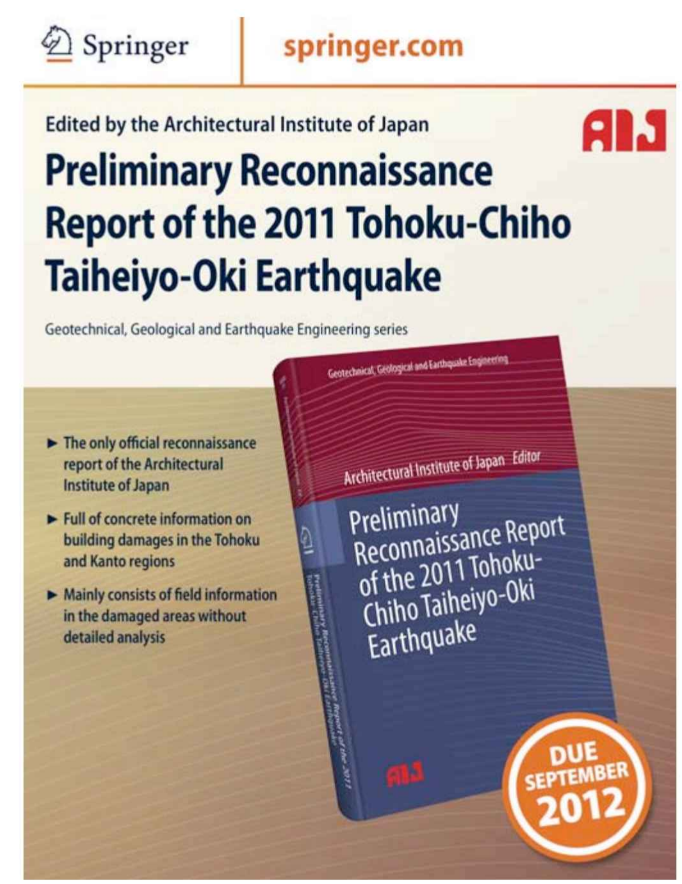
US-Japan Collaborative Study on Seismic Damage of Buildings and their Mechanism

Japanese PI: Hitoshi Shiohara, The University of Tokyo
Counterpart PI: John W. Wallace, UCLA

Objective: To collect and recording of the the data on structural damage of engineered buildings as well as to investigate the factor which caused each structural damage, carried out as a joint effort of Japan (AIJ) and US (EERI).

Major Outcomes

1) Joint reconnaissance efforts of building damage by Japanese and US researchers
2) Jointly participated and presented at International Symposium of JAEE in March 2012, Tokyo
3) Presentation at special session of 11WCEE
4) Contribution to the publication of reconnaissance report from AIJ in 2013

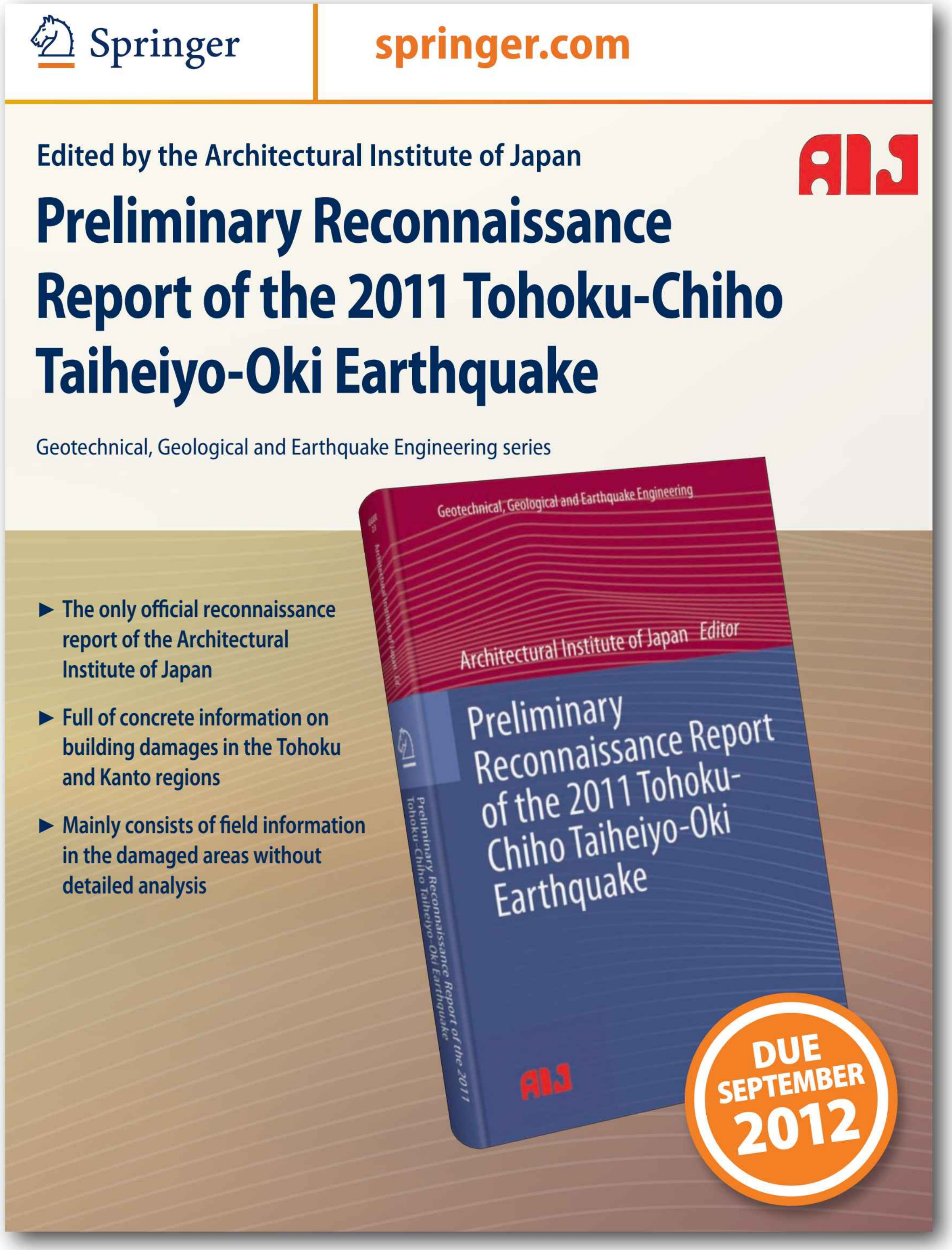


Publication: Reconnaissance Report (by AIJ)

PREFACE

Devastating damage in the Tohoku region of Japan occurred during and after the earthquake off the Pacific coast of Tohoku earthquake on March 11, 2011.

The report summarizes damage associated with **ground failures** including landslide and liquefaction as well as **non-structural damages** such as to equipment and facilities, partitioning walls and ceilings, and **functional failures in skyscrapers**. Also brief description of the Japanese Seismic Design Code will be provided in the Appendix. A proposed scheme of **anti-tsunami design for buildings** is also included.



NEES/E-Defense Collaboration Memorandum of Understanding (MOU)

MEXT & NSF (National Science Foundation)：
Research Collaboration on Disaster Mitigation
NIED & NEES (J. Brown Jr. Network for Earthquake Engineering Simulation)：
Collaboration on Joint Research Using NEES/E-Defense

NIED-NEES, August 3, 2005

MEXT-NSF, Sept 13, 2005

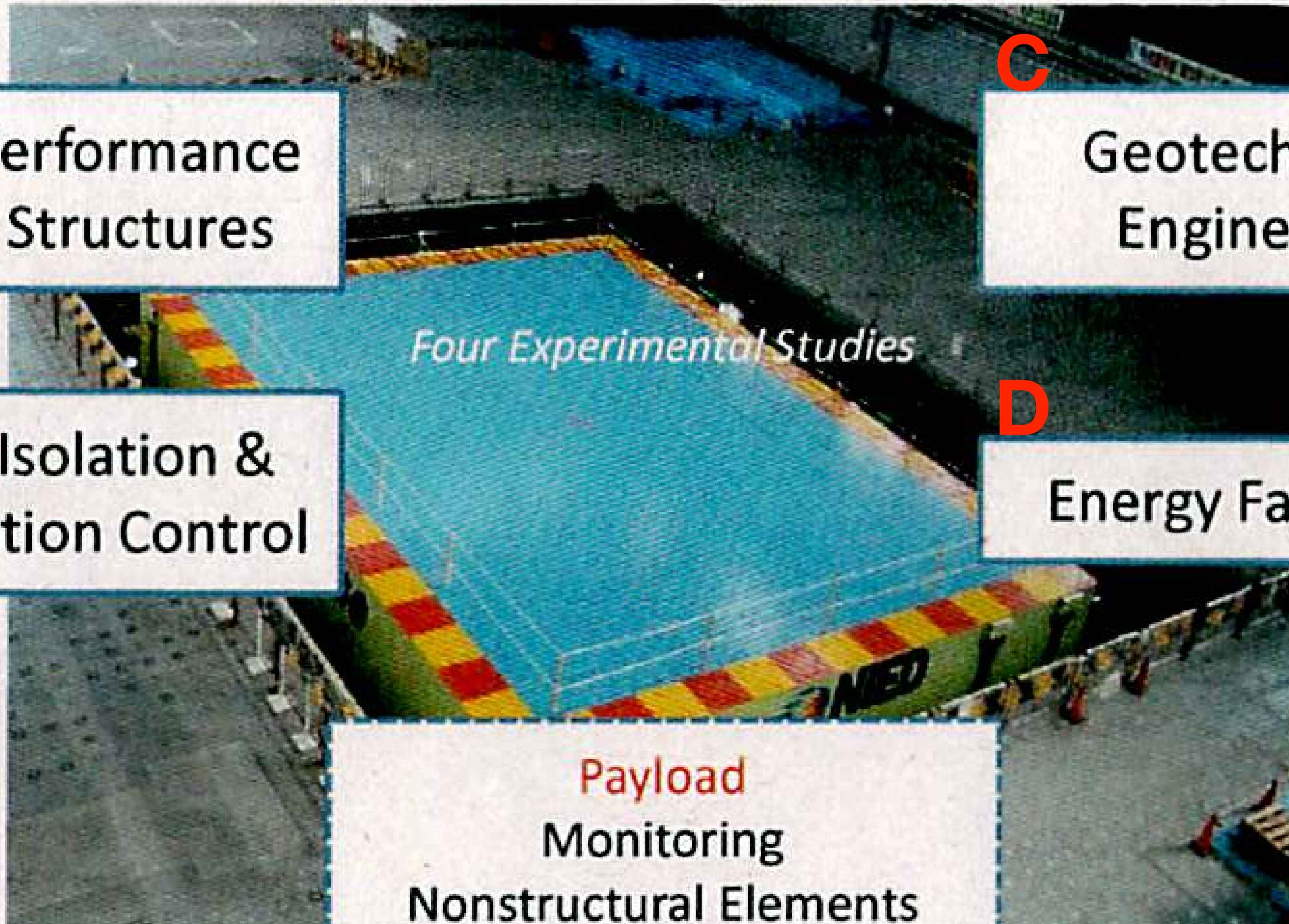
Resolutions Adopted in First Joint Planning Meeting for Second Phase of NEES/E-Defense Collaborative Research
Washington DC, USA
January 11 to 12, 2009

Resilient City as a Common Meta-Theme

The three meta-themes discussed in the meeting, i.e., "**Disaster Resilient Communities**", "**Preparing for the Big One**", and "**Low-Probability, High-Consequence Events**" are linked in many ways. The fundamentals of the first meta-theme are the damage reduction and quick recovery. These require developments of new materials and technologies that would enhance the performance of various components that form the urban area. Methods to detect the damage quickly and systems that can be repaired (or re-built) with minimal interruption of life and business are also the important topics to consider. In the second meta-theme, developments of new materials and technologies are the key to the prevention of a downward spiral of deterioration. The third meta-theme has much in common with the preceding two in light of the specific scientific challenges to be pursued. Thus, it was agreed that the 'Resilient City' provided a mutually important goal upon which members of the US and Japanese earthquake engineering communities could work and that US-Japan collaboration would accelerate realization of this goal and leverage the resources available in both countries.

Introduction of NIED Earthquake Engineering Project

Second Phase: 2010〜



A

High Performance
R/C Structures

B

Base Isolation &
Vibration Control

C

Geotechnical
Engineering

D

Energy Facilities

Payload
Monitoring
Nonstructural Elements

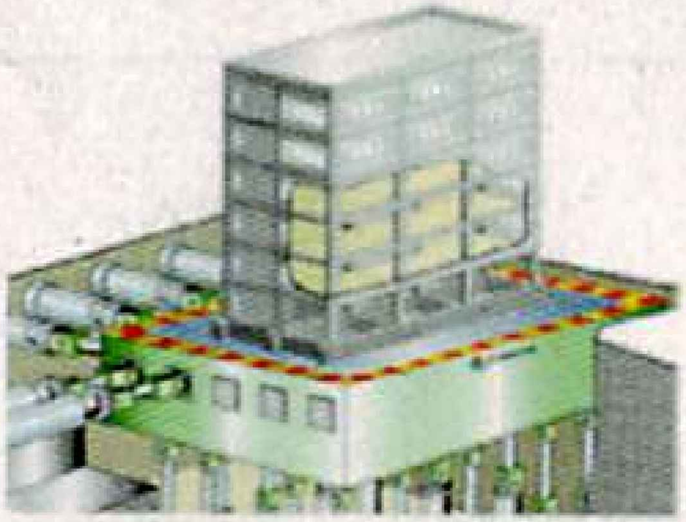
Data Archival System

Numerical Simulation

Four Experimental Studies

A
High Performance R/C Structures

Takuya Nagae
Kenichi Tahara



- ✓ High-strength concrete and steel
- ✓ High-performance walls
- ✓ Self-centering systems

➢ Verify seismic performance of reinforced concrete building structures in which new materials, new elements, and new systems are incorporated.

C
Geotechnical Engineering

Kentaro Tabata
Yousuke Kawamata

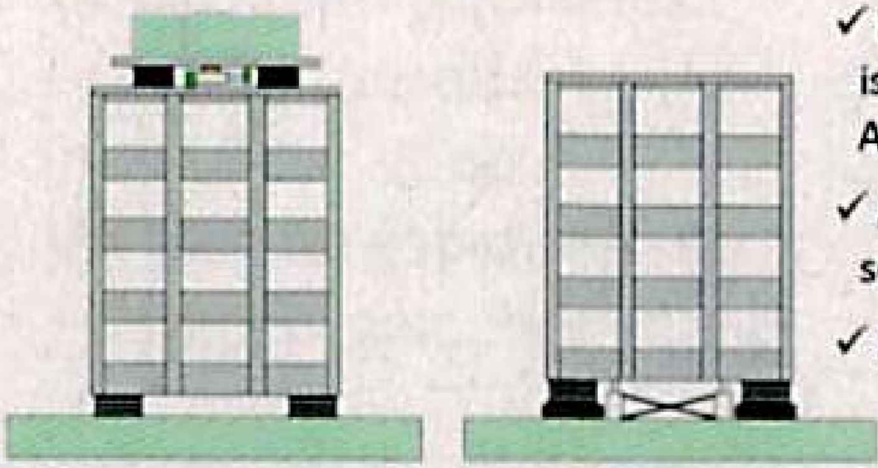
shear soil container

Targets = transportation systems in an urban area (subways, railroads, expressways...)

