CIVIL 449: Nonlinear Analysis of Structures

School of Architecture, Civil & Environmental Engineering
Civil Engineering Institute

Introduction

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EPFL, ENAC, IIC, RESSLab

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EPFL, ENAC, IIC, EESD

Objectives of today's lecture

To introduce:

- Course personnel
- Course logistics
- Learning objectives
- Nonlinear analysis of structures

Course personnel

Instructors:

- Prof. Dr. Dimitrios G. Lignos (GC B3 485)
- Dr. Savvas Saloustros (GC B2 485)

Teaching Assistants:

- Mr. Hnat Lesiv (GC B2 484, hnat.lesiv@epfl.ch)
- Dr. Diego Heredia (GC B3 464, diego.heredia@epfl.ch)

Assessment methods

Graded Assignments (40% of the total grade)

- Four written assignments
- You are allowed to work in groups of 2

Final Examination (60% of the total grade)

- Covers the entire course material
- Location & time to be announced later this year
- Exam is closed notes: (standard calculator and 2 sheets, i.e., 4 pages of your own notes are permitted)

Resources and other information

- Lecture notes will be distributed through *Moodle* the week before the lecture.

- Other reading material will be provided through *Moodle*.

Lectures & announcements

- **Lectures:** ***Mondays: 14h15 to 16h00, Wednesdays 9h15 to 10h00***
- **Exercise:** ***Wednesdays: 10h15 to 12h00***

- All announcements will be made through *Moodle*

In-Class exercise session

- Exercises will be posted ahead of time together with lecture notes
- An online forum has been posted in *Moodle* per exercise for Q & A
- Detailed solutions will be posted in *Moodle* within a week after the exercise session

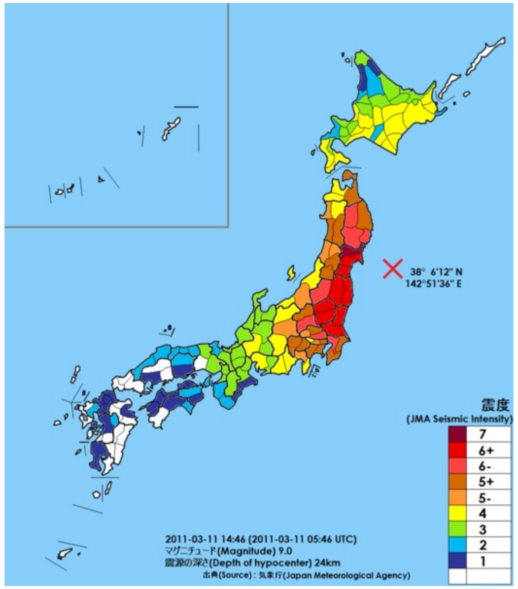
What is this course about?

- Behavior of linear versus nonlinear structures
- Idealization of structures and their elements for nonlinear analysis
- Constitutive modeling of construction materials
  - Plasticity
  - Continuum damage mechanics
- Geometric transformations (geometric nonlinearities)
- Solution techniques for nonlinear problems
- Zero length and beam-column elements
- Integration techniques for nonlinear elements
- Mesh sensitivity
- Nonlinear static versus dynamic analysis
- Applications

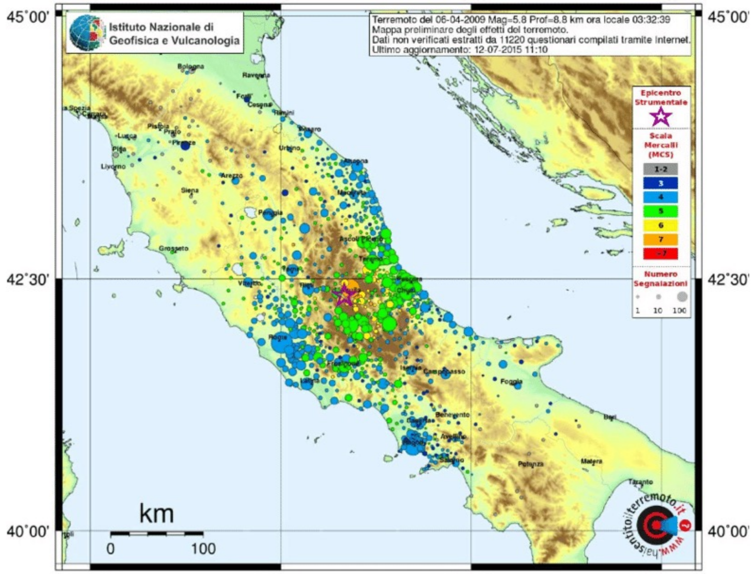
Motivation: Large earthquakes in recent years…

Demonstrated that the magnitude of earthquake forces applied to buildings were (or can be) significantly larger than the corresponding design earthquake loads based on regional seismic design.

Chile 2010



Japan 2011



Italy 2009

Images Source: EERI Reconnaissance Reports

Collapse risk during large earthquakes

Hyogoken-Nanbu 1995

Taiwan 1999

Loma Prieta 1989

Northridge 1994

Hyogoken-Nanbu 1995

Tohoku 2011

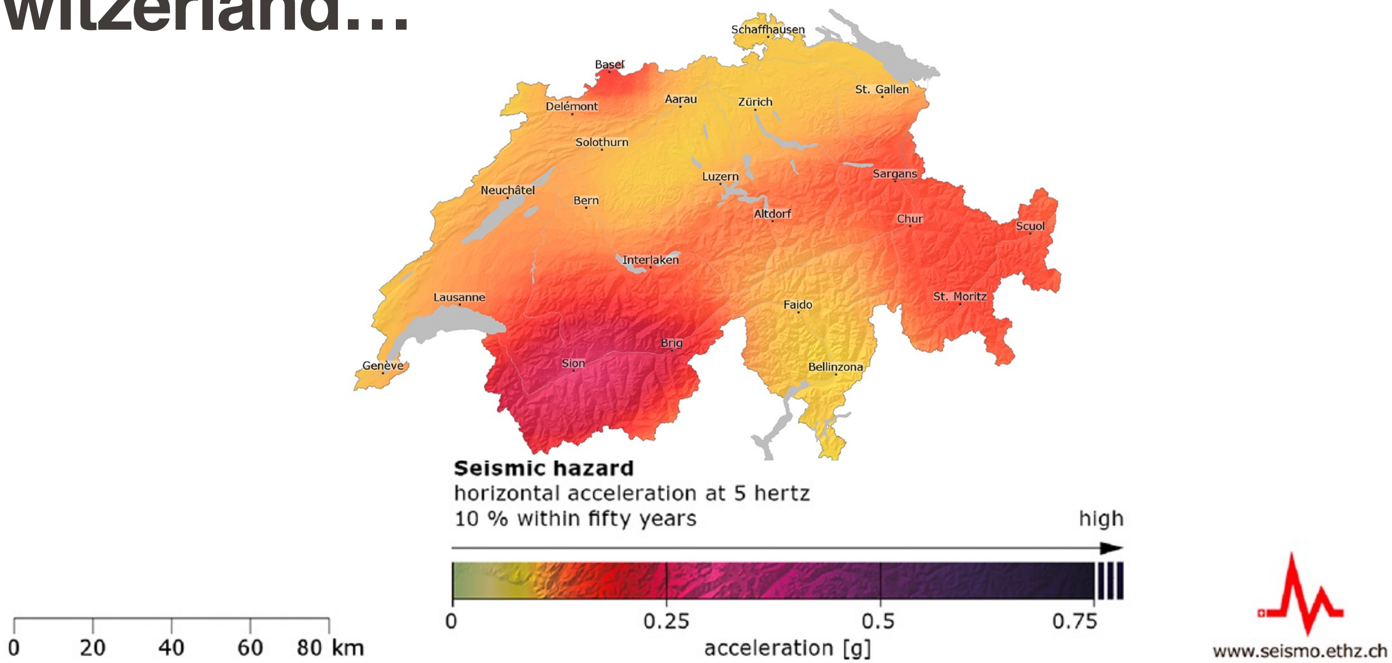
Images Source: NISEE, E-Library

2011 Christchurch, New Zealand ($M_w = 6.1$)

- Casualties: 185
- Financial losses NZ$40B (20% of New Zealand's GDP)
  - Insured only NZ$20B (source: Swiss Re)
  - 1200+ buildings were demolished
  - Displaced population, downtime

Clearly not sustainable

In Switzerland…



- Seismic risk: ranked 3rd after pandemics & electric shortages
- Scenario $M_w = 6.5$ earthquake
  - collapse risk is high
  - Up to 6000 casualties, over 60000 injured
  - Expected financial losses: CHF50 to 100Billion

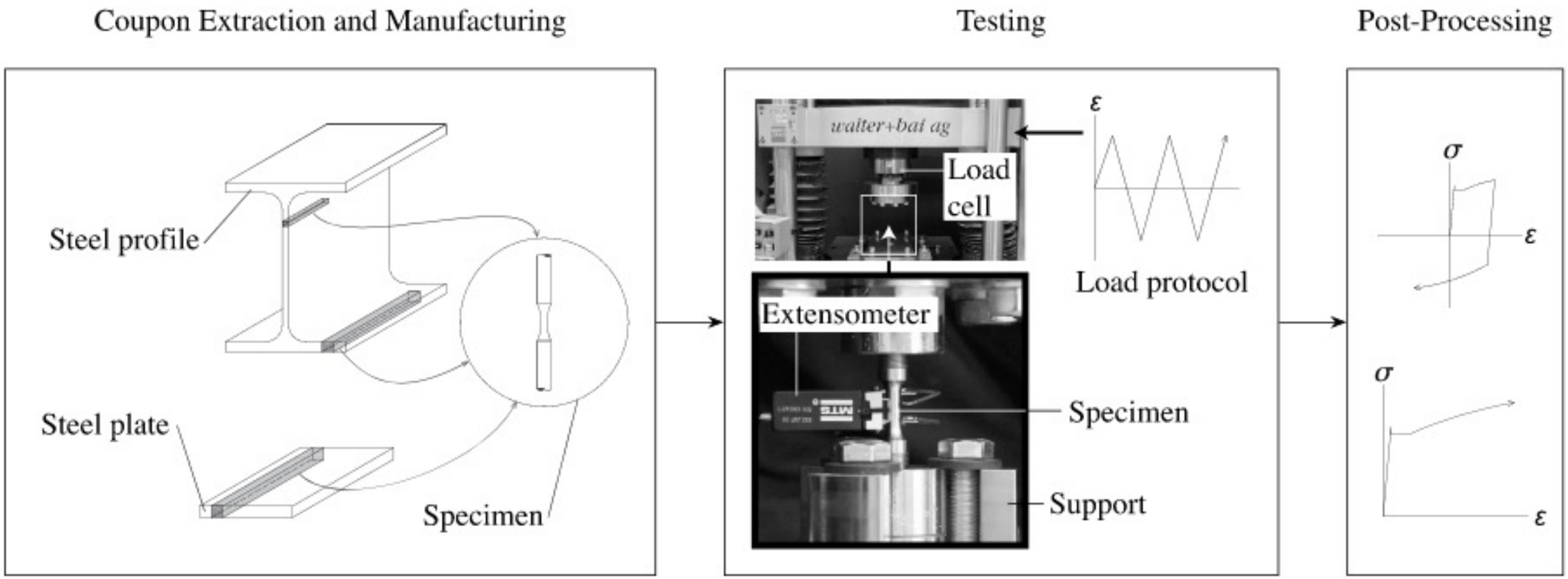
Sources: Fäh et al. (2000), Federal Office for Civil Protection (2020)

