Capacity-Based Inelastic Displacement Spectra for Reinforced Concrete Bridge Columns Subjected to Far-Field and Near-Fault Ground Motions

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Outline

1) Background and Objective
2) Smooth Hysteretic Model
3) Capacity-Based Inelastic Displacement Spectrum
4) Demonstrative Example Bridge
5) Conclusion

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Roadmap for Seismic Design and Evaluation

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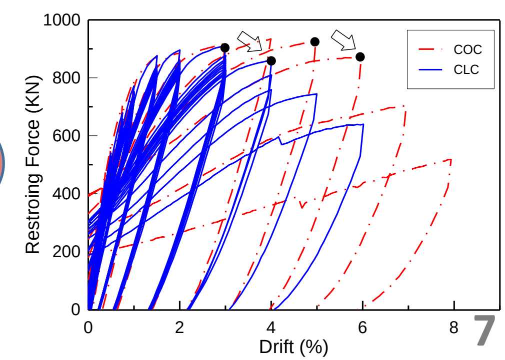
Force-Based Design	AASHTO LRFD Bridge Design Specification, 2012
In-Between	Eurocode 8-Design of structures for earthquake resistance, 2005
Force-Based Design + Disp.-Based Evaluation	FHWA Seismic Retrofitting Manual, 2006
	AASHTO Guide Specification for LRFD Seismic Bridge Design, 2011
	Caltrans Seismic Design Criteria, SDC, 2013
	Caltrans Seismic Design Specifications for Steel Bridges, 2016

Displacement

Dissipated Energy

Damage-Based Design and Evaluation

Need a powerful hysteretic model



Displacement Coefficient Method

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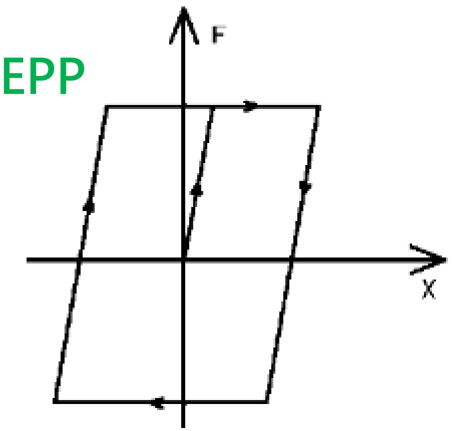
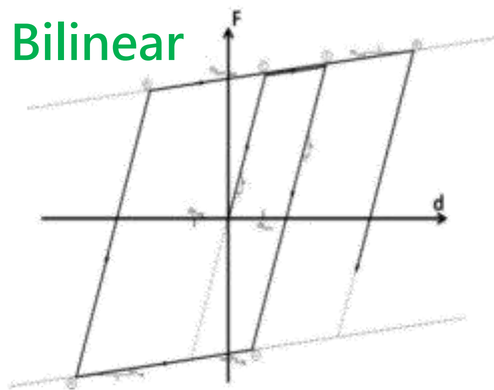
- Most, if not all, of the well-known displacement coefficient formulae were constructed based on some polygonal hysteretic models.

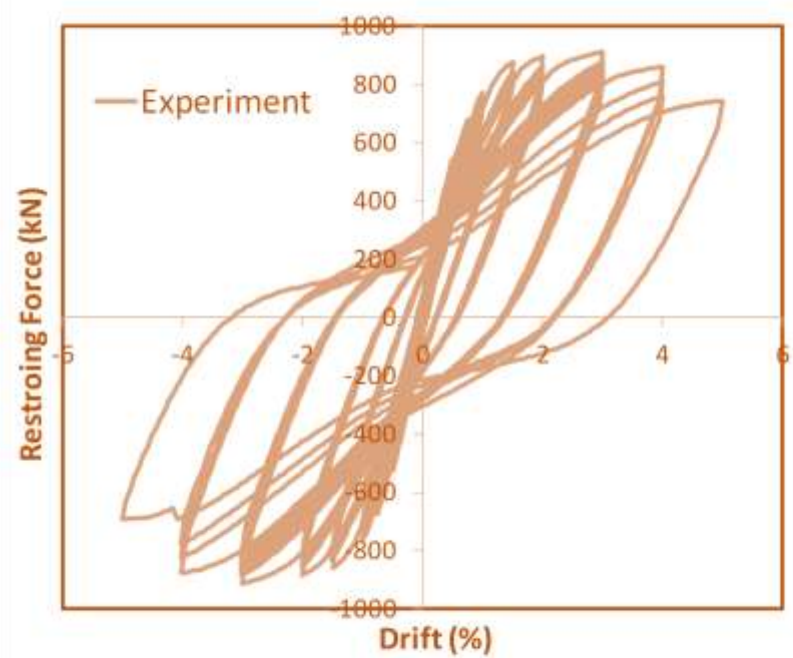
EPP



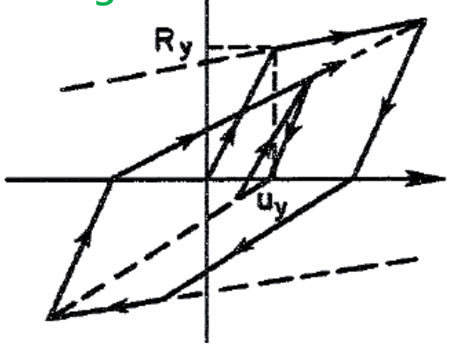
Bilinear



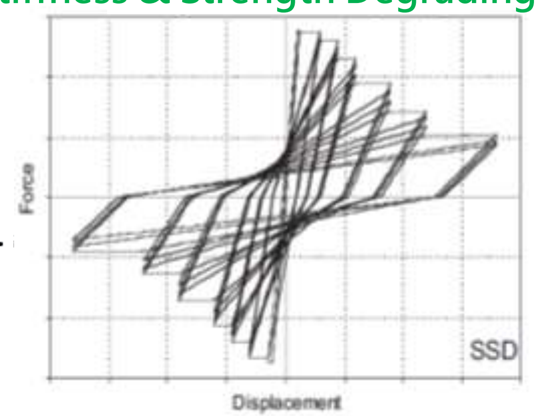
Real Hysteresis Behavior



Modified Clough



Stiffness & Strength Degrading



- These displacement ratios lack direct connection with design parameters of bridges and can not tell information about the damage state corresponding to the calculated displacement.

Objective

To construct inelastic displacement spectra associated with the corresponding damage states (capacity-based inelastic disp. spectra) for RC bridges using a newly developed smooth hysteretic model to better evaluate the seismic performance of bridges subjected to far-field and near-fault ground motions.

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New Smooth Hysteresis Model

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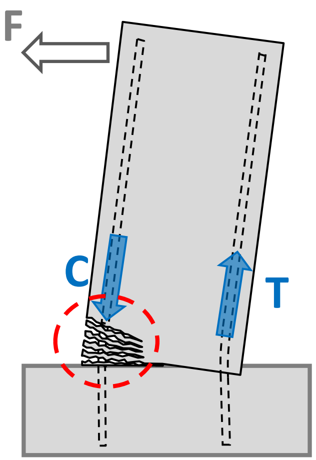
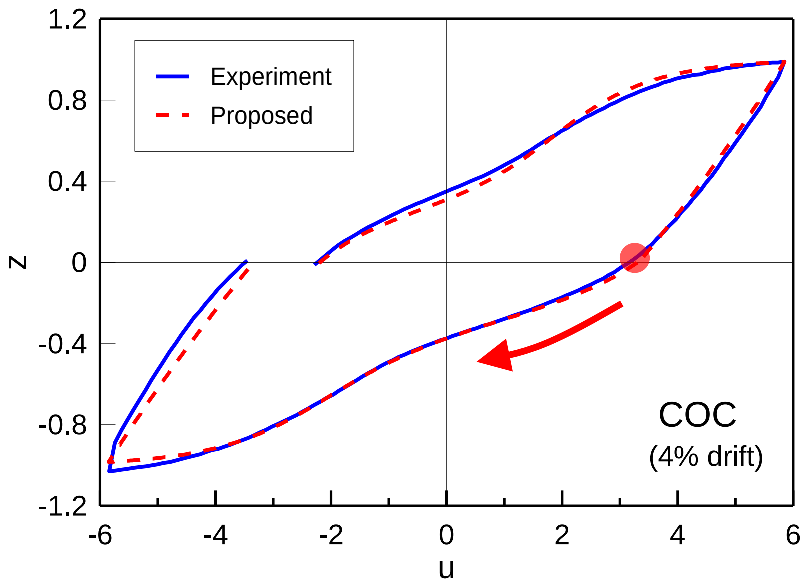
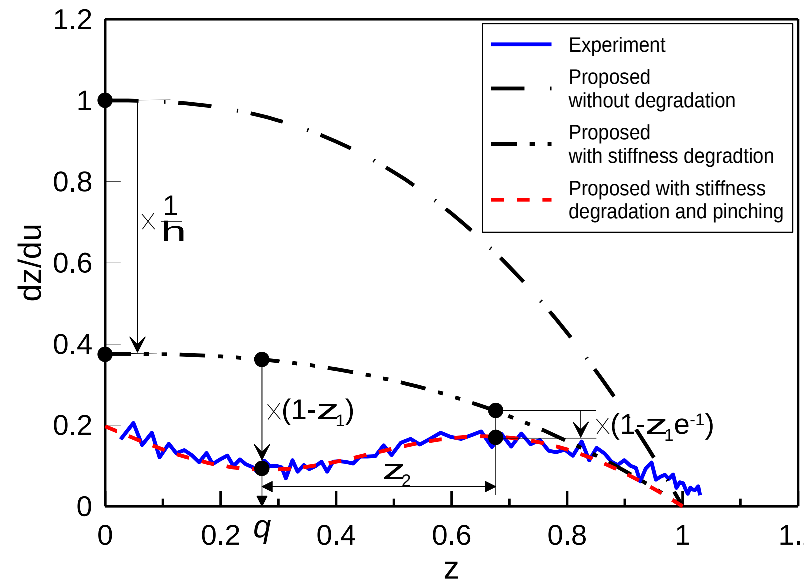
- The model is based on the well-known Bouc-Wen model with significant modification to consider hysteretic rules for damage accumulation and path dependence of RC bridge columns.



$$\dot{z}(t) = h(z)\frac{\{A\dot{u} - \nu[\beta|\dot{u}||z|^{n-1}z + \gamma\dot{u}|z|^{n}]\}}{\eta}$$

$$h(z) = 1 - \xi_1 \exp\left\{-\frac{[z\,sgn(\dot{u}) - q\,z_u]^2}{\xi_2^2}\right\}\left|\frac{sgn(\dot{u}) + sgn(z)}{2}\right|$$





Damage Index

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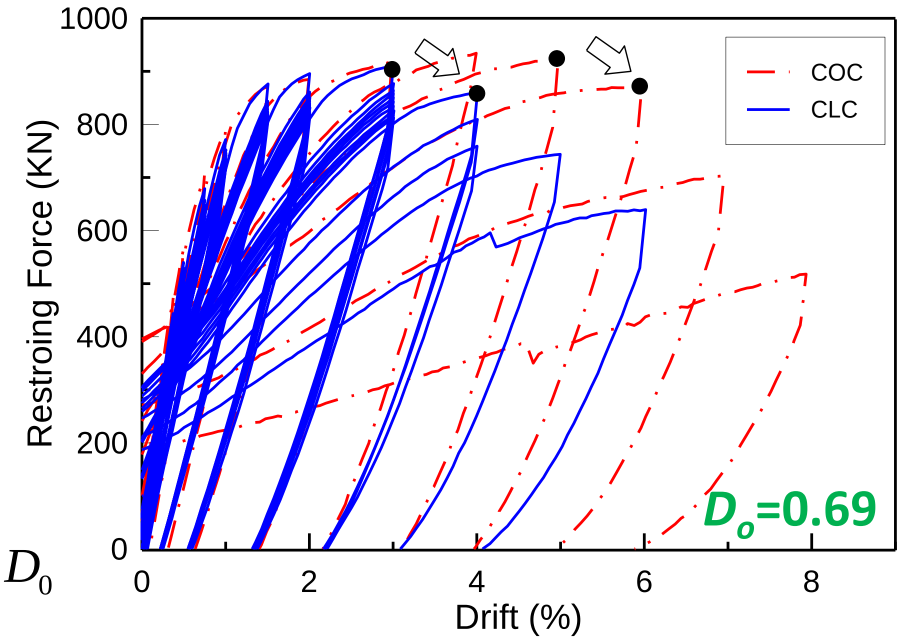
- The **damage index** proposed by **Park and Ang (1985)** was used to predict the onset of strength deterioration.
- **Strength deterioration** can be well predicted via **damage index regardless of different types of loading history**.

$$D = \frac{\delta_m}{\delta_u} + \lambda \frac{\int dE}{F_y \delta_u}$$

Damage caused by **maximum displacement**

Damage caused by **hysteretic energy dissipation**

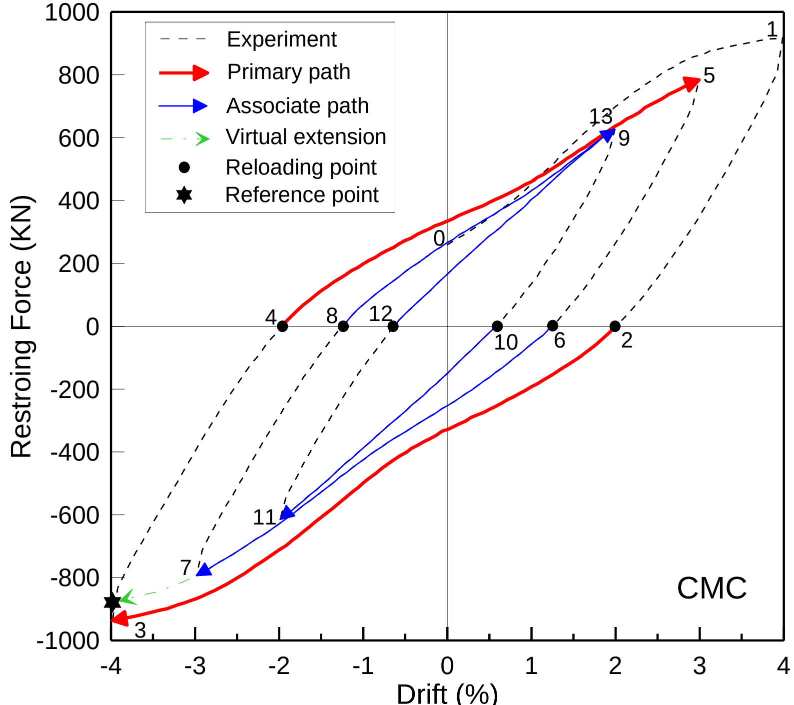
$$\nu = \begin{cases} 1.0 & D < D_o \\ 1.0 + (D - D_o) \times \dfrac{(1.747 - 1.0)}{(1.0 - D_o)} & 1.0 \geq D \geq D_0 \end{cases}$$

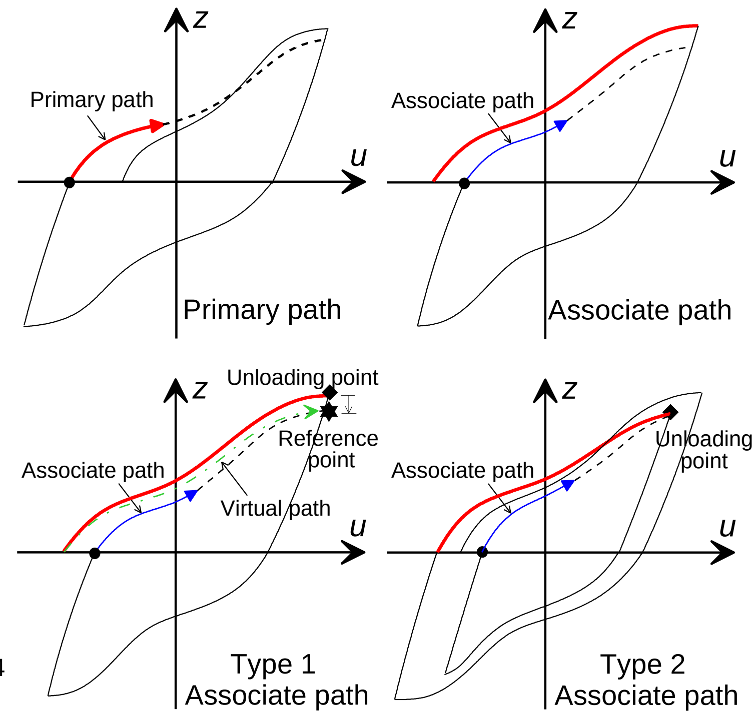


D=1.0 corresponds to 20% strength deterioration

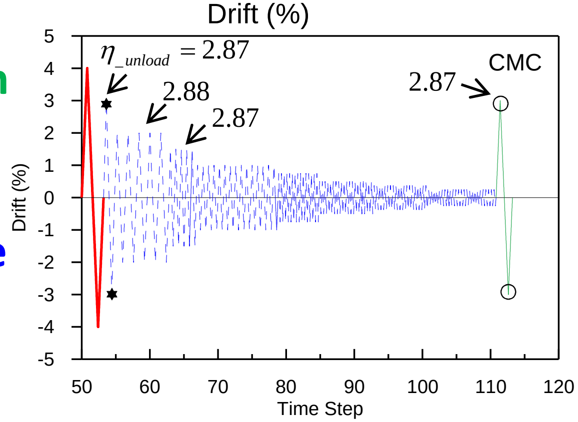
Path Dependence Rule

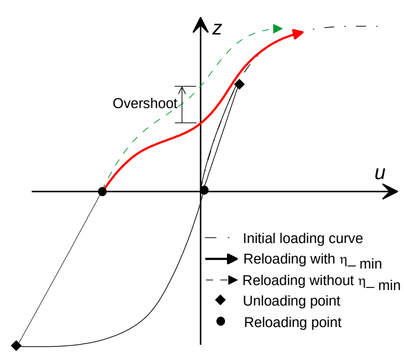
- Reloading paths can be classified into two categories, **Primary Path** and **Associate Path**.
- **Associate Path** is always directed toward certain point corresponding to **Primary Path**.

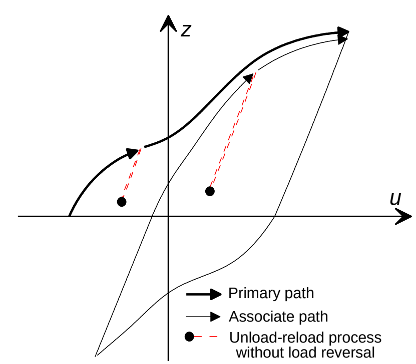




- **Deactivation** of Stiffness degradation on **Associate Path**.