➢ Investigate behavior of underground structures such as shielded/cut-and-cover tunnels, curves, complicated sections, traversing heterogeneous layers.

B
Base Isolation & Vibration Control

Eiji Sato
Taichiro Okazaki



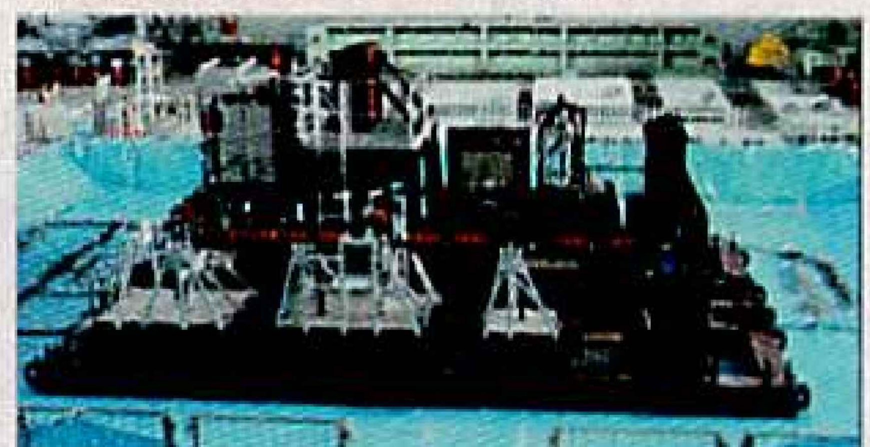
- ✓ Hybrid seismic isolation with TMD or AMD
- ✓ Active or Semi-Active seismic isolation
- ✓ 3D seismic isolation

➢ Develop next generation seismic isolation and vibration control systems that mitigates both long period and short period earthquake motions.

D
Energy Facilities

Izumi Nakamura
Manabu Nakayama

- Electric generating facilities
- High-pressure gas facilities, ...



- ✓ Piping systems
- ✓ Supports
- ✓ Containers
- ✓ Tanks, ...

➢ Clarify the seismic safety margins and structural integrity of energy facilities and their components under large seismic motions exceeding the design level.

Timetable of E-Defense Large-Scale Shaking Table Tests

Plan as of September 2009

	Fiscal year	2010	2011	2012	2013	2014	2015
A	High performance R/C structures	O		O			
B	Base isolation & vibration control		O		O		
C	Geotechnical engineering		O		O		
D	Energy facilities	O		O			

Plan as of September 2010

Japanese fiscal year begins on April 1.

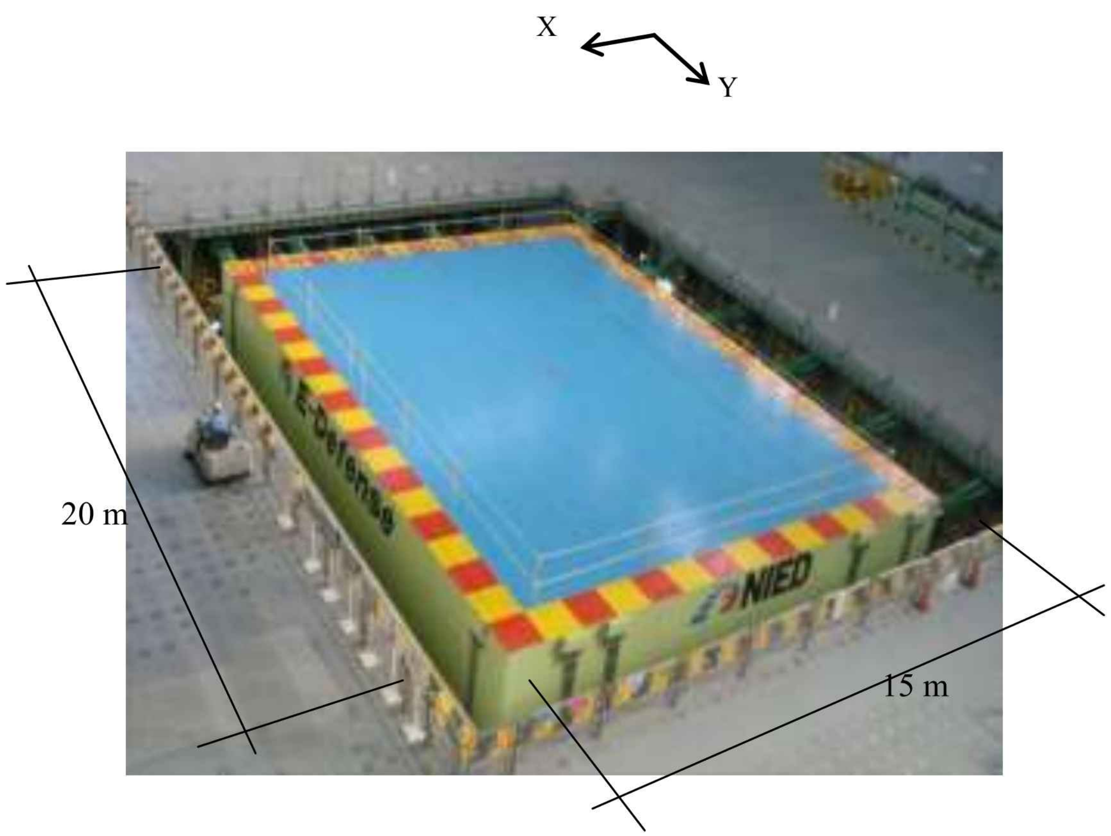
	Fiscal year	2010	2011	2012	2013	2014	2015
A	High performance R/C structures	O			O		
B	Base isolation & vibration control		NEES	O			O
C	Geotechnical engineering		O			O	
D	Energy facilities		O			O	
	Equipments, Nonstructural elements	o		o	o		o

Pending budget approval

Beam-column joint:

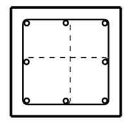
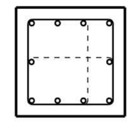
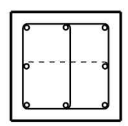
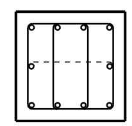
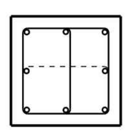
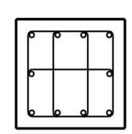
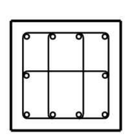
Full Scale Shaking Table Test at E-Defense in 2010

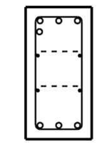
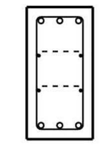
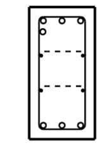
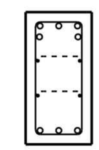
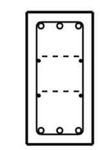
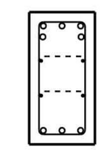
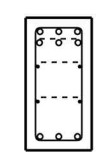
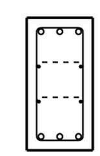
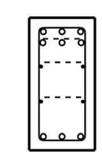
E-Defense test on RC Building in December 2010



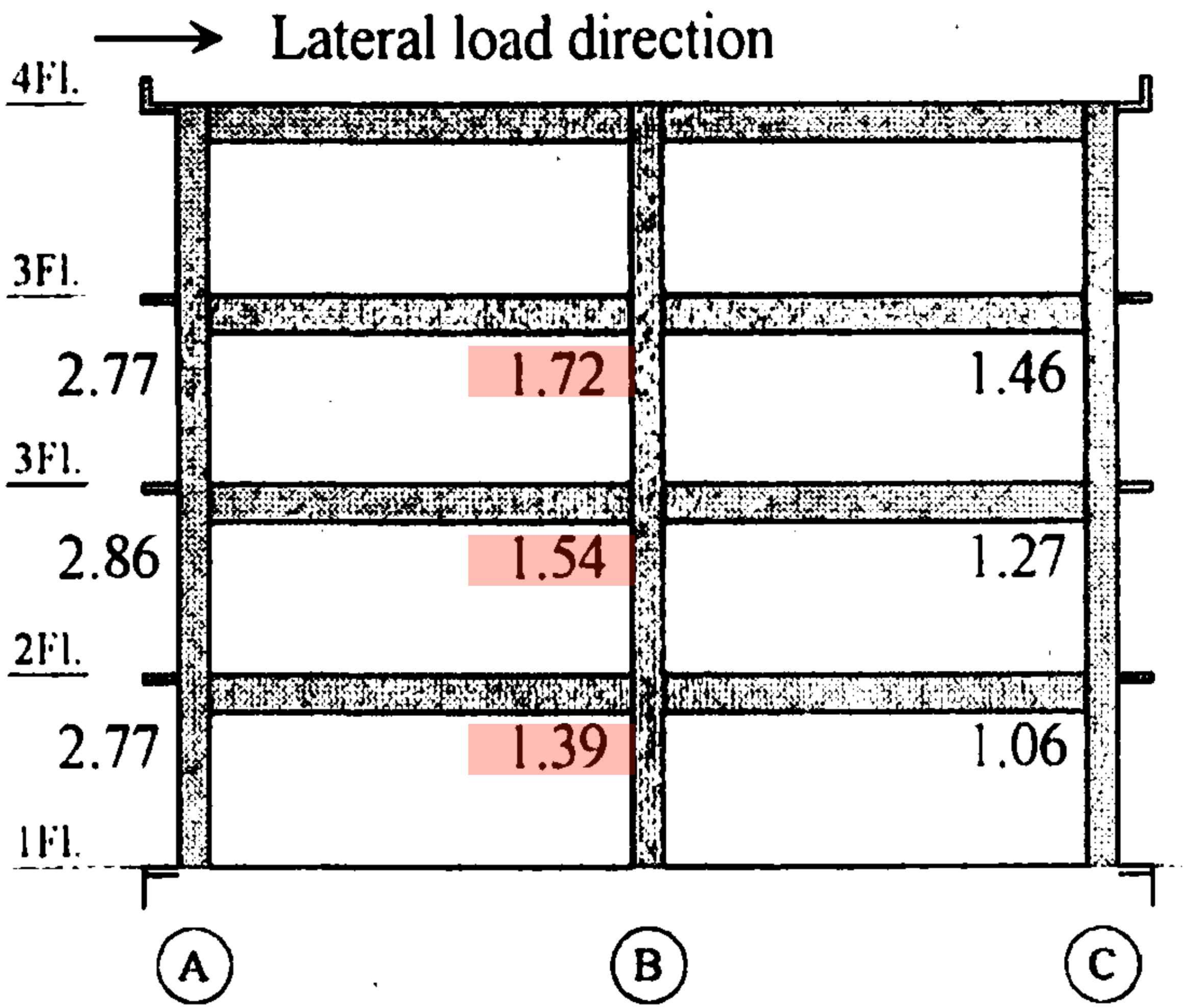
E-Defense 3D Shaking Table

Four Storied Wall-Frame
RC Structure

List of Column			
		C1	C2
4Fl. 3Fl.	Section		
	B x D	500 x 500	500 x 500
	Rebar	8-D22	10-D22
	Hoop	2,2-D10@100	2,2-D10@100
	Joint	2,2-D10@140	2,2-D10@140
2Fl.	Section		
	B x D	500 x 500	500 x 500
	Rebar	8-D22	10-D22
	Hoop	2,3-D10@100	2,4-D10@100
	Joint	2,2-D10@140	2,2-D10@140
1Fl.	Top Section		
	B x D	500 x 500	
	Rebar	8-D22	
	Hoop	2,3-D10@100	
	Joint	2,2-D10@140	
	Bottom Section		
	B x D	500 x 500	500 x 500
	Rebar	10-D22	10-D22
	Hoop	3,4-D10@100	3,4-D10@100
	Joint	2,2-D10@140	2,2-D10@140

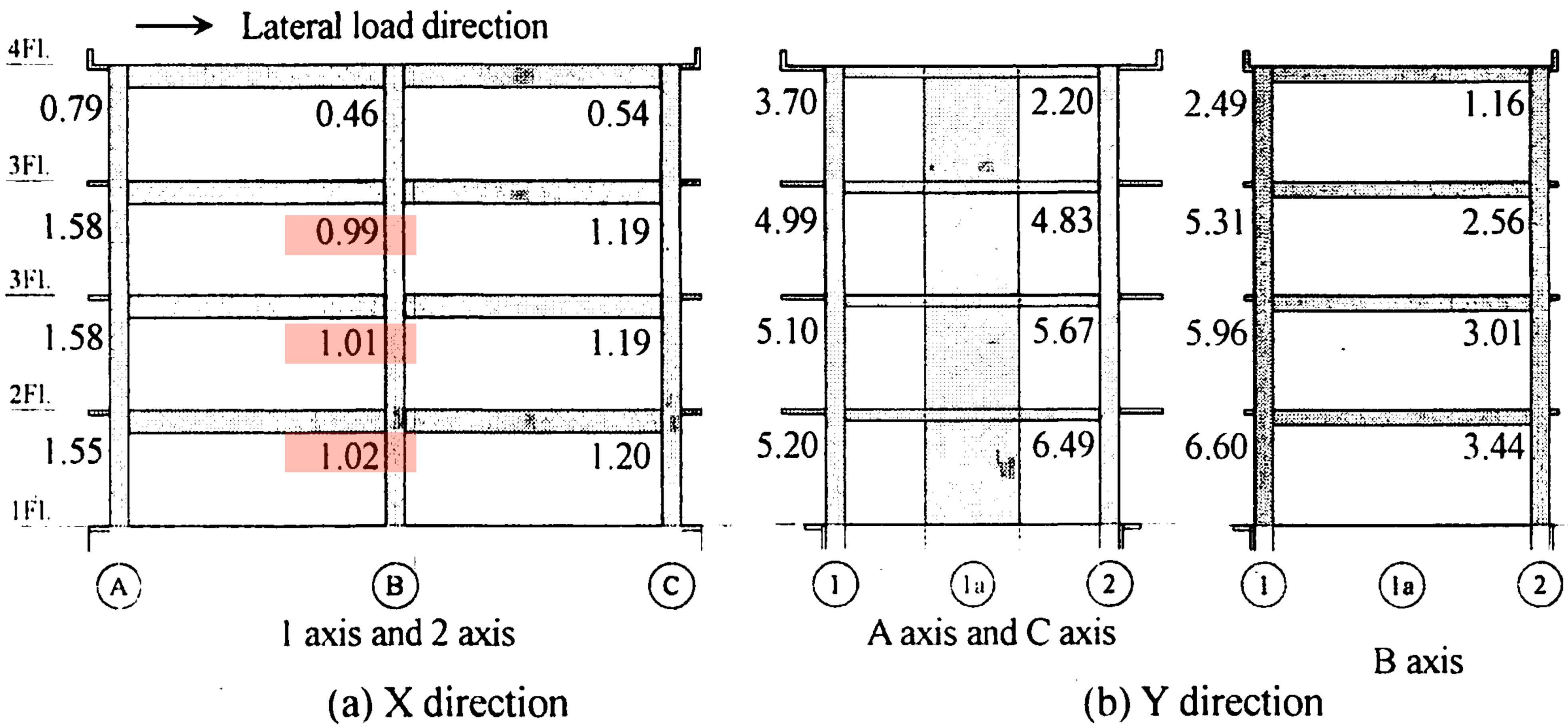
List of Girder				
		G1		
	Location	End	Center	End
RFl. 4Fl.	Section			
	B x D	300 x 600		
	Top	4-D22	3-D22	4-D22
	Bottom	3-D22	3-D22	3-D22
	Web	4-D10		
	Stirrup	2-D10@200		
3Fl.	Section			
	B x D	300 x 600		
	Top	5-D22	3-D22	5-D22
	Bottom	3-D22	3-D22	3-D22
	Web	4-D10		
	Stirrup	2-D10@200		
2Fl.	Section			
	B x D	300 x 600		
	Top	6-D22	3-D22	6-D22
	Bottom	3-D22	3-D22	3-D22
	Web	4-D10		
	Stirrup	2-D10@200		

