CIVIL 369: “Structural Stability”

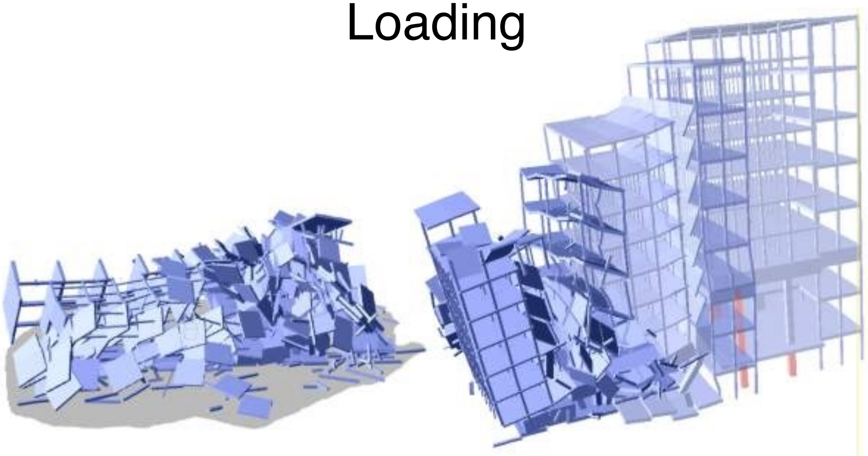
School of Architecture, Civil & Environmental Engineering
Civil Engineering Institute
Resilient Steel Structures Laboratory (RESSLab)

Introduction and Background, Basic Concepts of Stability

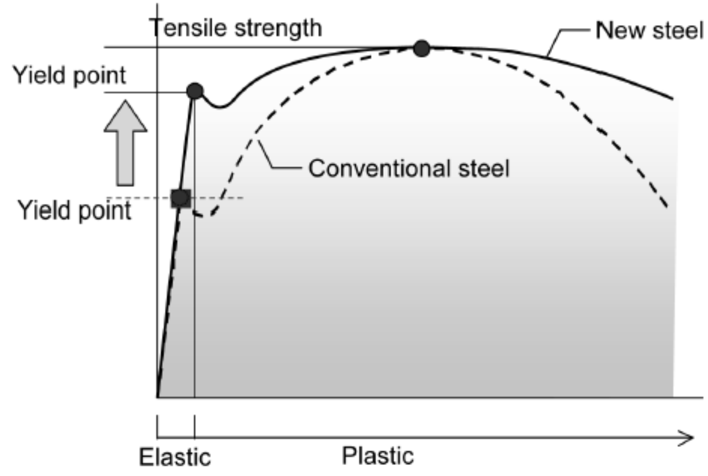
Instructor: Prof. Dr. Dimitrios G. Lignos,
Dr. Albano Casto e Sousa & Diego Heredia
GC B3 485 (bâtiment GC)
E-mail: dimitrios.lignos@epfl.ch

My Current Work at EPFL

(1) High-Fidelity Modeling of Steel Structures for Mitigating Extreme Loading

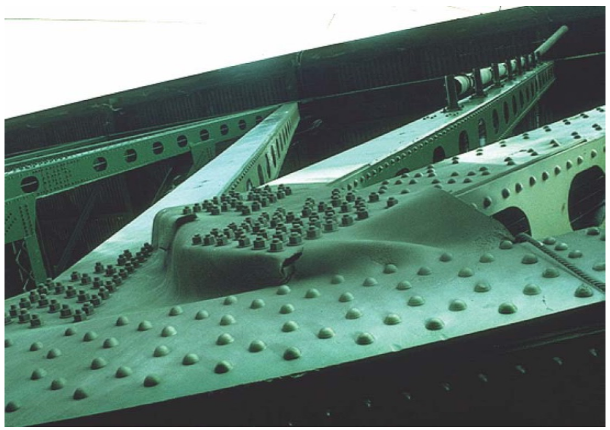


(2) High Performance Steel Materials For Resilient Infrastructure



(3)Stability and Nonlinear Finite Element Modeling of Steel Elements

(4) Composite Steel Bridge Infrastructure under Environmental Hazards



Objectives of Today's Lecture

To introduce:

✧ Course personnel

✧ Course logistics

✧ Learning objectives

✧ Why this class is important

✧ Basic concepts of stability theory

✧ "Smart Statics"

EPFL Course Personnel

Instructor: Professor Dr. Dimitrios Lignos

✧ Director, Resilient Steel Structures Laboratory (RESSLab)

✧ Office: GC B3 485

Co-Instructor: Dr. Albano Antonio Sousa

✧ Resilient Steel Structures Laboratory (RESSLab)

✧ Office: GC B3 445

Co-Instructor: Diego Heredia Rosa, Doctoral Assistant

✧ Resilient Steel Structures Laboratory (RESSLab)

✧ Office: GC B3 454

Teaching Assistant: Mr. Arthur Paul Antonin Carmès

✧ Resilient Steel Structures Laboratory (RESSLab)

✧ In Class Assistance

EPFL Course Examination– Important Dates

Three Take-home Assignments (30%)

✧ Given during Week #4, Week #7 and Week #11

✧ Individual or groups of 2

Final Examination (70%)

✧ Covers the entire course material

✧ Location & time to be announced

✧ Open notes (only)

EPFL Resources and Other Information

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

✧ Reports and other reading material will be provided through *Moodle*.

✧ The lecture notes of this course are available online from the following link:

https://www.youtube.com/playlist?list=PLMHpK8_AJLyMbro9Izf35ShtBzYxD7up8

What Are You Going to Learn in This Course?

- ✧ Fundamentals of stability theory and nonlinear behavior
- ✧ Nonlinear behaviour of structural components
  - ✧ Material & geometric nonlinearities
- ✧ Imperfections and their influence on structural stability
- ✧ Column and beam-column buckling
- ✧ Plate buckling
- ✧ Bridge girders
- ✧ Lateral torsional buckling with emphasis on bridges
- ✧ Stability of frame structures
- ✧ Examples and failures from real-world applications

Motivation: Art and Science
-Challenging Structures

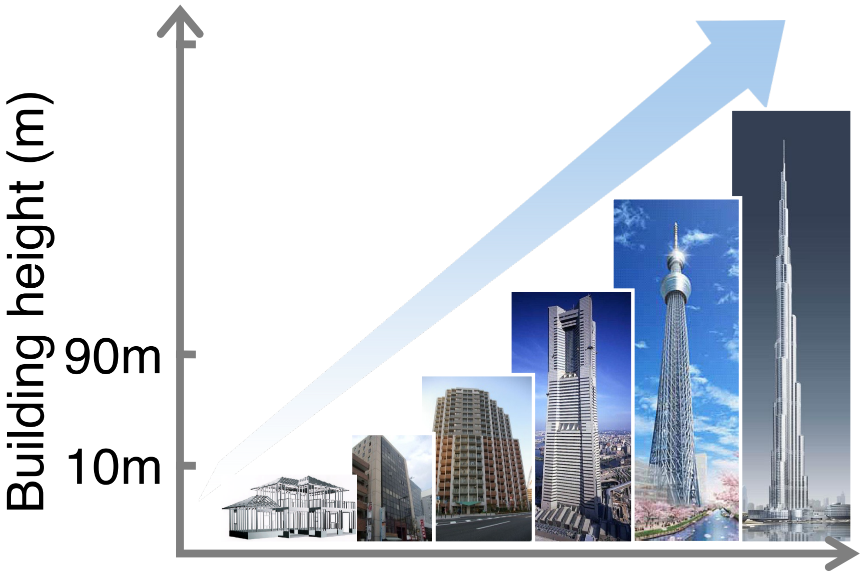
Dr. AR Dykes, British Institution of Structural Engineers:

"Engineering is the art of modelling materials we do not wholly understand, into shapes we cannot precisely analyze so as to withstand forces we cannot properly assess, in such a way that the public has no reason to suspect the extent of our ignorance".

Guggenheim Museum, Bilbao

International Tokyo Forum, Japan

New Bay Bridge, San Francisco, CA



On the Nature of Structural Design - Art

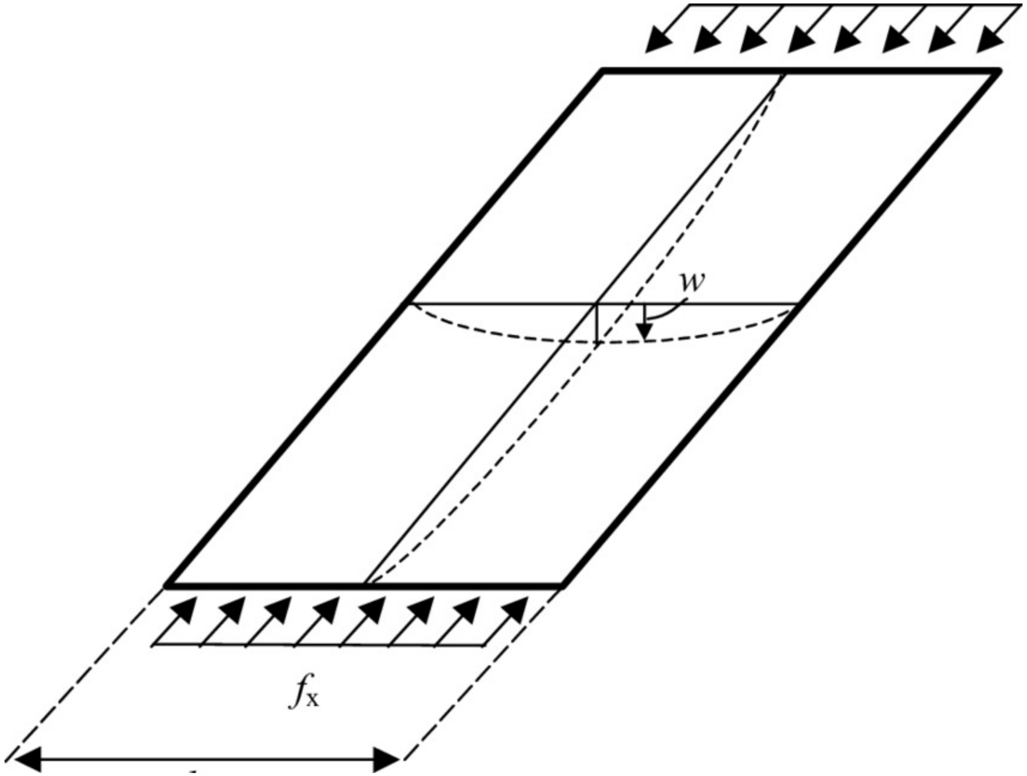
Guggenheim Museum, Bilbao

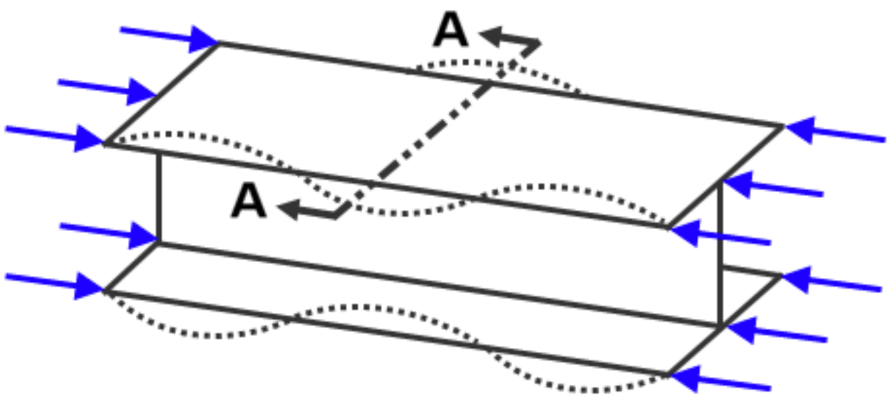
International Tokyo Forum, Japan

On the Nature of Structural Design - Science

Finite Element Simulation of Steel Columns (source Elkady and Lignos 2016)