Verification with Cyclic Loading Test

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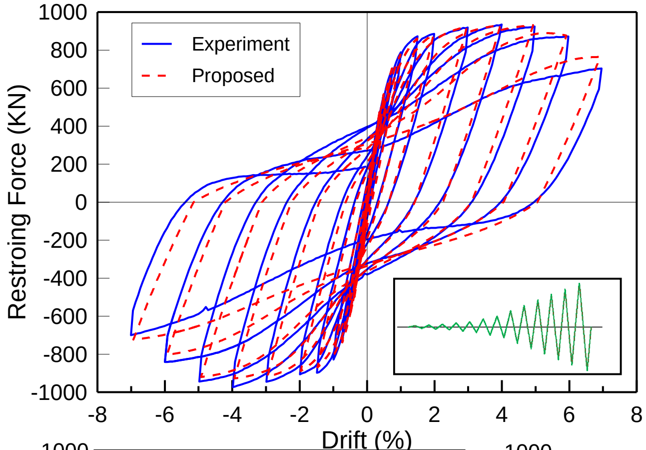
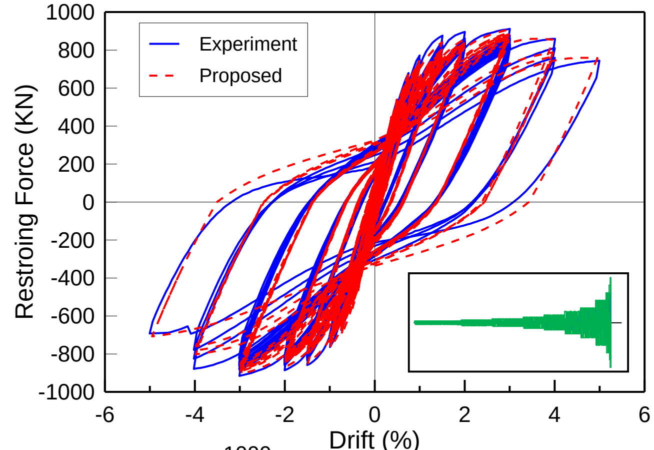
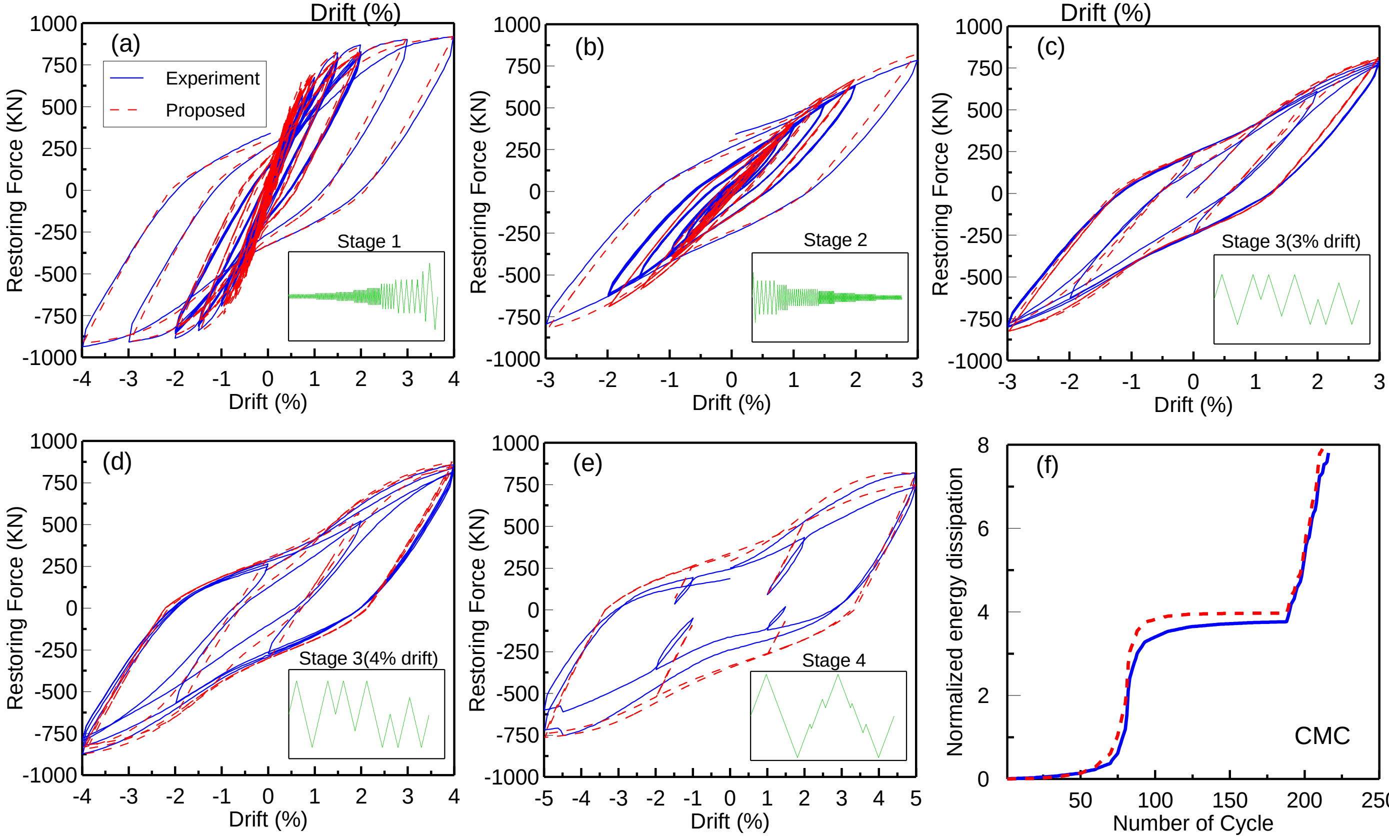
COC



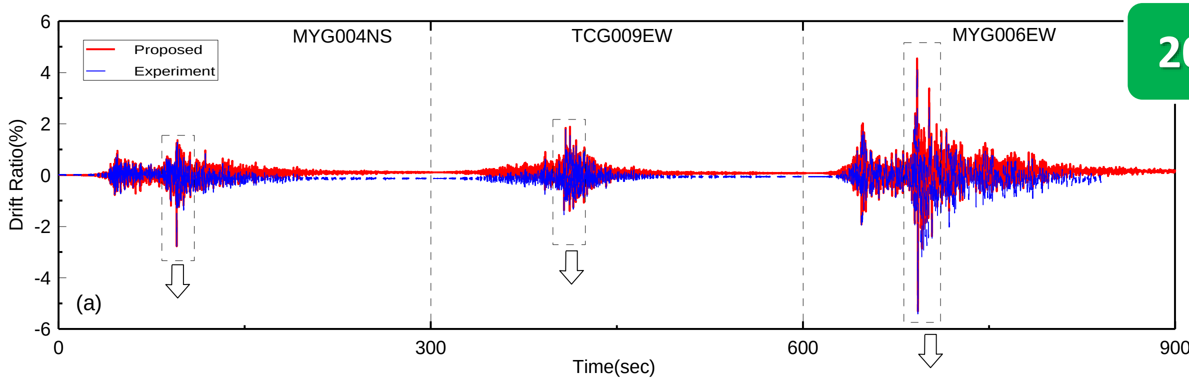
CLC

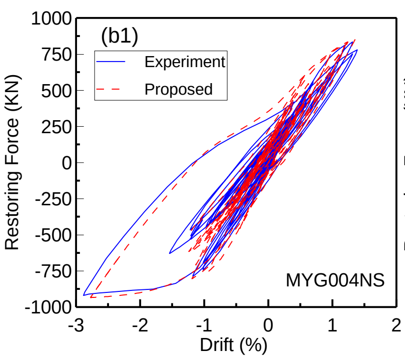


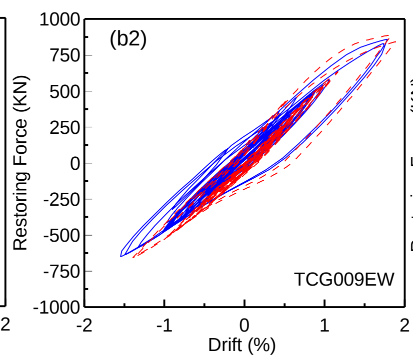
CMC

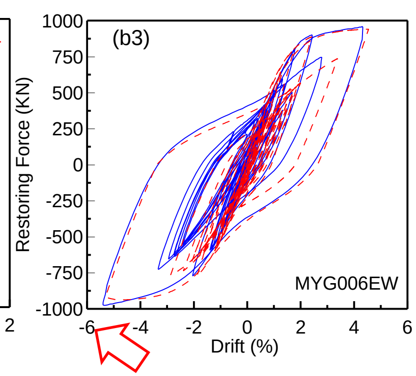


Verification with Pseudo Dynamic Test

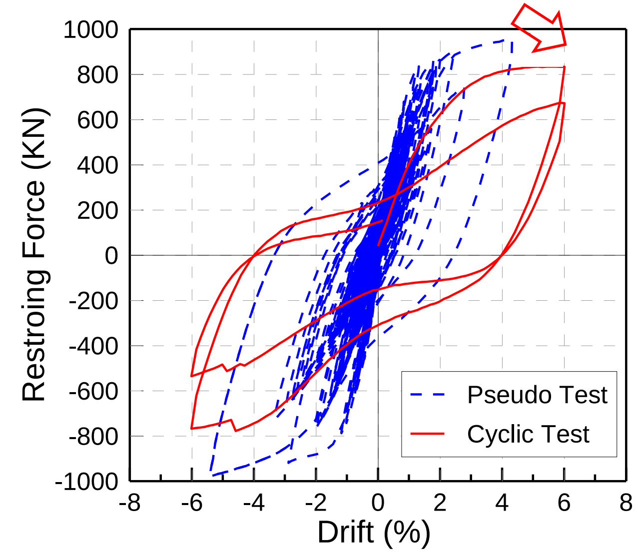


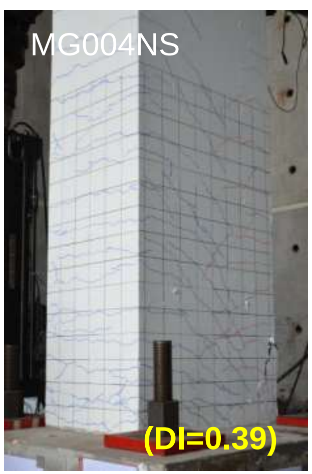


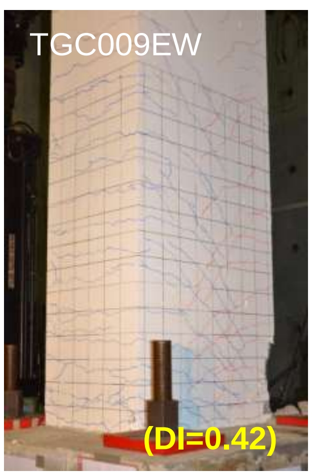


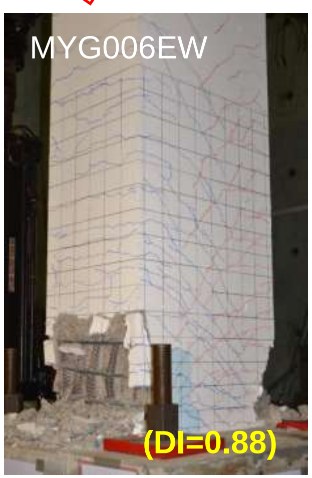


2011 Tohoku earthquake in Japan









Damage Index vs. Actual Damage State

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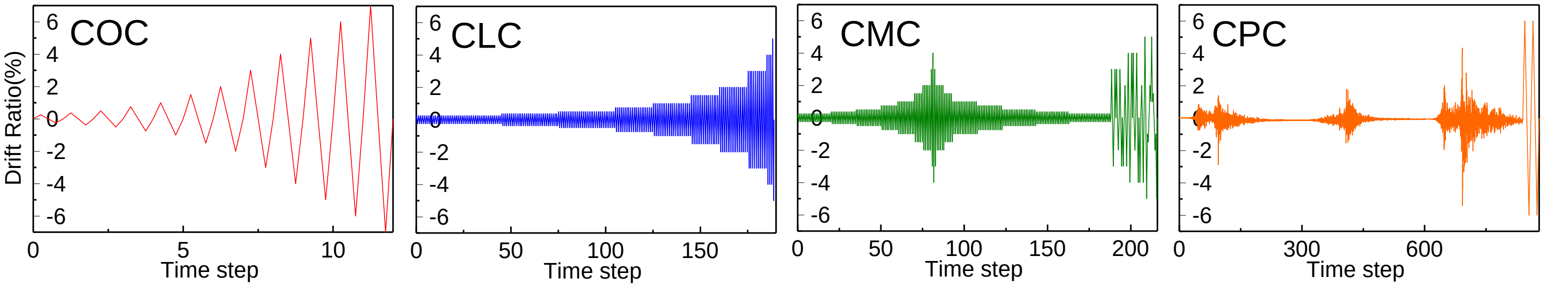
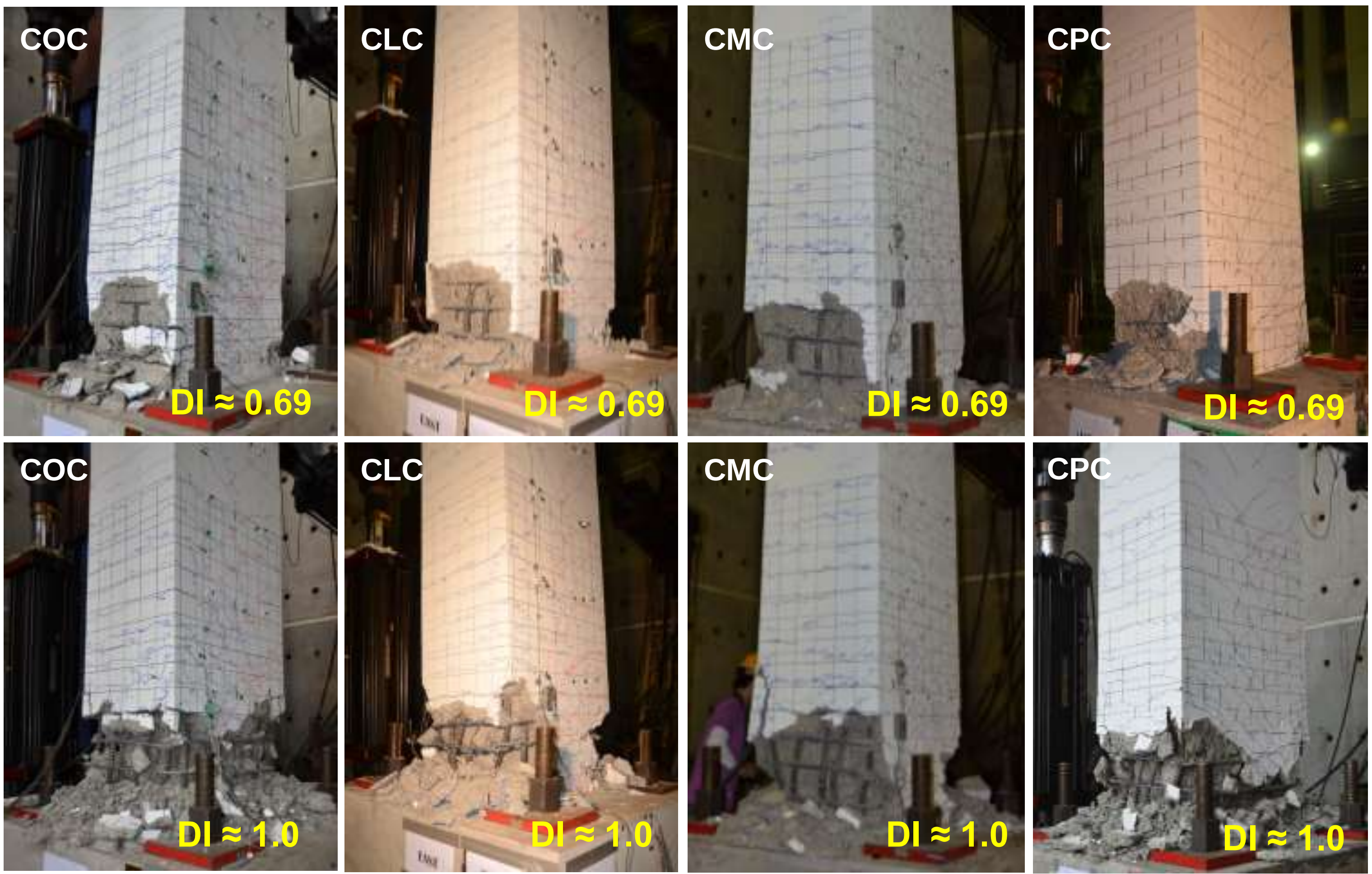




