Study on Performance of Steel Moment-Resisting Frames Subjected to Multiple Earthquakes

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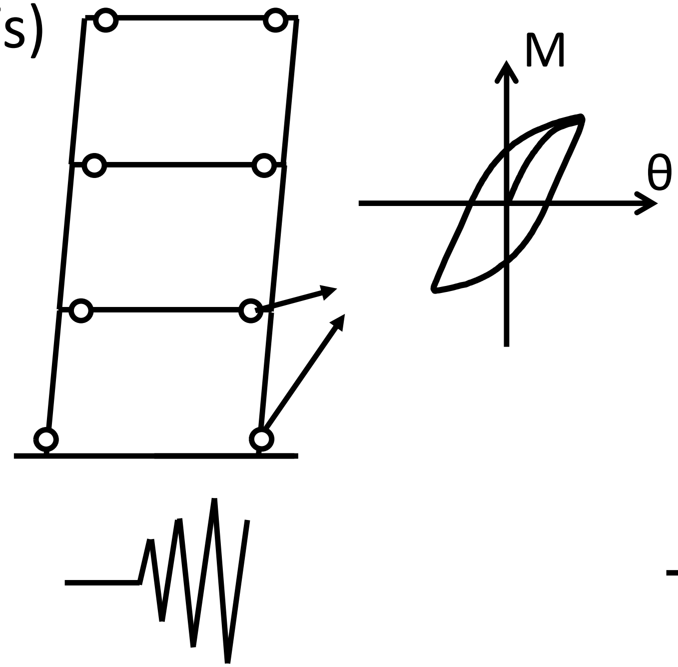
SATURDAY, 25 SEPT 2021 • 9 AM

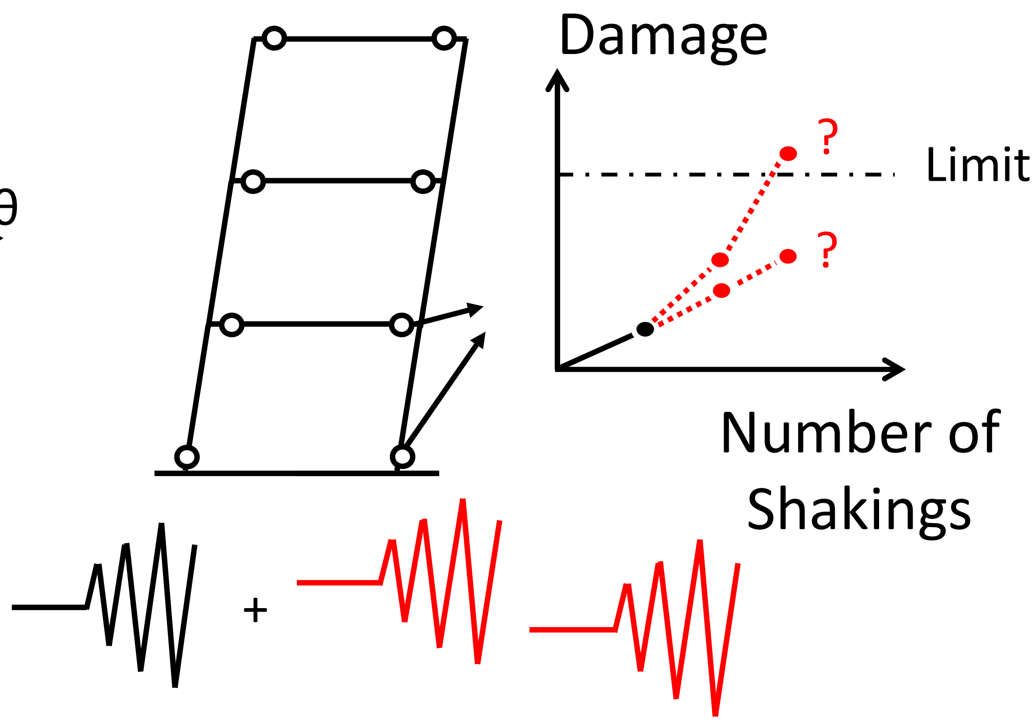
Introduction

Steel Moment Resisting Frames
(SMRFs)



Main shock

Could be guaranteed safe by
following seismic design code



Multiple Strong Shocks

Seismic Performance??

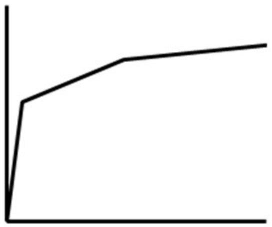
Research Objectives & Contents

Comprehensively evaluate the actual seismic performance (behavior, damage accumulation, collapse fragility) of SMRFs under multiple earthquakes

Ch. 1 Introduction

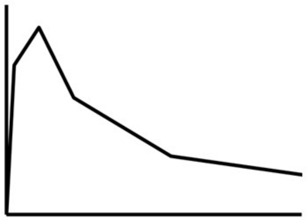
Ch. 2 Response Analysis of Nondeteriorated Models

Purpose: To evaluate the seismic performance of SMRFs under multiple earthquakes focusing on the ductile fracture failure of beam-to-column connection



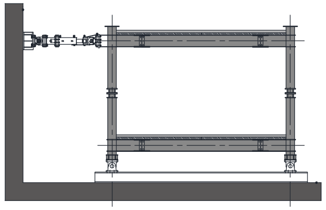
Ch. 3 Response Analysis of Deteriorated Models

Purpose: To evaluate the seismic performance of SMRFs under multiple earthquakes considering the strength deterioration caused by local buckling of columns



Ch. 4 Full-Scale Steel Frame Test

Purpose: To further verify the seismic performance of SMRFs under multiple earthquakes through the experimental test



Ch. 5 Conclusions

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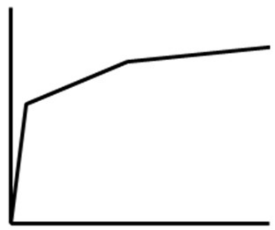

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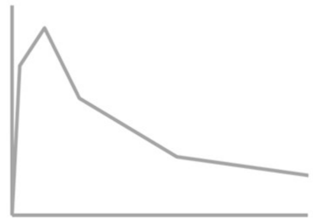

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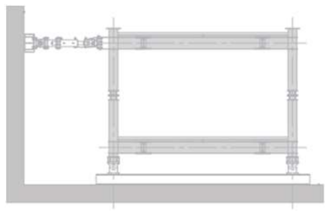
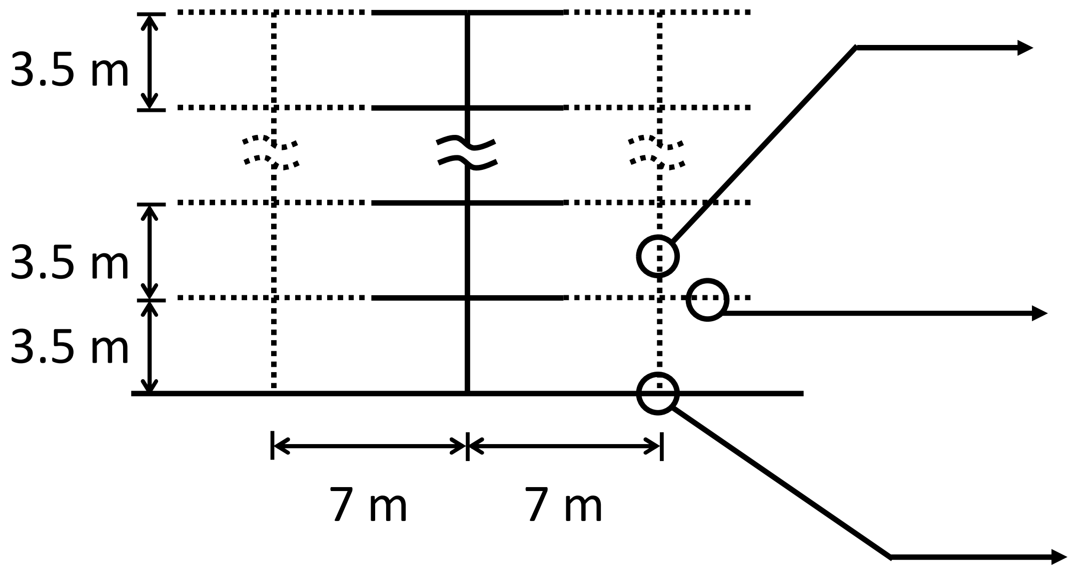
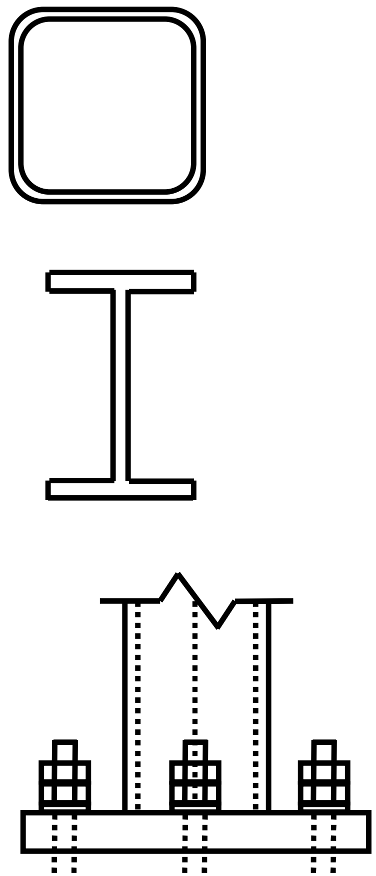


Ch. 5 Conclusions

Analytical Model

Infinite Uniform Plane Frame Model





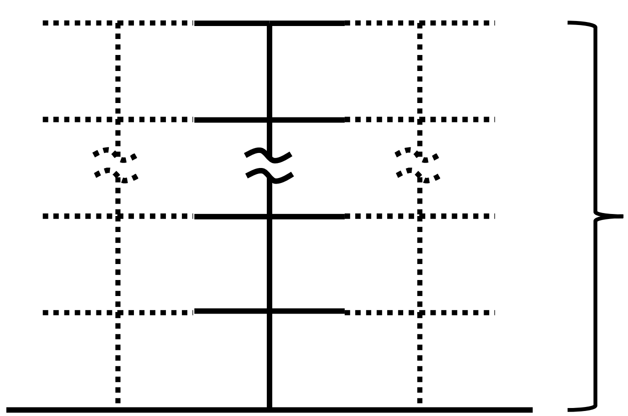
Weight per story per span *400kN*

Considering *P-Δ effect*

2% Rayleigh Damping for 1st and 2nd mode

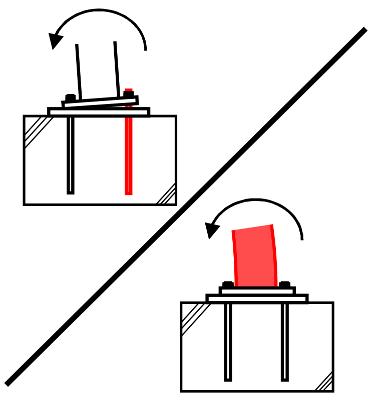
Parameter of Model

①



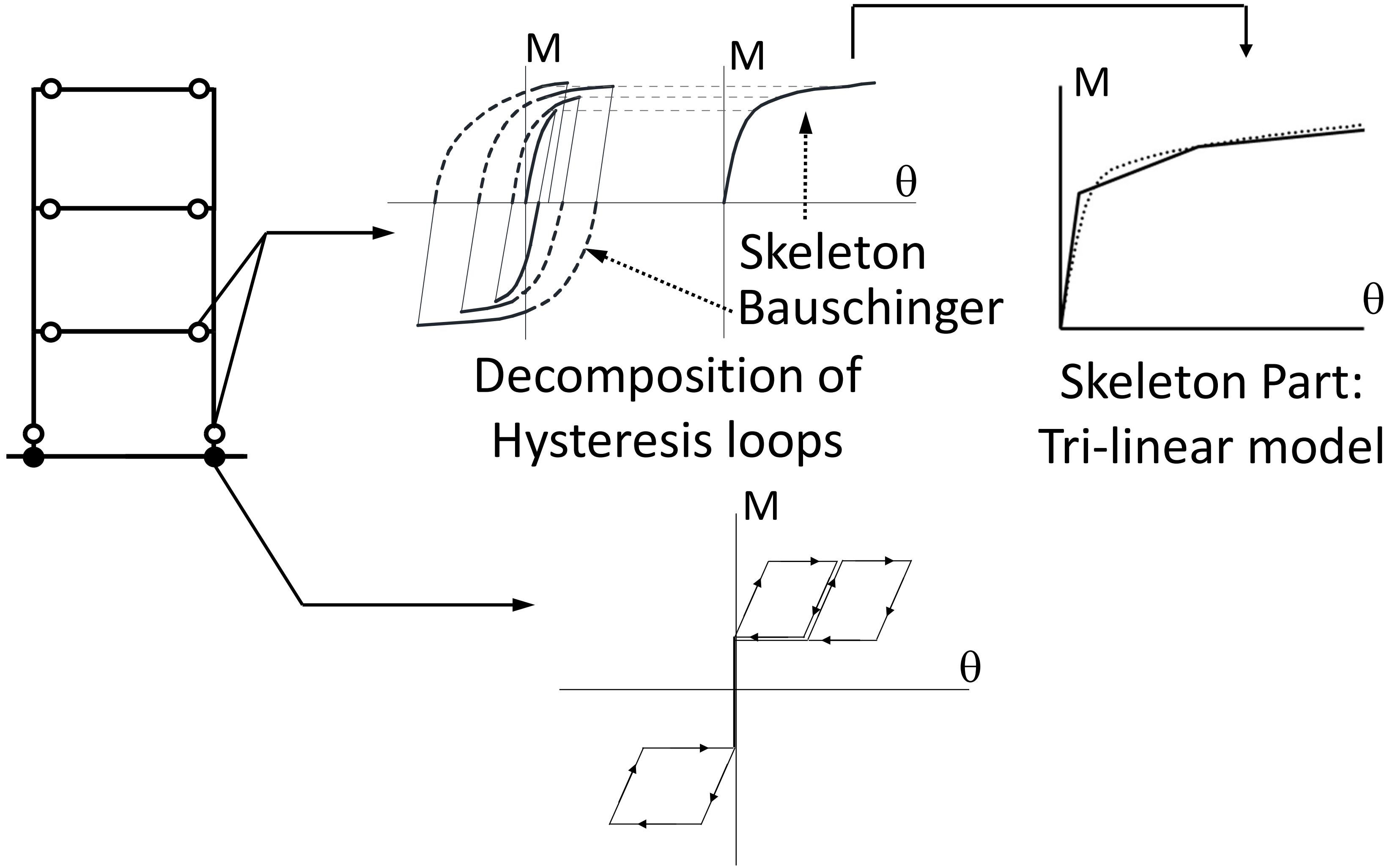
Number of Stories:
3-, 6- , and 9-story

②



$$\frac{M_{cb}}{M_{col}} = \begin{cases} 1.3 \text{ (Strong Column Base)} \\ 0.7 \text{ (Weak Column Base)} \end{cases}$$