Nonlinear behavior of structures

Coupling of nonlinear phenomena

- Material nonlinearity (inelastic straining)
- Nonlinear geometric instabilities (large deformations)

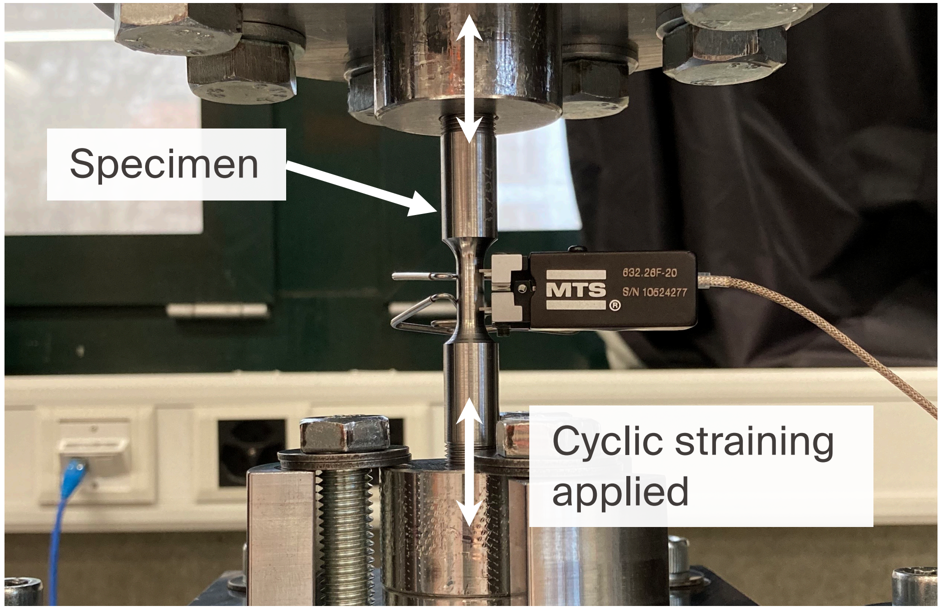
Material nonlinearity



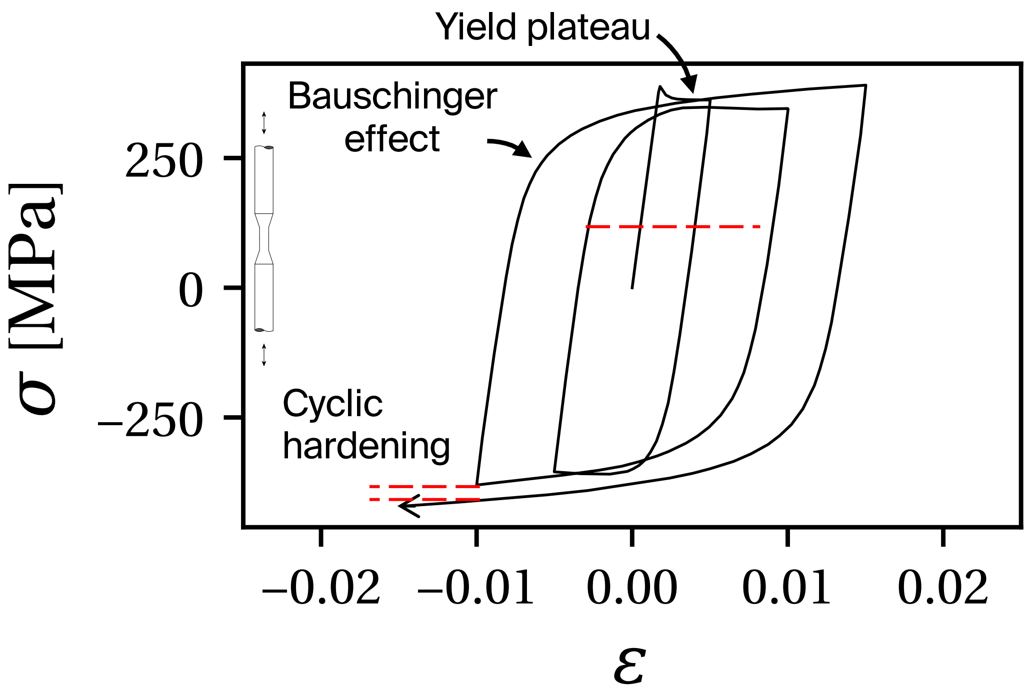
Source: Hartloper et al. (2023)

Material nonlinearity

Material testing



Resulting stress-strain response



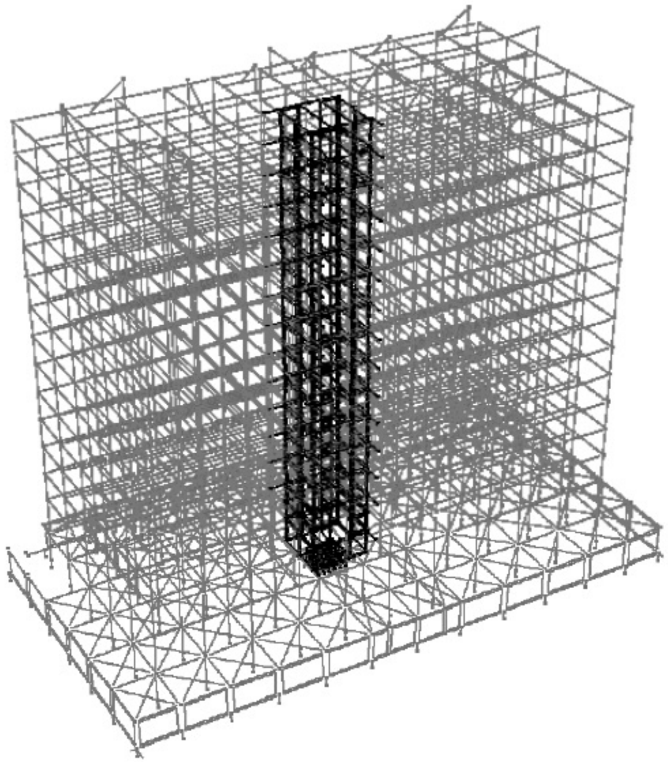
Source: Hartloper, de Castro e Sousa and Lignos (2020)

Geometric nonlinearities

Geometric nonlinearities

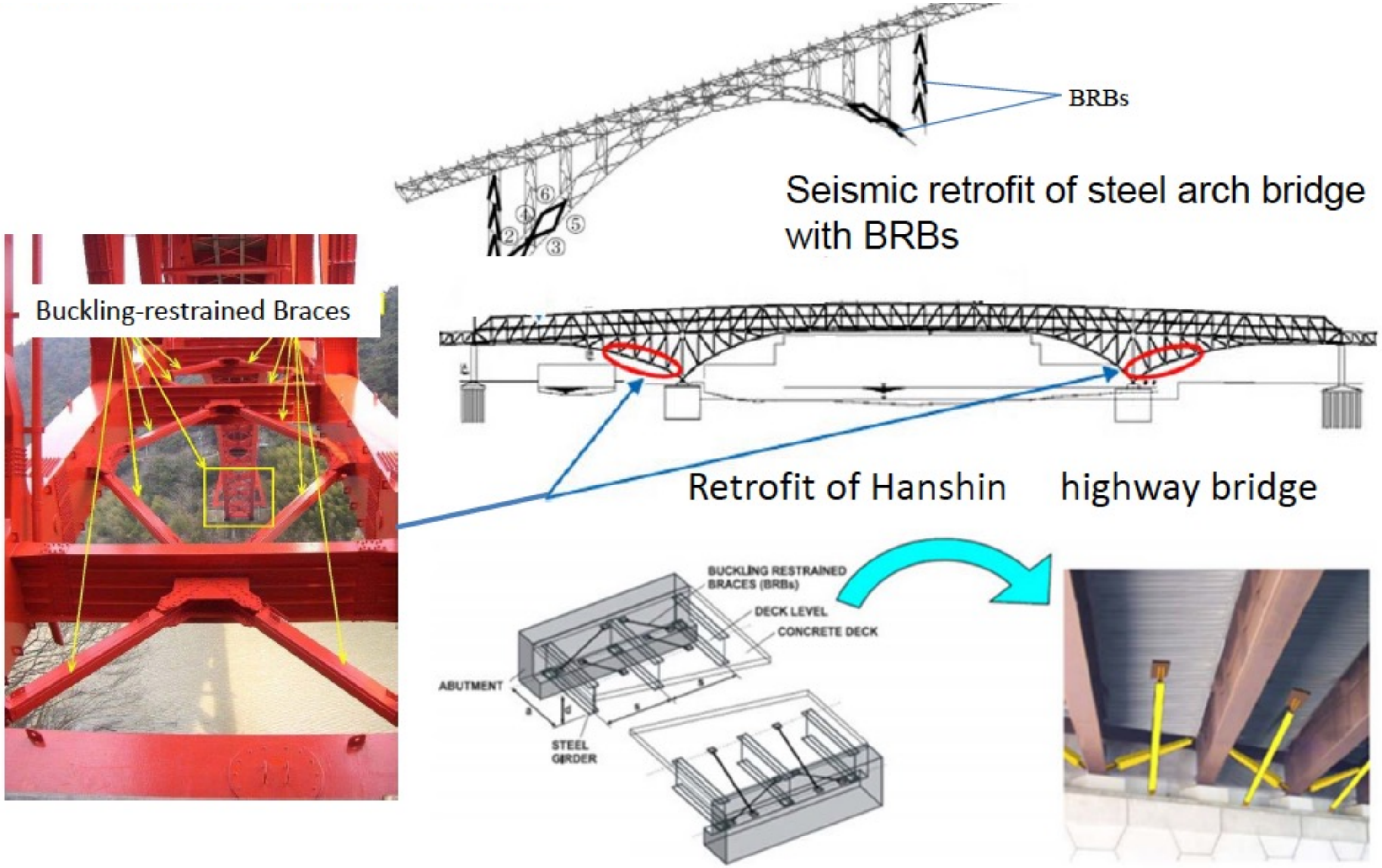
Seismic interventions of existing buildings

680 Folsom Street, San Francisco, USA



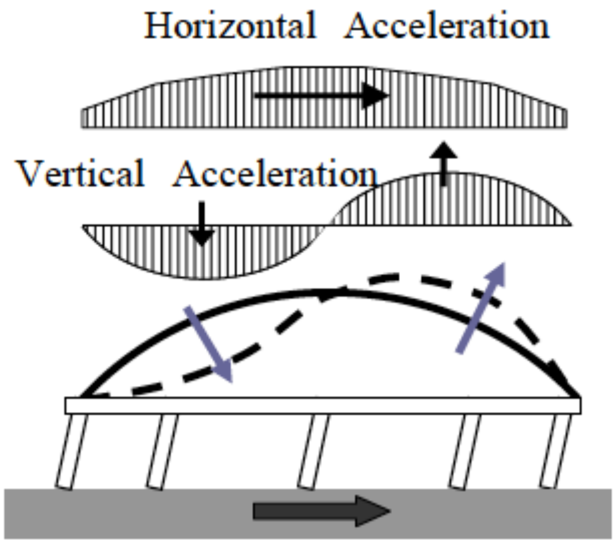
Source: Janhunen et al. (2013)

