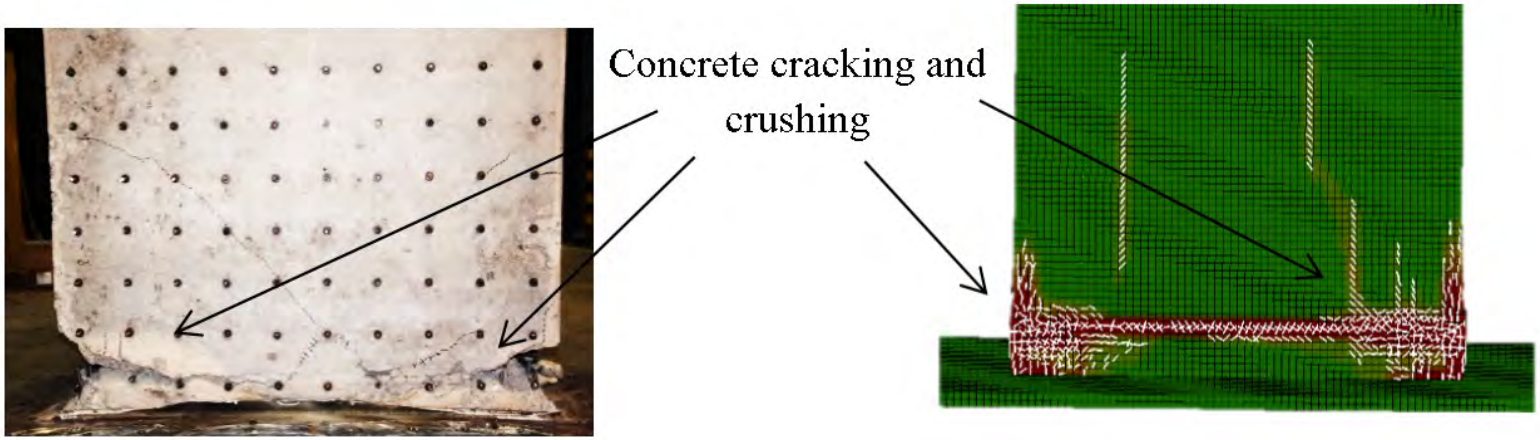


0.70% drift ratio

Damage to SC walls



Damage to specimen; test (left panel) and analysis (right panel)



Damage to infill concrete; test (left panel) and analysis (right panel)

8. A PARAMETRIC STUDY: DESIGN OF SC WALLS

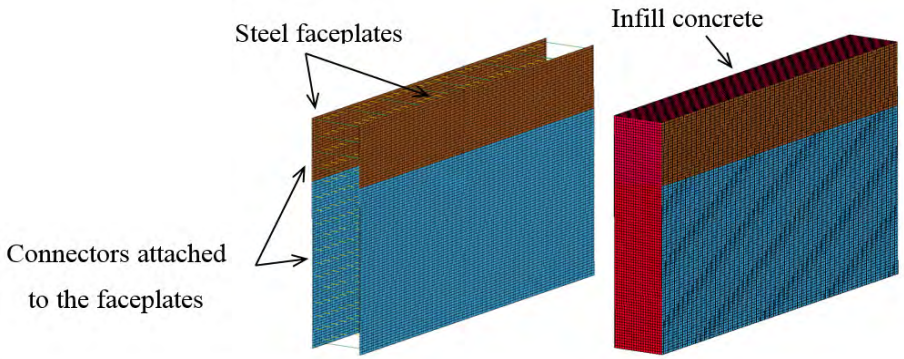
DYNA modeling of SC walls and design variables

- Six design parameters were considered:

Levels of the design parameters			
Variable	Low	Intermediate	High
Aspect ratio	0.5 (-1)	1.25 (0)	2.0 (+1)
Reinforcement ratio (%)	1.67 (-1)	3.33 (0)	5.0 (+1)
Slenderness ratio	10 (-1)	25 (0)	40 (+1)
Axial load ratio	0 (-1)	0.1 (0)	0.2 (+1)
Yield strength of the steel faceplates (MPa)	235 (-1)	350 (0)	460 (+1)
Concrete compressive strength (MPa)	27.6 (-1)	41.4 (0)	55.2 (+1)

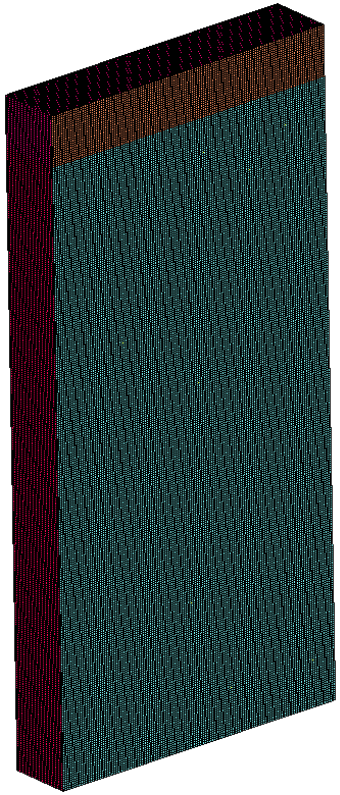
8. A PARAMETRIC STUDY: DESIGN OF SC WALLS

DYNA modeling of SC walls and design variables



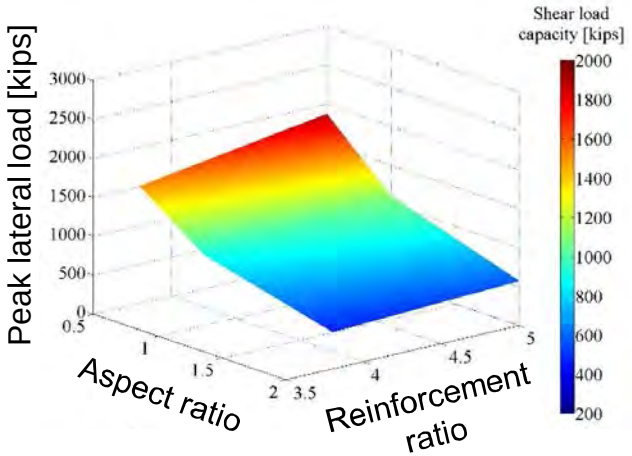
Low-aspect ratio wall

Intermediate-aspect ratio wall

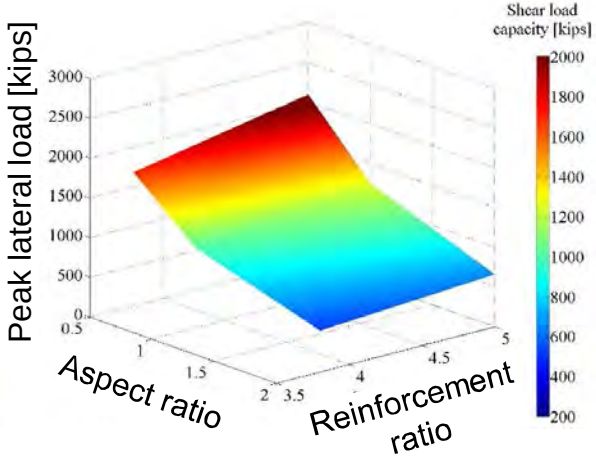


High-aspect ratio wall

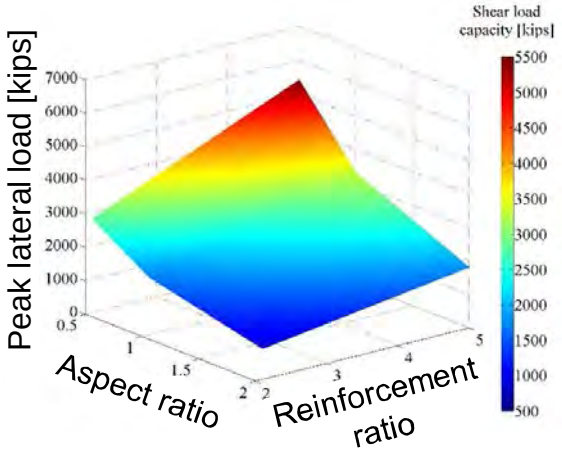
Analysis results



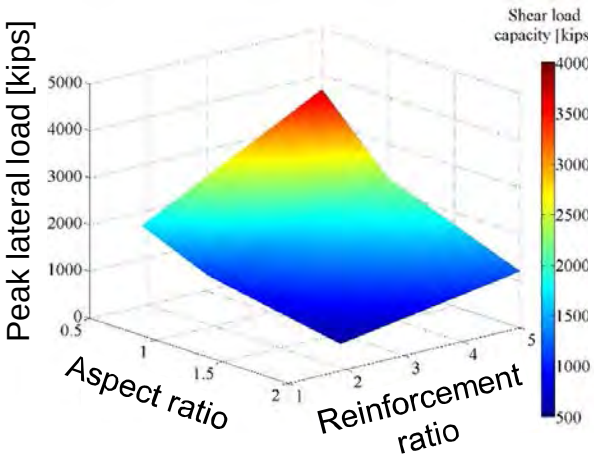
10-in. thick wall with normal-strength concrete