EPFL Plate Buckling

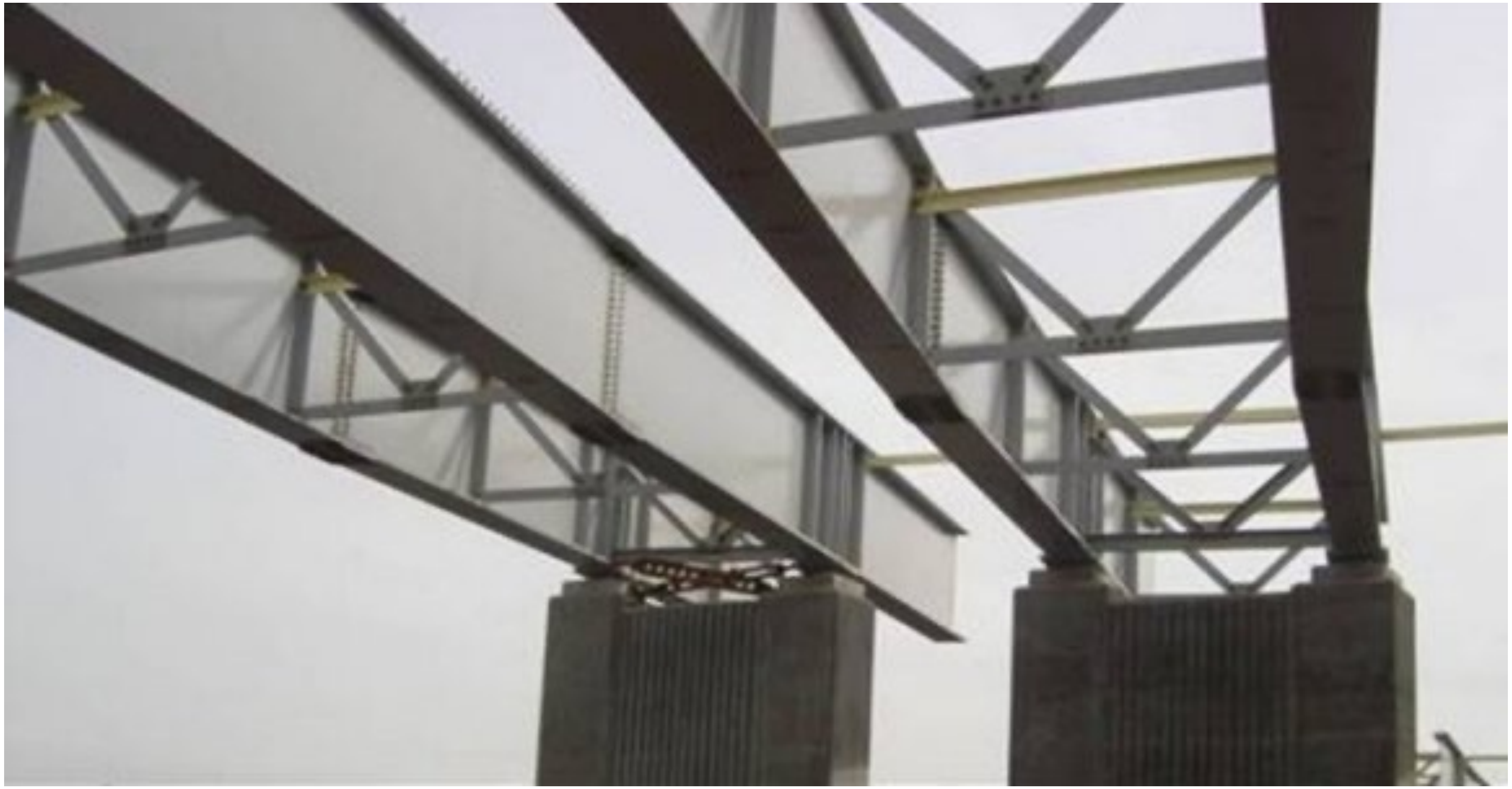




Steel Bridges

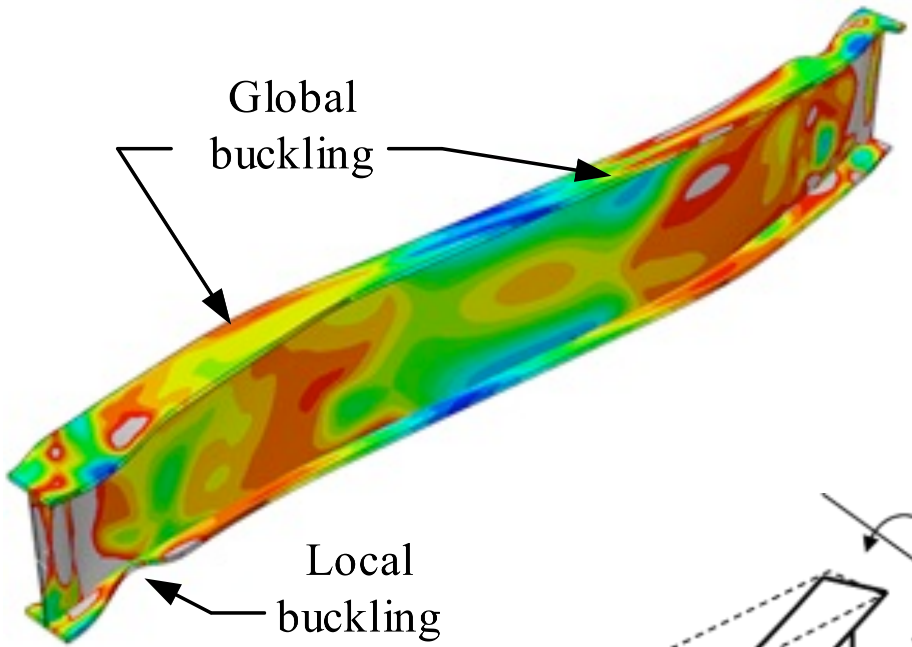
New Bay Bridge, San Francisco, CA

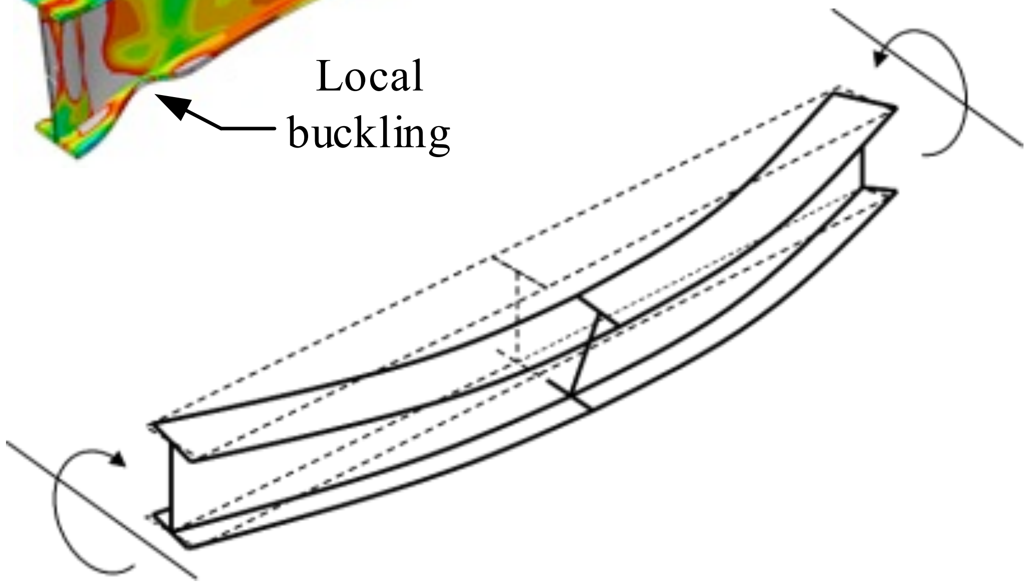
Steel Bridges-Girder Stability
-Lateral Torsional Buckling



Stability of Bridge Girders due to Lateral Torsional Buckling

Edmonton Bridge, Canada

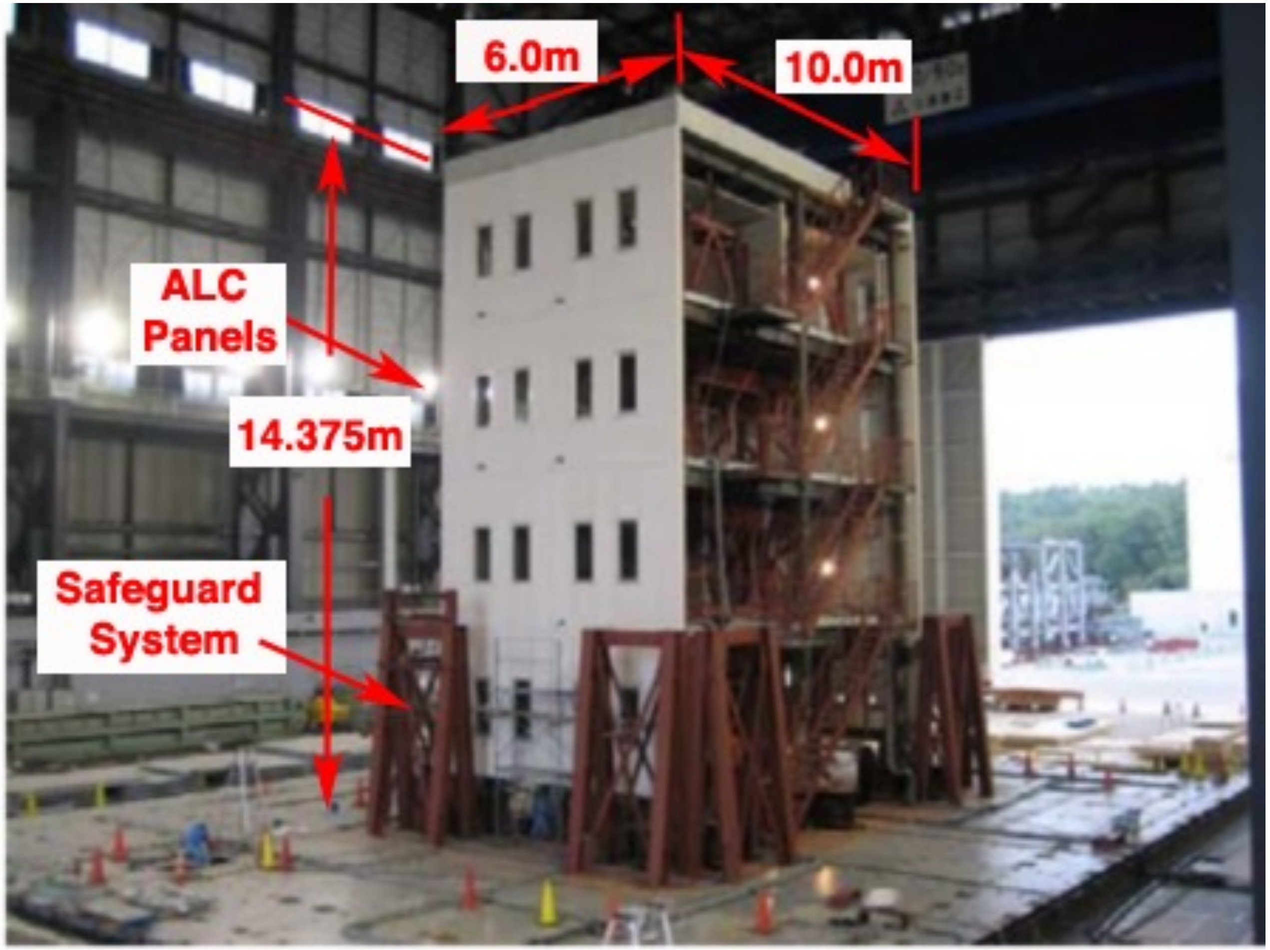




Performance of Buildings in Past Earthquakes
-Stability of Structures - Structural Collapse