Margin of joint shear capacity



Joint shear / Nominal joint shear capacity

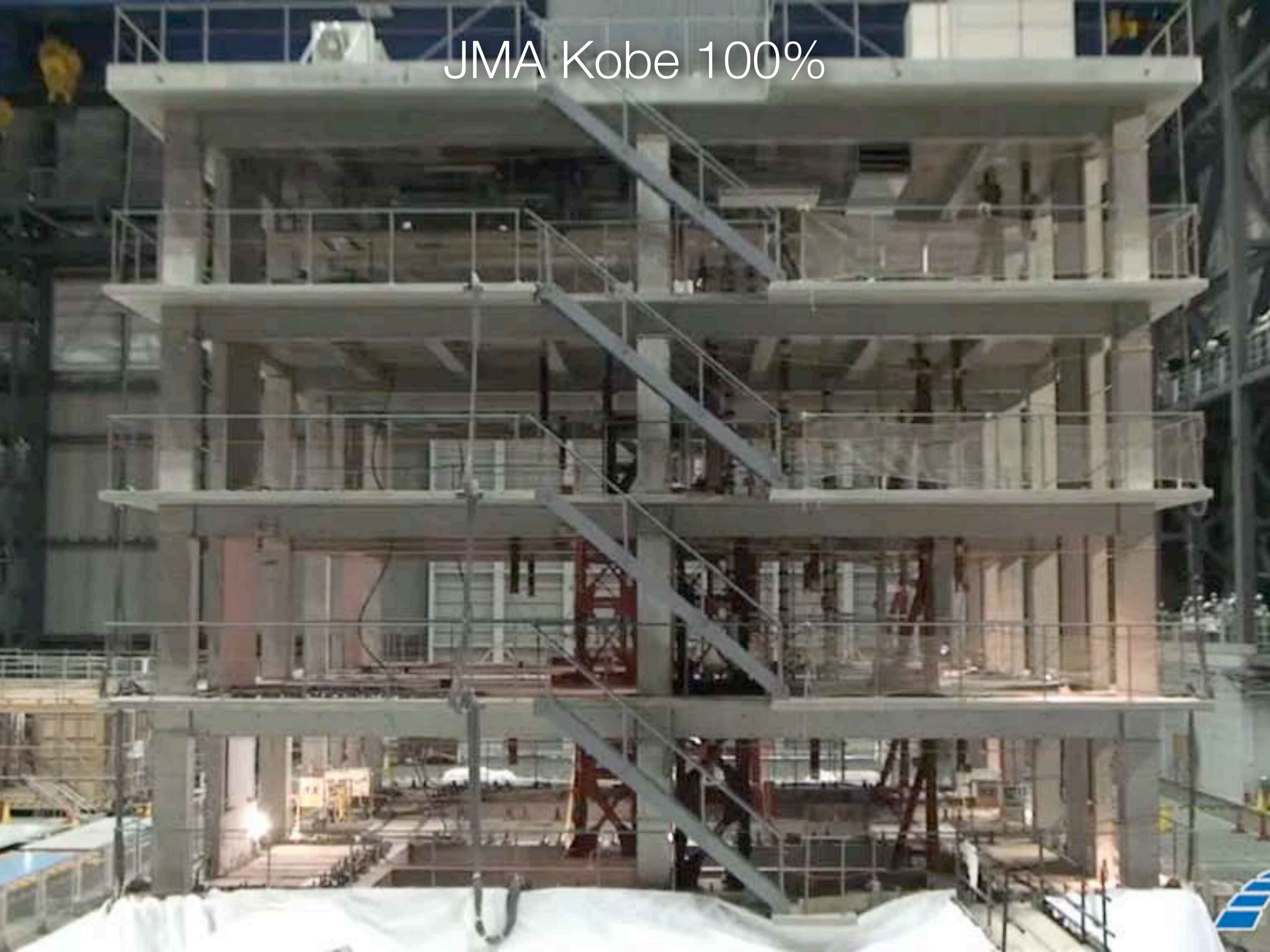
Column-to-beam strength ratio



Column-to-beam strength ratios

JMA Kobe 50%

JMA Kobe 50%


JMA Kobe 100%


JMA Kobe 100%
E-Defense
NIED

3D Full Scale RC Frame Structure Shaking Table Test at E-Defense in 2010

- *Four-story full scale RC frame structures were tested,*
  - The building structure was designed and constructed such that it conforms to current seismic provisions in Japan and the US.
- *Shear failure of lightly reinforced beam-column joints were confirmed,*
  - BC joints with column-to-beam strength ratio between 1.0 showed joint shear failure.
  - Vulnerabilities of frame structure with lightly BC joint has been demonstrated.

SEISMIC DAMAGE OF A NINE-STORY RC RESIDENTIAL BUILDING IN SENDAI DESIGNED BY OLD SEISMIC CODES

Nagamachi - Dwelling Complex

Brief History of RC buildings and Seismic Codes in Japan

1968 1971 1978 1981 1995 2000 2011

- **1968 Tokachi-oki Earthquake**

*BSL : Building Standard Law

- **Amendment of BSL Enforcement Order**
  (Prevention of column shear failure)

- **1978 Miyagiken-oki Earthquake**
- **Amendment of BSL Enforcement Order**
  (The "shin-taishin", new standard)

- **1995 Hyogo-ken Nambu Earthquake**
  (Effectiveness of the 1981 revision was confirmed)
- **Act on Promotion of Seismic Retrofitting of Existing Buildings**
  (To urge building owners to retrofit existing vulnerable buildings)
- **Amendment of BSL Enforcement Order**
  (Performance based criteria introduced)

I ～ 1971

II ～ 1981

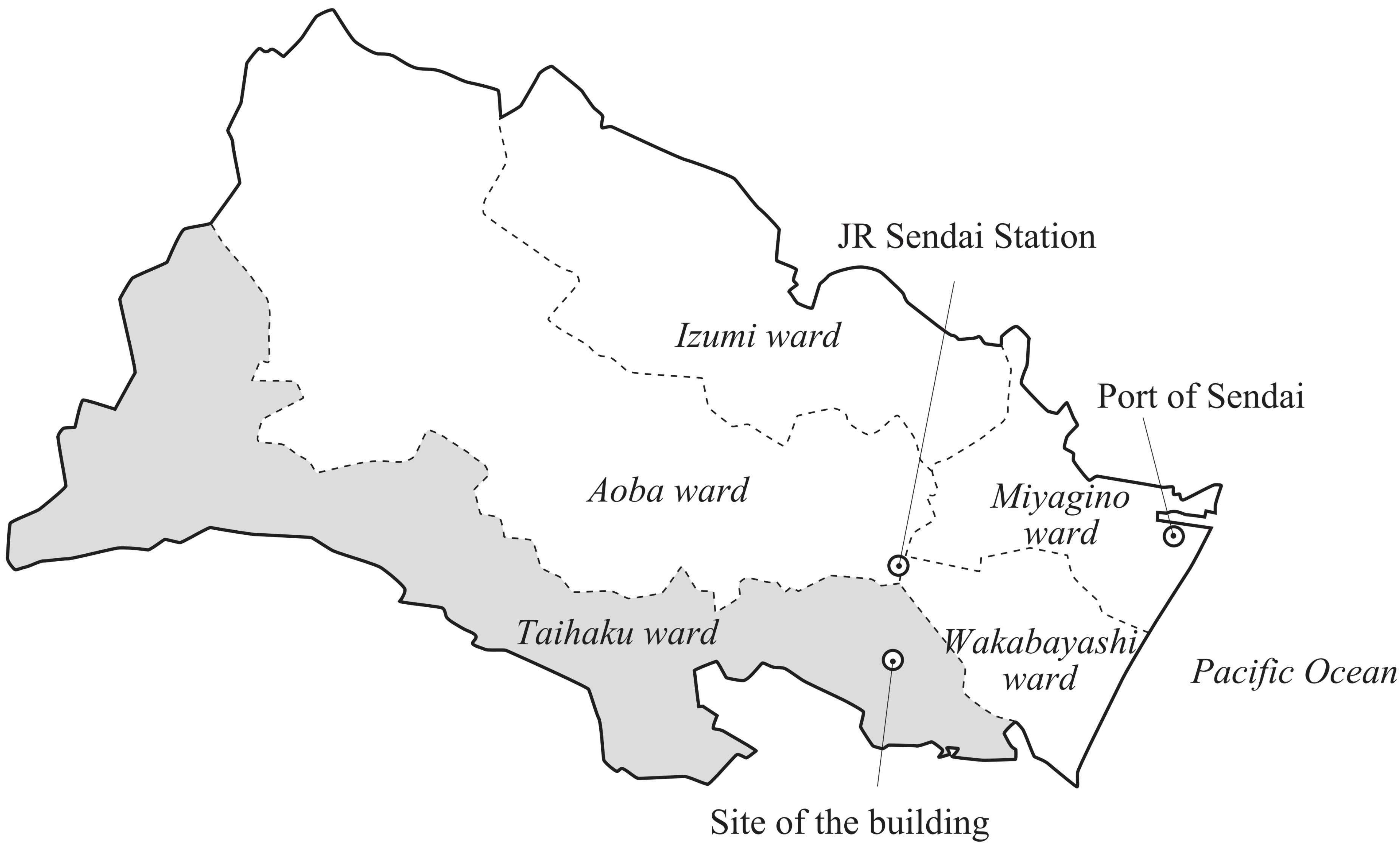
III 1981 ～

- **2011 Tohoku-chiho Taiheiyo-oki Earthqukae**

Nagamachi - Dwelling Complex

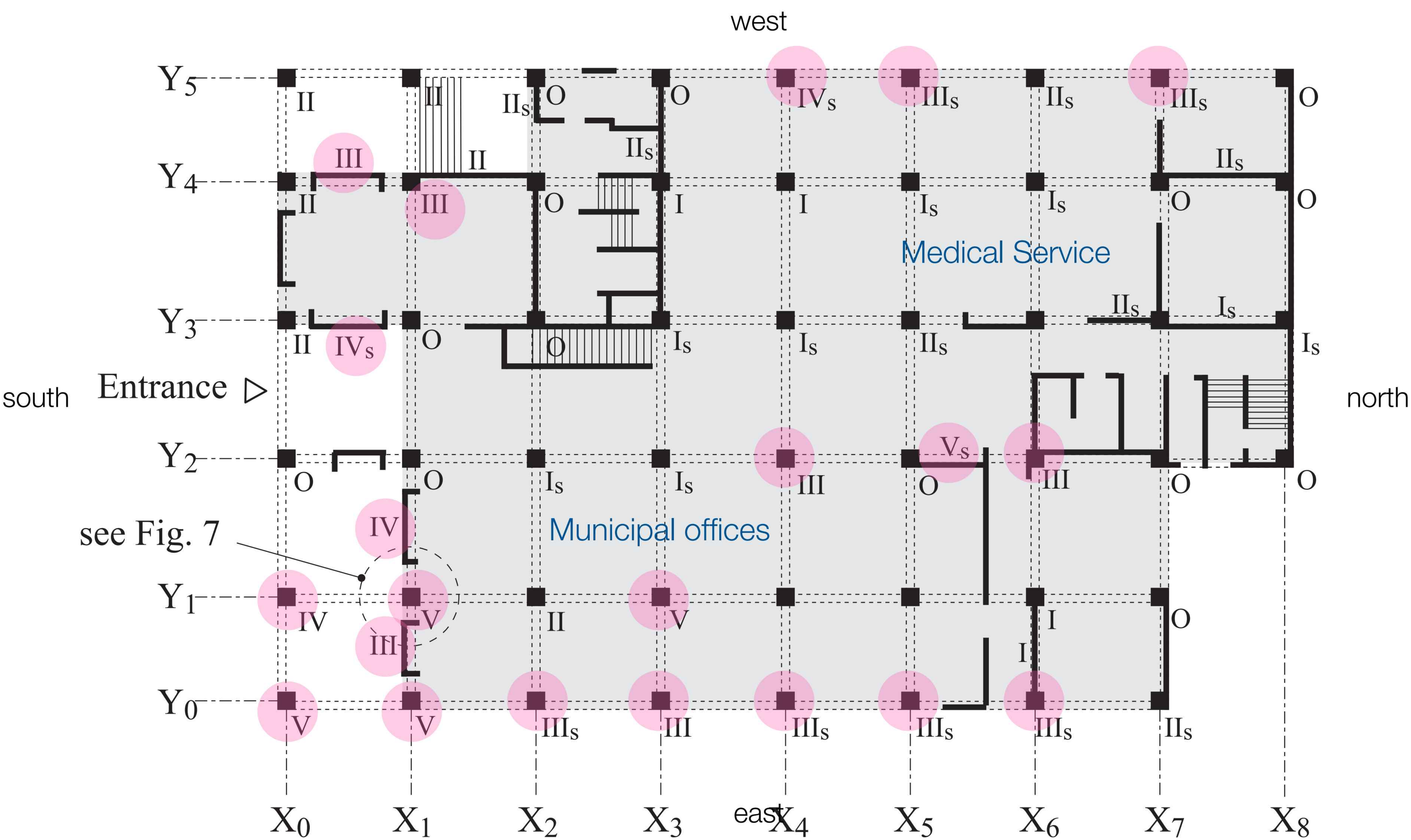
- RC/SRC 9 floors.
- Completed in 1969
- No seismic retrofit
- Survived major earthquakes in 1978, 2003 and 2005.
- Fc 210 & 180
- Grade SD35 rebars