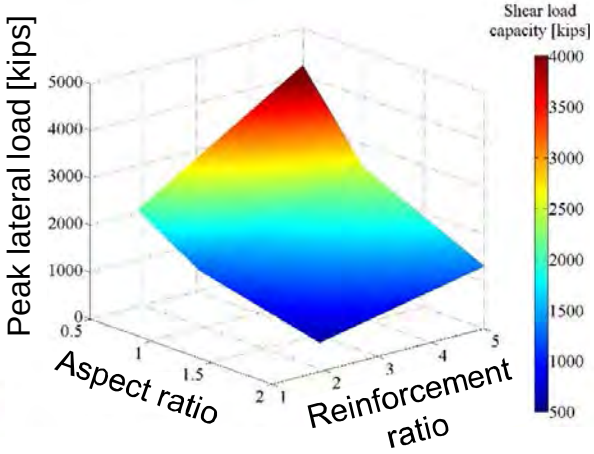
10-in. thick wall with intermediate-strength concrete



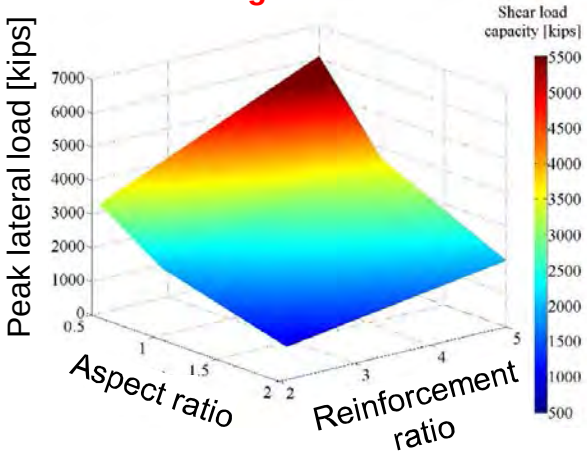
30-in. thick wall with normal-strength concrete



20-in. thick wall with normal-strength concrete

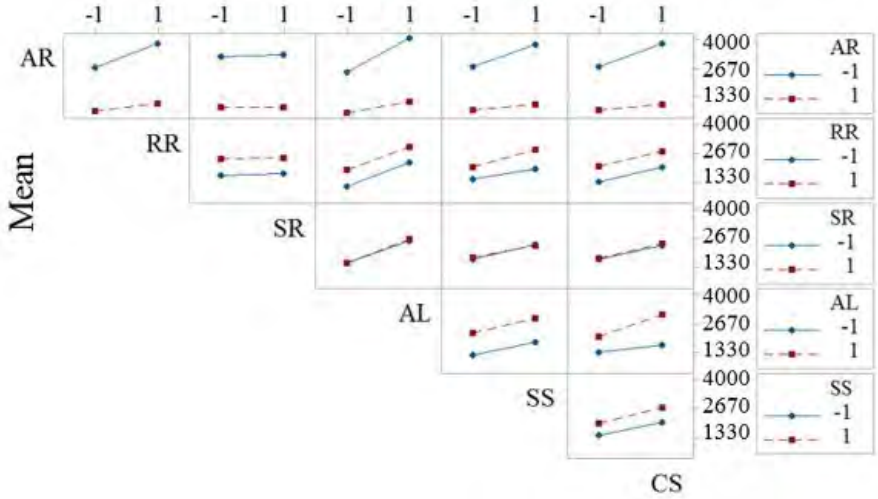


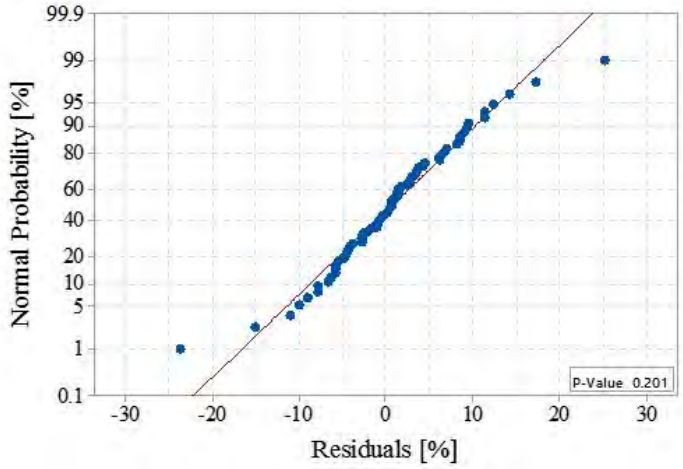
20-in. thick wall with intermediate-strength concrete

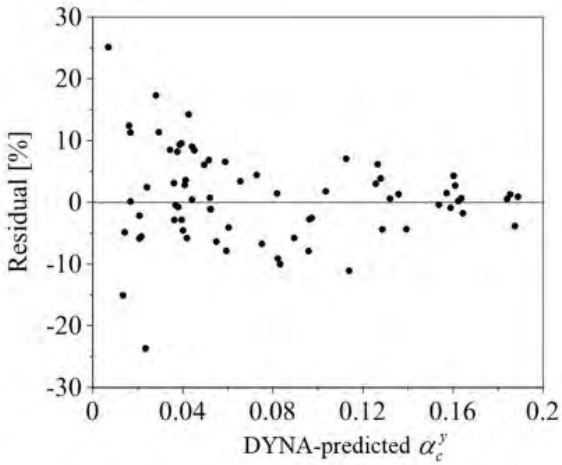


30-in. thick wall with intermediate-strength concrete

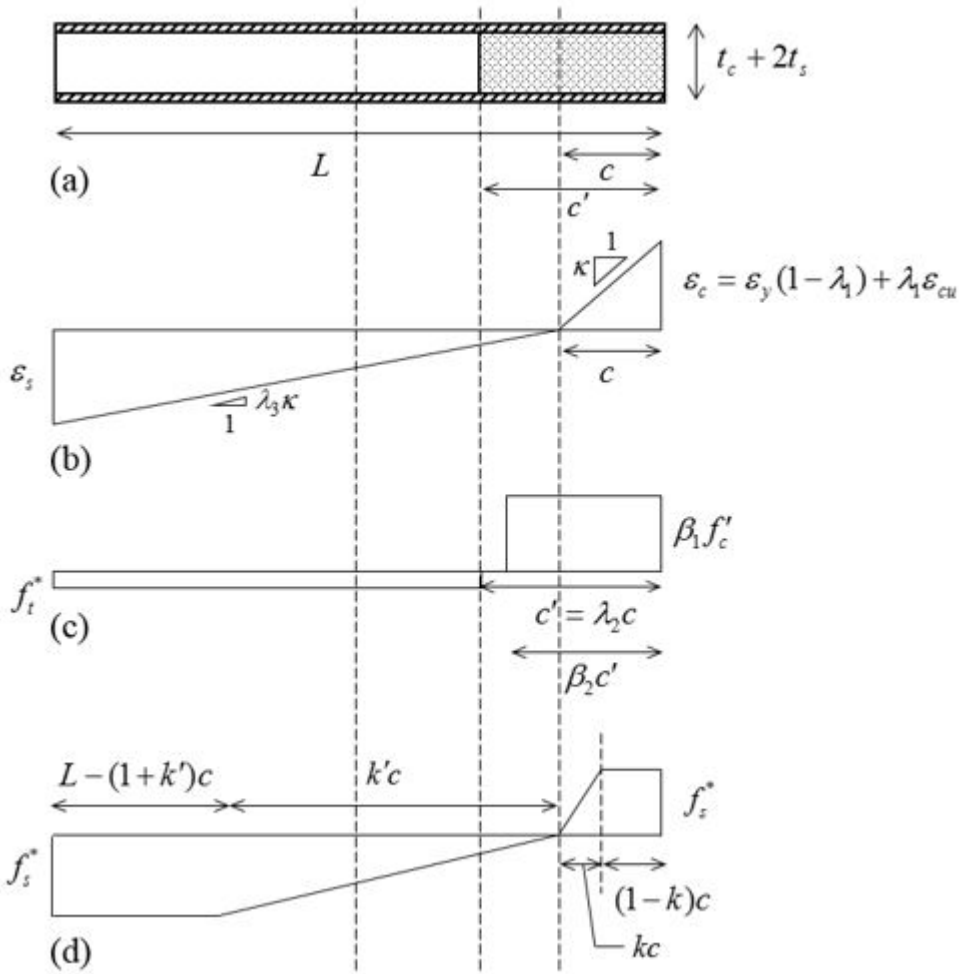
Design of Experiments (DOE)

