
Seismic Simulation of Concrete Structures

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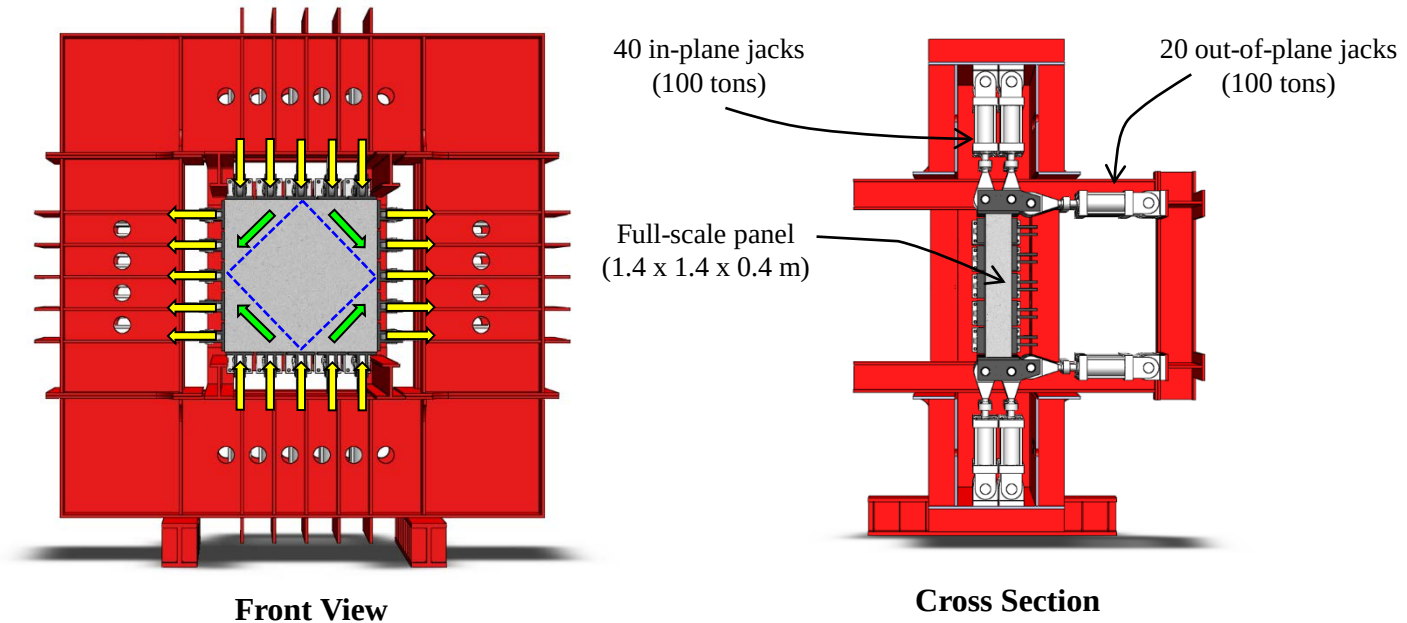
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Taiwan**

August 9-11, 2017

Introduction

Universal Panel Tester (1988 - Now)



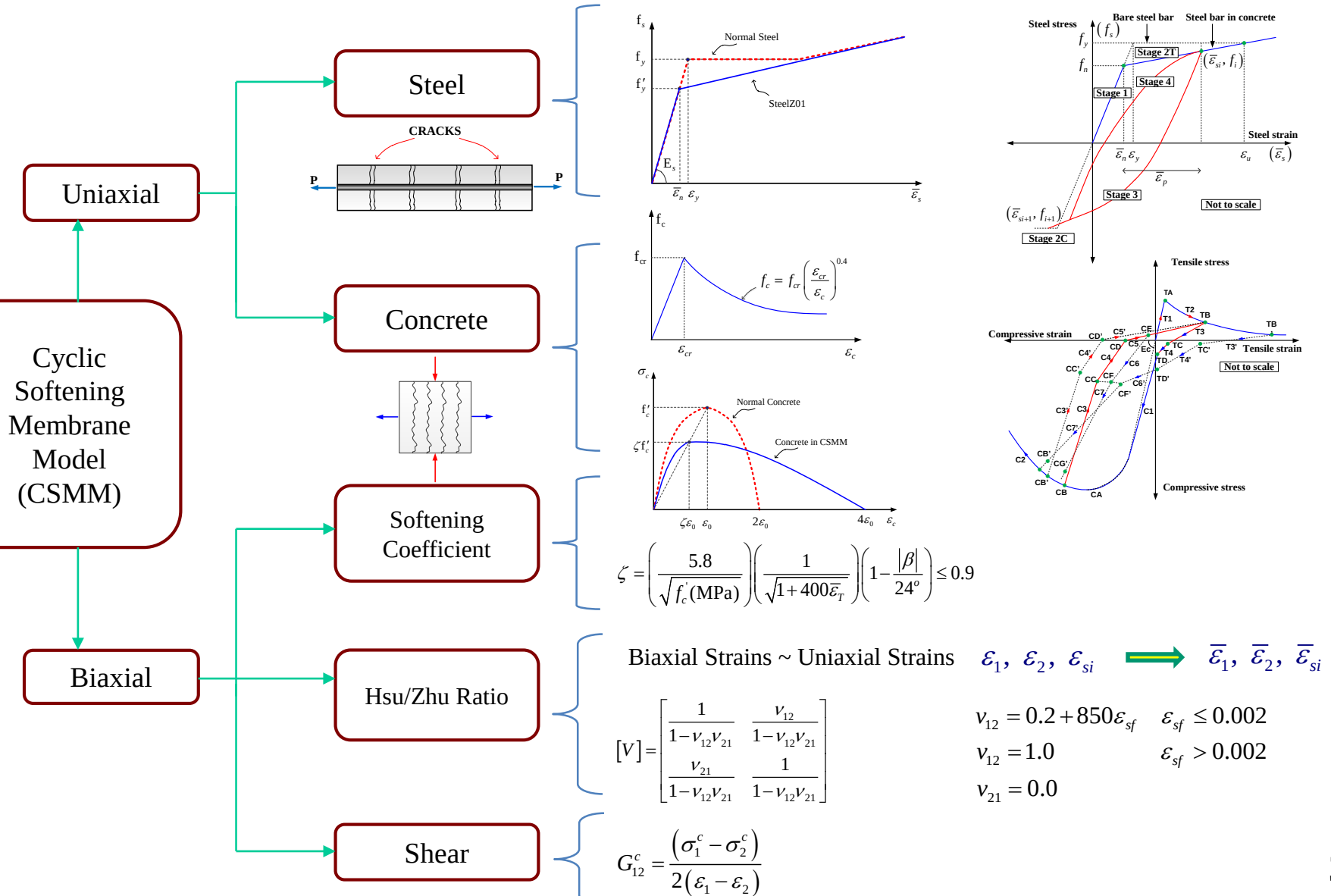
Constitutive Models Developed at UH

- (1) Rotating-Angle Softened Truss Model (RA-STM)
- (2) Fixed-Angle Softened Truss Model (FA-STM)
- (3) Softened Membrane Model (SMM)
- (4) Cyclic Softened Membrane Model (CSMM)
- (5) Cyclic Softened Membrane Model for Prestressed Concrete (CSMM-PC)
- (6) Cyclic Softened Membrane Model for Prestressed Steel Fiber Concrete (CSMM-PSFC)
- (7) Cyclic Softened Membrane Model for ECC (CSMM-ECC)

Introduction



Cyclic Softened Membrane Model (CSMM)



Introduction



Research on Finite Element Analysis (FE) at UH

Year	Authors	Developed Modules in OpenSees	Applications
2000	Jeng, Mo, and Hsu	Concrete J01 Steel J01	RC Beams, Columns
2005	Zhong, Mo, and Hsu	ConcreteZ01, ConcreteZ02 SteelZ01 FAFourSteelRCPlaneStress FAReinforceConcretePlaneStress	2-D RC Beams, Columns, Walls
2009	Laskar, Mo, and Hsu	ConcreteL01 TendonL01 FAPrestressConcretePlaneStress FAFourSteelPCPlaneStress	2-D PC Beams, Columns, Walls
2011	Rao, Mo, and Hsu	ConcreteR01	2-D PSFC Beams, Columns, Walls
2012	Xiang, Mo, and Hsu	FARCFiberShellX01	3D RC Walls
2013	Luu, Li, Mo, and Hsu	ConcreteECC01	2-D ECC Beams, Columns, Walls
2014	Tan, Mo, Hsu and Luu	ConcreteS01 Steel02 (Modified for Slipped Tendons)	PC Thin Slab Beams
2016	Luu, Mo and Hsu	ConcreteZ01 SteelZ01 CSMMLayer CSMMShellS8	Shell-Type Structures

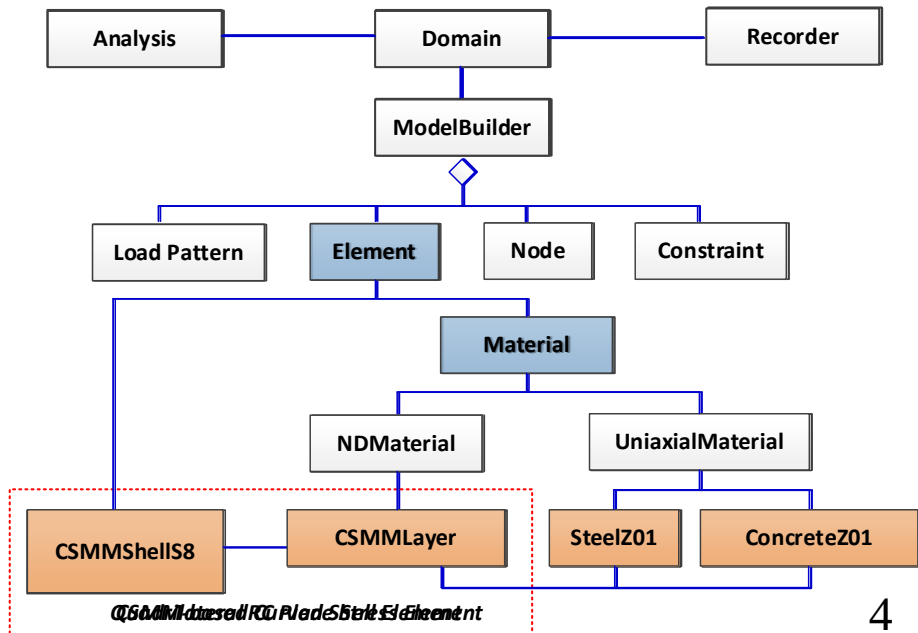
OpenSees

An object-oriented software framework (C++) for simulation applications in earthquake engineering using finite element methods.

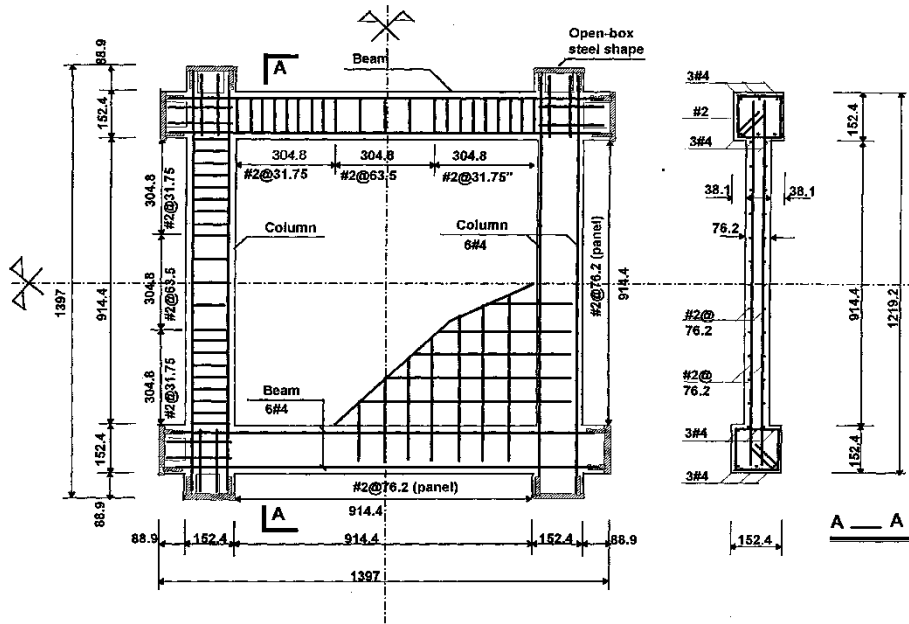
Key features of OpenSees include the interchangeability and the ability to integrate existing libraries and new components into the framework without changing the existing code.

OpenSees is open-source software. OpenSees is a research tool.

