CIVIL 449: Nonlinear Analysis of Structures

School of Architecture, Civil & Environmental Engineering
Civil Engineering Institute

Case Studies on the Use of Nonlinear Analysis

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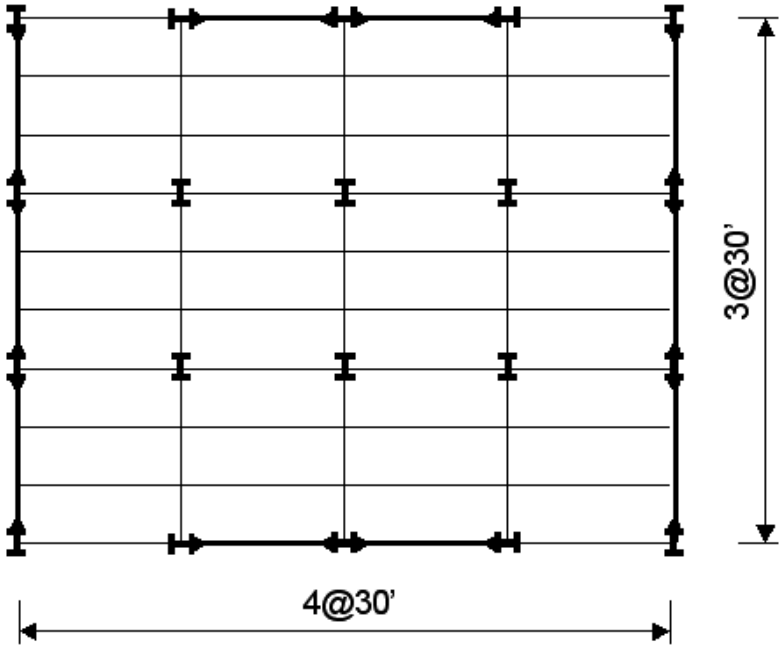
EPFL, ENAC, IIC, RESSLab

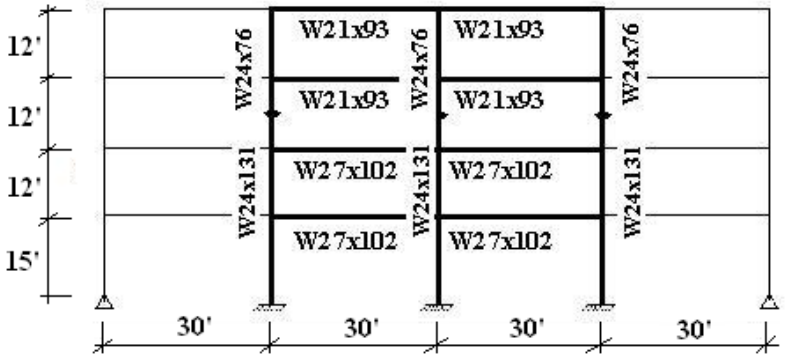
Objectives of today's lecture

- "Blind" nonlinear analysis of a 4-story steel building
  - archives from a previous nonlinear analysis course
- Case study #1: Prediction of nonlinear response of a 4-story steel frame building tested at full-scale through collapse
- Case study #2: Seismic retrofit of existing structures
  - Application to an existing hospital building
- Concluding remarks

4-story steel building with moment-resisting frames

- Archives: Nonlinear Analysis for Buildings
- McGill University, Quebec, Canada / Instructor: D.Lignos (2014)

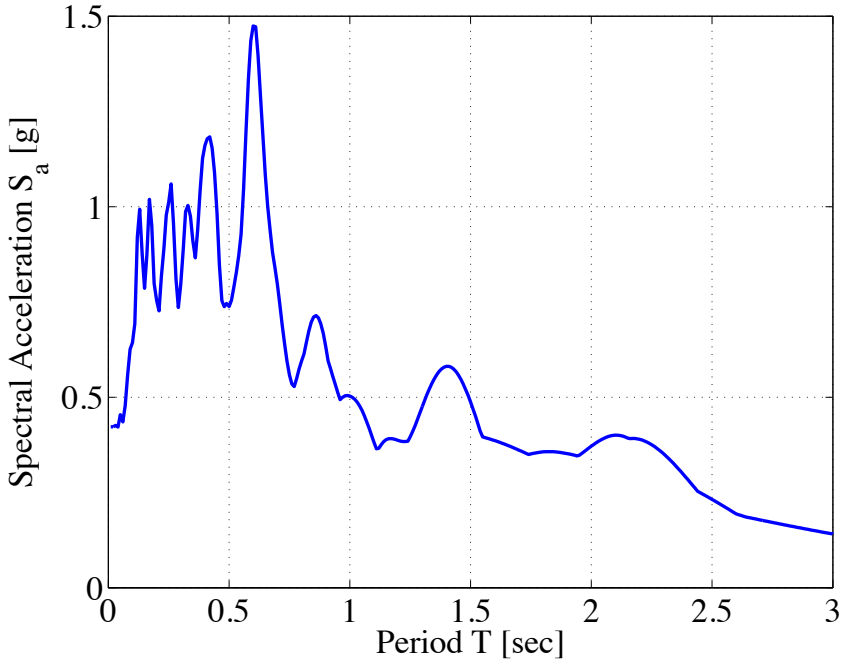




Source: Lignos et al. (2011)

4-story steel building with moment-resisting frames

- Canoga Park record from 1994 Northridge earthquake
  - Los Angeles, California, USA

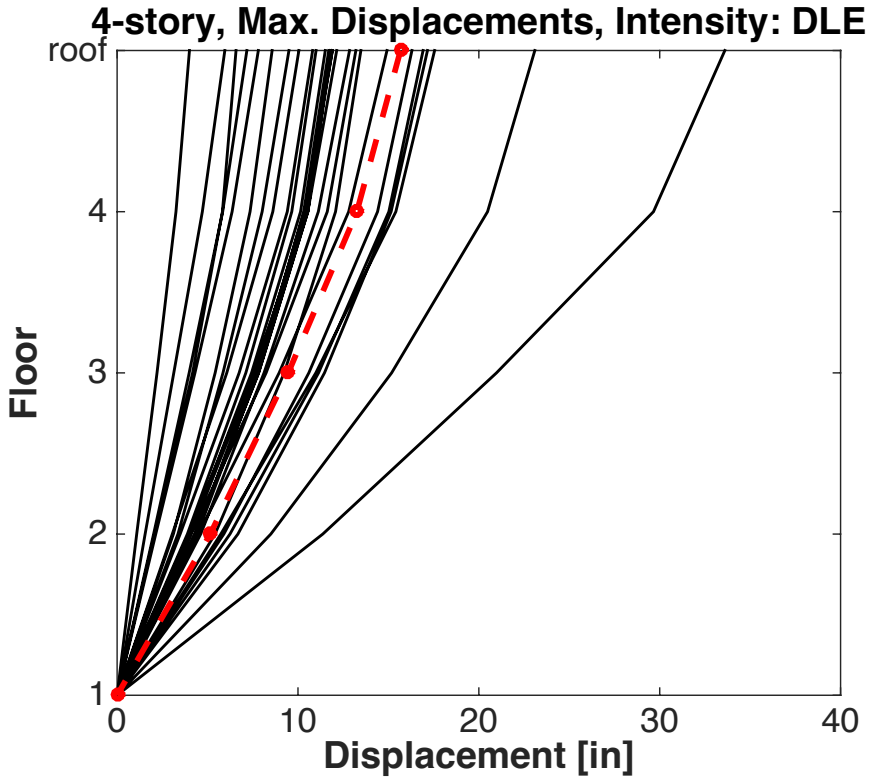


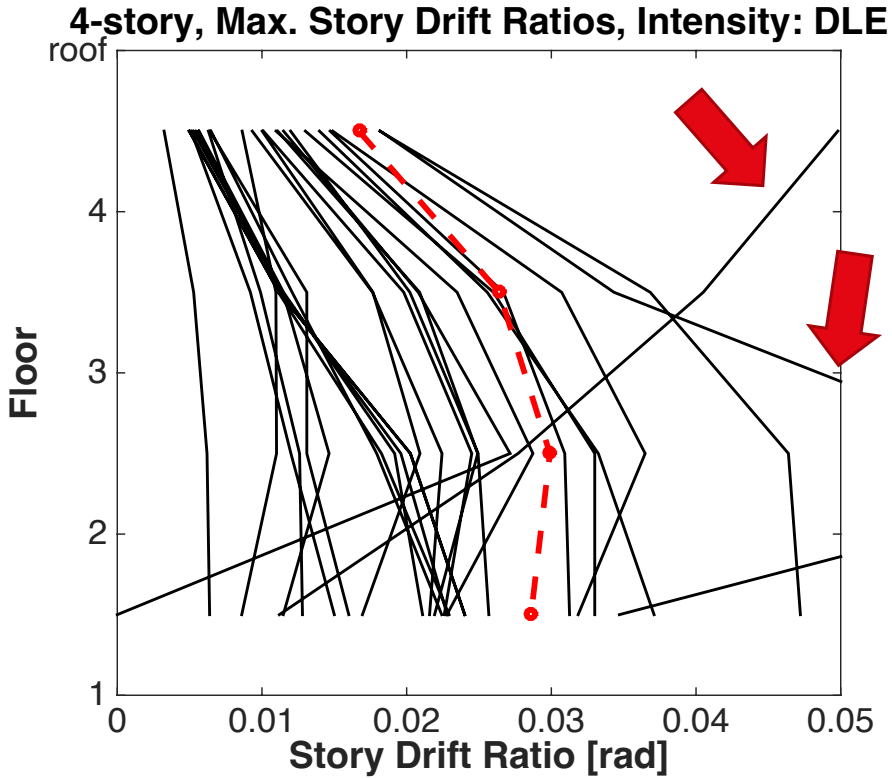
Source: Lignos et al. (2011)

4-story steel building with moment-resisting frames

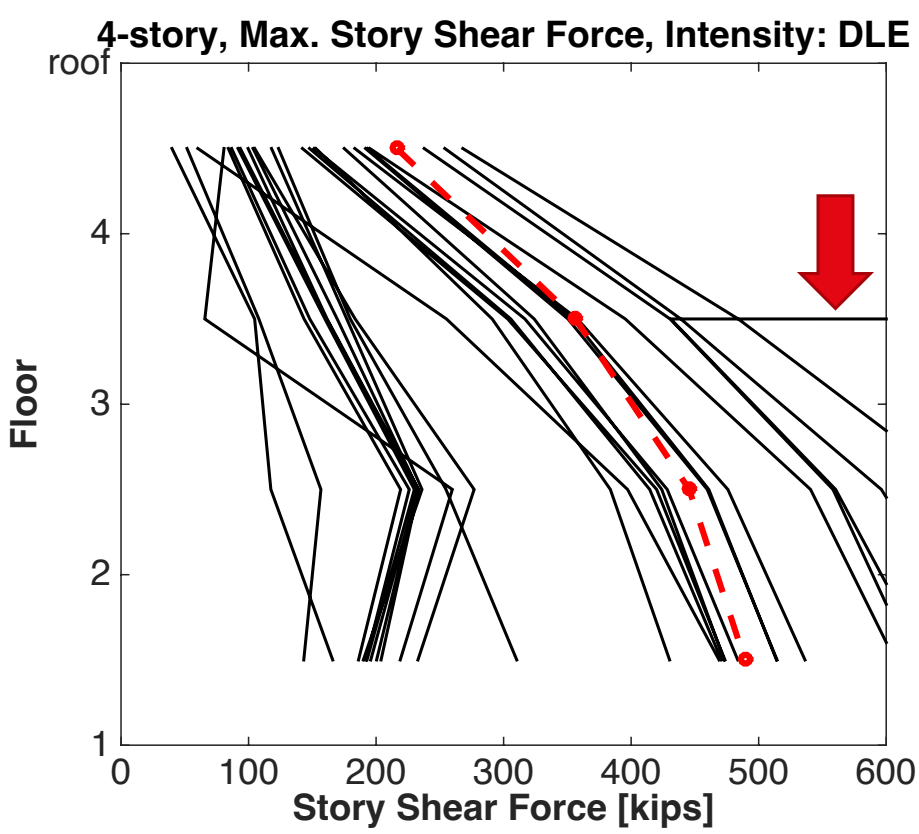
- 30 registered students
- Taught by the same instructor (Me ☺)
- Free to use any nonlinear analysis software and type of model
- Nonlinear analysis at 3 different target displacements
- Were given a spreadsheet to fill with their responses
- Questions: peak displacements, peak story drift angle, peak story shear forces and peak overturning moments (OTM) at each floor of the frame

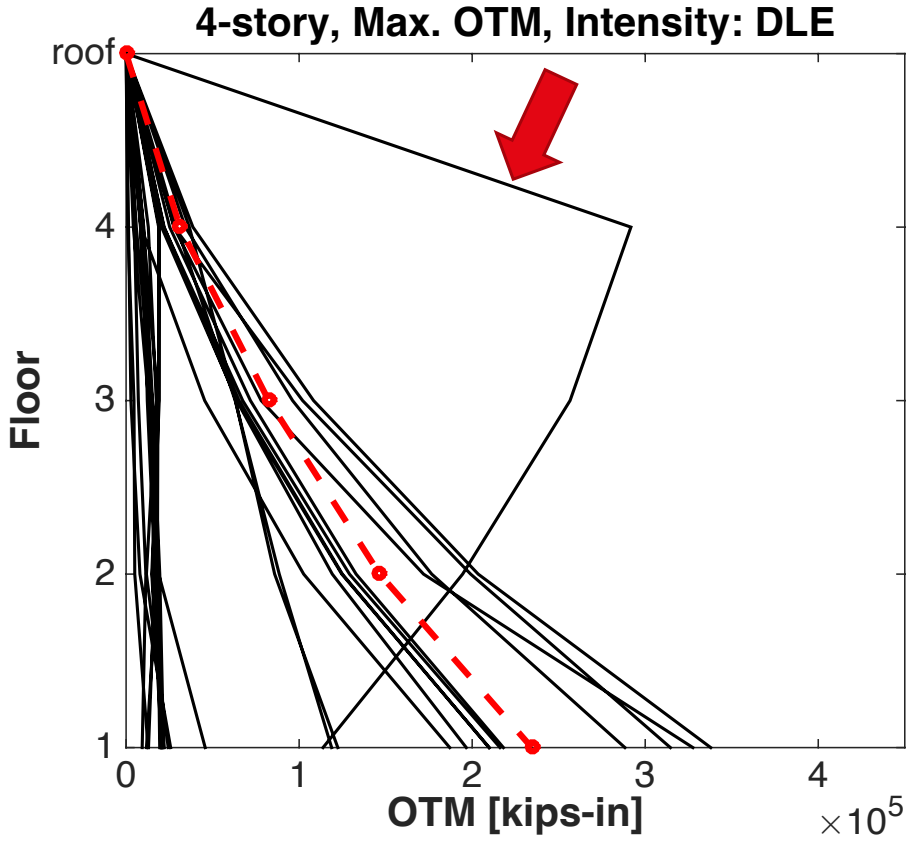
4-story steel building with moment-resisting frames