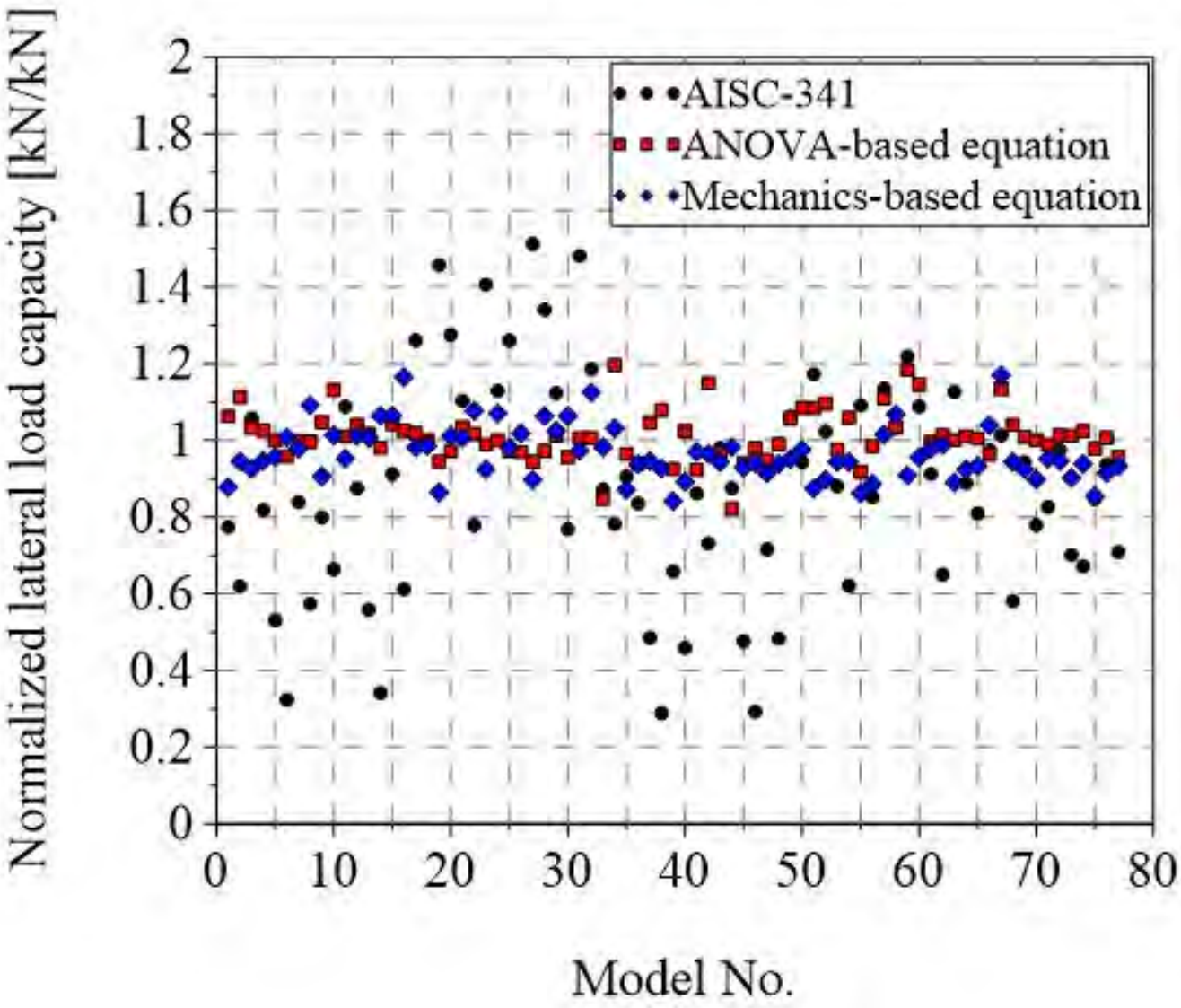






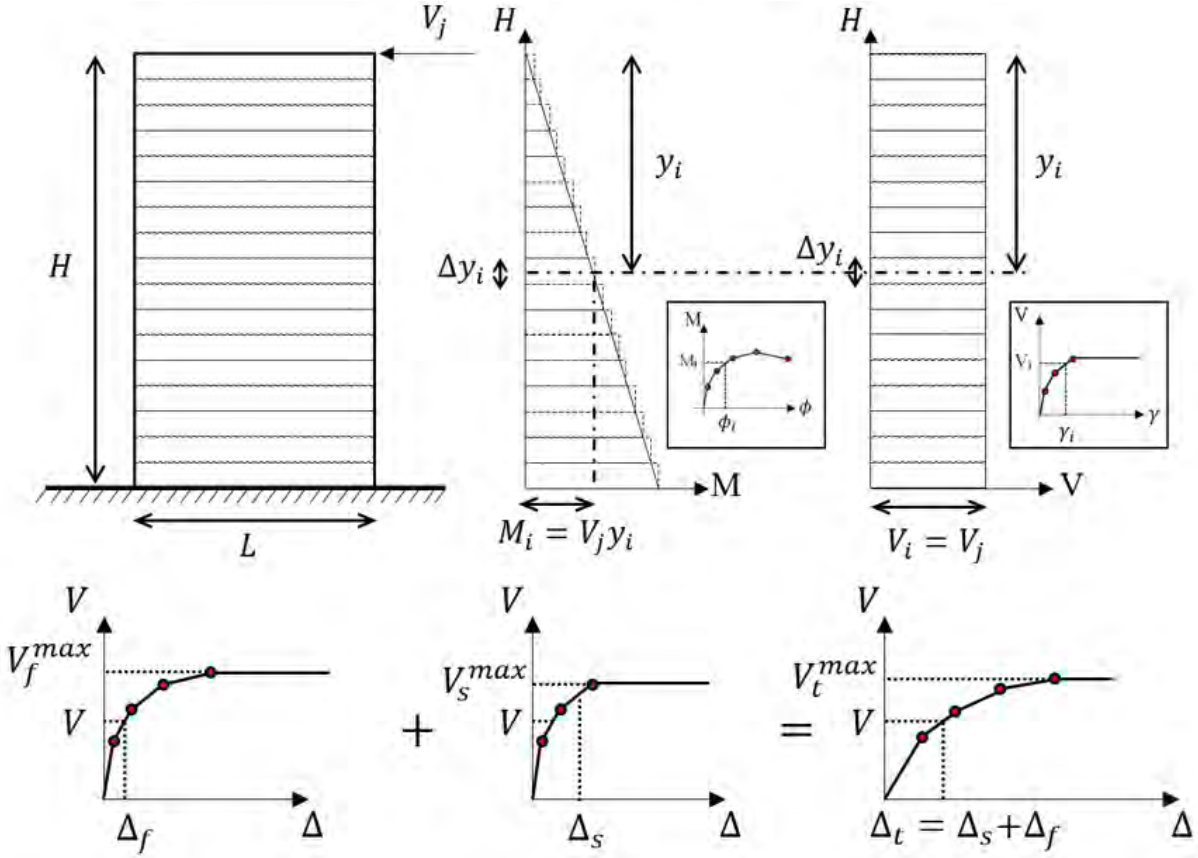
Mechanics-based Equations for Predicting Peak Flexural Strength




AISC-341
ANOVA-based equation
Mechanics-based equation
Normalized lateral load capacity [kN/kN]
Model No.
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
10
20
30
40
50
60
70
80