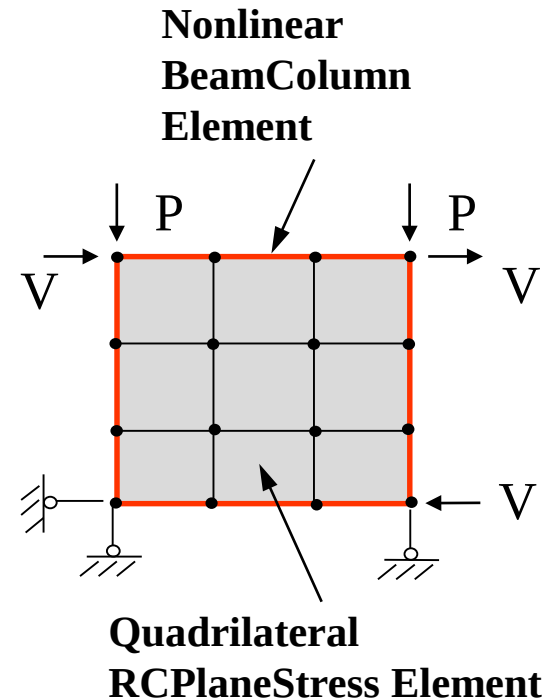
FE Program for Simulation of Concrete Structure (SCS)



RC Framed Shear Walls under Axial load and Reversed Cyclic Shear



Specimen



Finite Element Mesh

Two Variables: Axial Load and Steel Percentage

	Axial load		Wall Panel	
Specimen Name	P (KN)	Ratio P/P _o	Panel Steel (mm)	Panel Steel Percent
FSW-13	89	0.07	W2@152.4	0.23
FSW-6	89	0.08	#2@152.4	0.55
FSW-11	89	0.07	#2@76.2	1.10
FSW-8	267	0.24	W2@152.4	0.23
FSW-5	267	0.20	#2@152.4	0.55
FSW-9	267	0.23	#2@76.2	1.10
FSW-12	534	0.40	W2@152.4	0.23
FSW-4	534	0.46	#2@152.4	0.55
FSW-10	534	0.41	#2@76.2	1.10

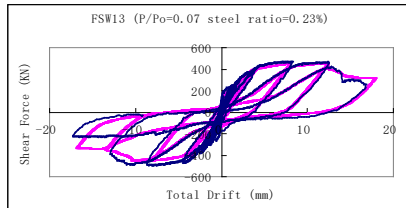
Shear Force vs. Total Drift: Analytical and Experimental Results



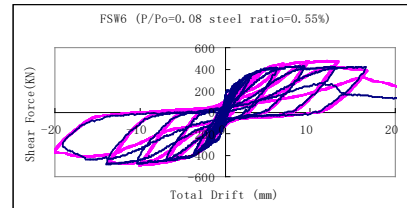
Test



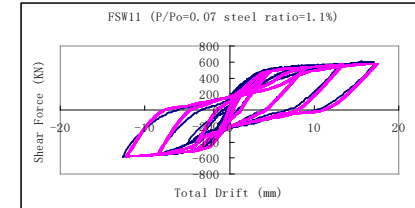
Analysis



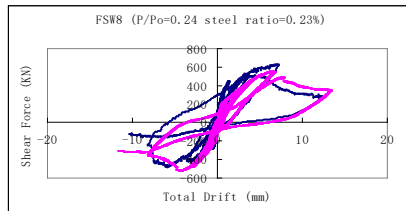
FSW13 ($P/P_o=0.07$, $\rho_v=0.23\%$)



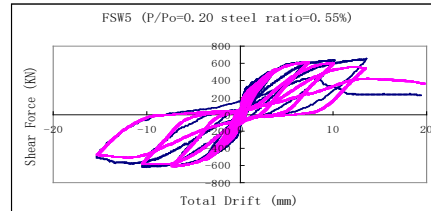
FSW6 ($P/P_o=0.07$, $\rho_w=0.55\%$)



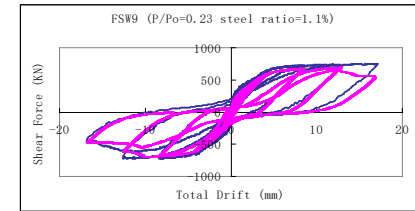
FSW11 ($P/P_o=0.07$, $\rho_v=1.1\%$)



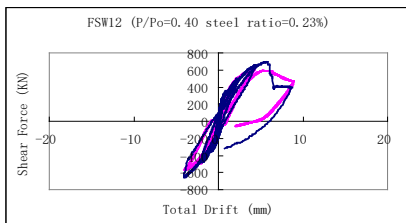
FSW8 ($P/P_o=0.2$, $\rho_v=0.23\%$)



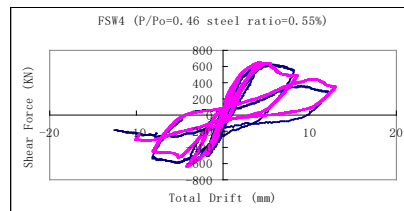
FSW5 ($P/P_o=0.2$, $\rho_w=0.55\%$)



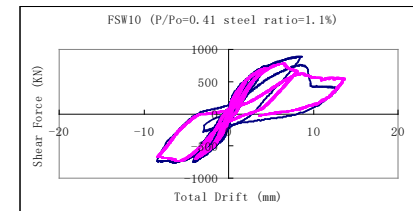
FSW9 ($P/P_o=0.2$, $\rho_w=1.1\%$)



FSW12 ($P/P_o=0.4$, $\rho_v=0.23\%$)



FSW4 ($P/P_o=0.4$, $\rho_w=0.55\%$)



FSW10 ($P/P_o=0.4$, $\rho_w=1.1\%$)

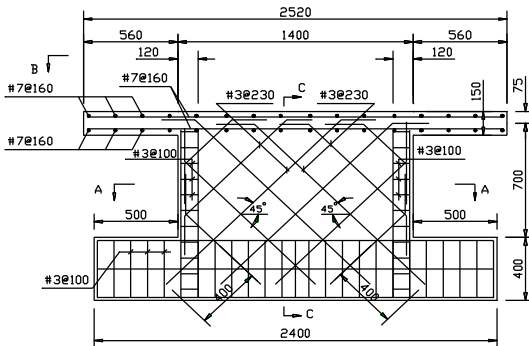
Shake Table Tests of RC Shear Walls



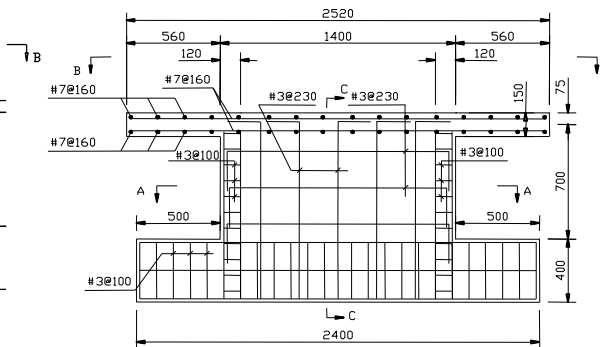
Test Program

Specimen Name	Boundary Columns	Steel Orientations	Concrete Strength
ST1	No	45 degrees	16.6 MPa
ST2	Yes	45 degrees	16.6 MPa
ST3	Yes	0 and 90 degrees	34.0 MPa
ST4	Yes	45 degrees	34.0 MPa

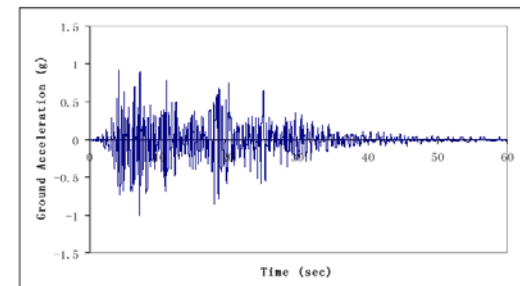
Test Set-up



Specimen ST1, ST2 & ST4



Specimen ST3



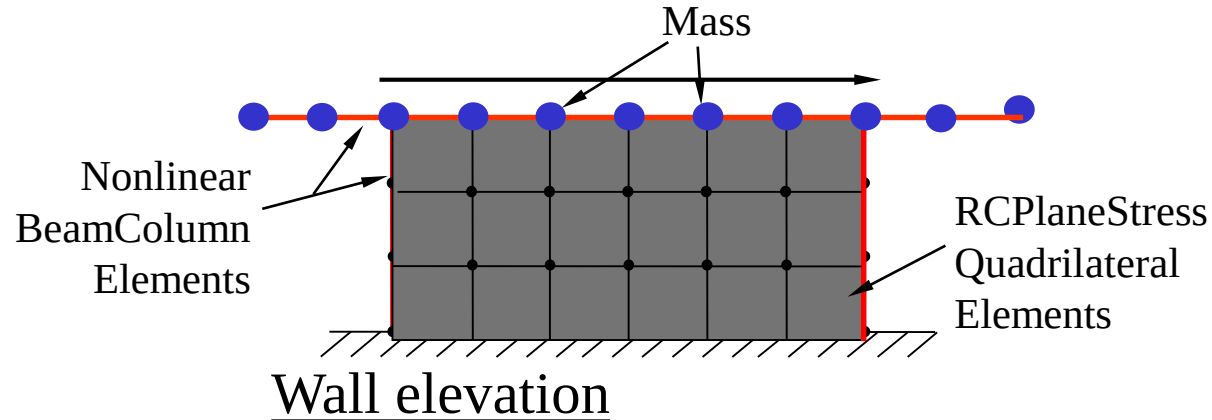
Normalized tcu078Eji seismogram of the 1999 Taiwan earthquake

Test runs of specimen ST4

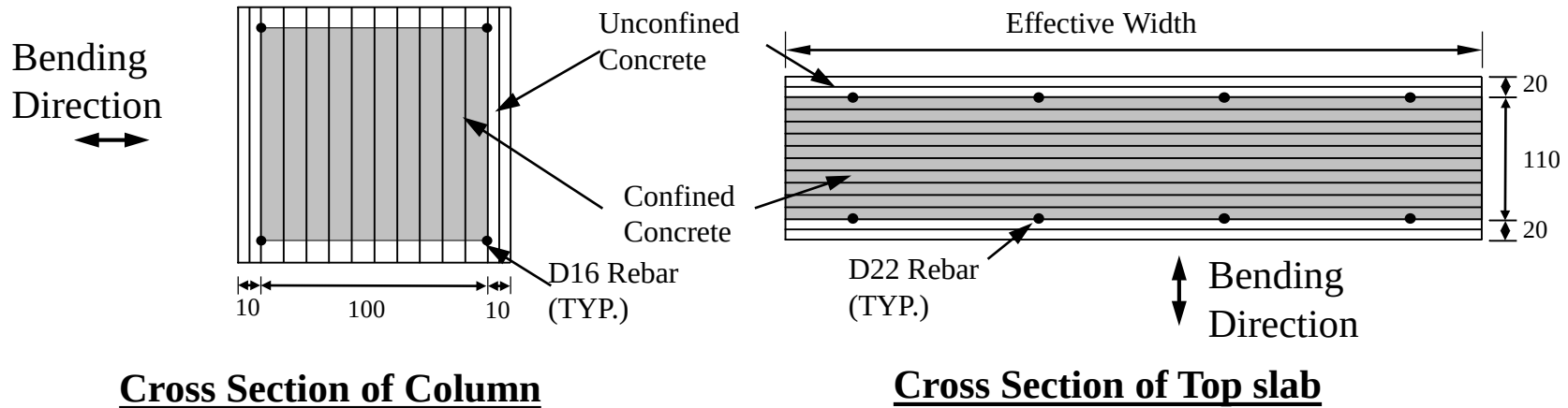
Test run	Predetermined PGA (g)	Real PGA (g)	State	Max. U (mm)	Max. $\ddot{U}$ (g)	Max. $m\ddot{y}$ (KN)
1	0.05	0.06		0.06	0.04	16.5
2	0.4	0.41		0.38	0.30	98.4
3	0.8	0.81	Steel yielded	0.84	0.64	190.0
4	1.2	1.08		1.20	1.11	284.0
5	1.6	1.48		2.07	2.12	418.0
6	2.0	1.52		2.54	2.58	582.0



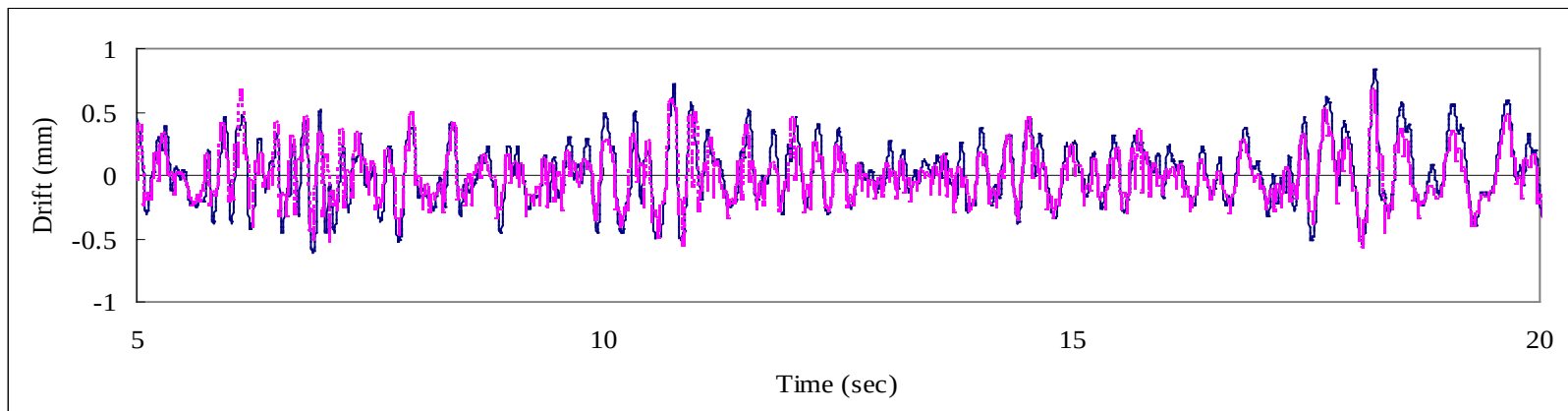
Finite Element Mesh of Specimens



Damping ratio: 2%, 4%, 8%



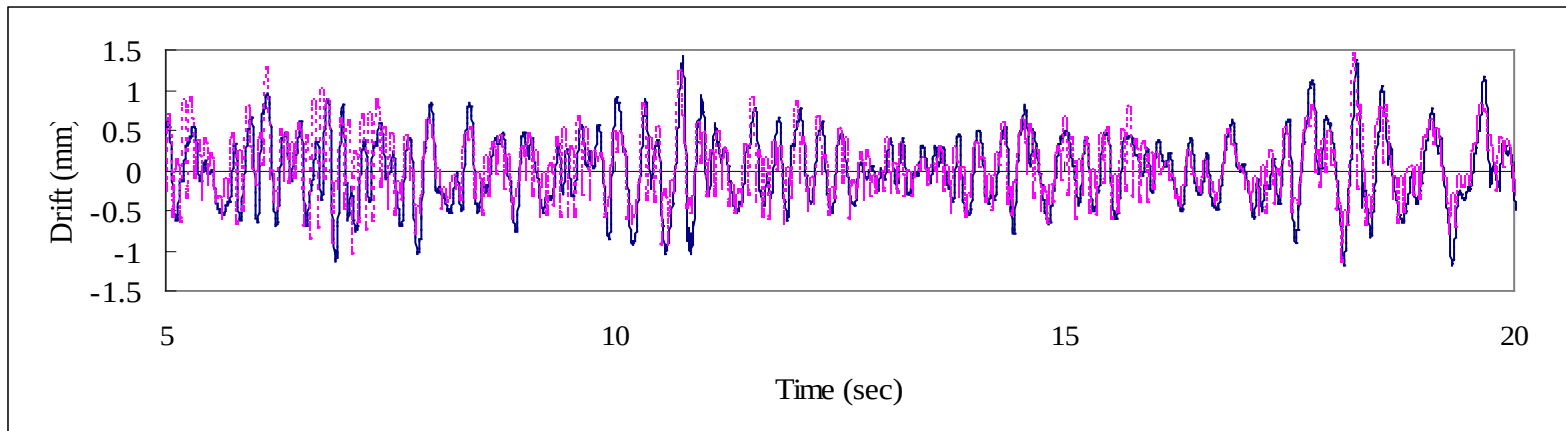
Response history of specimen ST4 at test run of PGA=0.8g