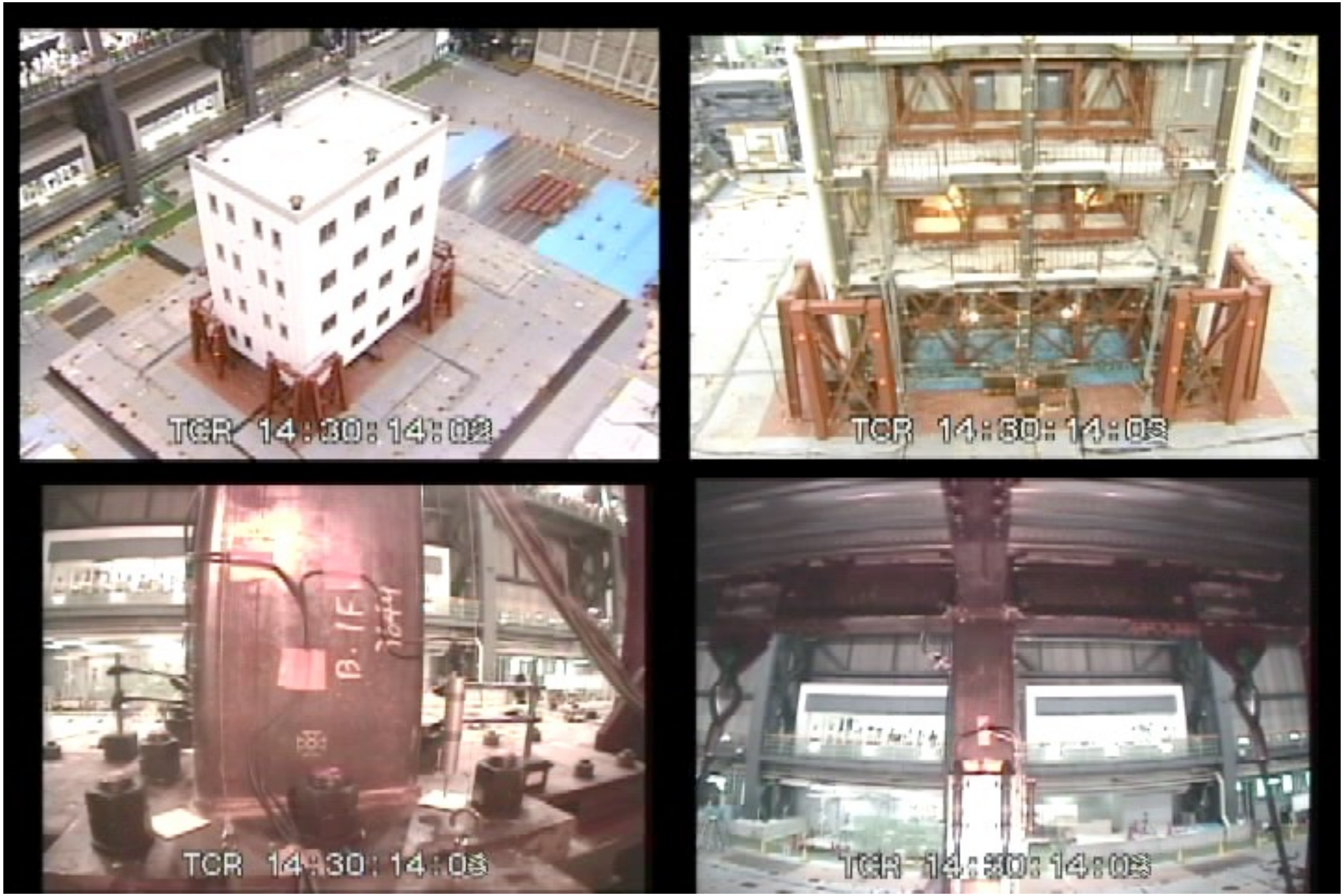
Figure courtesy of Prof. Tremblay

Stability of Frames under Earthquakes



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

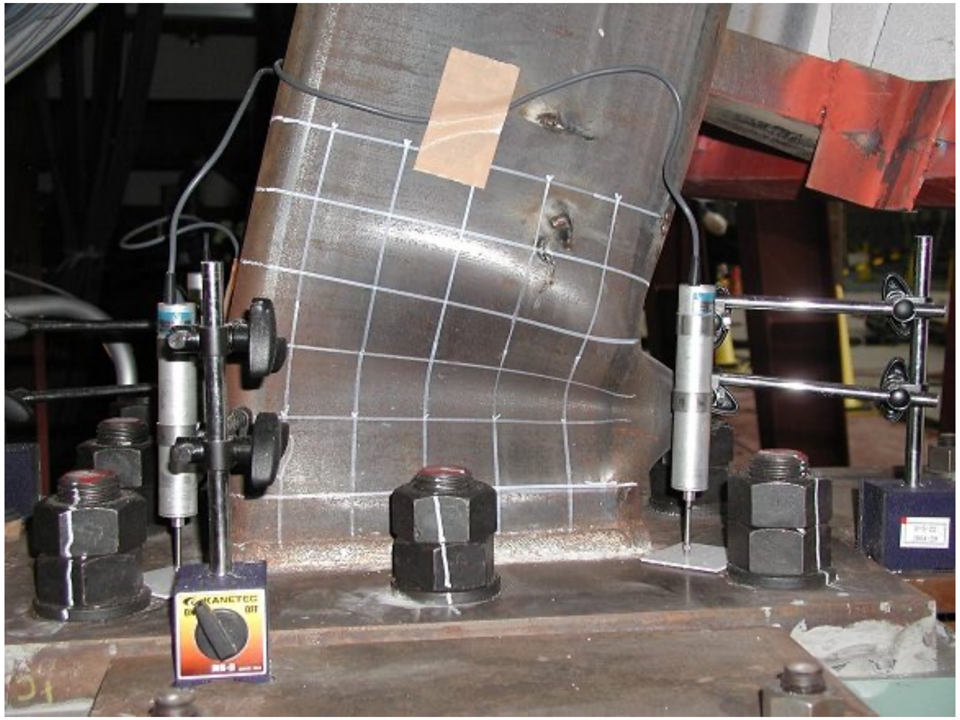
Stability of Frames under Earthquakes



Undesirable Collapse Mechanism – Soft Storey

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

Undesirable Collapse Mechanism – Soft Storey



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

Fundamental Understanding of Dynamic Stability

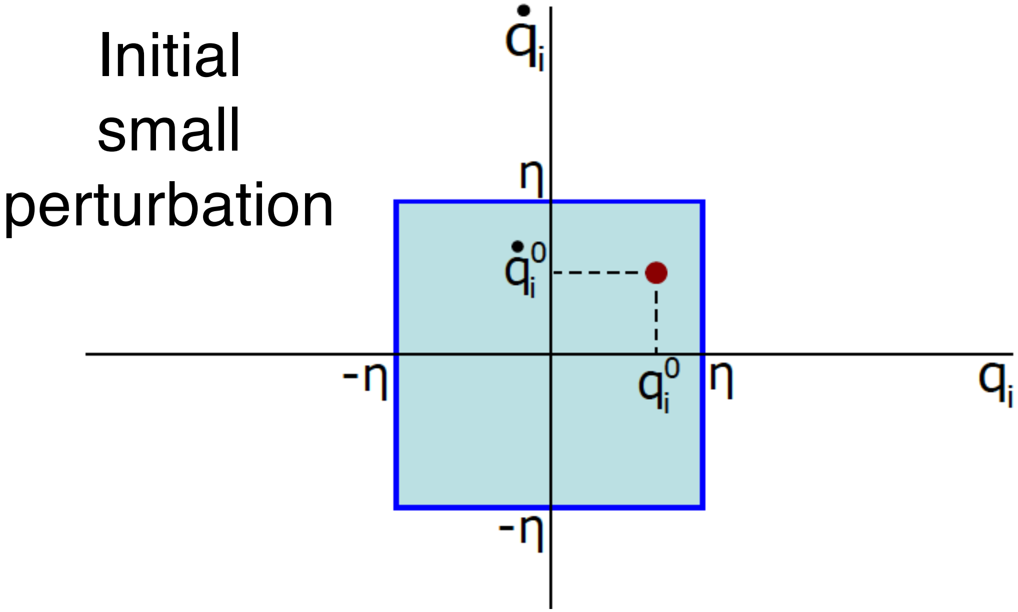
Dynamic Approach for Checking Stability

- Subject the system to an initial small perturbation

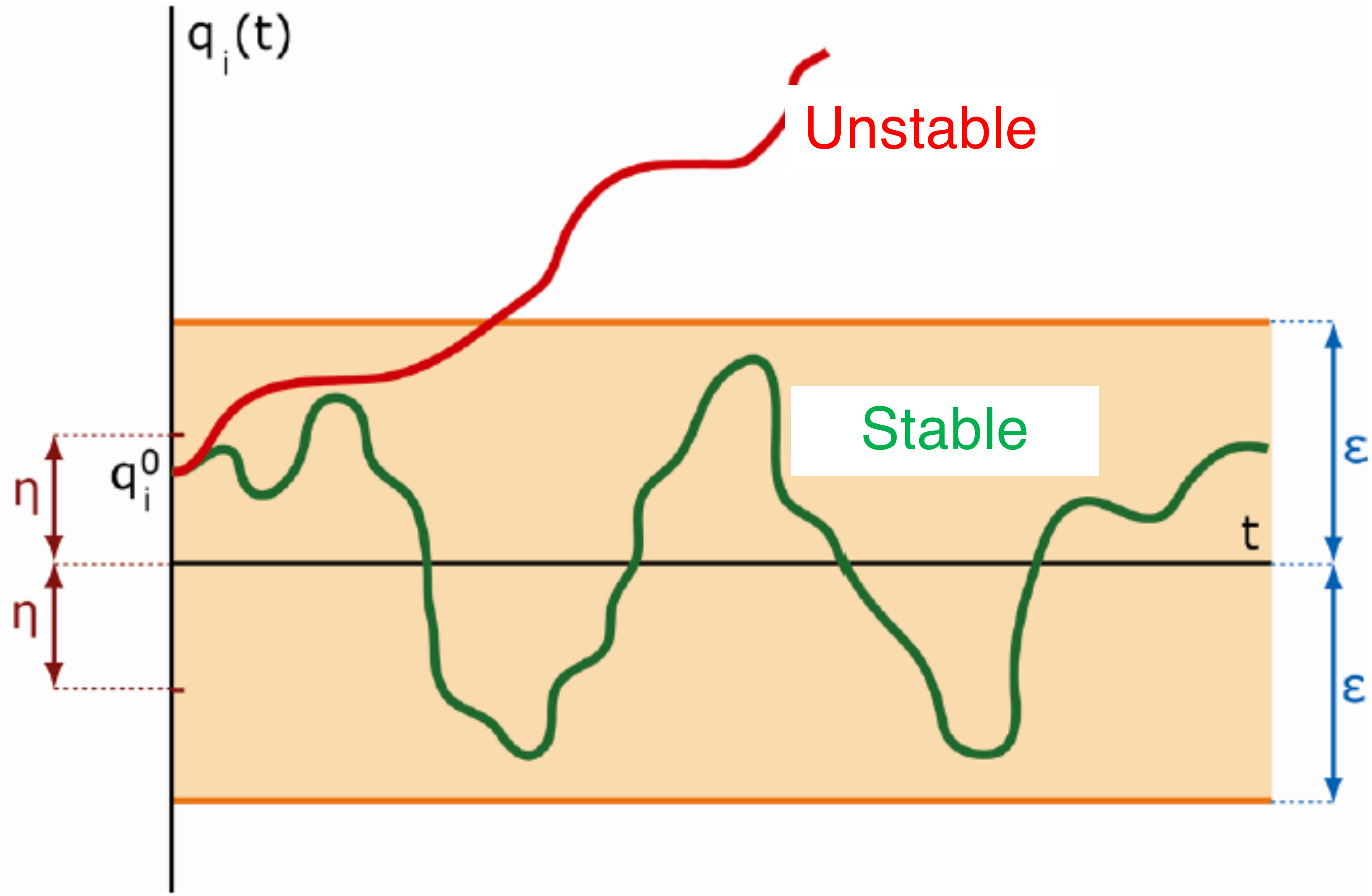
$$(q_i)^0, \left(\frac{\partial q_i}{\partial t}\right)^0 \ (i = 1,2,3,4,5, \dots, n)$$

- Therefore,

$$\|(q_i)^0\| \leq n, \left\|\left(\frac{\partial q_i}{\partial t}\right)^0\right\| \leq= n \ (i = 1,2,3,4,5, \dots, n)$$

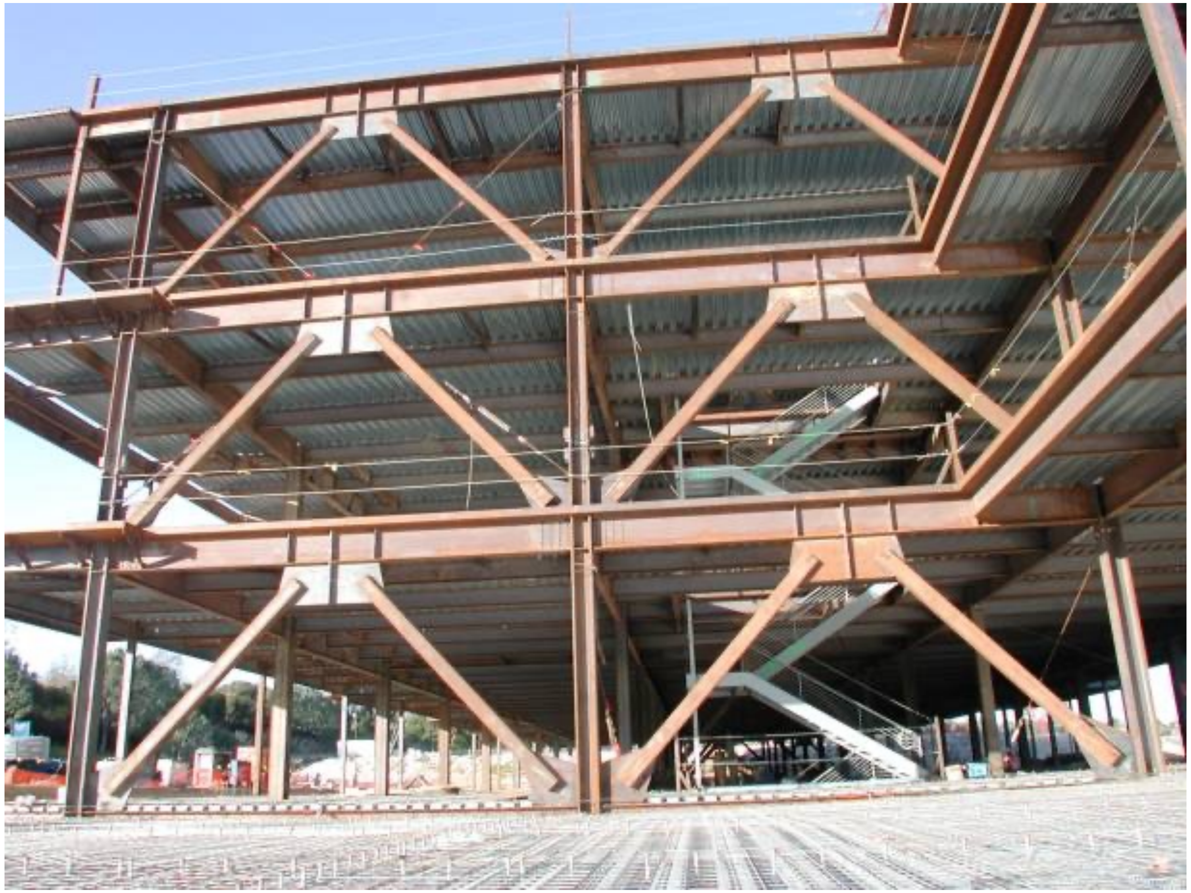


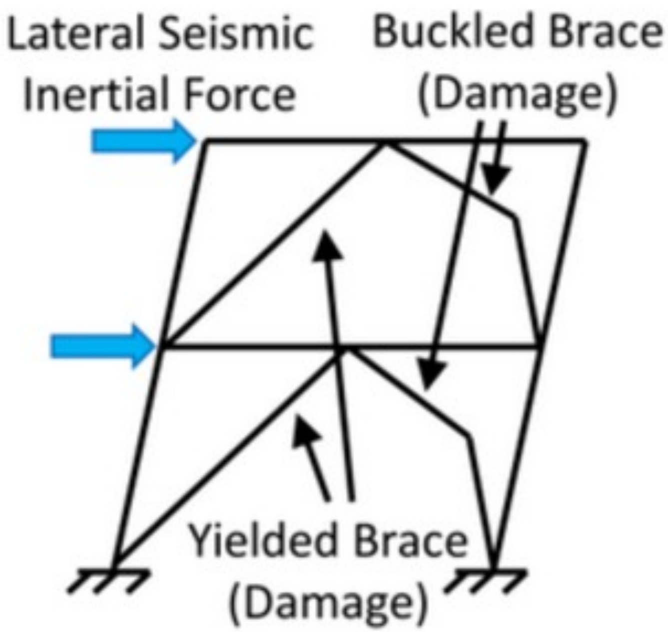
Dynamic Approach for Checking Stability
-Stability Criterion: Graphical Representation



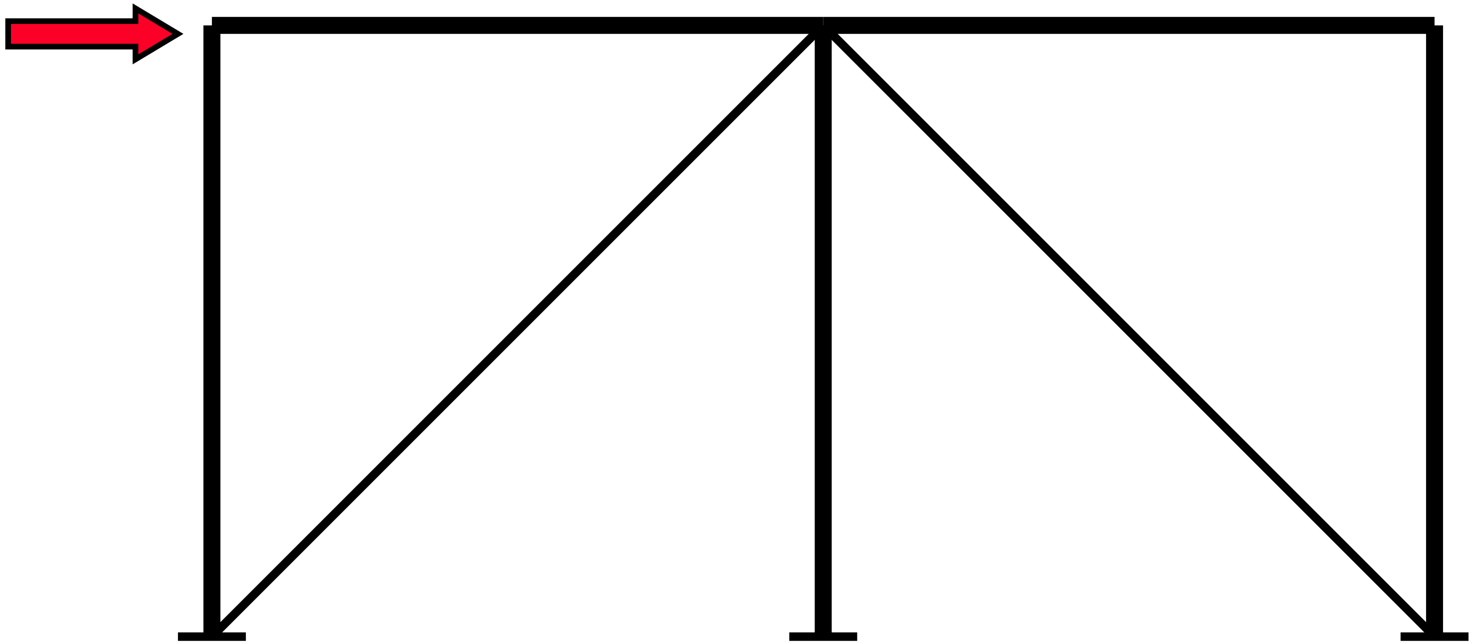
Stability of Compressive Members

-Behaviour under Dynamic Loading (earthquakes)