Taihaku ward, Sendai City



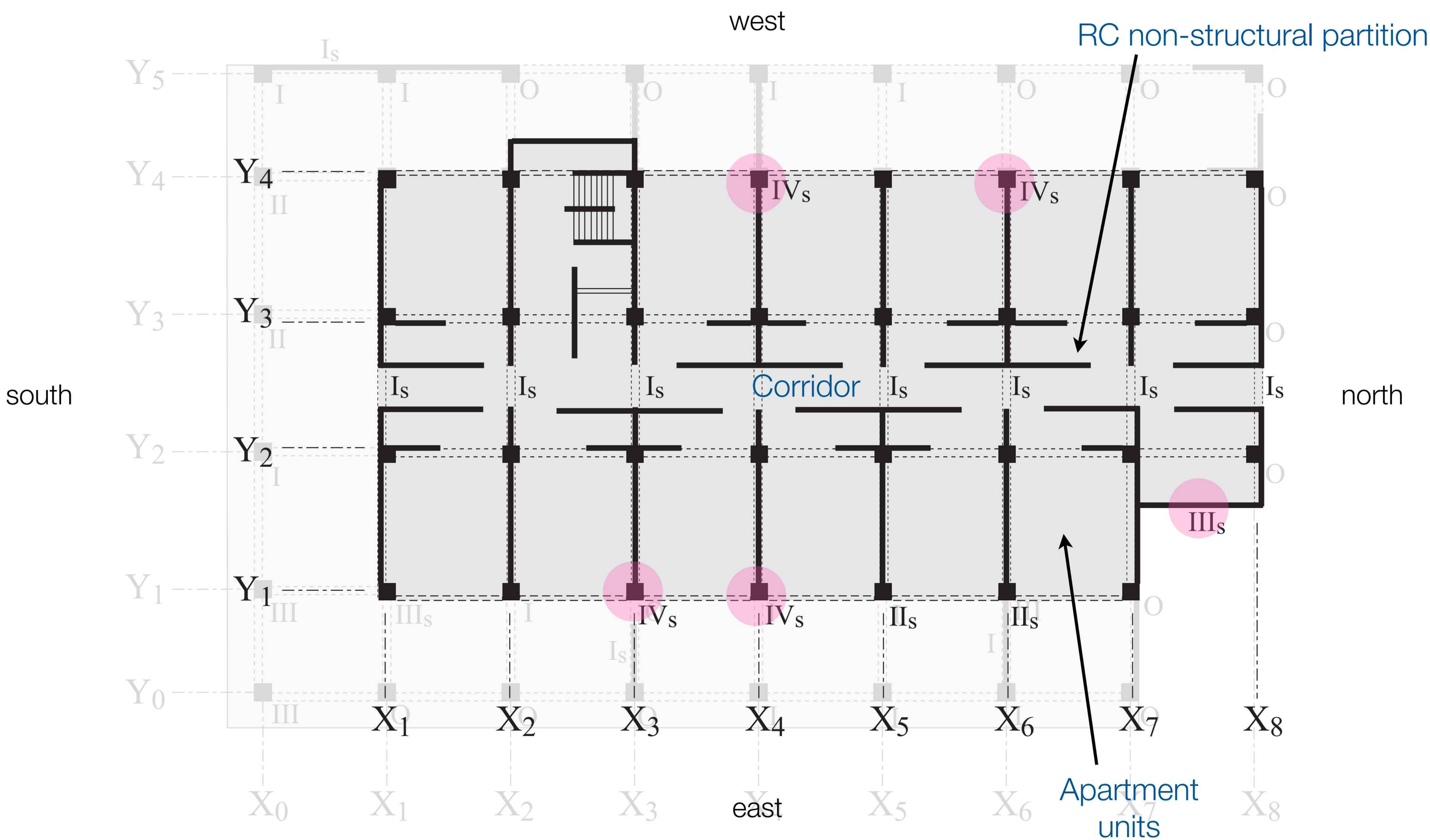
City of Sendai

1st floor plan and damage rate



2nd floor plan and damage rate

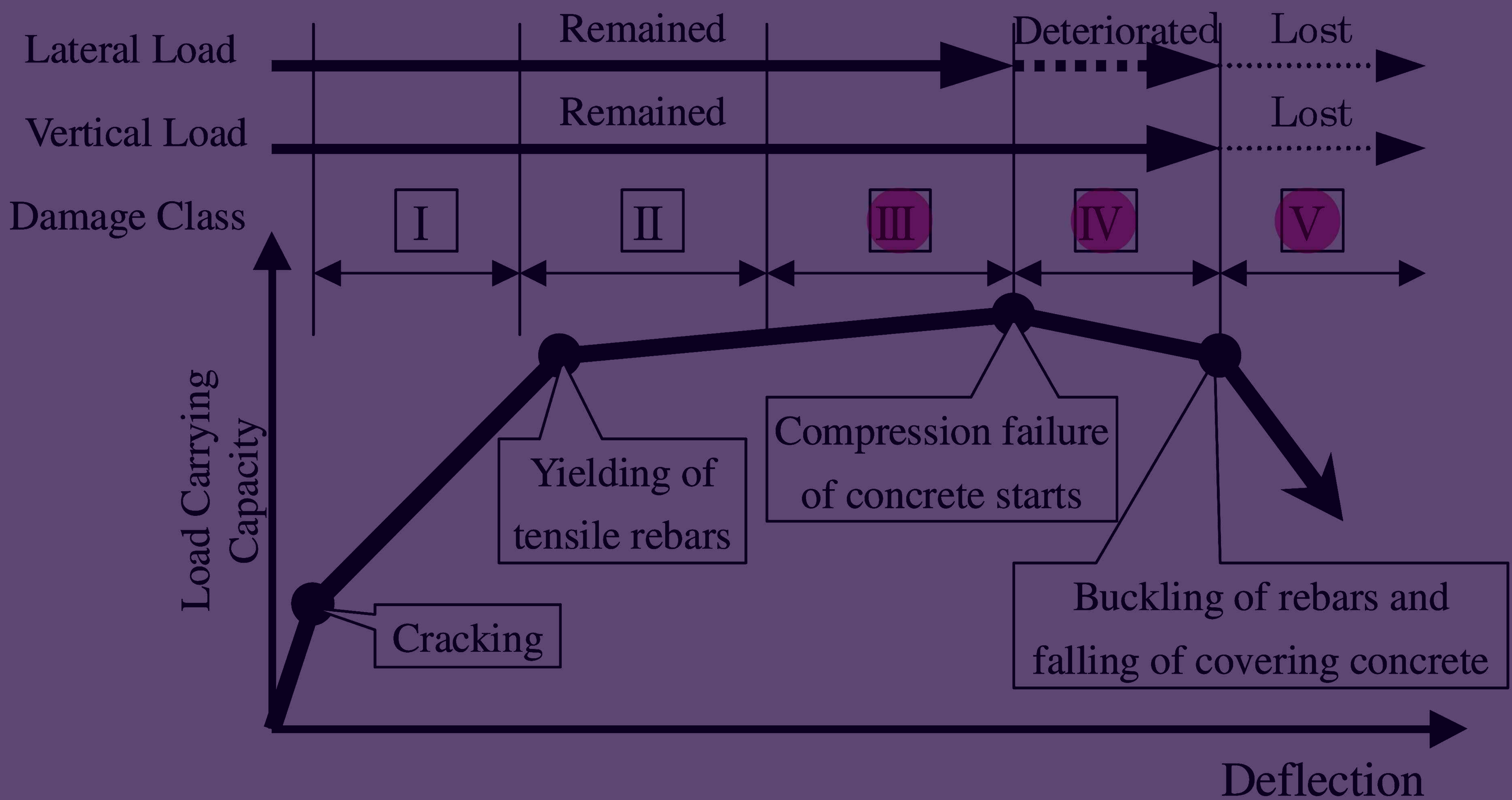
3rd floor plan and damage rate



Damage Grading Criteria of RC Members

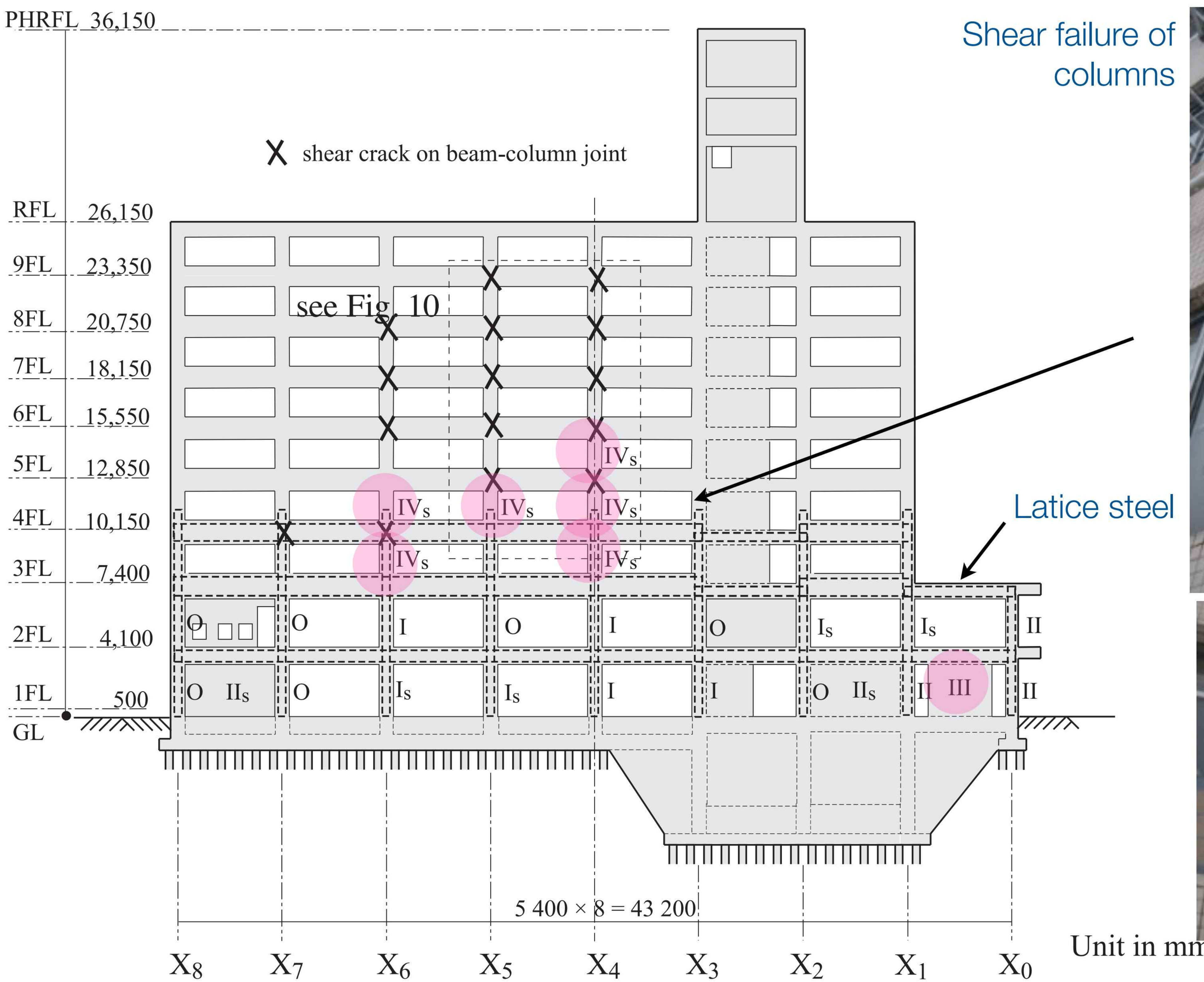
Damage grade		Criteria
0	No damage	No damage
I	Slight	Structural concrete cracking of width less than 0.2mm
II	Minor	Structural concrete cracking of width larger than 0.2mm and less than 1.0mm.
III	Moderate	Structural concrete cracking of width larger than 1.0mm and less than 2.0mm.
IV	Major	Structural concrete cracking of width larger than 2.0mm, with cover concrete spalling and visible reinforcement
V	Severe	Cover concrete spalling off, with some concrete crushes and longitudinal reinforcement buckling