Time history of drift u

— Analysis
— Test

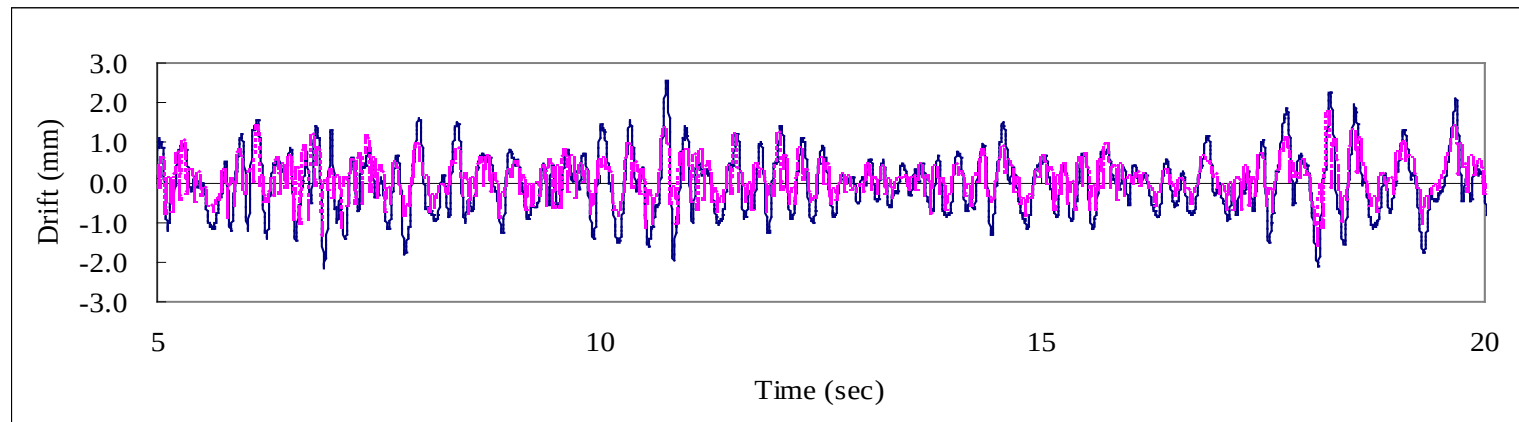
Response history of specimen ST4 at test run of PGA=1.2g



Time history of drift u

— Analysis
— Test

Response history of specimen ST4 at test run of PGA=1.6g



Time history of drift u

— Analysis
— Test

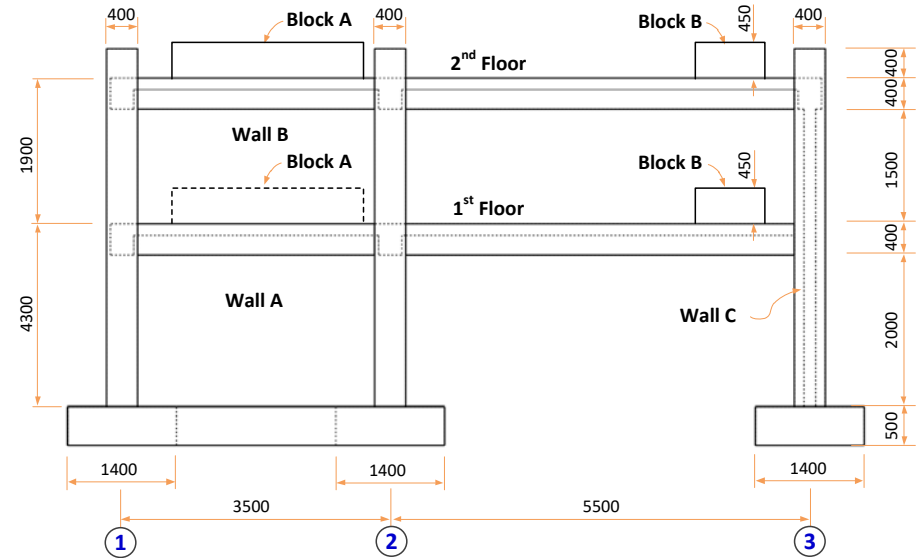
Two-Story Unsymmetrical RC Building



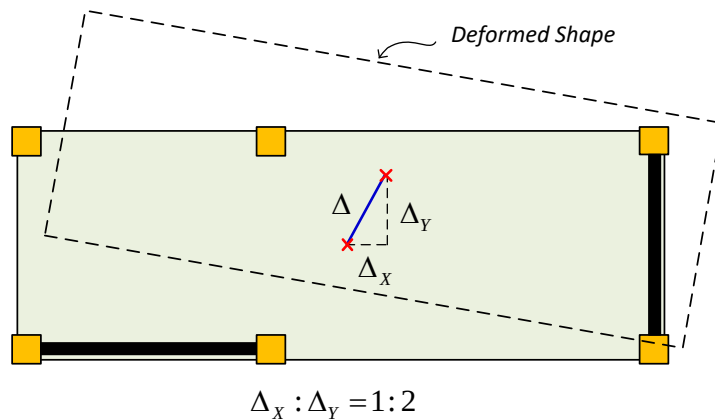
Dimensions of the Building Specimen



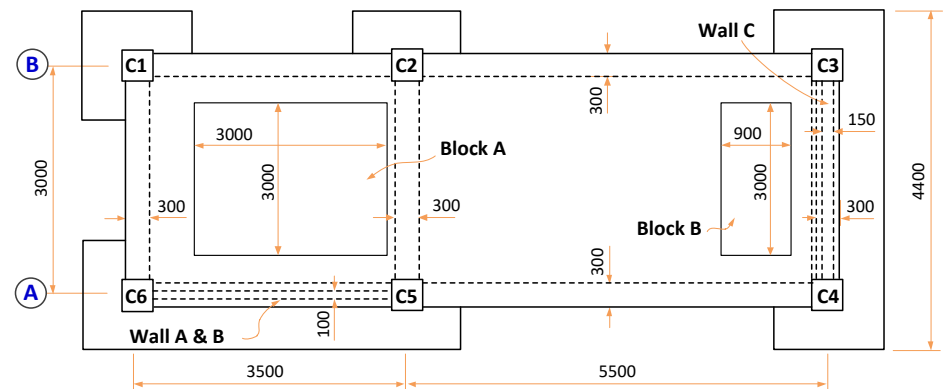
3D View



Elevation view



Testing concept

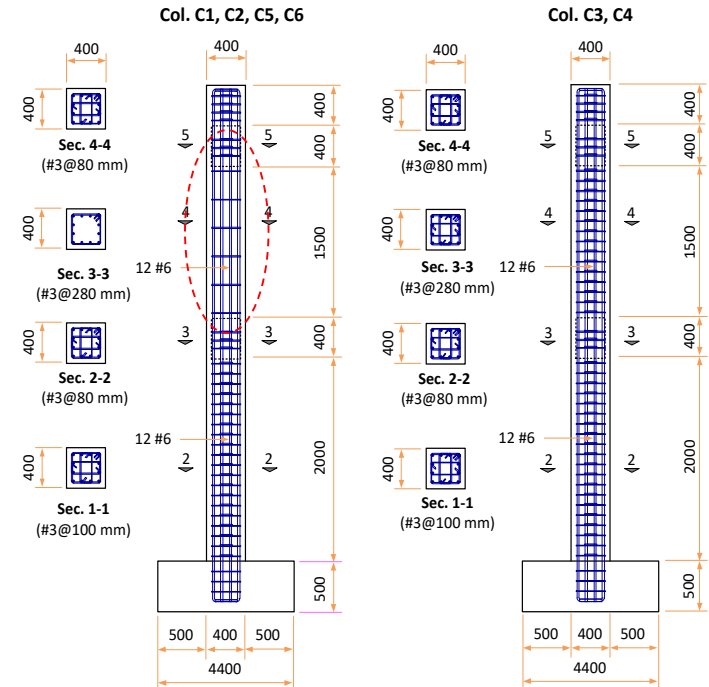
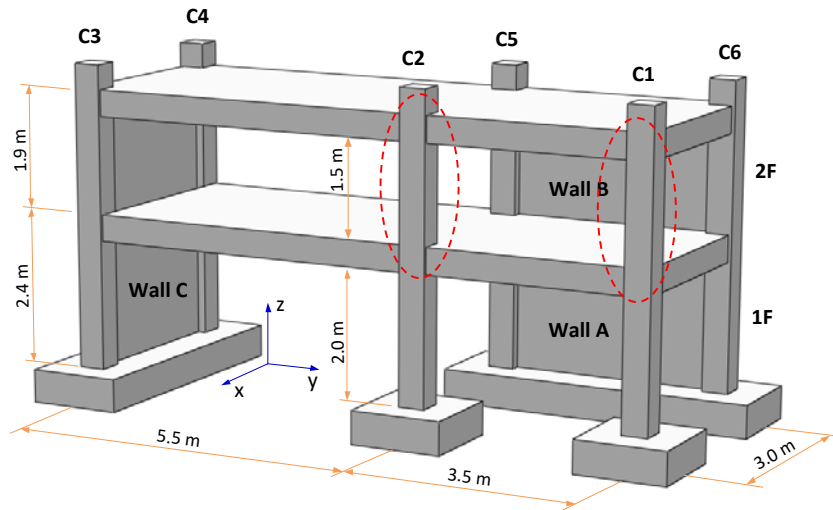


Plan view

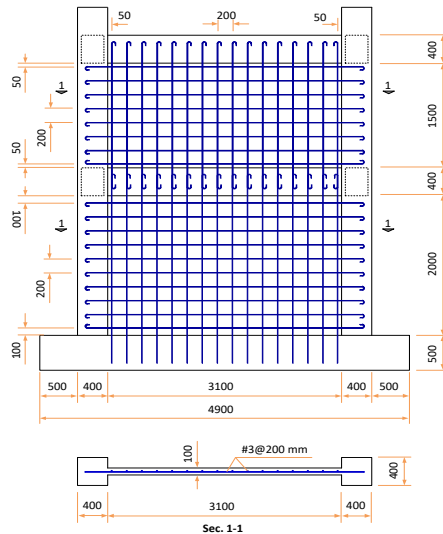
Two-Story Unsymmetrical RC Building



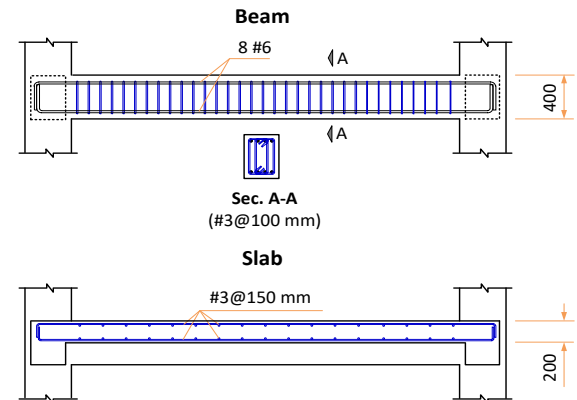
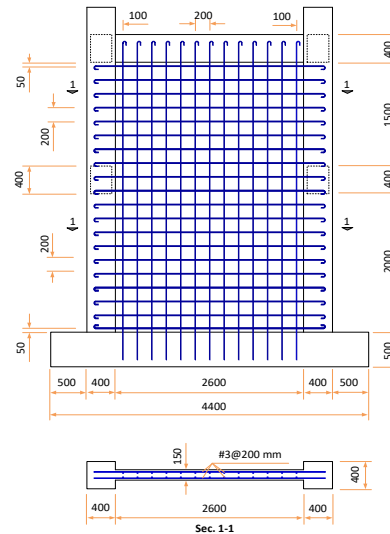
Reinforcement Detailing



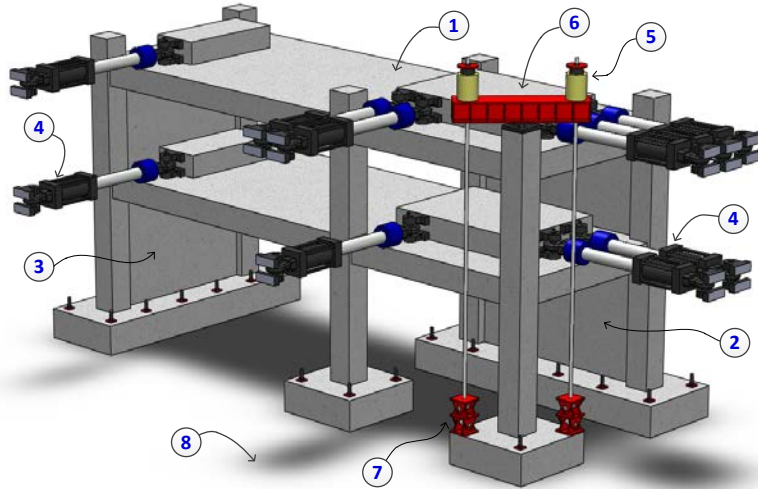
0.36 % Walls A&B



0.48 % Wall C

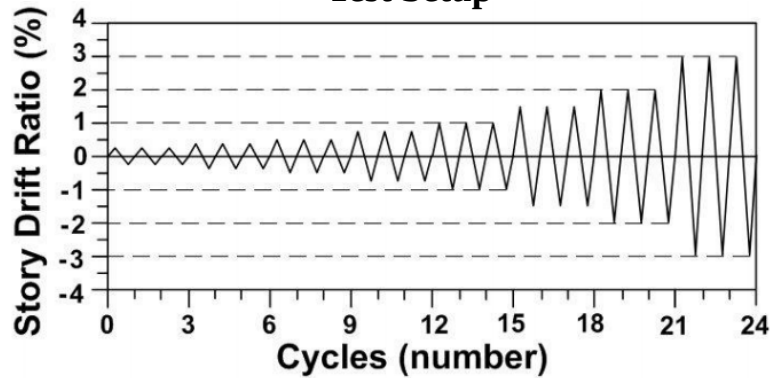


Two-Story Unsymmetrical RC Building



- | | |
|------------------------|-------------------------|
| ① Frame Specimen | ⑤ Vertical Jacks |
| ② Wall A&B Specimen | ⑥ Steel Frames |
| ③ Wall C Specimen | ⑦ Bi-directional Hinges |
| ④ Horizontal Actuators | ⑧ Rigid Foundation |