Seismic interventions of existing bridges

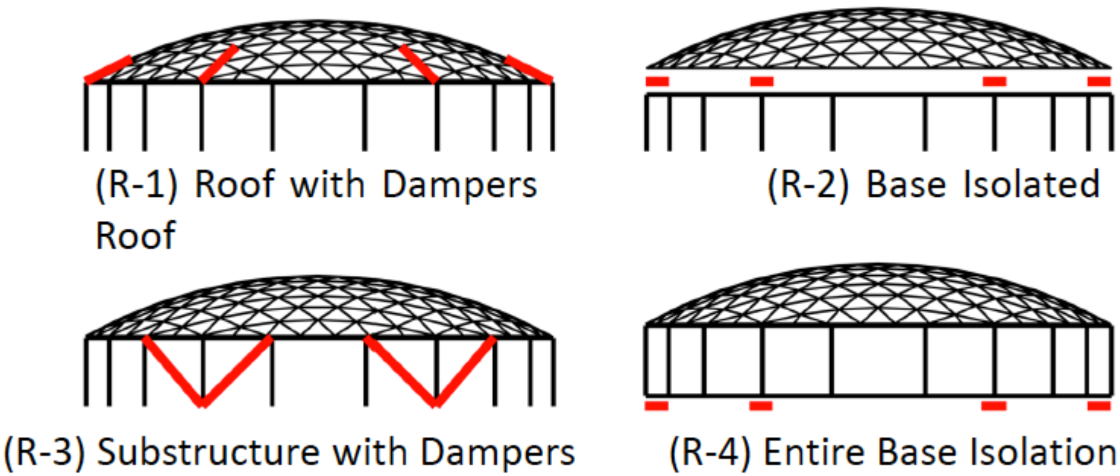


Source: Celik and Bruneau (2011)

Seismic interventions of special structures



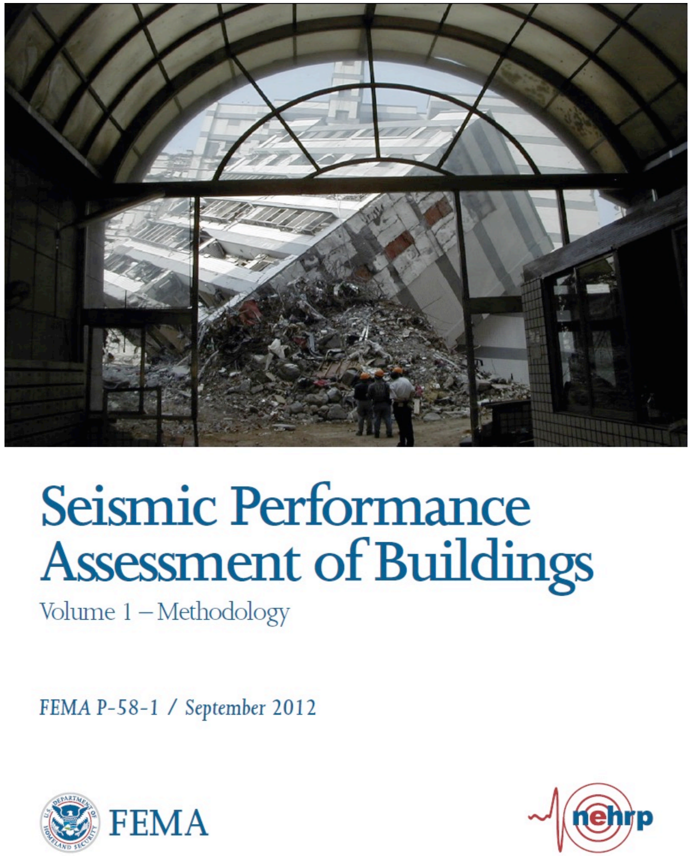
Seismic Response of Raised Roof



Device Layout for Response-controlled Roof Structures

Source: Prof. Dr. Takeuchi

Why nonlinear analysis of structures
-Linking performance with lifecycle analyses



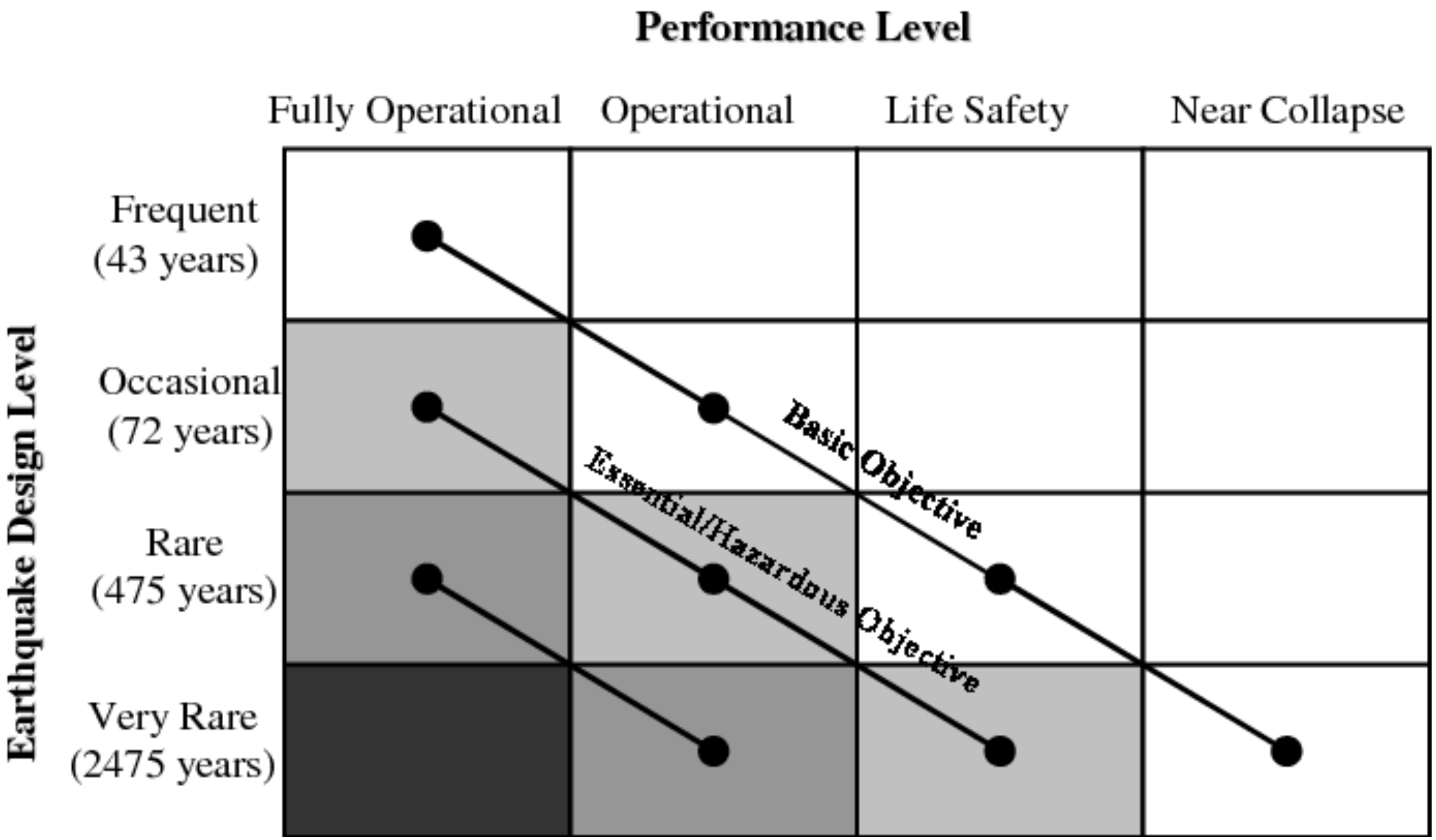
Performance-Based Earthquake Engineering (PBEE)

- Performance level: Definition of the expected performance for a specific seismic hazard level.
- Seismic hazard level: Intensity of ground shaking for a given return period

Performance levels

- **Operational:** Building suitable for normal intended occupancy.
- **Immediate Occupancy:** Building may be used for intended purpose, albeit in an impaired mode.
- **Life Safety:** Occupancy may be prevented until repairs can be instituted.
- **Collapse Prevention:** Little margin against collapse.

Performance-based earthquake engineering



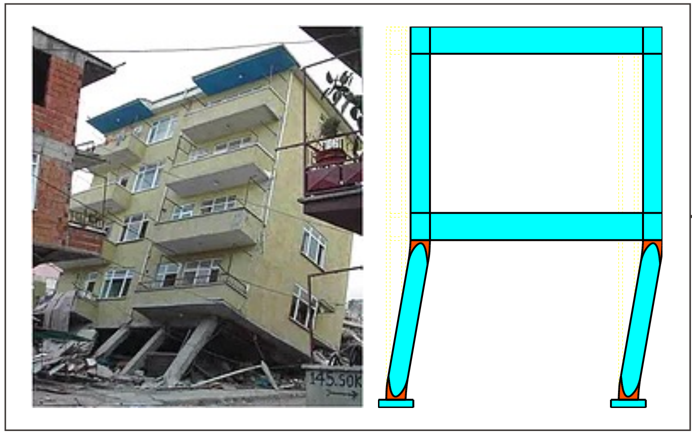
Cornell and Krawinkler (2001)

Performance-based earthquake engineering

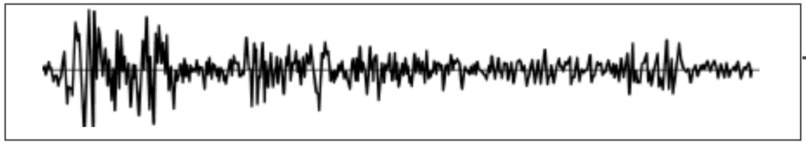
Collapse & casualties
Direct financial loss
Downtime

Decision Variable

Damage Measure



Engineering Demand Parameter



Intensity Measure

Source: Prof. Dr. D.Lignos, CIVIL 714 (PBEE), EPFL

Performance-based earthquake engineering

$$\boxed{\lambda(DV)} = \int_{\substack{all\\IMs}} \int_{\substack{all\\EDPs}} \int_{\substack{all\\DMs}} \boxed{G(DV|DM)\,dG(DM|EDP)\,dG(EDP|IM)}\,\boxed{d\lambda(IM)}$$

Impact — **Performance (Loss) Models and Simulation** — **Hazard**

IM: Intensity Measure

EDP: Engineering Demand Parameter

DM: Damage Variable

DV: Decision Variable

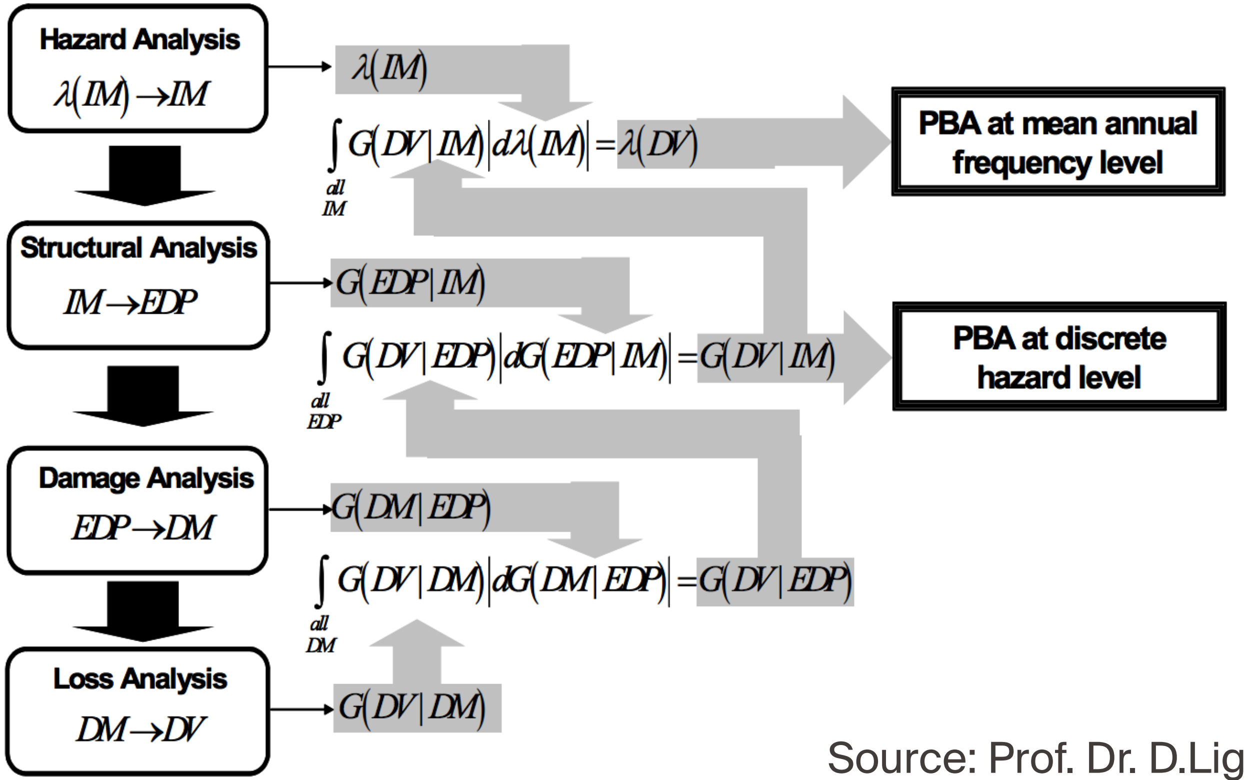
$\lambda(DV)$: Probabilistic description of decision variable