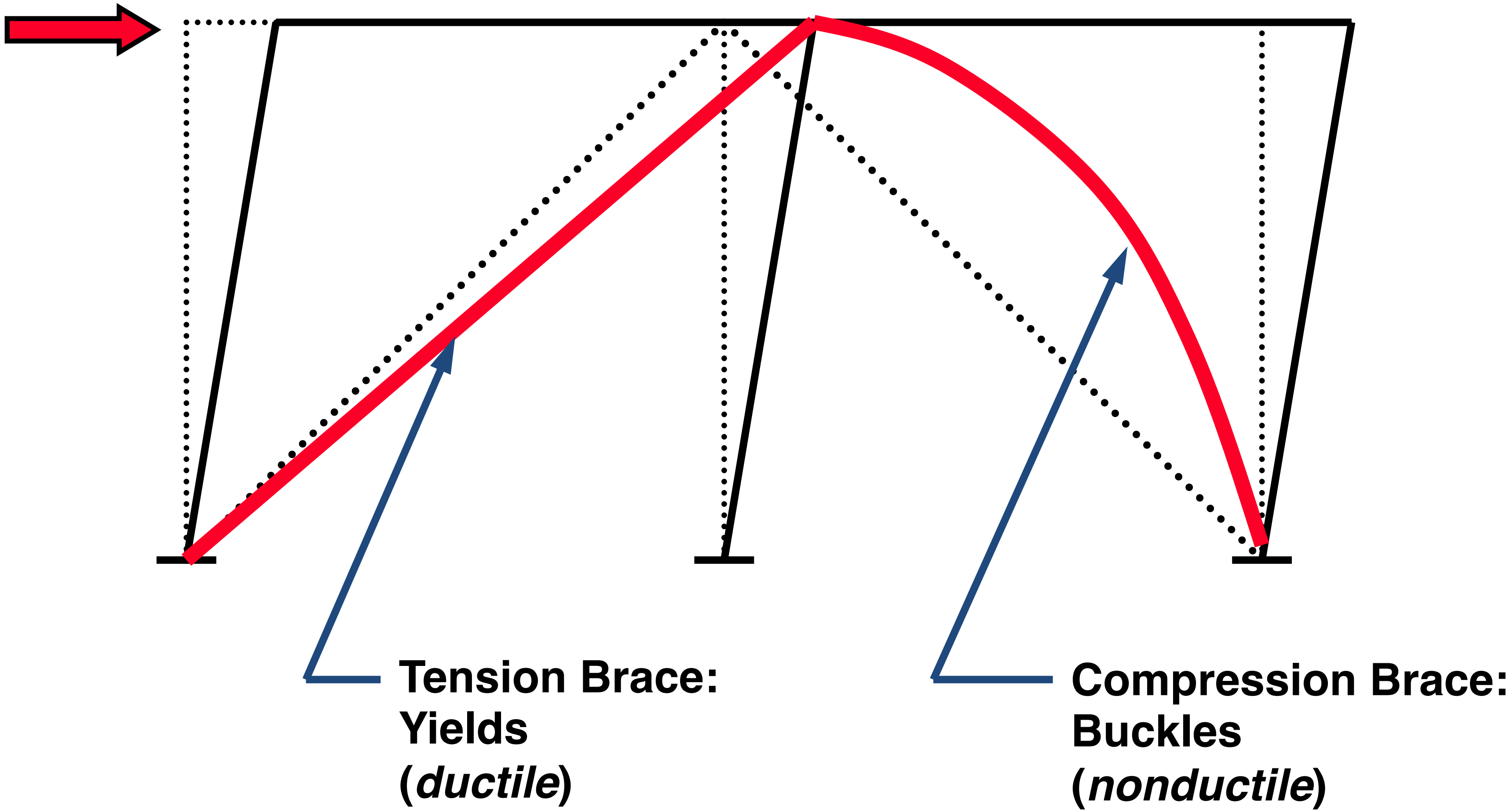




Inelastic Response of Braced Frame under Cyclic Loading

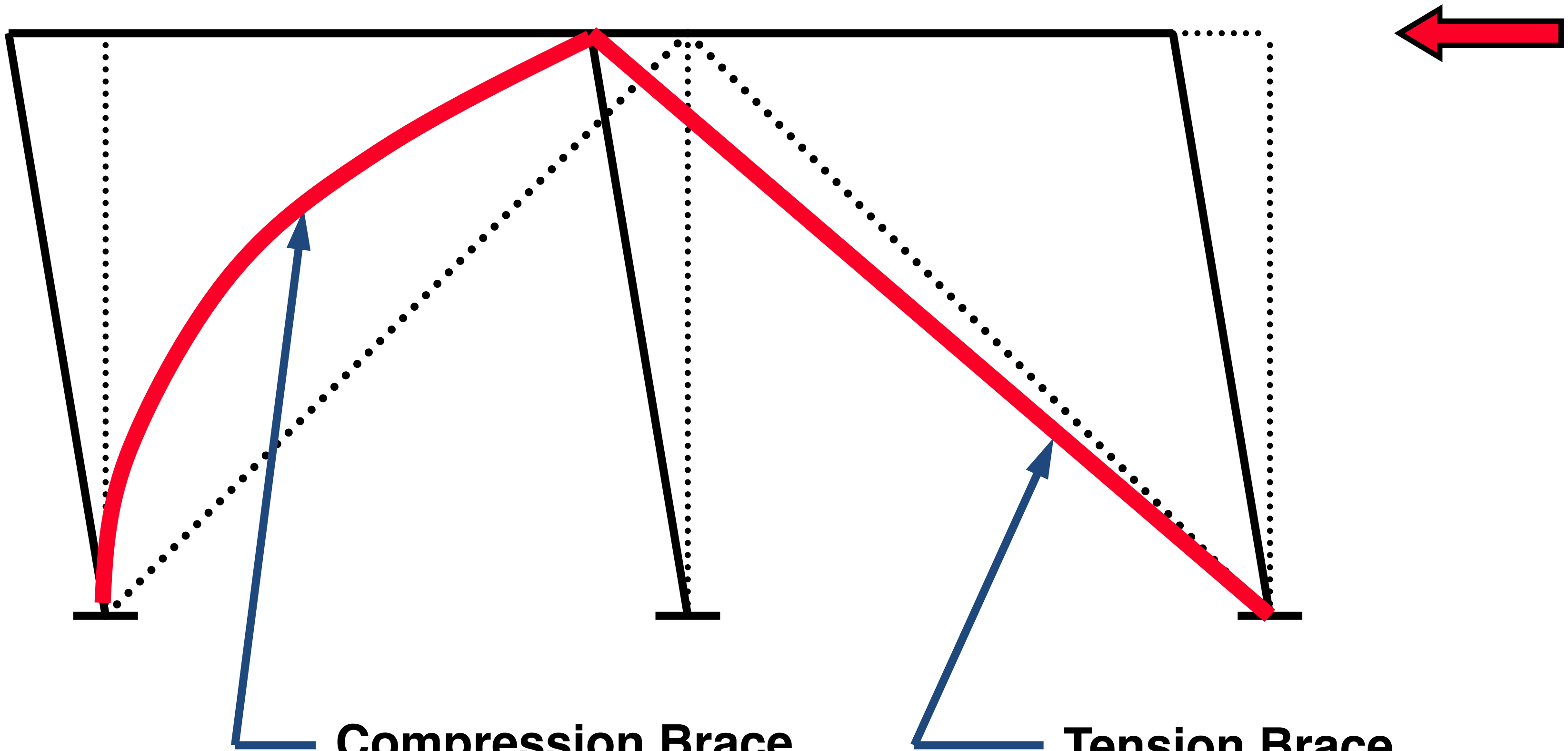


Inelastic Response of Braced Frame



Columns and beams: remain essentially elastic

Inelastic Response of Braced Frame

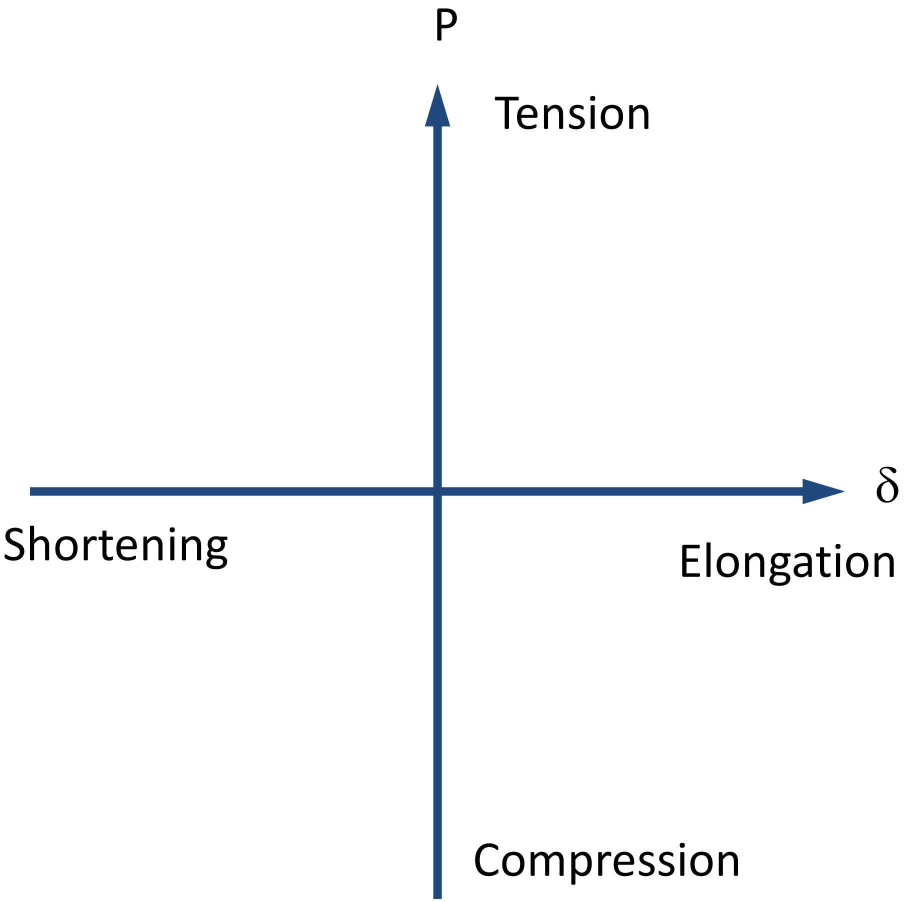


Compression Brace (previously in tension): Buckles (*nonductile*)

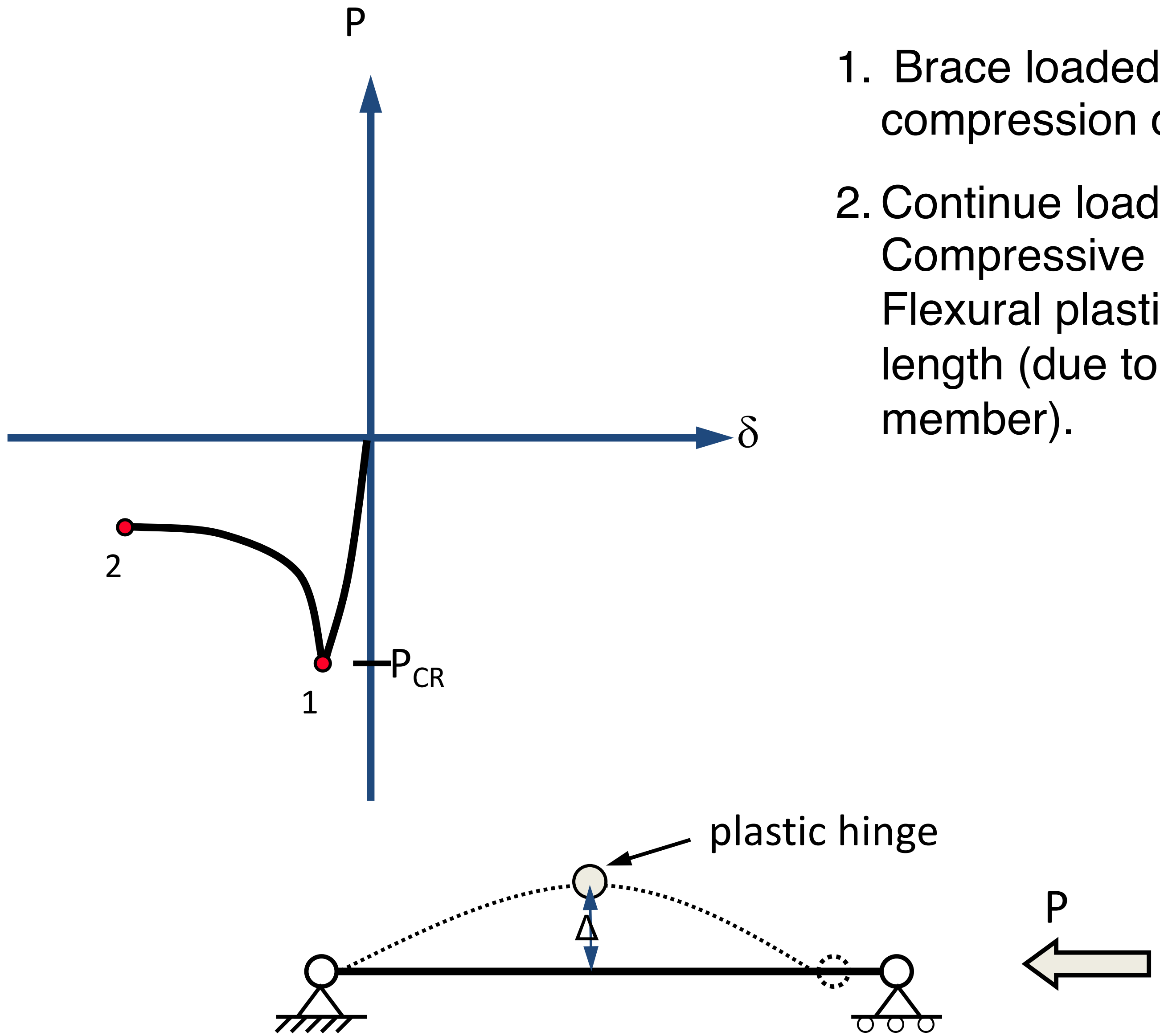
Tension Brace (previously in compression): Yields (*ductile*)

Columns and beams: remain essentially elastic

Stability of Steel Brace Under Cyclic Loading



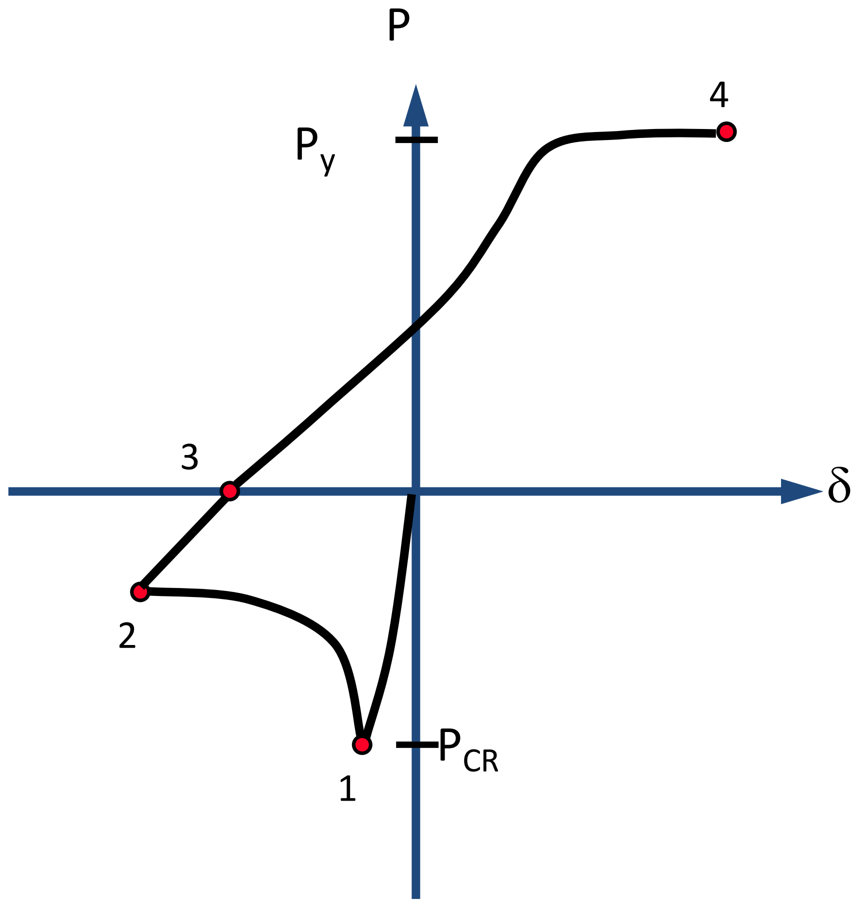
Stability of Steel Brace Under Cyclic Loading



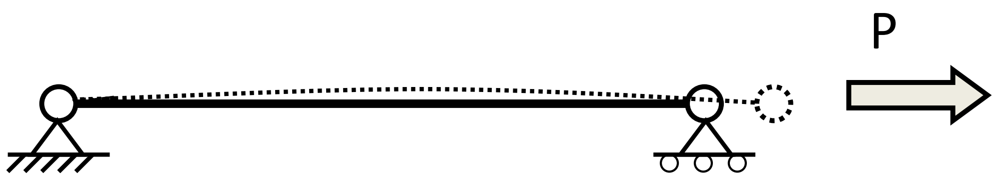
1. Brace loaded in compression to peak compression capacity (buckling).

2. Continue loading in compression. Compressive resistance drops rapidly. Flexural plastic hinge forms at mid-length (due to P-Δ moment in member).

Stability of Steel Brace Under Cyclic Loading



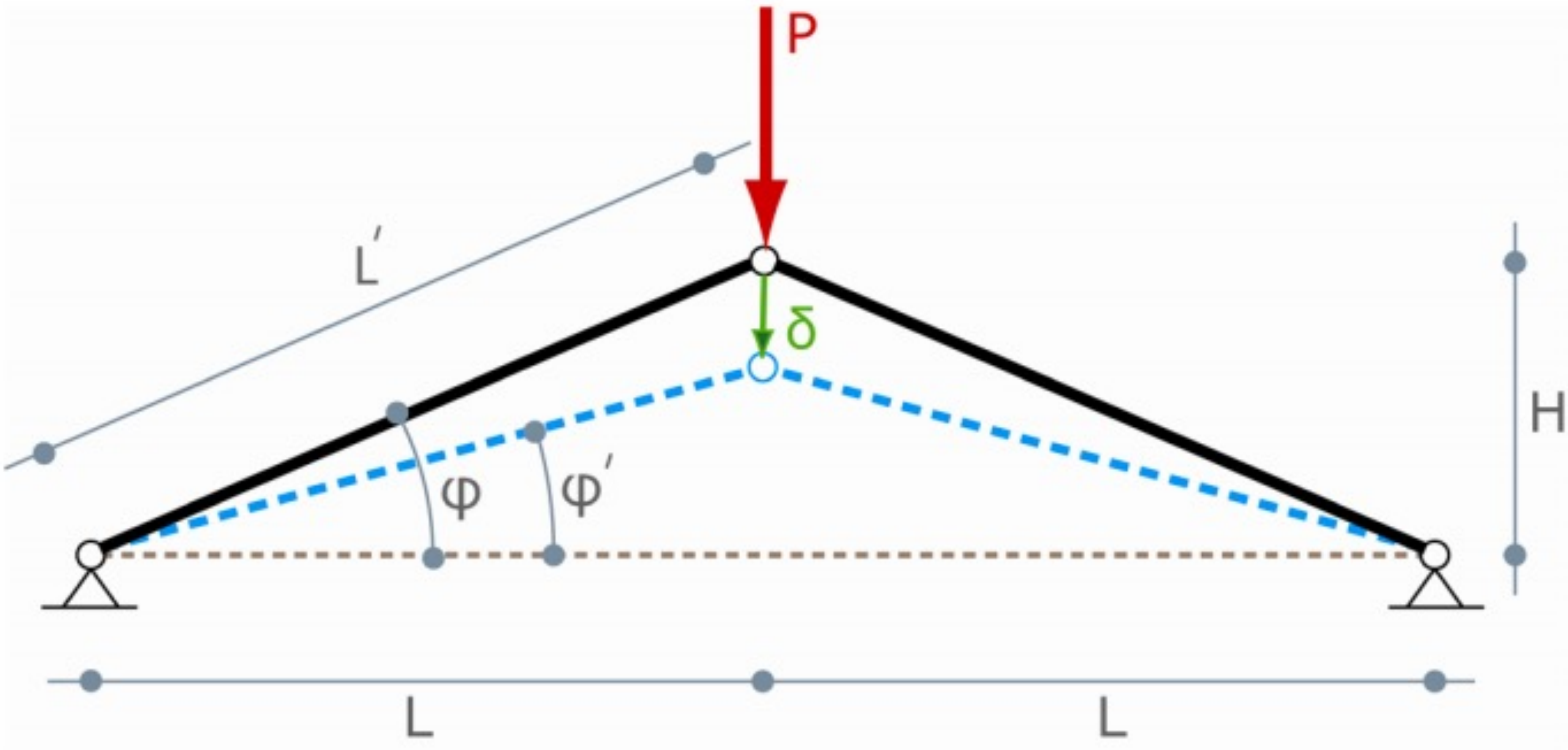
4. Brace loaded in tension to yield.