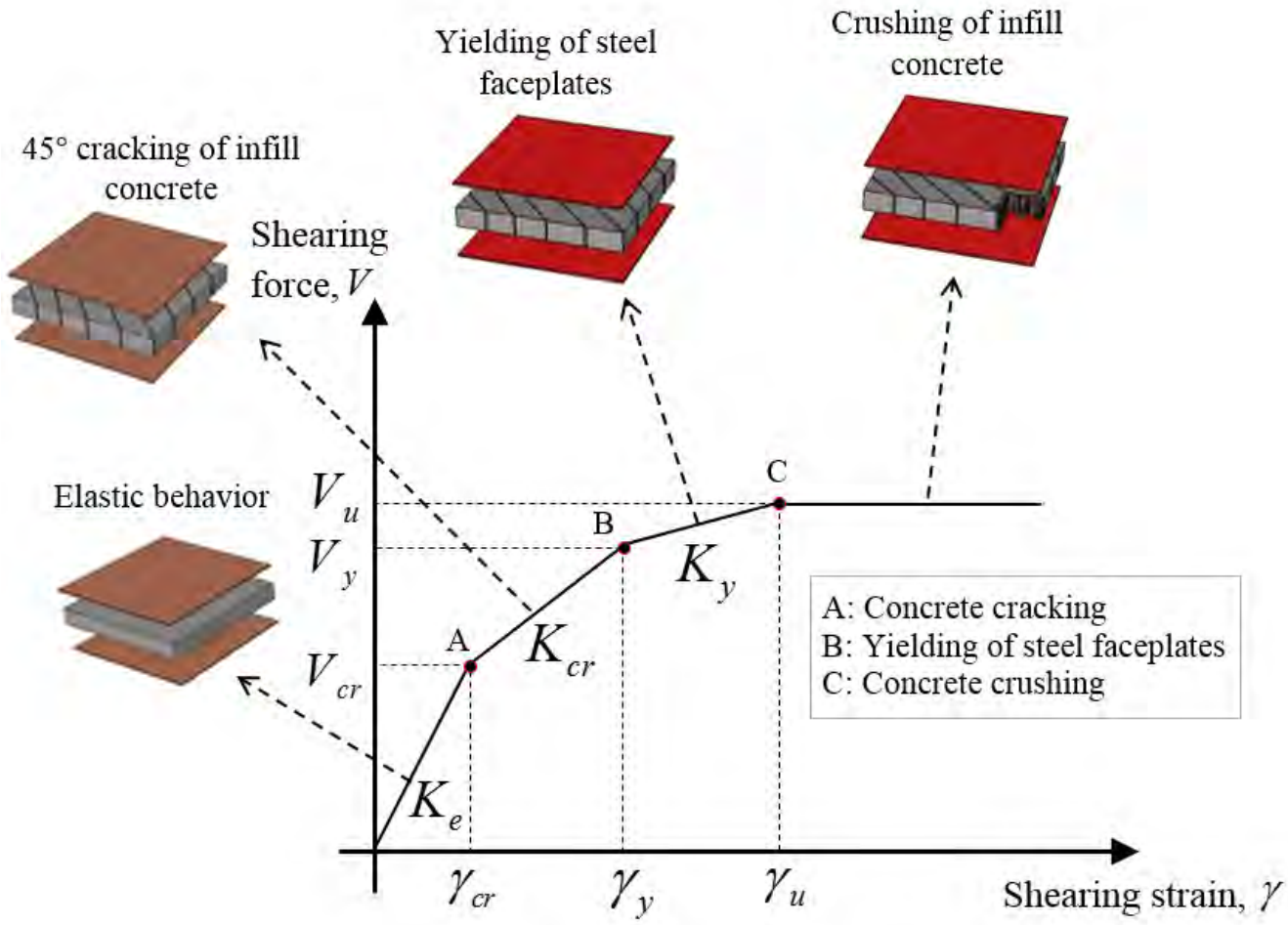
9. ANALYTICAL MODELING OF SC WALL PIERS

Simplified monotonic analysis of SC walls



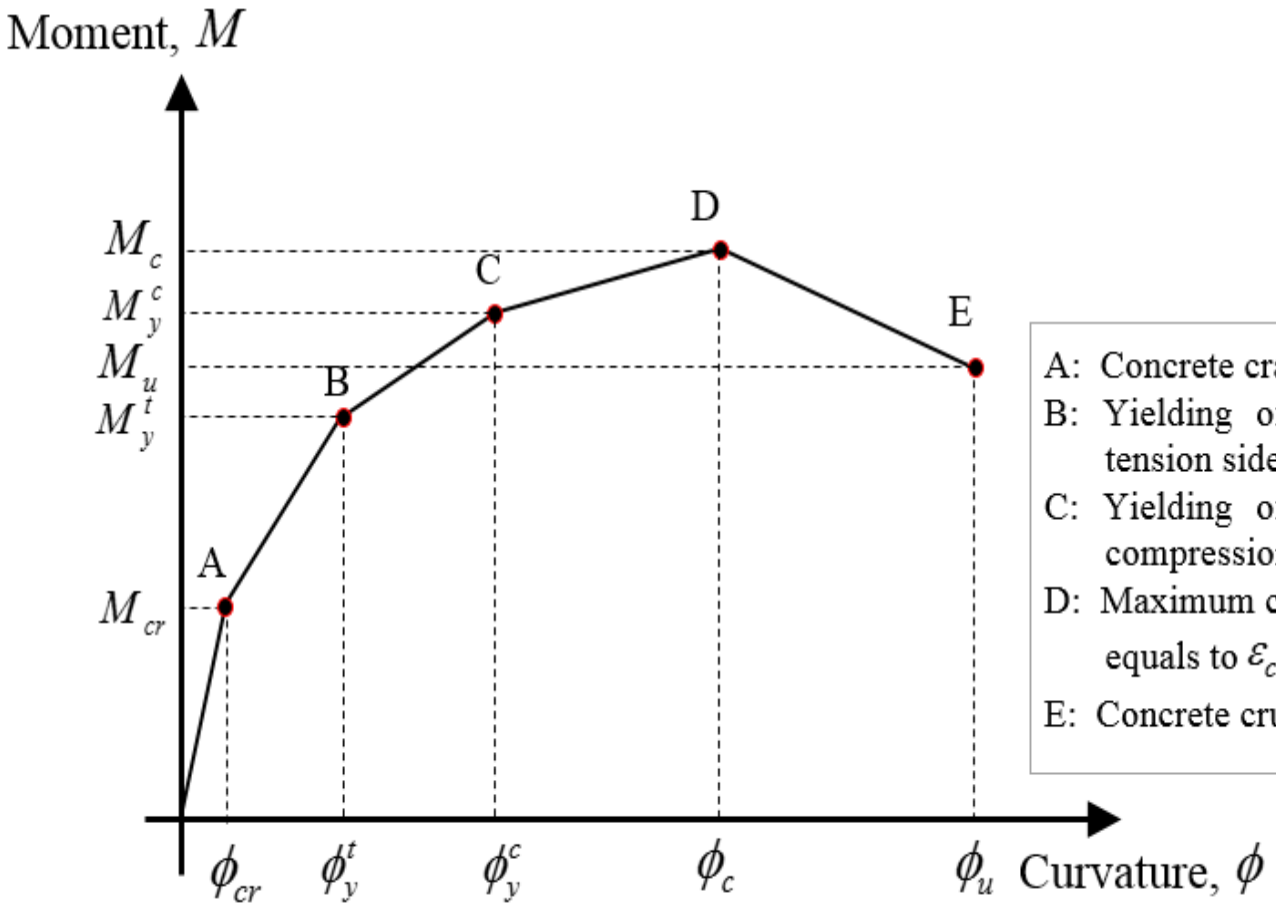
Simplified monotonic analysis of SC walls

Shearing force-shearing strain relationship



In-plane shear response of SC walls

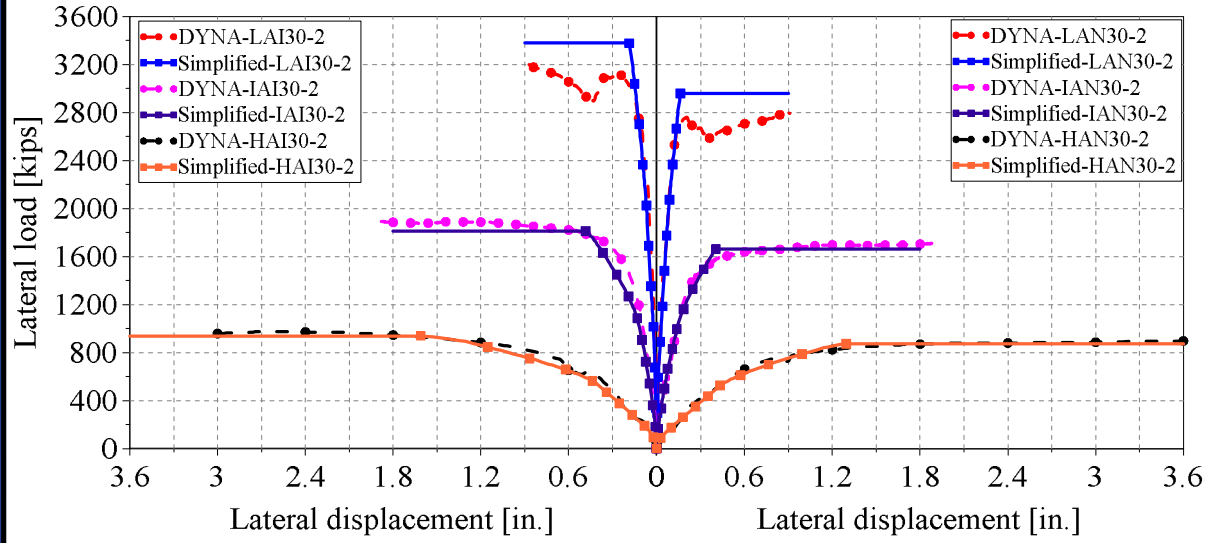
Moment-curvature relationship



A: Concrete cracking
B: Yielding of the steel faceplates on tension side
C: Yielding of the steel faceplates on compression side
D: Maximum concrete compressive strain equals to ε_{c0}
E: Concrete crushing