Residual Lateral Capacity of RC Structural Member

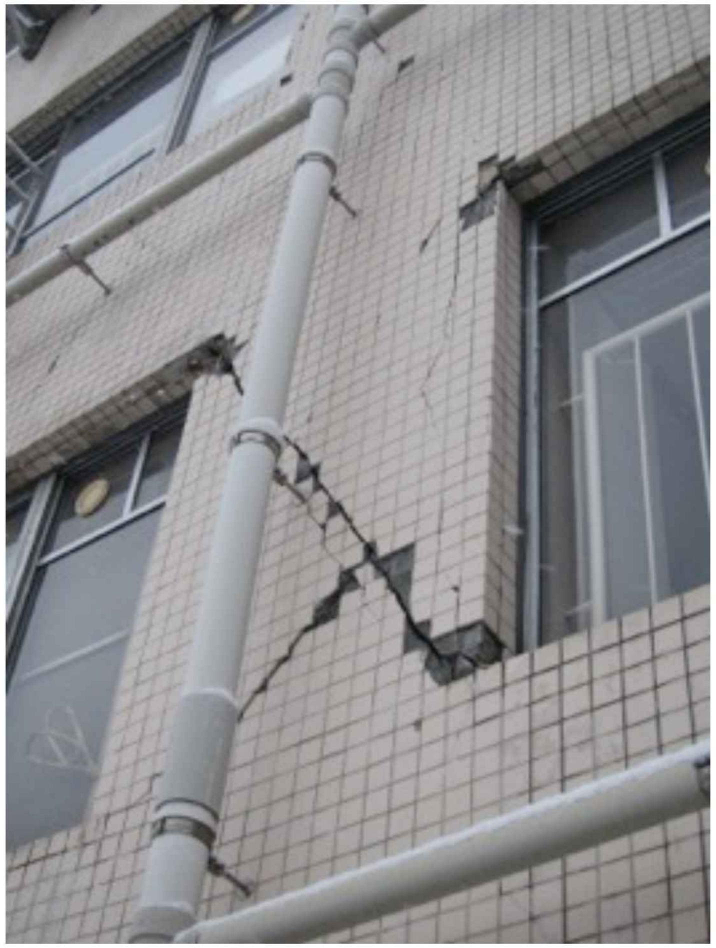


(a) Ductile member

Elevation of Y_4 frame in longitudinal direction



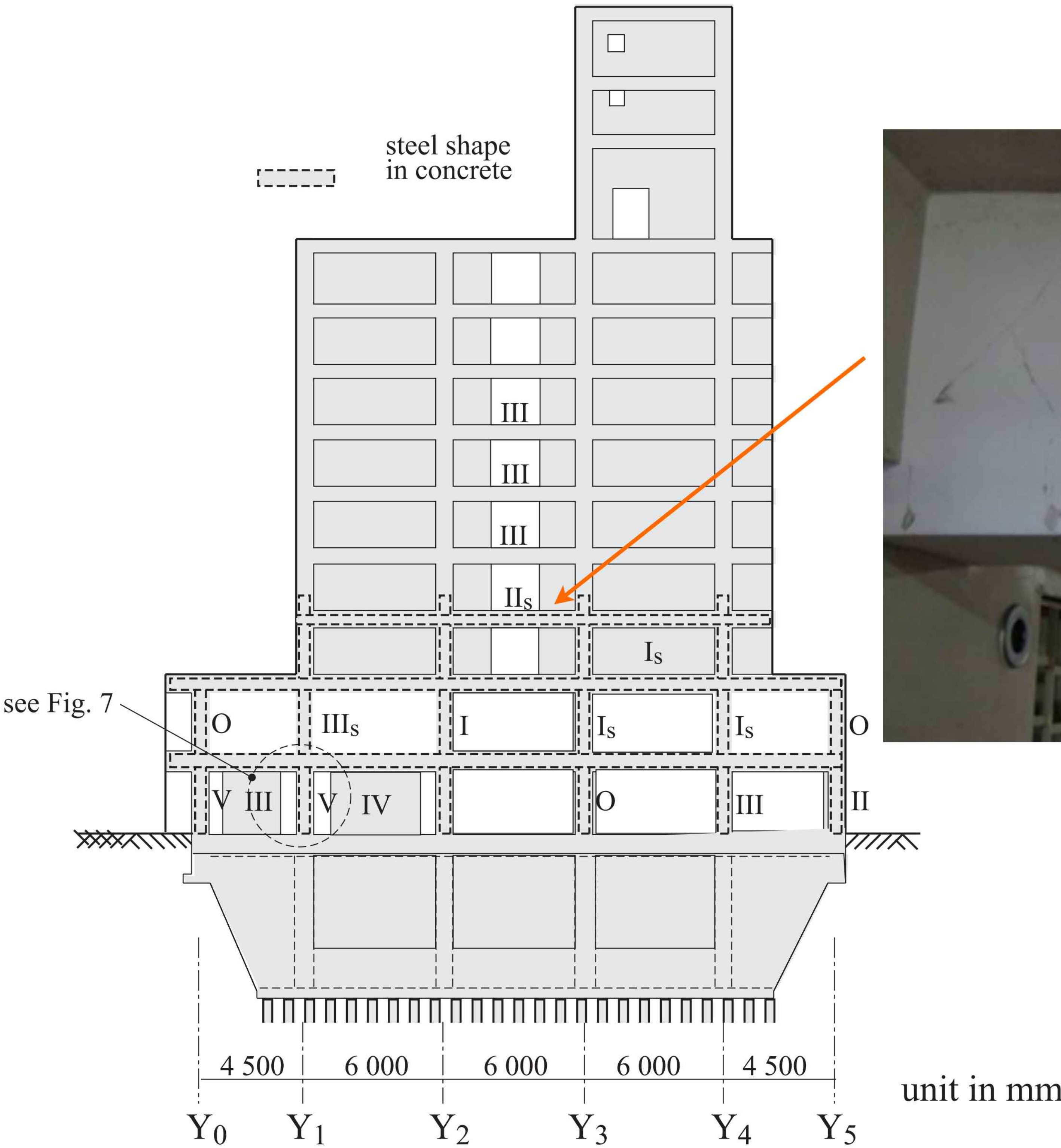
Shear failure of columns




Failure of Beam-column Joints

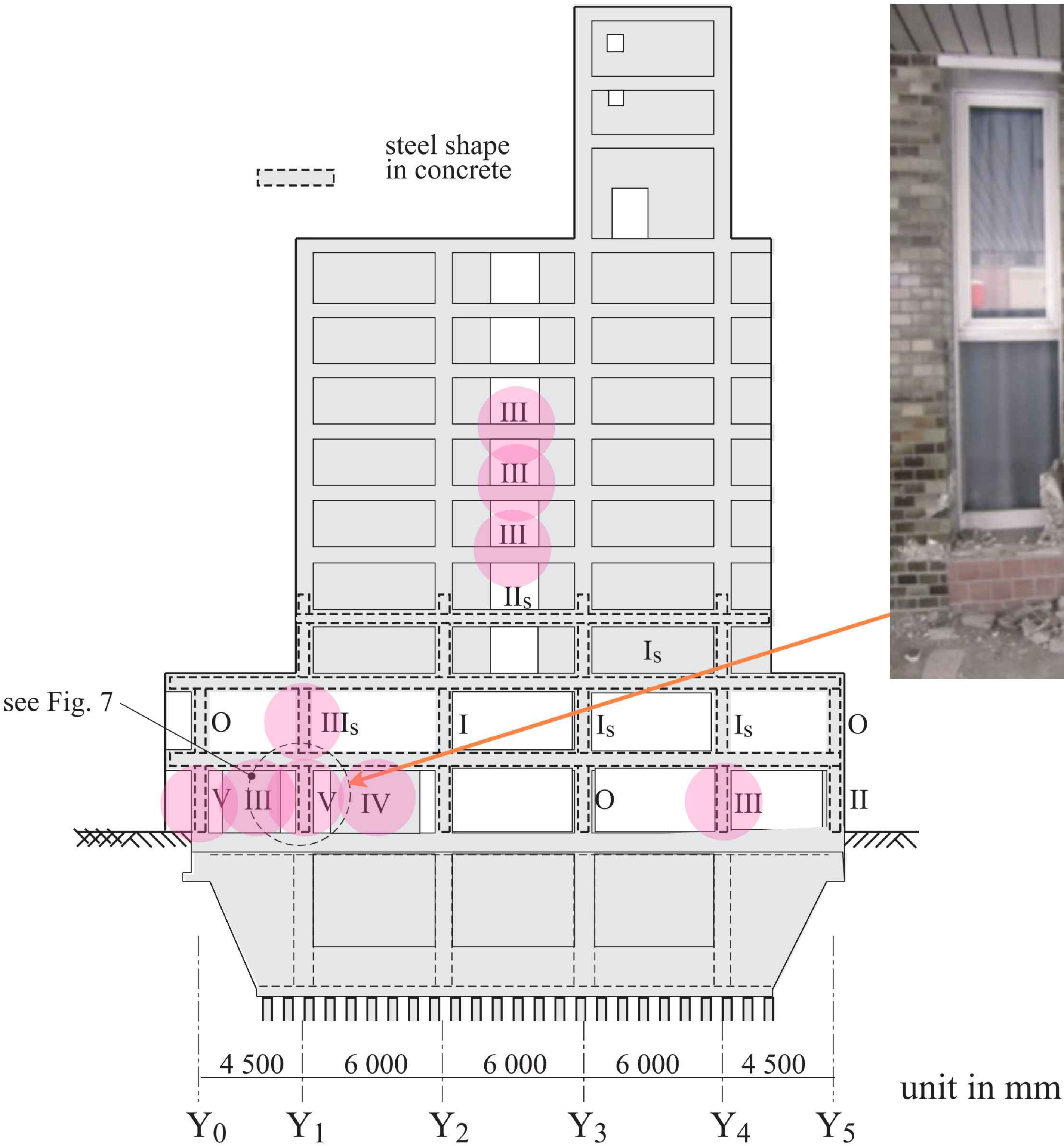
Failure of Beam-column Joints

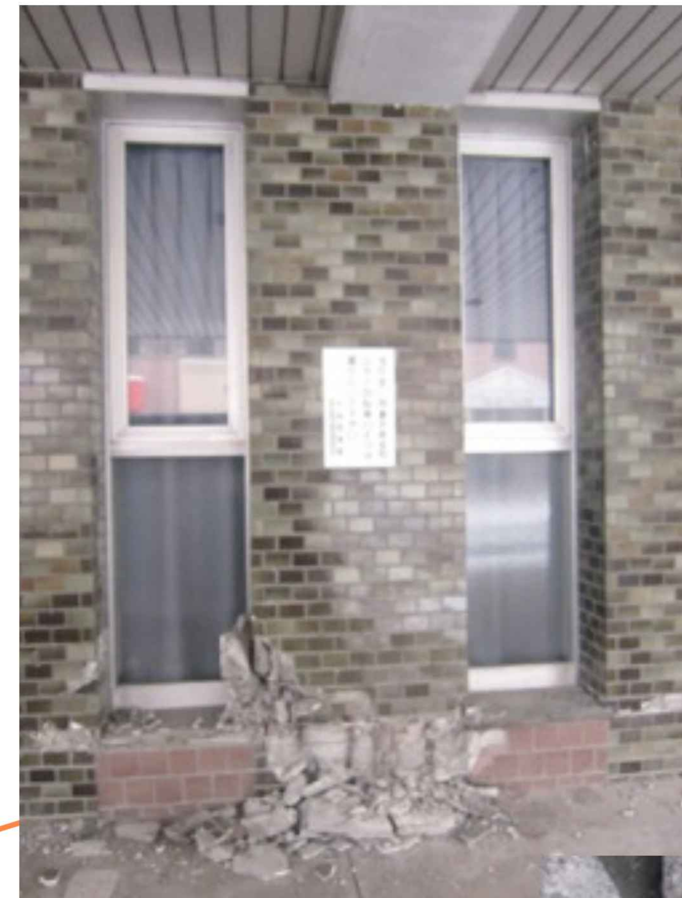
Elevation of X_1 frame in longitudinal direction



shear cracks on coupling beams

Elevation of X_1 frame in longitudinal direction





flexural failure and buckling of rebars at the bottom of column

Values of Seismic Index I_s

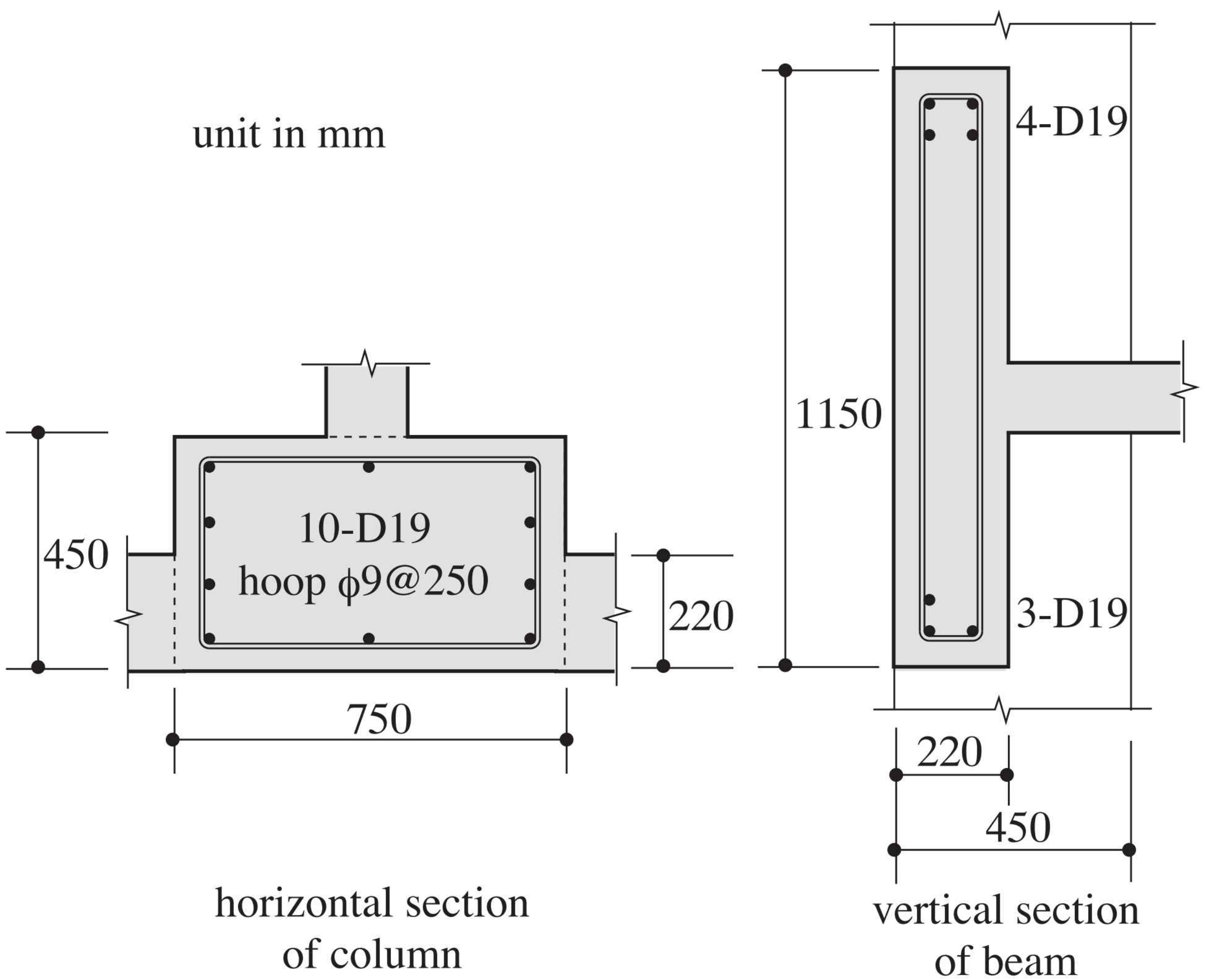
Story	Longitudinal direction	Transverse direction
9	0.37	1.49
8	0.27	1.04
7	0.23	0.82
6	0.20	0.70
5	0.21	0.62
4	0.19	0.51
3	0.20	0.71
2	0.44	0.44
1	0.62	0.39