Arches

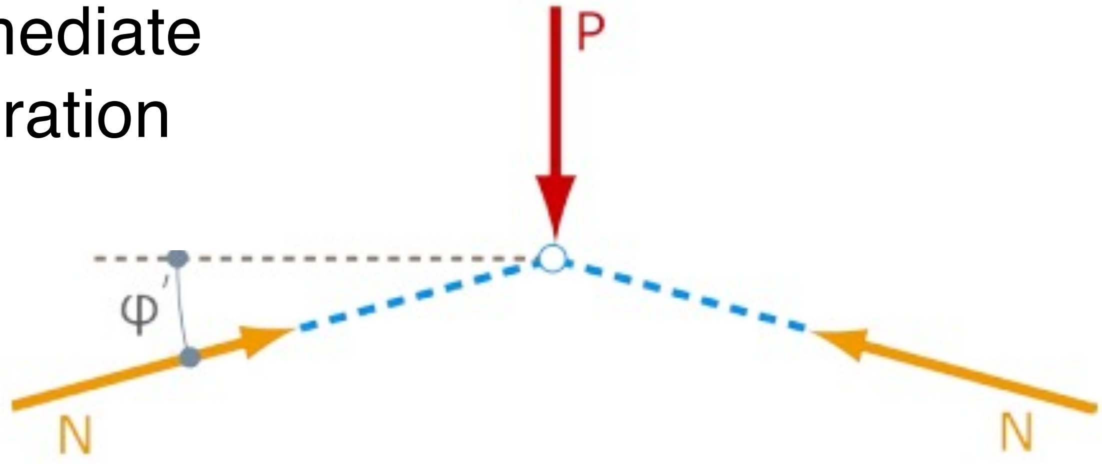
Arches National Park, Utah, USA

Arches – Idealized Model



Basic Equilibrium Equations for Arch

Equilibrium equation of intermediate node at the deformed configuration after the load application



$$P = 2N\sin\varphi'$$

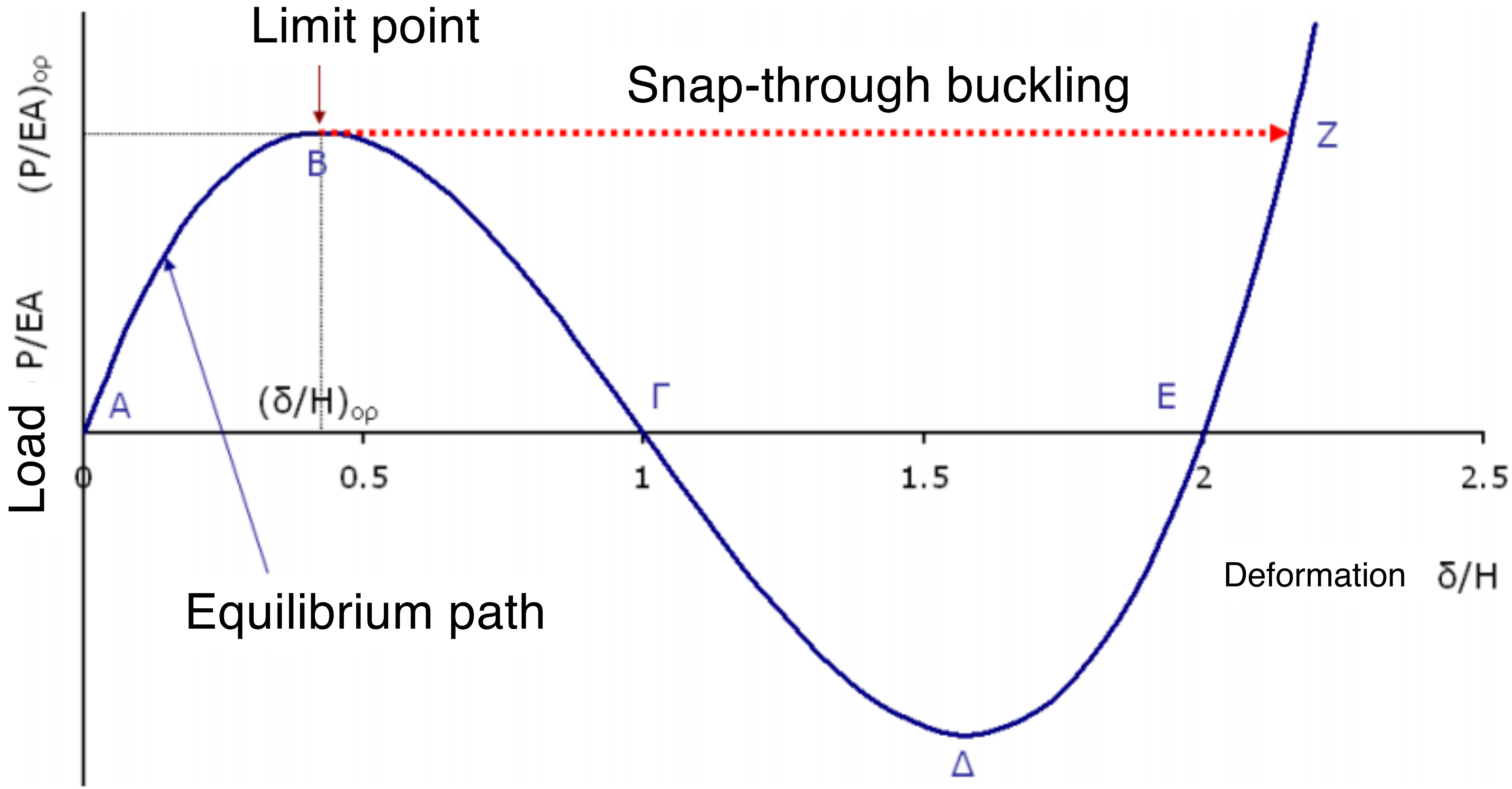
Deformation compatibility

$$\sin\varphi' = \frac{H-\delta}{\sqrt{L^2+(H-\delta)^2}}$$

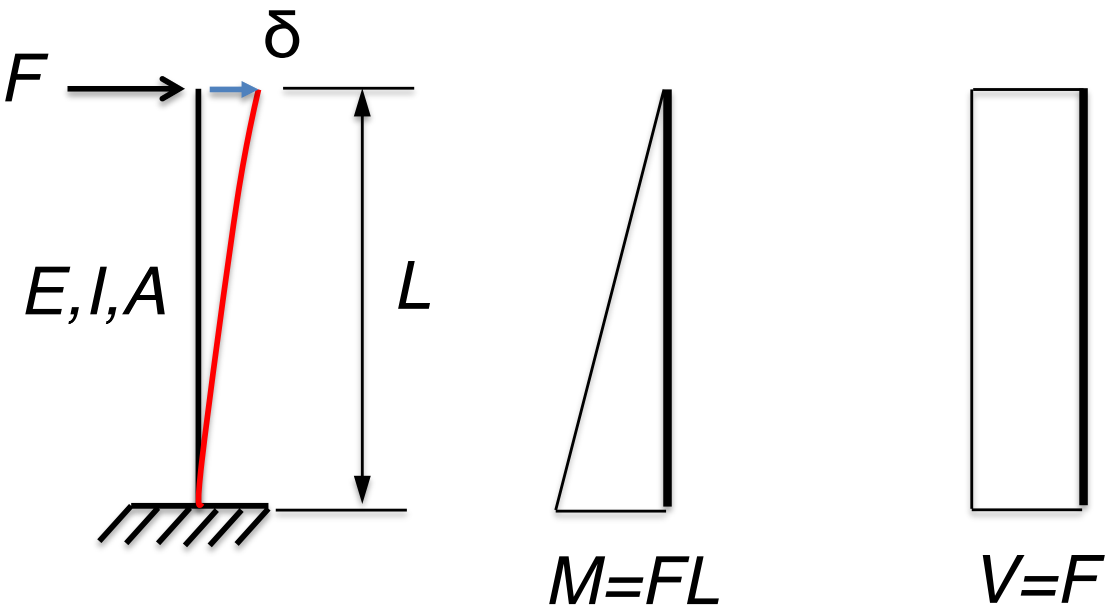
Material behavior (linear)

$$\sigma = E\varepsilon \Rightarrow \frac{N}{A} = E\frac{\Delta L'}{L'} \Rightarrow N = EA\frac{\sqrt{L^2+H^2}-\sqrt{L^2+(H-\delta)^2}}{\sqrt{L^2+H^2}}$$

Equilibrium Path for Arch



"Easy Statics" in Frame Structures

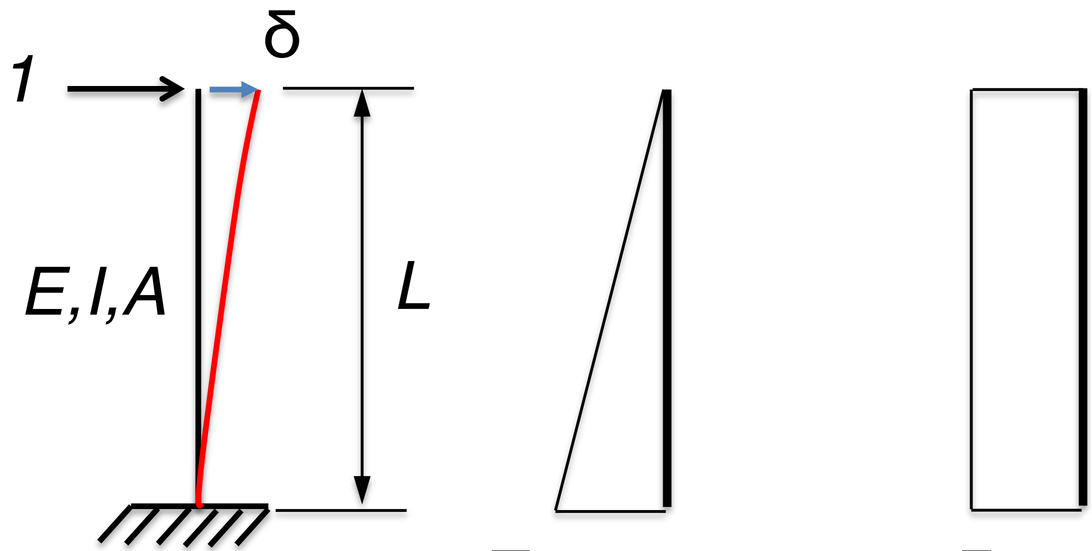


Principle of Virtual Work:

$$\delta = \int_0^L \frac{M\bar{M}}{EI}dx + \int_0^L \frac{V\bar{V}}{GA}dx + \int_0^L \frac{N\bar{N}}{EA}dx$$

Moment diagram due to unit load at the point
I am interested to compute the deflection

"Easy Statics" in Frame Structures



$\bar{M} = 1 \cdot L$ $\quad\quad$ $\bar{V} = 1$

Principle of Virtual Work:

$$\delta = \int_0^L \frac{M\bar{M}}{EI}dx + \int_0^L \frac{V\bar{V}}{GA}dx + \cancel{\int_0^L \frac{N\bar{N}}{EA}dx} \rightarrow 0$$

$M = F \cdot x \quad V = F$

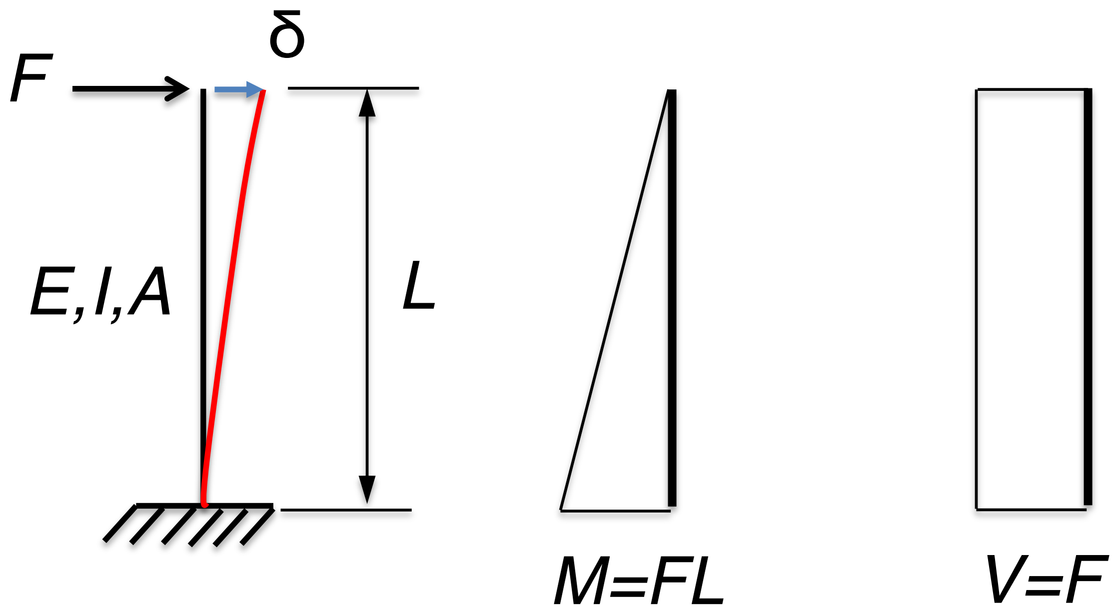
$\bar{M} = 1 \cdot x \quad \bar{V} = 1$

$$\delta = \int_0^L \frac{F \cdot x^2}{EI}dx + \int_0^L \frac{F}{GA}dx = \frac{F}{EI} \cdot \left[\frac{x^3}{3}\right]_0^L + \frac{FL}{GA} = F \cdot \left[\frac{L^3}{3EI} + \frac{L}{GA}\right]$$

Contribution due to flexure

Contribution due to shear

EPFL "Easy Statics" in Frame Structures

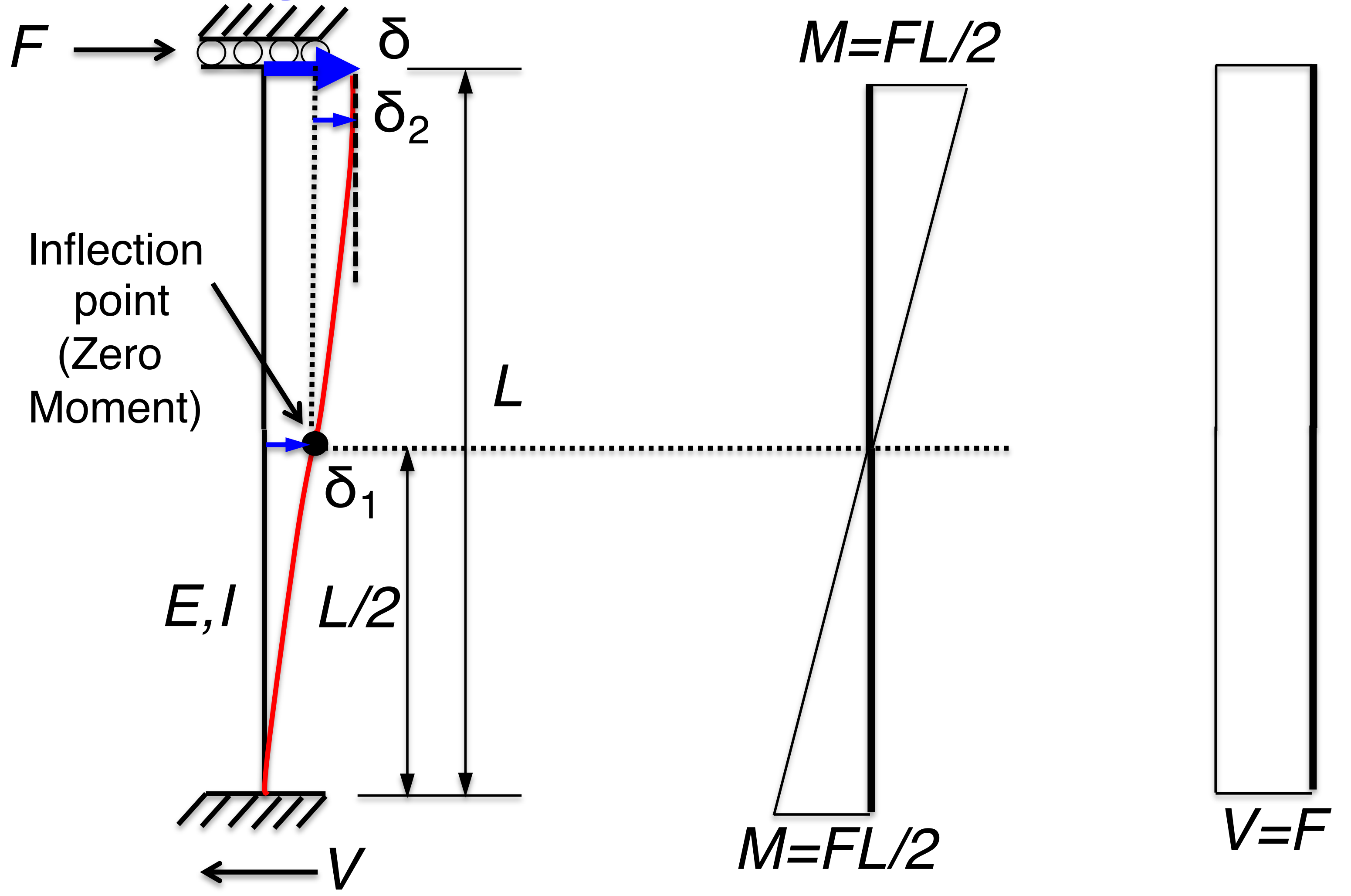


Principle of Virtual Work (Ignore contributions due to shear and axial load)

$$\delta = \int_0^L \frac{M\bar{M}}{EI}\,dx$$

$$K = \frac{F}{\delta} = \frac{3EI}{L^3} \qquad \delta = \frac{F}{K} = \frac{F}{\frac{3EI}{L^3}} = \frac{FL^3}{3EI}$$