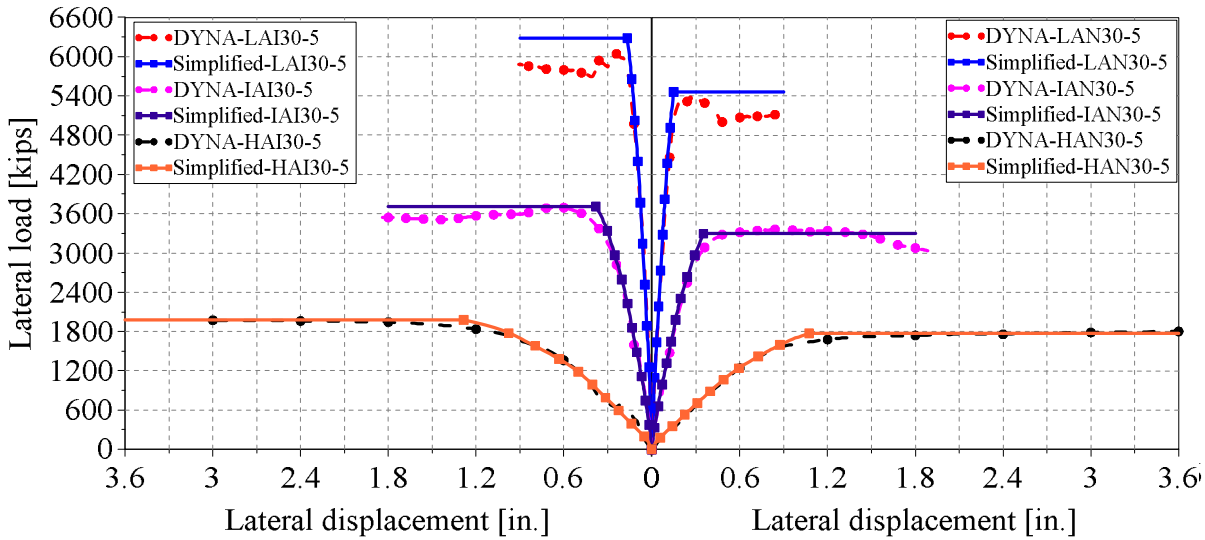
Moment-curvature relationship of SC wall

Validation of the simplified monotonic analysis

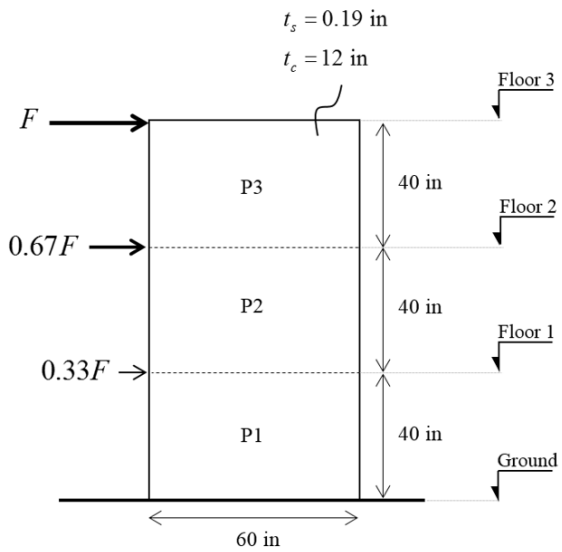


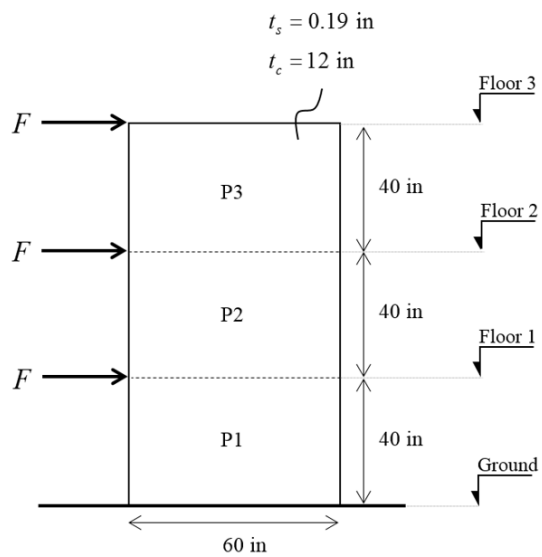
Force-displacement relationship for 30-in. thick walls with 2.1% reinforcement ratio

Force-displacement relationship for 30-in. thick walls with 5.0% reinforcement ratio



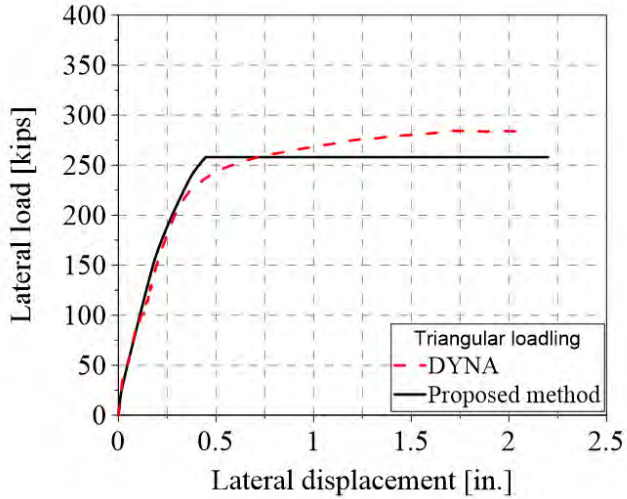
Force-displacement response of multi-story SC walls

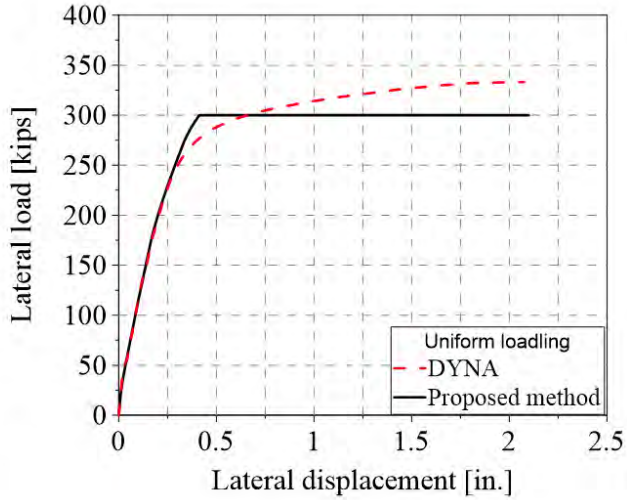




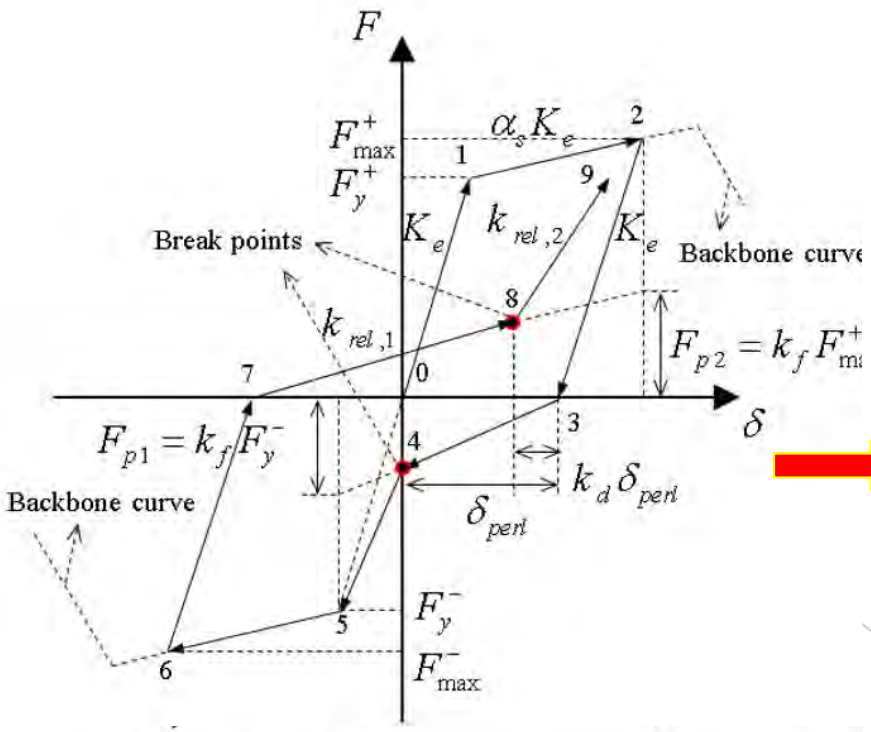
Elevation view of three-story SC walls subject to uniform and triangular loadings