Hysteresis Model



Column Base: Slip type model

Input Ground Motion Records

1. 1940 El Centro NS
2. 1952 Taft EW
3. 1968 Hachinohe EW
4. 1989 Gilroy Array #3 90^o
5. 1994 Newhall NS
6. 1994 OliveView NS
7. 1995 JMA Kobe NS
8. 1999 Chi Chi TCU 129 EW
9. 2011 JMA Sendai NS
10. 2016 Kik-net Mashiki EW

Scaled to three different intensities based on Peak Ground Velocity (PGV):

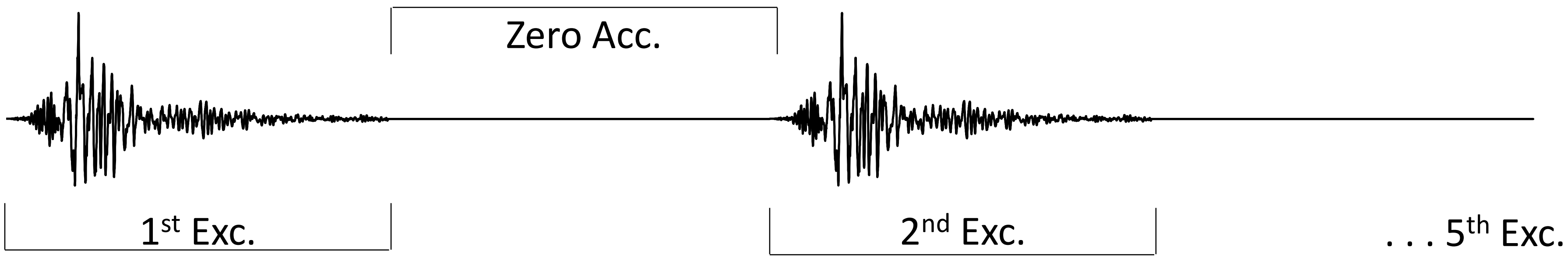
PGV 0.5 m/s (design level)

PGV 0.75 m/s

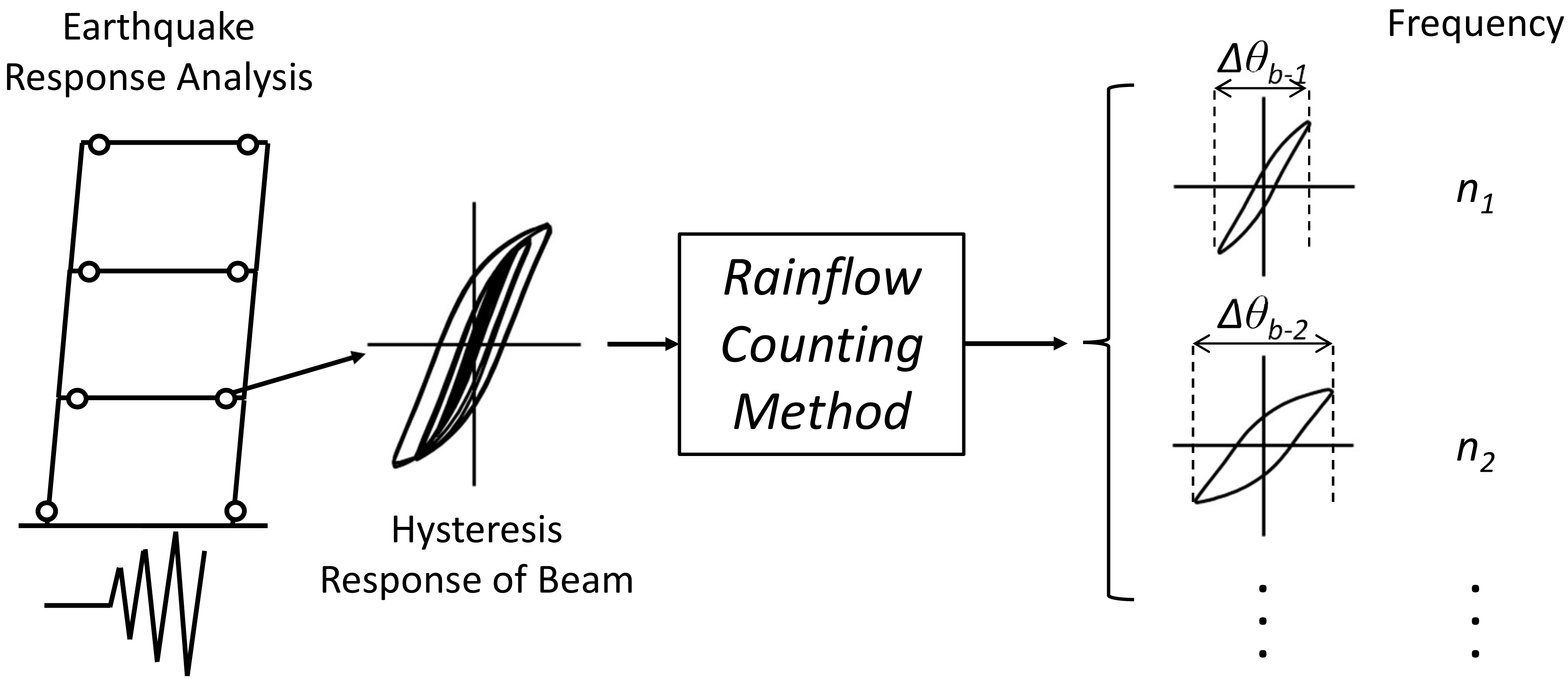
PGV 1.0 m/s

Simulation of Multiple Excitations:

Combination of 5 times excitation of Same Wave and Same Level with 30 sec. zero acceleration gap



Cumulative Damage of Beam



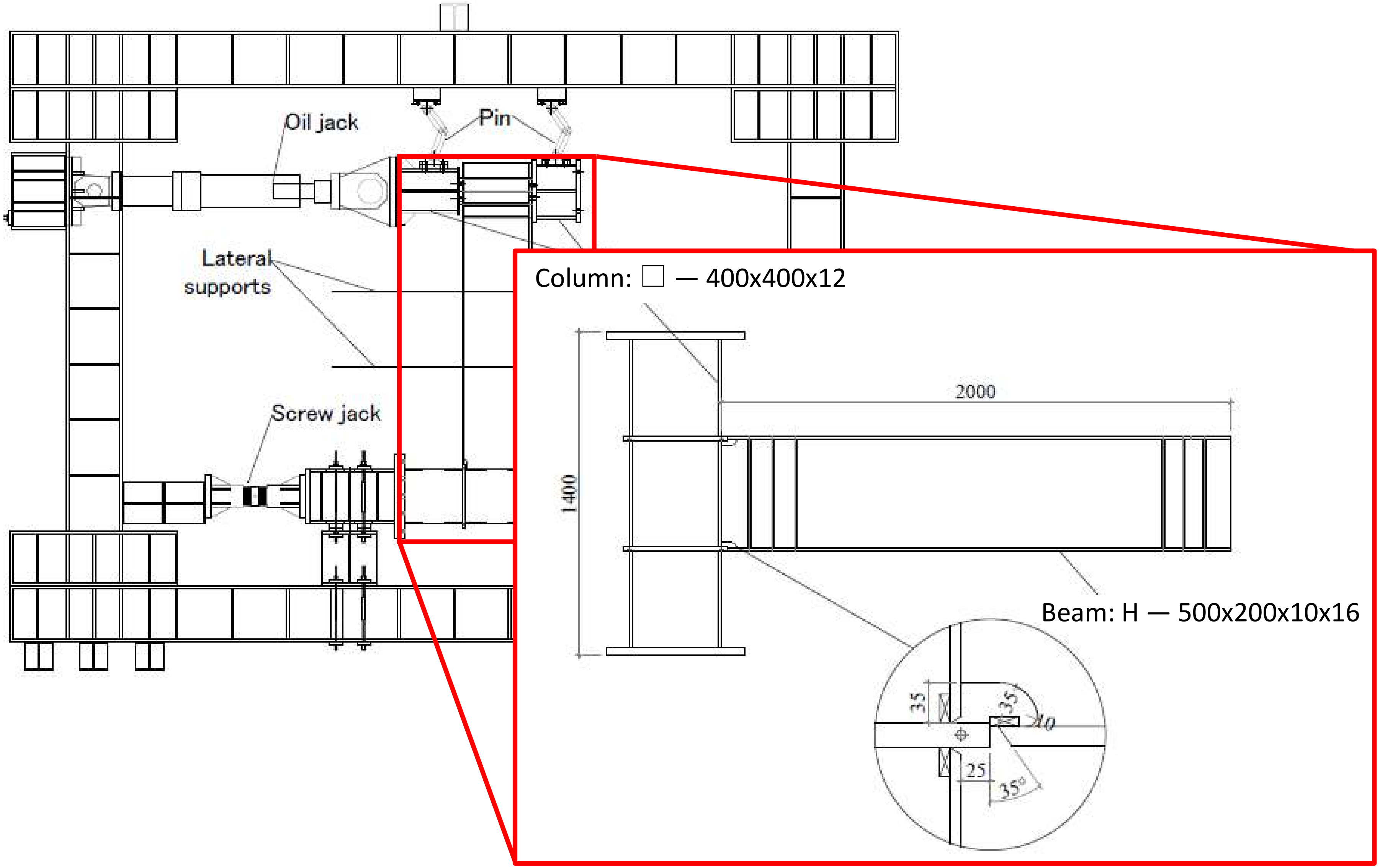
Miner's Rule: Cumulative Damage, $D = \sum_{i=1}^{k} \frac{n_i}{N_{fi}}$

$D \geq 1.0$ → Beam is estimated to be fractured

N_f = *The number of cycles to failure**

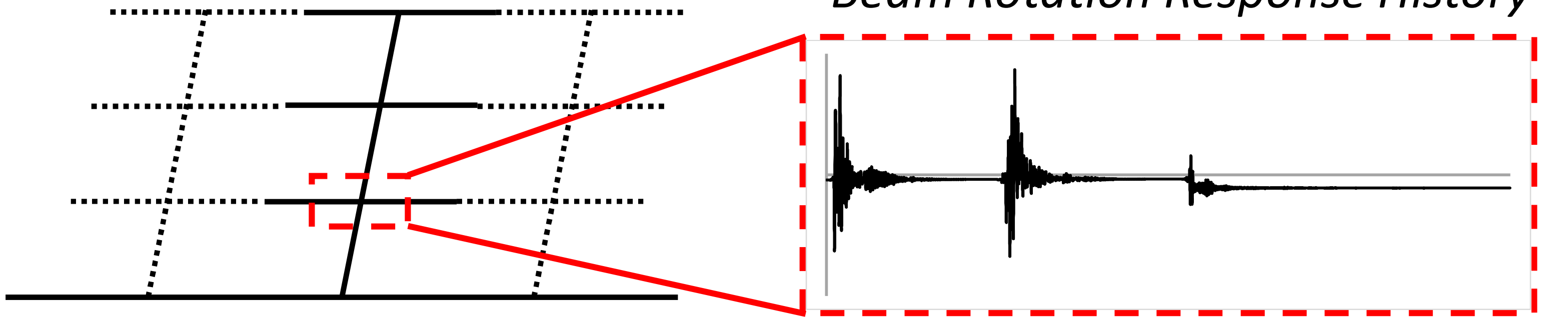
*Kishiki, S., Lee, D., Yamada, S., Ishida, T., and Jiao, Y., 2019. Low-Cycle Fatigue Performance Assessment of Current Japanese Steel Beam-to-Column Connections Determined by Ductile Fracture, *Engineering Structures* 182, 241–250

Outline of Test



Loading History

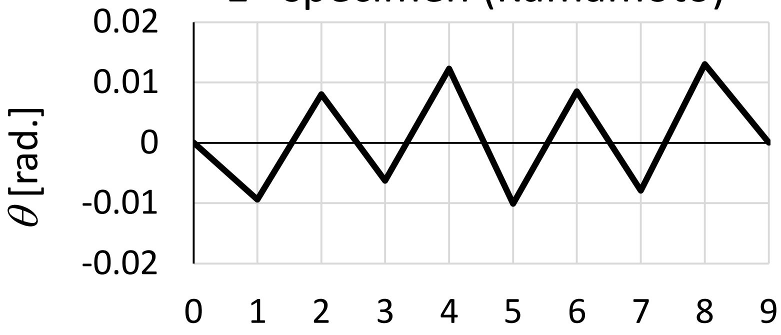
Beam Rotation Response History



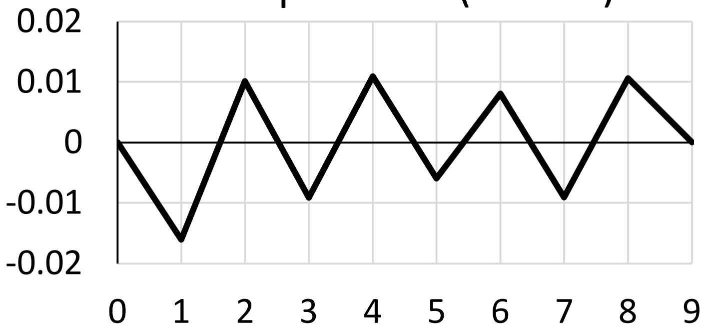
Input Seq.	Foreshock	Main shock	Aftershock
1st (Kumamoto)	2016/04/14-M6.5	2016/04/16-M7.3	2016/04/16-M5.9
2nd (Sendai)		2011/03/11-M9.0	2011/04/07-M7.1