no good correlation

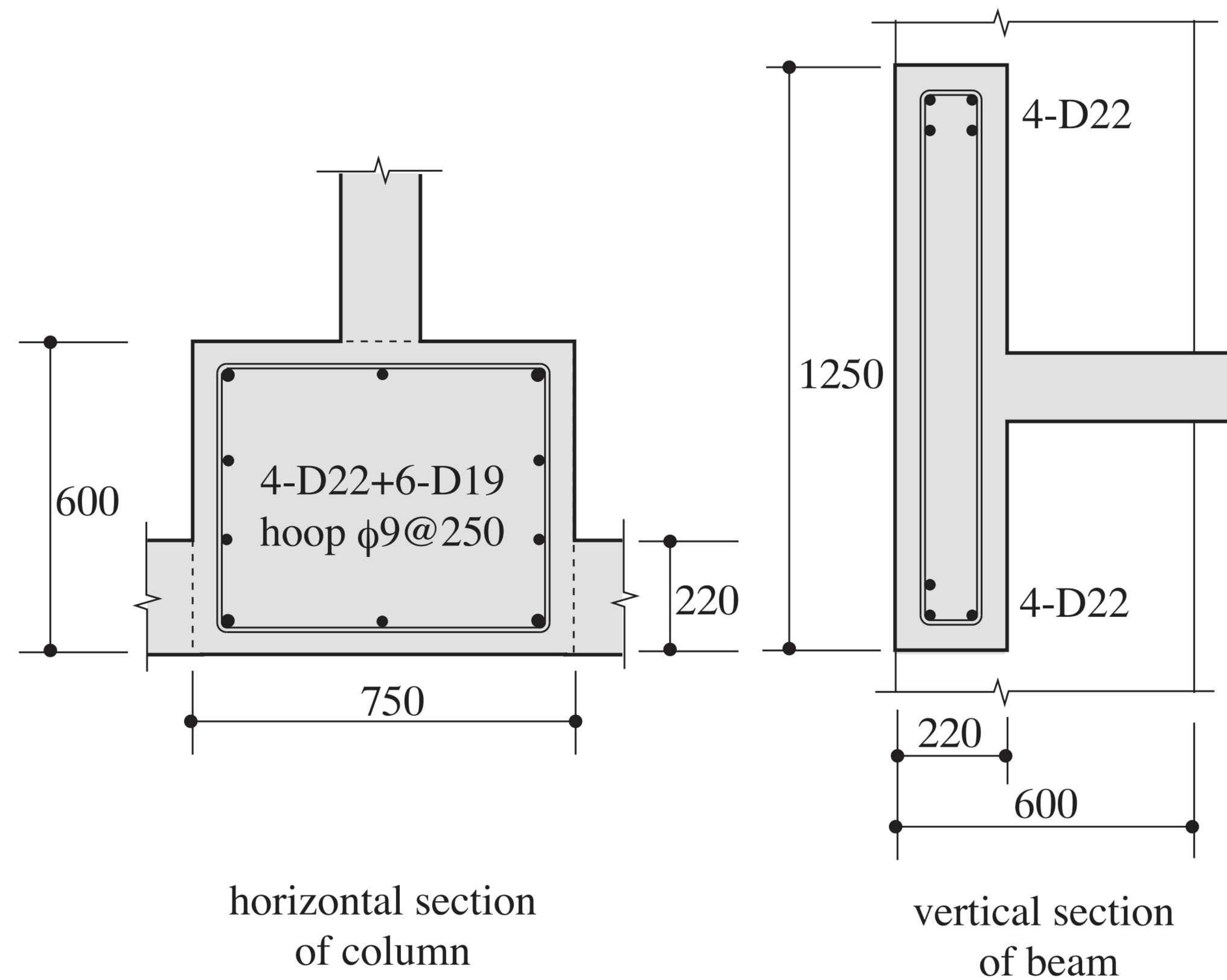
good correlation

Seismic Evaluation Standards by JBDPA

Beam-column Joints in Y_4 frame

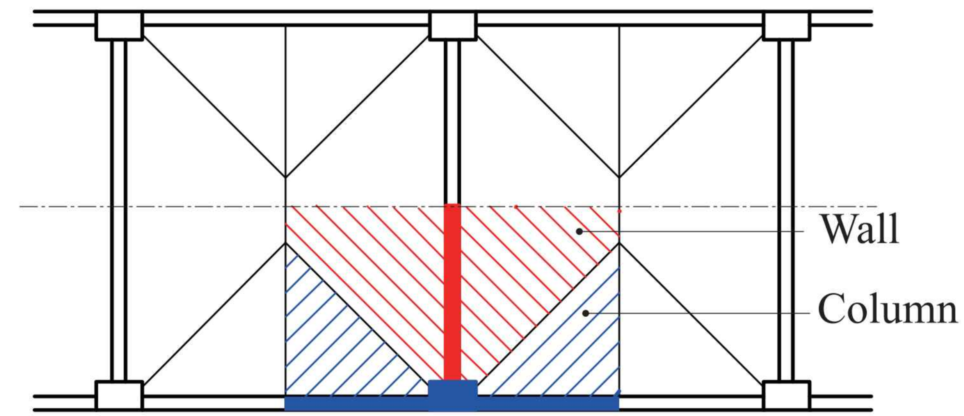


(a) Beam-column joint at 7F (X_5-Y_4)



(b) Beam-column joint at 5F (X_5-Y_4)

Calculated story shear



floor plan
Tributary area of gravity load

	Shear failure in kN			Flexural hinge in kN			Column-to-beam strength ratio		Joint shear strength margin*
	column	beam	joint	column case 1*	column case 2*	beam	case 1	case 2	
9FL	544.4	858.7	863.4	522.5	396.7	231.7	2.25	1.71	3.73
8FL	555.0	929.1	984.0	650.8	454.0	320.2	2.03	1.42	3.07
7FL	589.2	1043.2	1112.3	751.5	496.7	335.0	2.24	1.48	3.32
6FL	799.7	1148.5	1150.1	906.6	574.8	432.2	2.10	1.33	2.66
5FL	907.8	1162.5	1624.0	1082.9	664.0	528.3	2.05	1.26	3.07

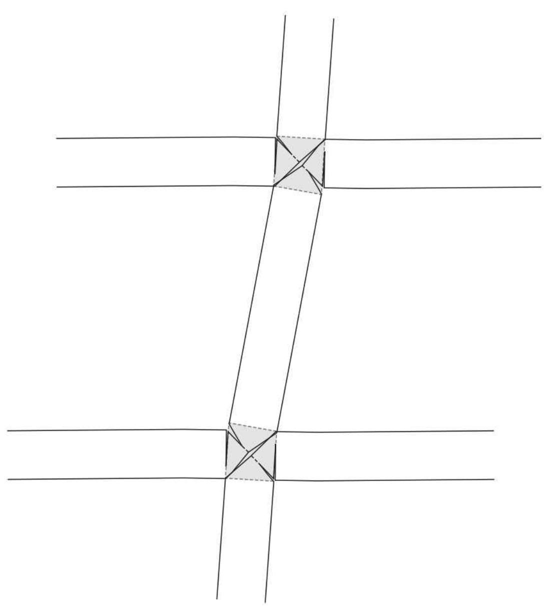
Concluding Remarks

- Nagamachi Dwelling Complex Building
- Flexural failure of the first story SRC column
    - deficiency of steel lattice not embedded into the foundation which just ends at the first floor level.
    - abrupt change of section caused the damage.
- Shear failure of lightly reinforced beam-column joints.
    - calculated margin of joint shear strength is 2.0 or more.
    - column-to-beam strength ratio is in the range of 1.26 to 1.48.
    - vulnerablity of column-to-beam strength ratio between 1.0 and 1.5 are to joint shear failure.
    - problem in failure mode prediction

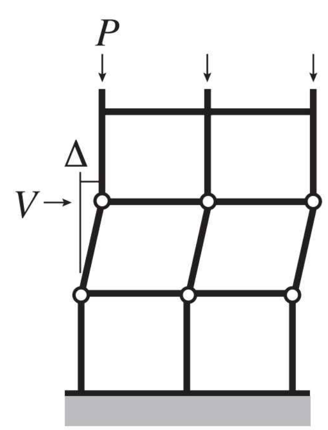
New beam-column joint macro element and nonlinear dynamic analysis on 4 story frame RC structure

Life Safety Requirements to Beam-Column Joint

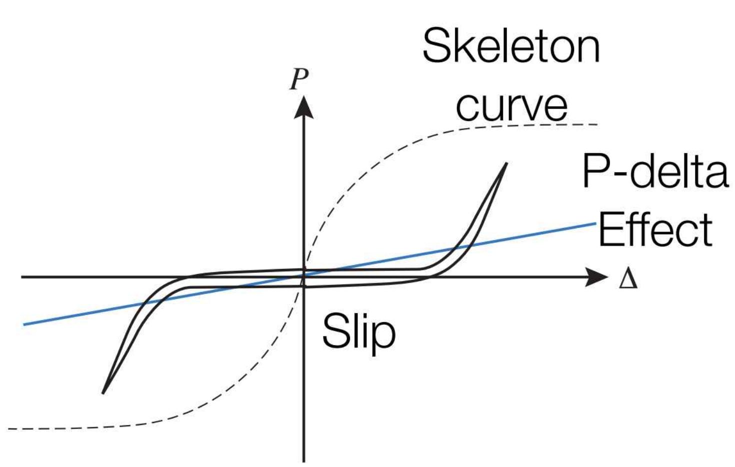
- *Members; beams or columns framing into the joints*
  - Full flexural capacity of the members to be achieved ← **Not easy to meet in practice**
- *Control Joint hinging in seismic Design*
  - Performance to prevent collapse and instability of lateral resisting frame due to subsequent repetitions of earthquake loading needs to be evaluated.



Joint hinging



Collapse mechanism by Joint hinging

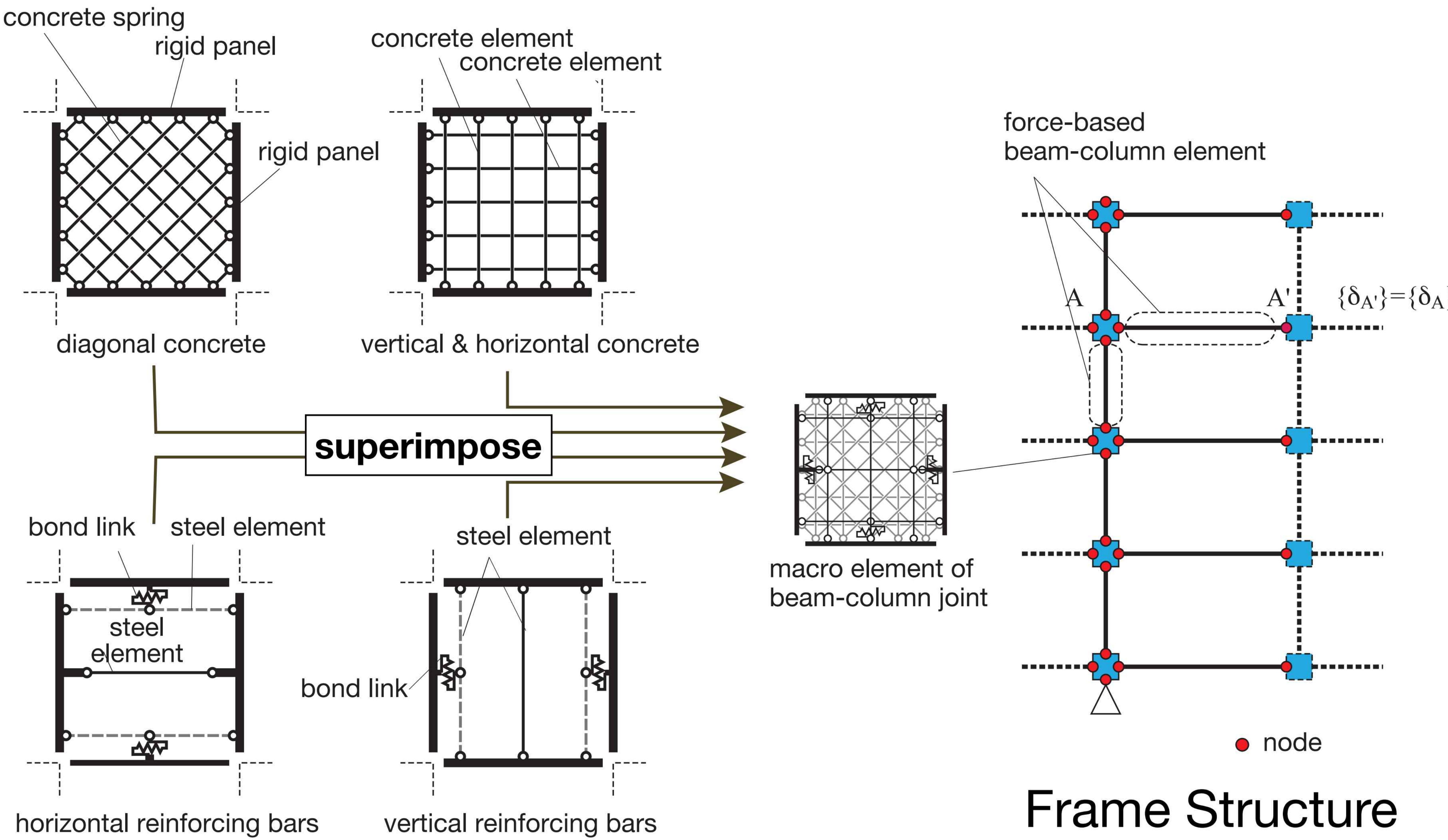


Subsequent repetition due to Cyclic loading

Collapsed Structure : Wencheuan Earthquake (2008)