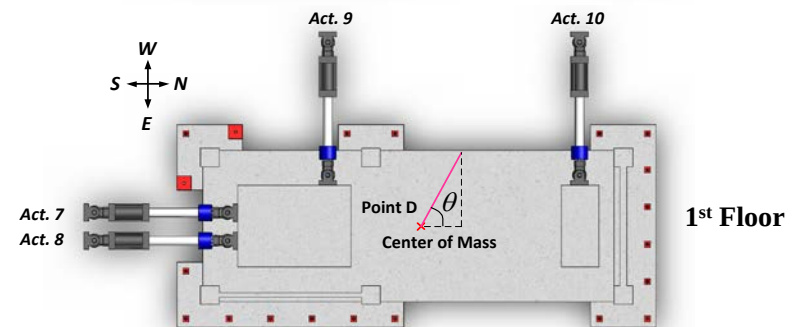
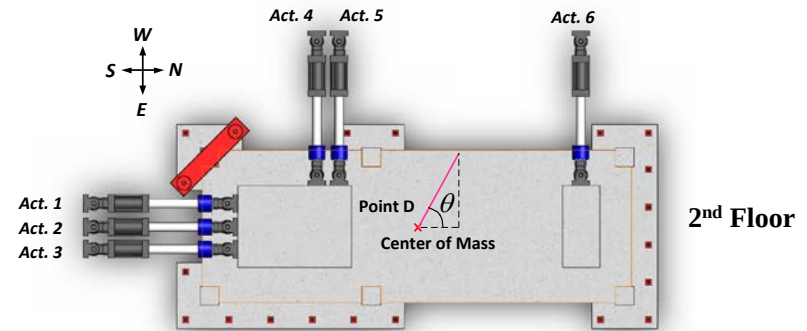
Test Setup



Loading Protocol

Control Modes and Equations of Actuators

Actuator NO.	Control Mode	Equation
1	force / calculation	$F1 = F2$
2	calculation / command	$D2 = Cal_D2 = -Cmd_D * \cos\theta$
3	force / calculation	$F3 = F2$
4	force / calculation	$F4 = F5$
5	calculation / command	$Cal_D5 = Cmd_D * \sin\theta$
6	force / calculation	$F6 = 4/7 * (F4 + F5)$
7	force / calculation	$F7 = (F1 + F2 + F3) / 1.83 / 2$
8	force / calculation	$F8 = (F1 + F2 + F3) / 1.83 / 2$
9	force / calculation	$F9 = (F4 + F5) / 1.83$
10	force / calculation	$F10 = F6 / 1.83$

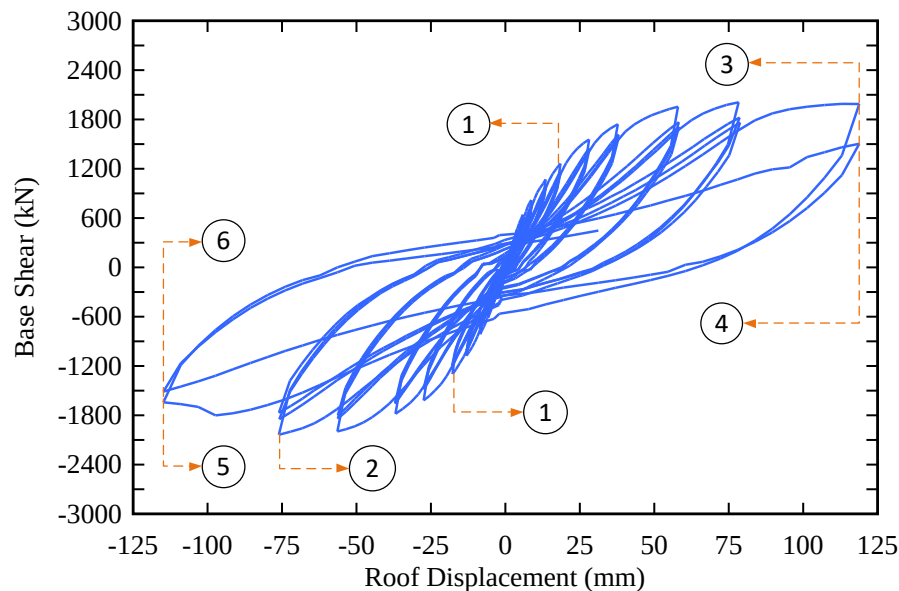
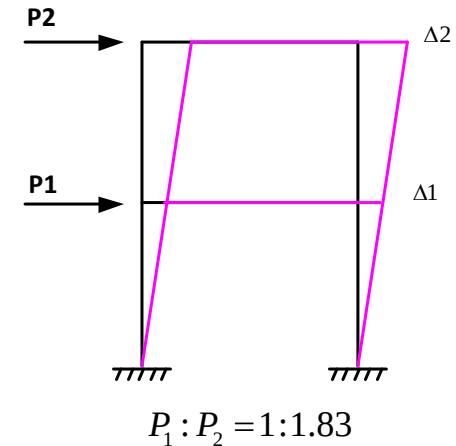
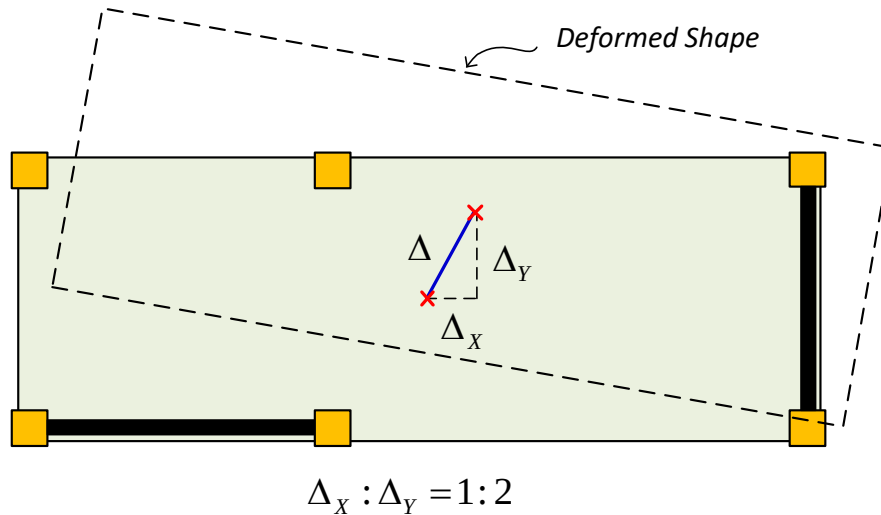


Locations of Actuators

Two-Story Unsymmetrical RC Building



Experimental Results



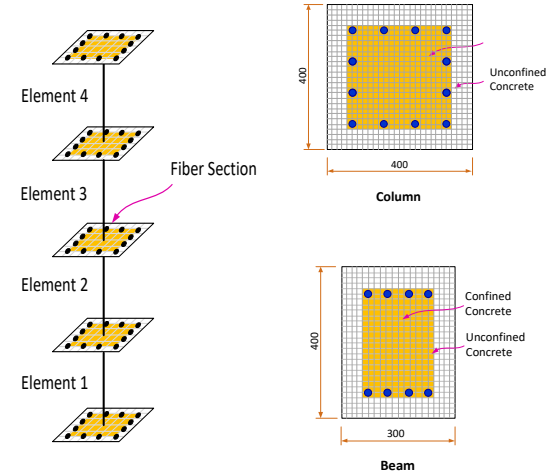
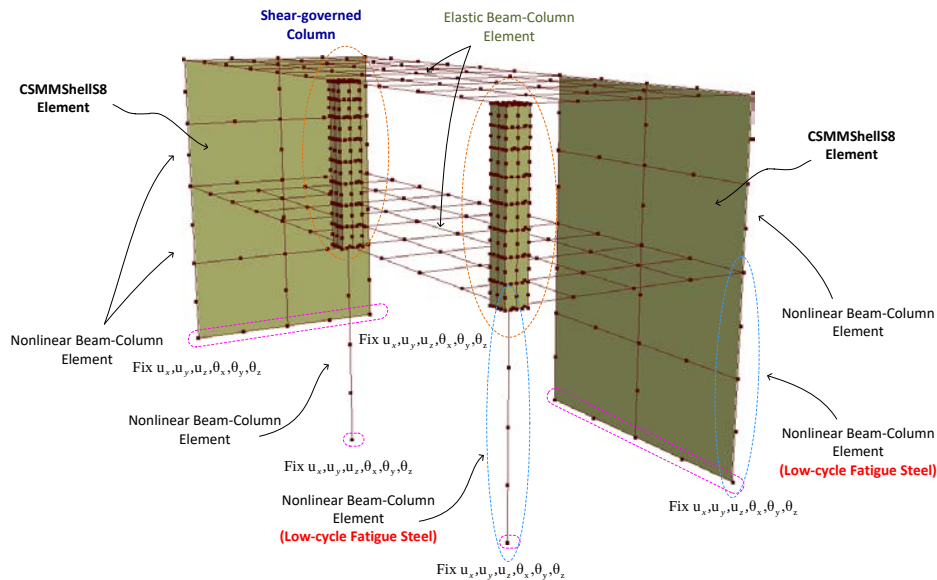
Drift

- ① +0.5 % : C1-1F rebar yield
- ② - 2.0 % : C6-1F rebar buckle
- ③ +3.0 % : C2-2F shear failure
- ④ +3.0 % : C1-1F rebar buckle
- ⑤ - 3.0 % : C1-2F shear failure
- ⑥ - 3.0 % : C1-2F collapse

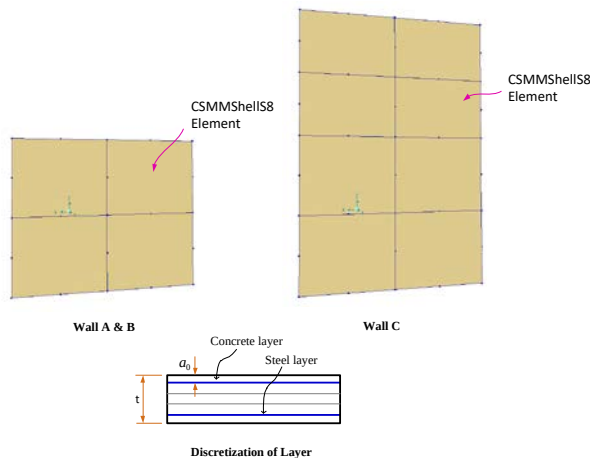
Two-Story Unsymmetrical RC Building



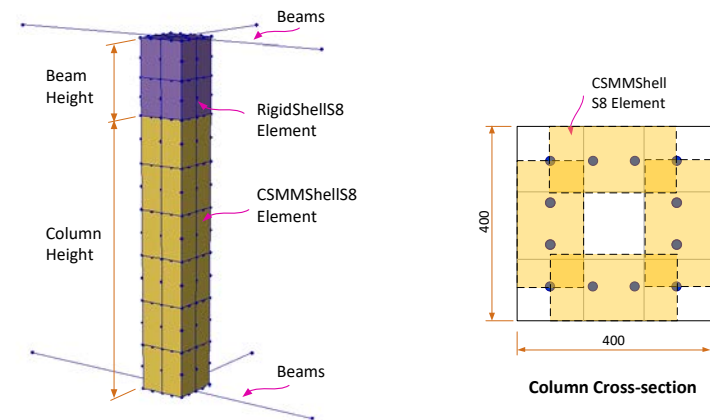
Finite Element Model



Modeling of Beam & Column using Nonlinear Beam-Column Element (OpenSees)



Modeling of shear walls using CSMMShellS8 element



Modeling of shear-governed columns using CSMMShellS8 element

Two-Story Unsymmetrical RC Building



Analytical Results (Video)

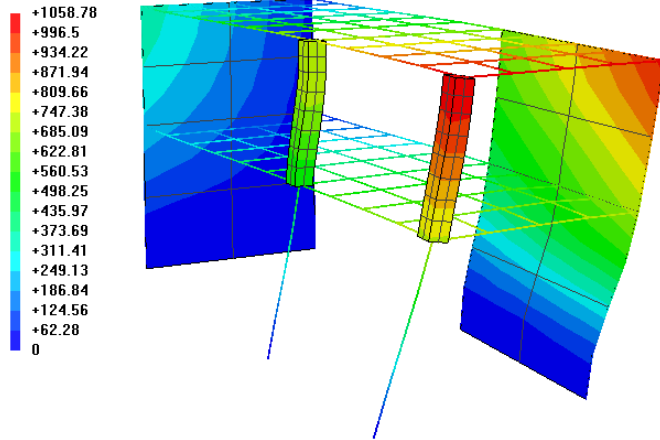


Two-Story Unsymmetrical RC Building

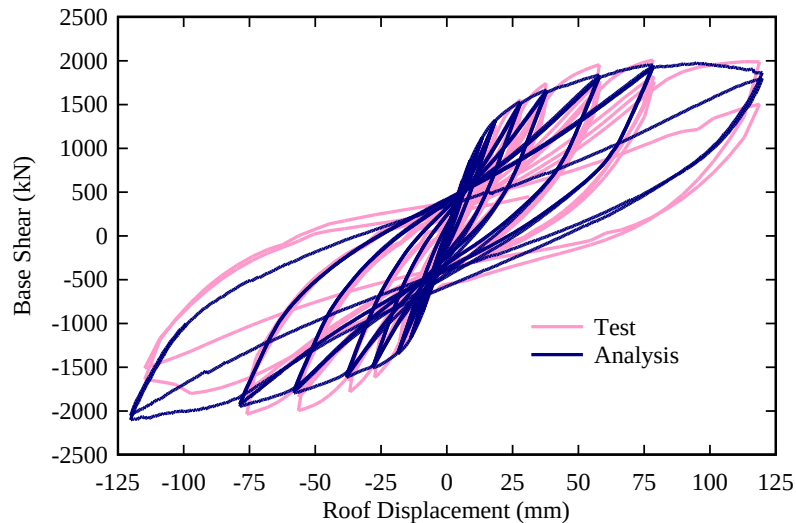
Analytical and Experimental Results



Total Displacement
Unit: mm

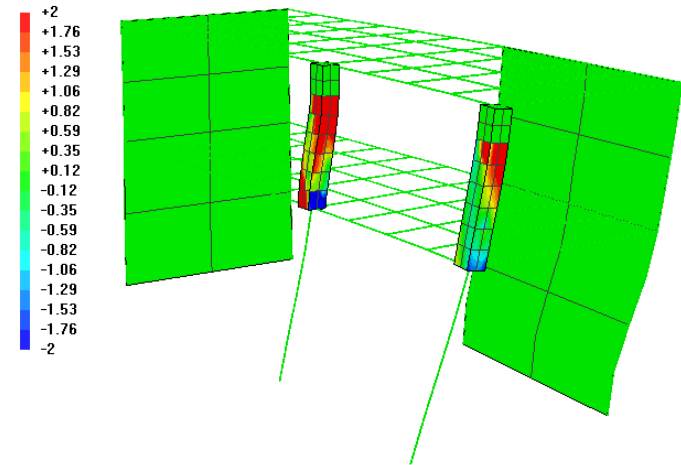


Deformed shape of the building specimen (Drift 3%)