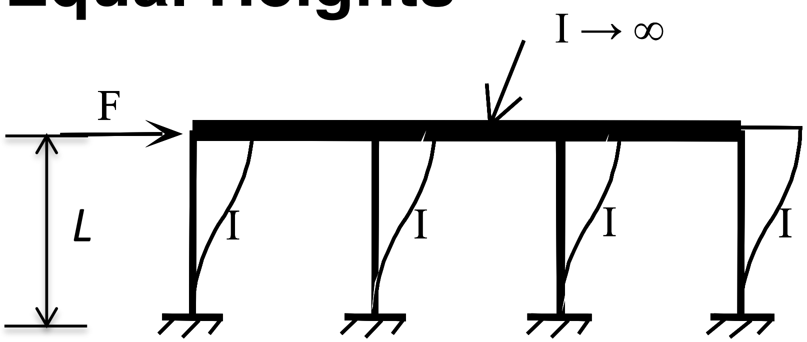
EPFL "Easy Statics" in Frame Structures



$$\delta = \delta_1 + \delta_2 = \frac{F}{K_1} + \frac{F}{K_2} = \frac{F\left(L/2\right)^3}{3EI} + \frac{F\left(L/2\right)^3}{3EI} = \frac{FL^3}{12EI} \qquad K = \frac{F}{\delta} = \frac{12EI}{L^3}$$

Case 1: Flexible Columns/Stiff Girders

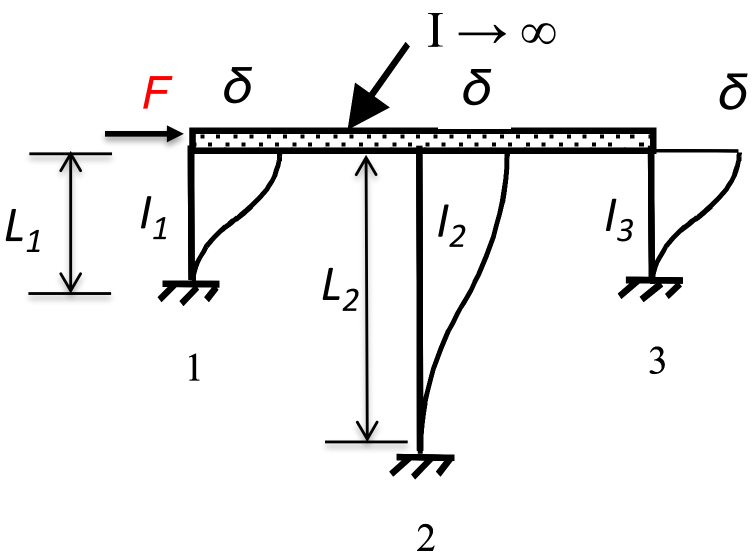
Equal Heights



One Column $K_1 = \dfrac{12EI}{L^3}$

Four Columns $K_{total} = 4K_1 = \dfrac{48EI}{L^3}$

Different Heights

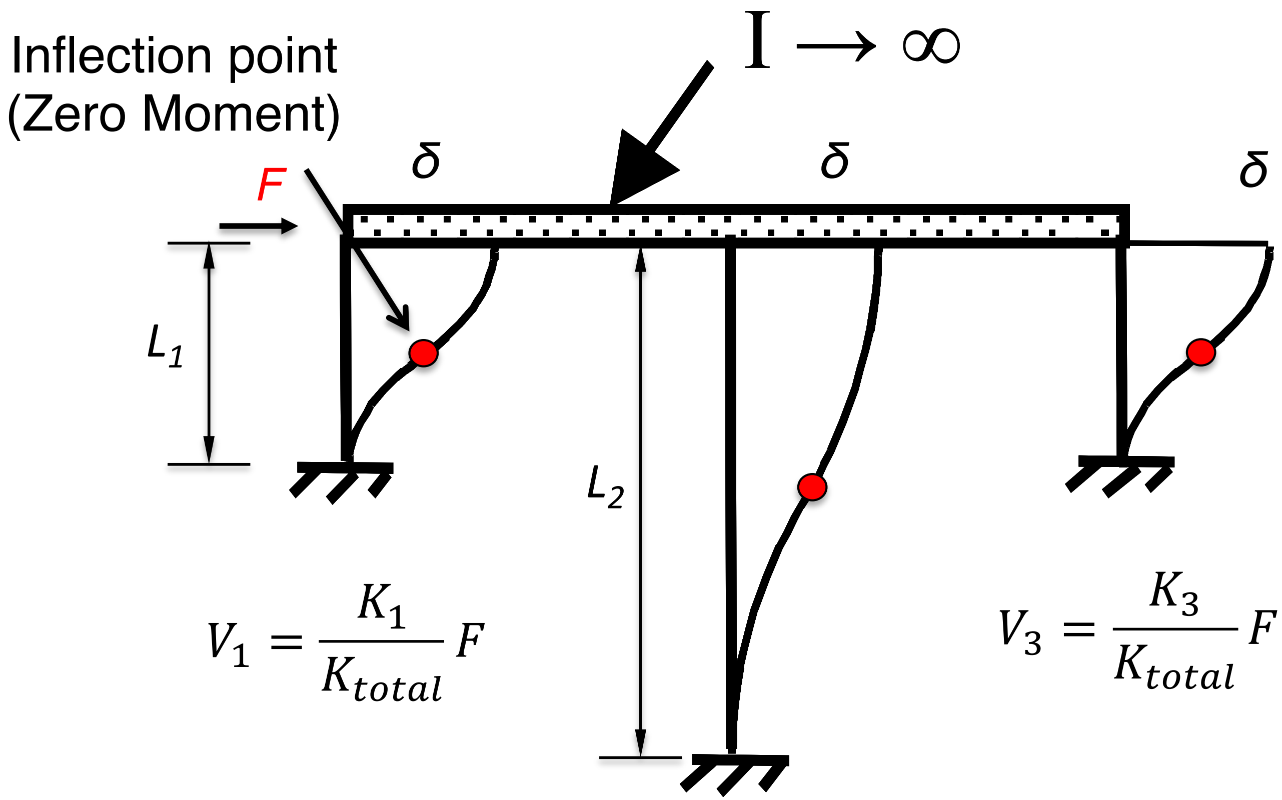


$$K_1 = \frac{12EI_1}{L_1^3} \quad K_2 = \frac{12EI_2}{L_2^3} \quad K_3 = \frac{12EI_3}{L_3^3}$$

$$K_{total} = K_1 + K_2 + K_3$$

$$V_1 = \frac{K_1}{K_{total}}F \quad V_2 = \frac{K_2}{K_{total}}F \quad V_3 = \frac{K_3}{K_{total}}F$$

Case 1: Flexible Columns/Stiff Girders

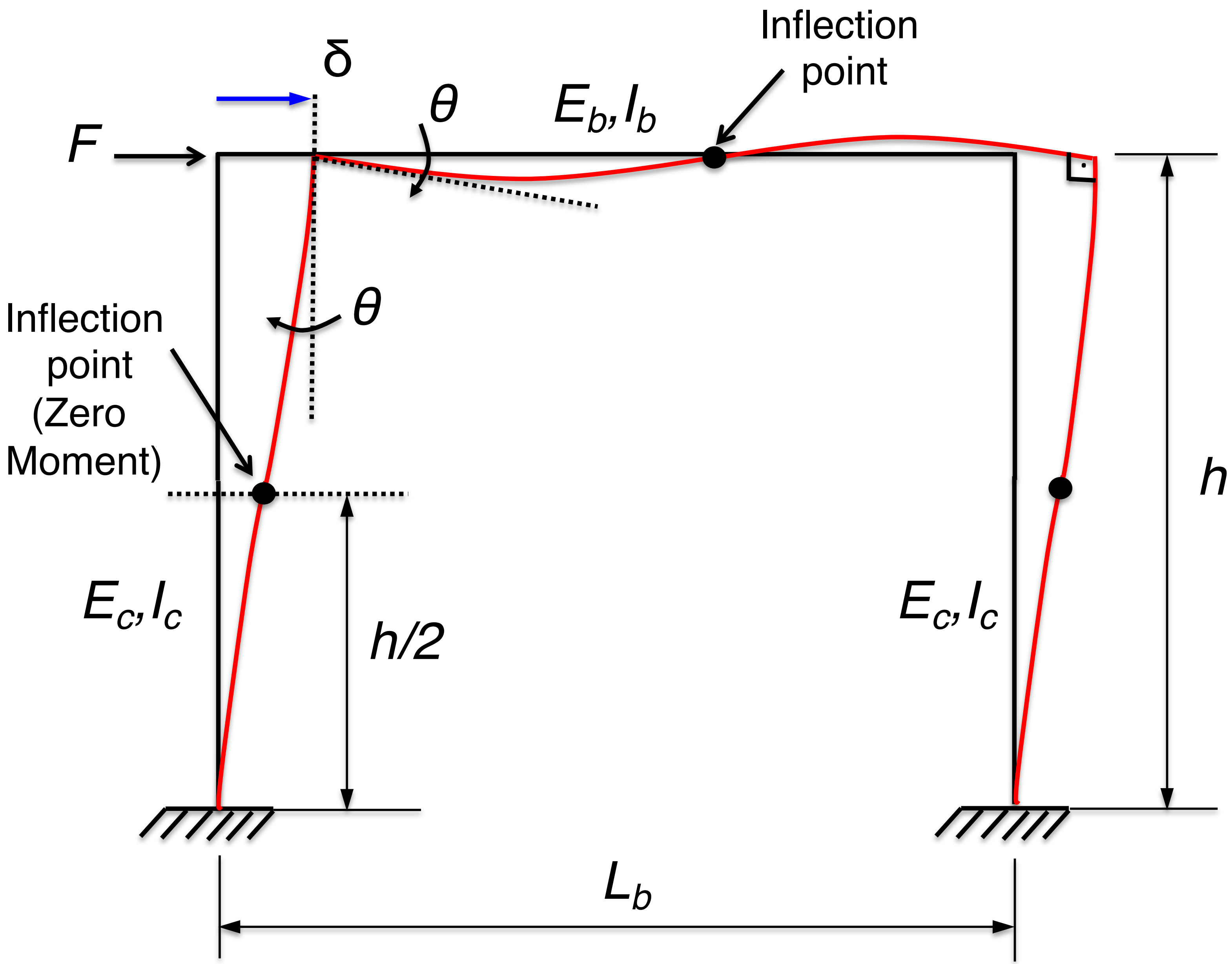


$$V_1 = \frac{K_1}{K_{total}} F$$

$$V_3 = \frac{K_3}{K_{total}} F$$

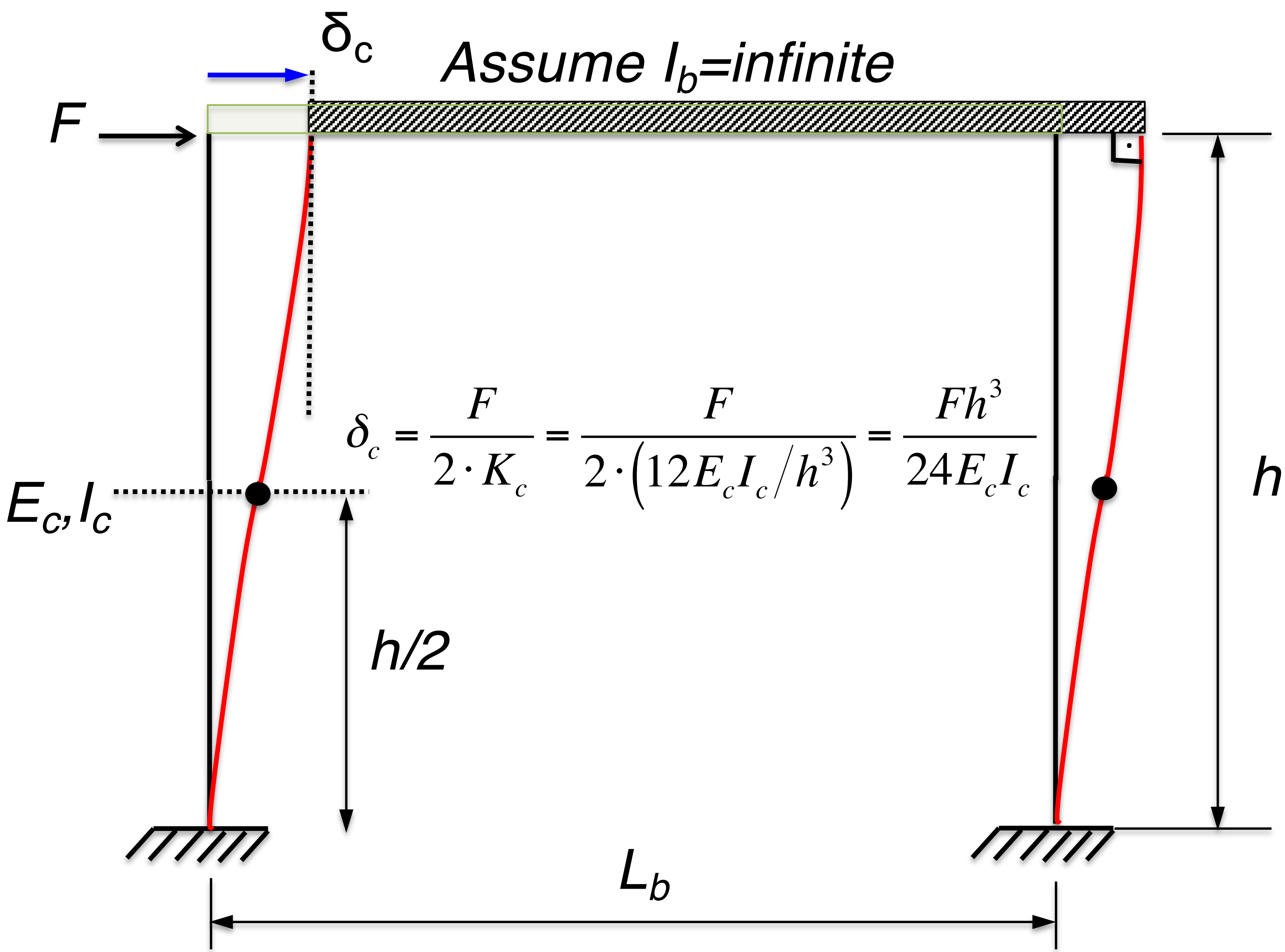
$$V_2 = \frac{K_2}{K_{total}} F$$

Case 2: Flexible Columns and Girders (Common Case)