(e.g., Mean Annual Frequency of Collapse, λ_c over a structure's life-expectancy)

Source: Prof. Dr. D.Lignos, CIVIL 714 (PBEE), EPFL

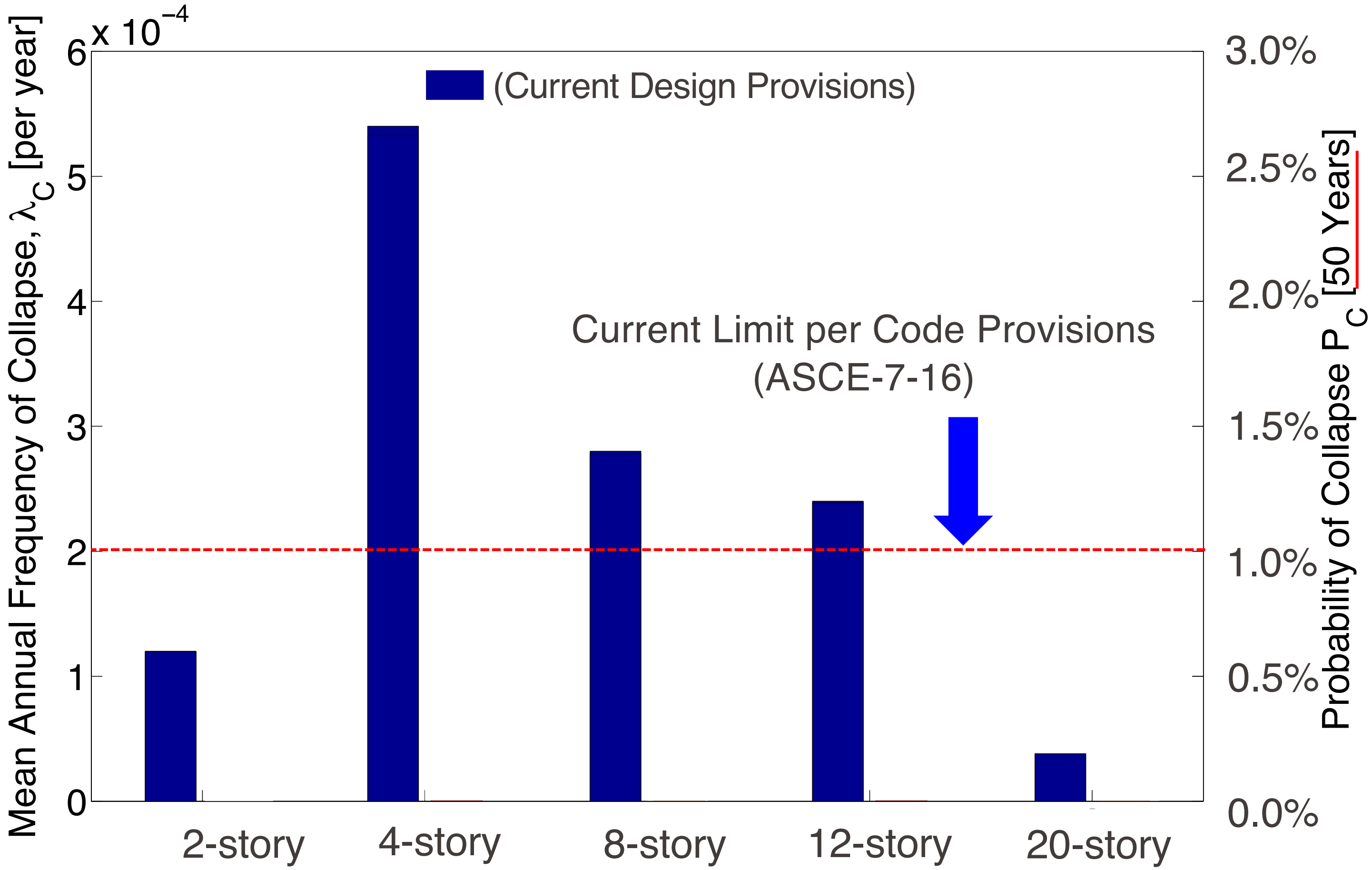
Performance-based earthquake engineering

$$\lambda(DV) = \int\limits_{\substack{all\\IMs}} \int\limits_{\substack{all\\EDPs}} \int\limits_{\substack{all\\DMs}} G(DV|DM)\,dG(DM|EDP)\,dG(EDP|IM)\,d\lambda(IM)$$



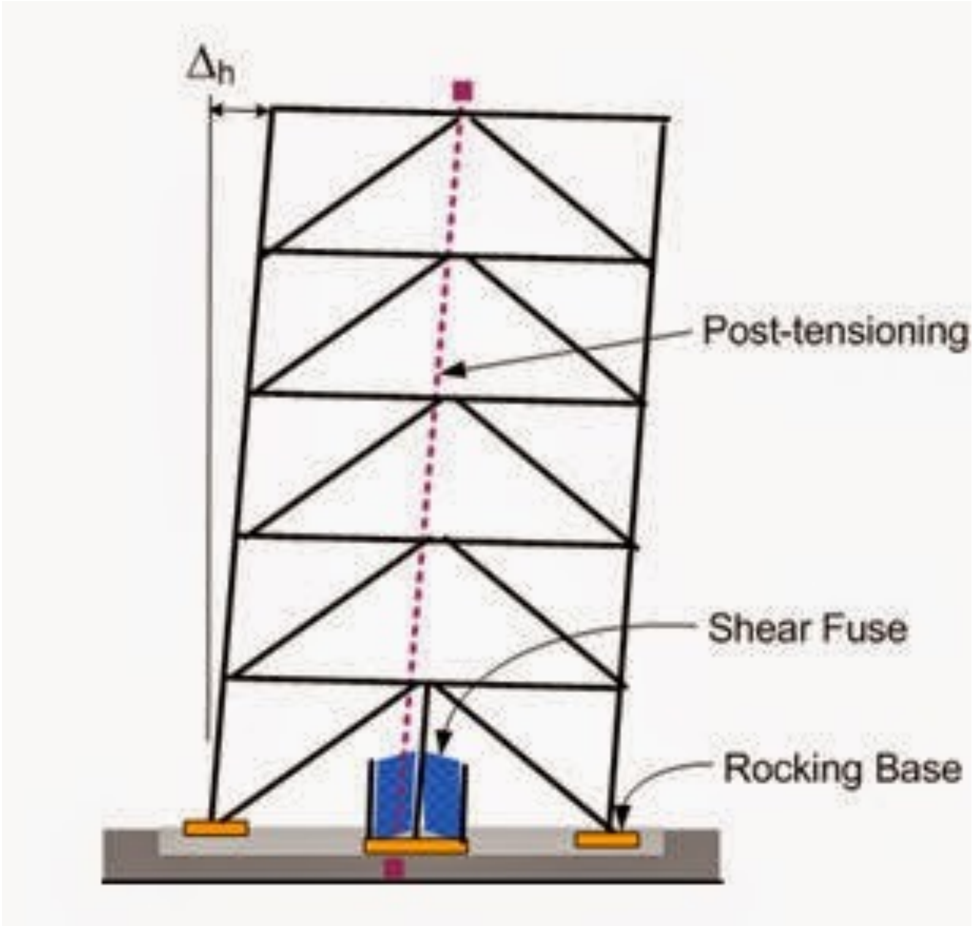
Source: Prof. Dr. D.Lignos, CIVIL 714 (PBEE), EPFL

An example on collapse risk assessment of steel moment frames



Source: Elkady and Lignos (2016)