Sorted out nearly elastic cycles

1st specimen (Kumamoto)



2nd specimen (Sendai)



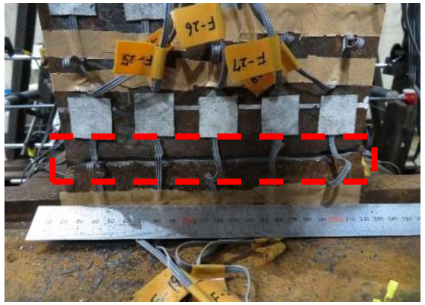
Number of Sets to Fracture

1st specimen

16th set: crack initiated

23rd set: crack almost penetrated through

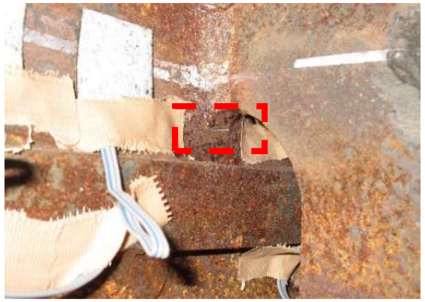
28th set: fully fractured



***D*_calc.**: 99.1%

2nd specimen

10th set: crack initiated



17th set: crack almost penetrated through

19th set: fully fractured

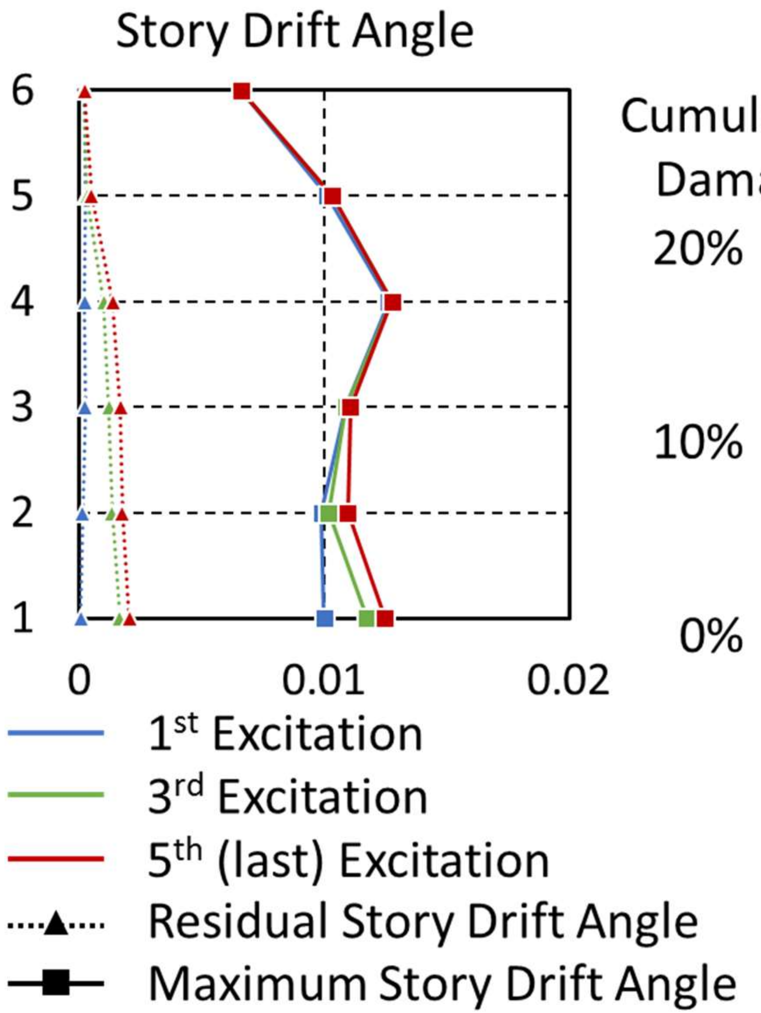
***D*_calc.**: 87.6%

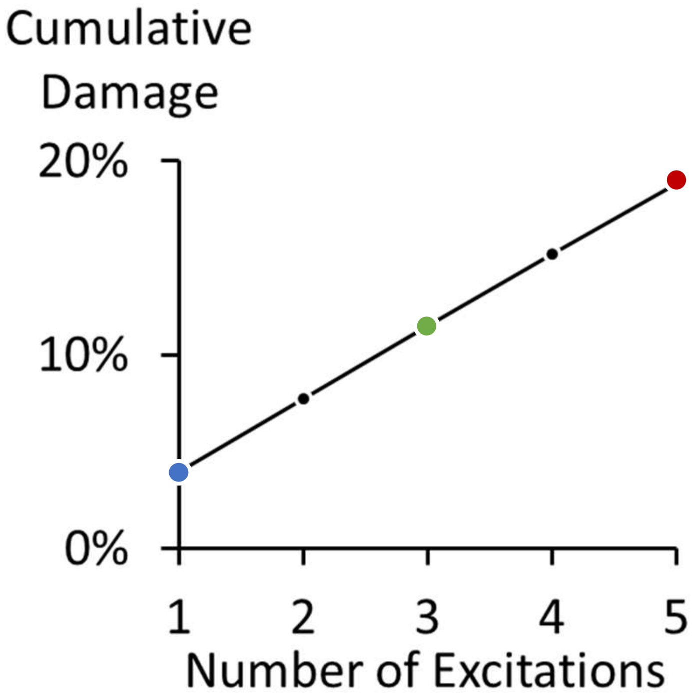
The reliability of the cumulative damage evaluation method under random loading is acceptable