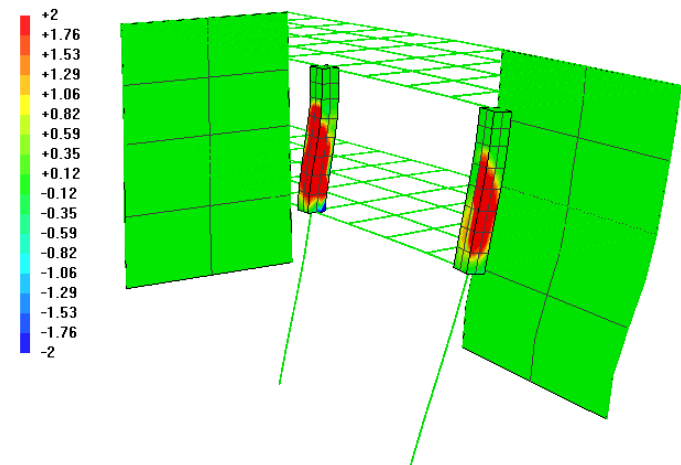
Comparison of analytical and experimental results

Unit: 10^{-3} mm/mm



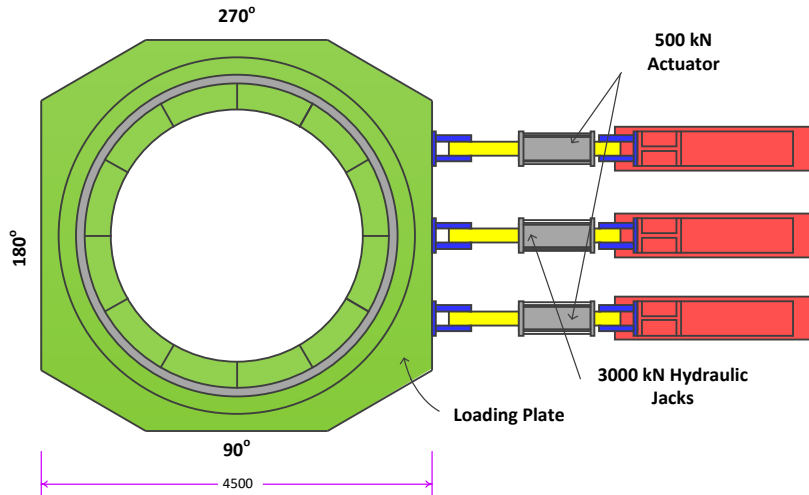
Analytical strains of longitudinal steel bars of shear-governed columns (Peak load stage)

Unit: 10^{-3} mm/mm

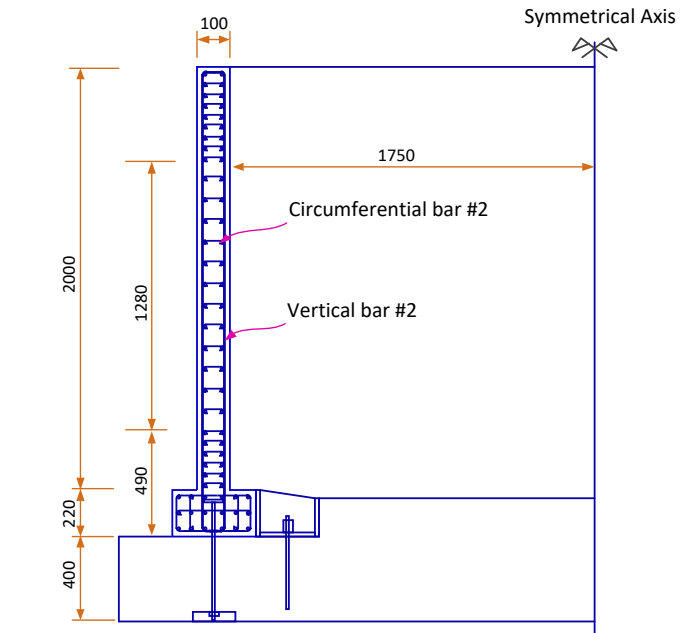


Analytical strains of transverse steel bars of shear-governed columns (Peak load stage)

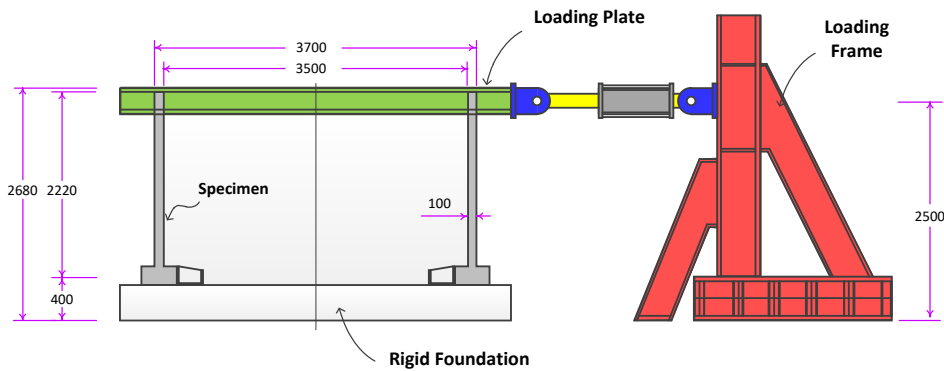
RC Cylindrical Tank (Maekawa et al., 2003)



Test Setup (Plan view)



Dimension and reinforcement detailing of the specimen



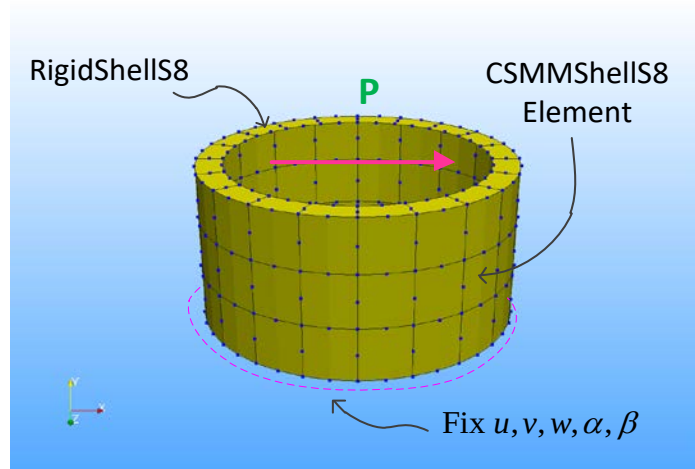
Test Setup (Elevation view)

Dimension and material properties

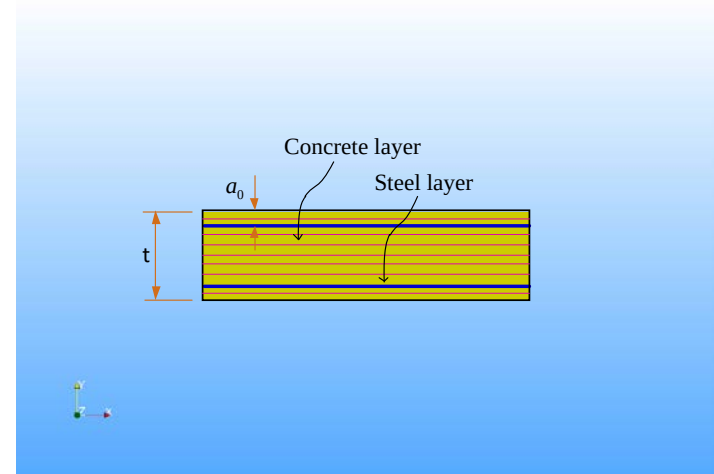
Specimen	f'_c (MPa)	D (mm)	H (mm)	t (mm)	Vertical Reinforcement		Horizontal Reinforcement	
					f_y (MPa)	ρ_v (%)	f_y (MPa)	ρ_h (%)
1	28.0	3600	2000	100	384.0	0.8	410.0	0.8

Note : f'_c = Compressive strength of concrete; D = Diameter of the tank;
 t = Thickness f_y = Yielding strength of steel; H = Effective height of the tank;
 ρ_v = Percentage of the vertical steel; ρ_h = Percentage of horizontal steel.

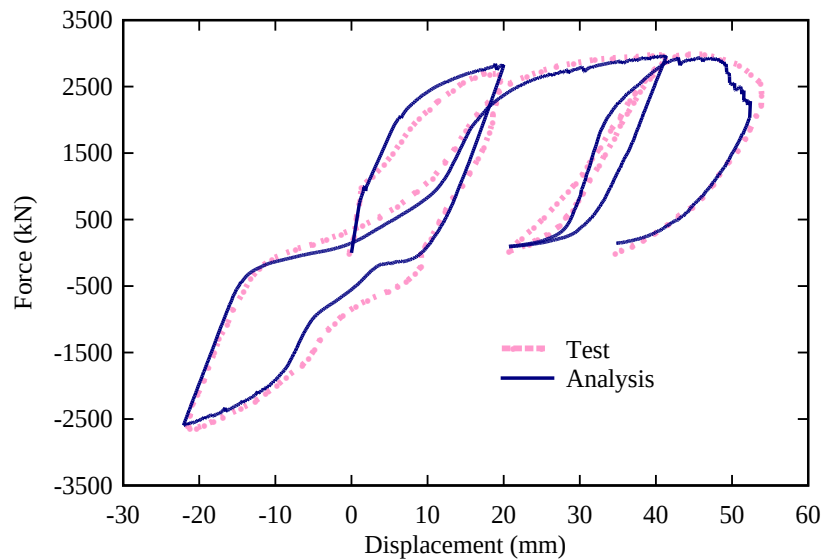
RC Cylindrical Tank (Maekawa et al., 2003)