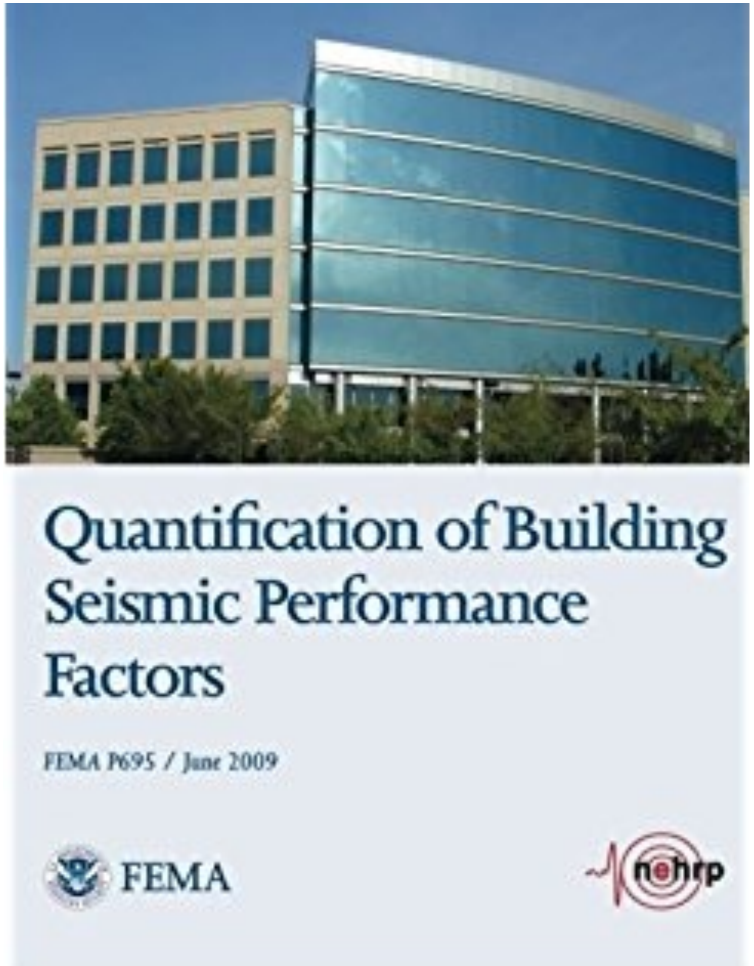
New lateral load-resisting systems

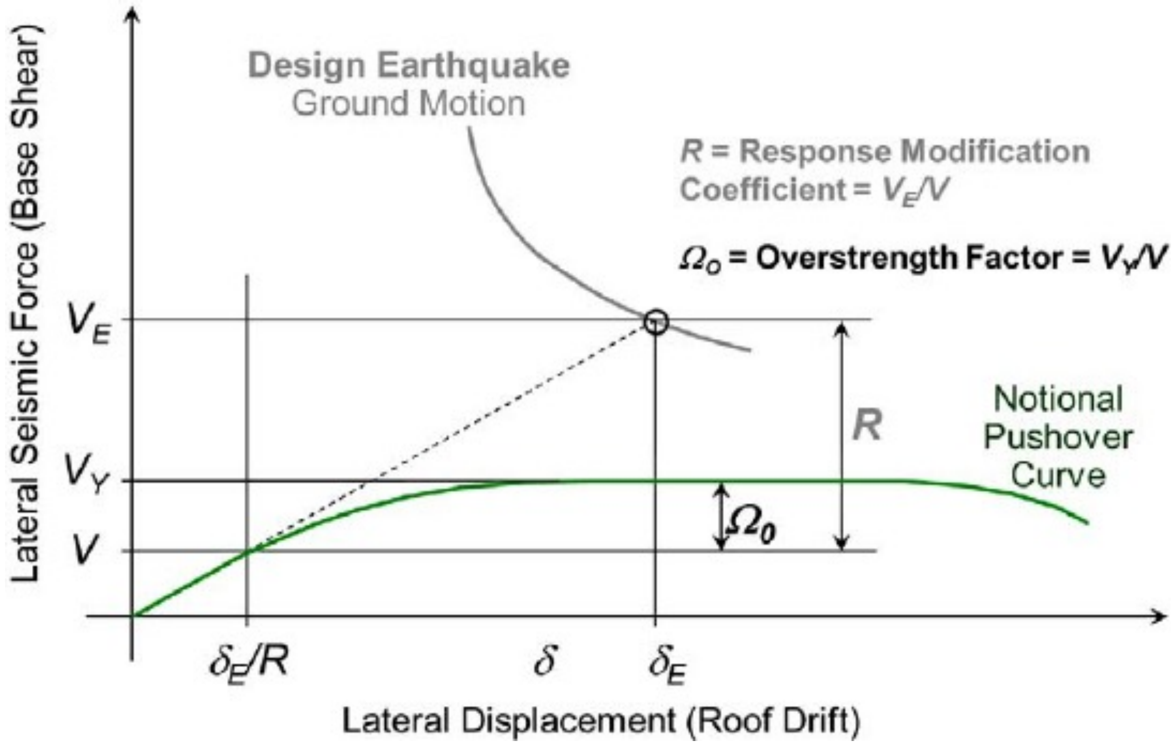


- For implementation
  - q-factor (R-) quantification
  - System Overstrength (Ω) quantification

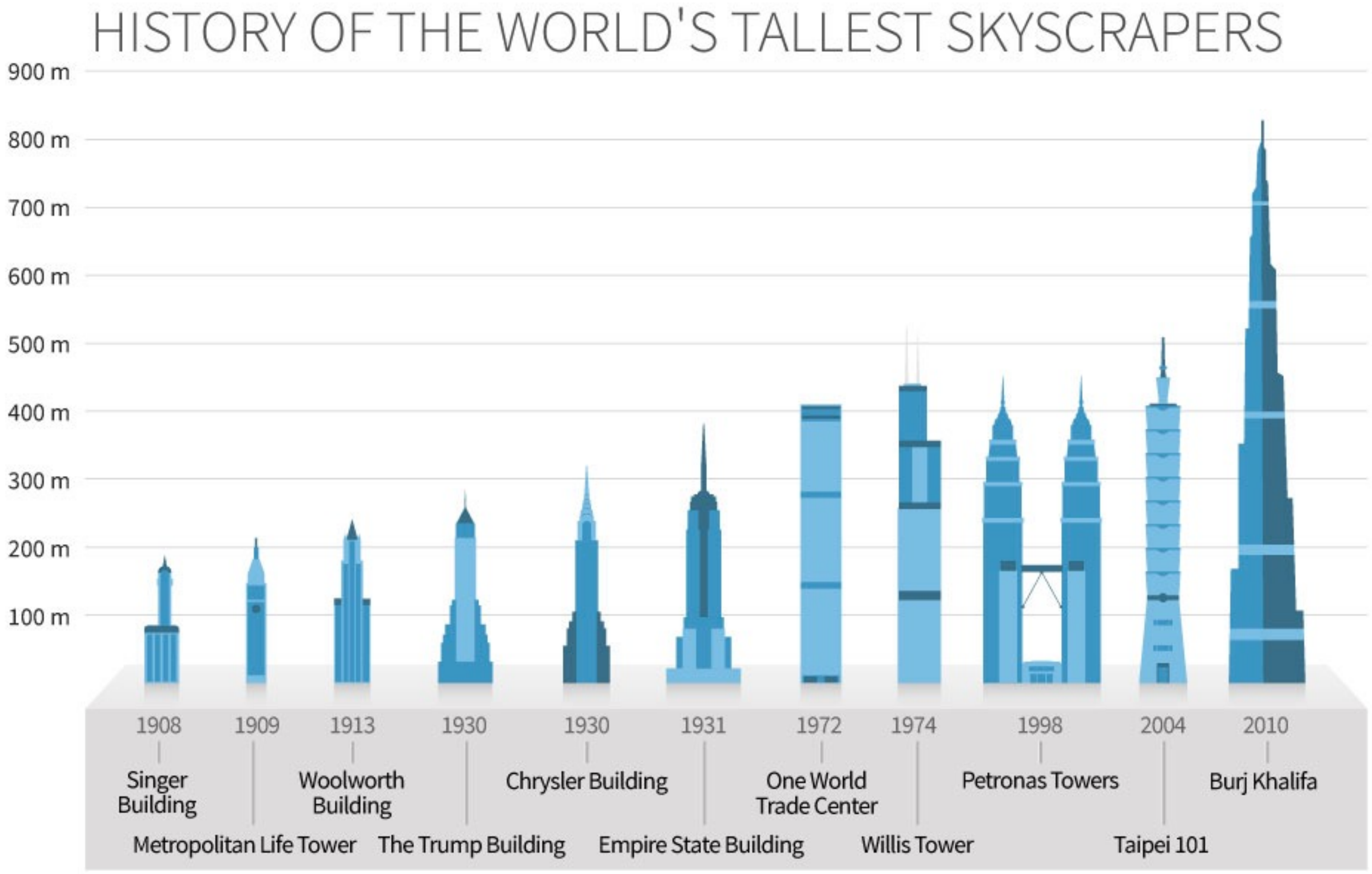
Image source: Prof. Ricles

New lateral load-resisting systems



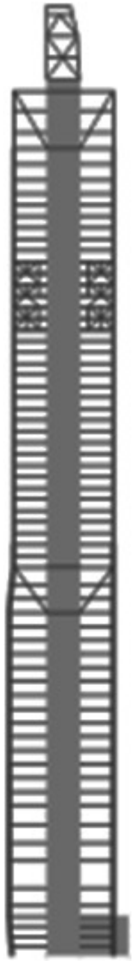


Use of nonlinear analysis in special projects



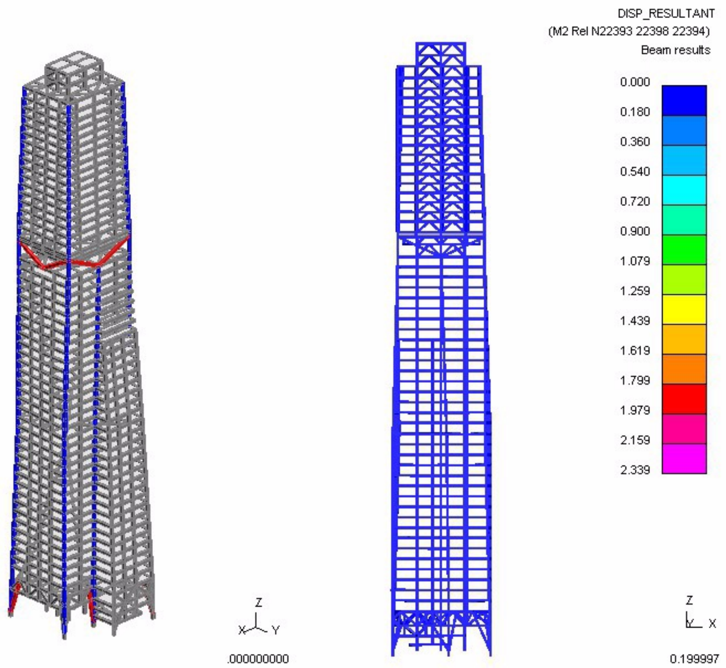
Source: www.emporis.com

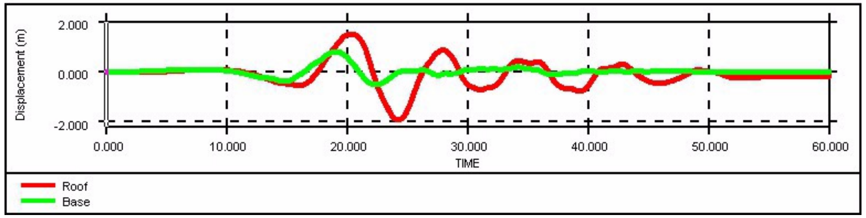
Use of nonlinear analysis in special projects



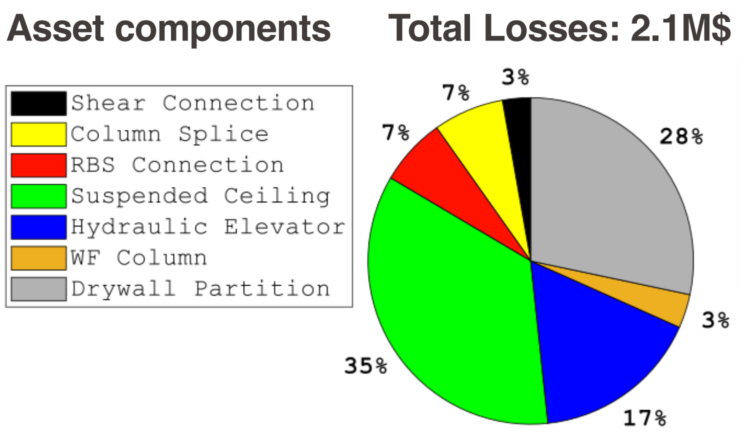
Figures, Courtesy of Prof. Dr. D. Lignos, 2018