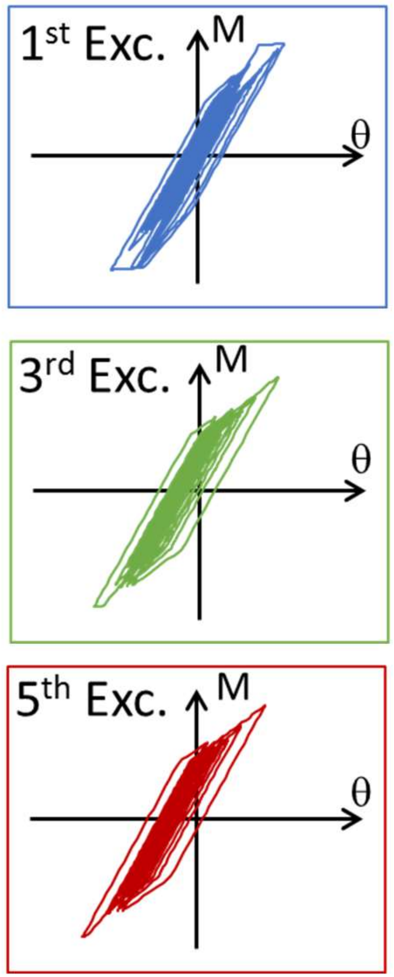
Analytical Result: PGV 0.5 m/s

Stable Behavior

6-story Strong Col. Base Model Excited by JMA Sendai NS Record



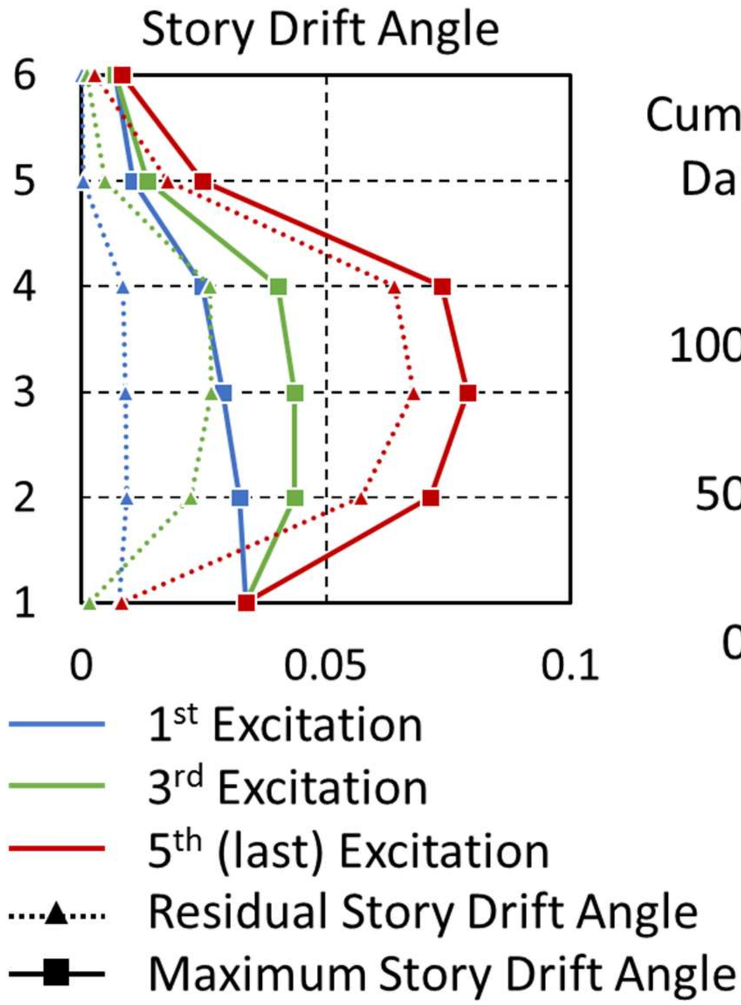


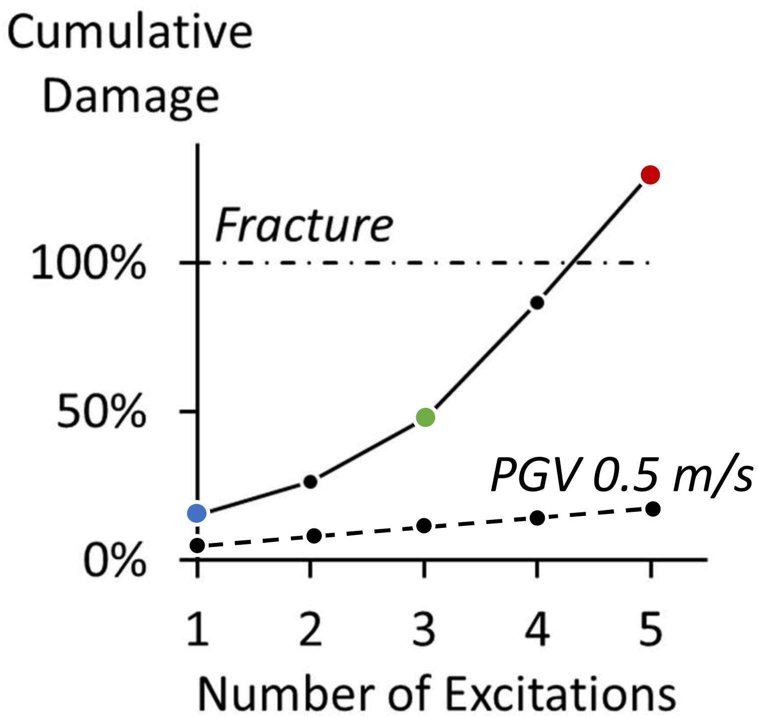


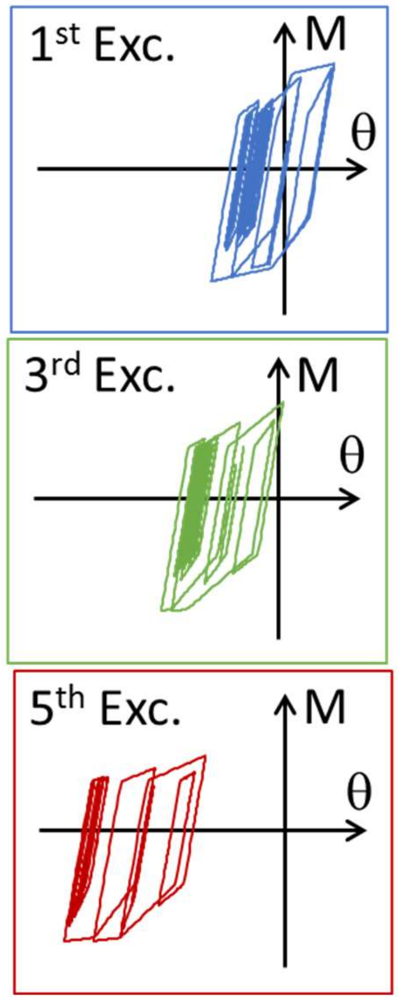
Analytical Result: PGV 0.75 & 1.0 m/s

Ductile Fracture

6-story Strong Col. Base Model Excited by PGV 1.0 m/s Hachinohe EW Record

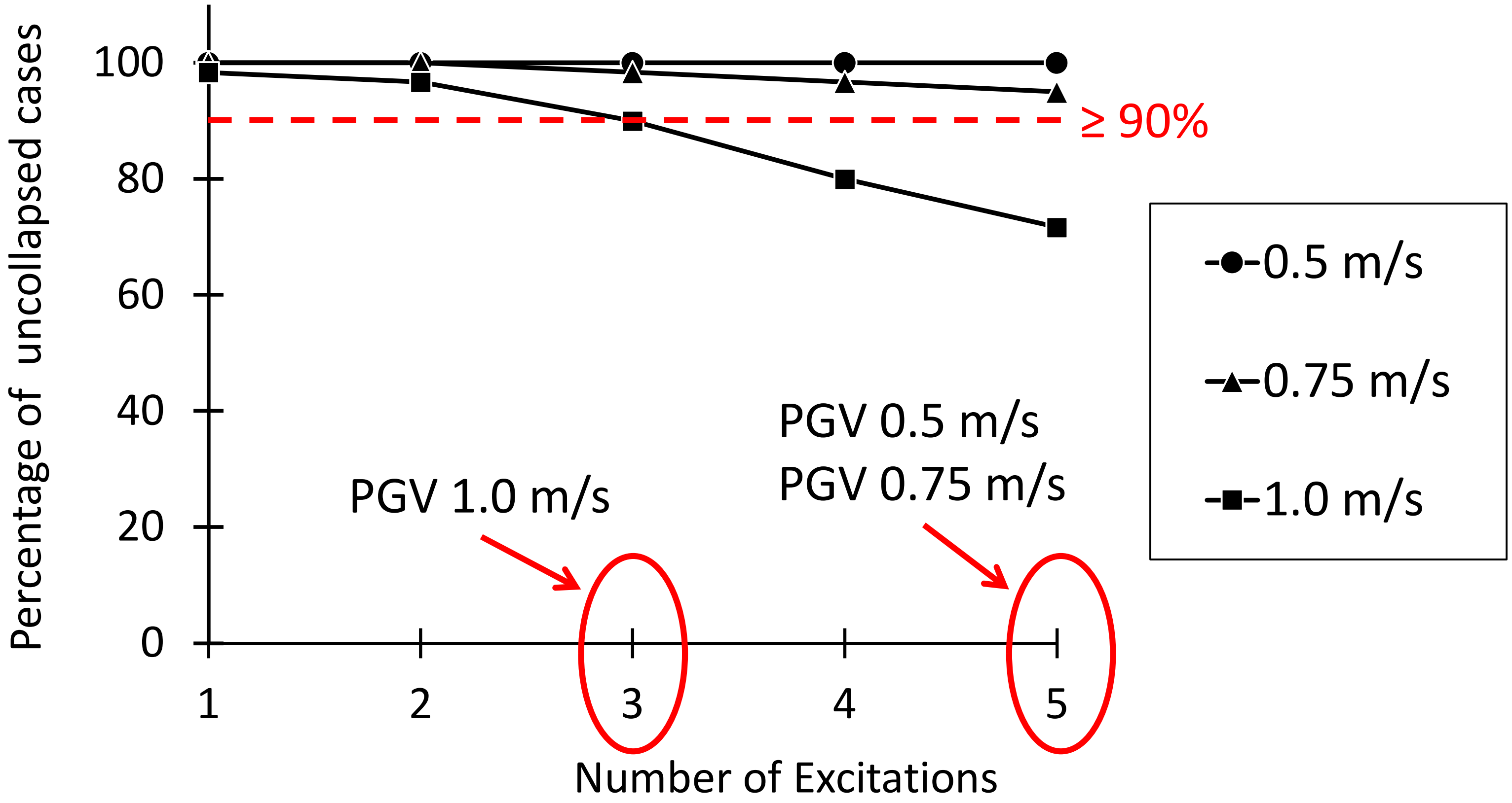






Collapse Fragility

6 different models x 10 different ground motion seq. = 60 cases



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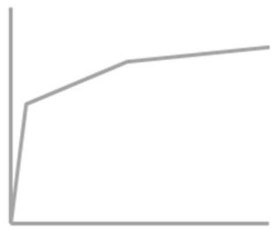

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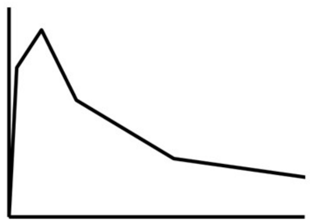

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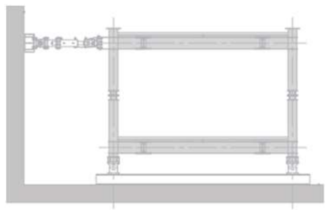

Ch. 5 Conclusions

Parameter of Models

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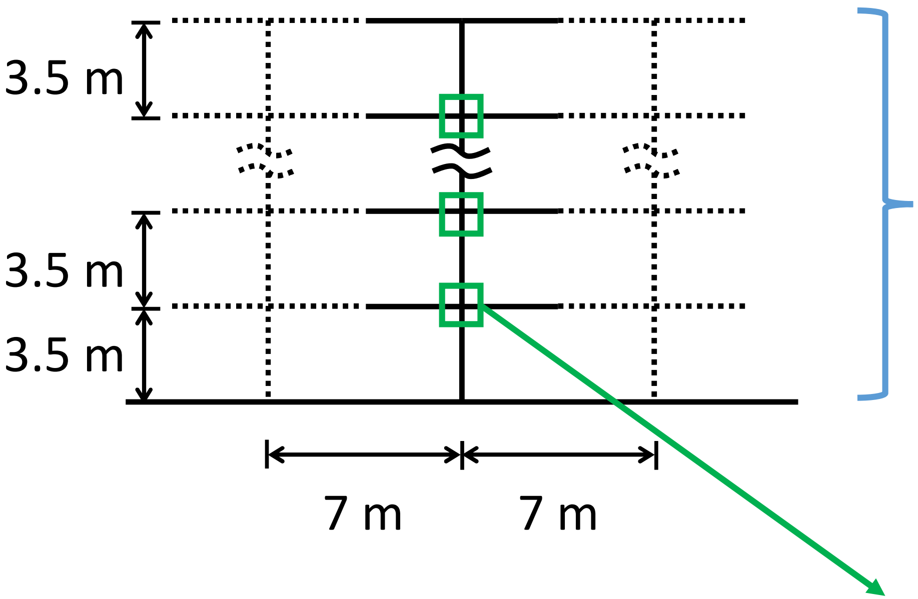
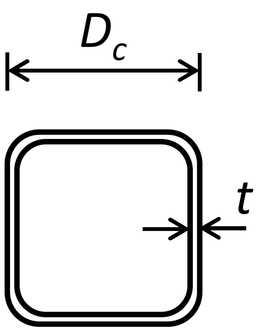


Number of Stories:
3-, 6-, and 9-story

Column-to-beam moment capacity ratio (${}_{c}M_{p}/{}_{b}M_{p}$):
1.1, 1.25, 1.5, 1.75, and 2.0

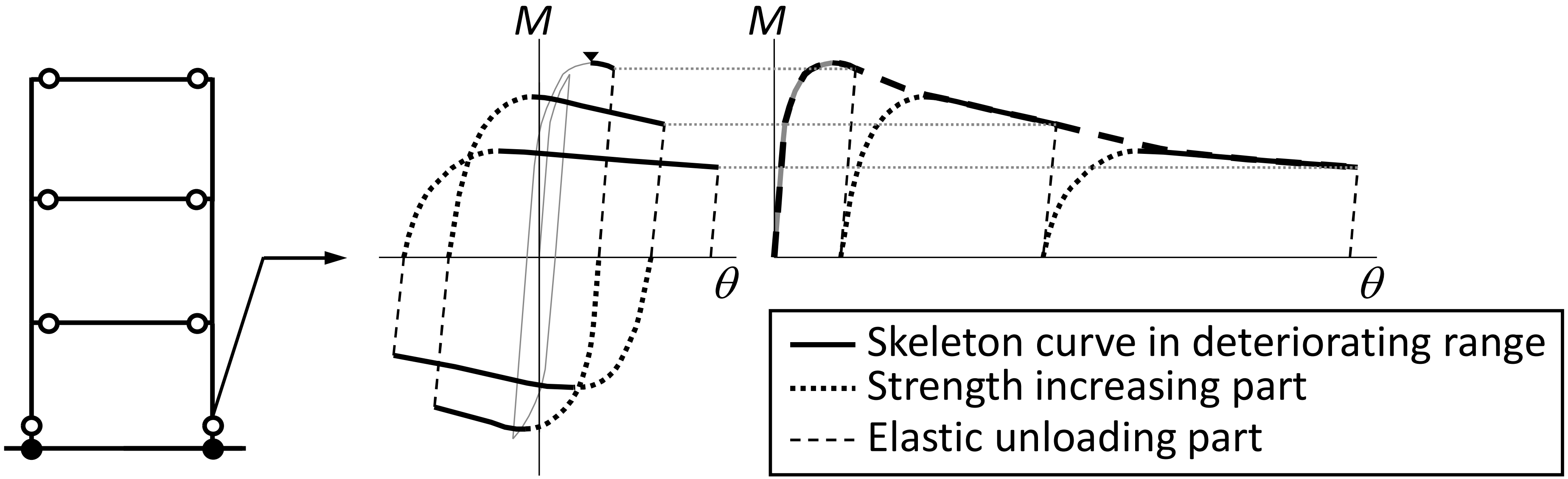


D_c/t = 29.45, 25, and 20

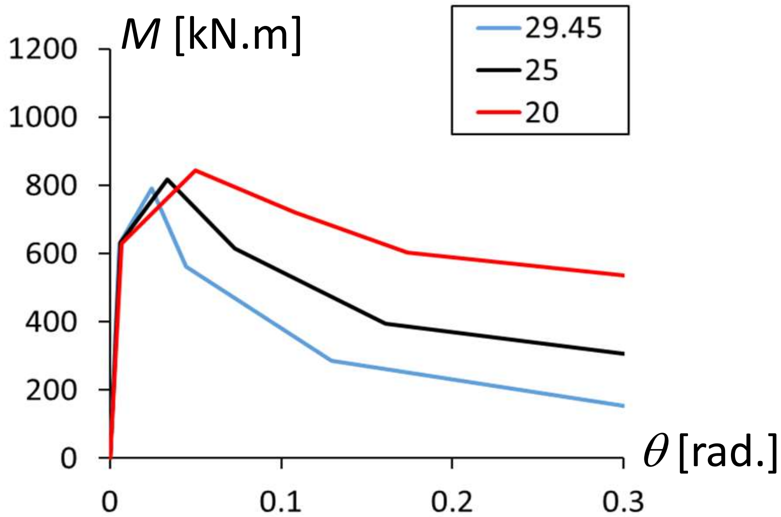
↓

Limit value for FA rank

Hysteresis Model of Columns



Comparison of Skeleton Curve **By D_c/t**



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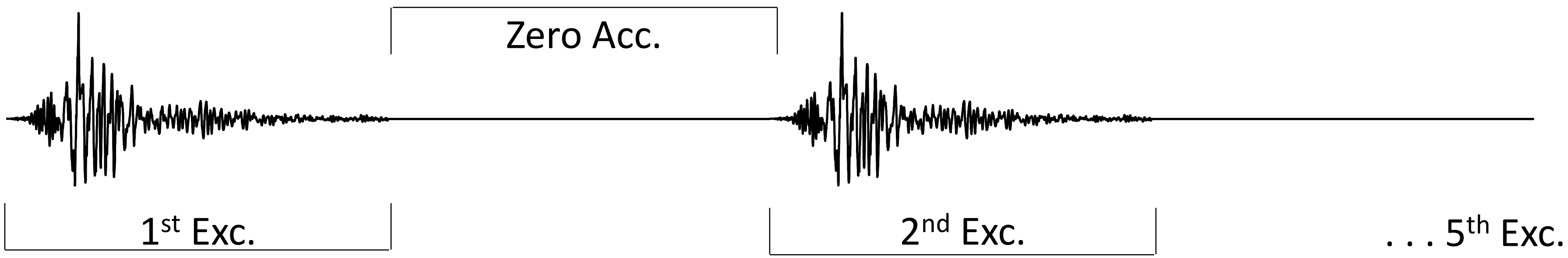
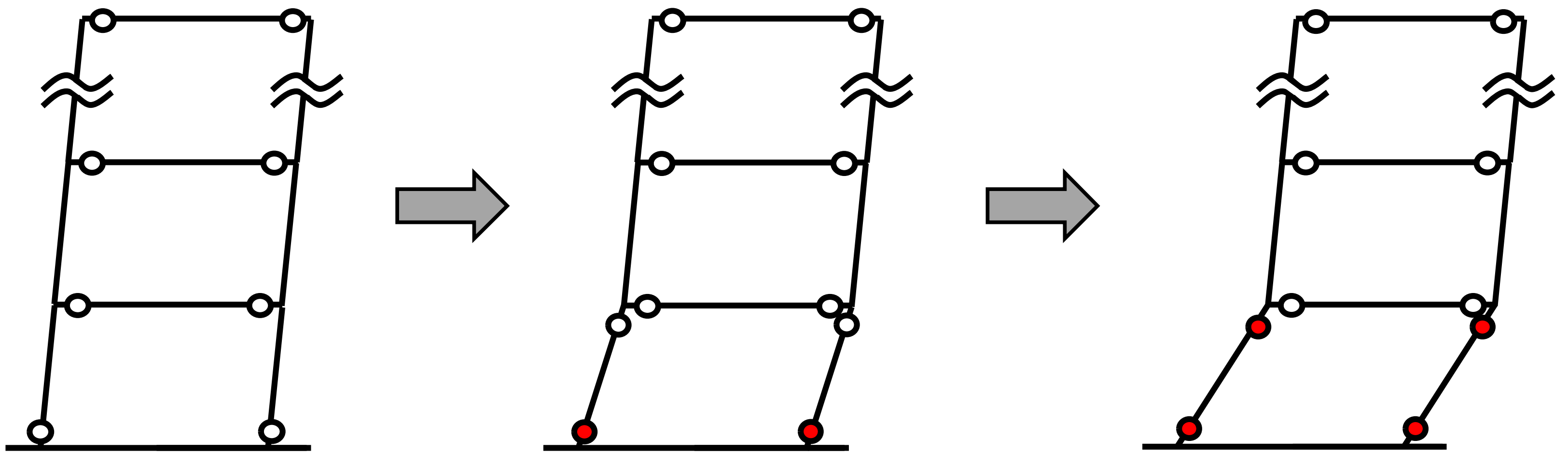