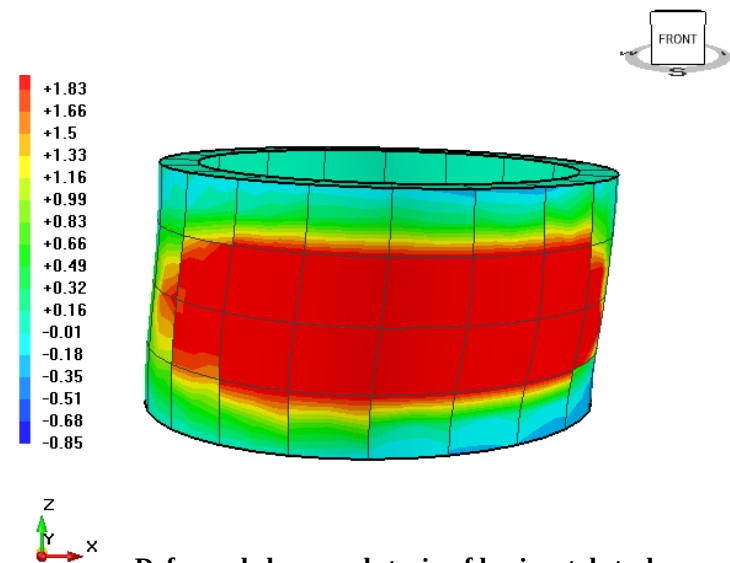
Finite element model



Cross section mesh

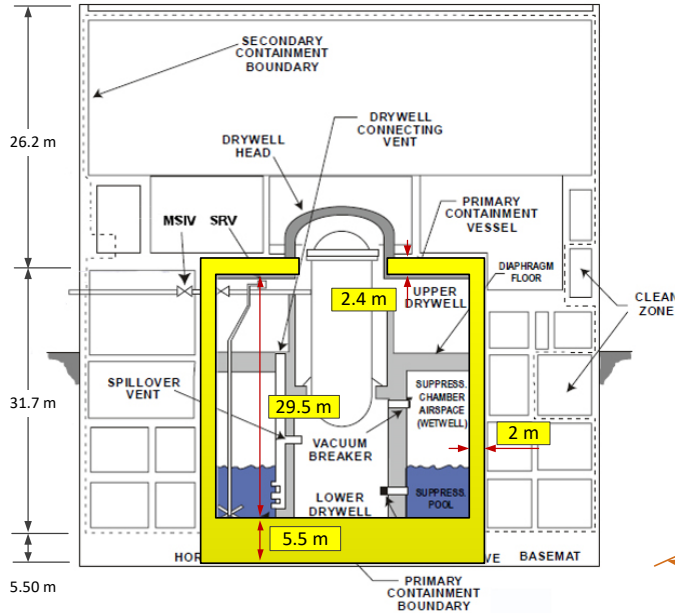


Comparison of experimental and analytical results

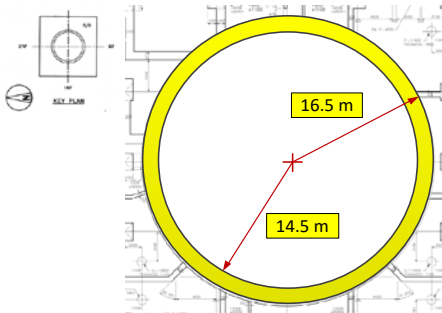


Deformed shape and strain of horizontal steel bars at the peak load

Nuclear Containment Vessels



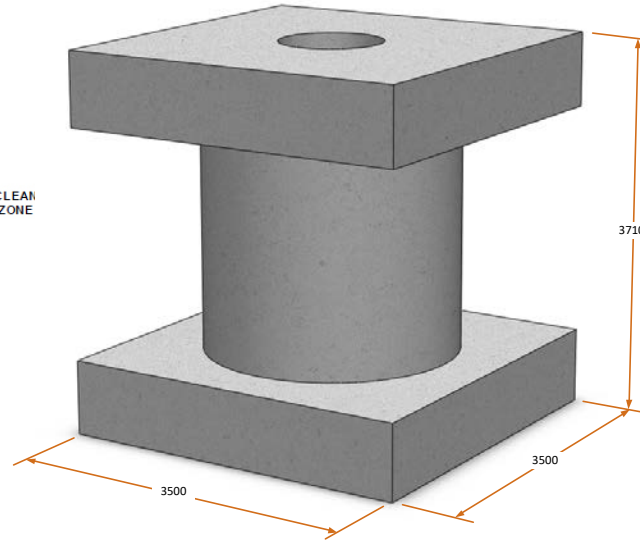
Elevation view



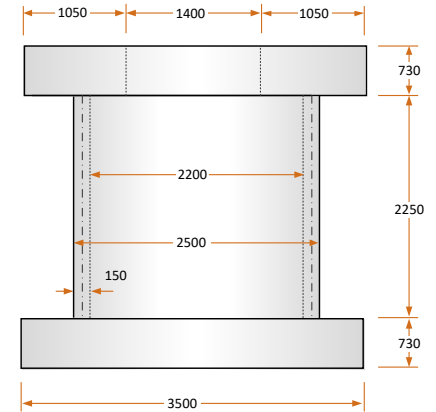
Plan view

Prototype of Lungmen containment vessel

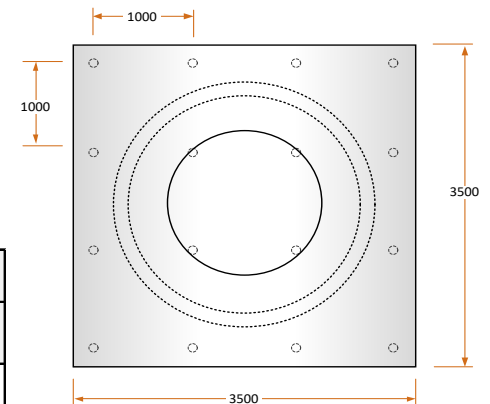
1/13 Scale



3D view of RCCV specimens



Elevation view



Plan view

Dimensions of RCCV specimens

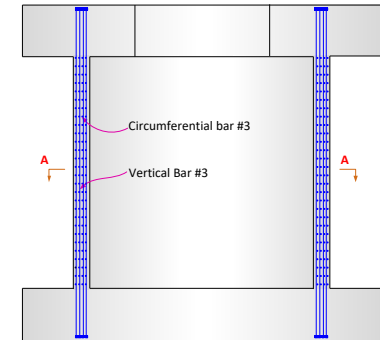
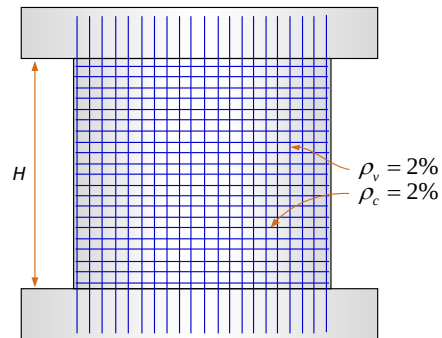
Specimen No.	f'_c (MPa)	D (mm)	H (mm)	t (mm)	Vertical Reinforcement			Horizontal Reinforcement		
					d_b (mm)	f_y (MPa)	ρ_v (%)	d_b (mm)	f_y (MPa)	ρ_h (%)
RCCV #1	35	2350	2250	150	9.5	365	2	9.5	365	2
RCCV #2	37	2350	2250	150	9.5	365	2 (4)	9.5	365	2

Note : f'_c = Compressive strength of concrete; D = Diameter; H = Net height;
 t = Thickness; f_y = Yielding strength of steel; d_b = Diameter of steel bar;
 ρ_v = Steel ratio in the vertical direction; ρ_h = Steel ratio in horizontal direction

Nuclear Containment Vessels

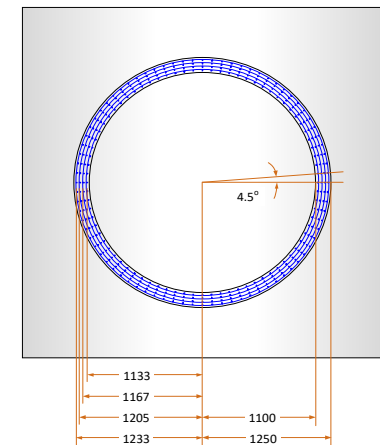
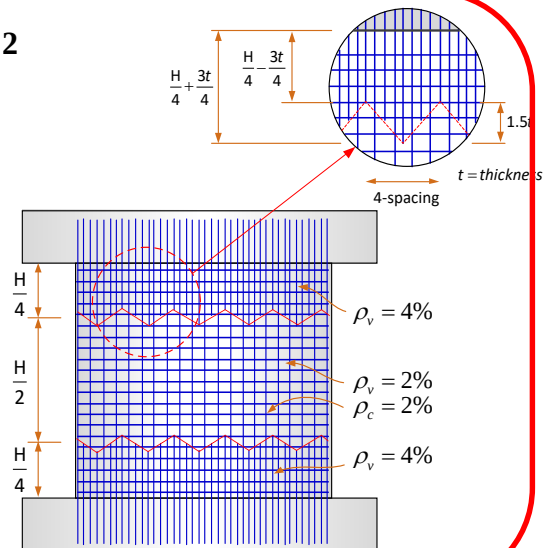
Reinforcement Detailing

Specimen No. 1



Vertical cross-section

Specimen No. 2

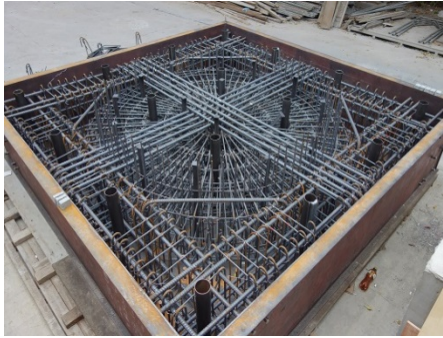


Horizontal cross-section

Nuclear Containment Vessels



Manufacturing of Specimens



①



②



③



④



⑤



⑥

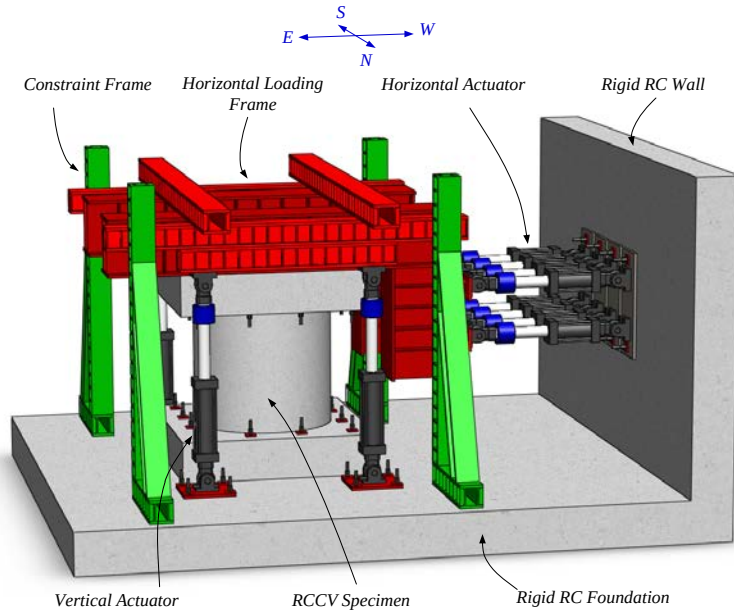


⑦

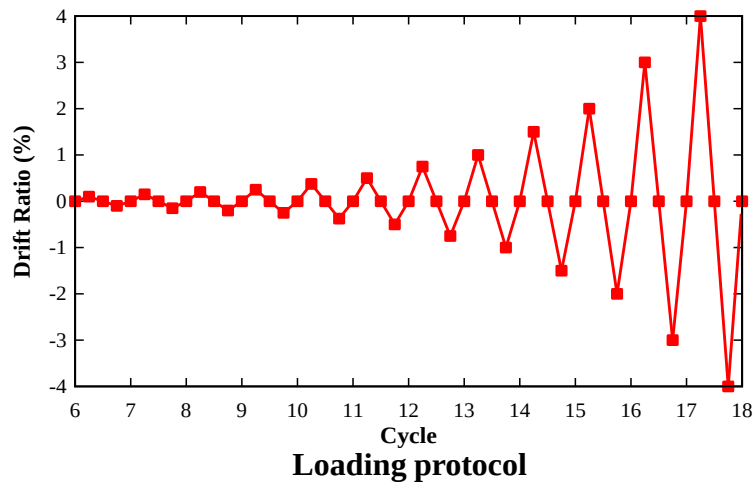


⑧

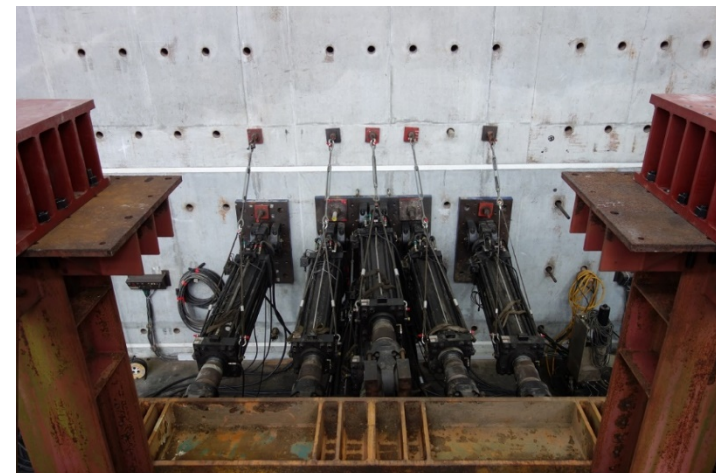
Nuclear Containment Vessels



Test setup



Testing plan view

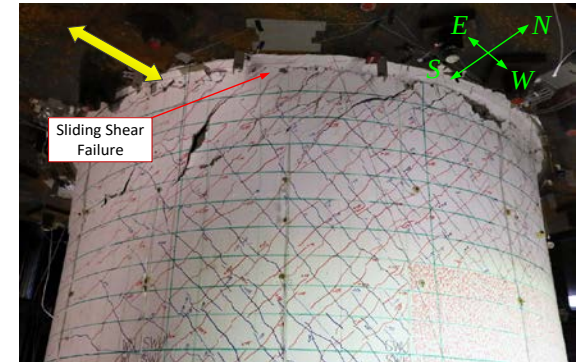
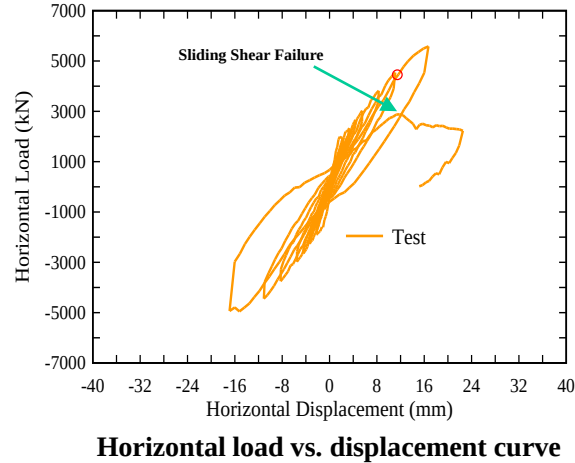
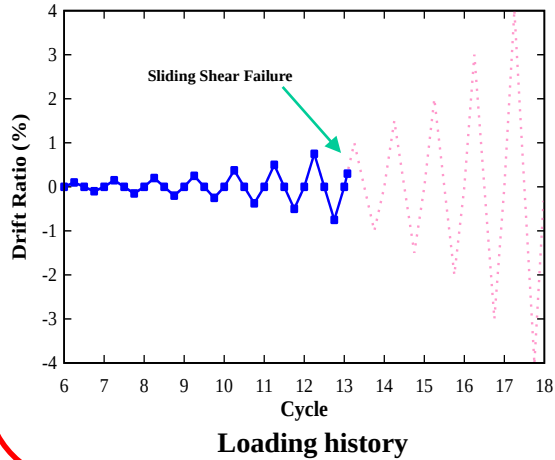


Horizontal actuators (Total: 8000 kN)

Nuclear Containment Vessels

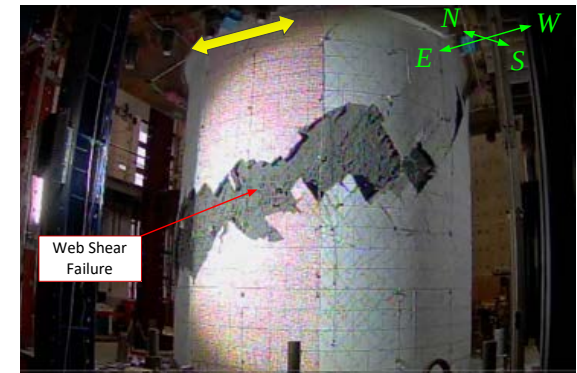
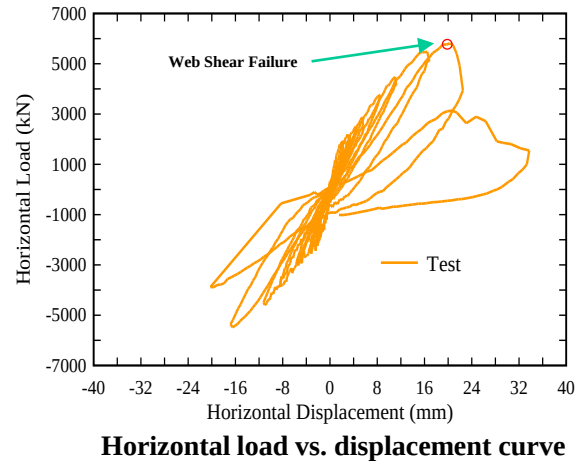
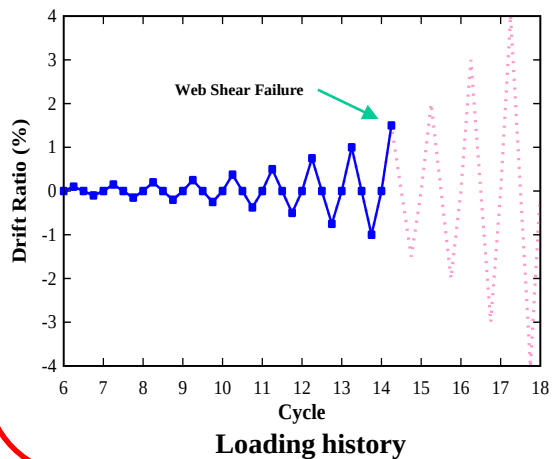


Failure Mode of Specimen No. 1



Sliding shear failure
(Cycle 13 – Drift 0.3%)