Damage Index vs. Actual Damage State


DI =0.1


DI =0.2


DI =0.3


DI =0.4


DI =0.5


DI =0.6


DI =0.7

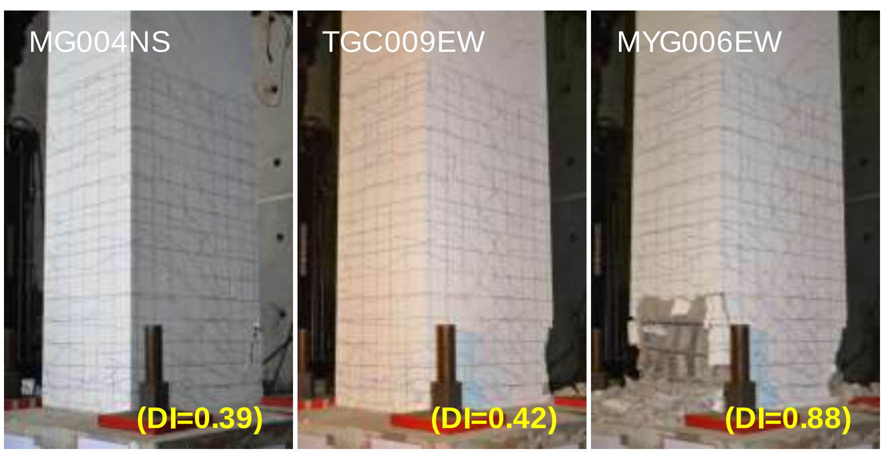

DI =0.8

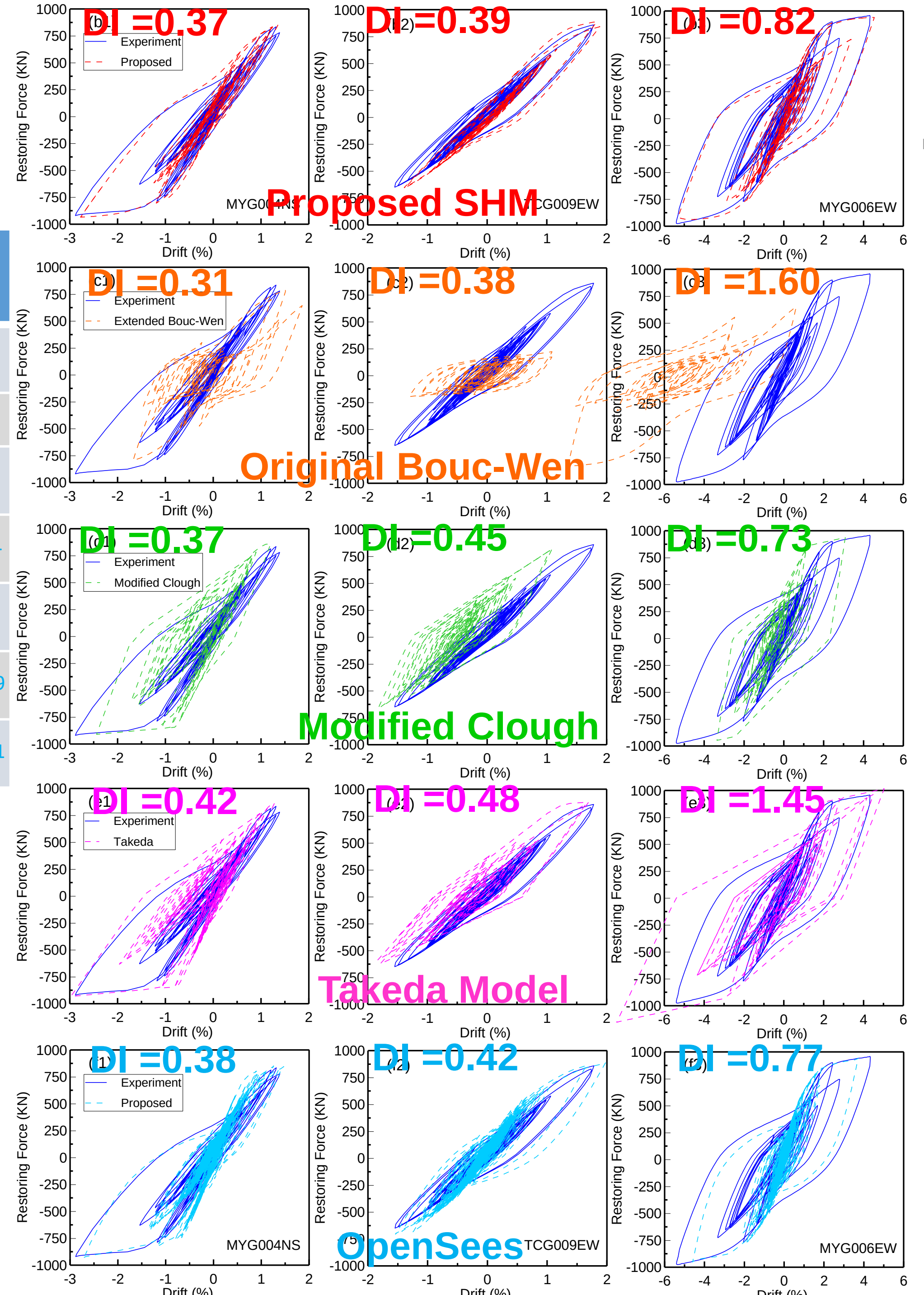

DI =0.9


DI =1.0

Damage Assessment

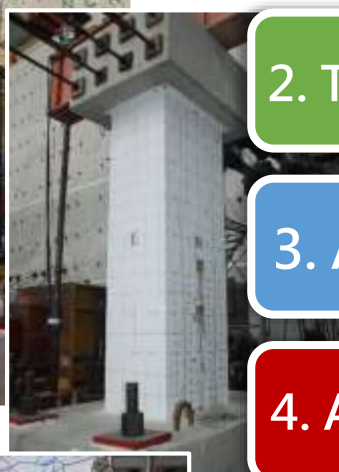
Event	Dir.	Exp.	Proposed		Extended Bouc-Wen		Modified Clough		Takeda		OpenSees	
		Drift (%)	Drift (%)	Error (%)	Drift (%)	Error (%)	Drift (%)	Error (%)	Drift (%)	Error (%)	Drift (%)	Error (%)
MYG004 NS	+	1.39	1.36	-2.46	1.86	33.95	1.20	-13.48	1.28	-7.79	1.47	5.76
	-	-2.88	-2.77	-3.84	-1.68	-41.86	-2.44	-15.42	-2.98	3.26	-2.74	-4.86
TCG009 EW	+	1.78	1.88	5.81	1.09	-39.02	1.08	-39.16	1.70	-4.65	1.98	11.24
	-	-1.55	-1.39	-10.01	-2.20	42.07	-1.83	18.11	-1.83	18.52	-1.54	-0.65
MYG006 EW	+	4.32	4.54	5.09	0.62	-85.66	3.08	-28.65	5.04	16.47	3.72	-13.89
	-	-5.40	-5.31	-1.68	-10.85	100.70	-3.36	-37.85	-8.39	55.24	-4.60	-14.81



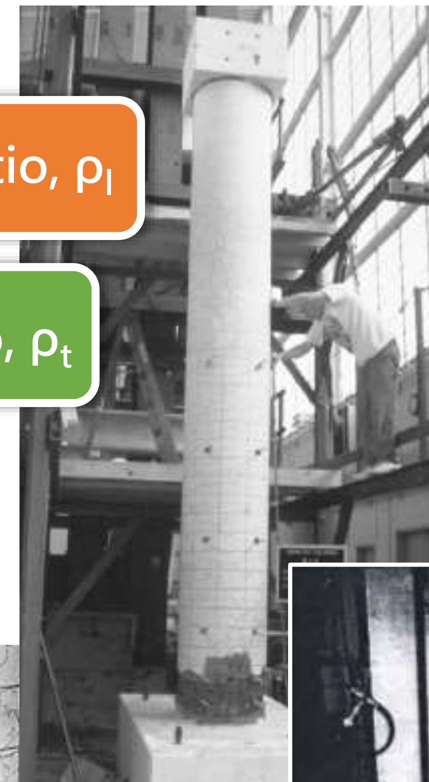


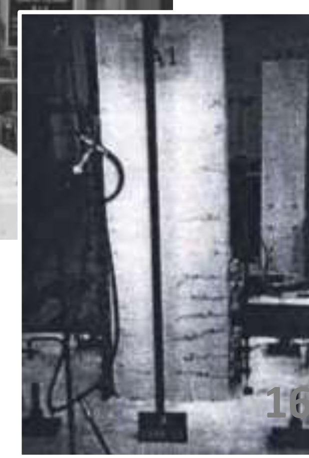
Effects of Various Design Parameters

- To quantitatively evaluate the effects of **bridge design parameters** on the deteriorated hysteretic behaviors and obtain the modal parameters.


1. Longitudinal Reinforcement Ratio, ρ_l
2. Transverse Reinforcement Ratio, ρ_t
3. Aspect Ratio, a/D
4. Axial Load Ratio, P





Experimental and simulated results

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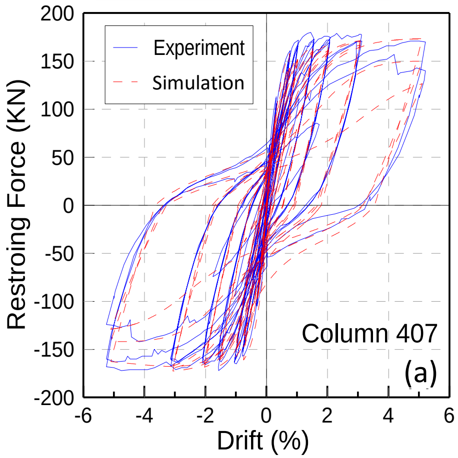
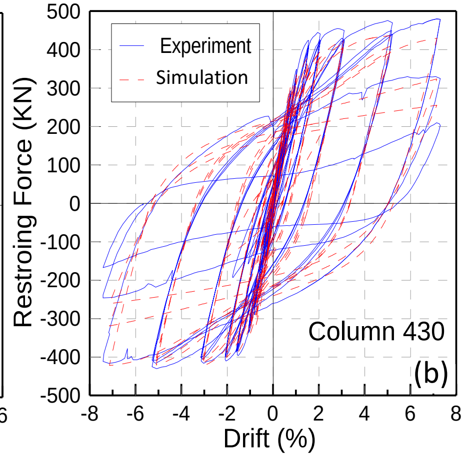
Effect of ρ_l

ρ_l=0.75、3.0%

[Leman and Moehle, 2000]

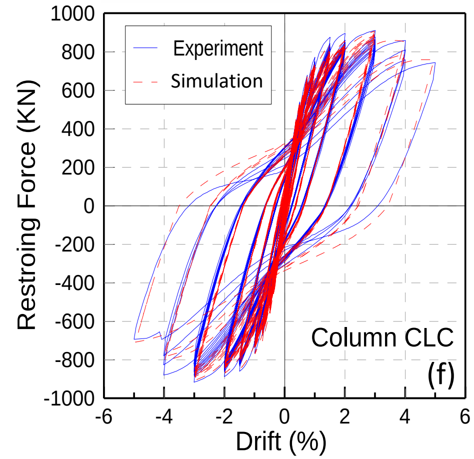


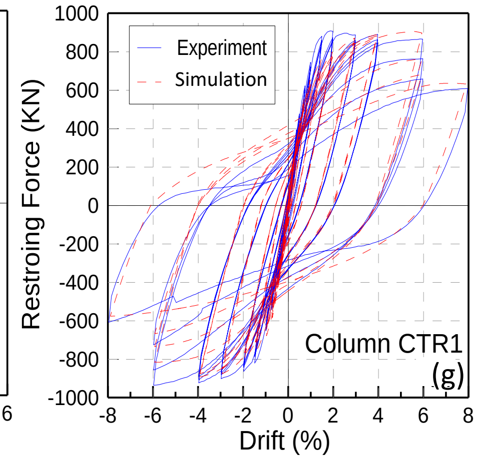


Effect of ρ_t

ρ_t=1.26、1.79%

[Ou et al., 2014, 2015]

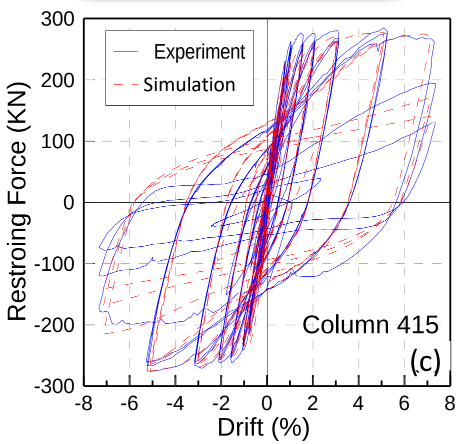


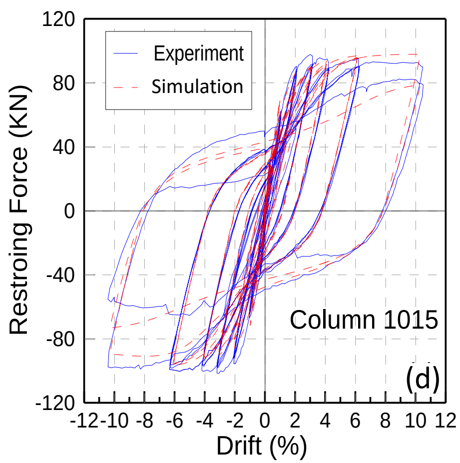


Effect of a/D

a/D=4、10

[Leman and Moehle, 2000]

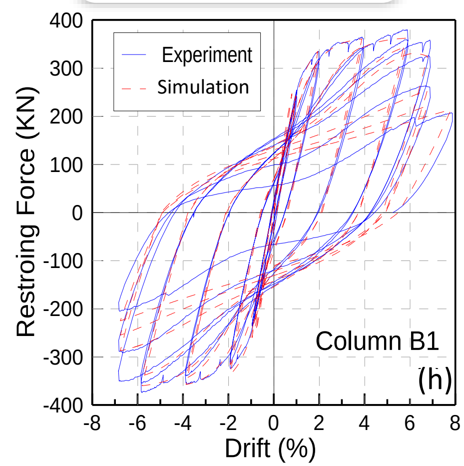


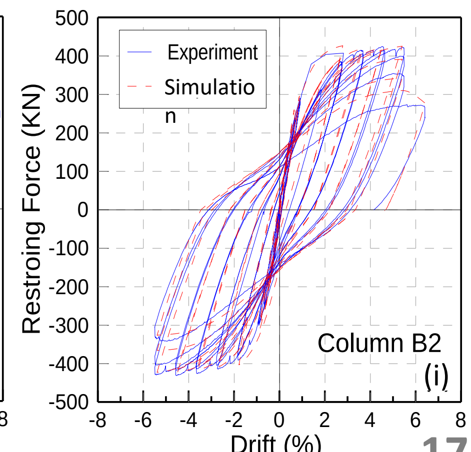


Effect of P

a/D=0.09、0.23f'$_c$A$_g$

[Wehbe et al., 2001]





Identified model parameters

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Effect of ρ_l

ρ_l=0.75、3.0%

Effect of ρ_t

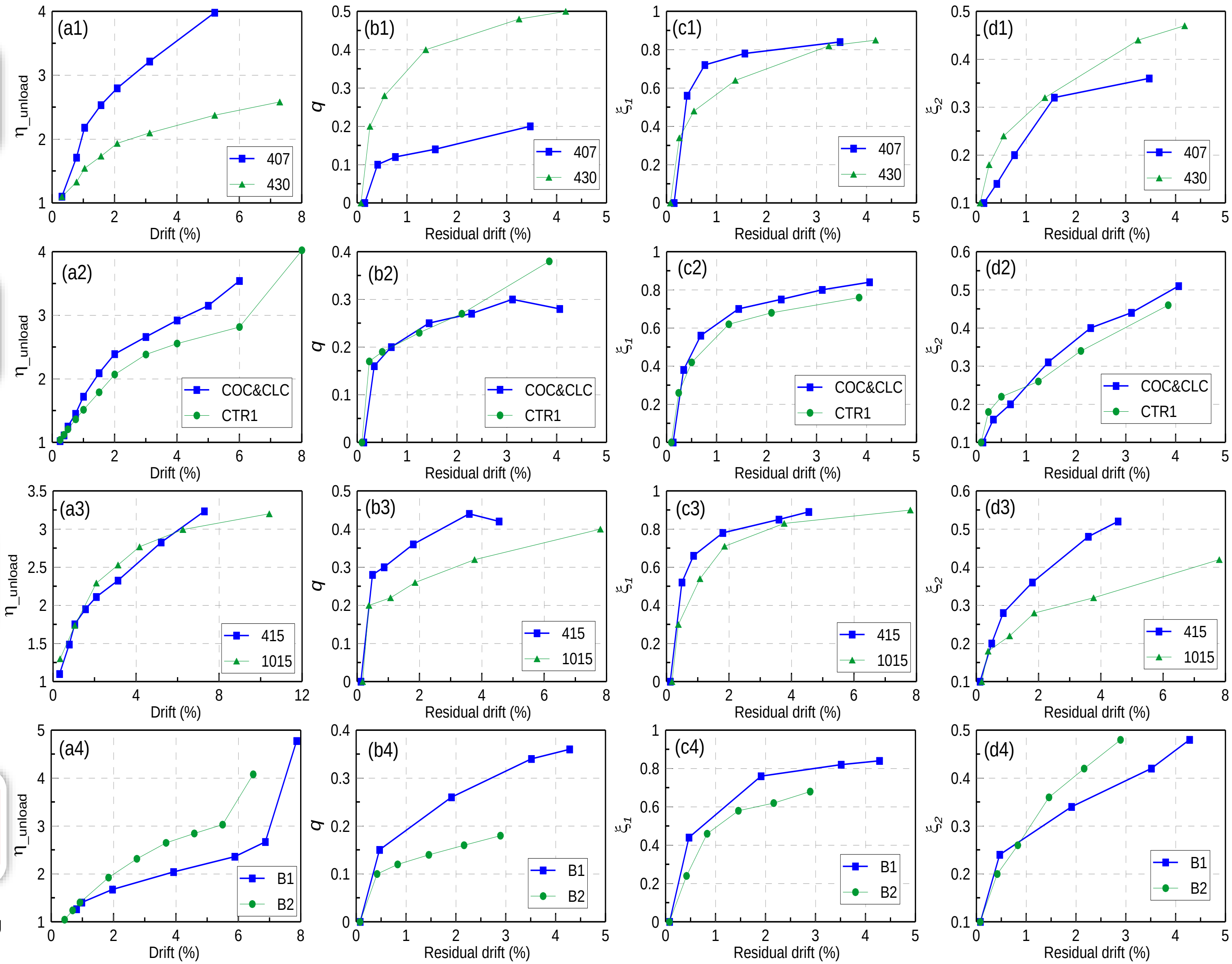
ρ_t=1.26、1.79%

Effect of a/D

a/D=4、10

Effect of P

a/D=0.09、0.23f'$_c$A$_g$



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Capacity-based inelastic displacement spectra

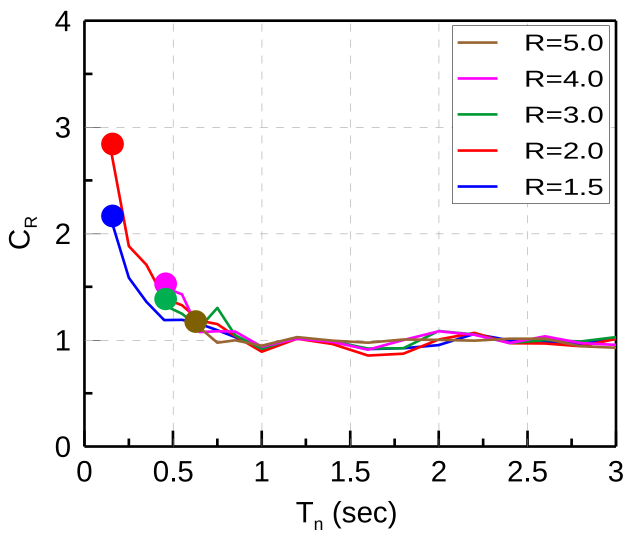
- To construct **inelastic displacement ratio (C_R) spectrum** associated with corresponding **damage state (DI) spectrum,** which can account for **various column design parameters**.
- To evaluate the well-known C_R formulae that were developed based on PHMs.
- To propose C_R and **DI** formulae not only for **far-field earthquake** but also for **pulse-like near-fault earthquake**.