Analytically- and numerically-predicted responses of three story SC wall

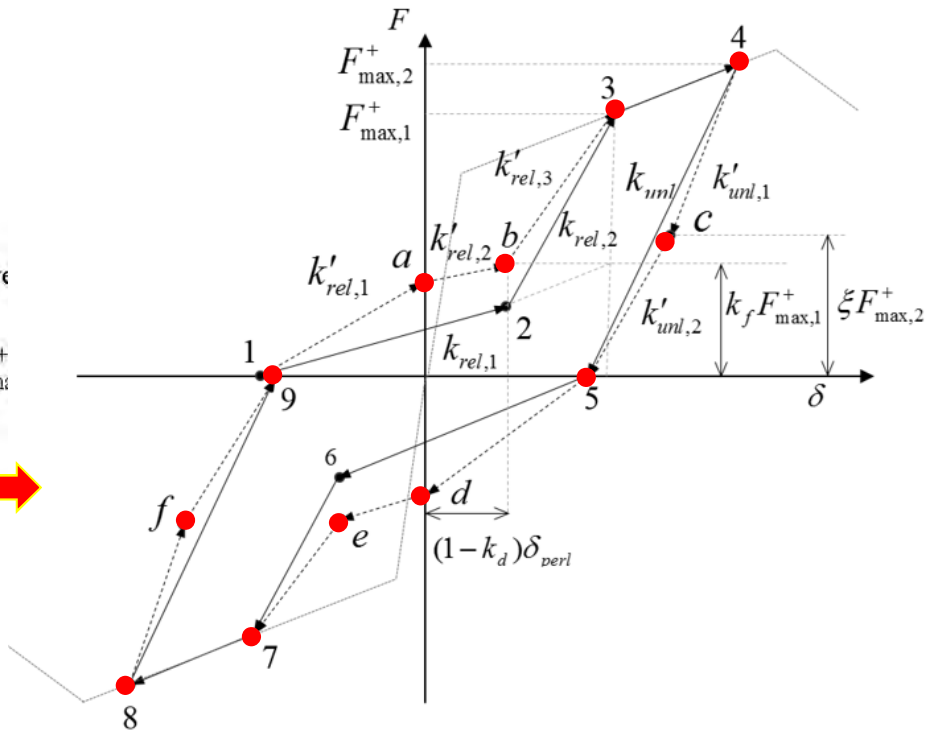




Simulation of cyclic response

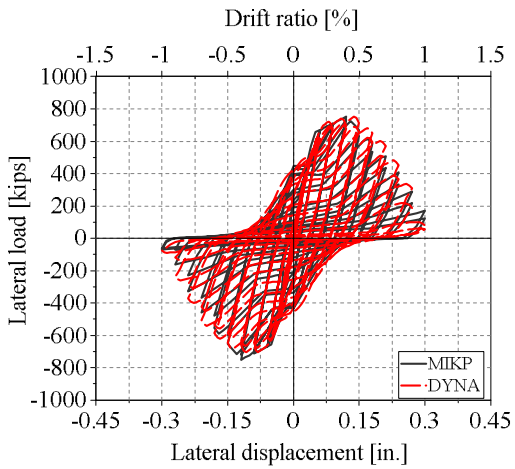


Cyclic loop of the IKP model

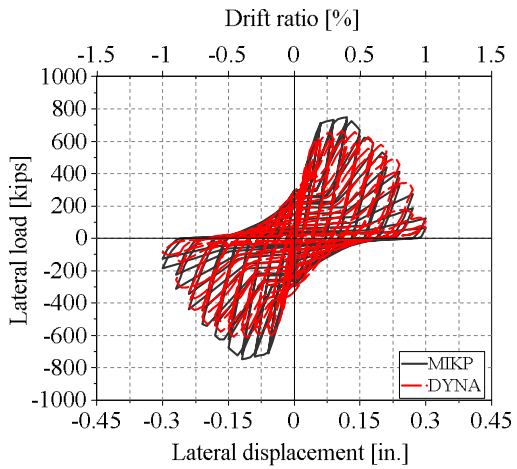


Cyclic loop of the MIKP model

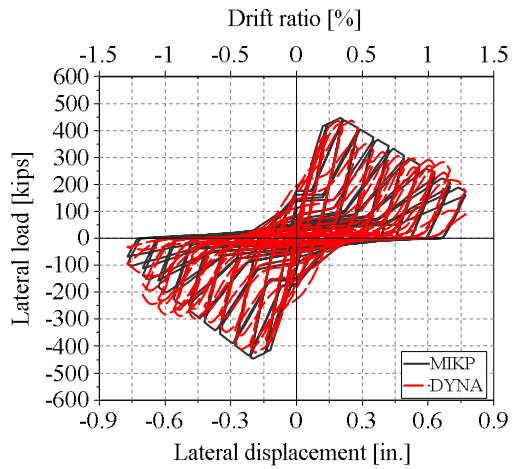
Simulation of the cyclic analysis of SC walls



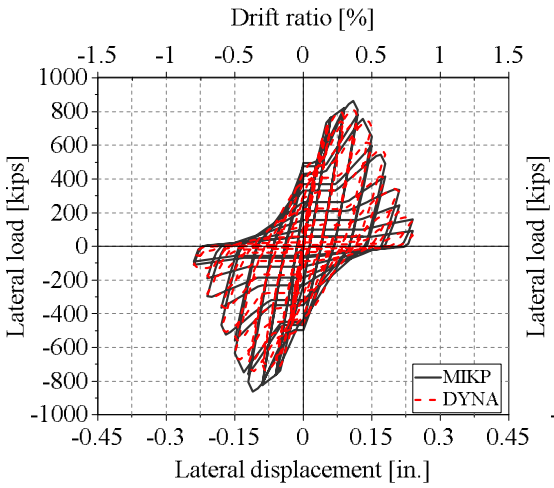
LAN10-5



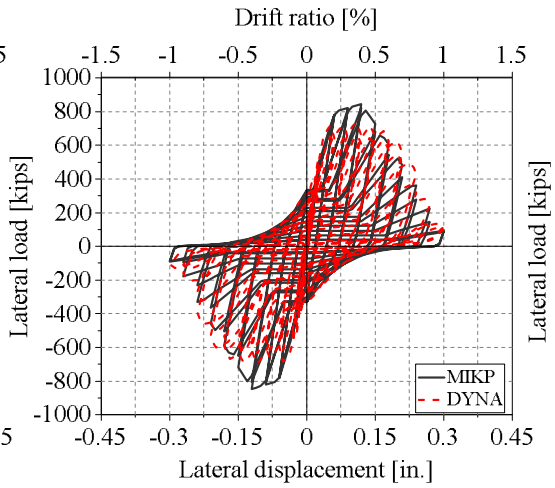
LAN20-2



IAN10-5



LAH10-5



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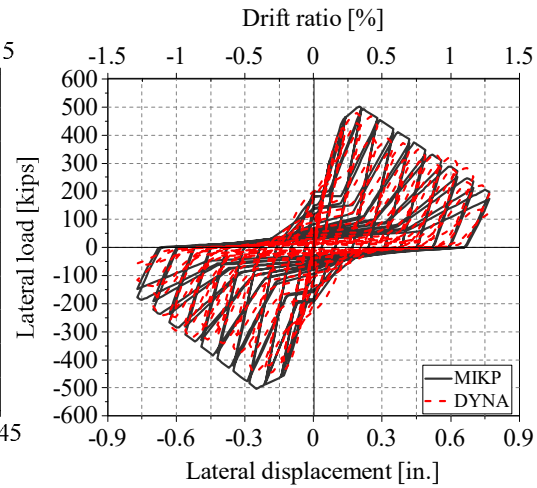