Case 2: Flexible Columns and Girders

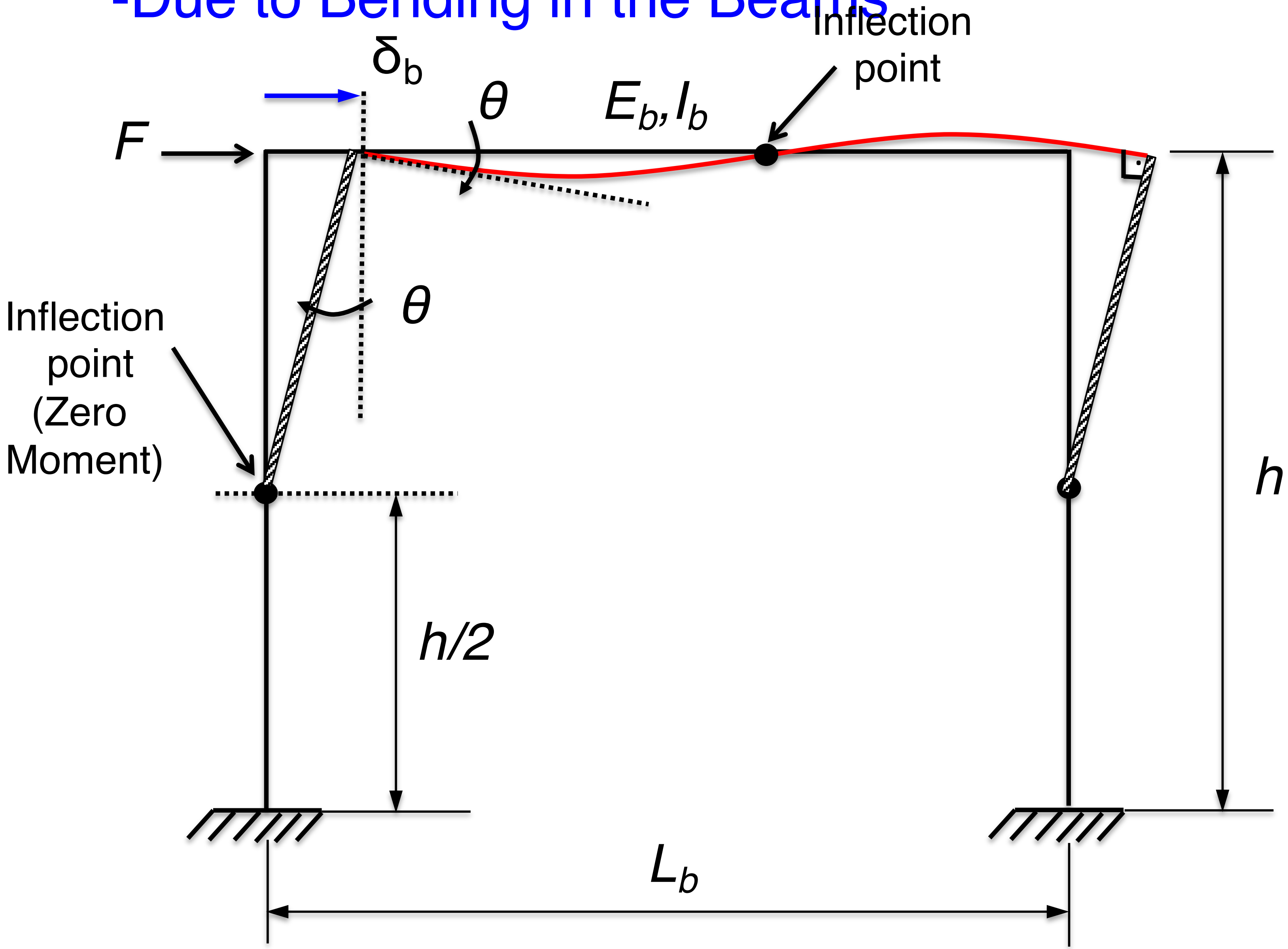
-Due to Bending in the Columns



$$\delta_c = \frac{F}{2 \cdot K_c} = \frac{F}{2 \cdot \left(12 E_c I_c / h^3\right)} = \frac{F h^3}{24 E_c I_c}$$

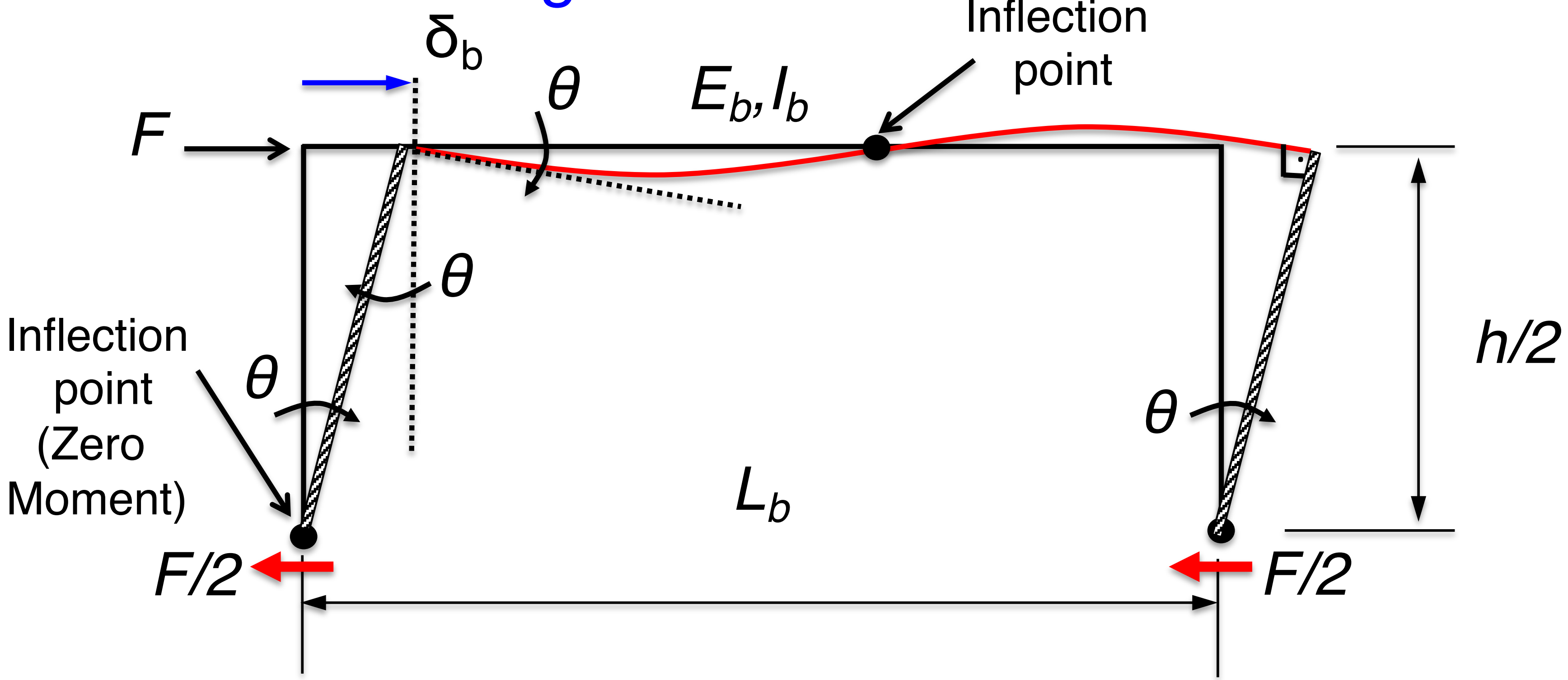
Case 2: Flexible Columns and Girders

-Due to Bending in the Beams



Case 2: Flexible Columns and Girders

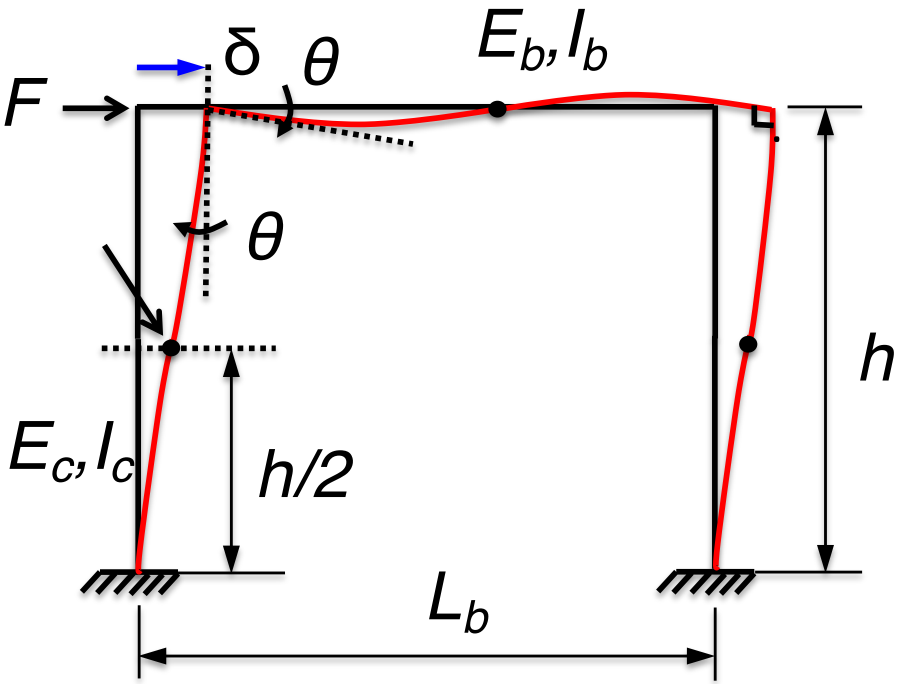
-Due to Bending in the Beams



$$\delta_b = \theta \cdot \frac{h}{2} = \frac{M_b}{K_b} \cdot \frac{h}{2} = \frac{M_b}{\frac{3E_b I_b}{L_b/2}} \cdot \frac{h}{2} = \frac{M_b \cdot L_b}{6E_b I_b} \cdot \frac{h}{2} = \frac{F \cdot L_b \cdot h^2}{48 E_b I_b}$$

$$M_b = \frac{F}{2} \cdot \frac{h}{2} = \frac{F \cdot h}{4}$$

Case 2: Flexible Columns and Girders
-Total Deflection and Lateral Stiffness

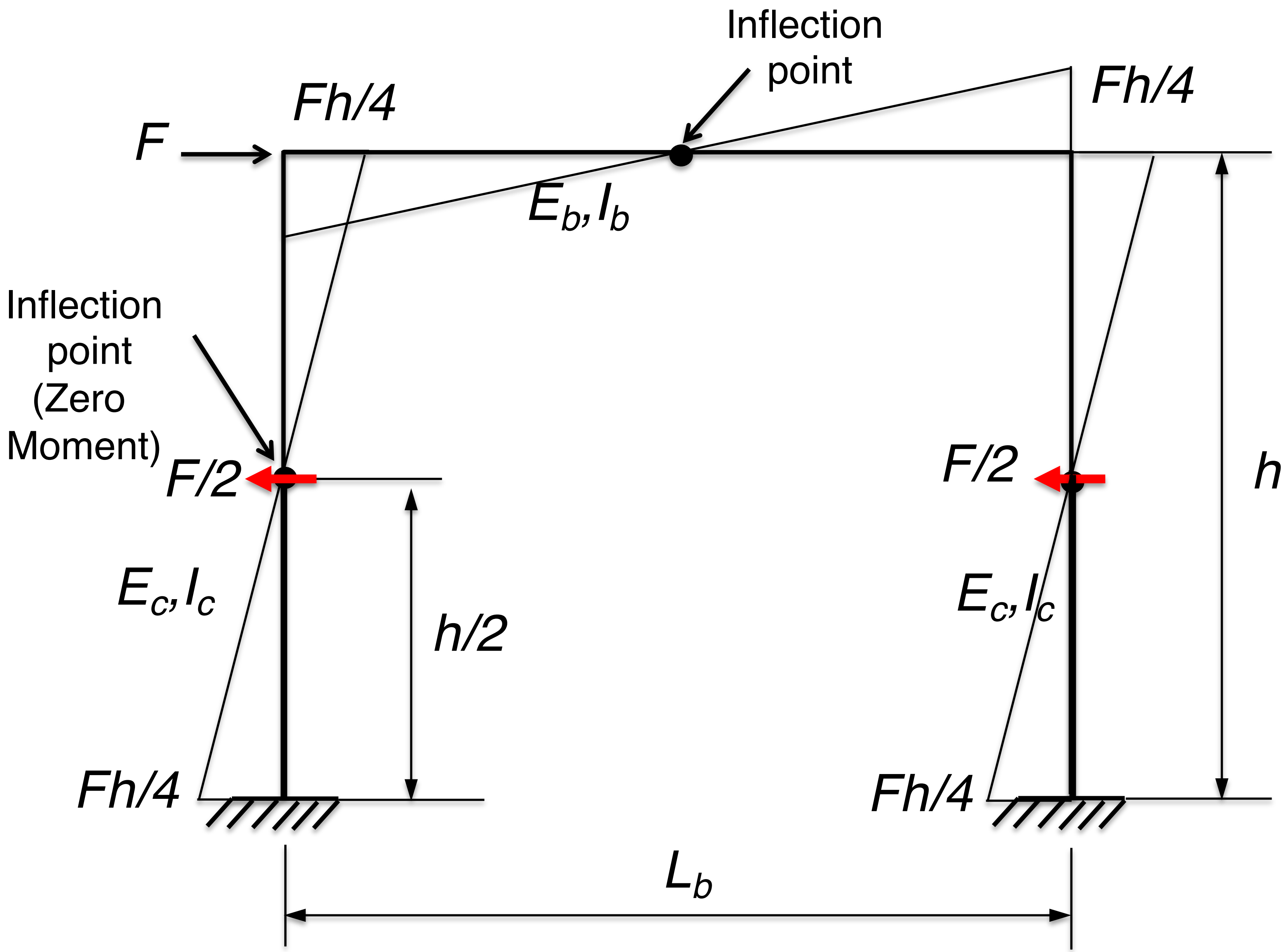


$$\delta = \delta_c + \delta_b = \frac{Fh^3}{24E_cI_c} + \frac{F \cdot L_b \cdot h^2}{48E_bI_b}$$

$$\delta = \frac{Fh^3}{24E_cI_c} + \frac{F \cdot L_b \cdot h^2}{48E_bI_b} = \frac{F \cdot h^2}{24} \cdot \left[\frac{h}{E_cI_c} + \frac{L_b}{2E_bI_b}\right]$$

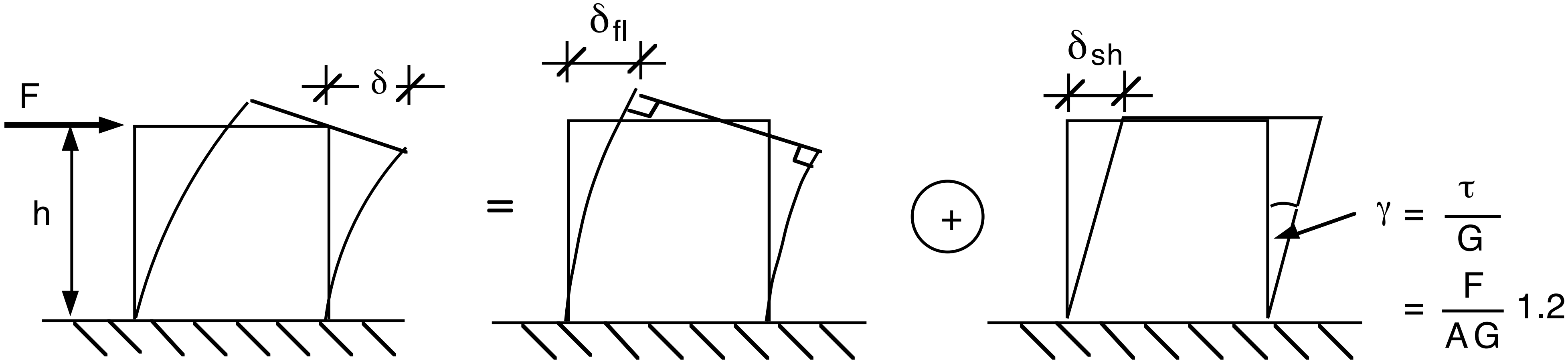
Lateral Stiffness $K = \dfrac{F}{\delta} = \dfrac{24}{h^2} \cdot \dfrac{1}{\left[\dfrac{h}{E_cI_c} + \dfrac{L_b}{2E_bI_b}\right]}$

Case 2: Flexible Columns and Girders



"Easy Statics" - Shear Wall Systems

Called "Shear Walls" because their primary function is to resist lateral loads, which create horizontal shear forces in walls.



$$\delta_{fl} = \frac{Fh^3}{3EI}$$

Flexural deformation

$$\delta_{sh} = \frac{1.2Fh}{AG}$$

Shear deformation

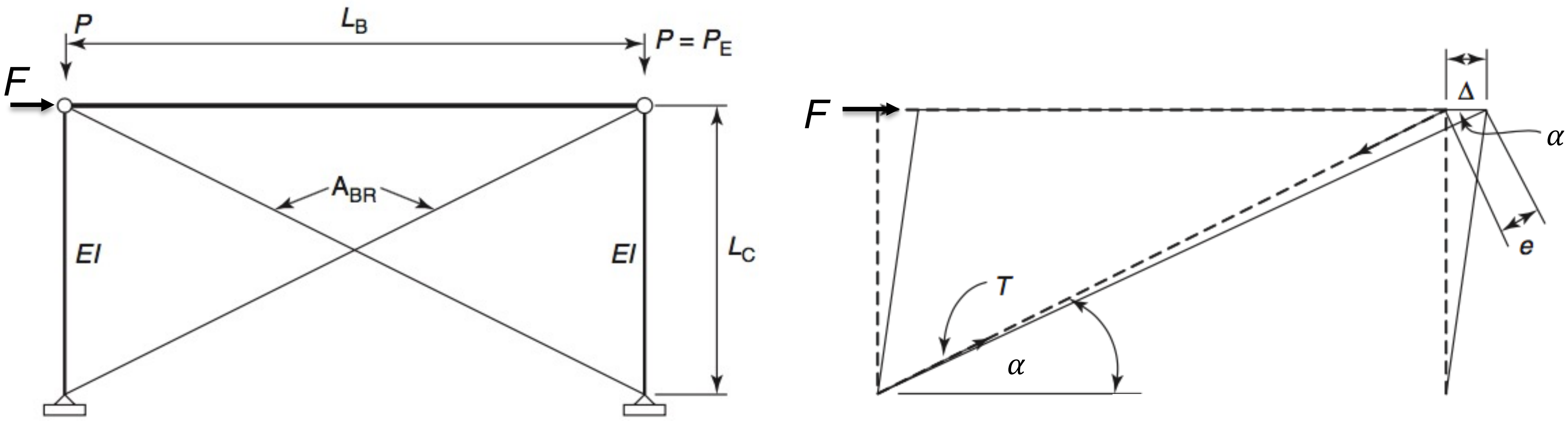
$$E_{cm} = 22\left[\frac{f_{cm}}{10}\right]^{0.3}$$ Secant Modulus E_{cm} (in Gpa), Mean compressive strength f_{cm} (in MPa)

$$G = \frac{E}{2(1+\nu)}$$ (ν_c = 0.15 to 0.2, use 0.17) Shear modulus

τ : Average shear stress

γ : angle of distortion

“Easy” Statics-Non-sway Frame with Bracings



Tensile Force in Brace: $T = F/cos\alpha$ Length of Brace: $L_{BR} = L_B/cos\alpha$