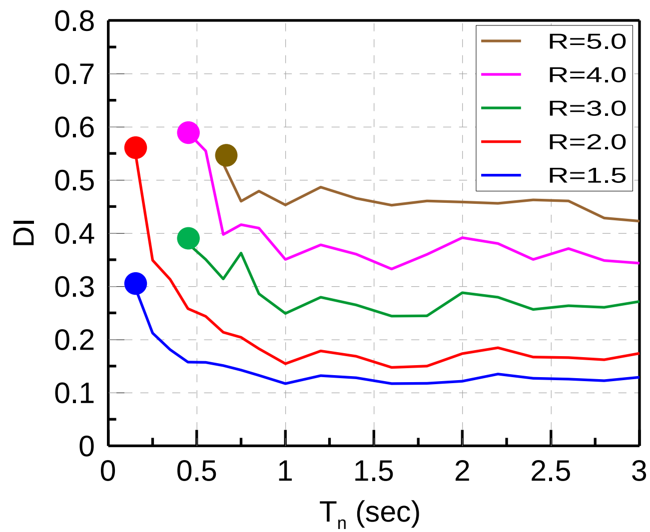
Capacity-based disp. spectra → **Dual spectra**

$$C_R = \frac{\Delta_{inelastic}}{\Delta_{elastic}}$$

$$DI = \frac{\delta_m}{\delta_u} + \lambda \frac{\int dE}{F_y \delta_u}$$

$$R = \frac{mS_a}{F_y}$$





Spectral parameters

1) **Fundamental period**, T_n

T_n = 0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0

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2) **Strength coefficient**, R

R = 1.5, 2.0, 3.0, 4.0, 5.0

5

3) **Hysteresis model**, M

M1 :	EPP	
M2, M3 :	a/D= 10, 4	(ρ_l= 1.5%, ρ_t = 0.72%, P=0.07f'_cA_g)
M4, M5 :	ρ_l= 0.75,3.0%	(ρ_t= 0.72%, P=0.07f'_cA_g, a/d=4)
M6, M7 :	ρ_t = 1.26, 1.79%	(ρ_l= 2.1%, P=0.1f'_cA_g, a/d ≈ 3.3)
M8, M9 :	P=0.09, 0.23f'_cA_g	(ρ_l= 2.2%, ρ_t =0.94%, a/d = 3.8)

9

4) **Ground excitation**, FF & NF

NEHRP 2000	
Site Class	V_{s30} (m/sec)
B	760-1525
C	360-760
D	180-360
E	<180

Far-Field : FFC (Site Class C)
FFD (Site Class D)

Near-Fault : NF1 (T_p=0.5~2.5 s)
NF2 (T_p=2.5~5.5 s)
NF3 (T_p=5.5~10.5 s)

75

67500 runs

Ground motion records

Far-field (FFC)

(PEER Ground Motion Database NGA West2)

No	RSN	Earthquake Name	Station Name	Year	M	R_{rup}(km)	T_p (sec)	Site class
FFC01	57	San Fernando	Castaic-Old Ridge Route	1971	6.6	22.63	-	C
FFC02	164	Imperial Valley	Cerro Prieto	1979	6.5	15.19	-	C
FFC03	265	Victoria_Mexico	Cerro Prieto	1980	6.3	14.37	-	C
FFC04	610	Whittier Narrows	Castaic-Old Ridge Route	1987	6.0	72.20	-	C
FFC05	771	Loma Prieta	Golden Gate Bridge	1989	6.9	79.81	-	C
FFC06	787	Loma Prieta	Palo Alto-SLAC Lab	1989	6.9	30.86	-	C
FFC07	875	Landers	La Crescenta-New York	1992	7.3	148.47	-	C
FFC08	1019	Northridge	Lake hughes	1994	6.7	35.81	-	C
FFC09	1072	Northridge	San Marino	1994	6.7	35.02	-	C
FFC10	1073	Northridge	San Pedro-Palos Verdes	1994	6.7	57.03	-	C
FFC11	1172	Kocaeli	Tekirdag	1999	7.5	165.02	-	C
FFC12	1295	Chi-Chi	HWA049	1999	7.6	50.76	-	C
FFC13	1315	Chi-Chi	ILA010	1999	7.6	80.18	-	C
FFC14	1471	Chi-Chi	TCU015	1999	7.6	49.81	-	C
FFC15	1837	Hector Mine	Valyermo Forest Fire Station	1999	7.1	135.77	-	C

Far-field (FFD)

		Earthquake Name	Station Name	Year	M	R_{rup}(km)	T_p (sec)	Site class
FFD01	66	San Fernando	Hemet Fire	1971	6.6	139.14	-	D
FFD02	93	San Fernando	Whittier Dam	1971	6.6	39.45	-	D
FFD03	169	Imperial Valley	Delta	1979	6.5	22.03	-	D
FFD04	316	Westmorland	Parachute Test Site	1981	5.9	16.54	-	D
FFD05	652	Whittier Narrows	Lakewood-Del Amo Blvd	1987	6.0	26.68	-	D
FFD06	653	Whittier Narrows	Lancaster-Med Off FF	1987	6.0	67.62	-	D
FFD07	777	Loma Prieta	Hollister City Hall	1989	6.9	27.60	-	D
FFD08	790	Loma Prieta	Richmond	1989	6.9	87.87	-	D
FFD09	800	Loma Prieta	salinas	1989	6.9	32.78	-	D
FFD10	836	Landers	Baker Fire Station	1992	7.3	87.94	-	D
FFD11	965	Northridge	Covina-S Grand Ave	1994	6.7	57.51	-	D
FFD12	1094	Northridge	West Covina-S Orange Ave	1994	6.7	51.70	-	D
FFD13	1237	Chi-Chi	CHY090	1999	7.6	58.42	-	D
FFD14	1304	Chi-Chi	HWA059	1999	7.6	49.15	-	D
FFD15	1540	Chi-Chi	TCU115	1999	7.6	21.76	-	D

Near-fault (NF1)

No	RSN	Earthquake Name	Station Name	Year	M	R_{rup}(km)	T_p (sec)	Site Class
NF101	77	San Fernando	Pacoima Dam (upper left abut)	1971	6.6	1.81	1.64	B
NF102	150	Coyote Lake	Gilroy Array #6	1979	5.7	3.11	1.23	C
NF103	159	Imperial Valley	Agrarias	1979	6.5	0.65	2.34	D
NF104	568	San Salvador	Geotech Investig Center	1986	5.8	6.30	0.81	C
NF105	764	Loma Prieta	Gilroy - Historic Bldg.	1989	6.9	10.97	1.64	D
NF106	766	Loma Prieta	Gilroy Array #2	1989	6.9	11.07	1.73	D
NF107	1004	Northridge	LA-Sepulveda VA Hospital	1994	6.7	8.44	0.93	C
NF108	1044	Northridge	Newhall - Fire Station	1994	6.7	5.92	1.37	[illegible]
NF109	1050	Northridge	Pacoima Dam	1994	6.7	7.01	0.59	[illegible]
NF110	1086	Northridge	Sylmar-Olive View Med FF	1994	6.7	5.30	2.44	C
NF111	1106	Kobe	KJMA	1995	6.9	0.96	1.09	D
NF112	1119	Kobe	Takarazuka	1995	6.9	0.27	1.81	D
NF113	1120	Kobe	Takatori	1995	6.9	1.47	1.55	D
NF114	1602	Duzce_ Turkey	Bolu	1999	7.1	12.04	0.88	D
NF115	3746	Cape Mendocino	Centerville Beach, Naval Fac	1992	7.0	18.31	1.97	C

T_p=0.5~2.5 s

Near-fault (NF2)

No	RSN	Earthquake Name	Station Name	Year	M	R_{rup}(km)	T_p (sec)	Site Class
NF201	161	Imperial Valley	Brawley Airport	1979	6.5	10.42	4.39	D
NF202	179	Imperial Valley	El Centro Array #4	1979	6.5	7.05	4.79	D
NF203	181	Imperial Valley	El Centro Array #6	1979	6.5	1.35	3.77	D
NF204	767	Loma Prieta	Gilroy Array #3	1989	6.9	12.82	2.64	D
NF205	802	Loma Prieta	Saratoga - Aloha Ave	1989	6.9	8.5	4.57	C
NF206	828	Cape Mendocino	Petrolia	1992	7	8.18	3.00	C
NF207	879	Landers	Lucerne	1992	7.3	2.19	5.12	B
NF208	982	Northridge	Jensen Filter Plant Admin. Bldg.	1994	6.7	5.43	3.16	[illegible]
NF209	983	Northridge	Jensen Filter Plant Generator Bldg.	1994	6.7	5.43	3.54	[illegible]
NF210	1045	Northridge	Newhall-W Pico Canyon Rd.	1994	6.7	5.48	2.98	[illegible]
NF211	1084	Northridge	Sylmar-Converter Sta	1994	6.7	5.35	2.98	D
NF212	1114	Kobe	Port Island	1995	6.9	3.31	2.83	D
NF213	1182	Chi-Chi	CHY006	1999	7.6	9.76	2.57	C
NF214	1510	Chi-Chi	TCU075	1999	7.6	0.89	4.99	C
NF215	3473	Chi-Chi	TCU078	1999	6.3	11.52	4.15	C

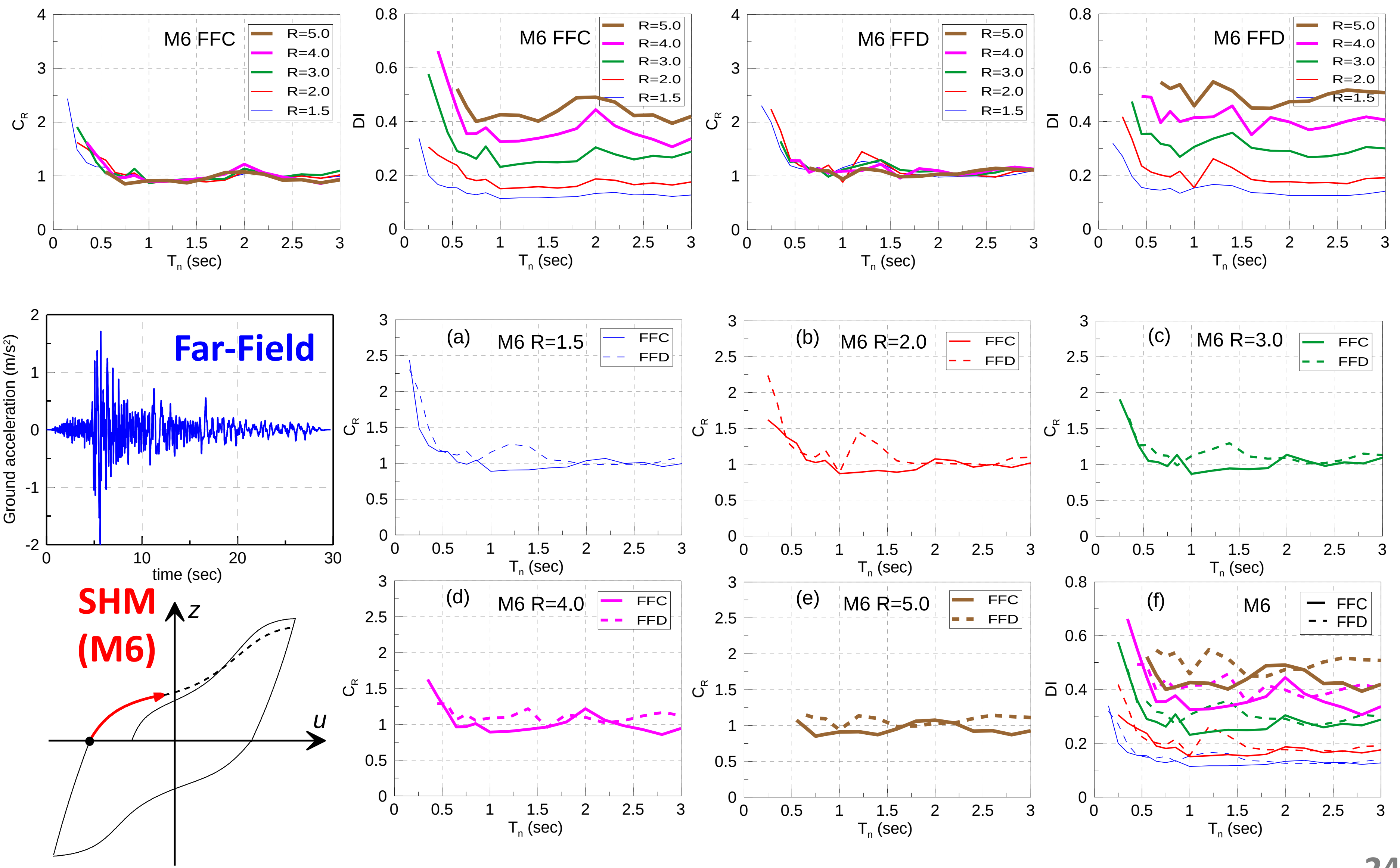
T_p=2.5~5.5 s

Near-fault (NF3)

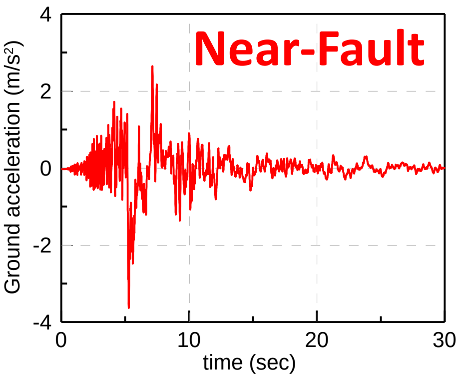
No	RSN	Earthquake Name	Station Name	Year	M	R_{rup}(km)	T_p (sec)	Site Class
NF301	184	Imperial Valley	El Centro Differential Array	1979	6.5	5.09	6.27	D
NF302	803	Loma Prieta	Saratoga-W Valley Coll.	1989	6.9	9.31	5.65	D
NF303	838	Landers	Barstow	1992	7.3	34.86	9.13	C
NF304	900	Landers	Yermo Fire Station	1992	7.3	23.62	7.5	D
NF305	1148	Kocaeli	Arcelik	1999	7.5	13.49	7.79	C
NF306	1161	Kocaeli	Gebze	1999	7.5	10.92	5.99	B
NF307	1491	Chi-Chi	TCU051	1999	7.6	7.64	10.38	[illegible]
NF308	1498	Chi-Chi	TCU059	1999	7.6	17.11	7.78	[illegible]
NF309	1501	Chi-Chi	TCU063	1999	7.6	9.78	6.55	[illegible]
NF310	1503	Chi-Chi	TCU065	1999	7.6	0.57	5.74	D
NF311	1515	Chi-Chi	TCU082	1999	7.6	5.16	8.10	C
NF312	1519	Chi-Chi	TCU087	1999	7.6	6.98	10.39	C
NF313	1528	Chi-Chi	TCU101	1999	7.6	2.11	10.32	C
NF314	1531	Chi-Chi	TCU0104	1999	7.6	12.87	7.19	C
NF315	6975	Darfield	TPLC	2010	7	6.11	8.93	D

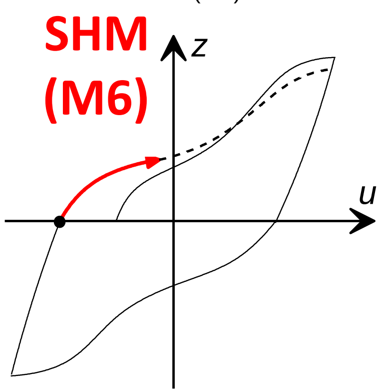
T_p=5.5~10.5 s

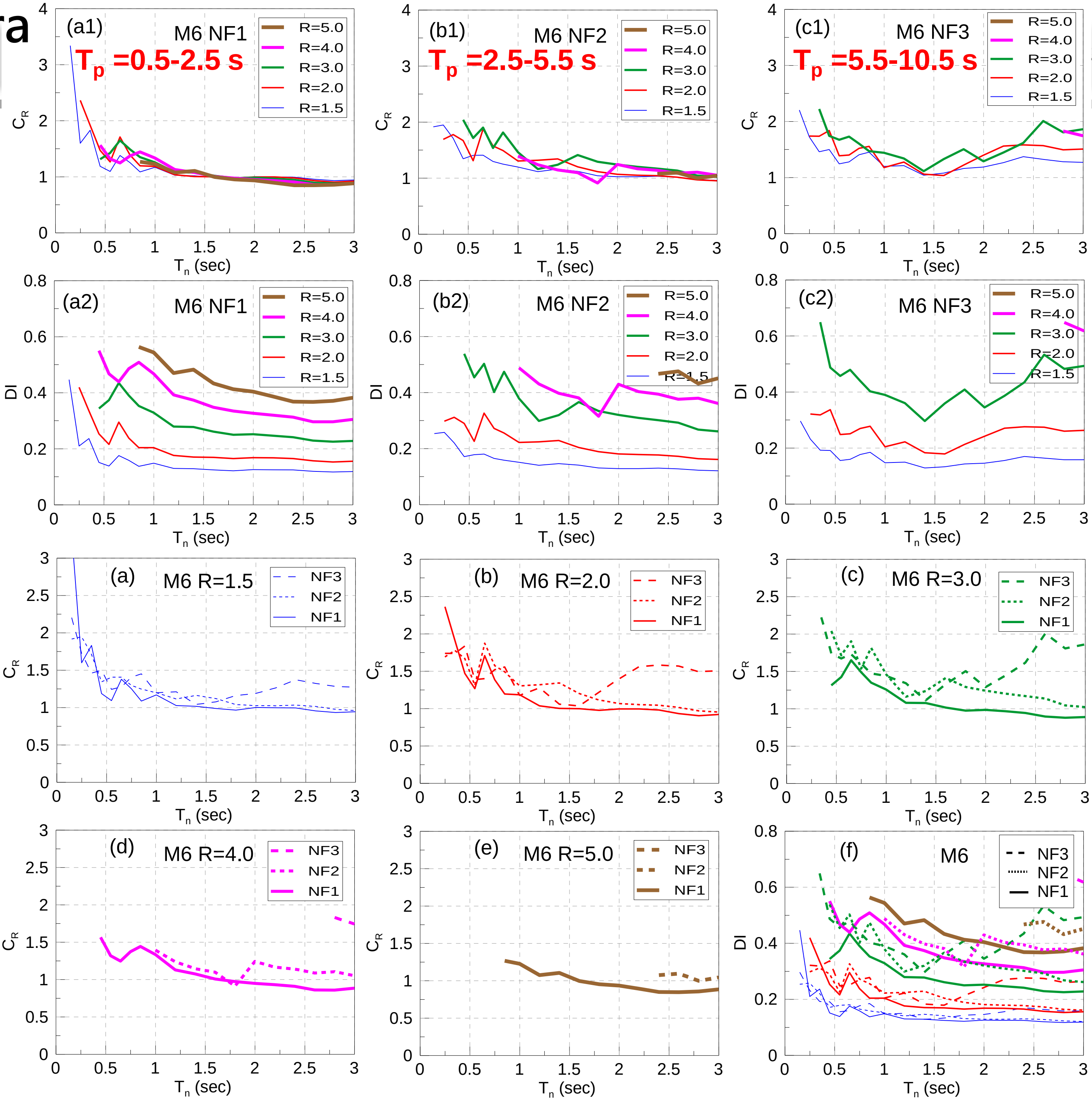
Comparison between FFC and FFD



C_R and DI Spectra Results for NF







Comparison between FFC and NF3

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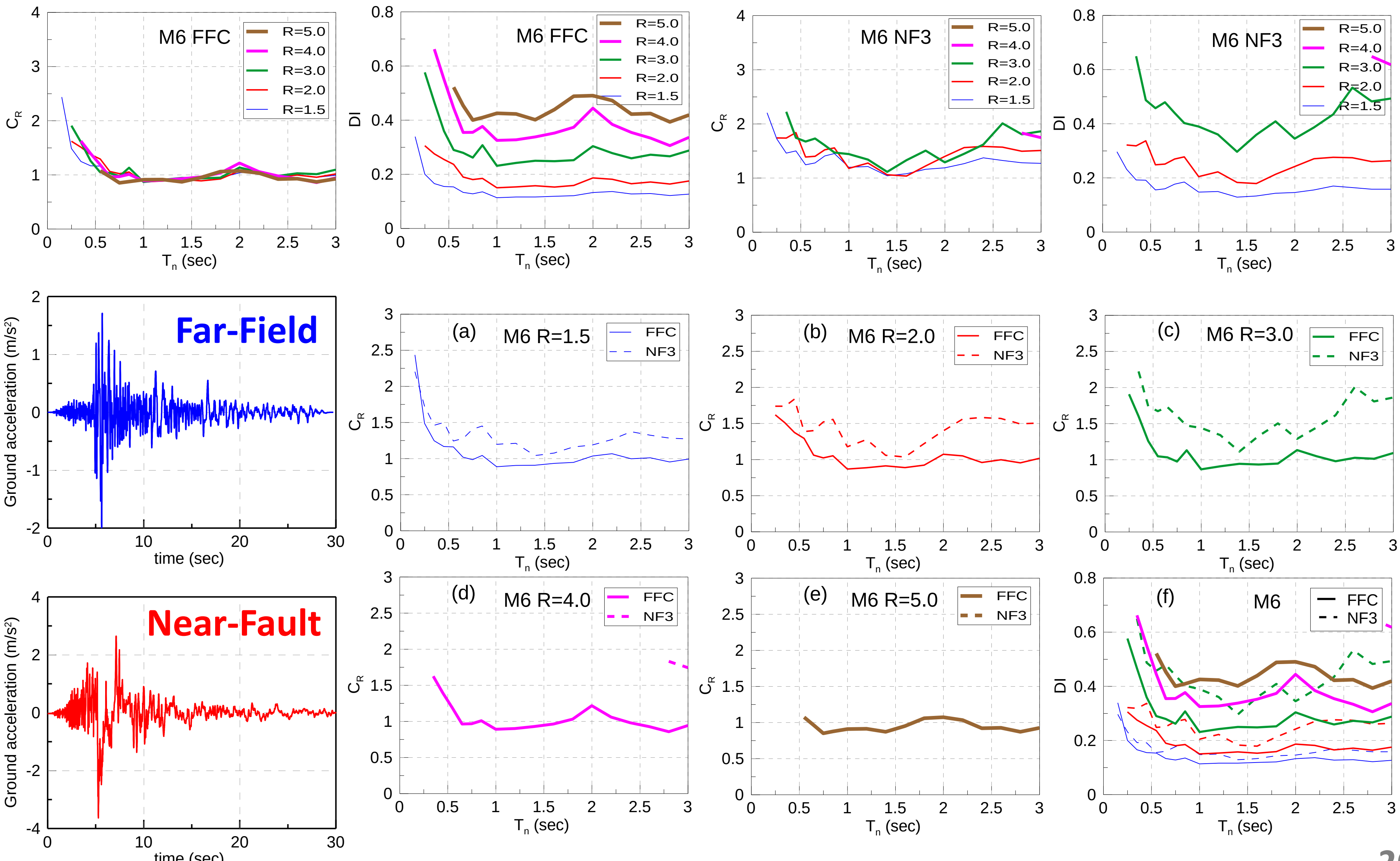