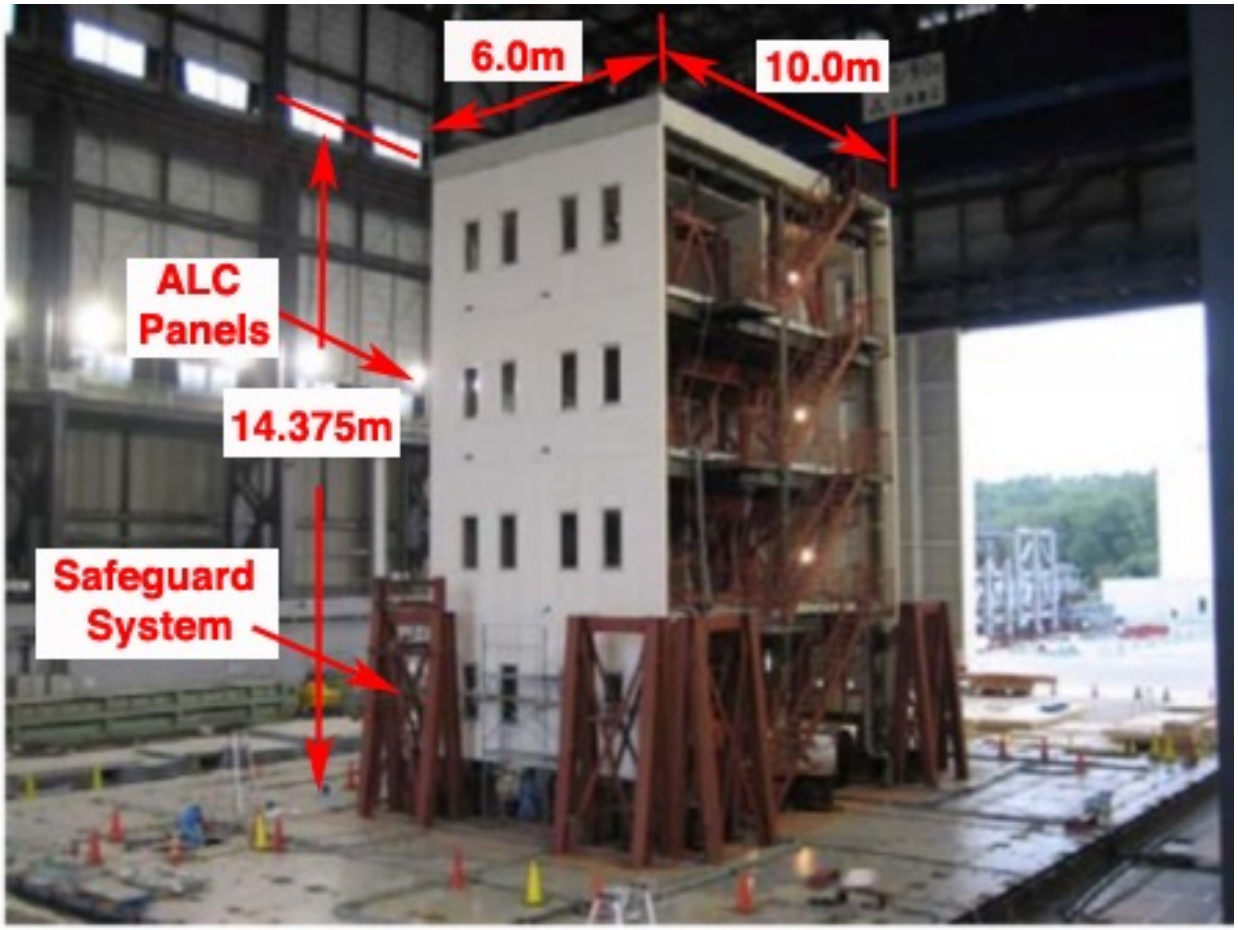


4-story steel building with moment-resisting frames



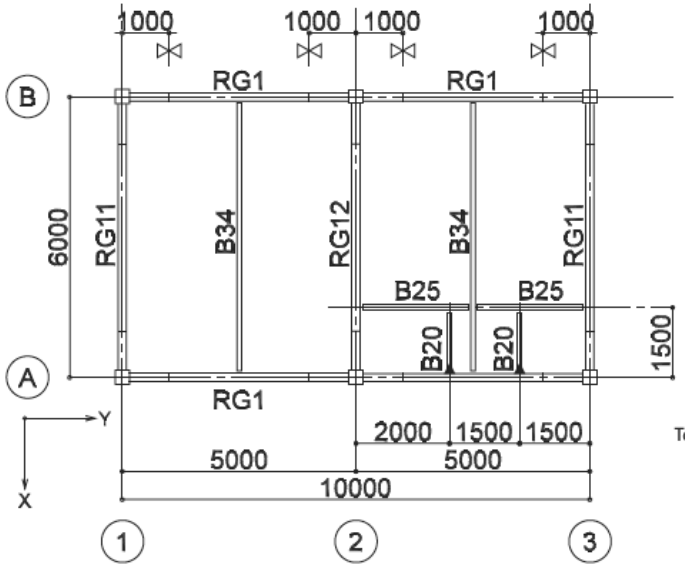


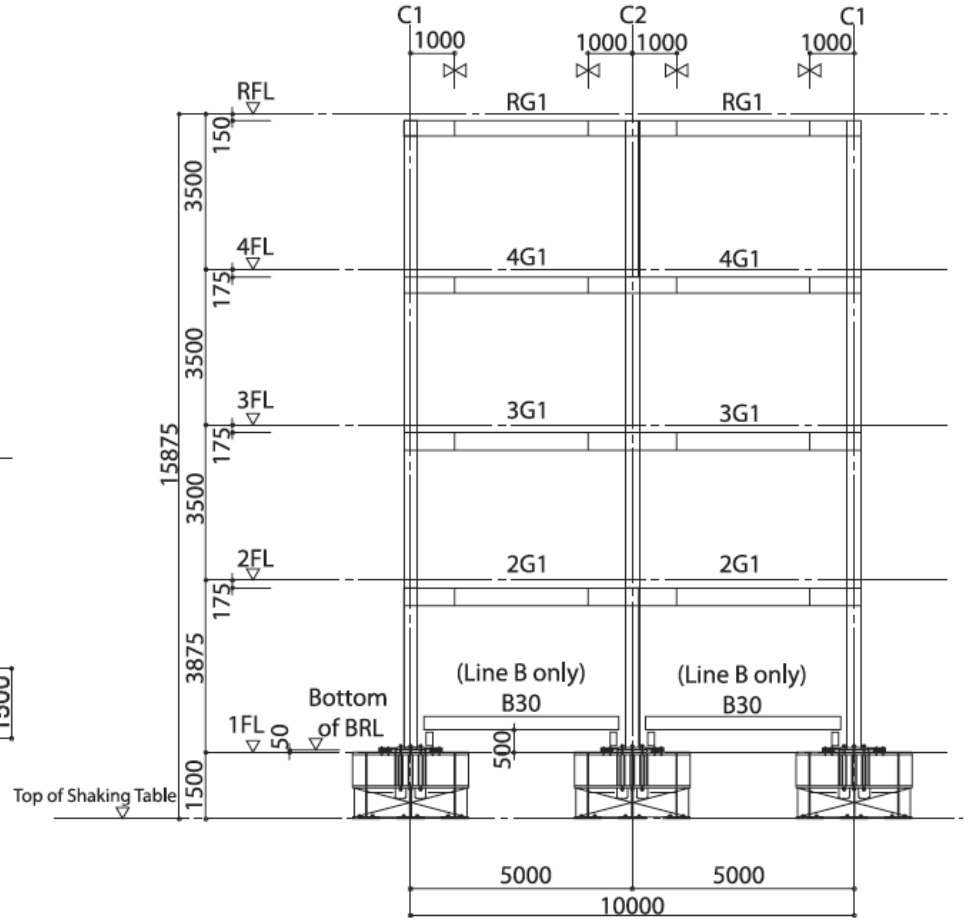
4-Story steel building tested at E-Defense



E-Defense, Japan, 2007
Image from Lignos et al. (2013)

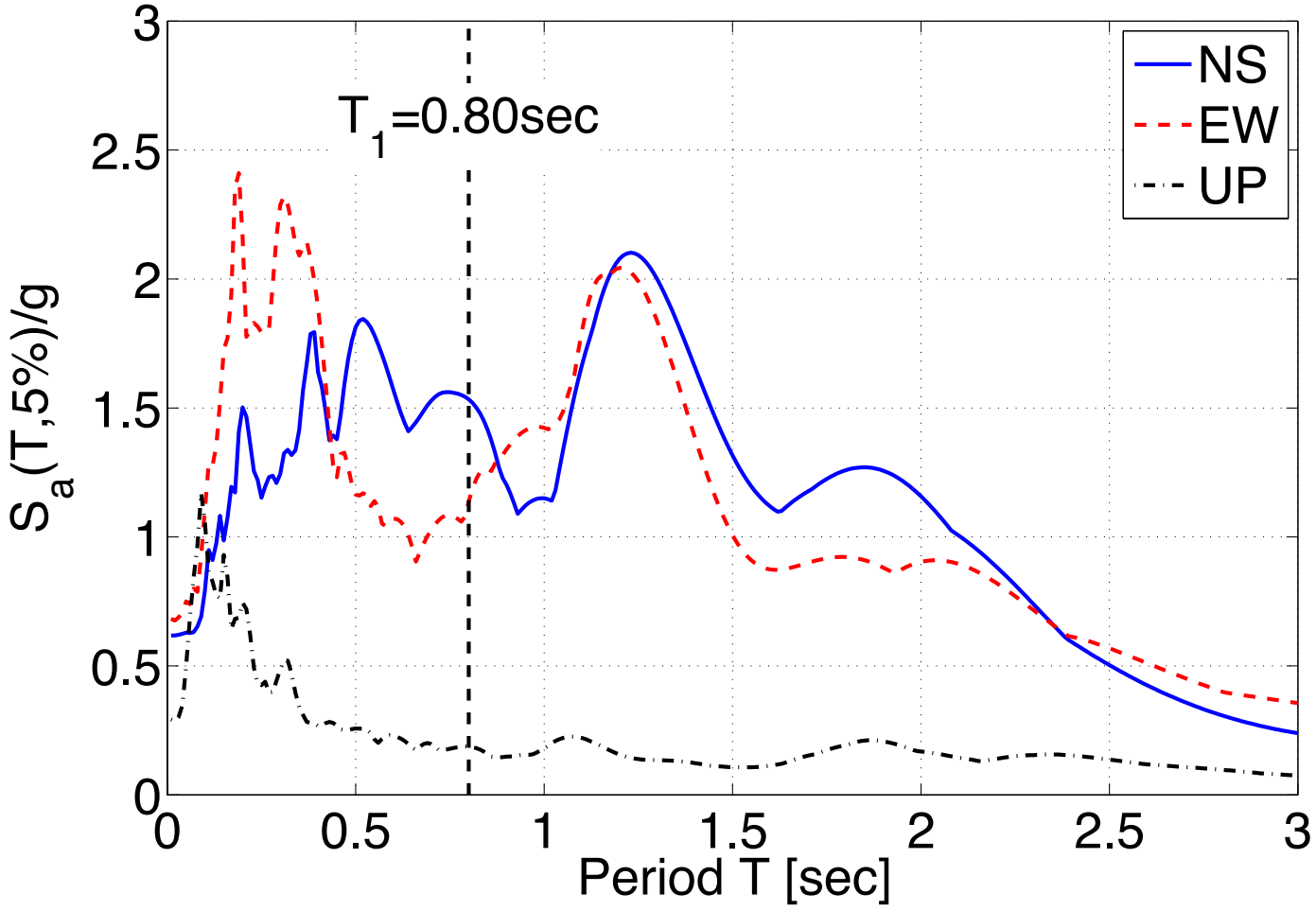
4-Story steel building tested at E-Defense





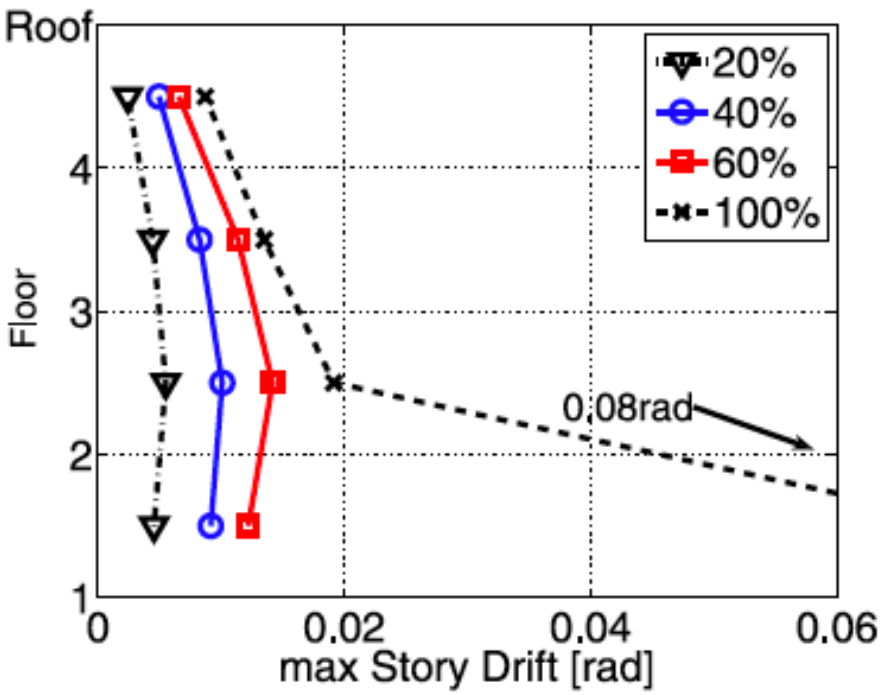
Source: Lignos et al. (2013)