Use of nonlinear analysis in special projects



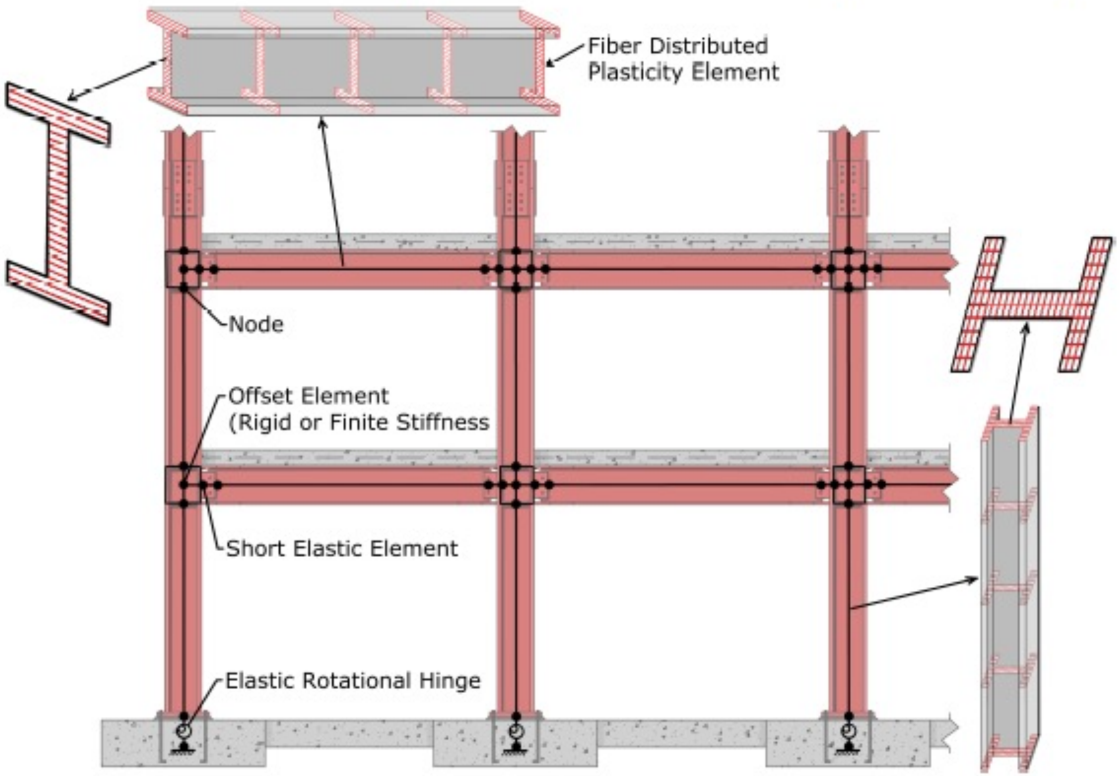


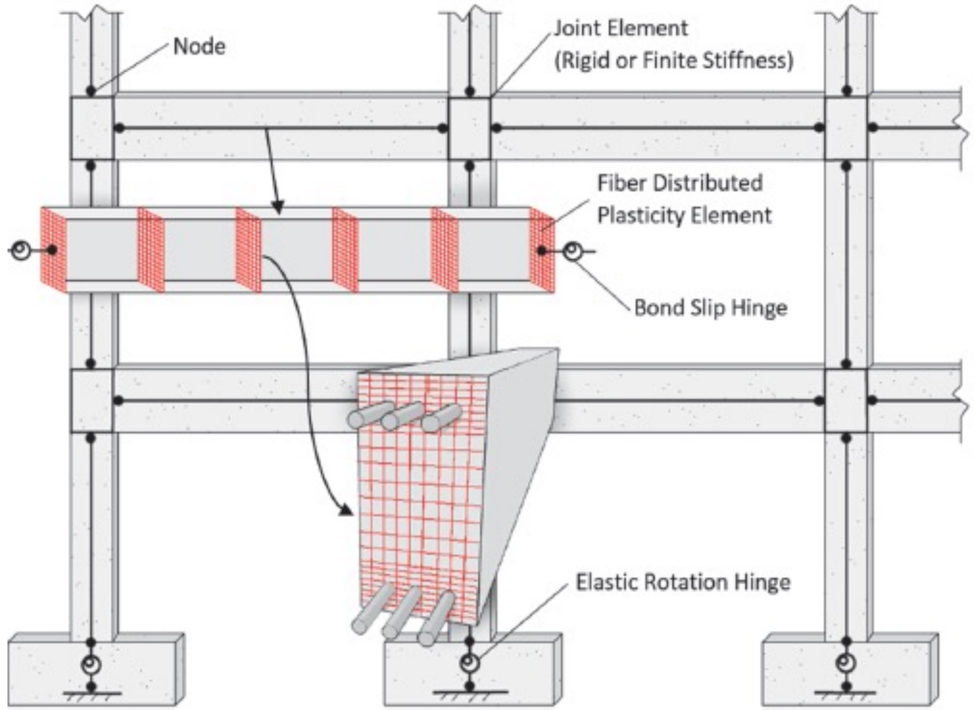
Financial loss dissagregation
For scenario-based events & planning



Source: Elkady and Lignos (2020)