IAH10-5

10. MODELING SQUAT REINFORCED CONCRETE SHEAR WALLS FOR SEISMIC ANALYSIS

ASCE 41-13 cyclic backbone curves

Table 1. Modelling parameters and acceptance criteria for nonlinear procedures—R/C shear walls and wall segments controlled by shear [11]

Conditions	Total drift ratio (%)			Strength ratio		Acceptable total drift ratio (%) Performance level		
	d	e	g	c	f	IO	LS	CP
$\frac{(A_s - A_s')f_y + P}{t_w l_w f_c'} \le 0.05$	1.0	2.0	0.4	0.2	0.6	0.4	1.5	2.0
$\frac{(A_s - A_s')f_y + P}{t_w l_w f_c'} > 0.05$	0.75	1.0	0.4	0.0	0.6	0.4	0.75	1.0

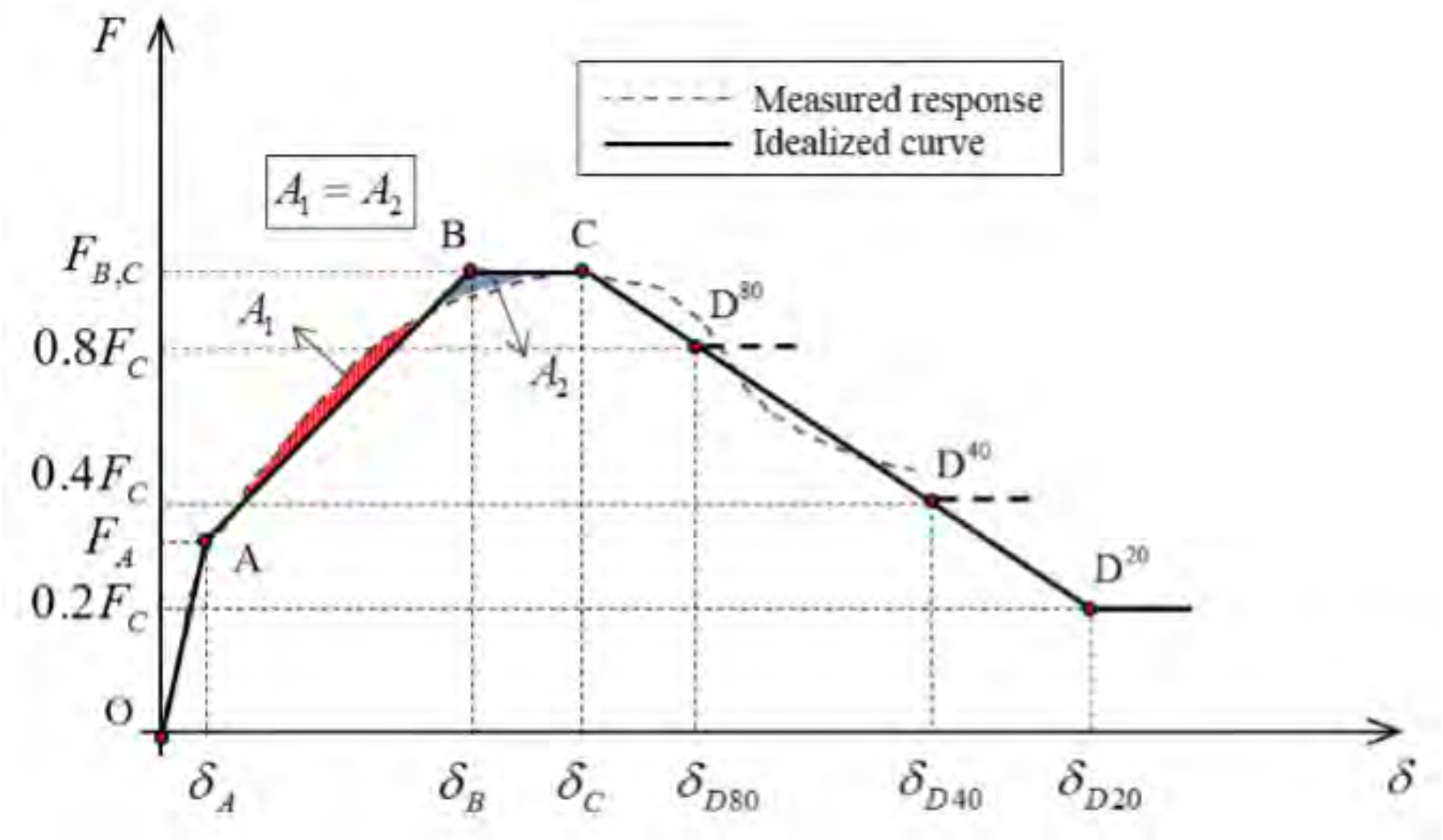
$\frac{\Delta}{h}$

Database development

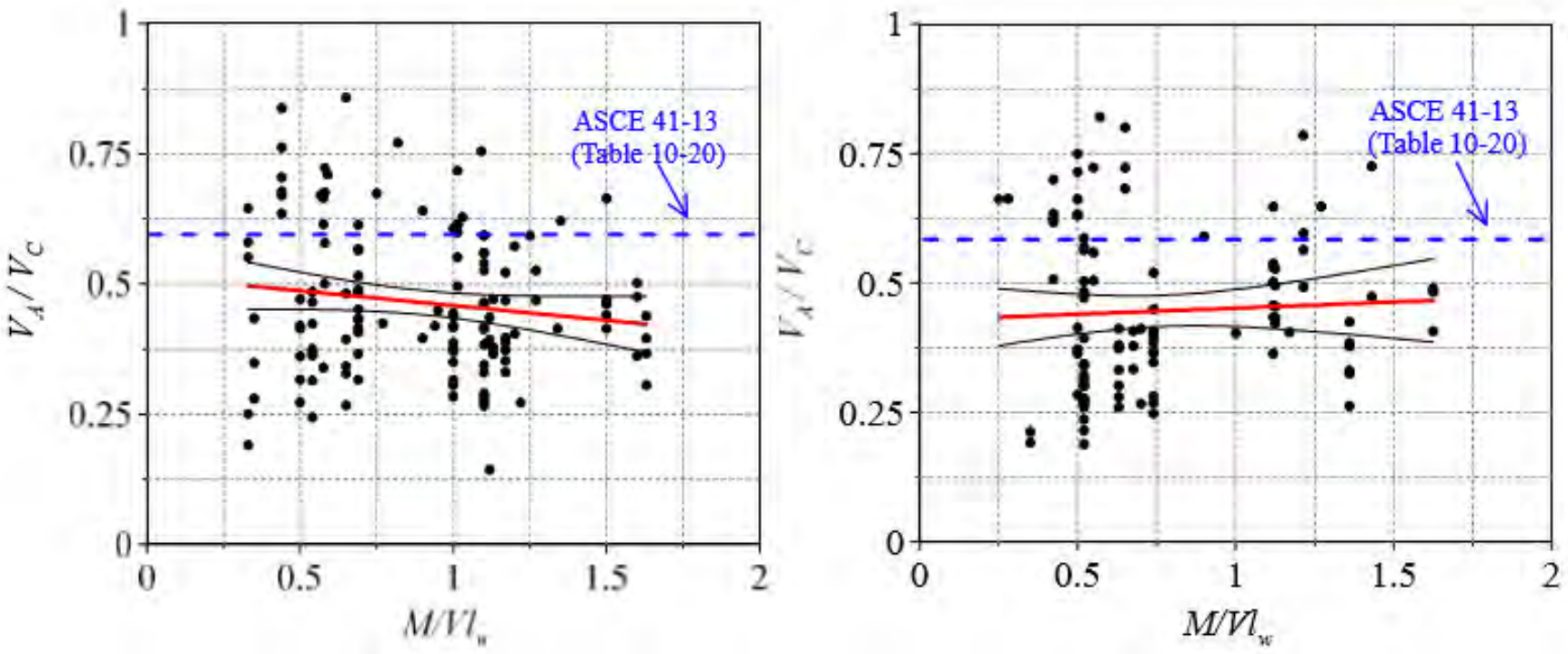
Data from the cyclic testing of 240 low-aspect ratio RC walls was assembled to evaluate the utility of the ASCE 41-13 backbone curve.