4-Story steel building tested at E-Defense

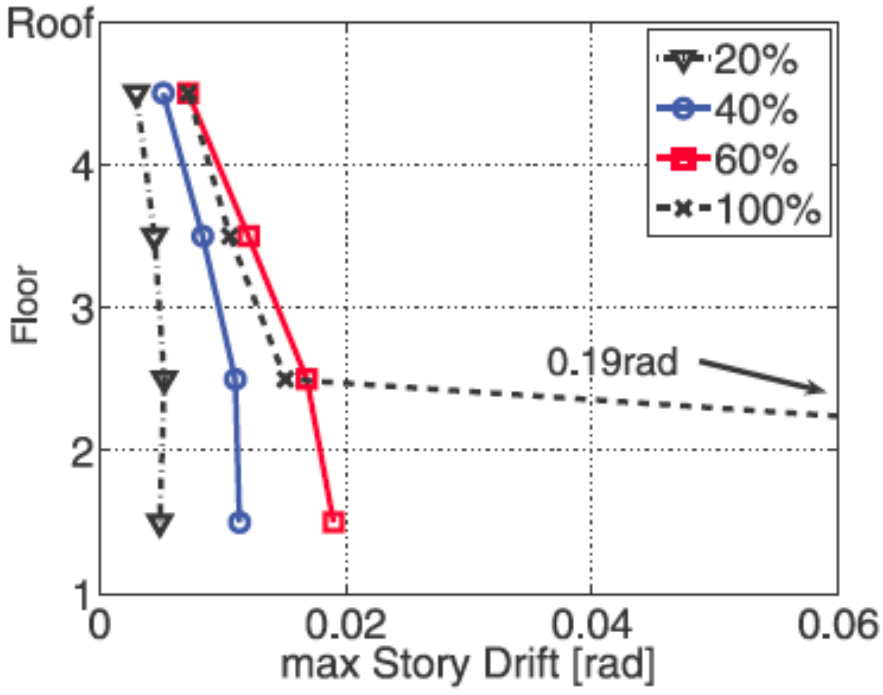


Source: Lignos et al. (2013)

4-Story steel building tested at E-Defense



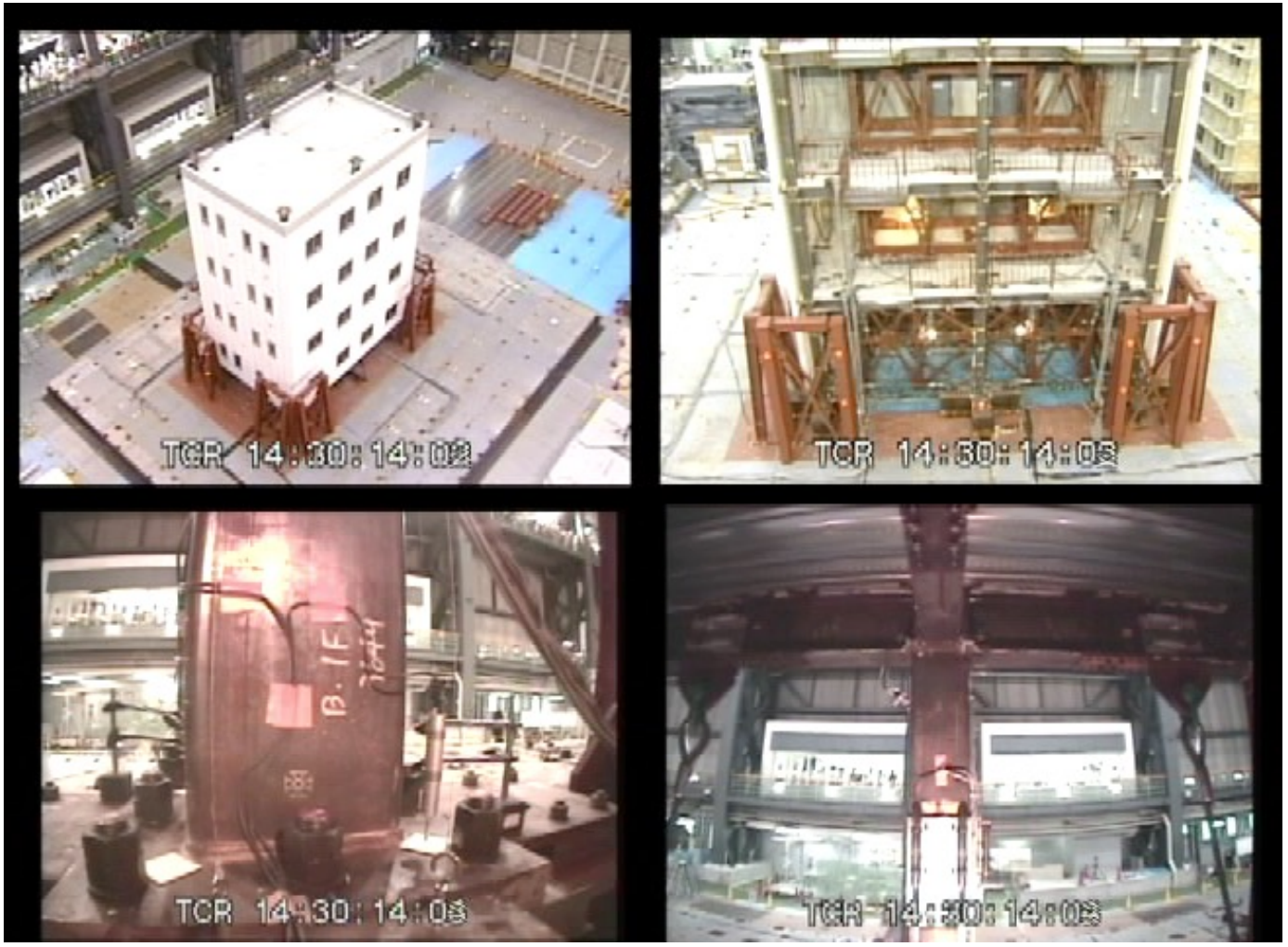
(a) X-loading direction



(b) Y-loading direction

Source: Lignos et al. (2013)

4-Story steel building tested at E-Defense



4-Story steel building tested at E-Defense

- Collapse was attributed to:
  - Composite effects (increase the beam flexural strength)
  - Flexibility of column bases
  - Steel material variability (columns versus beams)
  - 3D effects (N-Mx-My interaction)
  - Column plastic hinging at the base causes strength deterioration and inflection point shifting

Source: Lignos et al. (2013)

International blind analysis contest

- Winner is selected for each of the four categories:
  - Category 1: 3D Analysis (Researcher)
  - Category 2: 3D Analysis (Practicing Engineer)
  - Category 3: 2D Analysis (Researcher)
  - Category 4: 2D Analysis (Practicing Engineer)

International blind analysis contest

- 47 teams from 7 countries in total
- 7 teams participated in both 3D and 2D analysis

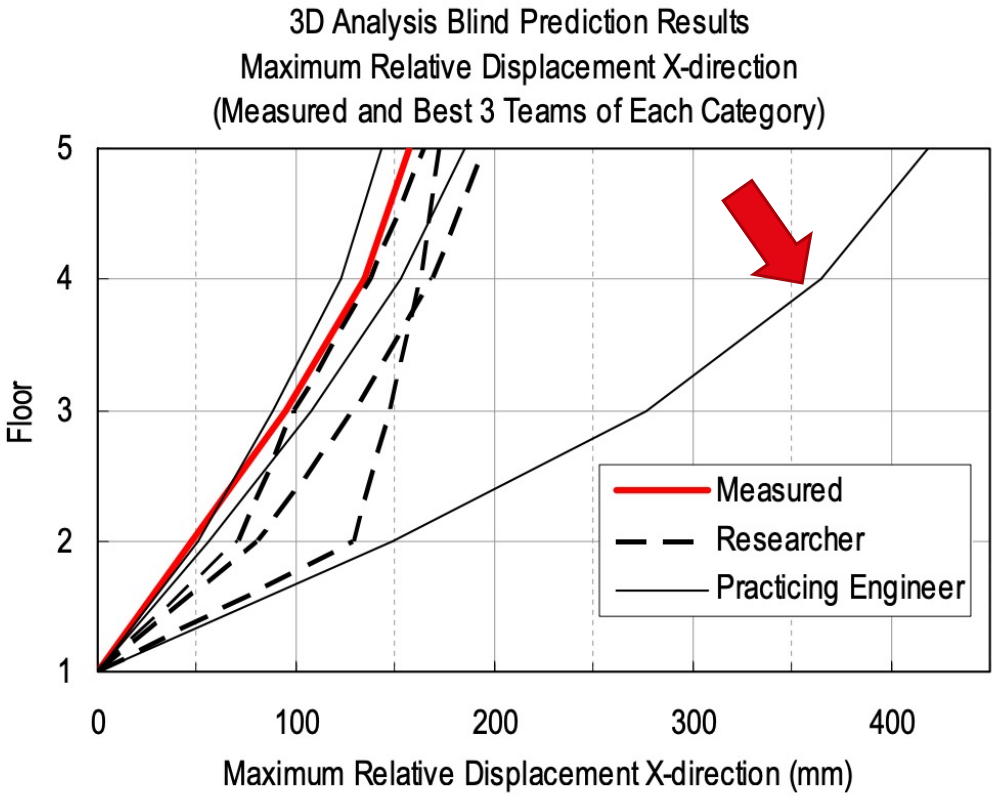
Country \ Category	3D-R	3D-P	2D-R	2D-P	TOTAL
Japan	6	5	4	2	17
U.S.	6	5	2	2	15
Taiwan	4	0	4	0	8
China	1	1	2	0	4
N.Z.	0	1	0	0	1
Italy	1	0	0	0	1
U.K.	0	0	0	1	1
TOTAL	18	12	12	5	47

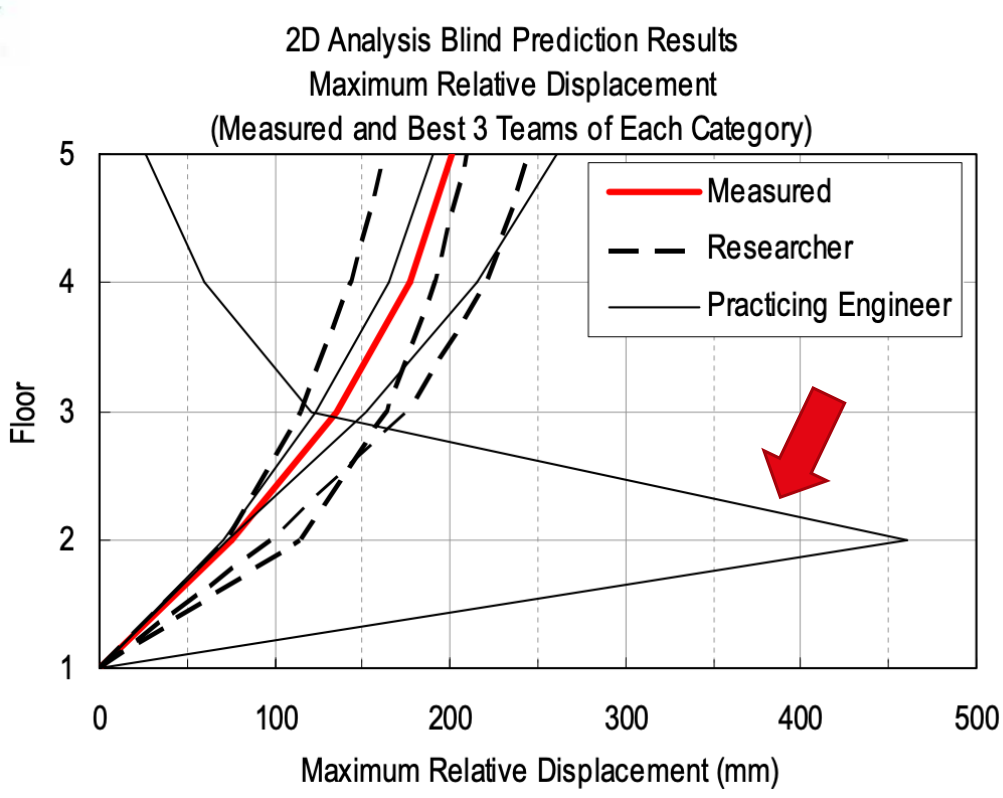
3D : Three-dimensional Frame Analysis 2D : Plane Frame Analysis