Proposed C_R and DI formulae

Far-field ground motions

$$C_R = \begin{cases} \left(1-\frac{1}{R}\right)\frac{T_1^*}{T_n}+\frac{1}{R} \geq C_{R\_min}, & T_n \leq T_1^* \\ C_{R\_min}, & T_1^* < T_n \leq 3.0s \end{cases}$$

$$T_1^* = \begin{cases} 1.25T_s & (Site\ Class\ C) \\ 1.45T_s & (Site\ Class\ D) \end{cases}$$

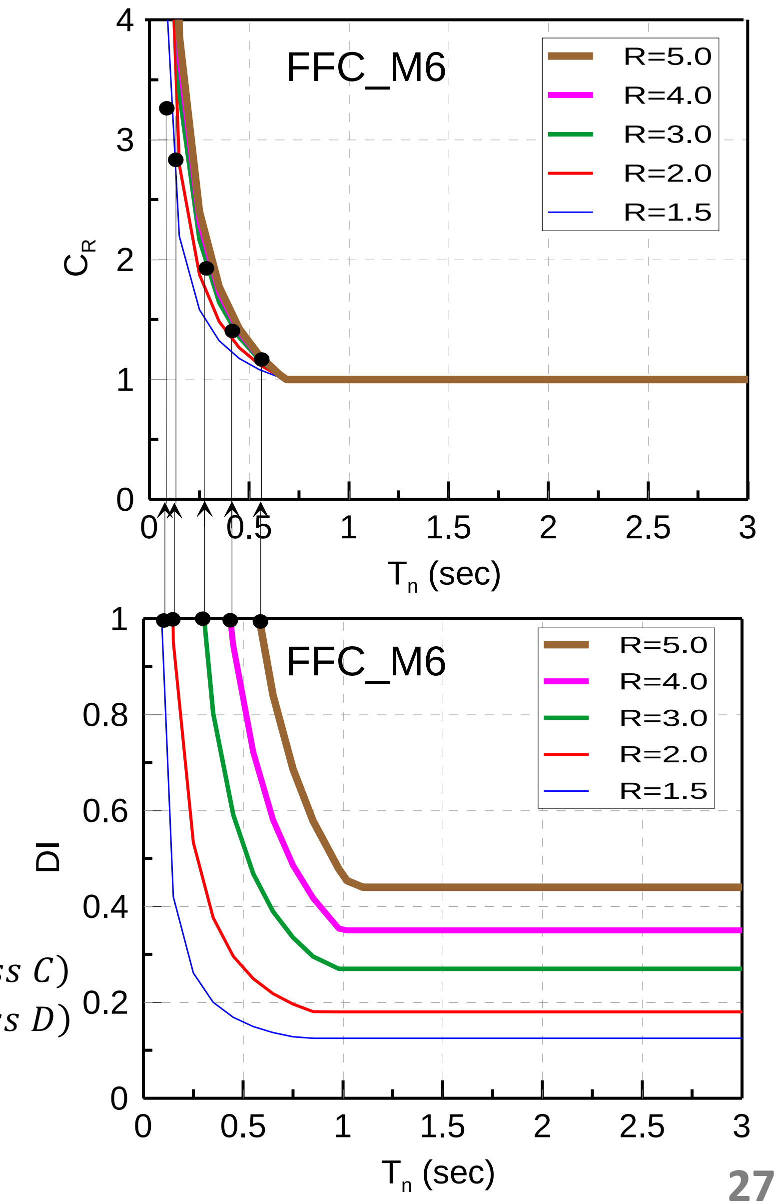
$$C_{R\_min} = \begin{cases} 1.0 & (Site\ Class\ C) \\ 1.1 & (Site\ Class\ D) \end{cases}$$

$$DI = \begin{cases} \left(C_{DI}-\frac{C_{DI}}{R}\right)\left(\frac{T_2^*}{T_n}\right)^n+\frac{C_{DI}}{R}, & T_n \leq T_2^* \\ C_{DI}, & T_2^* < T_n \leq 3.0s \end{cases}$$

$$T_2^* = \{0.37\,ln(R)+1.3\}T_s$$

$$C_{DI} = \begin{cases} \{0.065-0.010\,ln(AD)+0.017LR-0.013\,ln(TR)\}R & (Site\ Class\ C) \\ \{0.077-0.006\,ln(AD)+0.015LR-0.017\,ln(TR)\}R & (Site\ Class\ D) \end{cases}$$

$$n = 0.1R+1.1$$



Proposed C_R and DI formulae

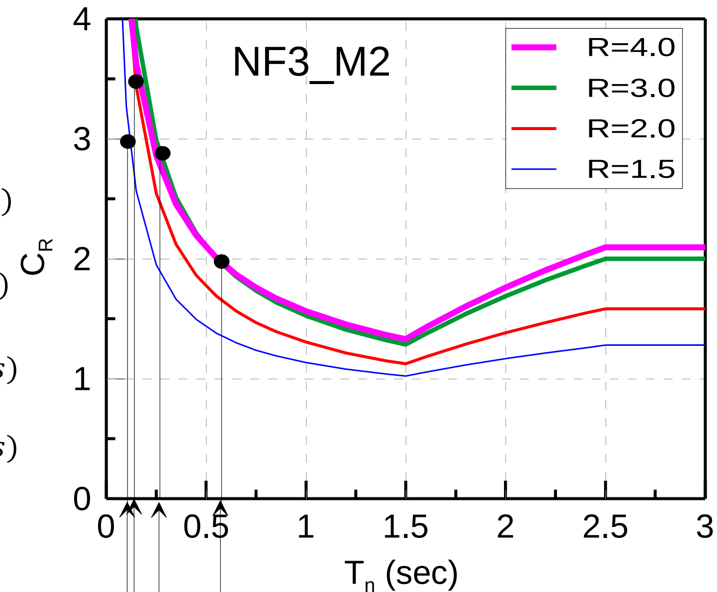
Near-fault ground motions

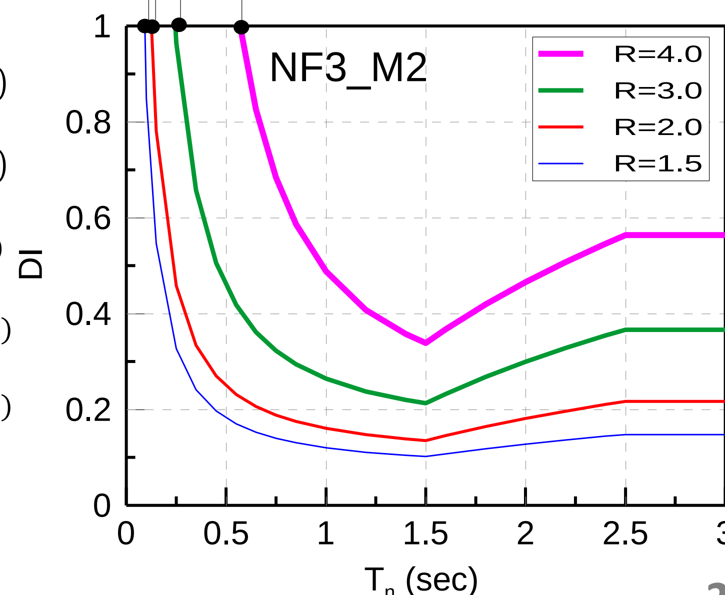
$$C_R = \begin{cases} \left(C_{BR} - \dfrac{C_{BR}}{R}\right)\left(\dfrac{T_1^*}{T_n}\right)^{n_1} + \dfrac{C_{BR}}{R} + \dfrac{\Delta_1}{3} T_n, & T_n \le 3.0s\ (T_p = 0.5 \sim 5.5s) \\ \left(C_{BR} - \dfrac{C_{BR}}{R}\right)\left(\dfrac{T_1^*}{T_n}\right)^{n_1} + \dfrac{C_{BR}}{R}, & T_n \le 1.5s\ (T_p = 5.5 \sim 10.5s) \\ \left(C_{BR} - \dfrac{C_{BR}}{R}\right)\left(\dfrac{T_1^*}{1.5}\right)^{n_1} + \dfrac{C_{BR}}{R} + k_1 \times ln\left(\dfrac{T_n}{1.5}\right), & 1.5s < T_n \le 2.5s\ (T_p = 5.5 \sim 10.5s) \\ \left(C_{BR} - \dfrac{C_{BR}}{R}\right)\left(\dfrac{T_1^*}{1.5}\right)^{n_1} + \dfrac{C_{BR}}{R} + k_1 \times ln\left(\dfrac{2.5}{1.5}\right), & 2.5s < T_n \le 3.0s\ (T_p = 5.5 \sim 10.5s) \end{cases}$$

$$C_{BR} = \begin{cases} 1 & (T_p = 0.5 \sim 2.5s) \\ -0.069R^2 + 0.473R + 0.546 & (T_p = 2.5 \sim 10.5s) \end{cases}$$

$$DI = \begin{cases} \left(C_{DI} - \dfrac{C_{DI}}{R}\right)\left(\dfrac{T_2^*}{T_n}\right)^{n_2} + \dfrac{C_{DI}}{R} + \dfrac{\Delta_2}{3} T_n, & T_n \le 3.0s\ (T_p = 0.5 \sim 2.5s) \\ \left(C_{DI} - \dfrac{C_{DI}}{1.5}\right)\left(\dfrac{T_2^*}{T_n}\right)^{n_2} + \dfrac{C_{DI}}{1.5} + \dfrac{\Delta_2}{3} T_n, & T_n \le 3.0s\ (T_p = 2.5 \sim 5.5s) \\ \left(C_{DI} - \dfrac{C_{DI}}{1.5}\right)\left(\dfrac{T_2^*}{T_n}\right)^{n_2} + \dfrac{C_{DI}}{1.5}, & T_n \le 1.5s\ (T_p = 5.5 \sim 10.5s) \\ \left(C_{DI} - \dfrac{C_{DI}}{1.5}\right)\left(\dfrac{T_2^*}{1.5}\right)^{n_2} + \dfrac{C_{DI}}{1.5} + k_2 \times ln\left(\dfrac{T_n}{1.5}\right), & 1.5s < T_n \le 2.5s\ (T_p = 5.5 \sim 10.5s) \\ \left(C_{DI} - \dfrac{C_{DI}}{1.5}\right)\left(\dfrac{T_2^*}{1.5}\right)^{n_2} + \dfrac{C_{DI}}{1.5} + k_2 \times ln\left(\dfrac{2.5}{1.5}\right), & 2.5s < T_n \le 3.0s\ (T_p = 5.5 \sim 10.5s) \end{cases}$$

$$C_{DI} = \begin{cases} \{0.056 - 0.010\ ln(AD) + 0.028LR - 0.029\ ln(TR)\}R & (T_p = 0.5 \sim 2.5s) \\ \{0.075 - 0.009\ ln(AD) + 0.021LR - 0.027\ ln(TR)\}R & (T_p = 2.5 \sim 10.5s) \end{cases}$$





Application to Performance-Based Seismic Design

1. Preliminary bridge design
Determine preliminarily the main design parameters of bridge (T_n, AD, LR, TR) to construct the C_R and DI spectra

2. Performance objective
Define the anticipated damage state and the corresponding damage index under design earthquake

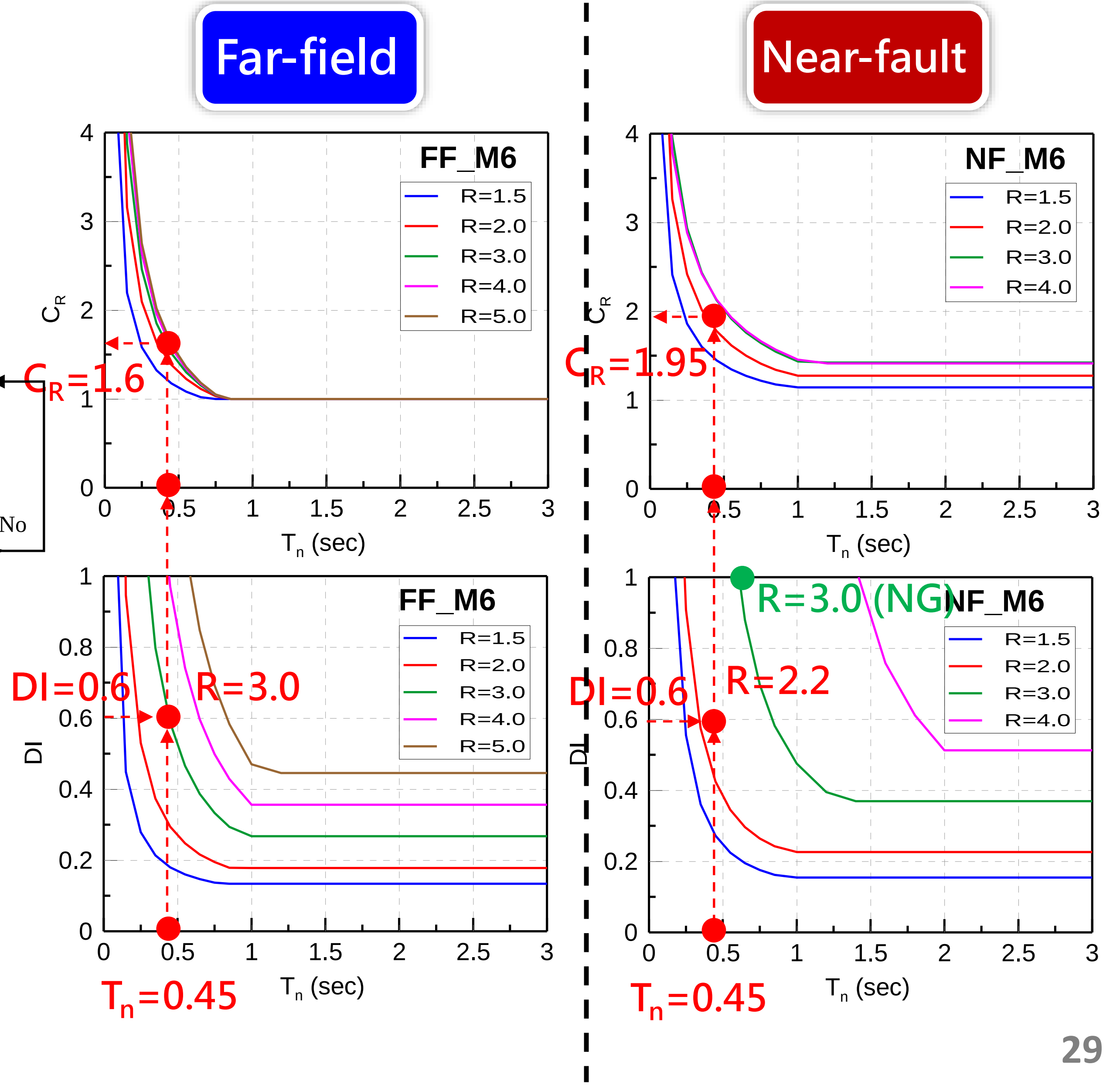
3. Strength reduction factor
Obtain the strength reduction factor from the DI spectrum and perform the detailed bridge design

4. Check
If the updated R based on the detailed design is within the tolerance compared to the previous R

No → 3. Strength reduction factor

Yes → 5. Expected displacement demand

5. Expected displacement demand
Obtain the inelastic displacement ratio from the C_R spectrum, check P-Δ effects, and perform capacity design

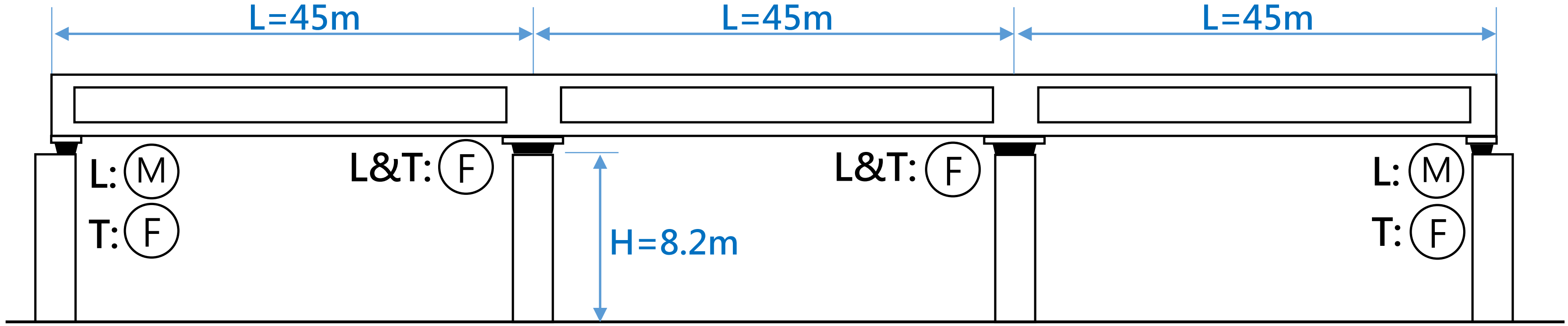


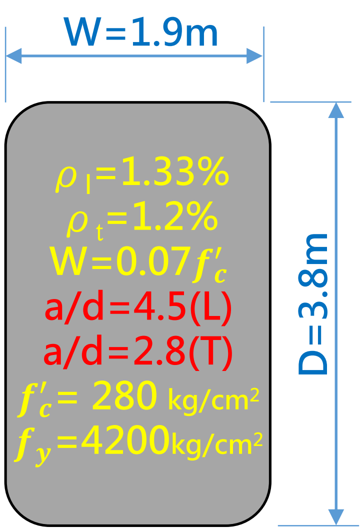
Outline

1) Background and Objective
2) Smooth Hysteretic Model
3) Capacity-Based Inelastic Displacement Spectrum
4) Demonstrative Example Bridge
5) Conclusion