- wall aspect (moment-to-shear) ratio (M/Vl_w)
- vertical web reinforcement ratio[1] ($\rho_v f_{yv}$)
- horizontal web reinforcement ratio ($\rho_h f_{yh}$)
- vertical reinforcement ratio in the boundary element[2] ($\rho_{vb} f_{yvb}$)
- normalized axial compressive load ($P/A_g f_c'$)
- concrete uniaxial compressive strength (f_c')

Database development

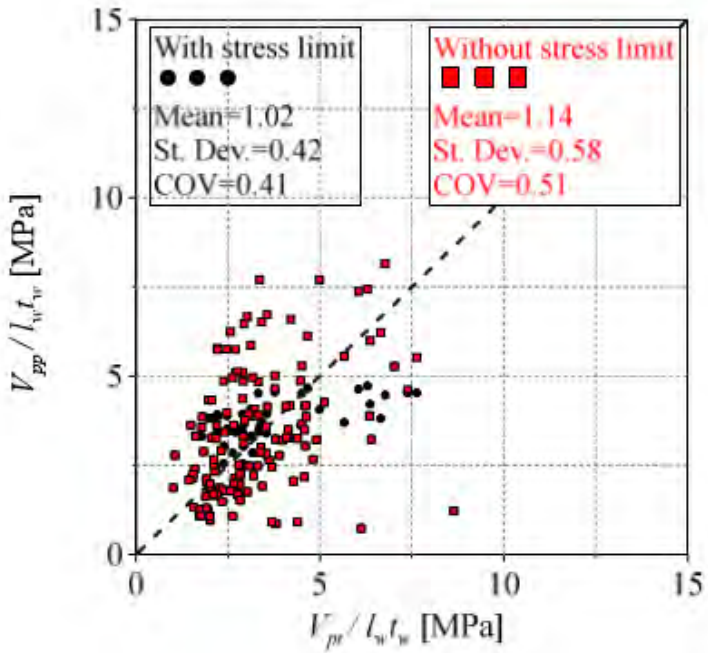


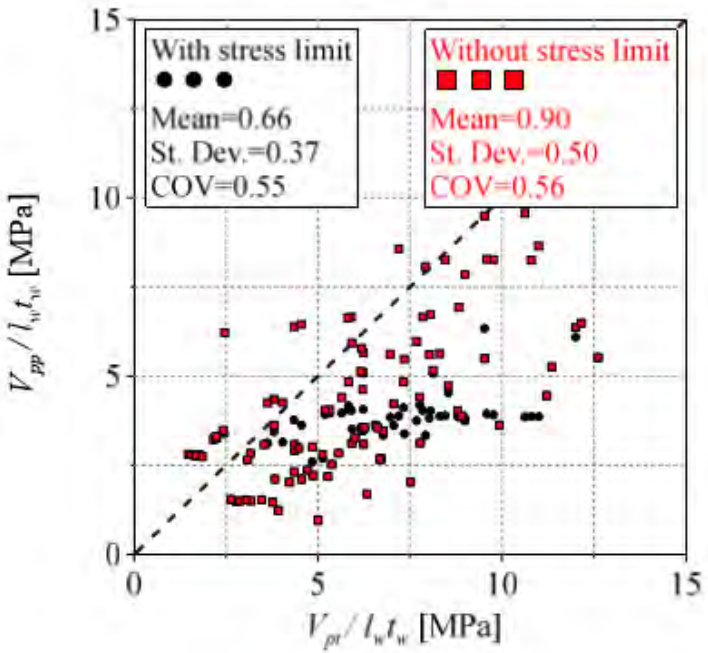
Database development



M/Vl_w : rectangular walls (left panel), and barbell and flanged walls (right panel)

Database development





ACI 318-14 Chapter 11; rectangular walls (left panel) and barbell and flanged walls (right panel)

9. CONCLUSIONS

Numerical and Analytical Studies

5. Tie rods instead of shear studs are recommended near the base of an SC wall, where the faceplates are likely to buckle and high tensile forces are imposed on the connectors, to improve the seismic response of SC walls.
6. The initial stiffness of SC walls constructed with a baseplate connection to an RC foundation may be substantially affected by the flexibility of the connection, with a potential significant impact on the dynamic response of the supported structure.
7. The contribution of the steel faceplates to the total lateral strength increases as the reinforcement ratio and/or the wall aspect ratio increases.

FUTURE RESEARCH

1. Studies on flanged SC walls with I- and H-shaped cross sections.
2. Numerical and analytical models for simulation of cyclic response of shear-critical SC walls.
3. Research on the response of SC walls subjected to both in-plane and out-of-plane loadings.
4. Development of macro model which can be easily implemented in an engineering computational platform for practical analyses of SC walls.
5. Identification of the response modification factor, R, for SC walls.
6. Generation of the fragility functions.
7. Comparison studies on SC and RC walls with identical shear span-to-depth ratios and reinforcement ratios.

References

Journal articles:

Epackachi, S., Whittaker, A.S, and Aref, A. (2016). "Seismic analysis and design of steel-plate concrete composite shear wall piers" Engineering Structures, DOI: 10.1016/j.engstruct.2016.12.024.

Epackachi, S., Whittaker, A.S, Varma, A.H., and Kurt, E.G. (2015). "Finite element modeling of steel-plate concrete composite wall piers" Engineering Structures, DOI: 10.1016/j.engstruct.2015.06.02.

Farhidzadeh, A., Epackachi, S., Salamone, S., Whittaker, A.S. (2015). "Bayesian decision and mixture models for AE monitoring of steel-concrete composite shear walls" Smart Materials and Structures, DOI: 10.1088/0964-1726/24/11/115028.

Epackachi, S., Whittaker, A.S, and Huang, Y.N. (2014). "Analytical modeling of rectangular SC wall panels" Journal of Construction Steel Research, DOI:10.1016/j.jcsr.2014.10.016.

Epackachi, S., Nguyen, N.H., Kurt, E.G., Whittaker, A.S, and Varma, A.H. (2013). "In-plane seismic behavior of rectangular steel-plate composite wall piers" Journal of Structural Engineering (ASCE), DOI: 10.1061/(ASCE)ST.1943-541X.0001148.

References

Conference proceedings:

Epackachi, S., and Whittaker, A. S. (2017). "Effective lateral stiffness of steel-plate concrete composite wall piers" Trans., 24th Int. Conf. on Structural Mechanics in Reactor Technology (SMiRT 24), Busan, Korea.

Epackachi, S., Whittaker, A. S. (2017). "Design of steel-plate concrete composite wall piers" Trans., 16th World Conference on Earthquake Engineering, Chile.

Terranova, B., Epackachi, S., and Whittaker, A. S. (2017). "Effect of out-of-plane loading on the in-plane response of SC wall piers" Trans., 16th World Conference on Earthquake Engineering, Chile.

Epackachi, S., Whittaker, A. S., and Varma, A.H. (2015). "An analytical model for a baseplate connection of an SC wall to an RC foundation" Proc., 8th International Conference on Steel Structures, Jeju, South Korea.

Epackachi, S., and Whittaker, A. S. (2015). "Numerical investigation of the in-plane behavior of low-aspect ratio reinforced concrete shear walls" Trans., 23rd Int. Conf. on Structural Mechanics in Reactor Technology (SMiRT 23), Manchester, UK.

Epackachi, S., Whittaker, A. S. and Varma, A.H. (2015). "Experimental behavior of flexure critical steel-Plate composite SC shear walls" Trans., 23rd Int. Conf. on Structural Mechanics in Reactor Technology (SMiRT 23), Manchester, UK.

Chang, C.C., Huang, Y.N., Chen, B.A., Epackachi, S., and Whittaker, A. S. (2015). "An experimental study for in-plane cyclic behavior of low aspect-ratio SC wall piers" Trans., 23rd Int. Conf. on Structural Mechanics in Reactor Technology (SMiRT 23), Manchester, UK.

References

Kurt, E.G., Varma, A.H., Epackachi, S., and Whittaker, A.S. (2015). "Rectangular SC wall piers: summary of seismic behavior and design" Trans., 2015 Structures Congress (ASCE), Portland, Oregon, USA.

Epackachi, S., Whittaker, A.S., and Varma, A.H. (2014). "Numerical and experimental investigation on in-plane behavior of steel-concrete composite walls" Trans., 2014 Structures Congress (ASCE), Boston, MA, USA.

Nguyen, N.H., Epackachi, S., Kurt, E.G., Whittaker, A.S., and Varma, A.H. (2013). "In-plane shear response of steel-concrete composite shear walls: results of experiments", Trans., Australian Earthquake Engineering Society 2013 Conference, Hobart, Tasmania, Australia.

Epackachi, S., Nguyen, N. H., Kurt, E. G., Whittaker, A. S. and Varma, A.H. (2013). "An experimental study of the in-plane shear response of steel concrete composite walls," Trans., 22nd Int. Conf. on Structural Mechanics in Reactor Technology (SMiRT 22), San Francisco, California, USA, Paper ID #938.


Thank you