R : Researcher P : Practicing Engineer

Table Source: E-Defense 2007

International blind analysis contest

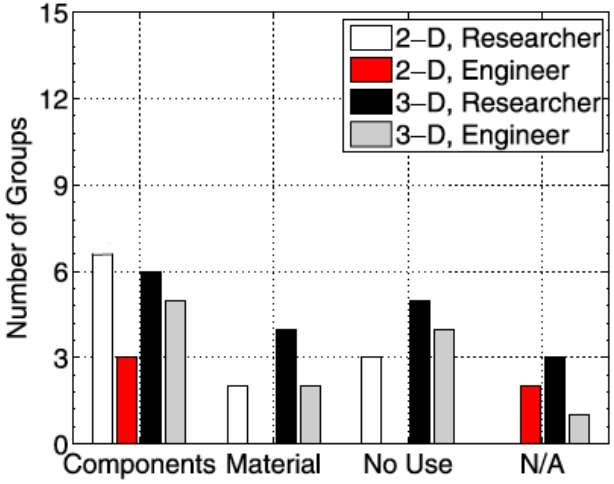




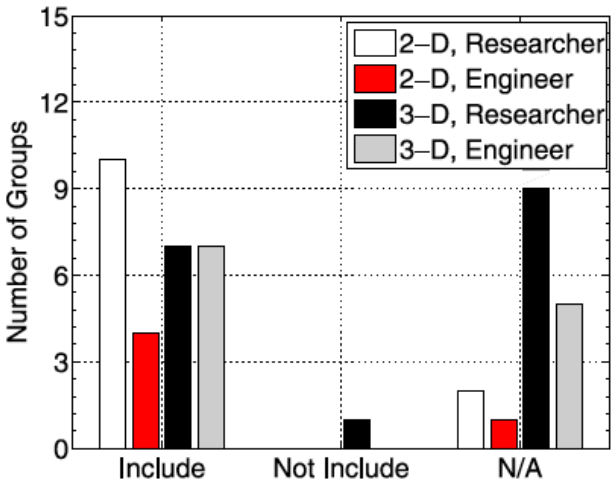
Images Source: E-Defense 2007

International blind analysis contest

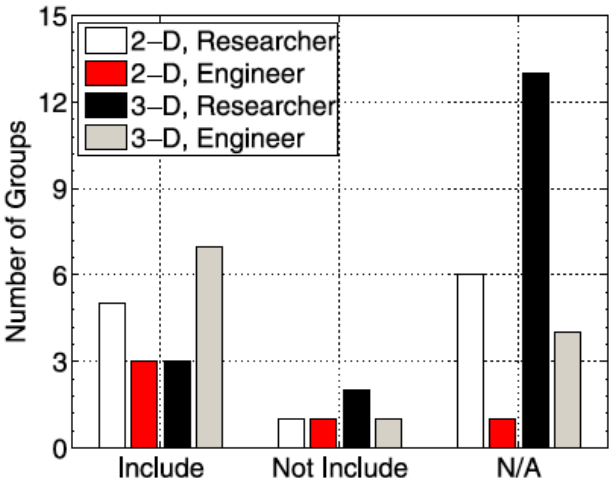
- Some key findings regarding the modelling assumptions of the participants



(a) Material & component tests



(d) Composite slab effects



(e) P -Delta effects

Source: Lignos et al. (2013)

Modeling strategies

- Zero length spring elements
- Distributed plasticity

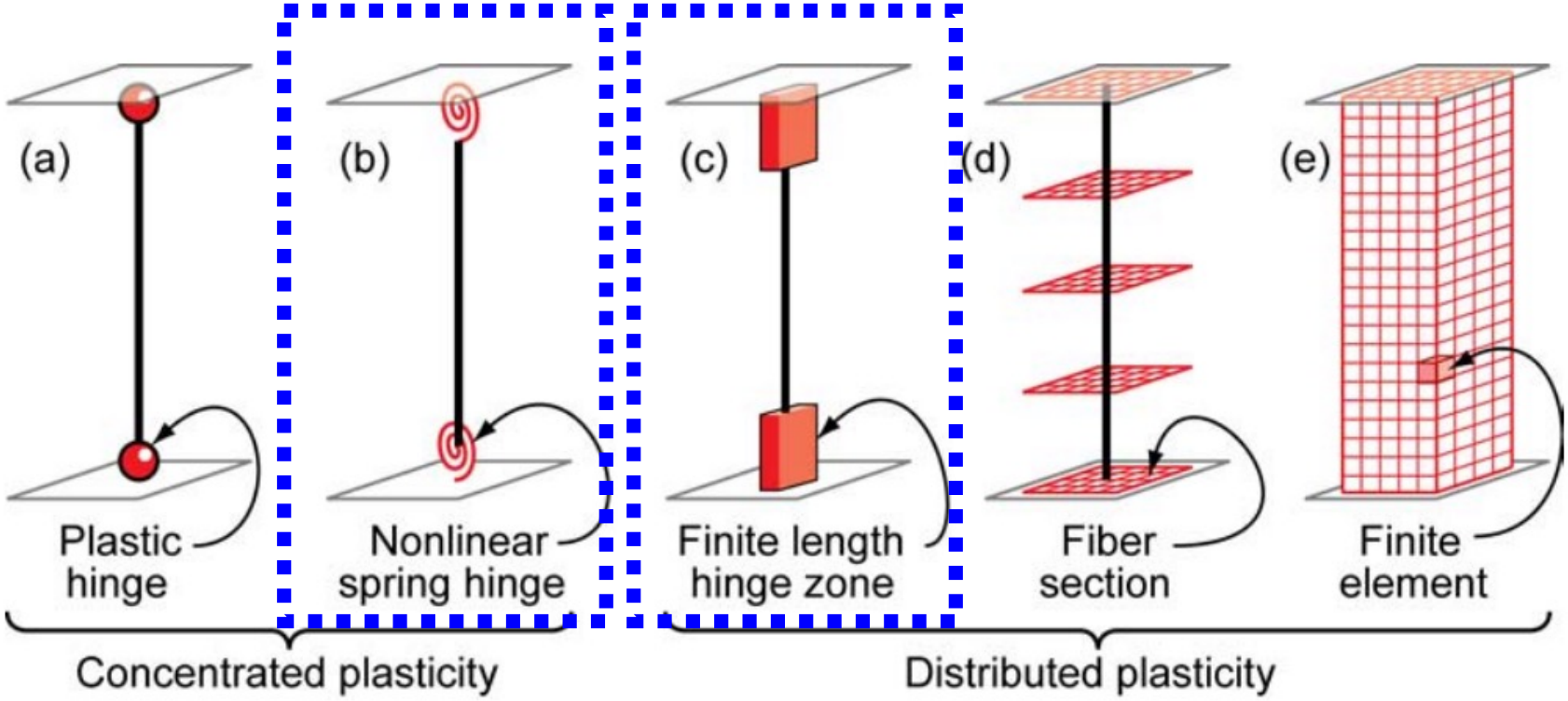
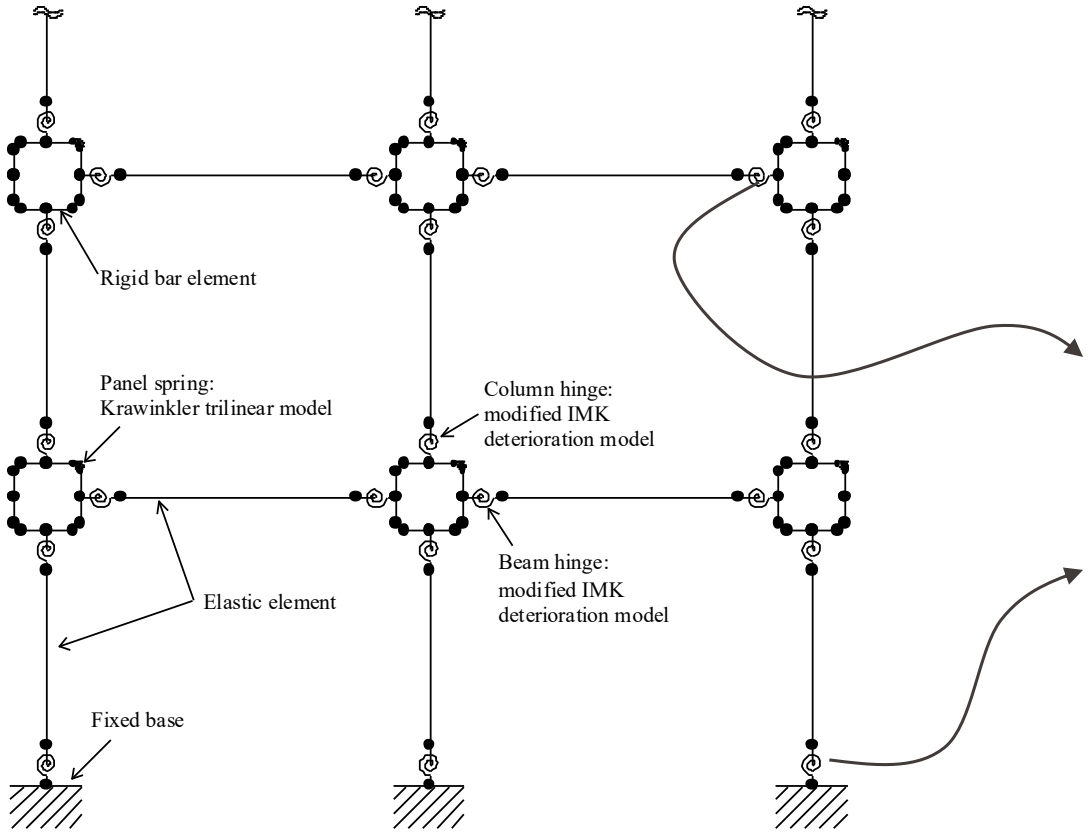
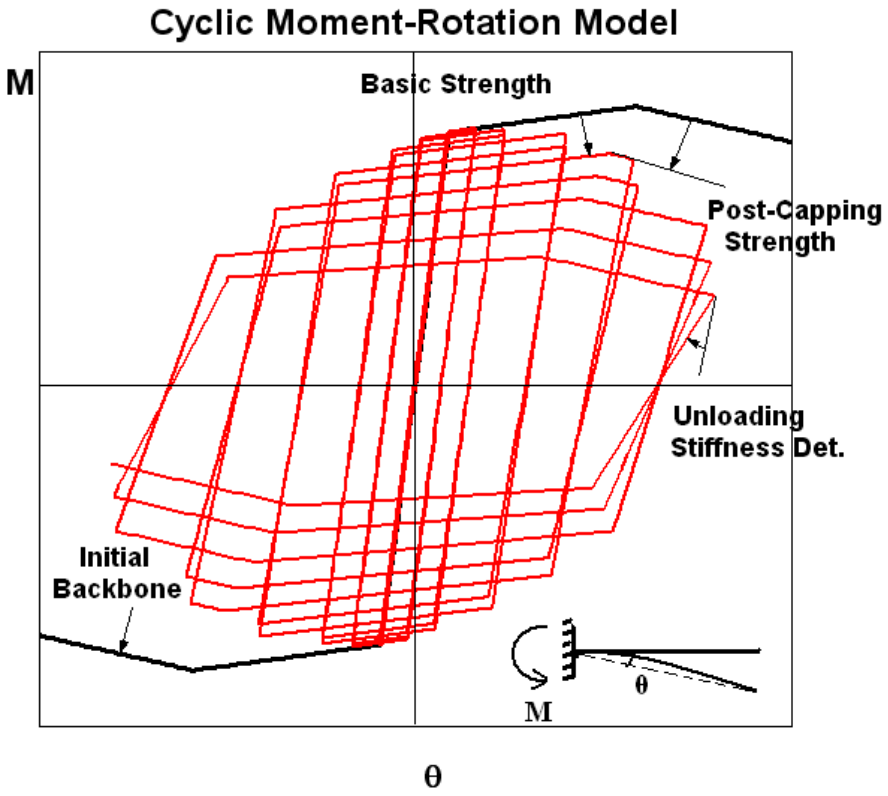


Image Source: NIST GSR 10-917-5

Modeling strategies

- Zero length spring elements

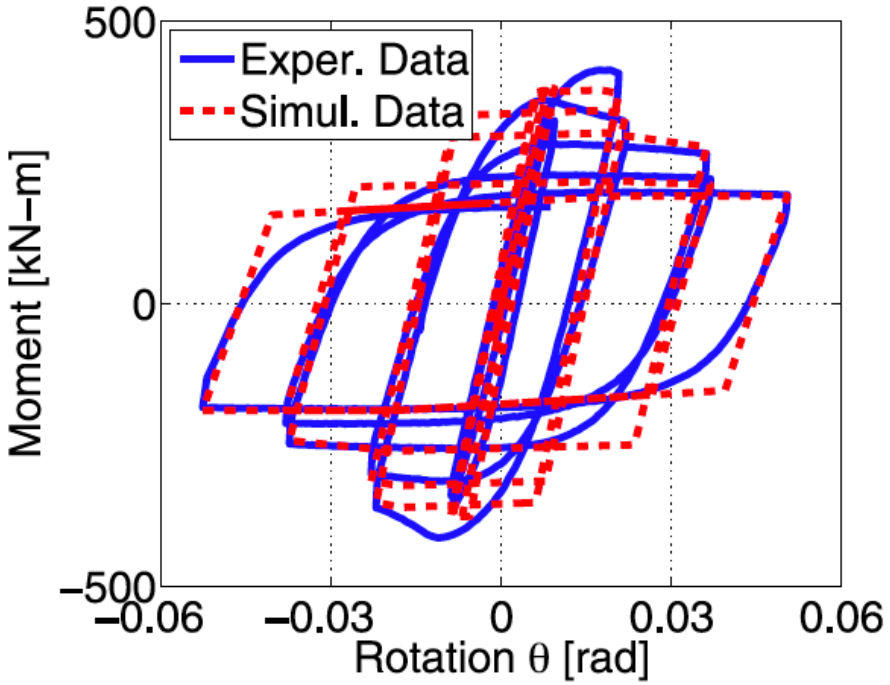




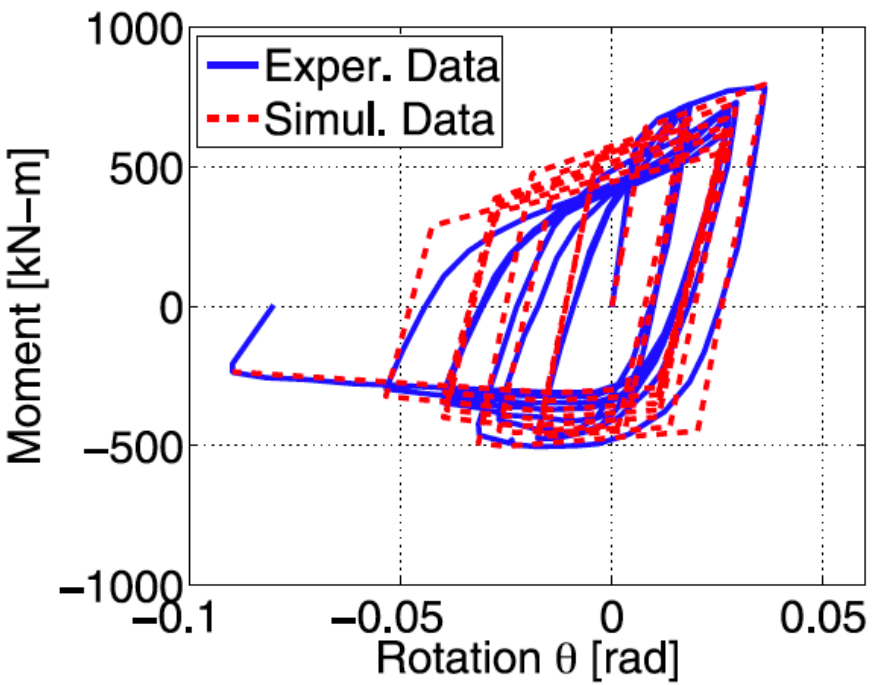
(Source: Lignos and Krawinkler 2011)