Example Bridge

- **Three-span prestressed reinforced concrete box girder bridge with regular configuration**

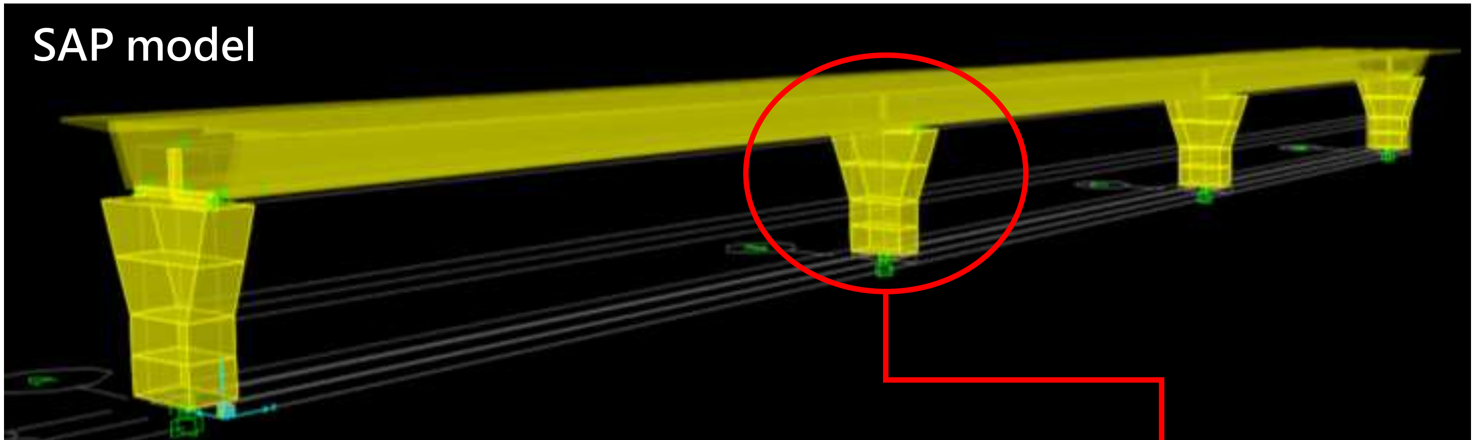


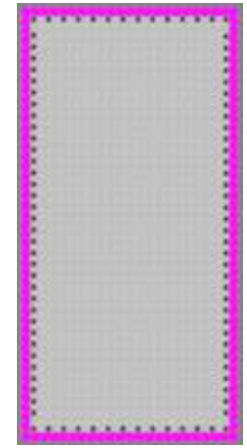


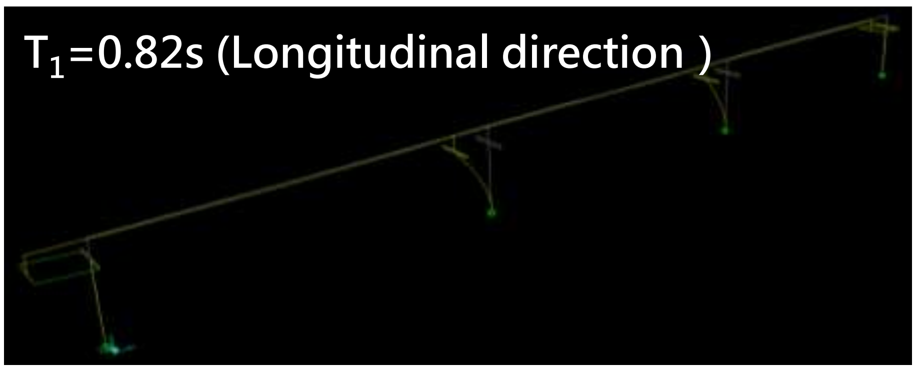
Column Section

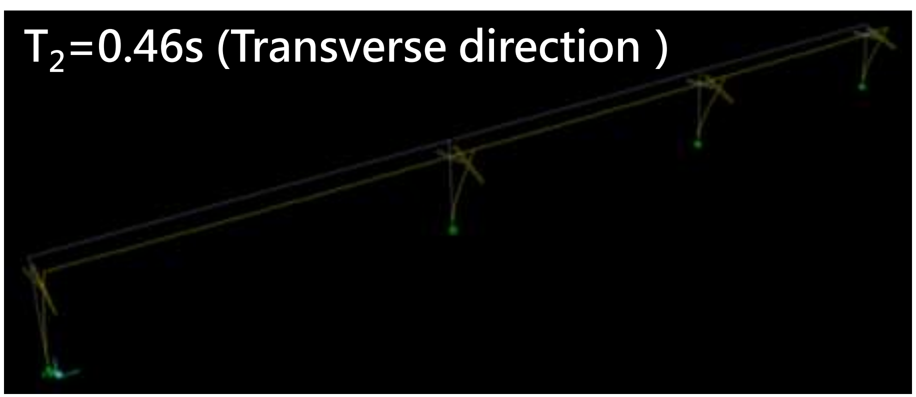
- Three analytical models, two MDOF models and one SDOF model, are used to demonstrate the proposed capacity-based spectra by using nonlinear time history analysis.

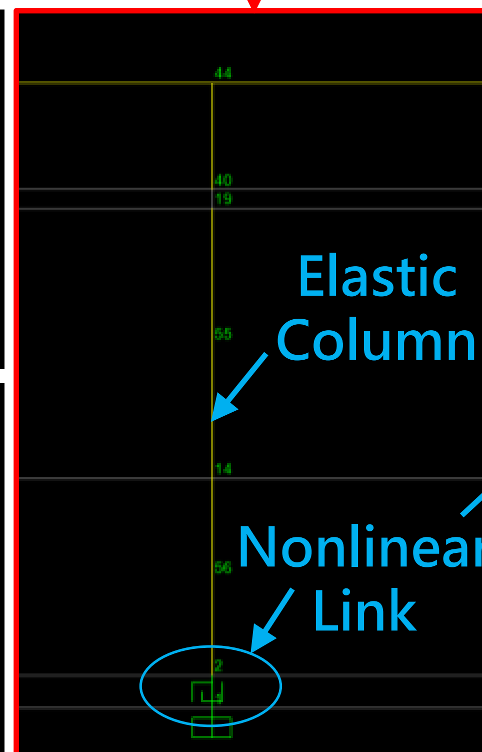
SAP Model











Takeda hysteretic model

OpenSees Model

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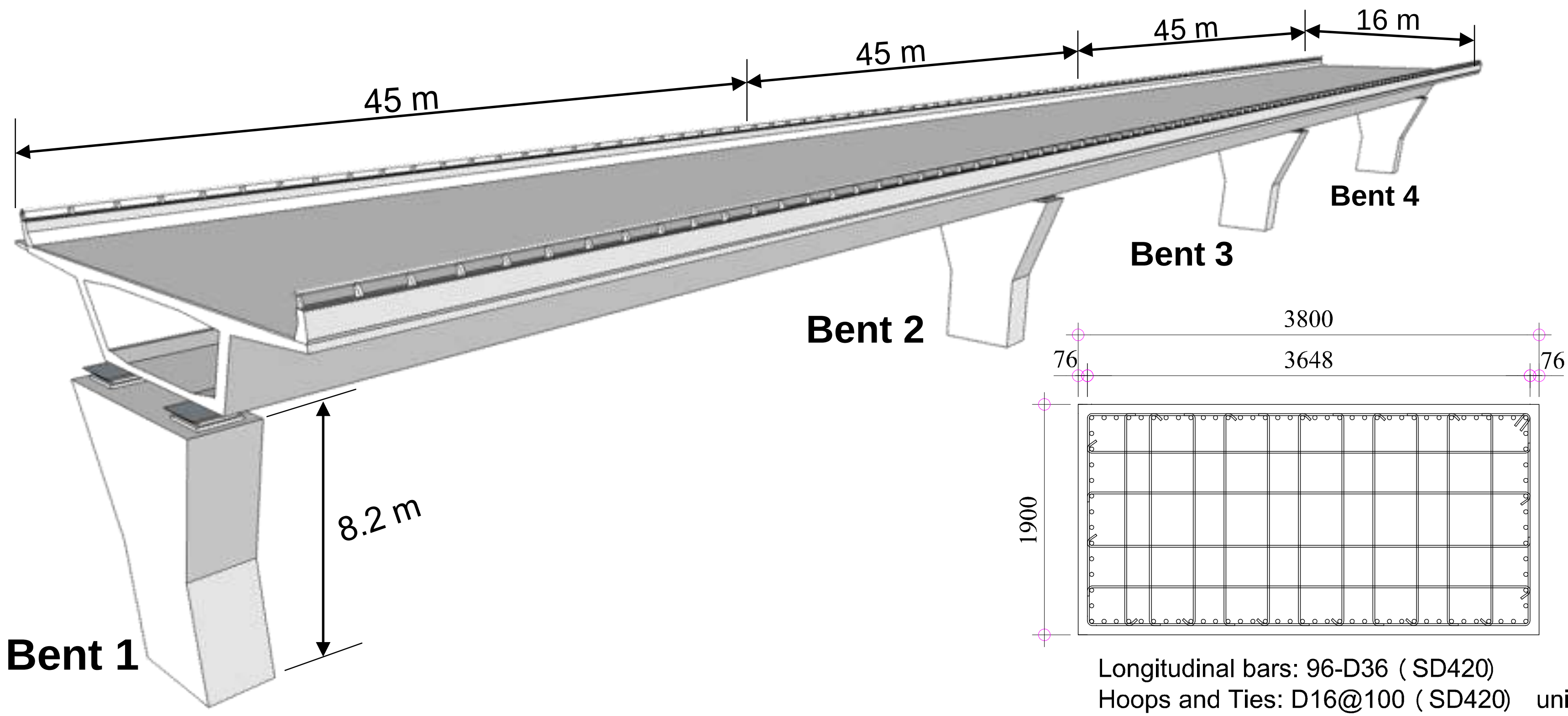
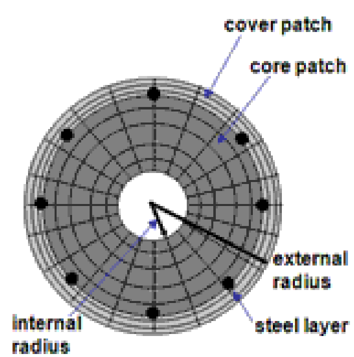
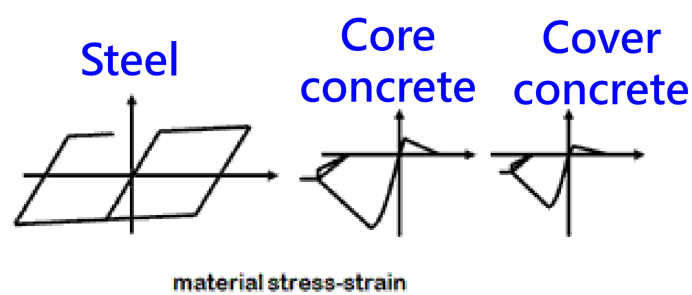


Longitudinal bars: 96-D36 (SD420)
Hoops and Ties: D16@100 (SD420) unit: mm

- Column: force-based fiber section beam-column element
- Box Girder: elastic beam-column element





Material hysteresis models

Normalized Records

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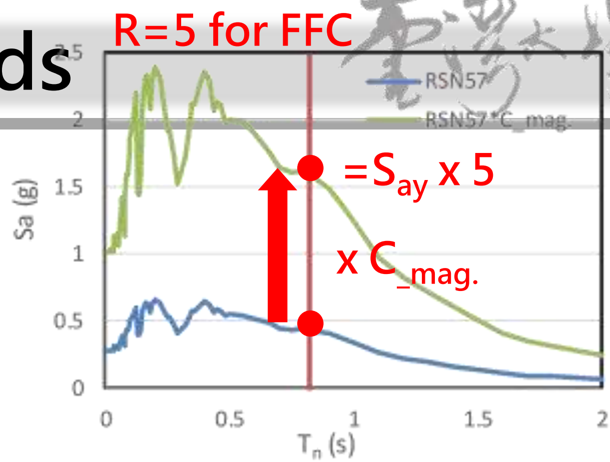
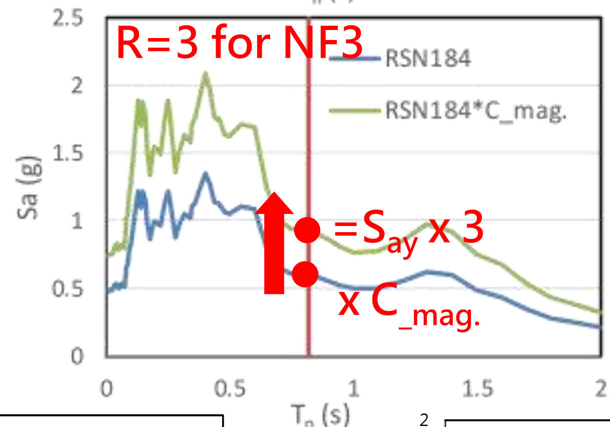
FFC

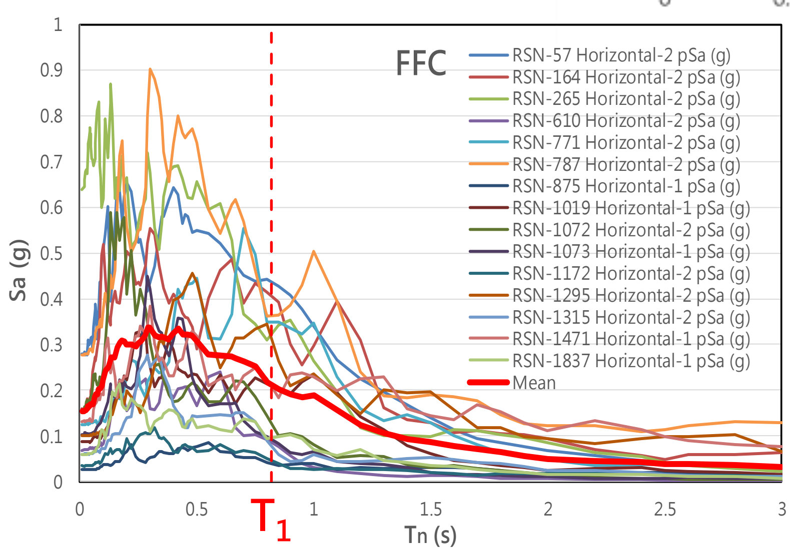
No	RSN	C_mag.
FFC01	57	3.5267
FFC02	164	3.7323
FFC03	265	2.958
FFC04	610	18.1624
FFC05	771	4.4509
FFC06	787	4.5567
FFC07	875	37.5493
FFC08	1019	7.171
FFC09	1072	12.616
FFC10	1073	16.8386
FFC11	1172	33.2767
FFC12	1295	6.7381
FFC13	1315	36.2499
FFC14	1471	7.4646
FFC15	1837	16.9387

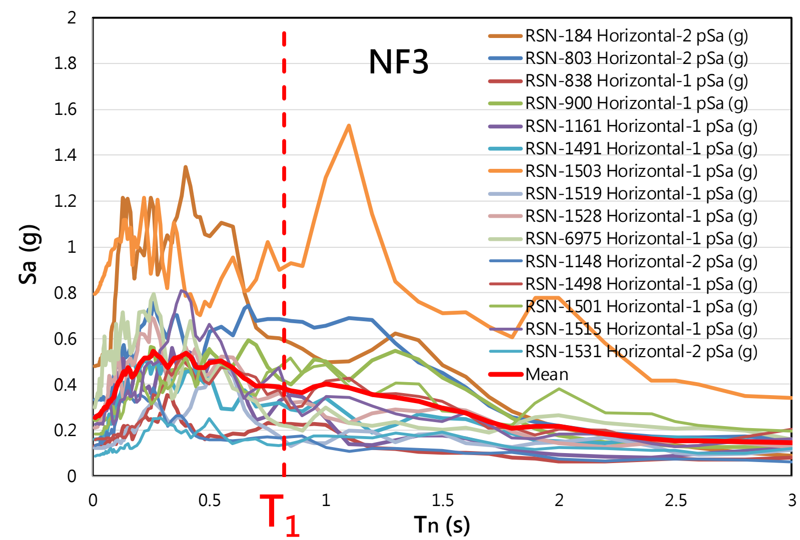


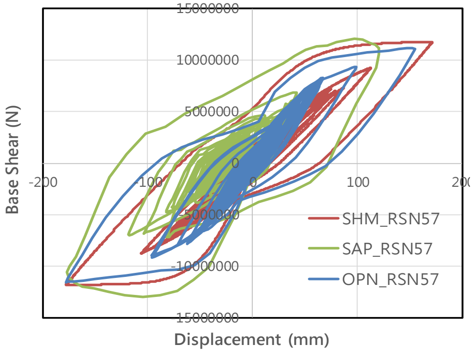


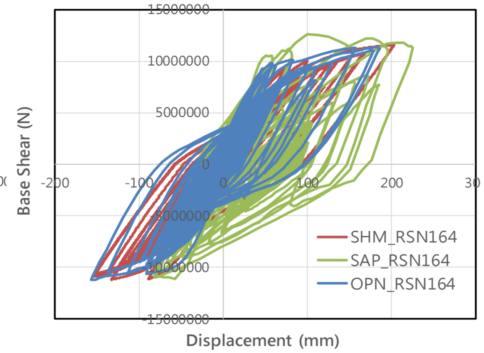
No	RSN	C_mag.
NF301	184	1.5484
NF302	803	1.3578
NF303	838	4.0362
NF304	900	2.18
NF305	1148	5.3754
NF306	1161	2.7892
NF307	1491	2.8673
NF308	1498	2.6265
NF309	1501	1.8328
NF310	1503	1.0018
NF311	1515	2.141
NF312	1519	6.1537
NF313	1528	2.5655
NF314	1531	6.7076
NF315	6975	4.3822