- *No suitable model has been developed before.*

New Macro Element for Interior BC Joint

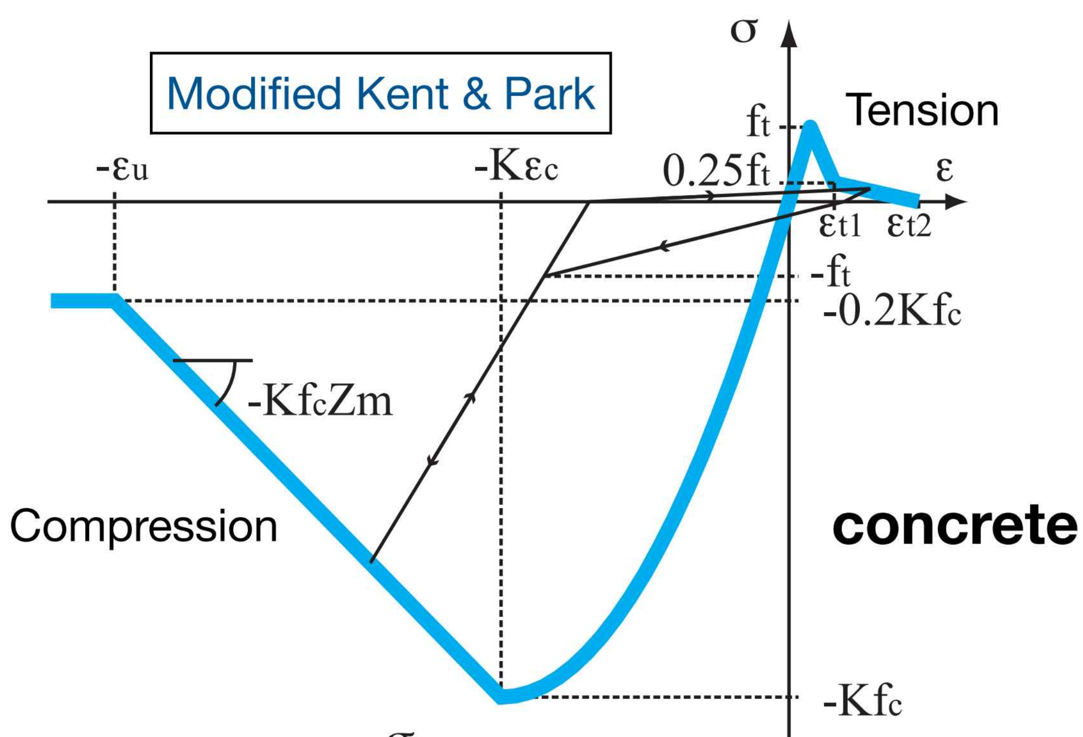


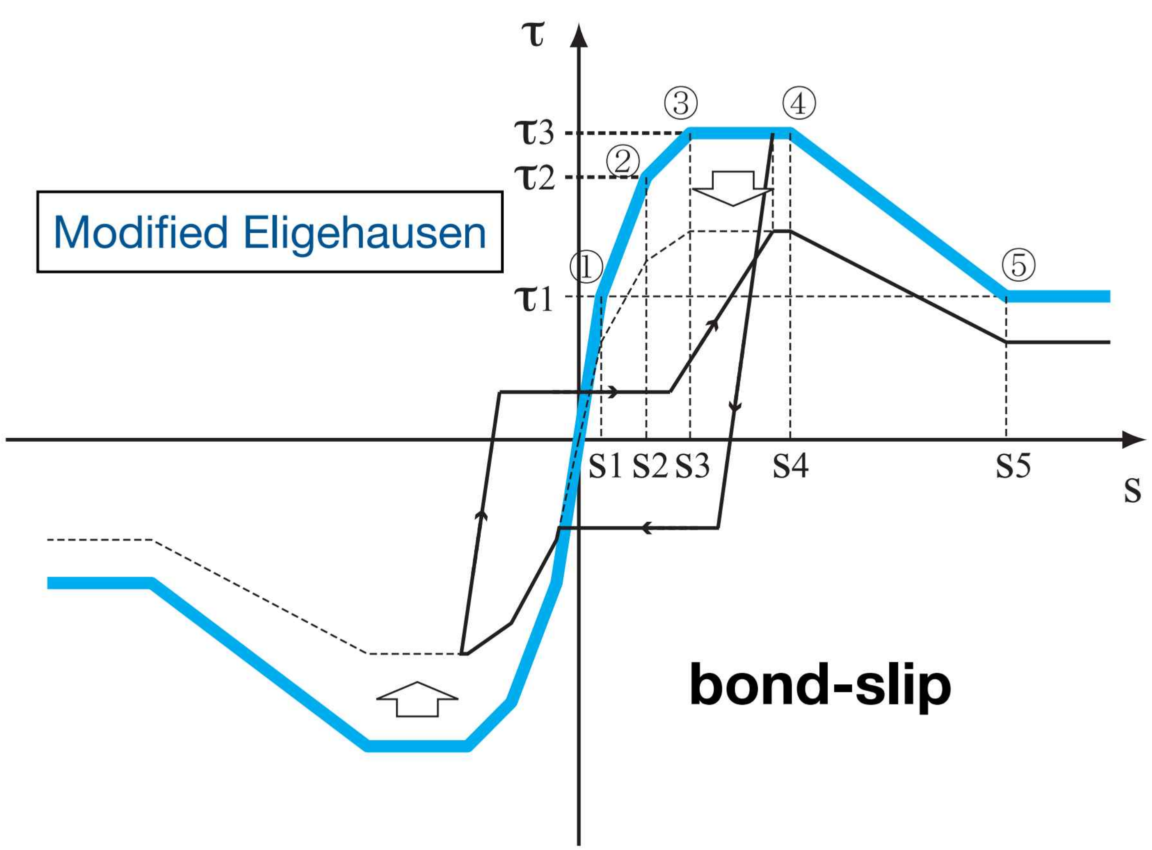
steel element axial stiffness is factored considering pull-out of bars from member end

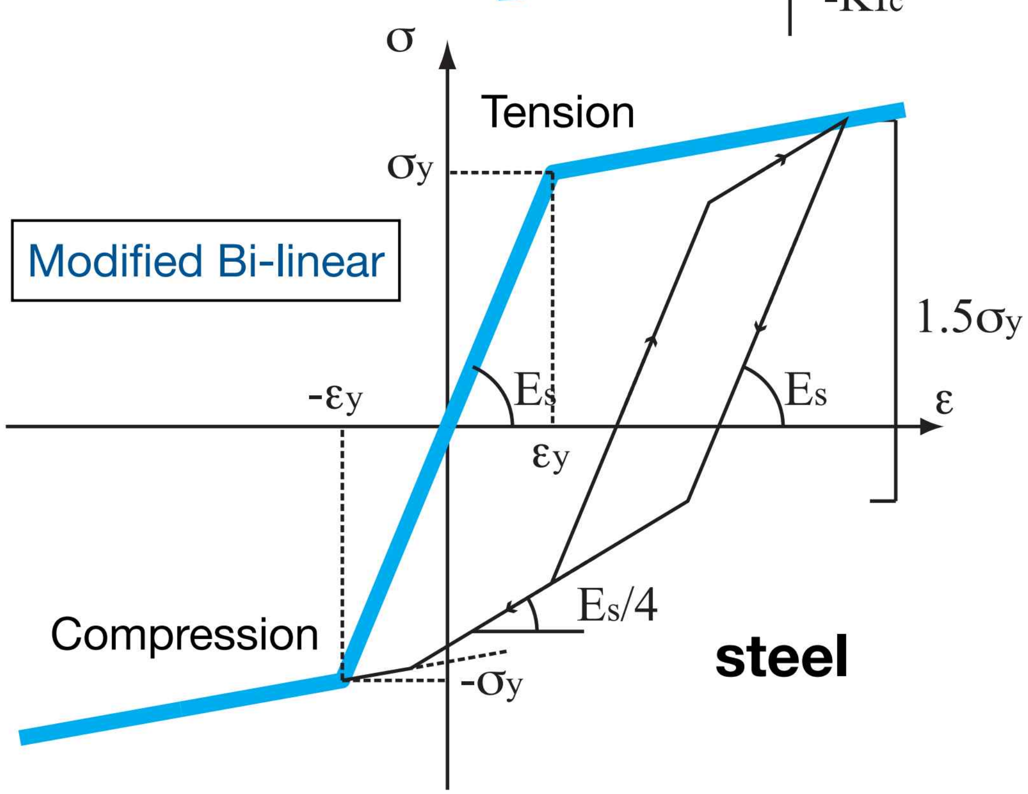
Frame Structure

P-Delta effect is incorporated to stiffness matrix

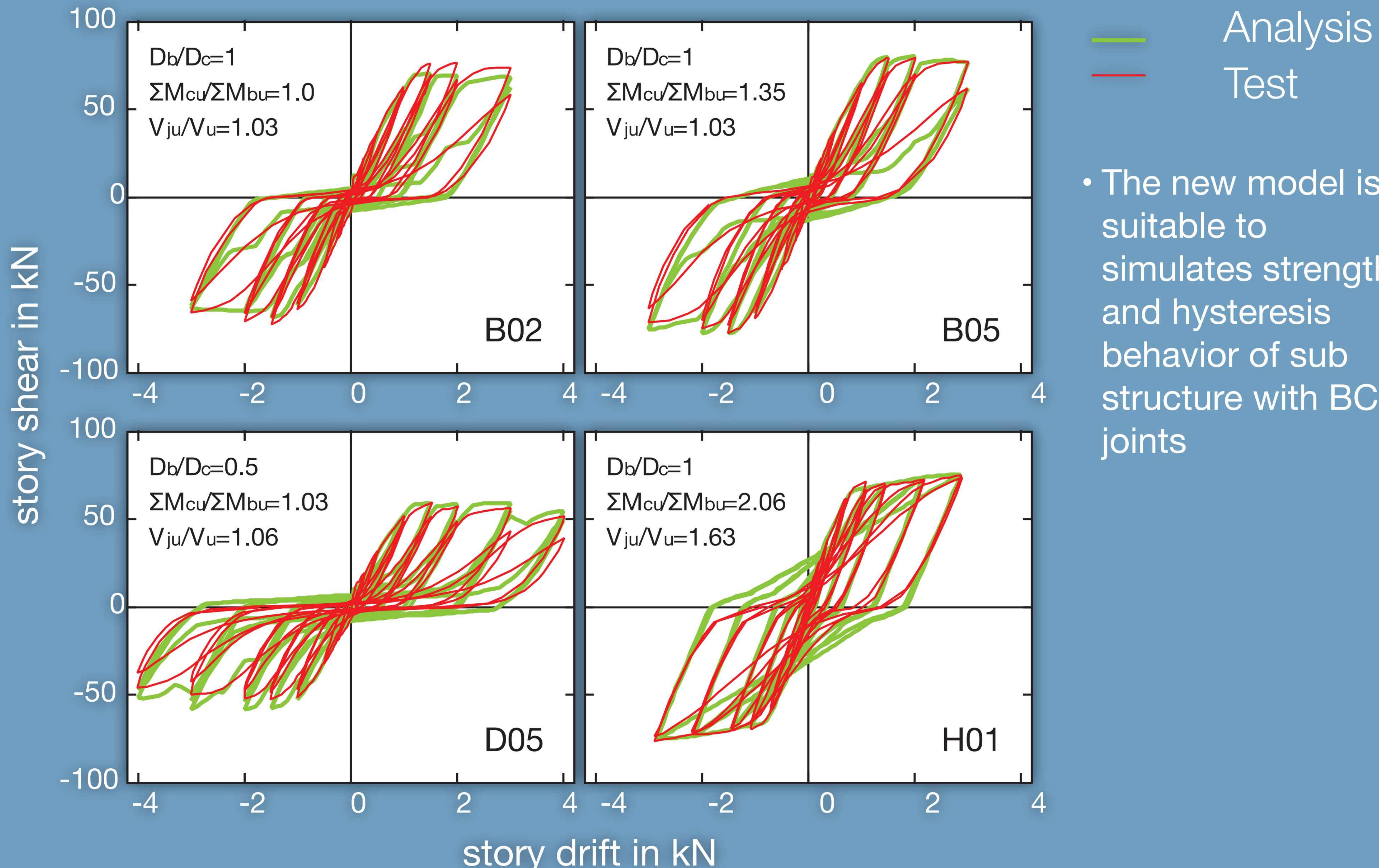
Uniaxial Constitutive Models for Elements





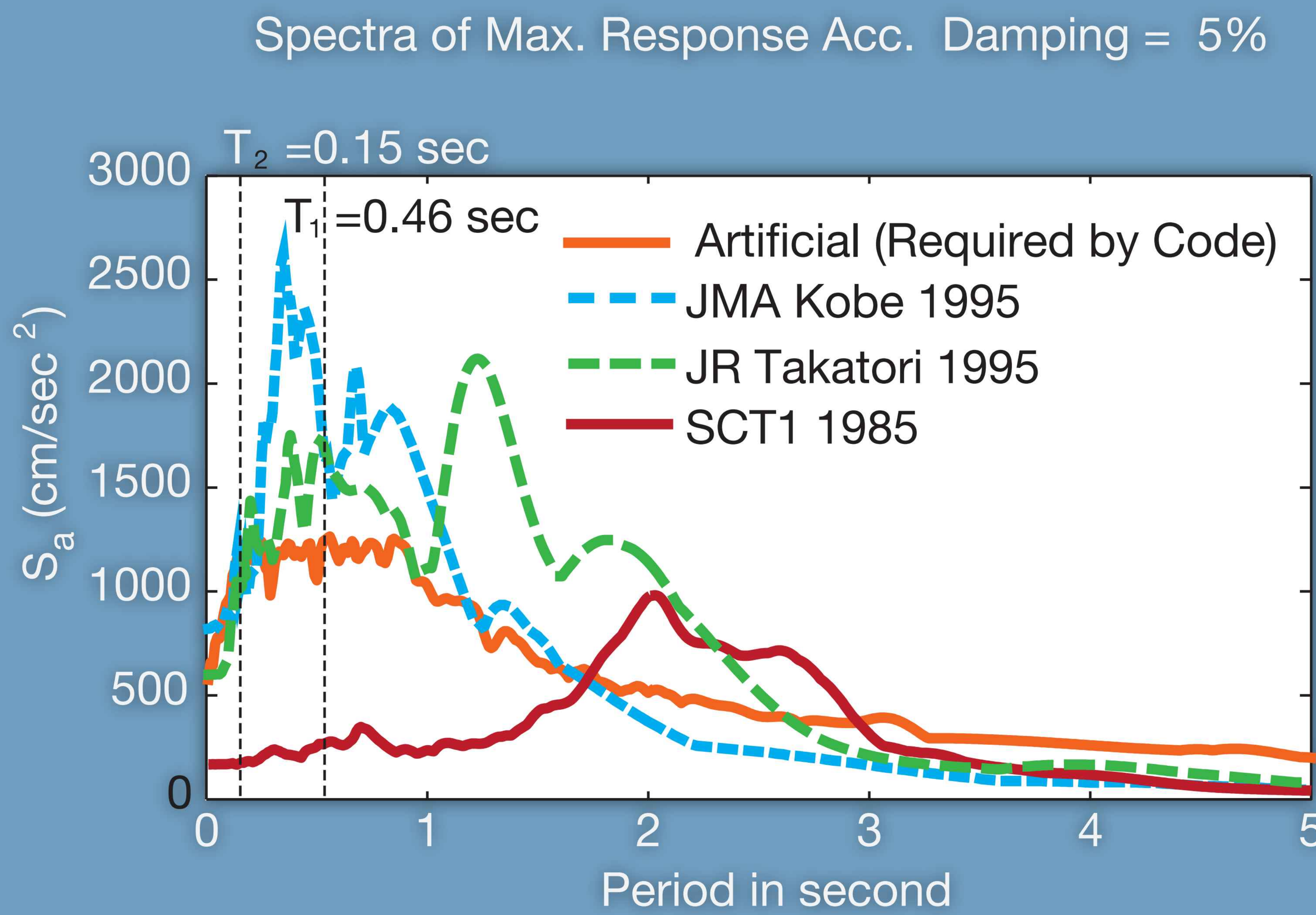


Validation of the Macro Element by the Tests



- The new model is suitable to simulates strength and hysteresis behavior of sub structure with BC joints