Modeling strategies

- Zero length spring elements



(a) HSS300x9 column tested in 45°

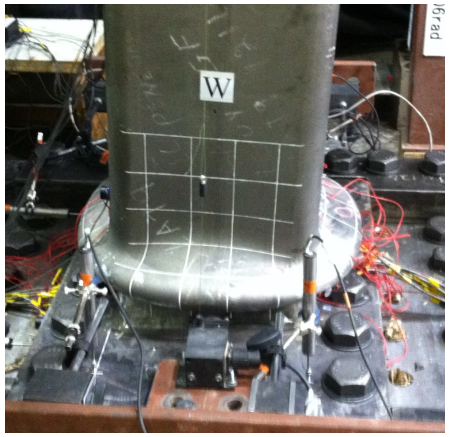


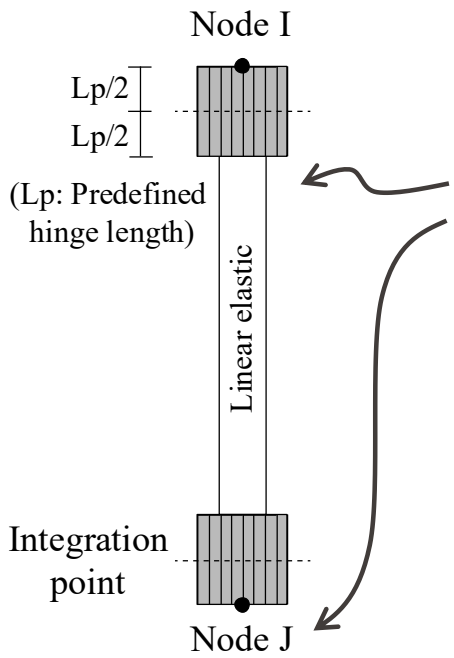
(b) H-400x200x8x13 composite beam

Source: Lignos et al. (2013)