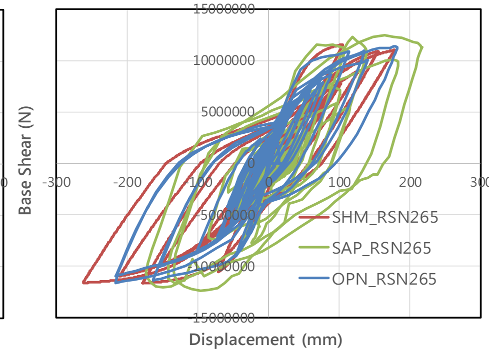
NF3

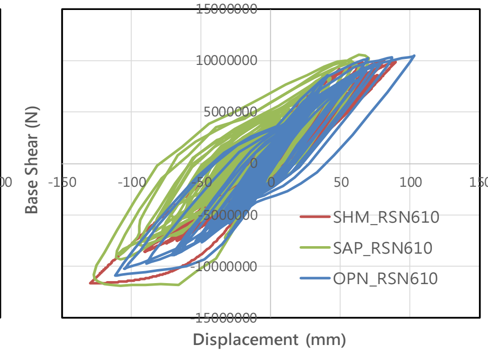


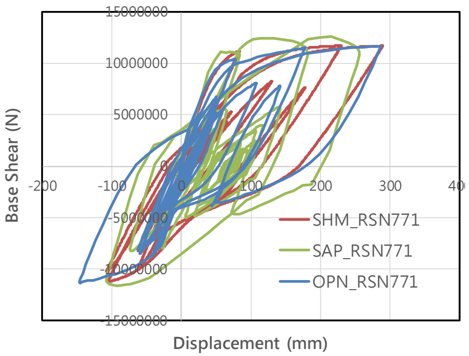


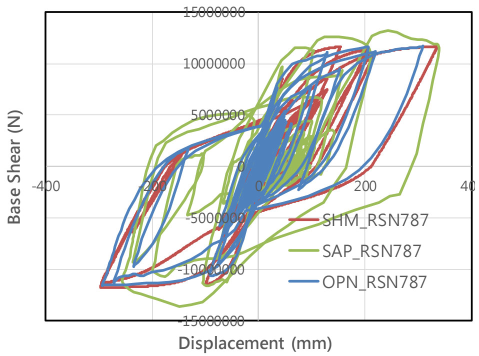


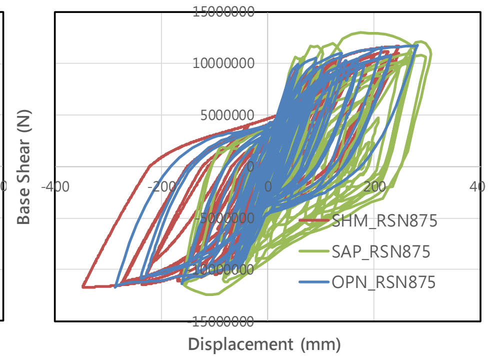


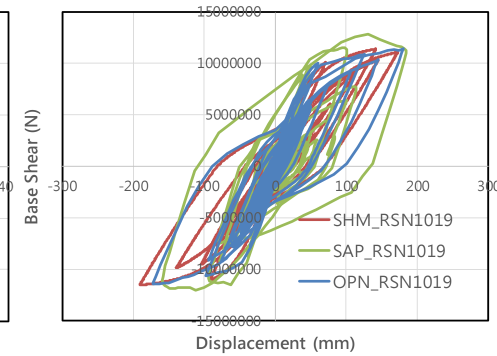


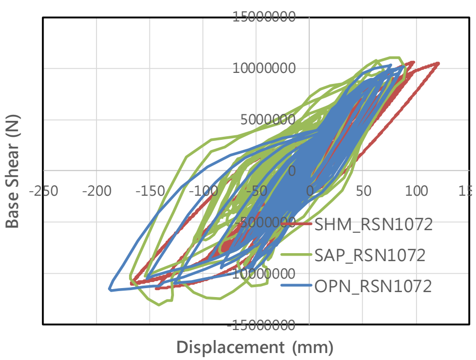


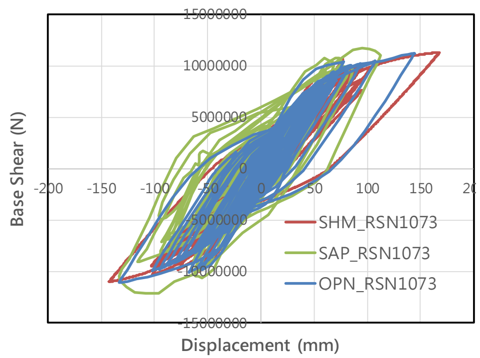


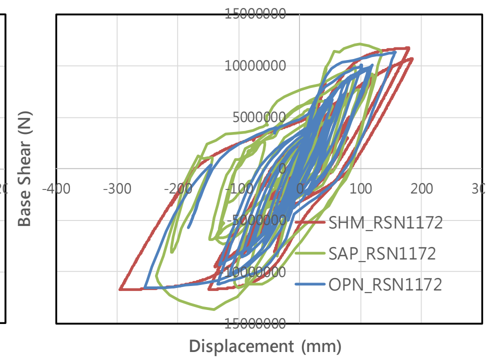


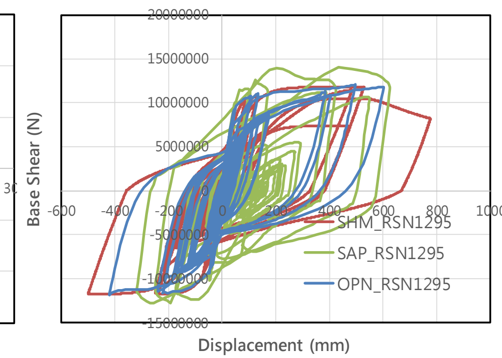


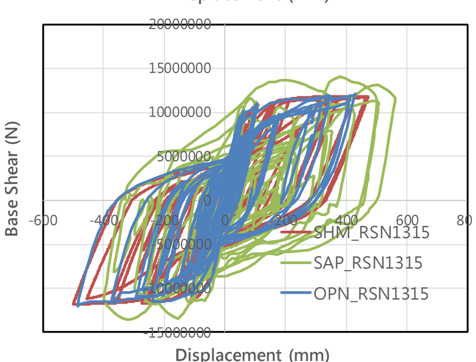


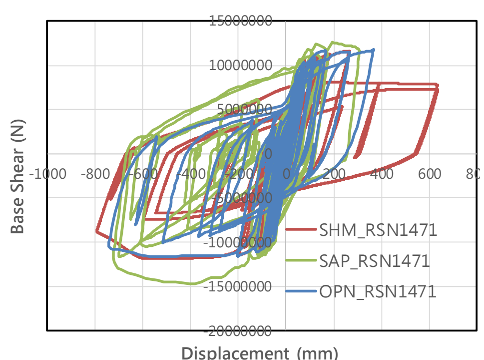


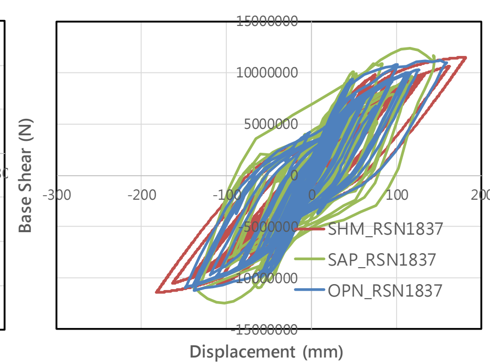




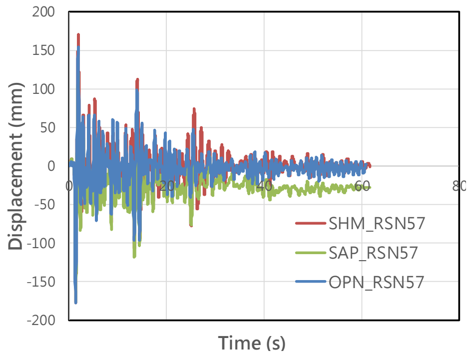


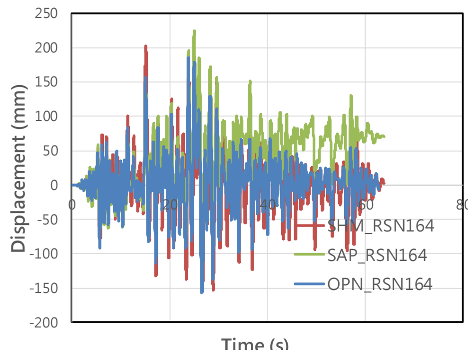


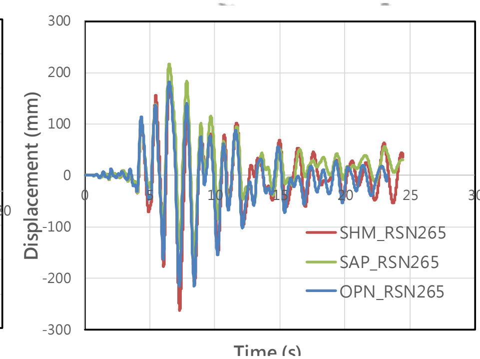


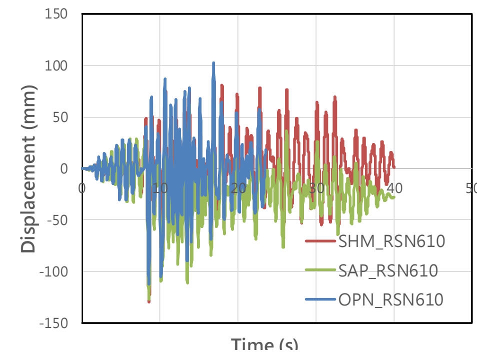


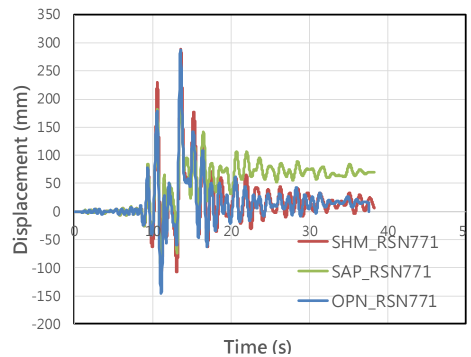
Comparisons of Hysteresis Loops (FFC)

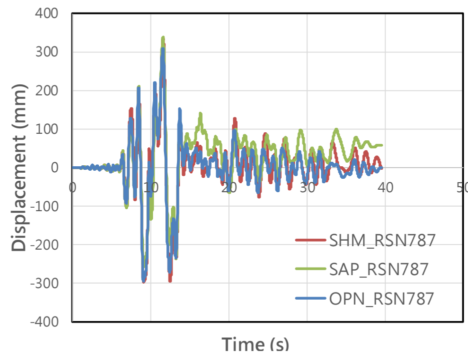


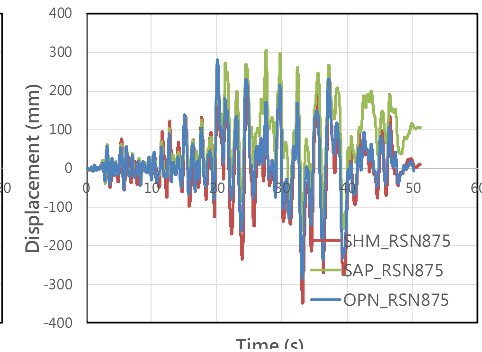


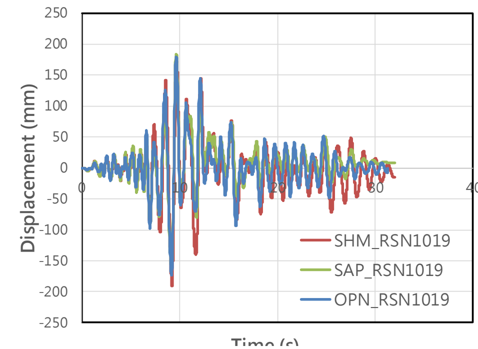


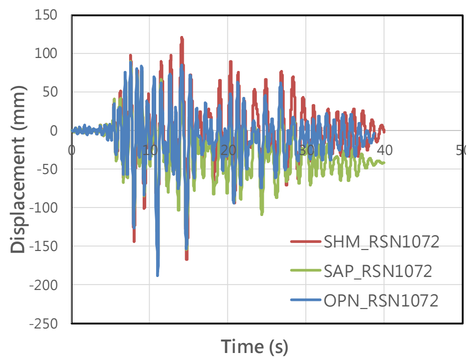


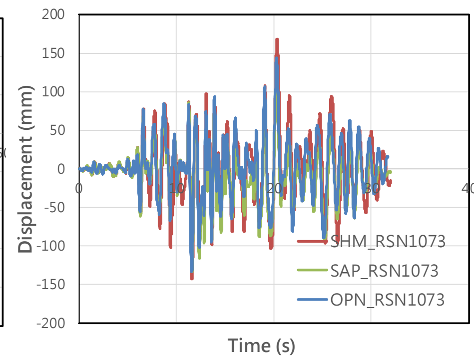


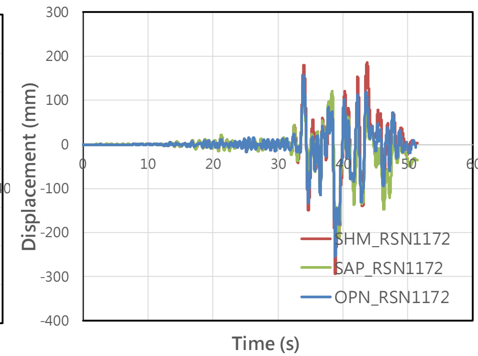


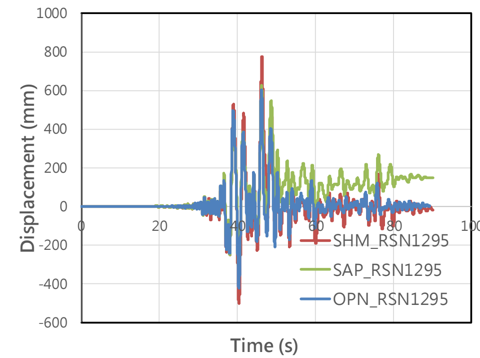


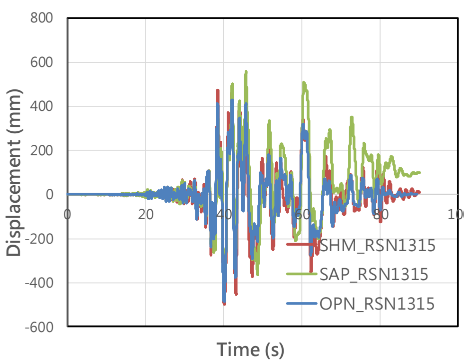


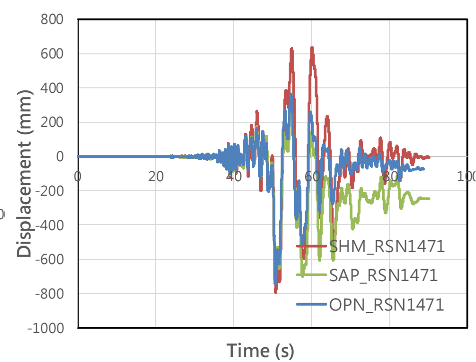


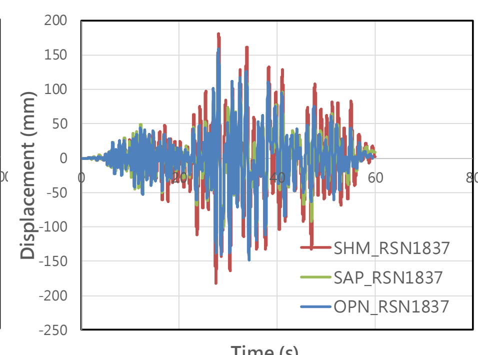












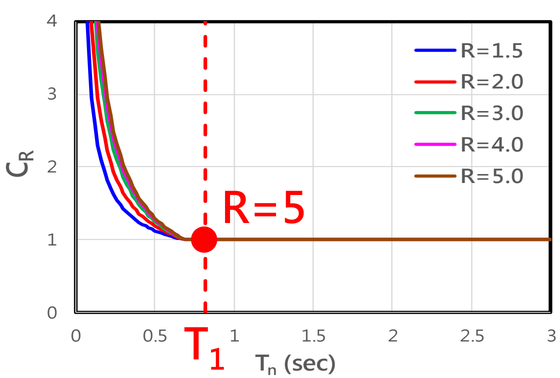
Comparisons of Displacement Histories (FFC)

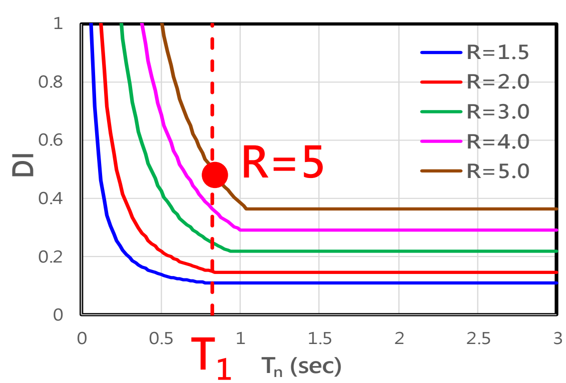
Comparisons of analytical results (FFC)

Department of Civil Engineering
National Taiwan University

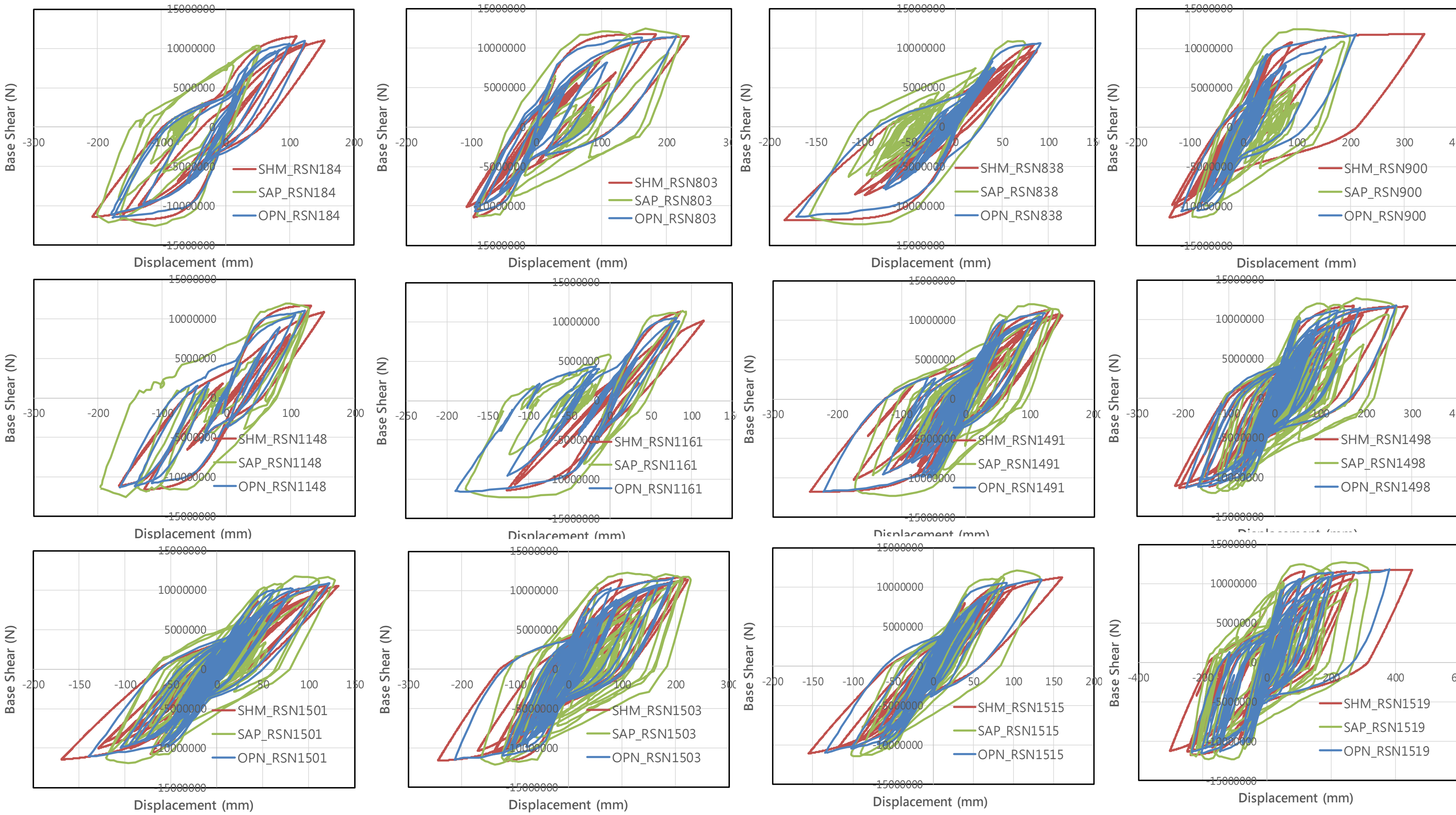
SHM		
RSN	Δ i/Δe	DI
57	0.69283	0.2574
164	0.79118	0.3782
265	1.02119	0.4114
610	0.5065	0.1852
771	1.12781	0.4072
787	1.30906	0.5422
875	1.35626	0.7213
1019	0.74338	0.2886
1072	0.6529	0.2607
1073	0.65488	0.2651
1172	1.14795	0.4396
1295	3.02506	**1.3811**
1315	1.94705	1.1147
1471	3.09163	**1.462**
1837	0.71133	0.3452
AVG=	**0.97402**	**0.4321**
Formula=	**1**	**0.5001**