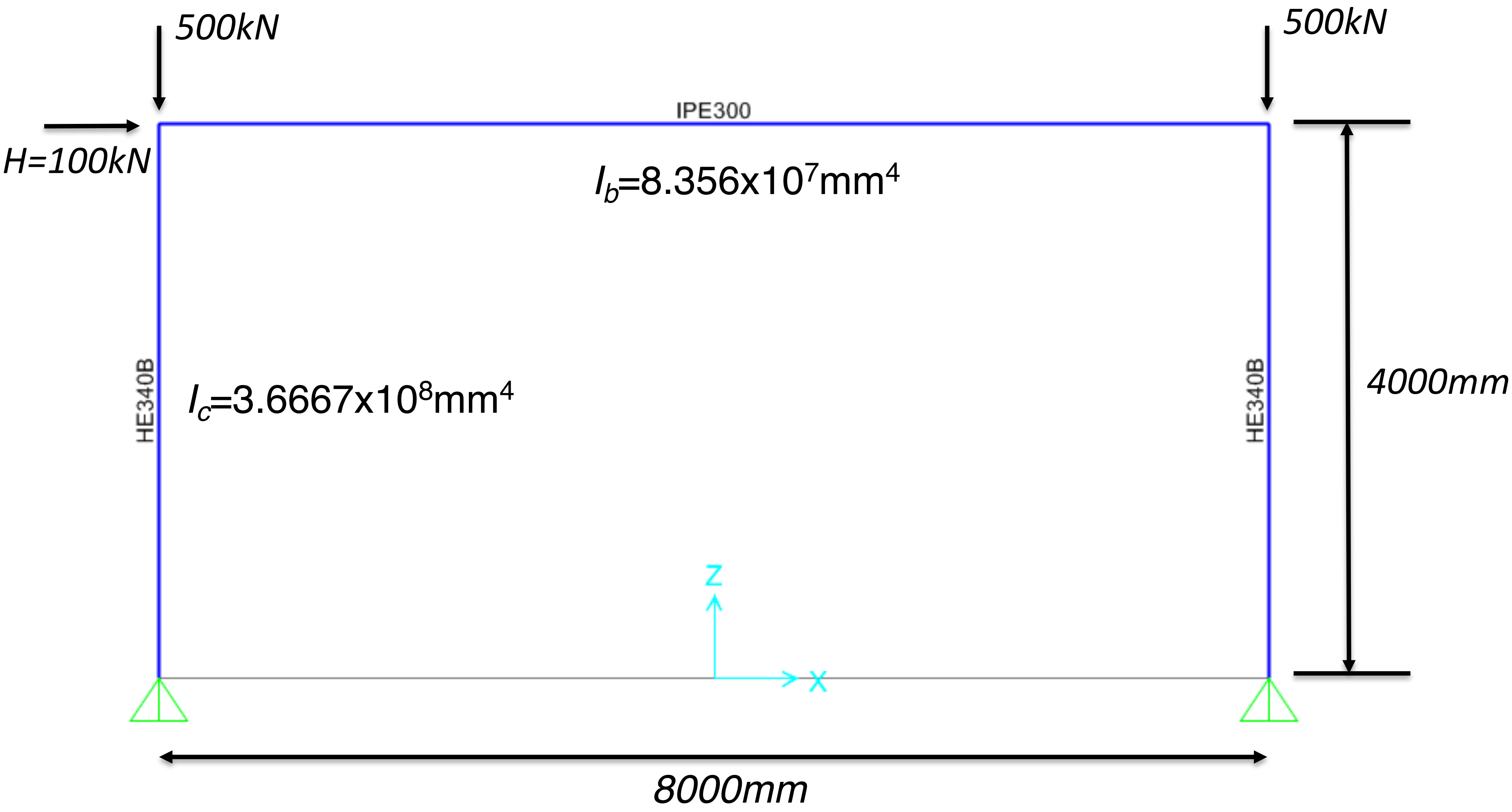
Brace elongation: $e = \dfrac{TL_{BR}}{EA_{BR}} = \dfrac{FL_B}{EA_{BR}\cos^2 a}$

Lateral Frame Displacement, $\Delta = \dfrac{e}{cosa} = \dfrac{FL_B}{EA_{BR}\cos^3 a} = \dfrac{F}{EA_{BR}} \cdot \dfrac{(L_B^2 + L_C^2)^{\frac{3}{2}}}{L_B^2}$

Lateral Frame Stiffness, $K = \dfrac{F}{\Delta} = \dfrac{EA_{BR}L_B^2}{(L_B^2 + L_C^2)^{3/2}}$

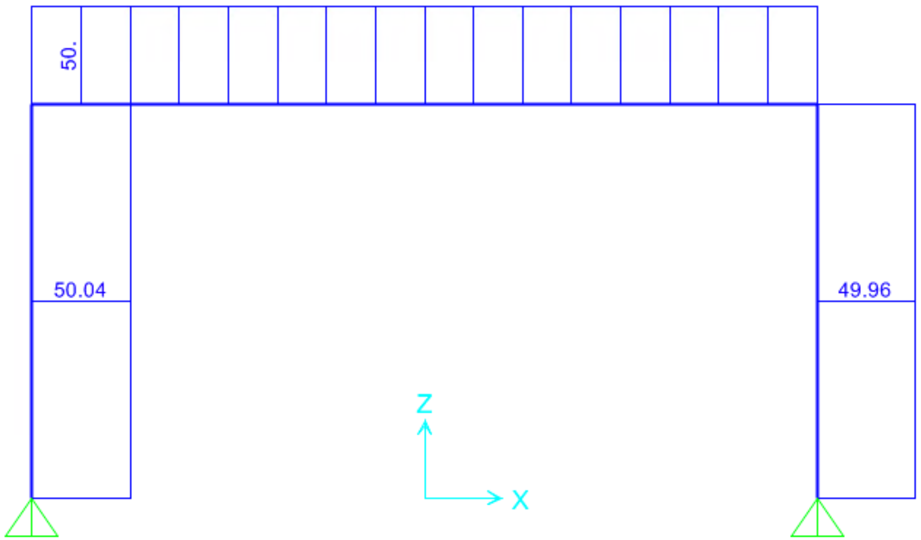
Example (in class & in SAP2000)

Compute the shear, moment diagrams and lateral deflection of the sway frame (Assume, $E=200kN/mm^2$)

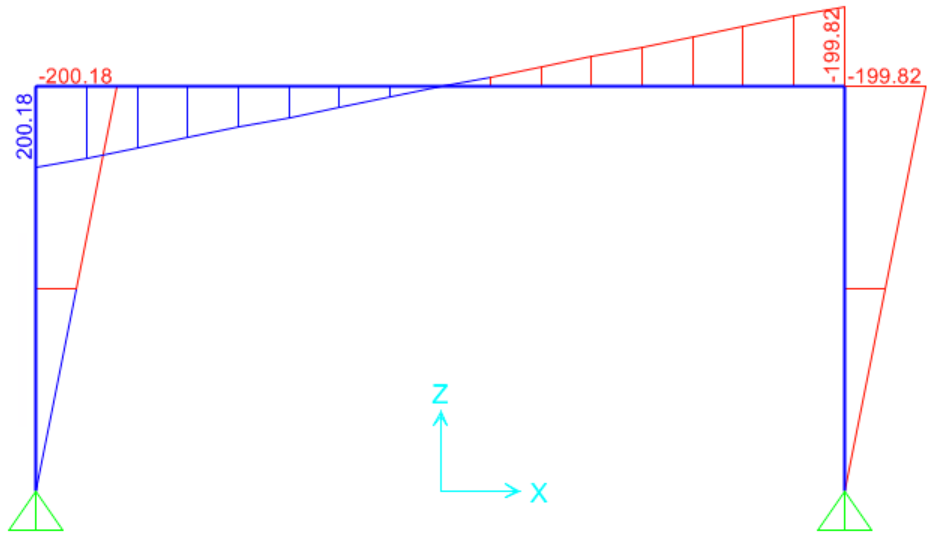


Example (in class & in SAP2000)
-Elastic Analysis

Shear diagram [V] (in KN)

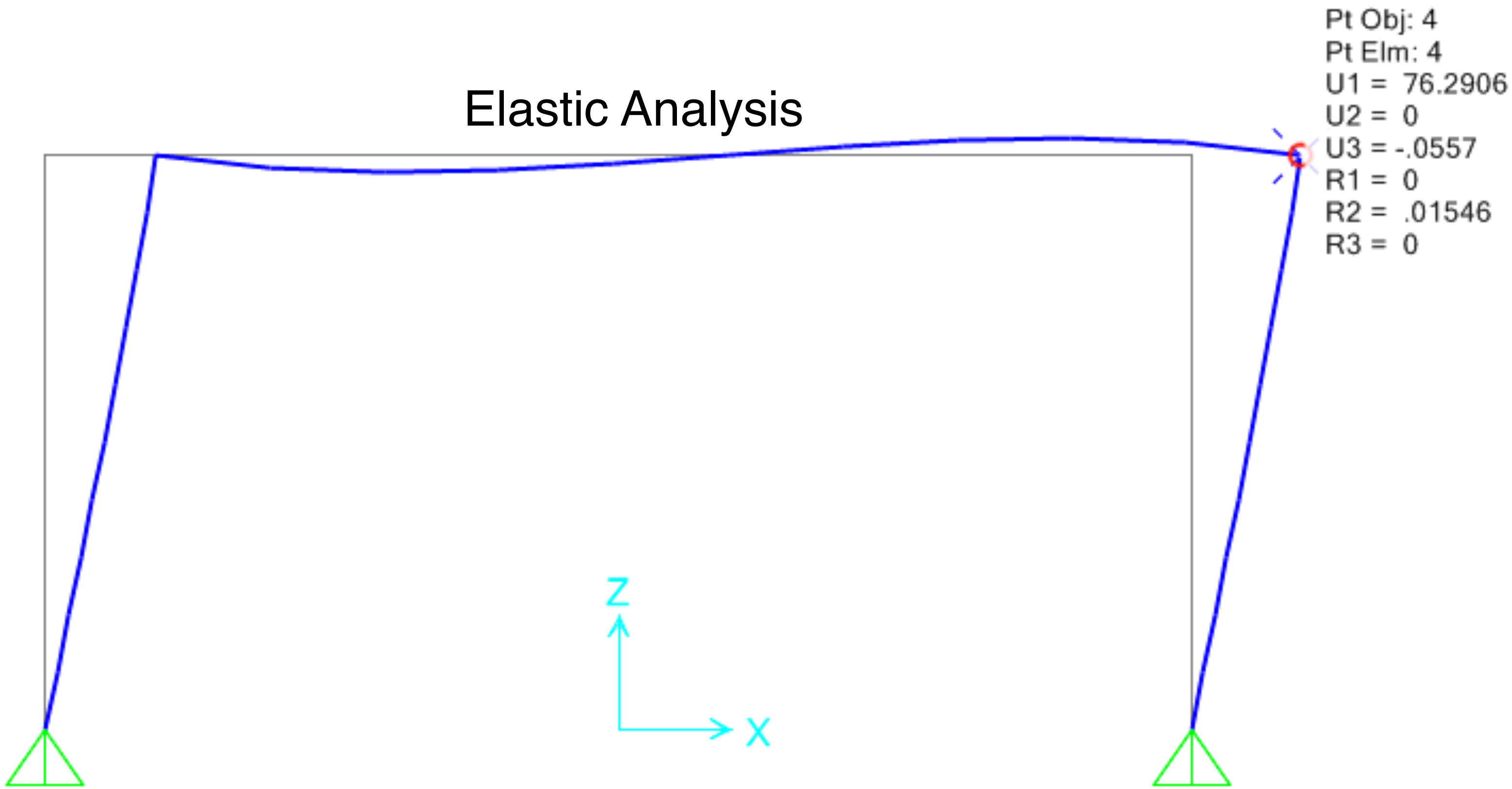


Moment diagram [M] (in KN-m)

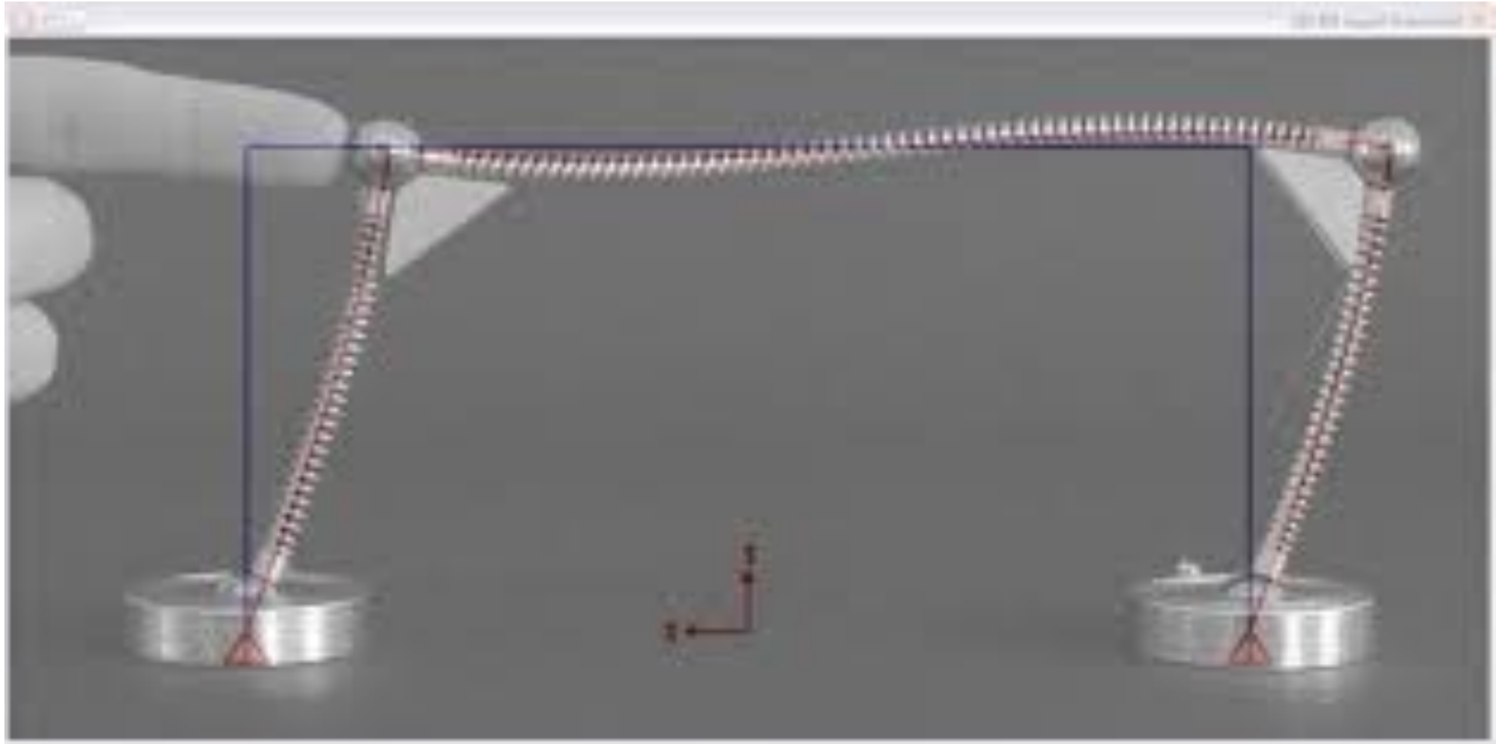


Example (in class & in SAP2000)

-Linear Analysis: Displacements



Example – MOLA
-Linear Analysis: Displacements



Example – MOLA
-Linear Analysis: Displacements

Example – MOLA
-Linear Analysis: Displacements