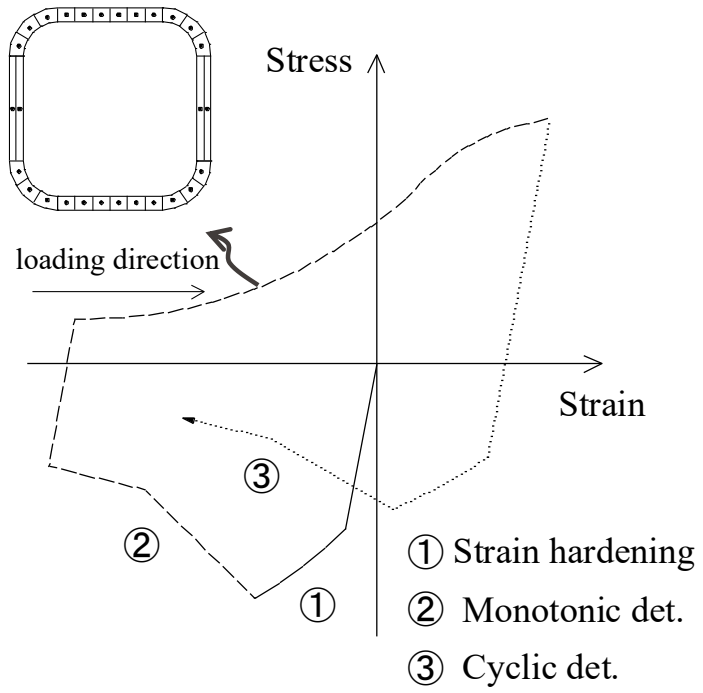
Modeling strategies

- Fiber—based force-based element





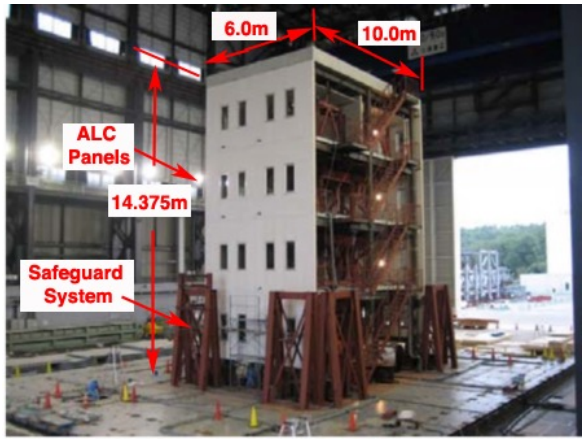
Force-based beam-column element

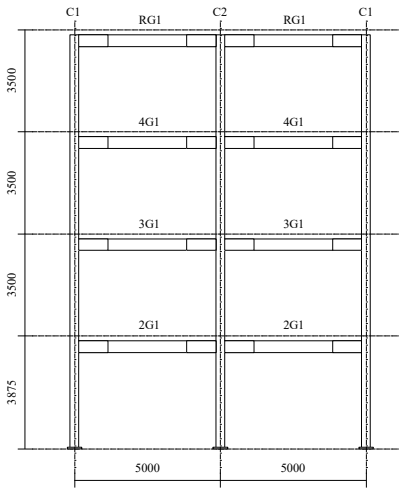


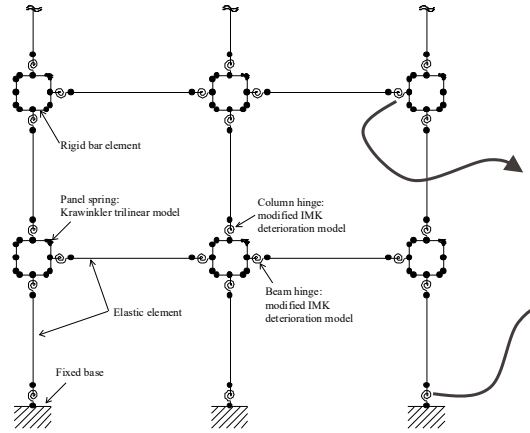
Engineering stress-strain

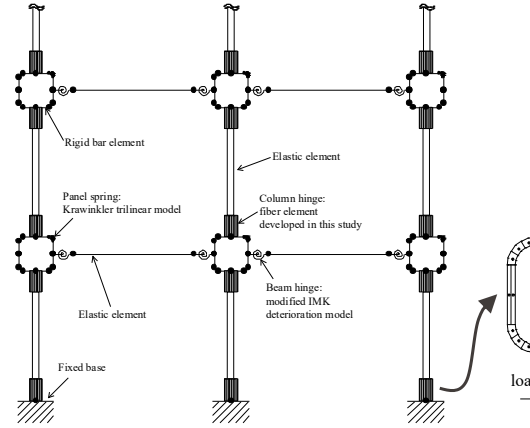
*Source: Suzuki and Lignos (2021)**

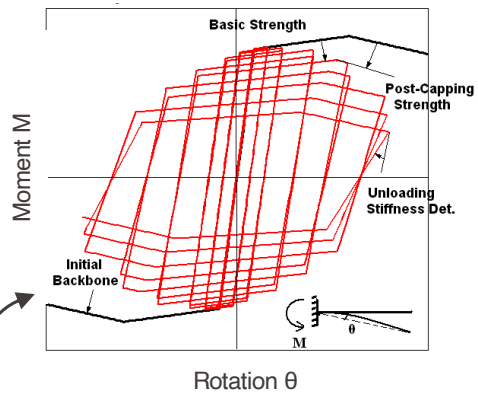
Modeling strategies

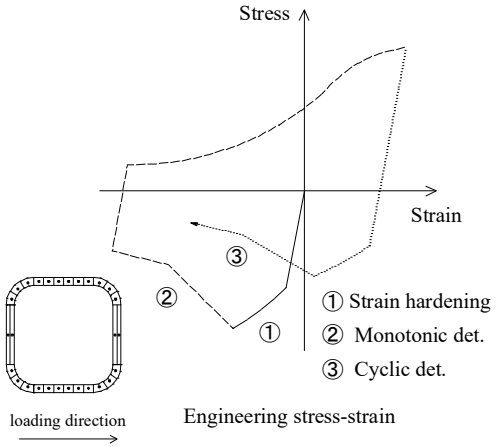








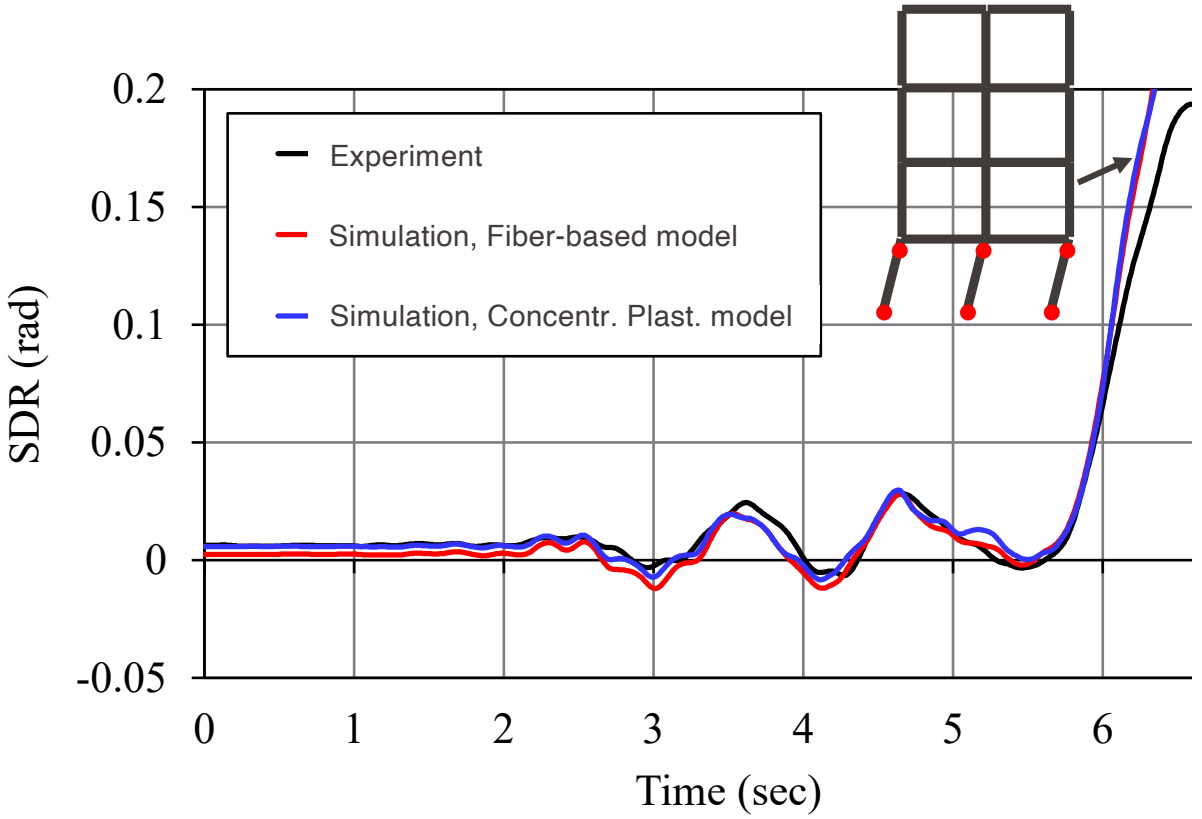




*Source: Suzuki and Lignos (2018)**

Predicted response

Prediction of 1st story collapse mechanism



*Source: Suzuki and Lignos (2021)**

3-dimensional beam-column elements

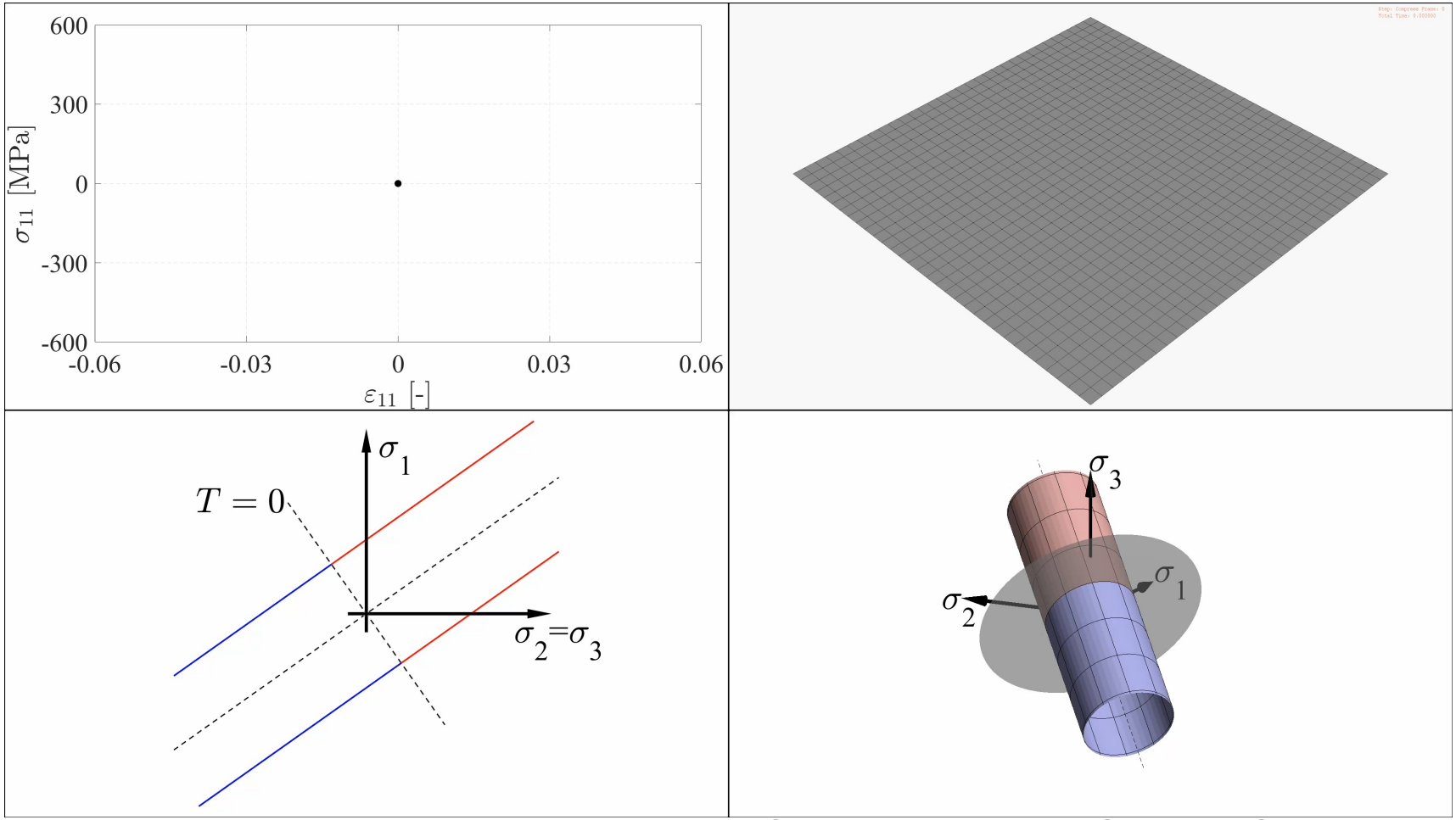
-Multiaxial plasticity formulation

- Yield surface

$$\phi = \begin{cases} \phi^{Tens}: \frac{3}{2}\boldsymbol{\xi}^T \boldsymbol{P}\boldsymbol{\xi} + \chi_{1t}(\boldsymbol{p}^T\boldsymbol{\sigma})^2 - \sigma_y^2 \leq 0, & T \geq 0 \\ \phi^{Comp}: \frac{3}{2}\boldsymbol{\xi}^T \boldsymbol{P}\boldsymbol{\xi} + \chi_{1c}(\boldsymbol{p}^T\boldsymbol{\sigma})^2 - \sigma_y^2 \leq 0, & T \leq 0 \end{cases}$$

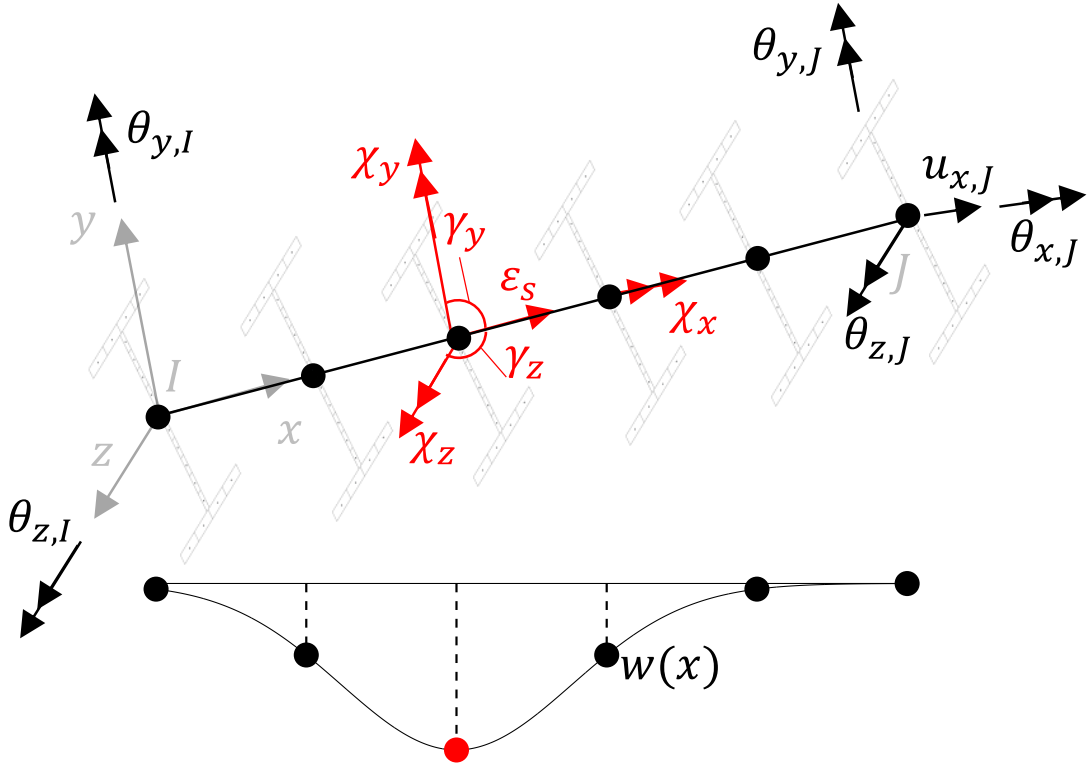
Source: Heredia, de Castro et Sousa and Lignos (2024)

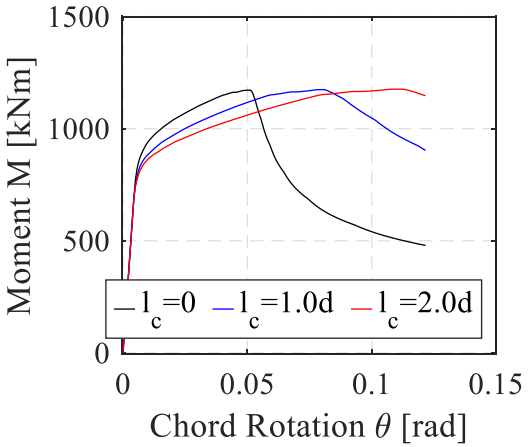
3-dimensional beam-column elements (2)

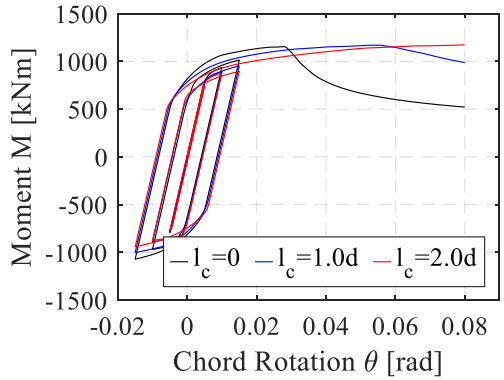


Source: Heredia, de Castro et Sousa and Lignos (2024)

3-dimensional beam-column elements (3)





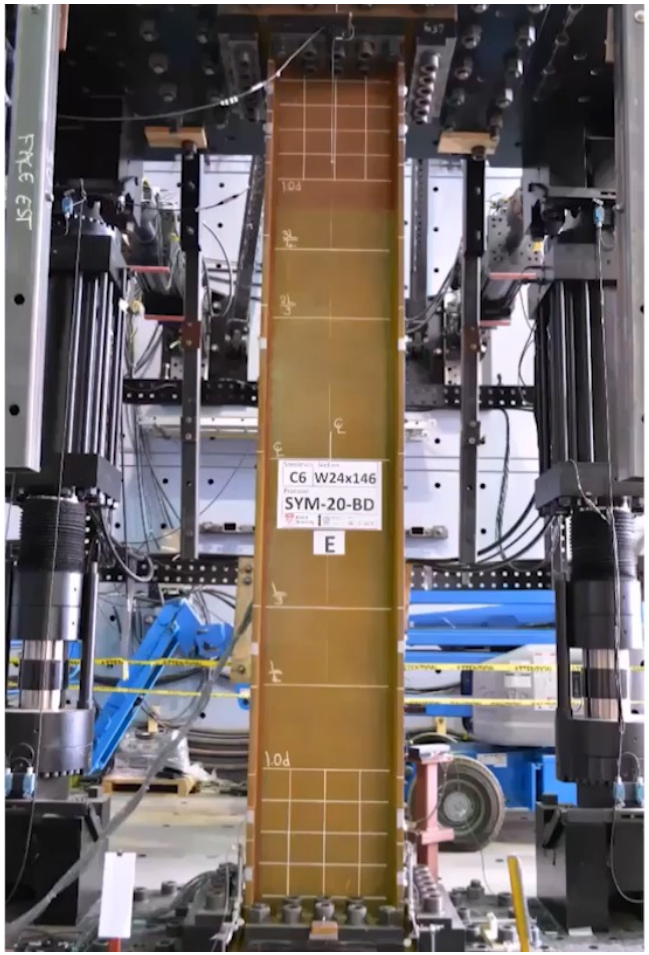


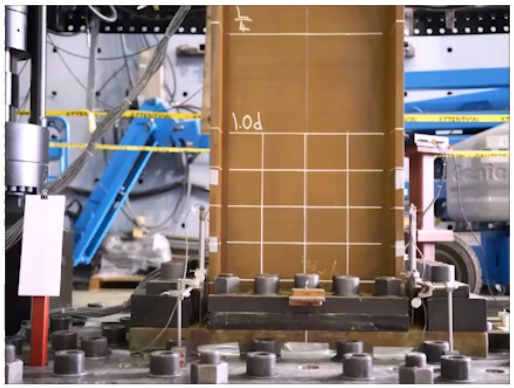
- Enhanced 3D Timoshenko force-based beam-column element (available in OpenSees)
- Implicit gradient nonlocal formulation

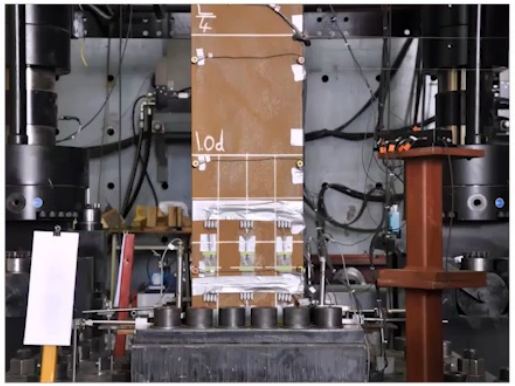
Source: Heredia, de Castro et Sousa and Lignos (2024)

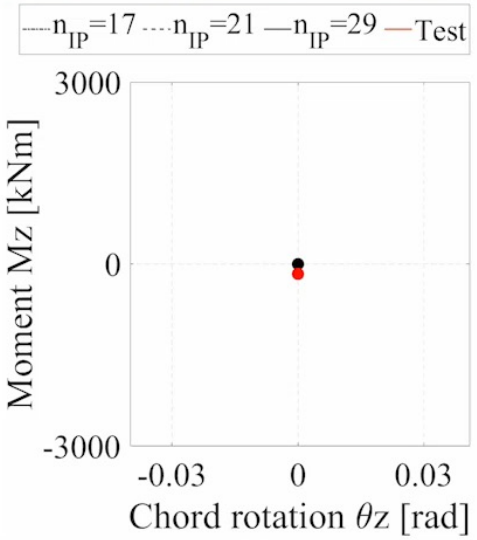
3-dimensional beam-column elements

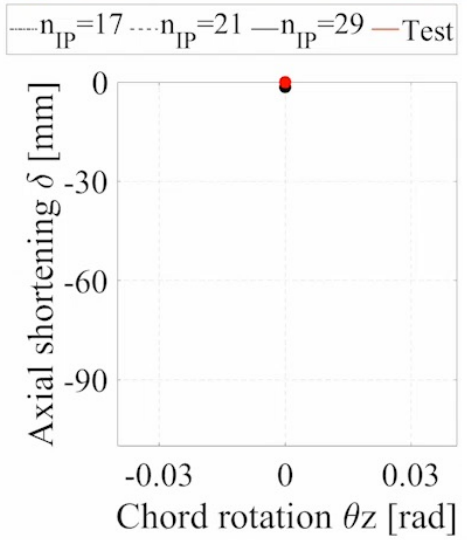
-Validation studies





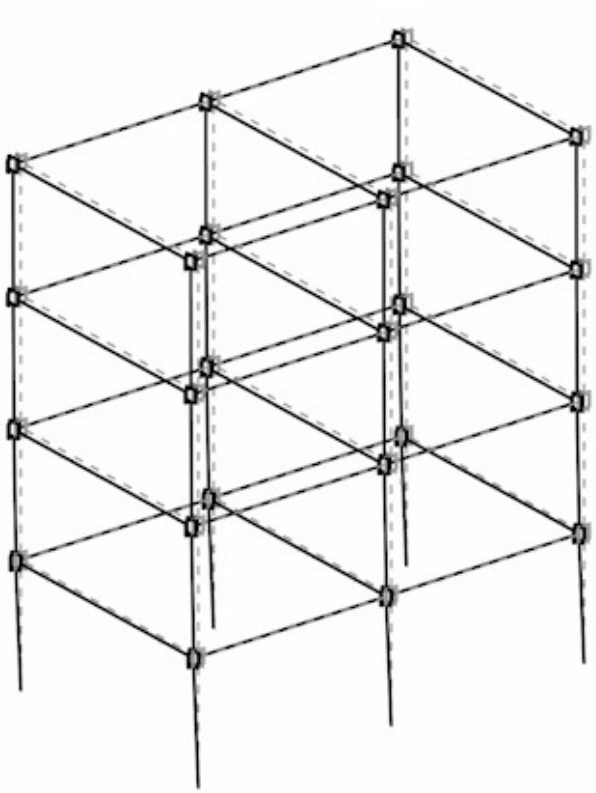






Source: Heredia, de Castro et Sousa and Lignos (2024)