Stages to Collapse

Excitation 1 → *Excitation 2* → . . . → *Excitation N*



Stage 1: No deterioration
- Sway mechanism
- Stable behavior

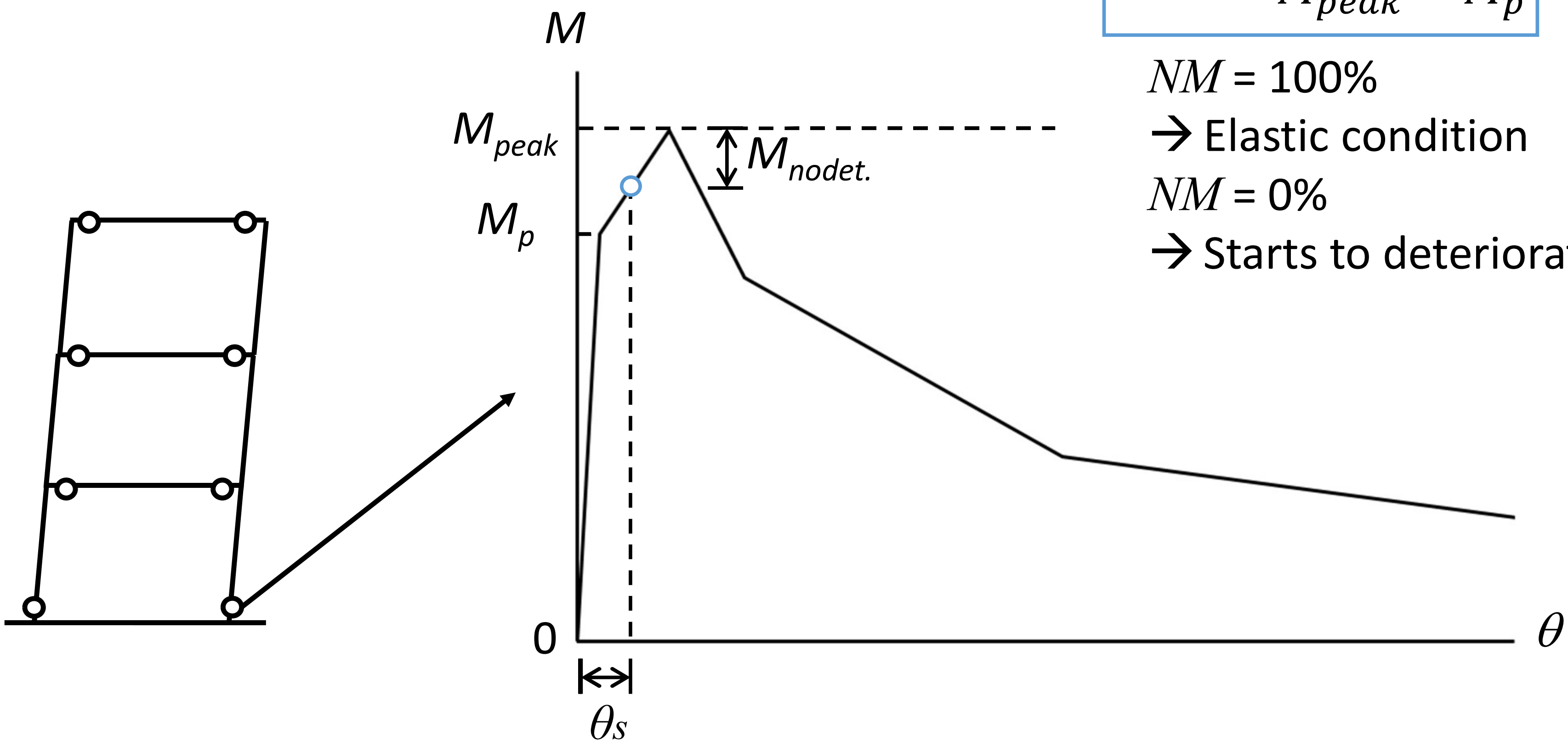
Stage 2: one end hinge of column deteriorated
- Damage concentration
- Moment redistribution

Stage 3: both end hinges of column deteriorated
- Shifting to weak story mechanism

Plastic hinge state
- ○ No deterioration
- ● Deteriorated

Damage Index

Hinge condition at 1st story column



(Plastic Deformation of Skeleton Part)