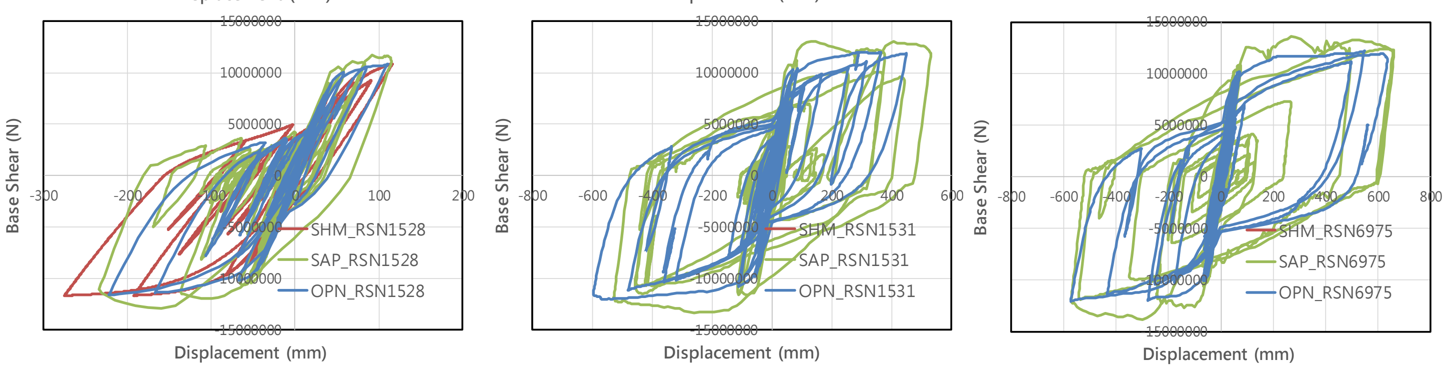
FFC	**SHM**			**OPN**			**SAP**		
RSN	**D_{max}(mm)**	**D_{min}(mm)**	**Δ_i(mm)**	**D_{max}(mm)**	**D_{min}(mm)**	**Δ_i(mm)**	**D_{max}(mm)**	**D_{min}(mm)**	**Δ_i(mm)**
57	171.26	-177.86	177.86	155.01	-177.99	177.99	120.64	-176.81	176.81
164	203.11	-153.95	203.11	185.76	-156.72	185.76	225.23	-81.75	225.23
265	178.14	-262.16	262.16	181.65	-216.49	216.49	216.87	-173.2	216.87
610	89.519	-130.03	130.03	102.59	-112.09	112.09	70.26	-127.43	127.43
771	289.53	-107.88	289.53	287.04	-146.27	287.04	256.08	-107.85	256.08
787	336.06	-297.7	336.06	308.58	-293.77	308.58	339.35	-256.66	339.35
875	246.56	-348.17	348.17	280.68	-287.56	287.56	306	-160.78	306
1019	172.27	-190.84	190.84	180.29	-172.59	180.29	184.08	-159.06	184.08
1072	121.24	-167.61	167.61	88.358	-188.07	188.07	89.73	-167.91	167.91
1073	168.12	-142.63	168.12	144.18	-133.34	144.18	112.12	-133.46	133.46
1172	185.36	-294.7	294.7	157.04	-254.78	254.78	134.58	-234.81	234.81
1295	776.58	-500.05	776.58	603.27	-420.72	603.27	625.26	-317.88	625.26
1315	472.71	-499.84	499.84	429.08	-485.71	485.71	560.27	-398.74	560.27
1471	636.65	-793.67	793.67	365.98	-743.57	743.57	307.61	-724.33	724.33
1837	181.46	-182.61	182.61	158.63	-148.39	158.63	144.6	-138.26	144.6
AVG(mm)=	**216.56**	**-227.38**	**250.05**	**204.53**	**-213.37**	**229.78**	**212.29**	**-178.21**	**236.38**
Error(%)=	**0.0**	**0.0**	**0.0**	**-5.9**	**-6.6**	**-8.8**	**-2.0**	**-27.6**	**-5.8**



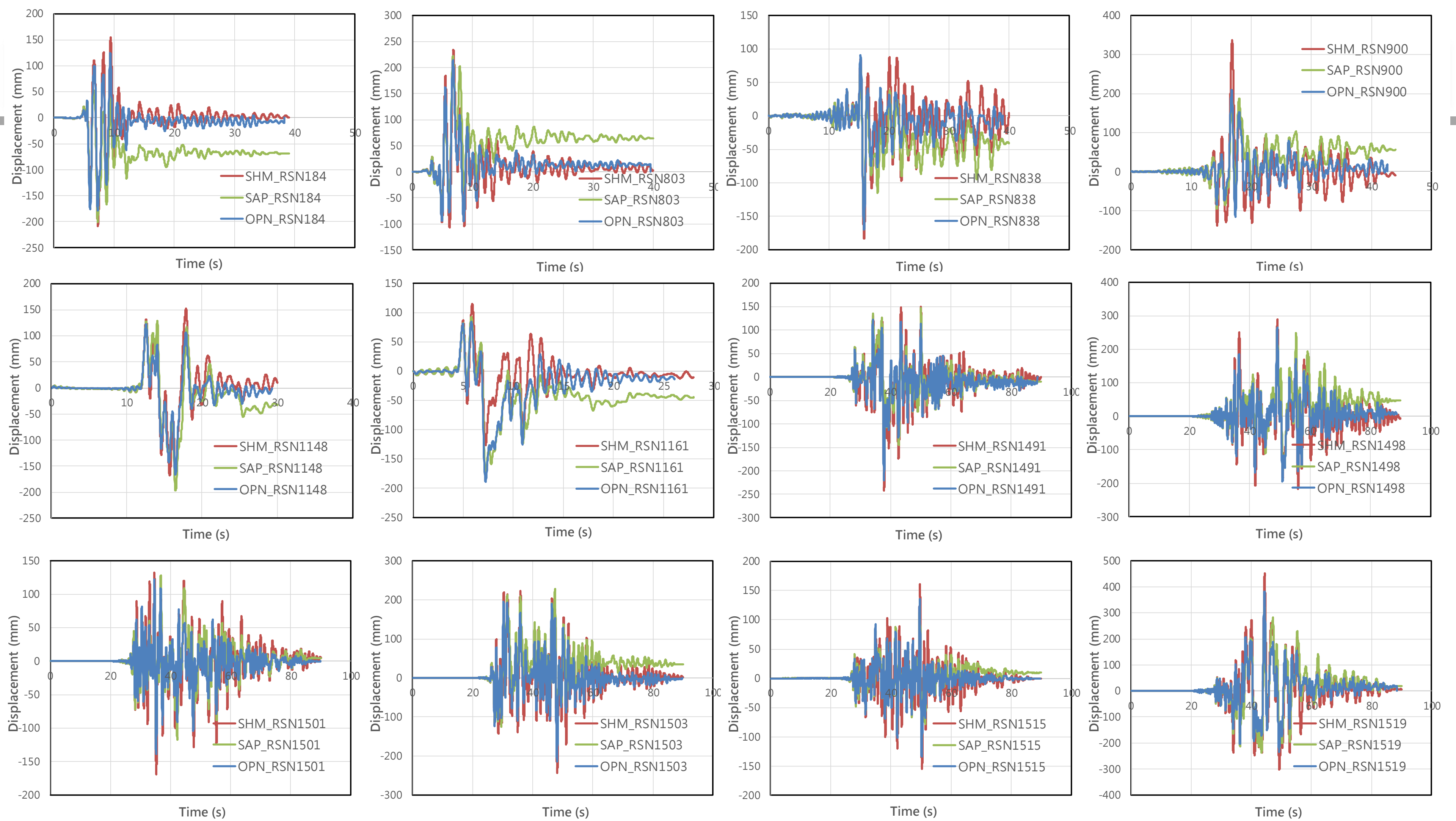


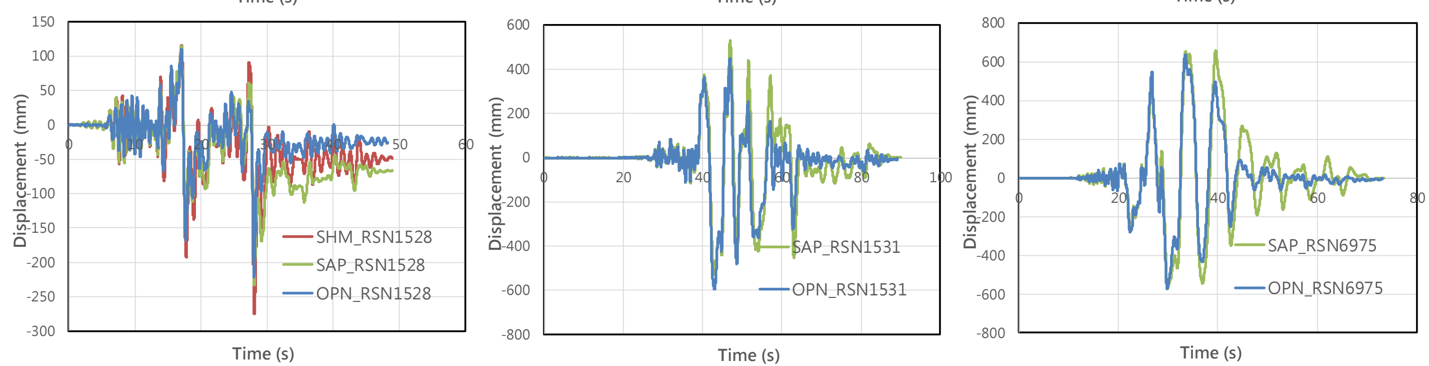
- It was suggested that the calculated maximum inelastic displacements from OpenSees and SAP models be magnified by 7% and 12%, respectively, for far-field ground motions recorded on site class C.





Comparisons of Hysteresis Loops (NF3)



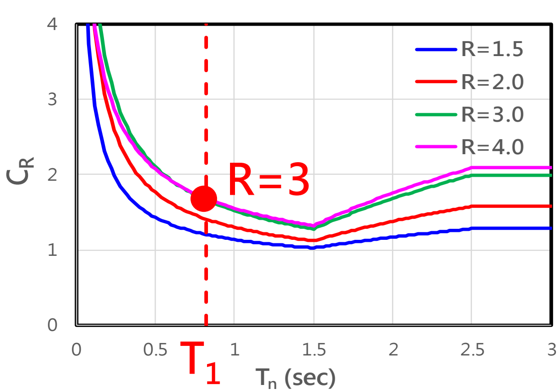


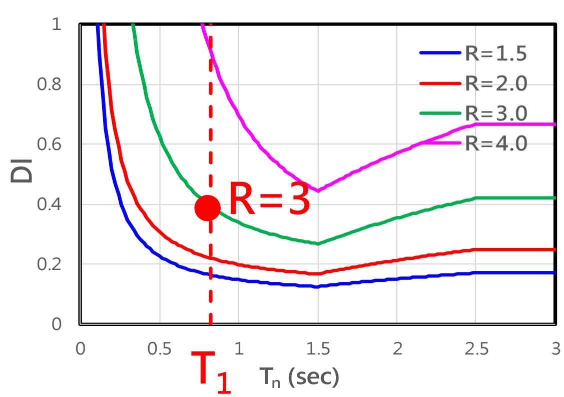
Comparisons of Displacement Histories (NF3)

Comparisons of analytical results (NF3)

SHM		
RSN	Δ i/Δ e	DI
184	1.35159	0.3042
803	1.52162	0.3299
838	1.19307	0.2481
900	2.18887	0.4775
1148	1.08796	0.2316
1161	0.81952	0.1645
1491	1.5733	0.3663
1498	1.88205	0.5315
1501	1.09892	0.2584
1503	1.58819	0.4731
1515	1.04437	0.2413
1519	2.93393	0.8116
1528	1.78522	0.3782
1531	NG	NG
6975	NG	NG
AVG=	1.54374	0.3705
Formula=	1.66141	0.3939

NF3	SHM			OPN			SAP		
RSN	D_{max}(mm)	D_{min}(mm)	Δ_i(mm)	D_{max}(mm)	D_{min}(mm)	Δ_i(mm)	D_{max}(mm)	D_{min}(mm)	Δ_i(mm)
184	154.8	-208.2	208.2	124.2	-178.4	178.4	54.2	-200.5	200.5
803	234.4	-107.4	234.4	215.2	-94.7	215.2	222.7	-90.8	222.7
838	87.5	-183.8	183.8	91.4	-170.9	170.9	74.6	-156.9	156.9
900	337.1	-138.0	337.1	209.9	-115.1	209.9	199.2	-95.3	199.2
1148	151.9	-167.6	167.6	122.0	-166.0	166.0	128.6	-196.8	196.8
1161	114.9	-126.2	126.2	84.9	-189.2	189.2	93.4	-176.8	176.8
1491	150.3	-242.3	242.3	123.0	-221.0	221.0	146.4	-172.3	172.3
1498	289.9	-217.2	289.9	265.4	-193.7	265.4	265.9	-161.7	265.9
1501	132.1	-169.3	169.3	122.7	-139.4	139.4	128.3	-120.5	128.3
1503	223.5	-244.6	244.6	195.9	-213.8	213.8	228.4	-163.4	228.4
1515	160.9	-155.0	160.9	135.4	-134.2	135.4	133.8	-102.4	133.8
1519	451.9	-301.6	451.9	382.5	-234.3	382.5	321.8	-237.2	321.8
1528	116.2	-275.0	275.0	110.5	-221.9	221.9	114.8	-233.6	233.6
1531	NG	NG	NG	449.7	-597.6	597.6	530.6	-528.8	530.6
6975	NG	NG	NG	634.8	-573.2	634.8	661.2	-572.4	661.2
AVG(mm)=	**200.4**	**-195.1**	**237.8**	**167.9**	**-174.8**	**208.4**	**162.5**	**-162.1**	**202.8**
Error(%)=	**0.0**	**0.0**	**0.0**	**-19.3**	**-11.6**	**-14.1**	**-23.4**	**-20.3**	**-17.2**





- It was suggested that the calculated maximum inelastic displacements from OpenSees and SAP models be magnified by 15% and 20%, respectively, for near-fault ground motions with pulse-periods ranging from 5.5s to 10.5s.

Evaluation of C_R (or R_d) Formulae

Guide Specification for LRFD Seismic Bridge Design, AASHTO, 2011

$$R_d = \left(1 - \frac{1}{\mu_D}\right)\frac{T^*}{T} + \frac{1}{\mu_D} \quad \text{for } T < T^*$$

$$= 1.0 \quad \text{for } T \geq T^*$$

$T^* = 1.25T_s = 1.25F_vS_1/F_aS_s$

μ_D = maximum local member disp. ductility demand

= 6 in lieu of a detailed analysis for SDC D

SHM (FFC)		
RSN	Δ i/Δ e	DI
57	0.69	0.26
164	0.79	0.38
265	1.02	0.41
610	0.51	0.19
771	1.13	0.41
787	1.31	0.54
875	1.36	0.72
1019	0.74	0.29
1072	0.65	0.26
1073	0.65	0.27
1172	1.15	0.44
1295	3.03	**1.38**
1315	1.95	1.11
1471	3.09	**1.46**
1837	0.71	0.35
Calculated AVG.=	**0.97**	**0.43**
Capacity-Based Spectra=	**1.00**	**0.50**
AASHTO R_d Formula=	**1.00**	**—**

SHM (NF3)		
RSN	Δ i/Δ e	DI
184	1.35	0.30
803	1.52	0.33
838	1.19	0.25
900	2.19	0.48
1148	1.09	0.23
1161	0.82	0.16
1491	1.57	0.37
1498	1.88	0.53
1501	1.10	0.26
1503	1.59	0.47
1515	1.04	0.24
1519	2.93	0.81
1528	1.79	0.38
1531	NG	NG
6975	NG	NG
Calculated AVG.=	**1.54**	**0.37**
Capacity-Based Spectra=	**1.66**	**0.39**
AASHTO R_d Formula=	**1.00**	**—**

Outline

1) Background and Objective
2) Smooth Hysteretic Model
3) Capacity-Based Inelastic Displacement Spectrum
4) Demonstrative Example Bridge
5) Conclusion

Conclusion

① It is demonstrated that the Park and Ang’s damage index (DI) can be a good indicator for assessing the actual visible damage condition of column regardless of its loading history, providing a better insight into the seismic performance of bridges.

② Capacity-based inelastic displacement spectra that comprise an inelastic displacement ratio (C_R) spectrum and the corresponding damage index (DI) spectrum are proposed in this study.

③ The computed spectra show that the inelastic response of a structural system increases as the pulse period (T_P) of a near-fault ground motion increases.

④ It is demonstrated by an example bridge that the proposed spectral formula can predict well the inelastic displacement and the corresponding damage index of the bridge, and both the SAP and OpenSees models could underestimate the inelastic responses of the bridge.

Future Work

① To complete the damage index database of RC bridge columns including a wide range of practical design scenarios.

② To verify the proposed smooth hysteresis model and capacity-based inelastic displacement spectra via experimental efforts conducted by the new shaking table of NCREE Tainan Lab. specific for near-fault characteristics.

③ To carry out a design example of RC bridge using the damage index as its seismic performance objective.


HOKKAIDO
SEAFOOD BUFFET

Thank You for Your Attention

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