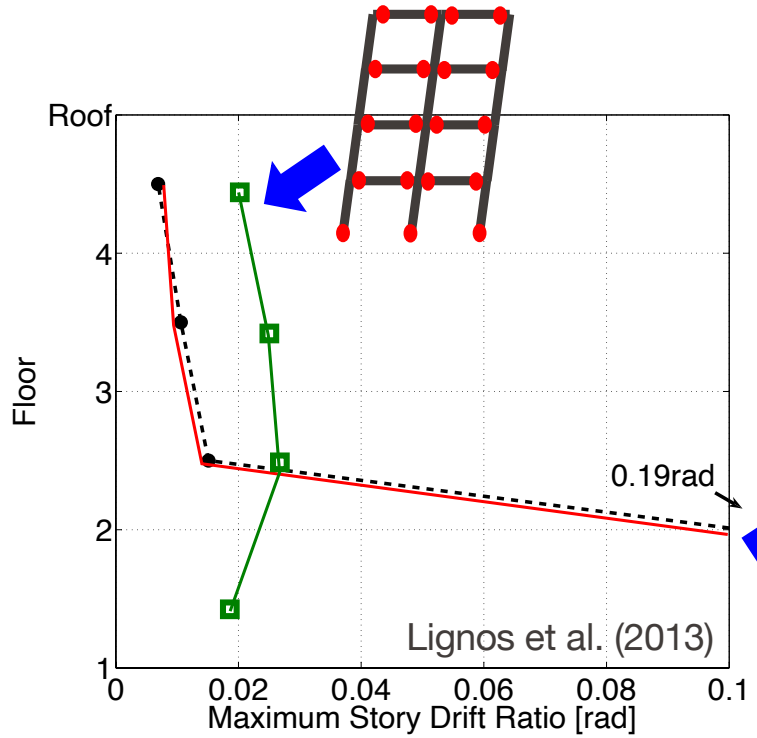
3-dimensional frame simulations to collapse

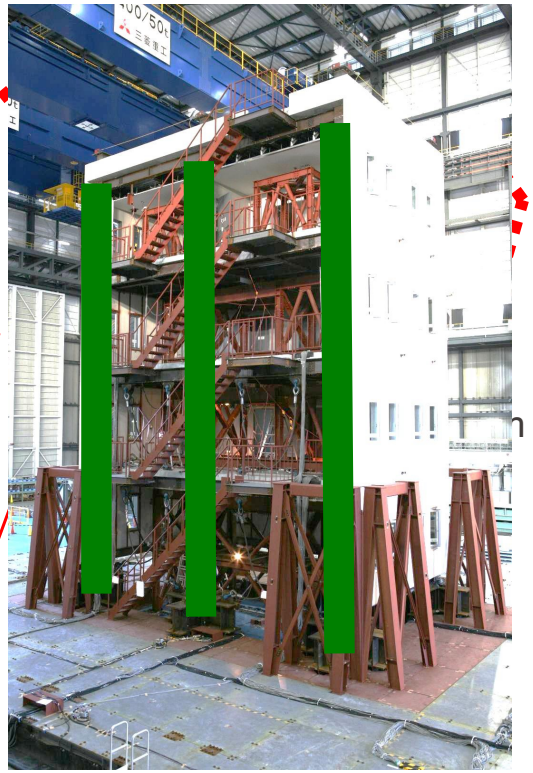


Source: Heredia, de Castro et Sousa and Lignos (2024)

Other benefits using nonlinear analysis

-Refinement of seismic standards





(Photo Source: E-Defense-2007)

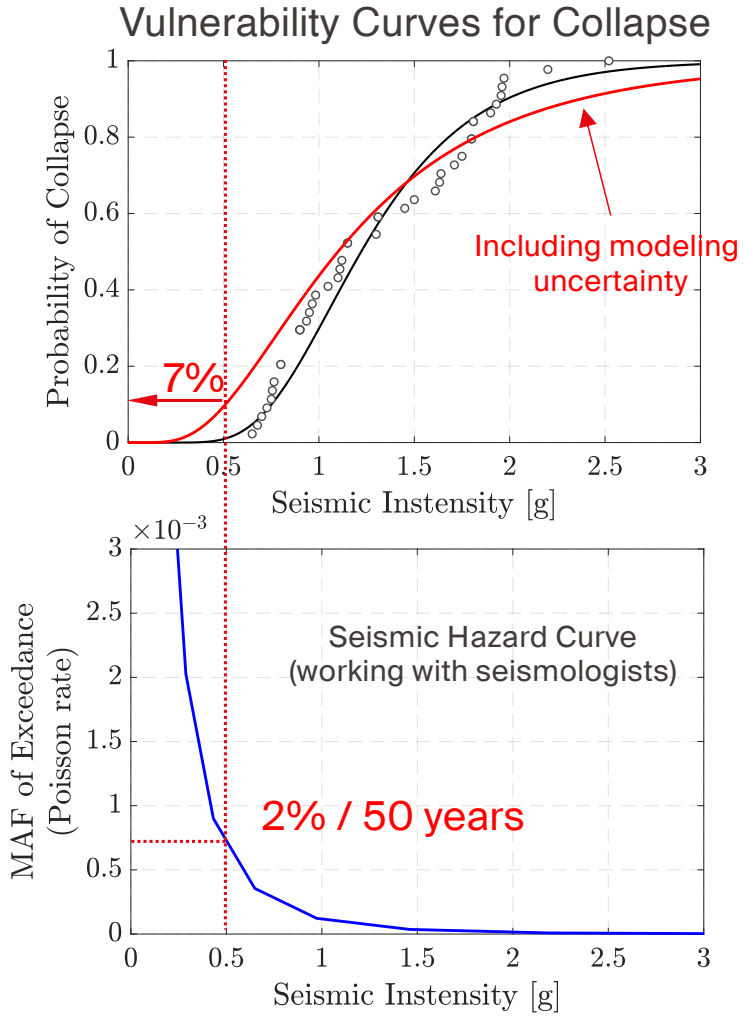
Measured Data → 100% Intensity of JR Takatori Record

Simulated Data (SCWB > 1.5) → 100% Intensity of JR Takatori Record

Simulated Data (Proposed SCWB > 2.0) → 100% Intensity of JR Takatori Record

Source: Lignos et al. (2013)

Benchmarking building performance to extreme events



Estimated Collapse Safety

- 7% probability of collapse under "Maximum Considered Earthquake"

  OR

- 0.7% Probability of collapse in 50 years

Question: Is this acceptable?

Perhaps…

In the meantime, such methodological developments can help improve our design standards in a systematic manner

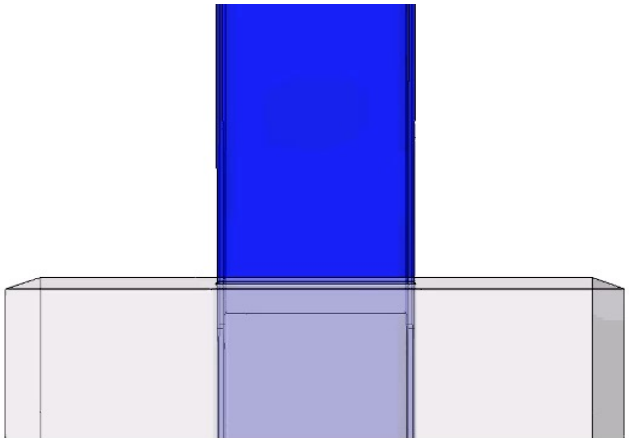
Elkady and Lignos (2015)

Eads, Miranda and Lignos (2016)

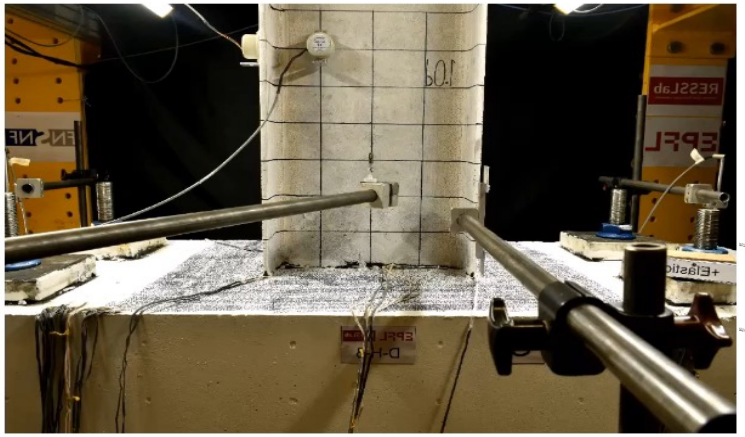
Other benefits using nonlinear analysis

-Steel columns resilient to earthquake damage

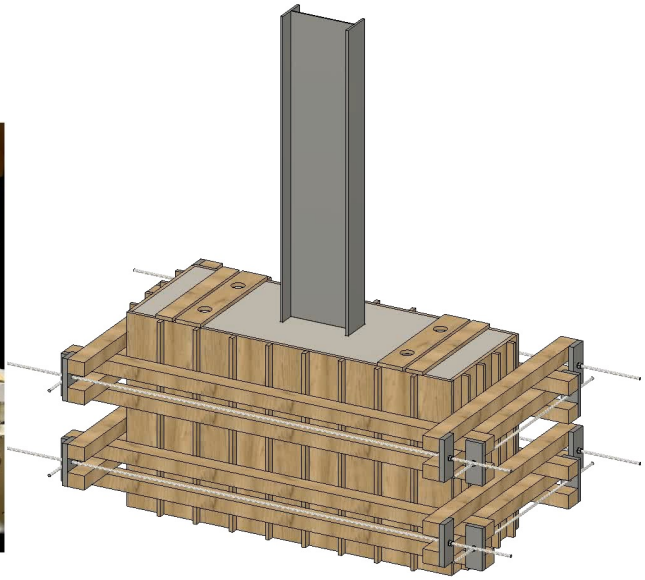
Conception assistée par simulation



Validation du prototype GIS @ EPFL



Séquence de fabrication



Inamasu, Sousa and Lignos (2022)

Other benefits using nonlinear analysis

Existing Medical Facilities 1960s

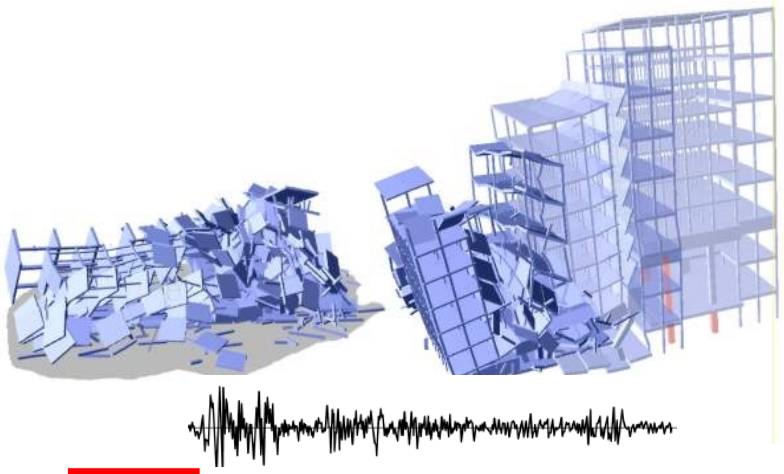
Photo courtesy of Prof. Robert Tremblay

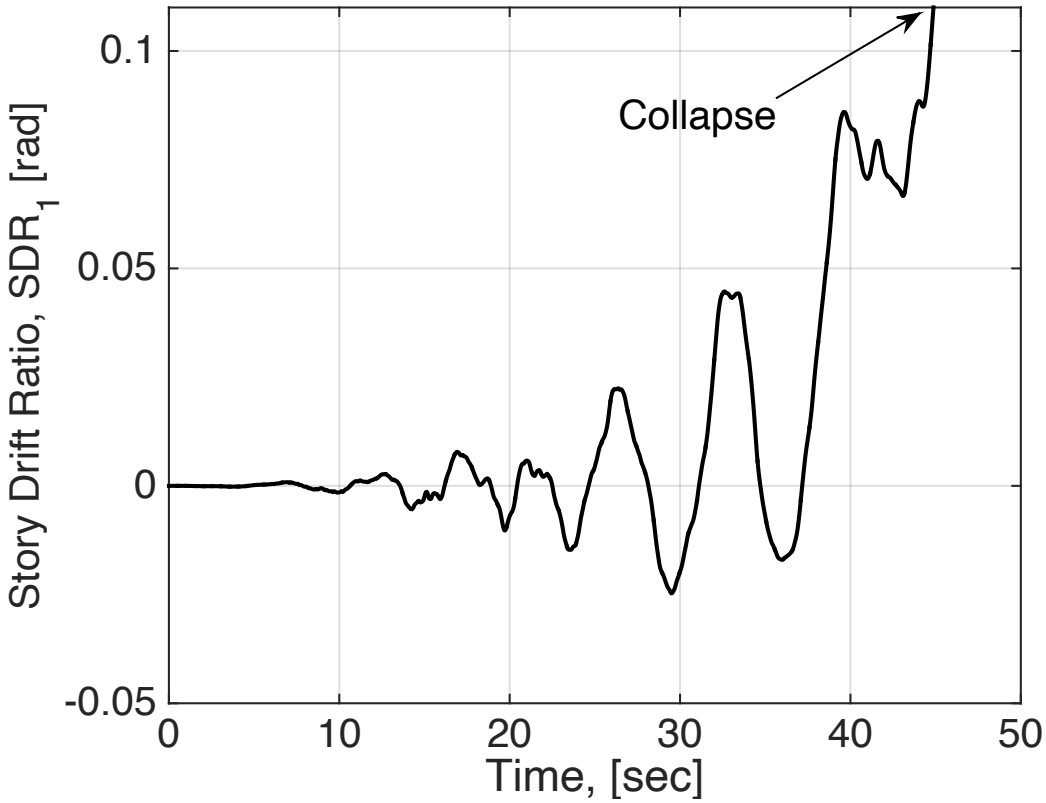
Existing Tall Buildings (>40 stories) 1970s