Nondeterioration Margin

$$NM = \frac{M_{nodet.}}{M_{peak} - M_p}$$

NM = 100%

→ Elastic condition

NM = 0%

→ Starts to deteriorate

Damage Index

Hinge condition at 1st story column

Deterioration Index

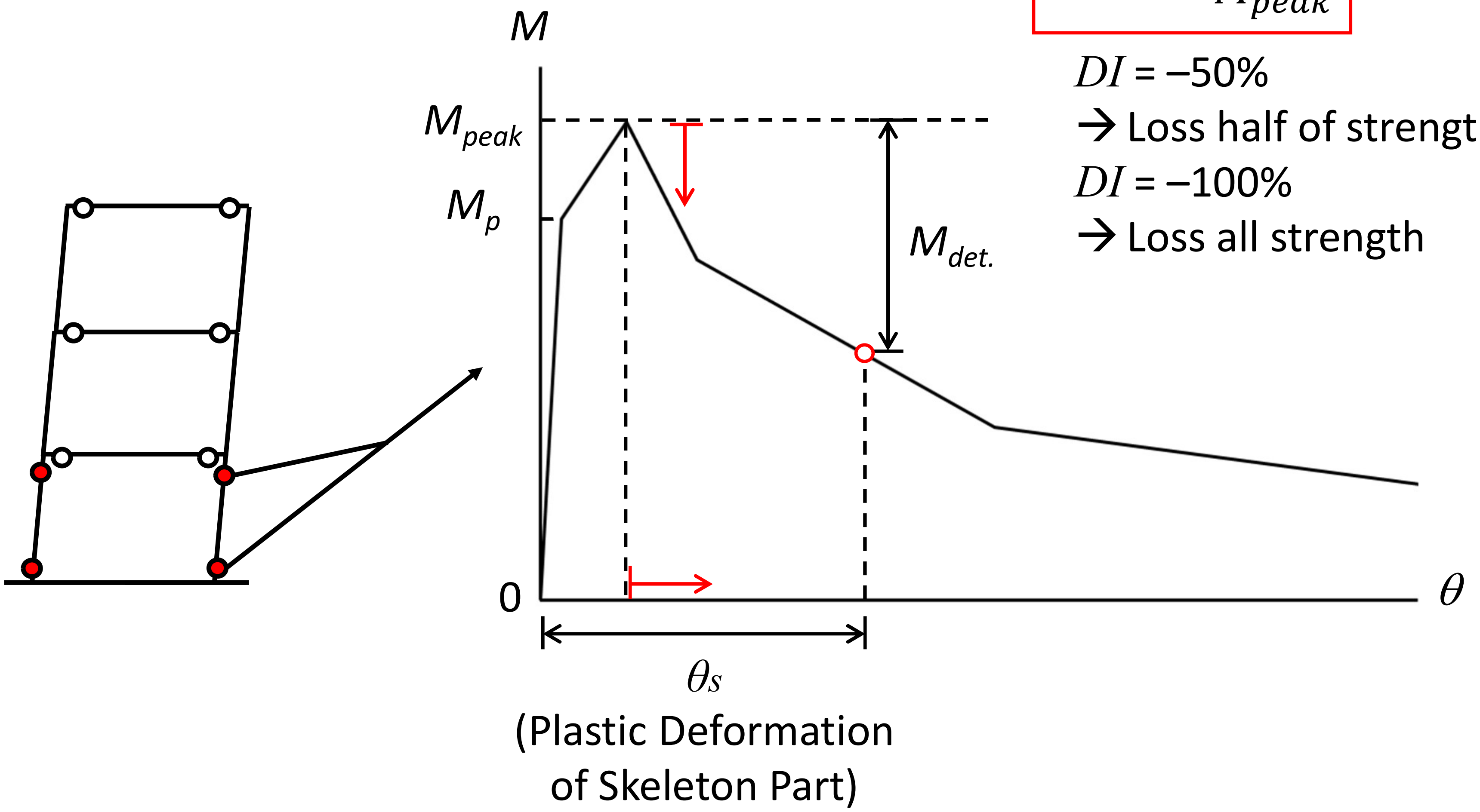
$$DI = -\frac{M_{det.}}{M_{peak}}$$

DI = –50%

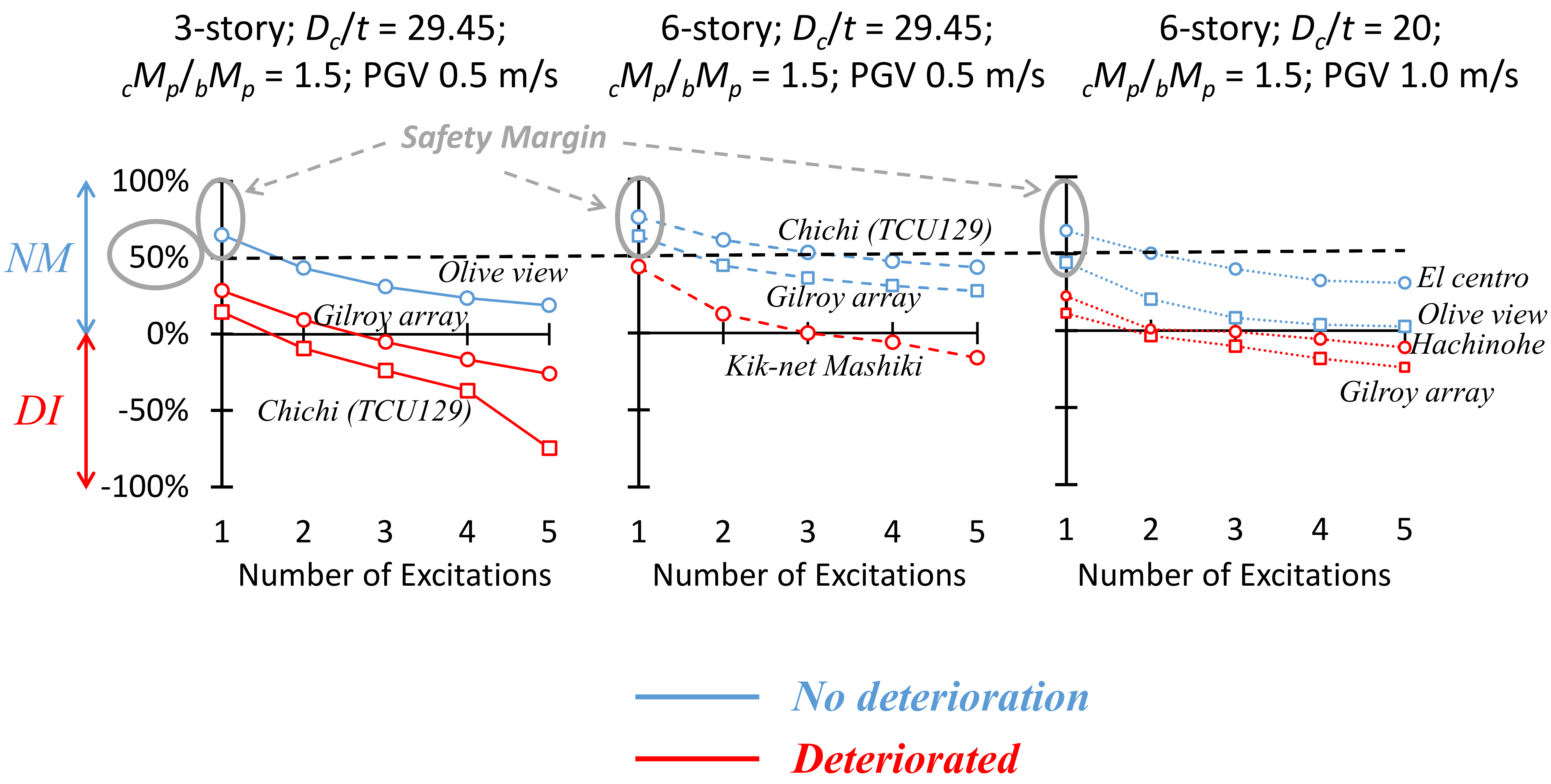
→ Loss half of strength

DI = –100%

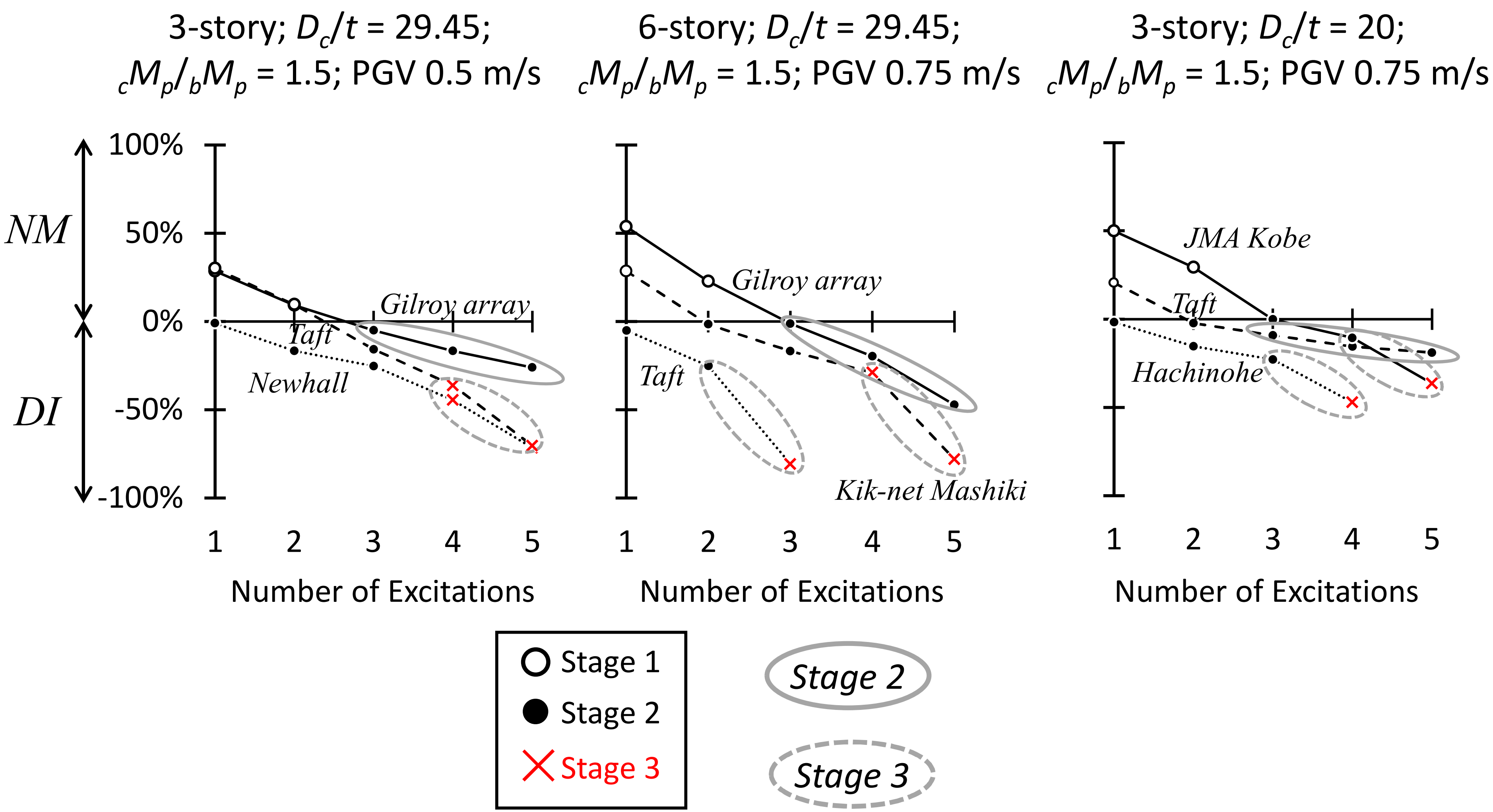
→ Loss all strength



Trend of Nondeterioration Margin



Trend of Deterioration Index



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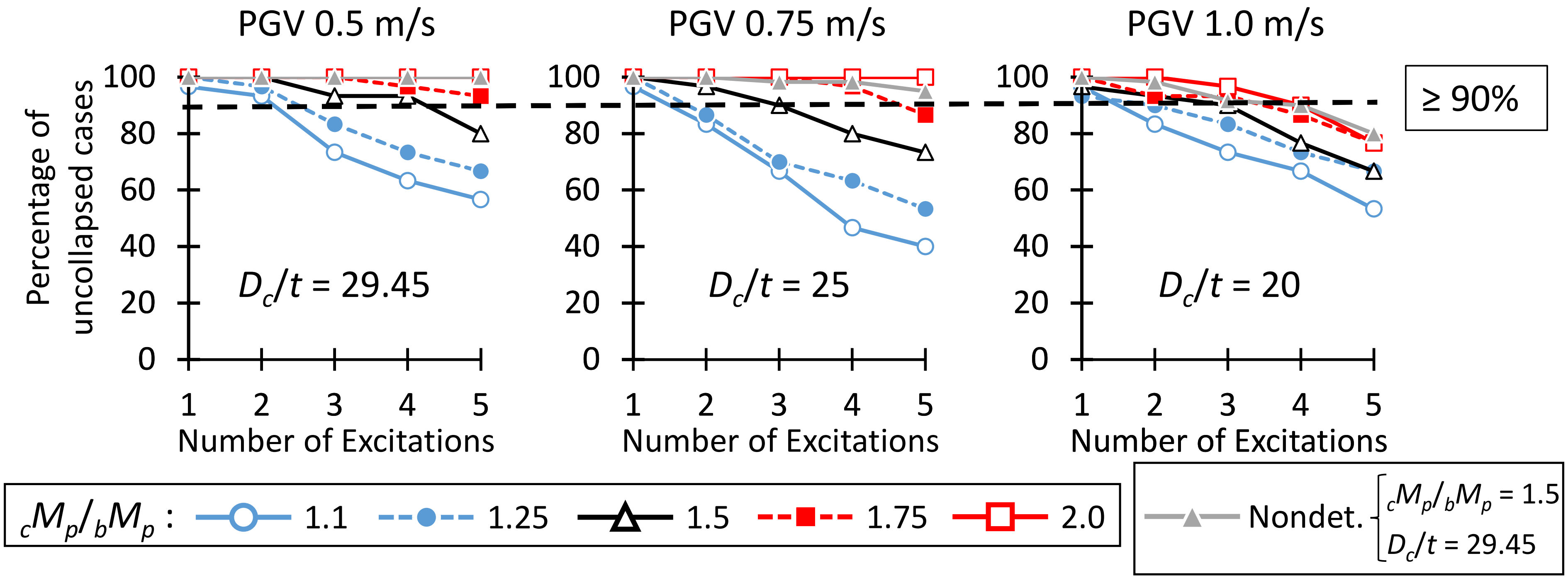

Intensity (PGV)	0.5 m/s				0.75 m/s				1.0 m/s			
Number of Excitations	2	3	4	5	2	3	4	5	2	3	4	5
D_c/t = 29.45	1.1	1.5	1.5	1.75	1.75	2	–	–	–	–	–	–
D_c/t = 25	1.1	1.1	1.1	1.25	1.5	1.5	1.75	2	1.75	–	–	–
D_c/t = 20	1.1	1.1	1.1	1.1	1.1	1.1	1.25	1.5	1.25	1.5	2	–

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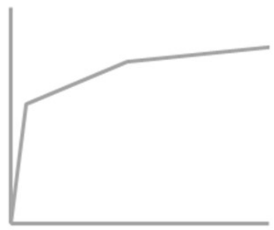

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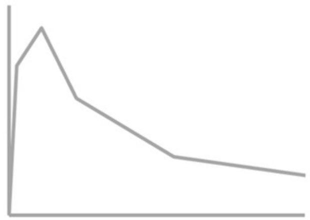

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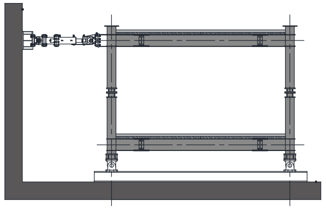
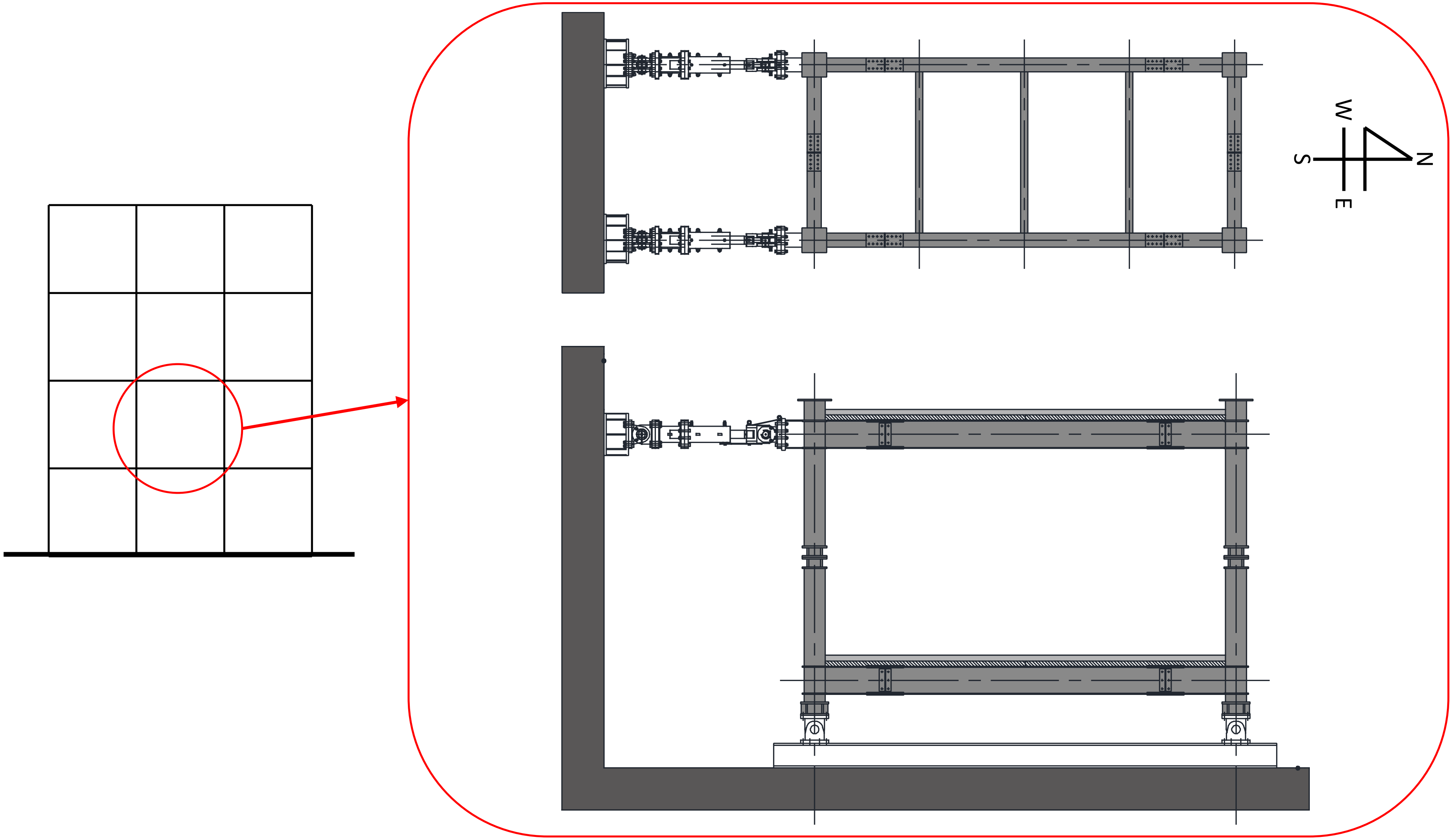


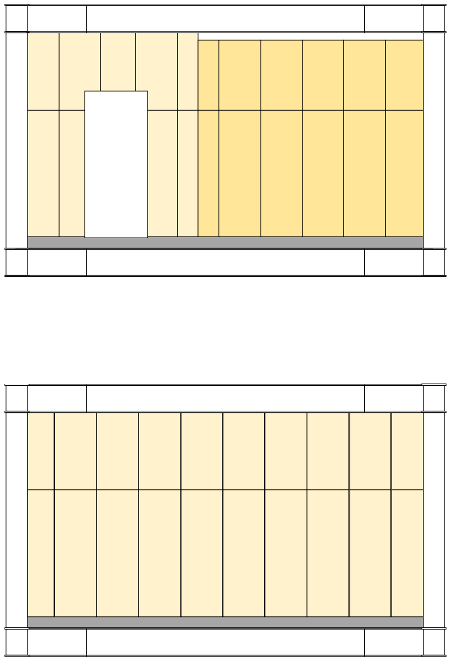
Ch. 5 Conclusions

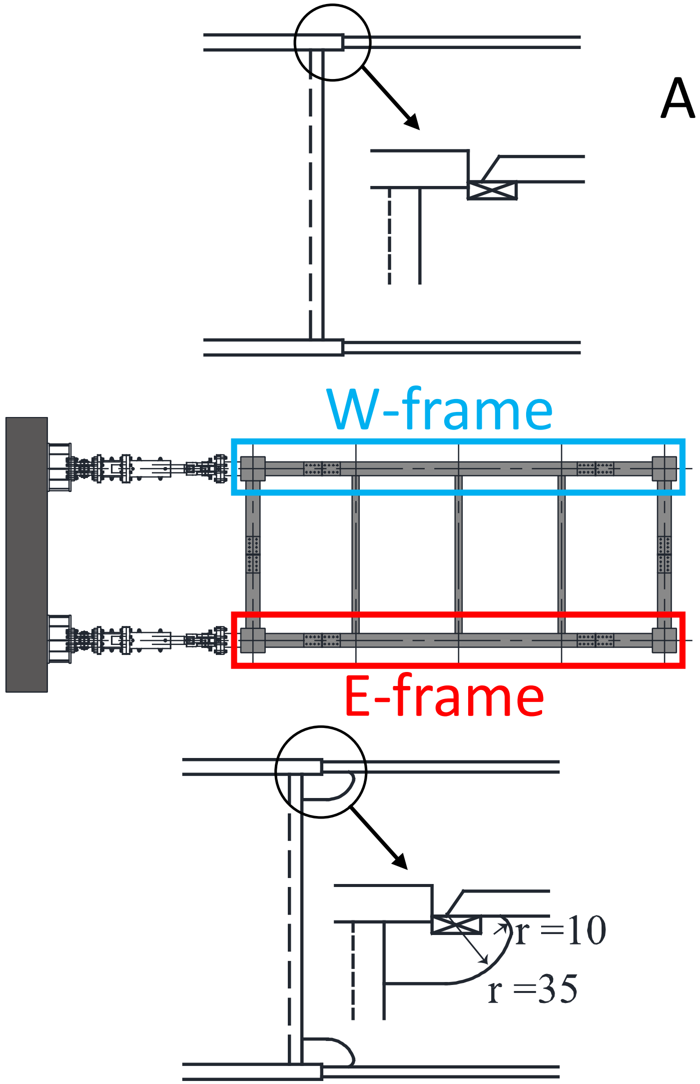
Outline of Test



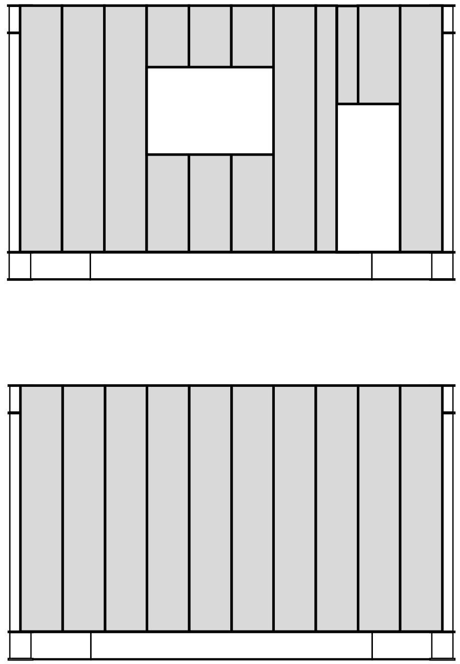
Specimens

1st specimen
Light gauge steel (LGS)