Elements for nonlinear modeling of frame structures

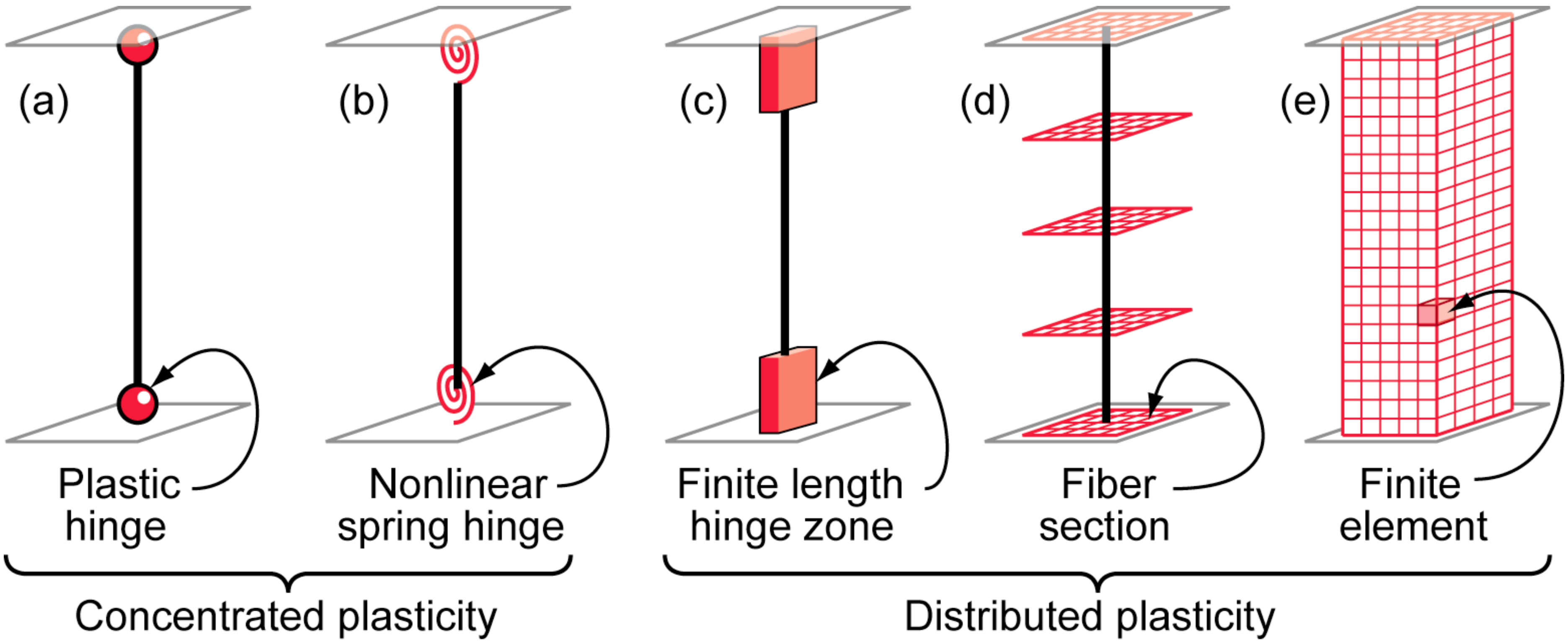




Source: GCR 17-917-46v2

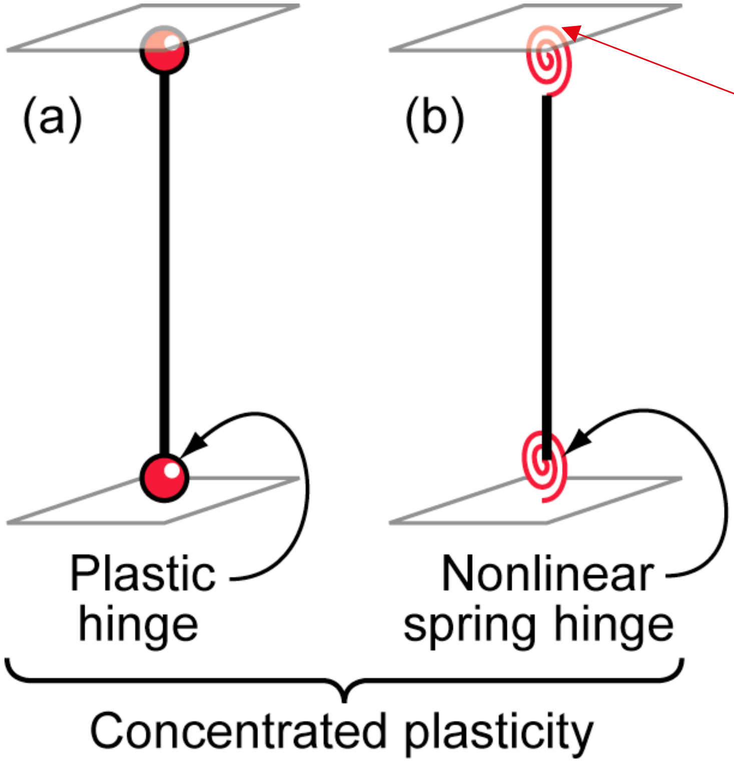
Source: GCR 17-917-46v3

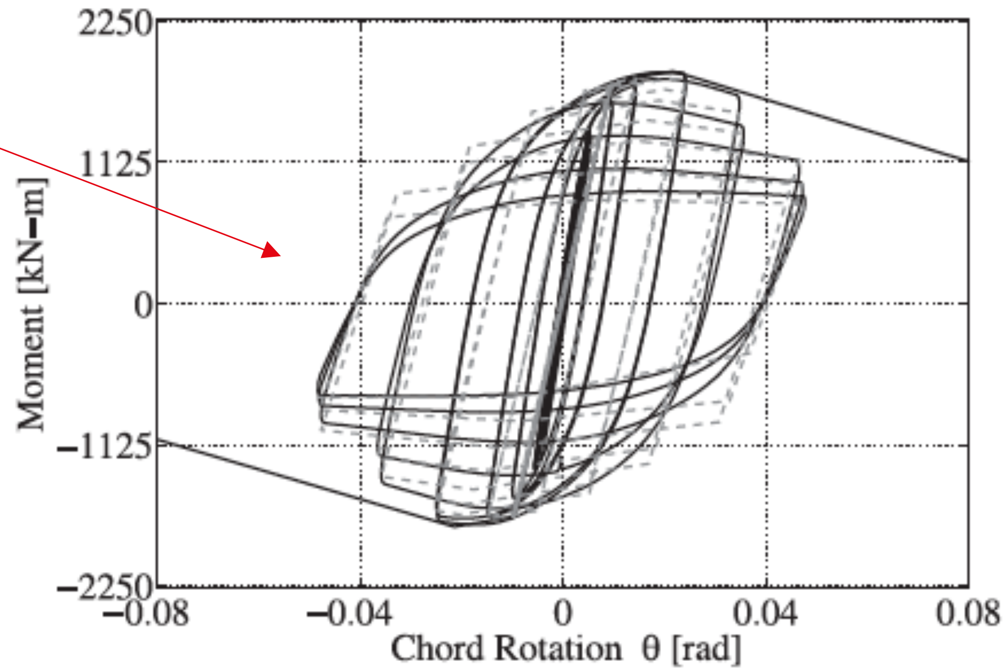
Model fidelity



Source: NIST 2010

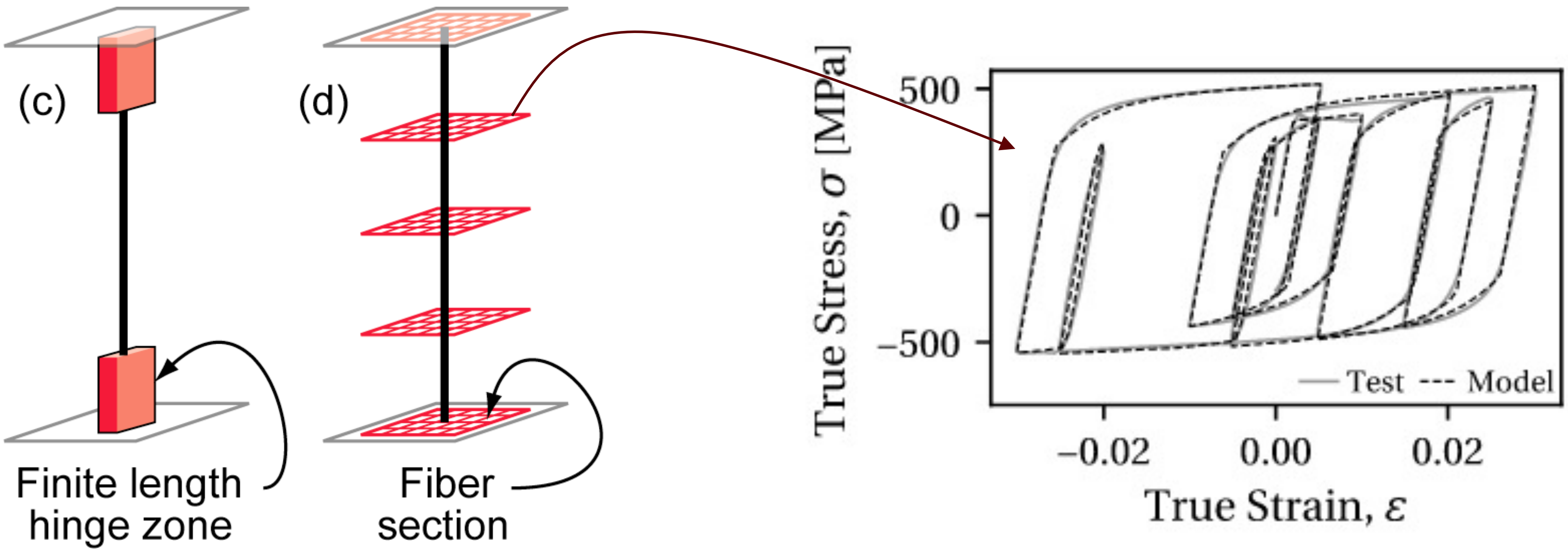
Concentrated plasticity models





(Source: Lignos and Krawinkler 2011)

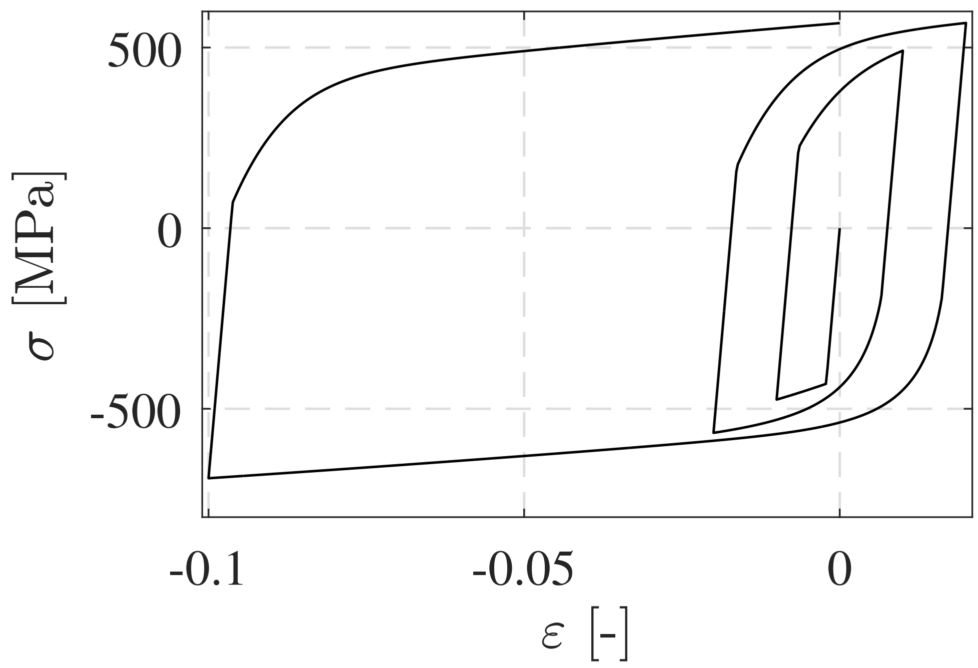
Distributed plasticity models



(Source: Hartloper et al. 2023)

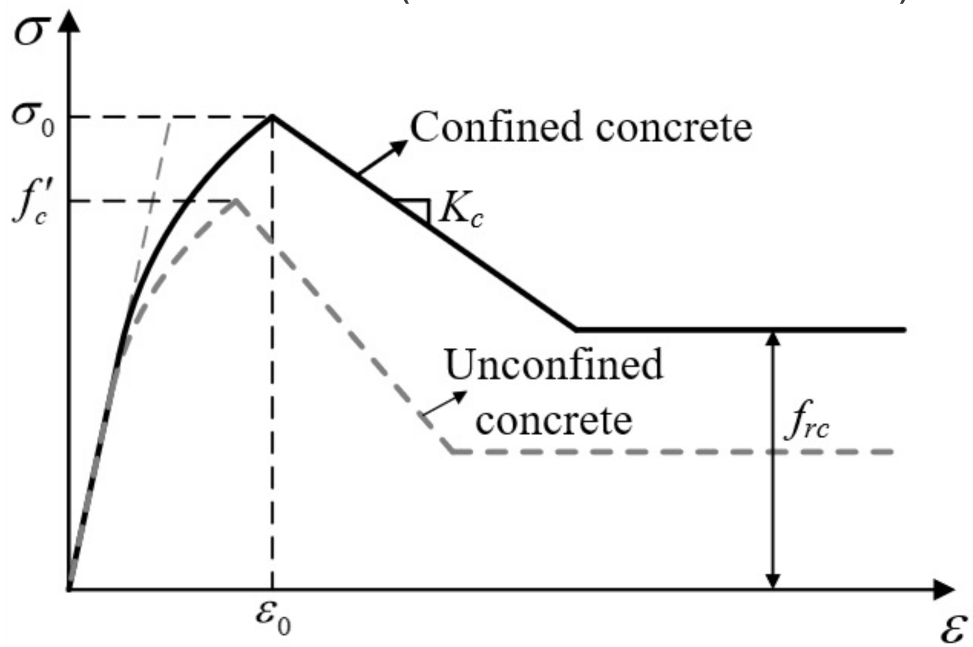
Constitutive models for construction materials

Structural steel



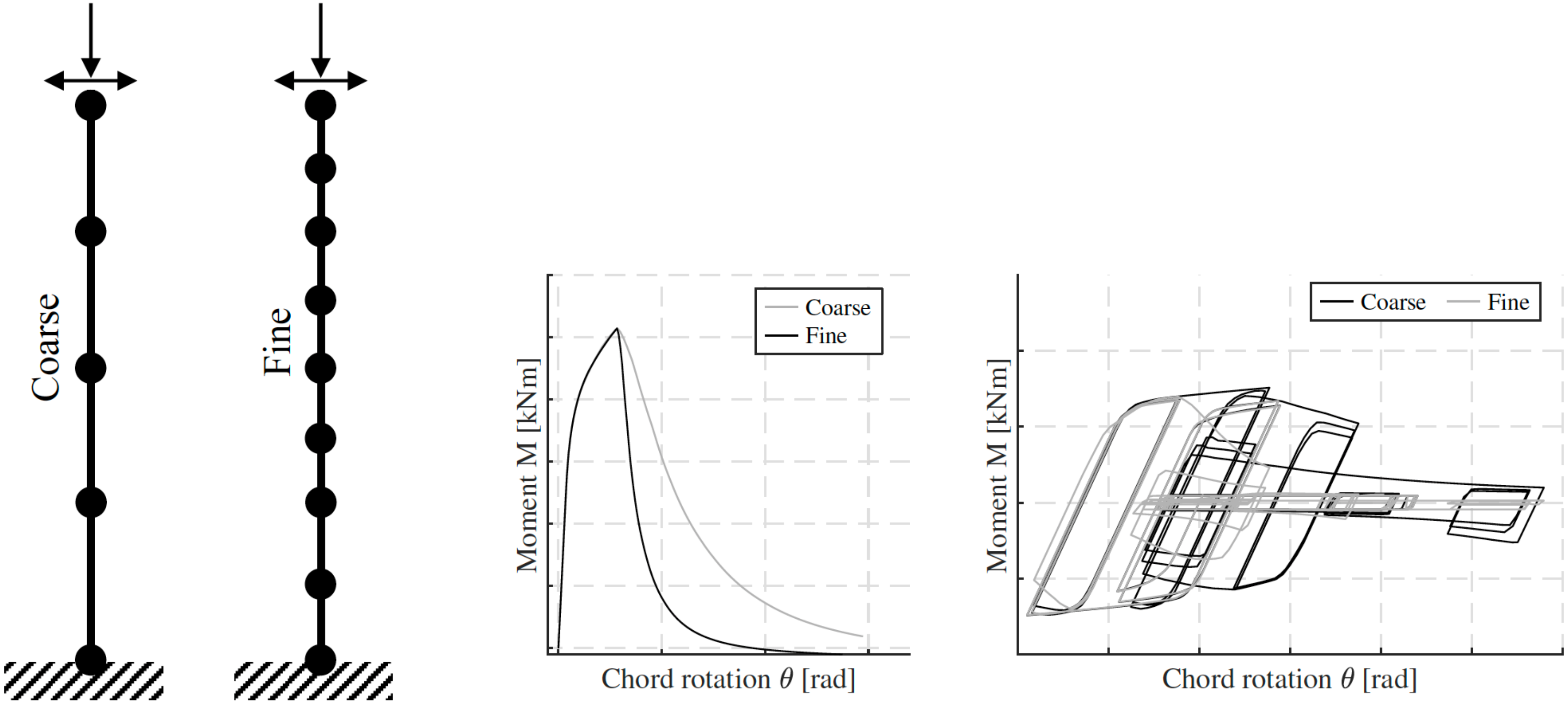
Source Hartloper et al. (2021)

Concrete (reinforced or unreinforced)