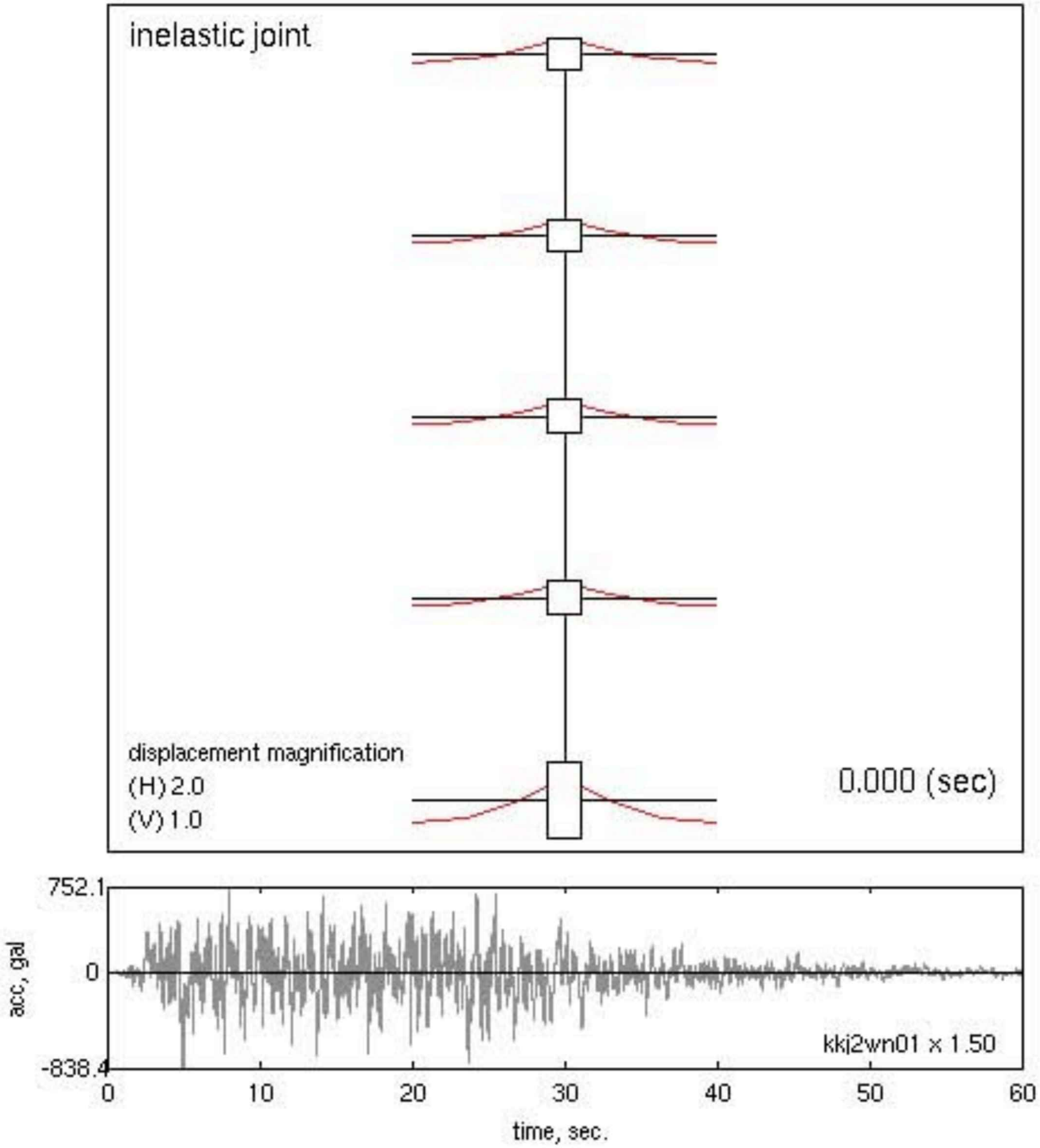
Input Ground Acceleration Record



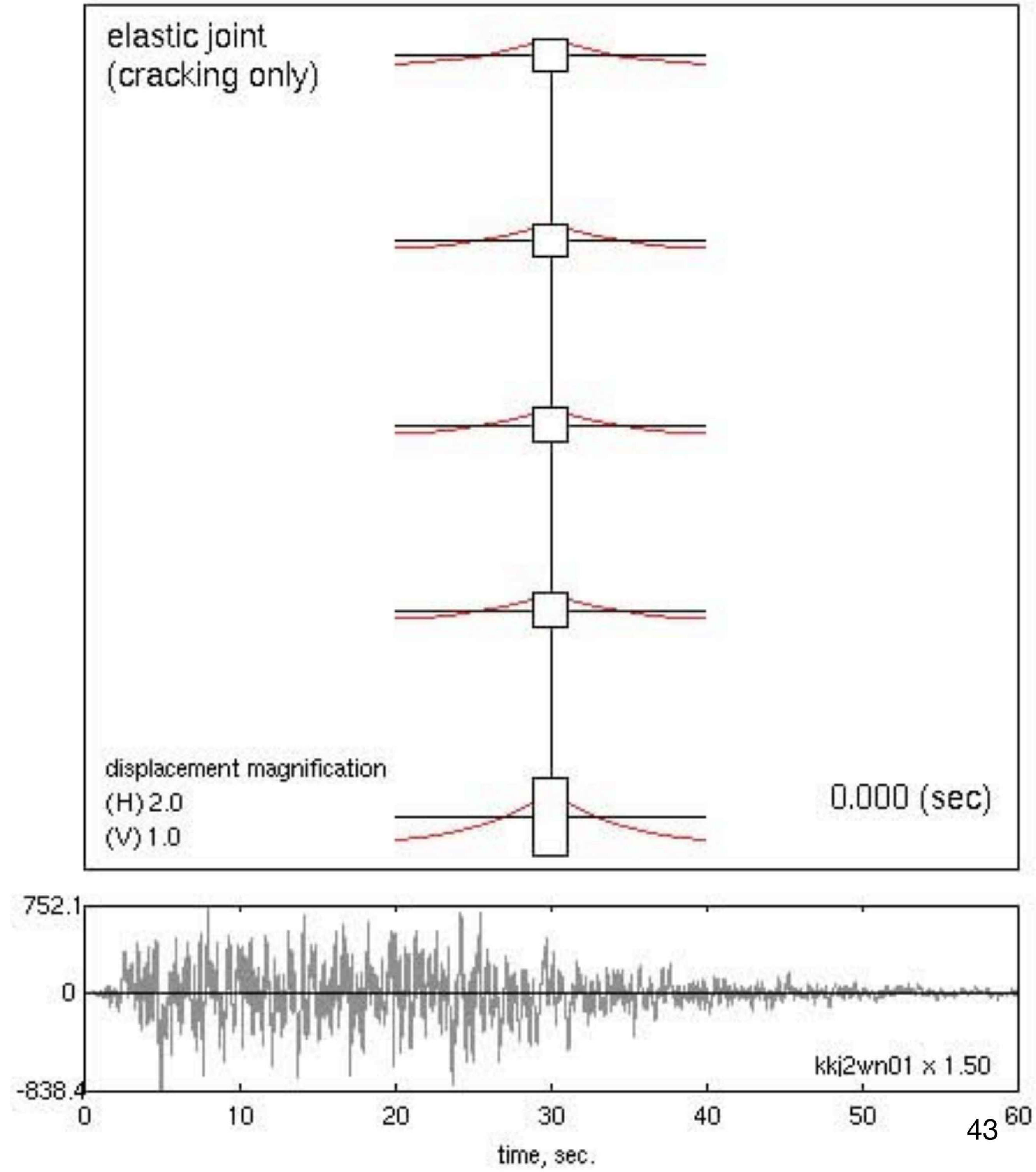
- Four input ground motions are selected for dynamic analysis

Four Story Building Collapse Simulation

with non-linear BC Joint model

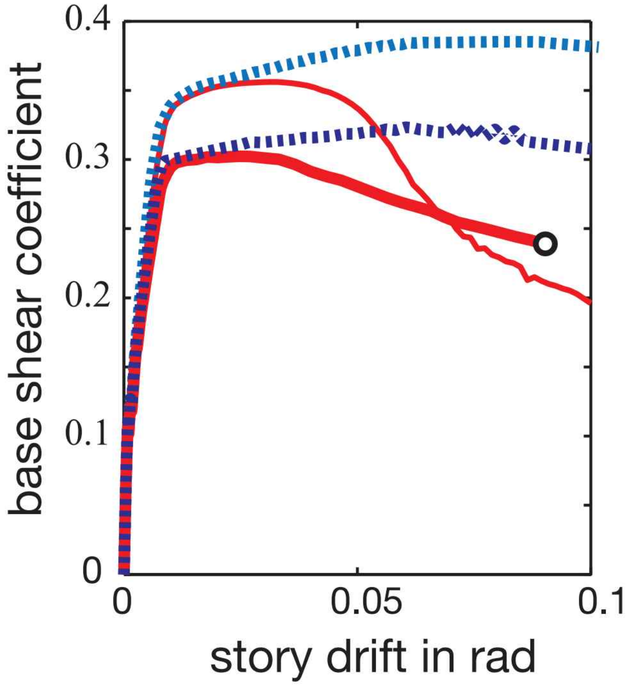


with elastic BC Joint model



Unstable Limit ; beyond Ultimate Limit

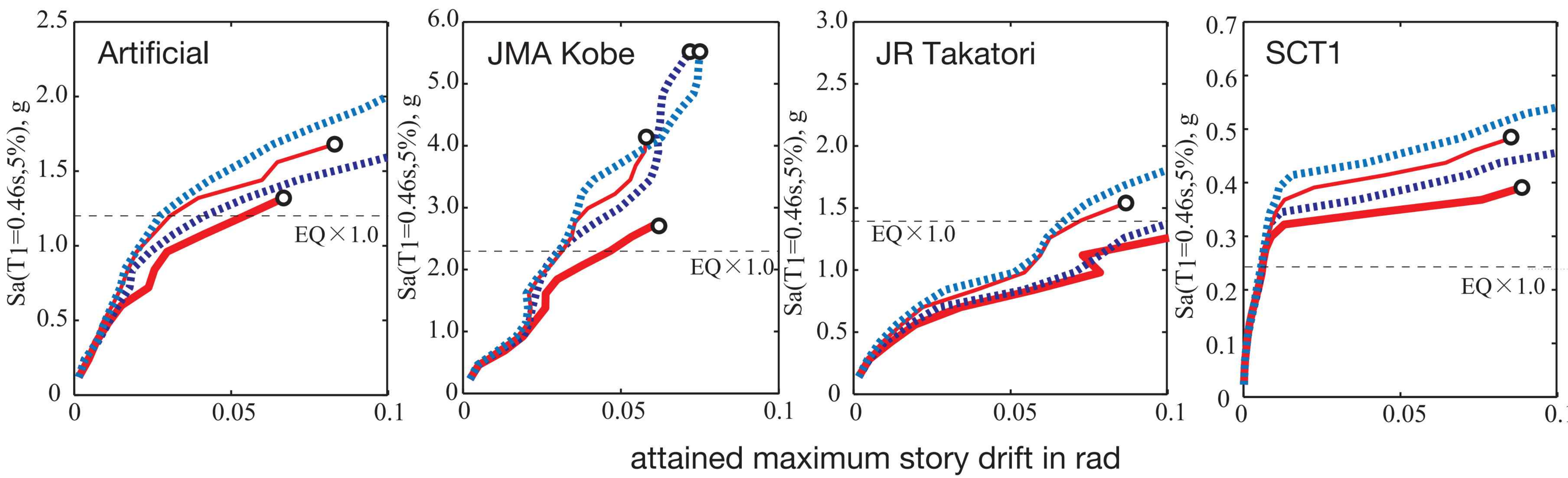
Static pushover analysis



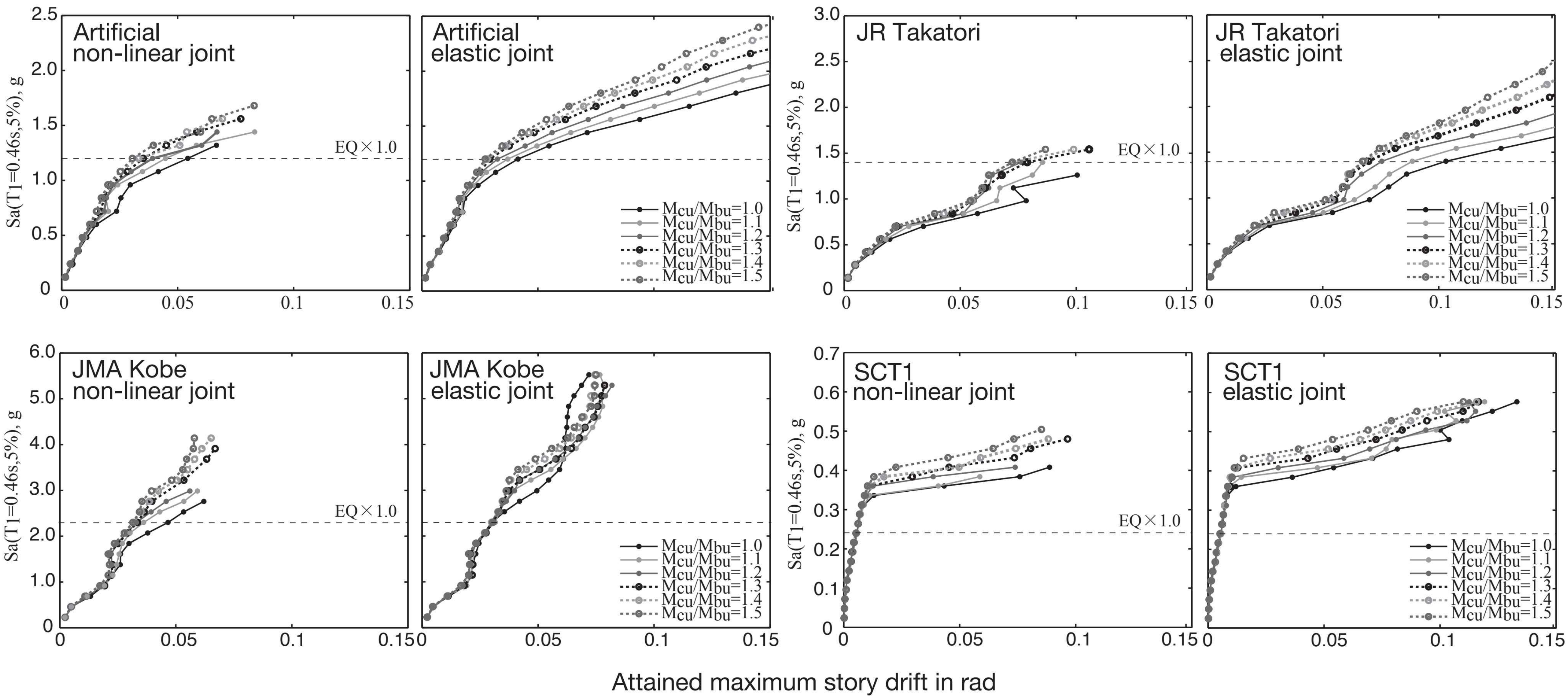
o unstable limit **= collapse limit**

Mcu/Mbu=1.0 non-linear joint
Mcu/Mbu=1.0 elastic joint
Mcu/Mbu=1.5 non-linear joint
Mcu/Mbu=1.5 elastic joint

Dynamic pushover analysis (IDA)



Column-to-beam Strength Ratio and Unstable Limit



- Frame with beam-column joint of C-to-B ratio of 1.0 become unstable at smaller ground motion amplification factor
- The difference is due to concentration of story drift at particular story

New beam-column joint macro model and nonlinear dynamic analysis on RC frames

- *Instability of moment resisting frame occurs at extremely large excitation*
  - Inappropriateness of non-linear frame model without consideration of non-linear beam-column joint is demonstrated,
  - Performance of beam-column joint is essential to attain stable seismic response at large displacement response level of ductility factor of 5 or more,
  - Joint hinging causes local concentration of story drift at particular story,
  - Then the frame becomes vulnerable to collapse due to P-Delta effect.
  - Large column-to-beam strength ratio is necessary to to avoid collapse due to instability
  - Safety margin for extremely large earthquake is smaller if small column-to-beam strength ratio is used for seismic design