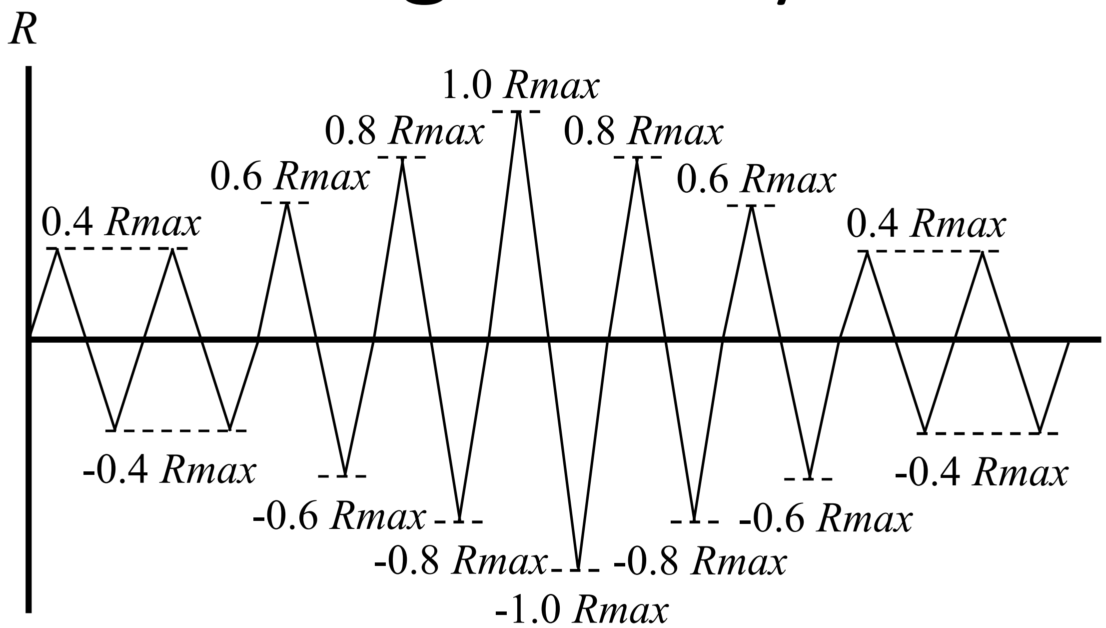




2nd specimen
Autoclaved lightweight concrete (ALC)

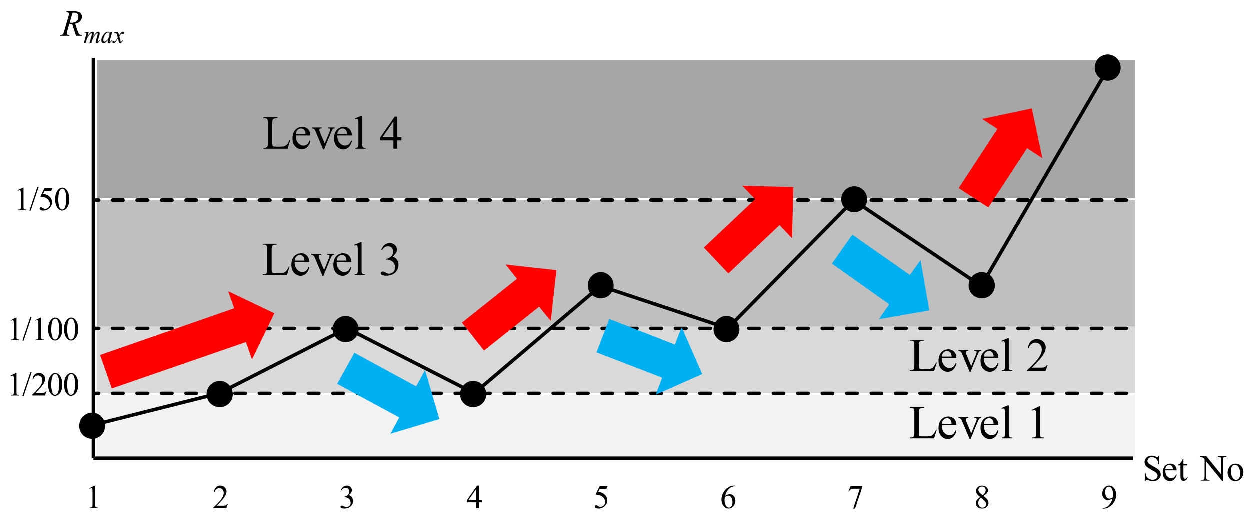


Loading History



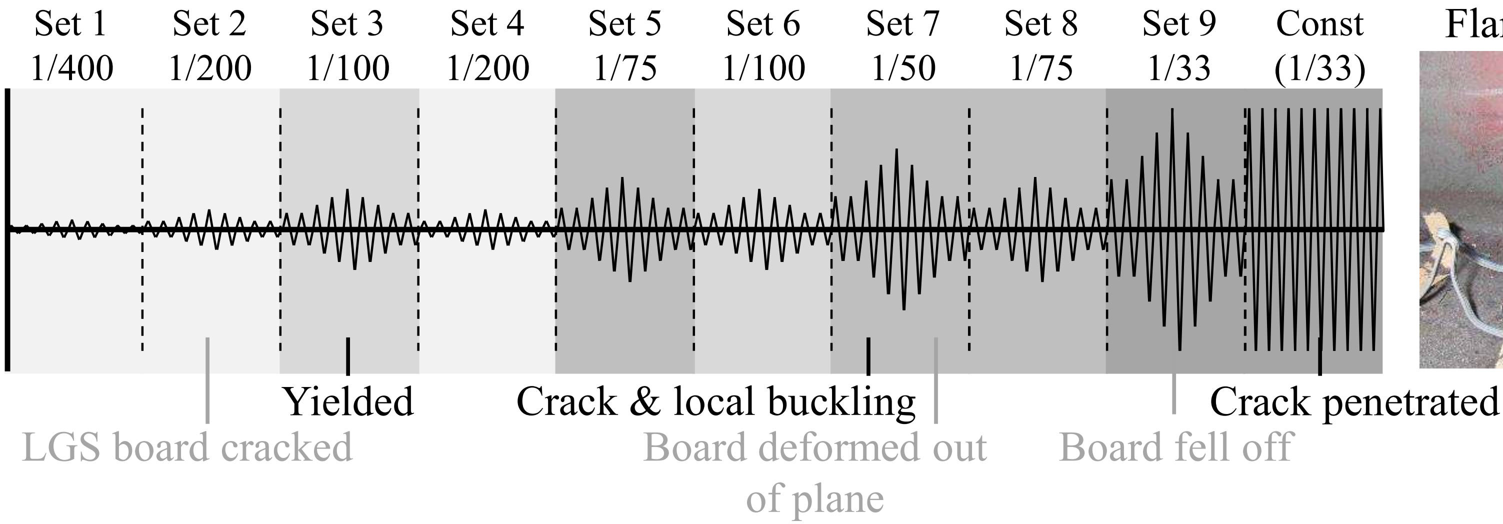
Typical one set of loading represents one earthquake

Nine sets of loading with various levels



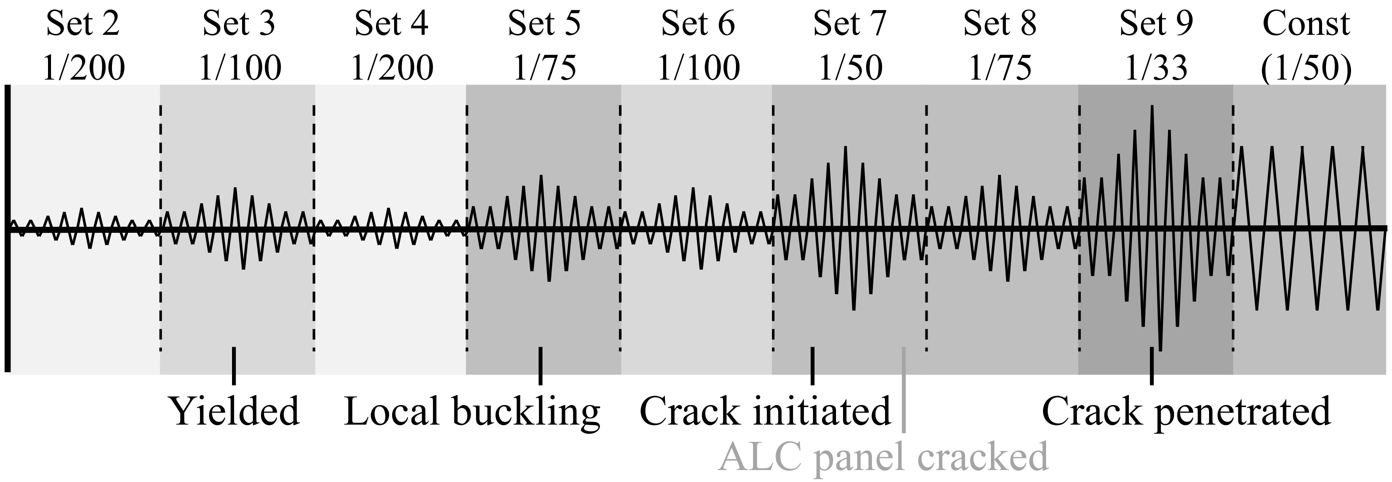
Experimental Progress

1st specimen (LGS)



End of loading:
Flange fully fractured

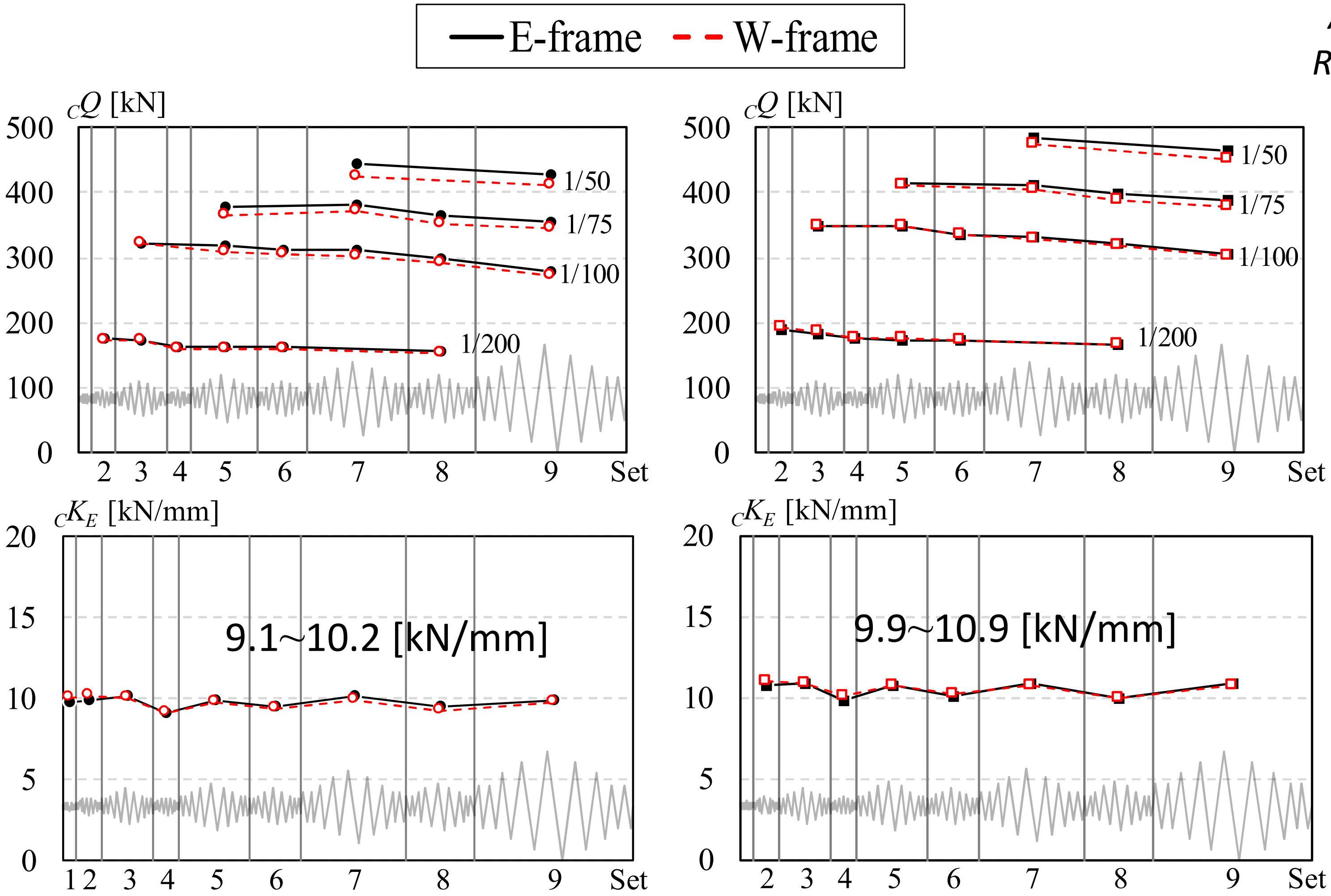
2nd specimen (ALC)