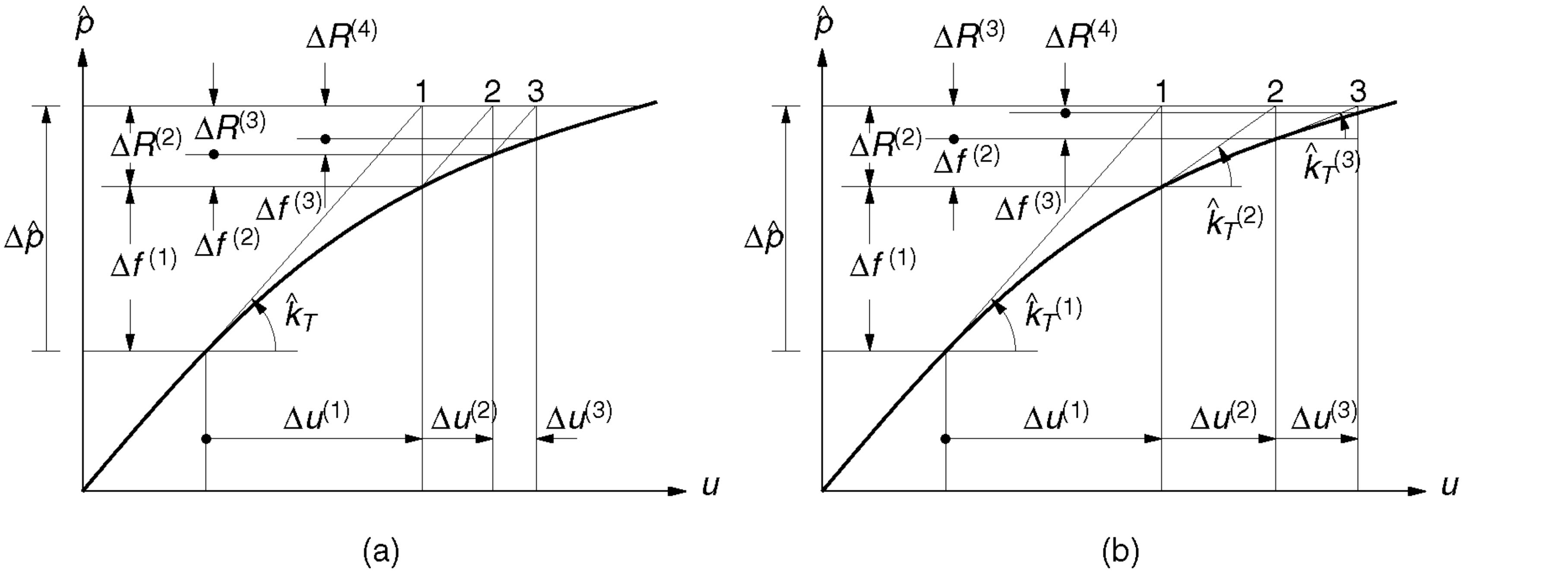
Source Mander (1988)

Mesh dependency in the presence of softening



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

Numerical solution techniques

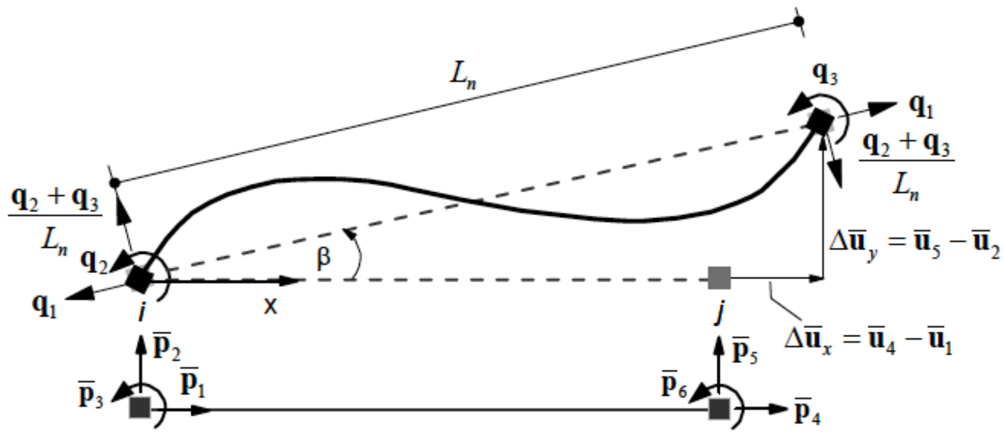


$$\left(\hat{k}\right)_T \Delta u^{(1)} = \Delta \hat{p}$$

$$\Delta R^{(2)} = \Delta \hat{p} - \Delta f^{(1)}$$

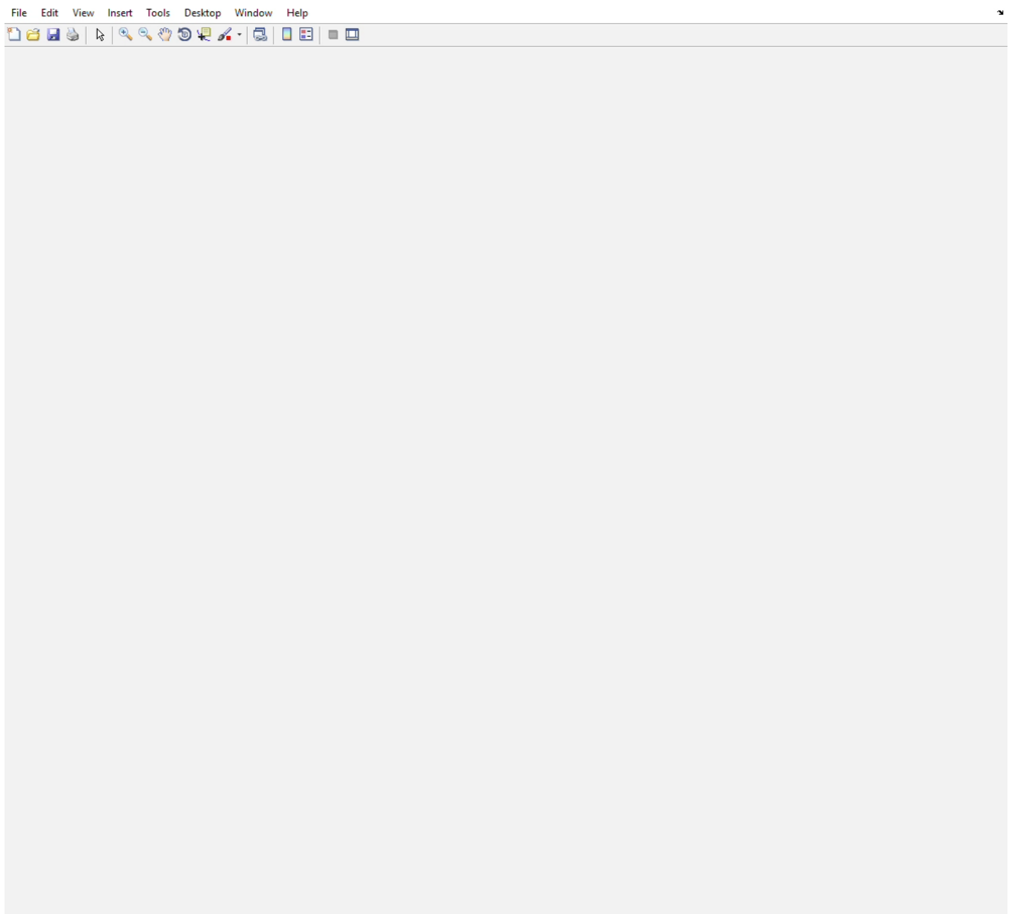
$$\left(\hat{k}\right)_T \Delta u^{(2)} = \Delta R^{(2)} = \Delta \hat{p} - \Delta f^{(1)}$$

Nonlinear geometric transformations

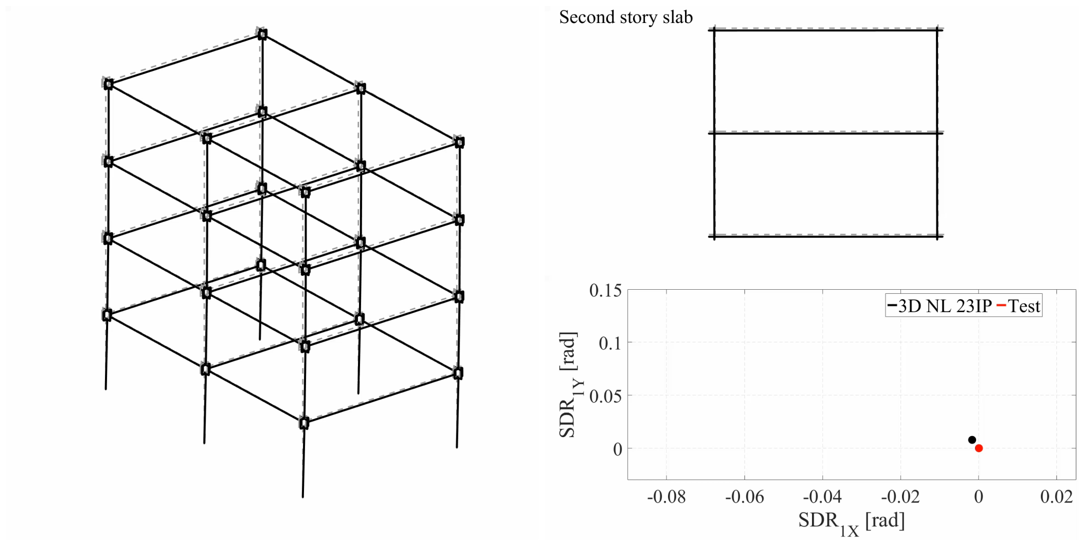


$$\begin{Bmatrix} \bar{p}_1 \\ \bar{p}_2 \\ \bar{p}_3 \\ \bar{p}_4 \\ \bar{p}_5 \\ \bar{p}_6 \end{Bmatrix} = \begin{bmatrix} -\frac{L+\Delta\bar{u}_x}{L_n} & -\frac{\Delta\bar{u}_y}{L_n^2} & -\frac{\Delta\bar{u}_y}{L_n^2} \\ -\frac{\Delta\bar{u}_y}{L_n} & \frac{L+\Delta\bar{u}_x}{L_n^2} & \frac{L+\Delta\bar{u}_x}{L_n^2} \\ 0 & 1 & 0 \\ \frac{L+\Delta\bar{u}_x}{L_n} & \frac{\Delta\bar{u}_y}{L_n^2} & \frac{\Delta\bar{u}_y}{L_n^2} \\ \frac{\Delta\bar{u}_y}{L_n} & -\frac{L+\Delta\bar{u}_x}{L_n^2} & -\frac{L+\Delta\bar{u}_x}{L_n^2} \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$$

Nonlinear static and dynamic analysis



Source Elkady and Lignos (2018)



Source Heredia and Lignos (2024)

Case studies

Lignos et al. (2013)

Vanin et al. (2020)

Syllabus

Week		Person	Course	Assignments
1	09/09/24 - 11/09/24	DL	Motivation; course organization and evaluation. Linear versus nonlinear systems / static versus dynamic loading	
2	16/09/24 - 18/09/24	DL	Revision on matrix structural analysis / static and dynamic equilibrium equations	Assignment #1
3	23/09/24 - 25/09/24	DL	Truss and frame elements	
4	30/09/24 - 02/10/24	DL	Linear and nonlinear geometric transformations	
5	07/10/24 - 09/10/24	DL	Material response and uniaxial constitutive formulations	Submission of Assignment #1 / Assignment #2
6	14/10/24 - 16/10/24	DL	Solution methods in nonlinear analysis	
7	21/10/24 - 23/10/24	Study break		
8	28/10/24 - 30/10/24	DL	Concentrated plasticity	
9	04/11/24 - 06/11/24	DL	Displacement-based beam-column elements	Submission of Assignment #2 / Assignment #3
10	11/11/24 - 13/11/24	DL	Integration methods	
11	18/11/24 - 20/11/24	DL	Flexibility-based beam-column elements / Multipoint constraints	
12	25/11/24 - 27/11/24	SS	Constitutive models based on plasticity	Submission of Assignment #3 / Assignment #4
13	02/12/24 - 04/12/24	SS	Constitutive models based on continuum damage mechanics	
14	09/12/24 - 11/12/24	SS	Smeared crack models / mesh dependency / Application examples of constitutive models for structural analysis	
15	16/12/24 - 18/12/24	DL/SS	Examples of nonlinear analysis of buildings – Discussion of choice of modelling approaches and their effect on the results	Submission of Assignment #4

Simulation tools

Programming tools

Matlab

python™

Finite element analysis

OpenSees

opensees.berkeley.edu