Failure Mode of Specimen No. 2

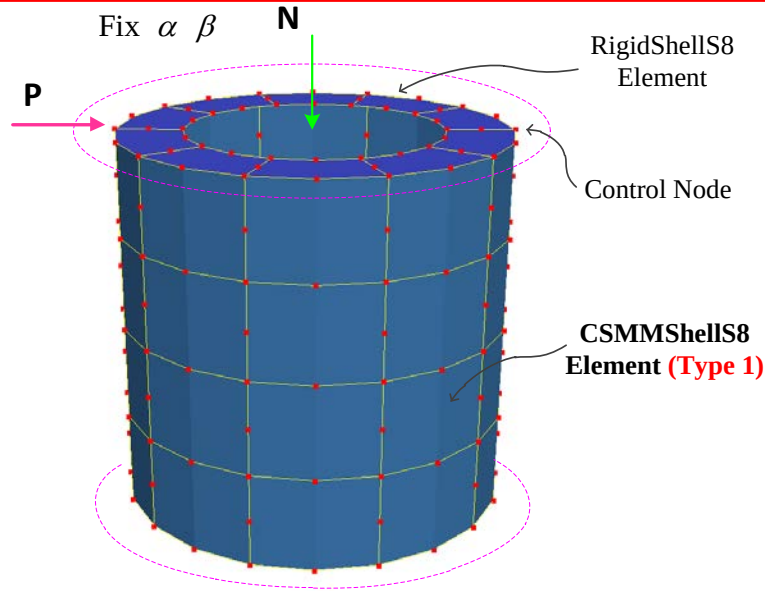


Web shear failure
(Cycle 14 – Drift 1.5%)

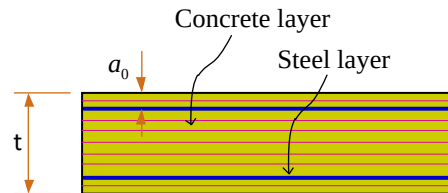
Nuclear Containment Vessels



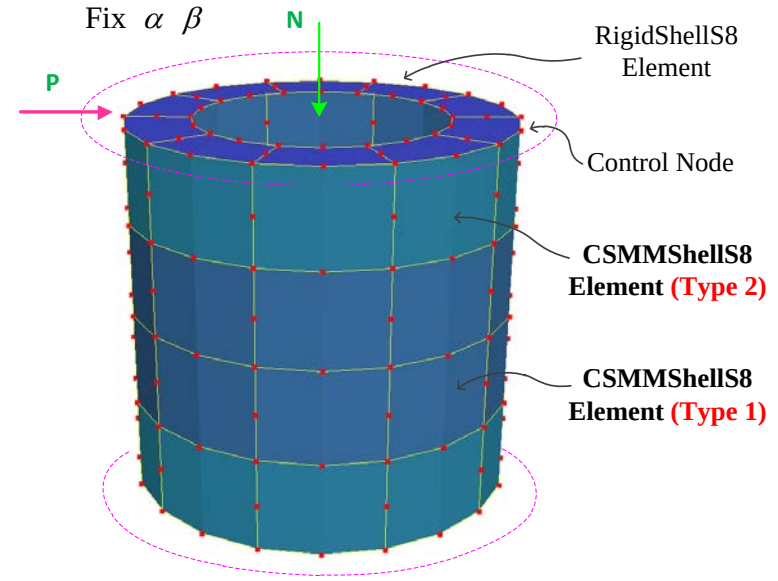
Finite element models of RCCV specimens



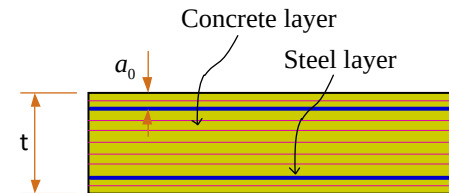
Fix $u_x u_y u_z \alpha \beta$



Specimen No. 1



Fix $u_x u_y u_z \alpha \beta$



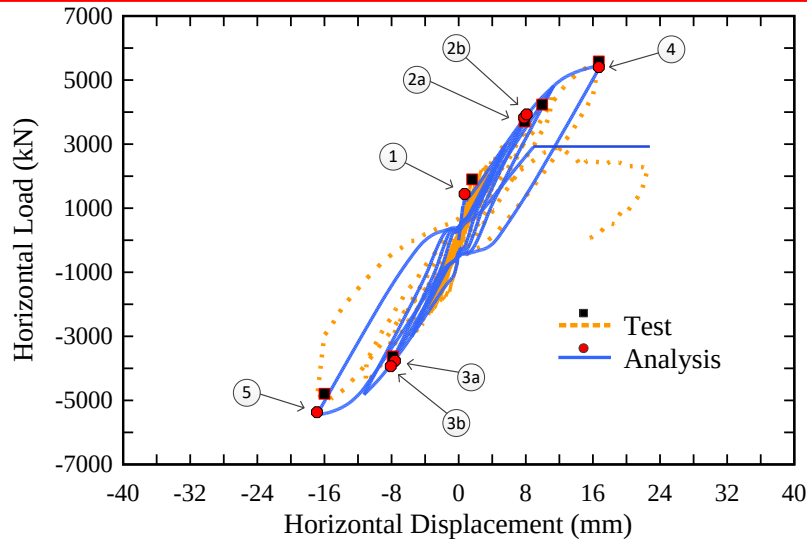
Specimen No. 2

Element Type	ρ_v	ρ_h
CSMMSHELLS8 Element (Type 1)	2 %	2 %
CSMMSHELLS8 Element (Type 2)	4 %	2 %

Nuclear Containment Vessels



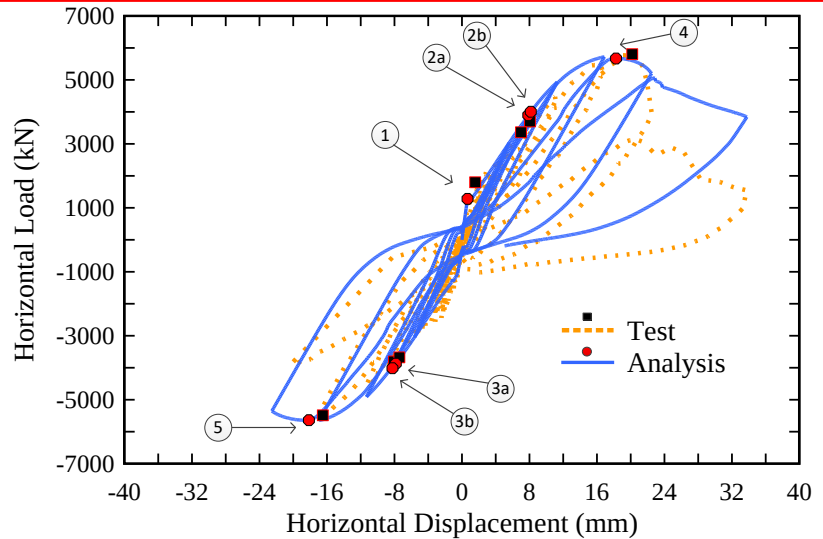
Comparisons of analytical and experimental results



Horizontal load versus displacement curve of Specimen No. 1

Critical Points on the load vs. displacement curves

Point s	Status
1	First cracking of concrete
2a	First yield of vertical steel bars in the positive direction
2b	First yield of horizontal steel bars in the positive direction
3a	First yield of vertical steel bars in the negative direction
3b	First yield of horizontal steel bars in the negative direction
4	Peak load in the positive direction
5	Peak load in the negative direction



Horizontal load versus displacement curve of Specimen No. 2

Experimental Results

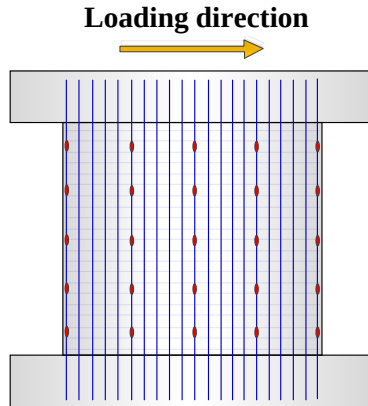
Specimen	Loading Direction	Δ_y (mm)	P_y (kN)	Δ_{max} (mm)	P_{max} (kN)	μ
1	(+)	7.84	3706	16.7	5580	2.13
	(-)	7.86	3634	16.0	4794	2.04
2	(+)	7.04	3363	20.2	5805	2.87
	(-)	7.38	3675	16.5	5487	2.23

Analytical Results

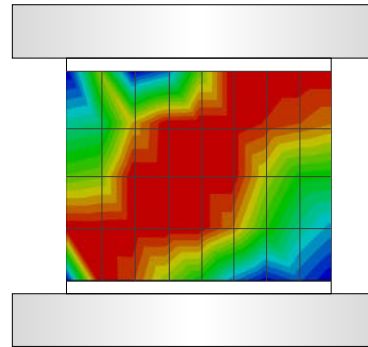
Specimen	Loading Direction	Δ_y (mm)	P_y (kN)	Δ_{max} (mm)	P_{max} (kN)	μ
1	(+)	7.8	3829	16.7	5400	2.14
	(-)	7.6	3764	16.9	5367	2.22
2	(+)	7.9	3897	18.3	5669	2.31
	(-)	7.8	3873	18.1	5640	2.32

Nuclear Containment Vessels

Contour of strains of the vertical steel bars in Specimen No. 1 at (Peak load stage)

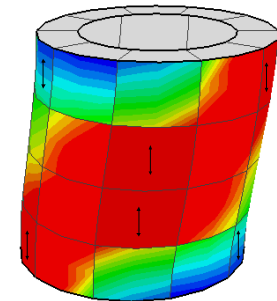


Strain gauge distribution on vertical steel bars



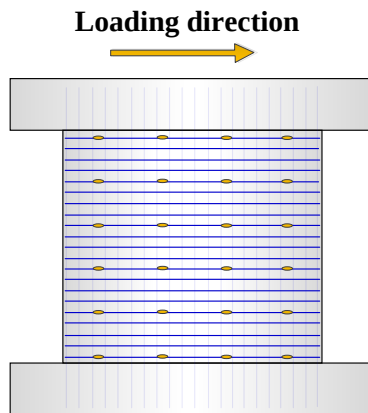
Experimental results

Vertical Steel Strain
Unit: 10^{-3} mm/mm

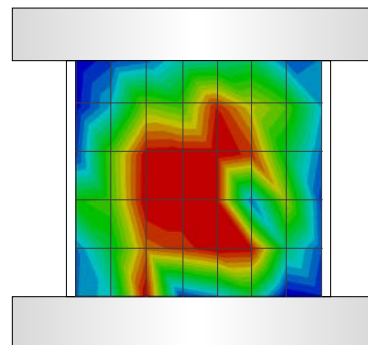


Analytical results

Contour of strains of the horizontal steel bars in Specimen No. 1 at (Peak load stage)

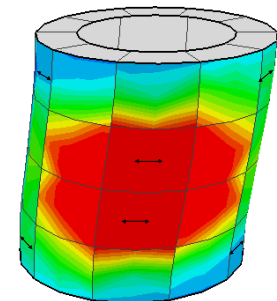


Strain gauge distribution on horizontal steel bars



Experimental results

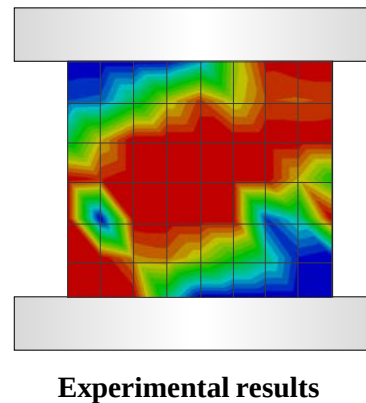
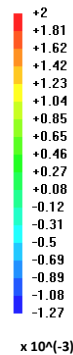
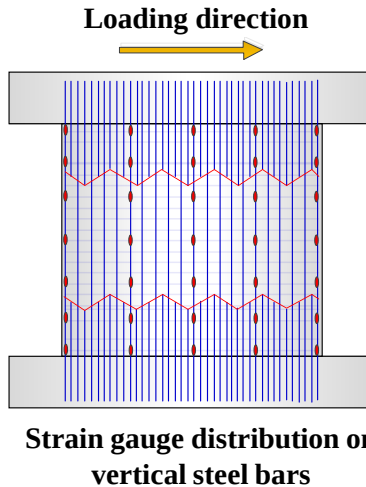
Horizontal Steel Strain
Unit: 10^{-3} mm/mm



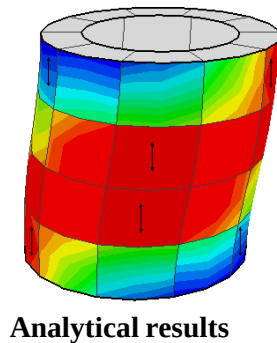
Analytical results

Nuclear Containment Vessels

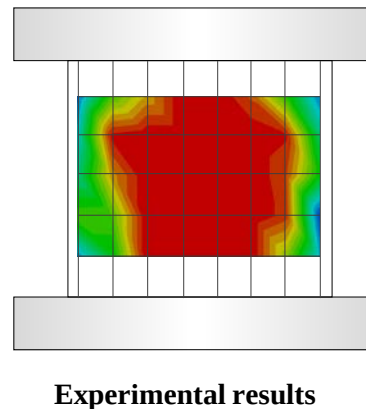
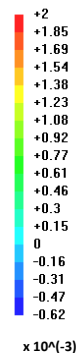
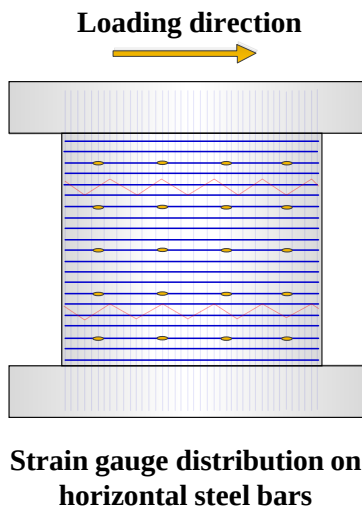
Contour of strains of the vertical steel bars in Specimen No. 2 at (Peak load stage)



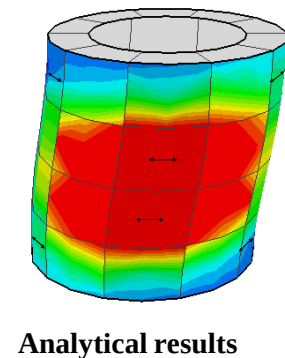
Vertical Steel Strain
Unit: 10^{-3} mm/mm



Contour of strains of the horizontal steel bars in Specimen No. 2 at (Peak load stage)