End of loading:
Flange fully fractured

Strength and Stiffness Transition of Steel Frames

Ave. str. Reduction ↓



Strength

3.8%

7.2%

13.6%

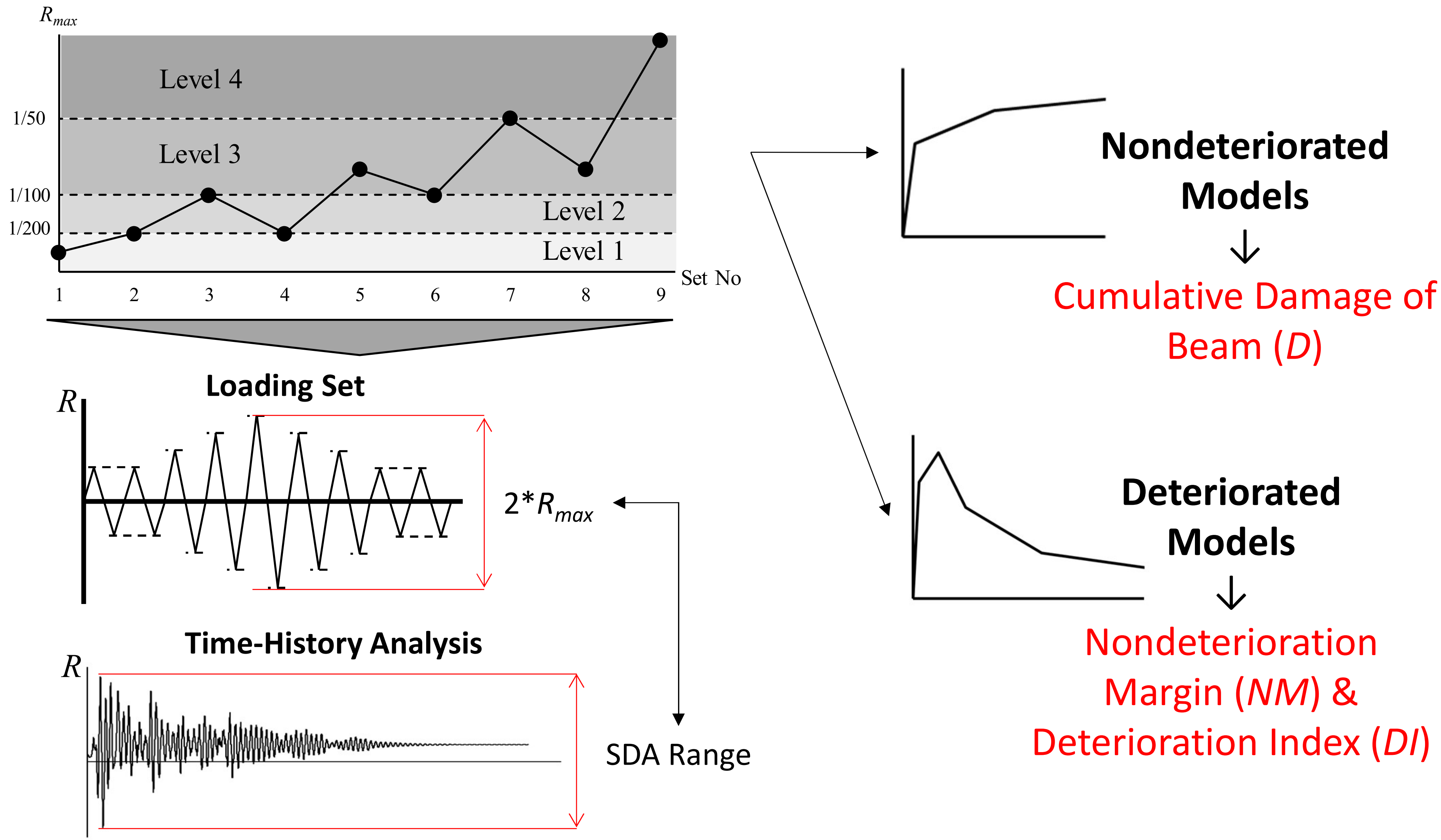
12.5%

Stiffness

1st specimen (LGS)

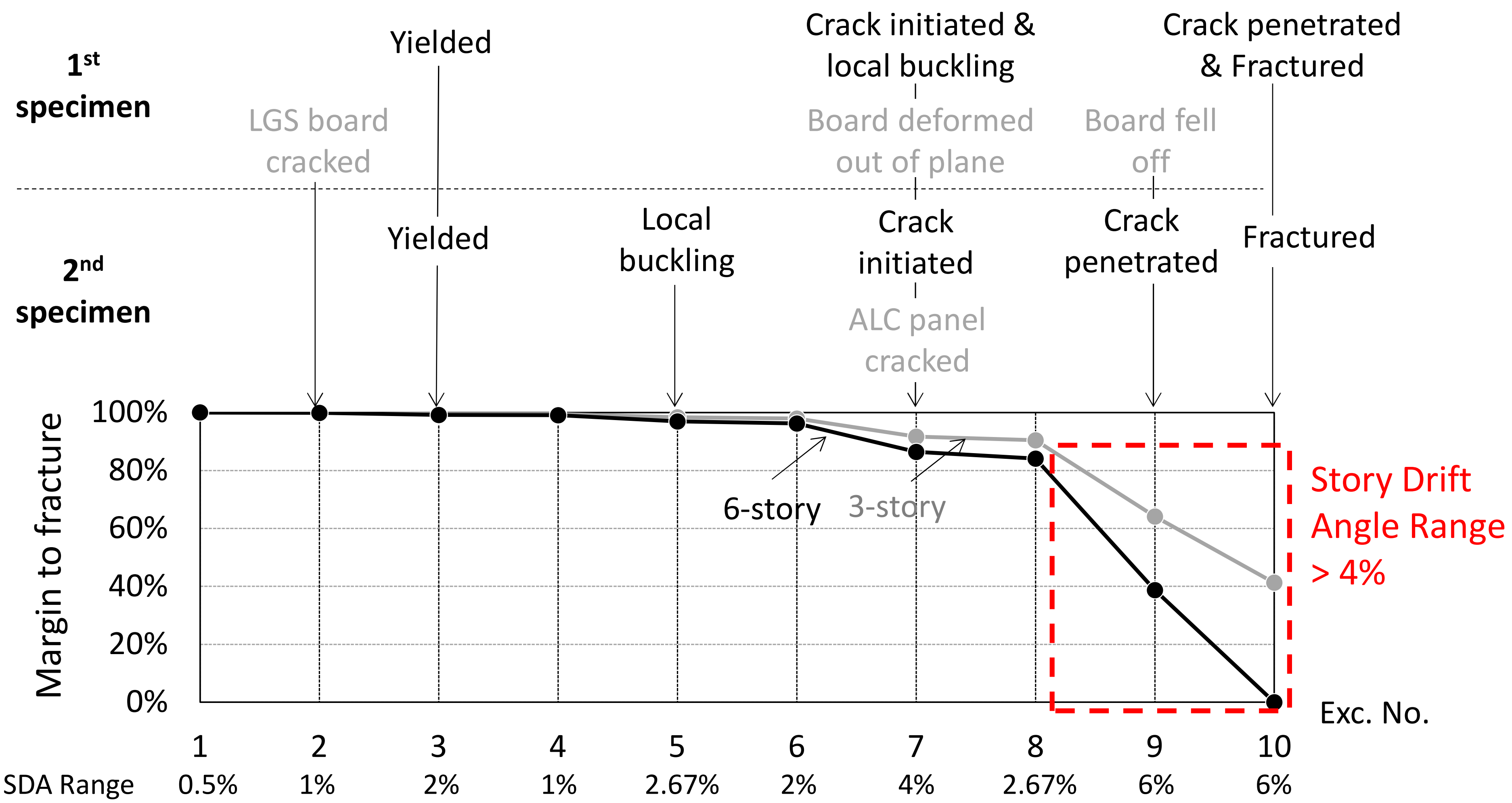
2nd specimen (ALC)

Examination by Numerical Analysis



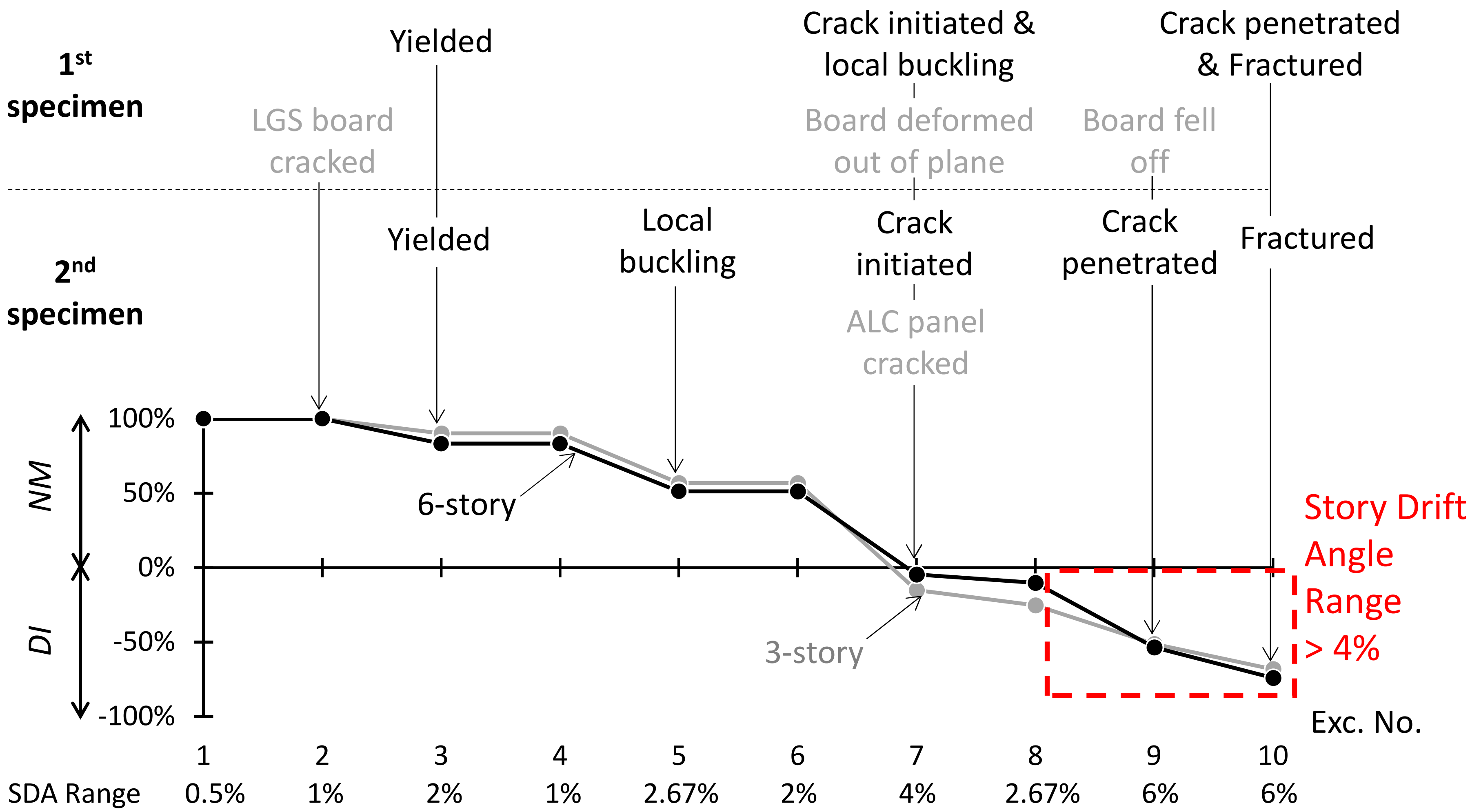
Comparison of Margin to Fracture and Observed Damages

NONDETERIORATED MODELS (Margin to fracture = 100% – cumulative damage)



Comparison of Deterioration Index and Observed Damages

DETERIORATED MODELS (*NM*: Nondeterioration margin; *DI*: Deterioration Index)



Conclusions

Ch. 2 Response Analysis of Nondeteriorated Models

→ The evaluation is focused on the cumulative damage at the beam end

→ Overall, the structure has a stable behavior and satisfying performance

Ch. 3 Response Analysis of Deteriorated Models

→ Story collapse more likely to occur due to column strength deterioration

→ Column strength deterioration could be prevented by providing enough nondeterioration margin at the 1^{st} Exc.

→ The performance could be improved by increasing the column-to-beam moment ratio or decreasing the column width-to-thickness ratio

Ch. 4 Full-Scale Steel Frame Test

→ The observed damages generated within the structure and the corresponding calculated damages are analyzed under various maximum story drift angle levels

→ Severe damages generated within the structure could be prevented by limiting maximum story drift angle range under multiple earthquakes to a certain degree

Research Papers

- **Ch. 2**: Randy Tenderan, Takanori Ishida, Yu Jiao, Satoshi Yamada. Seismic Performance of Ductile Steel Moment-Resisting Frames Subjected to Multiple Strong Ground Motions, Earthquake Spectra, Vol. 35, 1, pp. 289-310, Feb. 2019.
- **Ch. 3**: Randy Tenderan, Takanori Ishida, Satoshi Yamada. Effect of Column Strength Deterioration on the Performance of Steel Moment-Resisting Frames Subjected to Multiple Strong Ground Motions, Engineering Structure. (under review)
- **Ch. 4**: Takanori Ishida, Randy Tenderan, Keita Kohtaki, Shoichi Kishiki, Jun Iyama, Takashi Hasegawa, Tsuyoshi Seike, Satoshi Yamada. Experimental Study on Full-Scale Steel Moment-Resisting Frames Considering Multiple Earthquakes, Engineering Structure 2021.