- Were built without seismic considerations (1960s – 1970s)
- Collapse risk is high in this case due to non-ductile failure modes

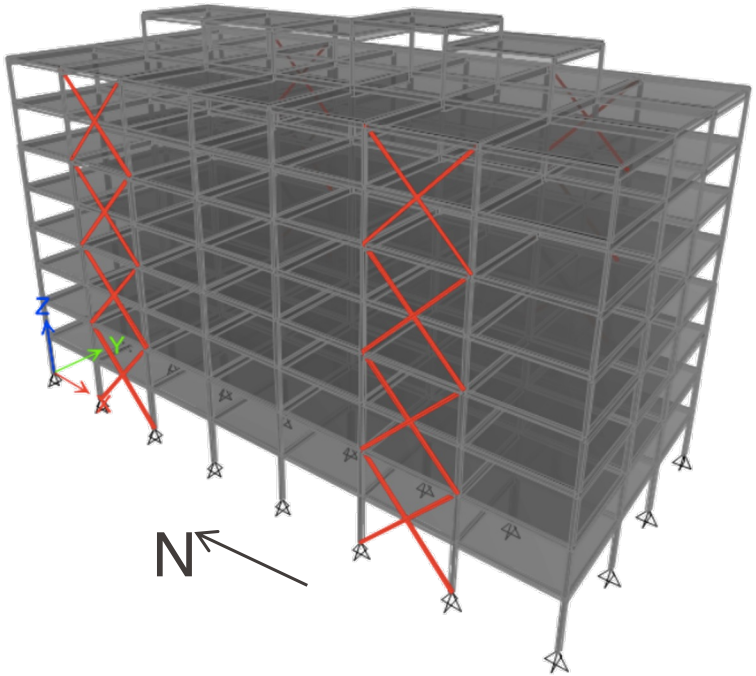
Other benefits using nonlinear analysis

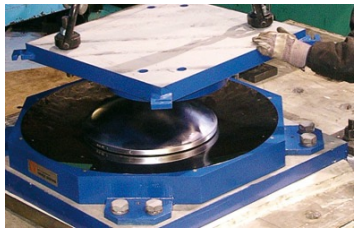
Nonlinear dynamic analysis simulation realization



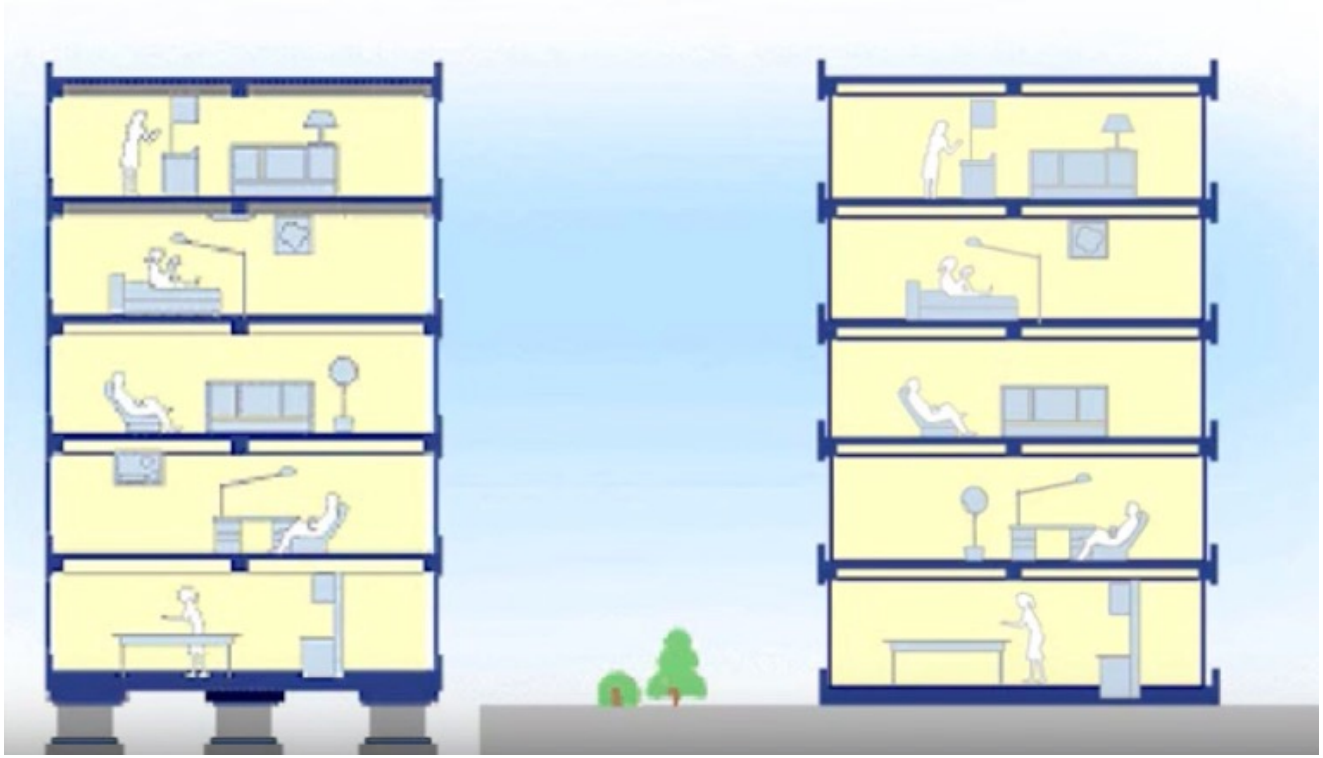


Other benefits using nonlinear analysis





Use of seismic isolator

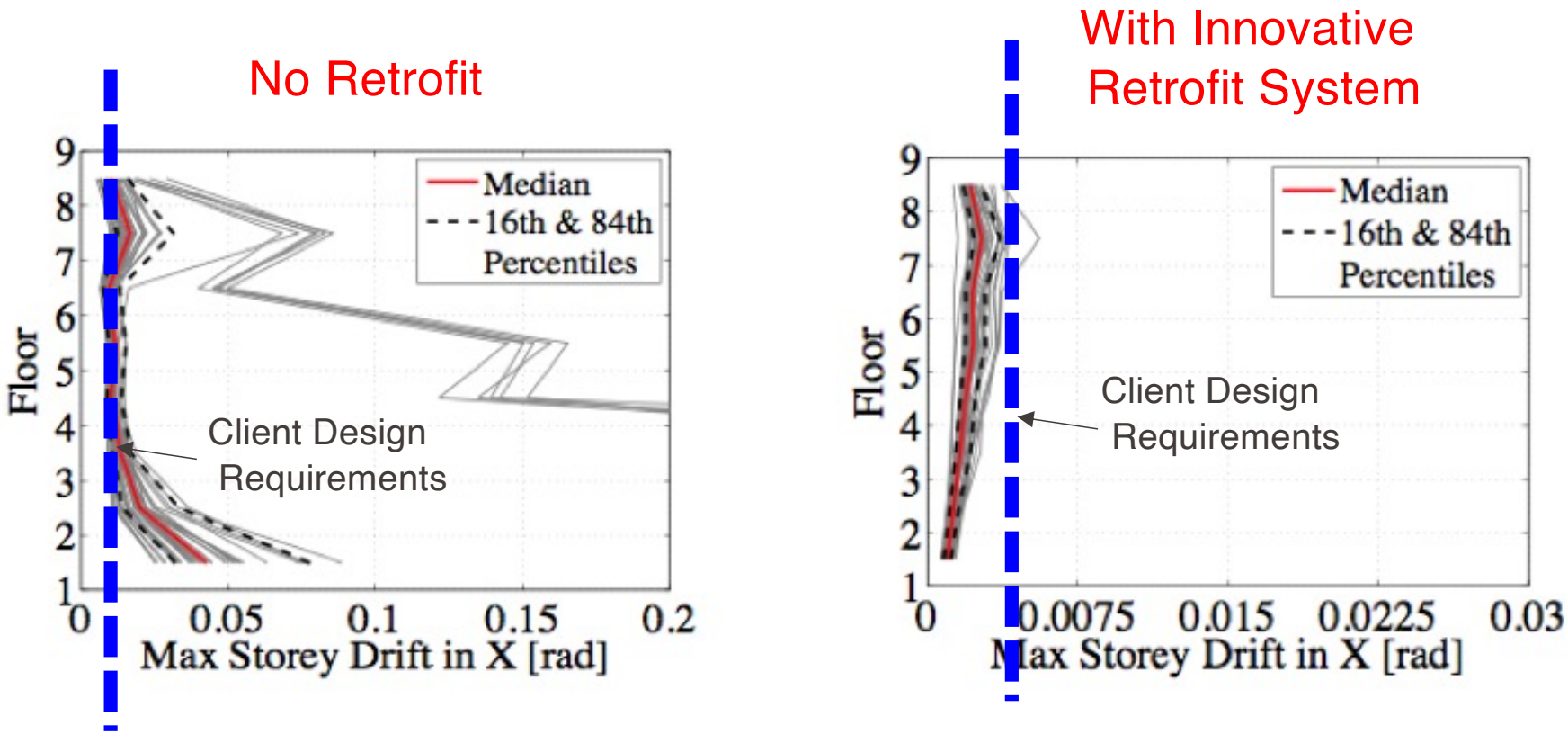


With isolation device

Without isolation device

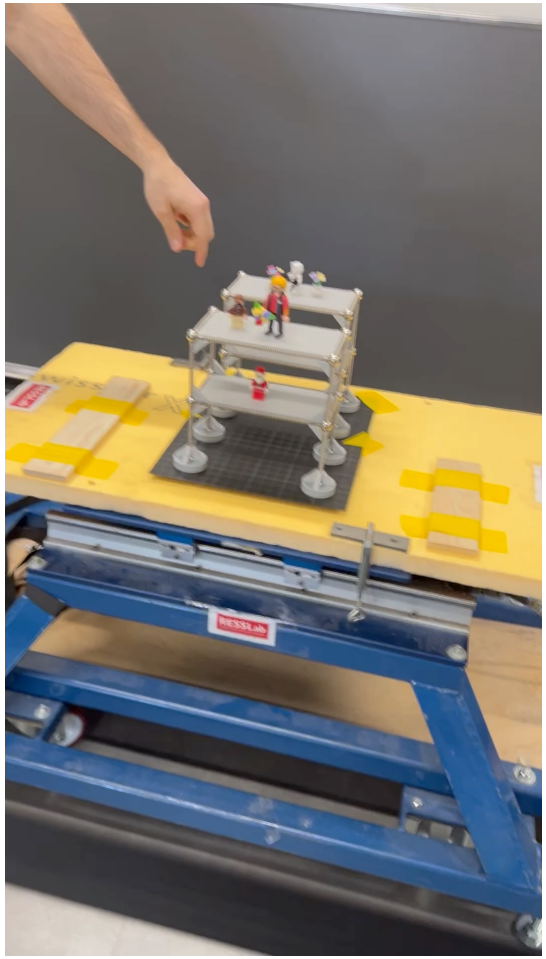
*Source: Walker and Lignos (2015)**

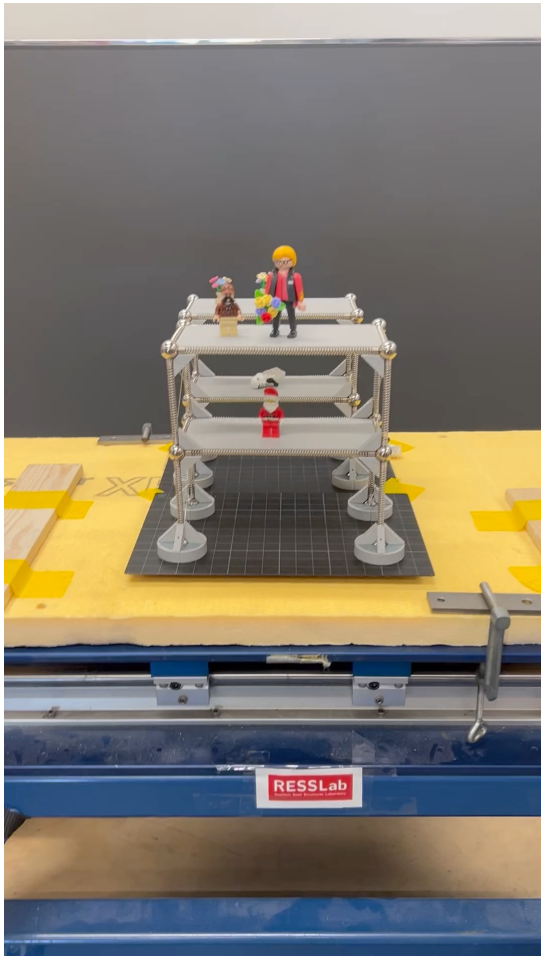
Other benefits using nonlinear analysis



*Source: Walker and Lignos (2015)**

Other benefits using nonlinear analysis





Source: RESSLab, Scientastic, EPFL 2024

Some personal remarks

- A more complex model does not necessarily mean it is a better model.
  - The quote “Everything should be made as simple as possible but not simpler (A. Einstein)” does apply in nonlinear analysis
- Errors often occur in the post-processing. Engineering intuition is essential in this case to trace fundamental errors
- Validate your nonlinear model with available (and meaningful) measurements from prior test data and or analytical solutions of known problems.
- Other aspects (e.g., role of slab, nonstructural elements & many others) may be important considerations for a rational nonlinear structural model

Things we did not talk about

- Nonlinear dynamics
  - Mass & damping matrices
  - Algorithms for nonlinear dynamics
  - Rate effects (e.g., impact, explosions)
  - Rate-dependent versus rate independent constitutive formulations
- Contact problems
- Time-dependent and temperature-dependent constitutive formulations
- 3-dimensional effects
- Come for at least one semester project in nonlinear analysis (with RESSLab ☺)!

Thank you!