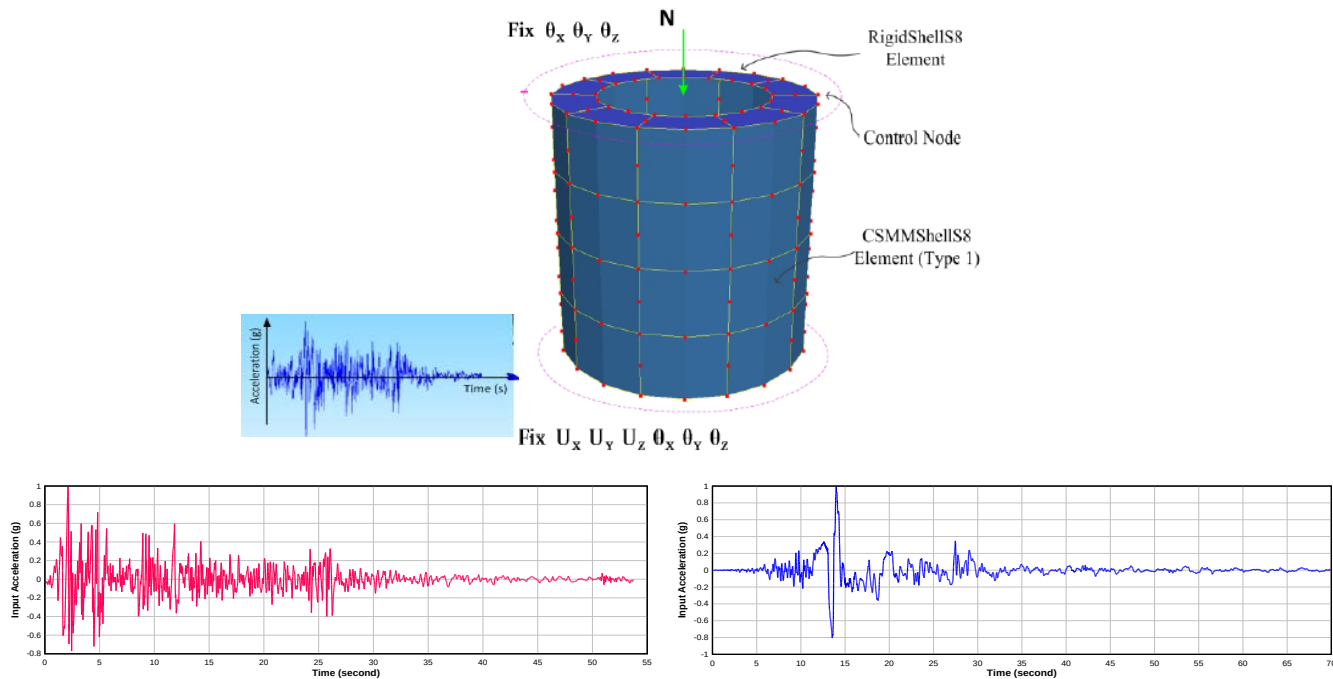
Horizontal Steel Strain
Unit: 10^{-3} mm/mm



Nonlinear Dynamic Response Analysis of Nuclear Containment Vessels



TIME – HISTORY ANALYSIS



The input ground acceleration of far-field earthquake
PGA = 1.0 g (El Centro)

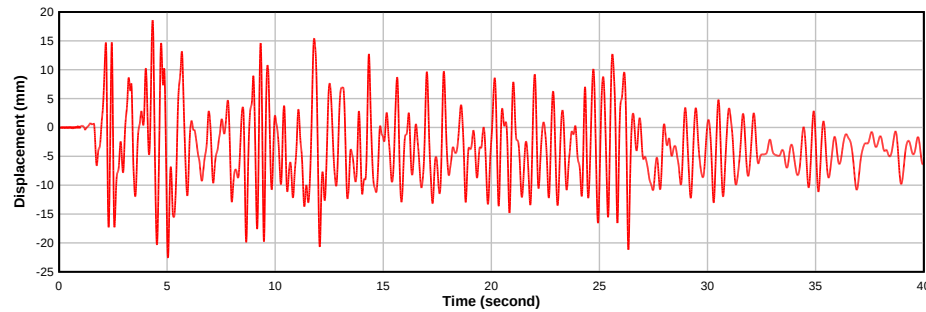
The input ground acceleration of near-fault earthquake
PGA = 1.0 g (TCU052)

Nonlinear Dynamic Response Analysis of Nuclear Containment Vessels

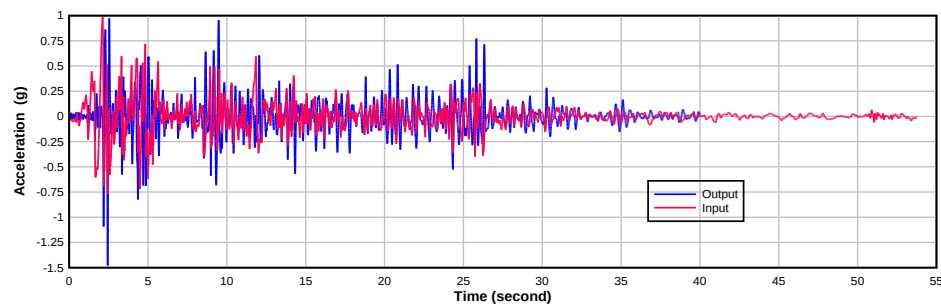


FAR FIELD TIME – HISTORY (El Centro) ANALYSIS

Phase 1: $m = 5.5 P_0/g$ and $PGA = 1.0 g$ (Ultimate State)



Displacement vs. Time



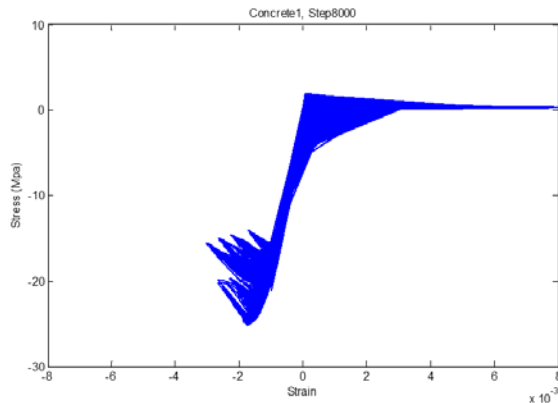
Comparison of Input and Output Acceleration

Nonlinear Dynamic Response Analysis of Nuclear Containment Vessels

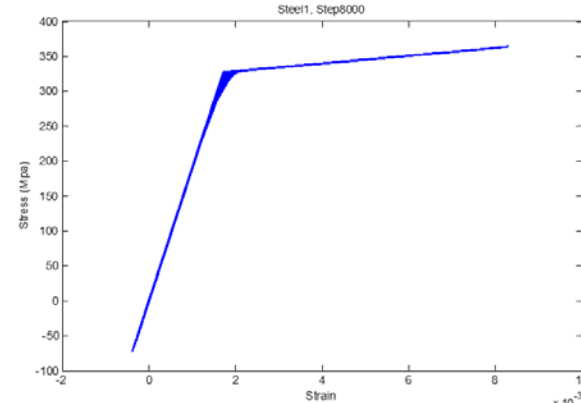


FAR FIELD TIME – HISTORY (El Centro) ANALYSIS

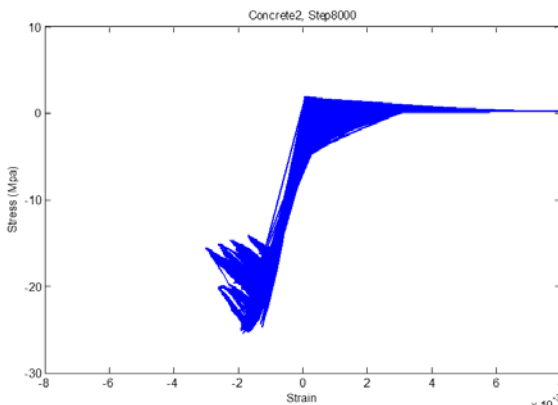
Phase 1: $m = 5.5 P_0/g$ and $PGA = 1.0 g$ (Ultimate State)



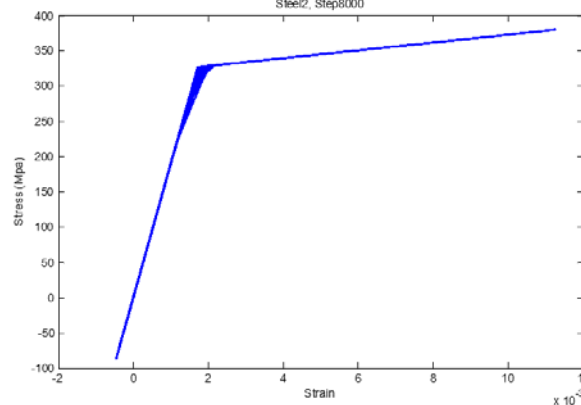
Stress-strain relationship of concrete in 1st principal direction



Stress-strain relationship of steel in vertical direction



Stress-strain relationship of concrete in 2nd principal direction



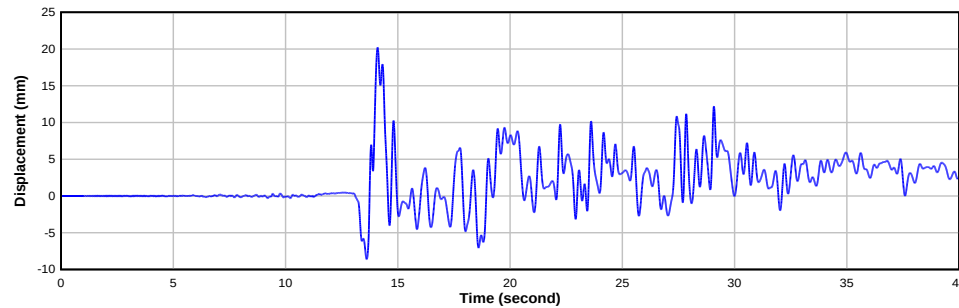
Stress-strain relationship of steel in horizontal direction

Nonlinear Dynamic Response Analysis of Nuclear Containment Vessels

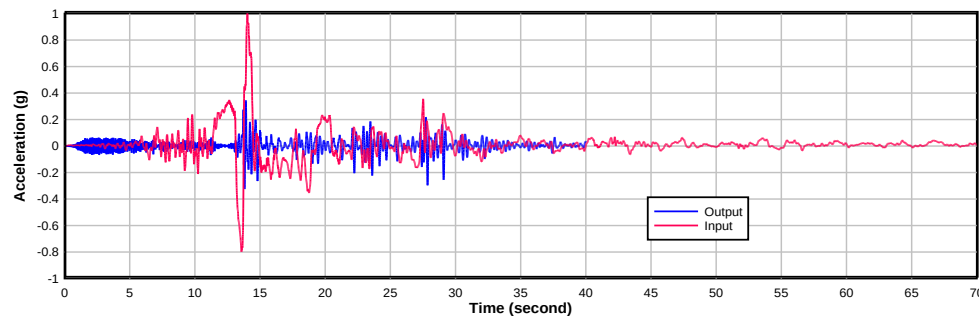


NEAR FAULT TIME – HISTORY (TCU052) ANALYSIS

Phase 3: $m = 5.5 P_0/g$ and $PGA = 1.0 g$ (Ultimate State)



Displacement vs. Time



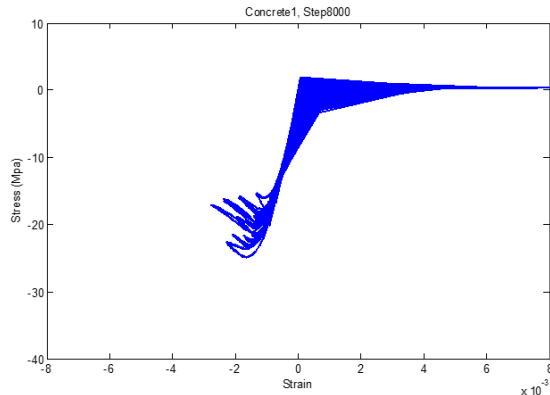
Comparison of Input and Output Acceleration

Nonlinear Dynamic Response Analysis of Nuclear Containment Vessels

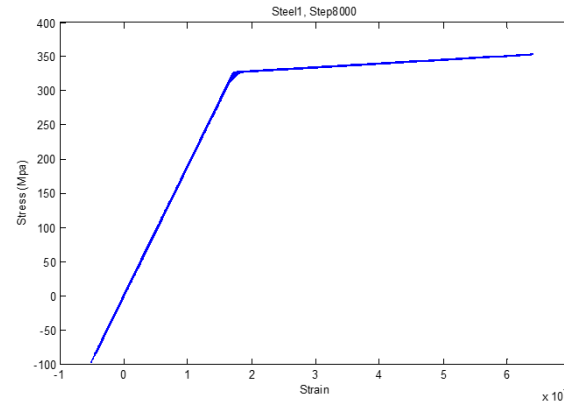


NEAR FAULT TIME – HISTORY (TCU052) ANALYSIS

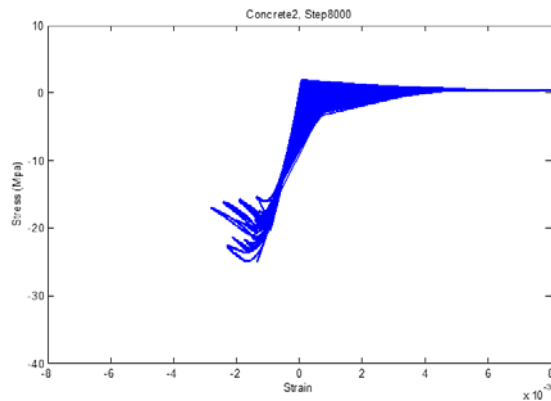
Phase 3: $m = 5.5 P_0/g$ and $PGA = 1.0 g$ (Ultimate State)



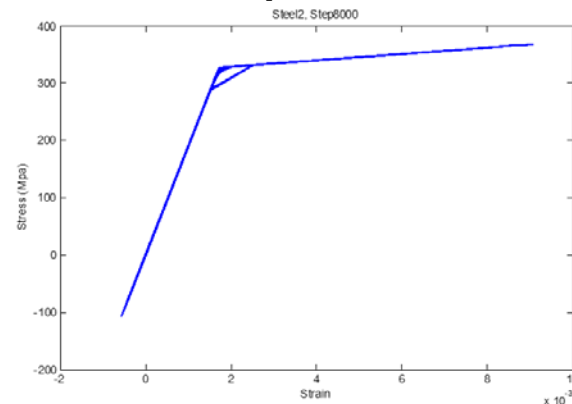
Stress-strain relationship of concrete in 1st principal direction



Stress-strain relationship of steel in vertical direction



Stress-strain relationship of concrete in 2nd principal direction



Stress-strain relationship of steel in vertical direction

**Shake table tests on scaled
nuclear containments are
needed.**