Development of Next-Generation High-Performance Seismic Force Resisting Systems

Tony T.Y. Yang, Ph.D., P.Eng.

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Director of Smart Structures Laboratory
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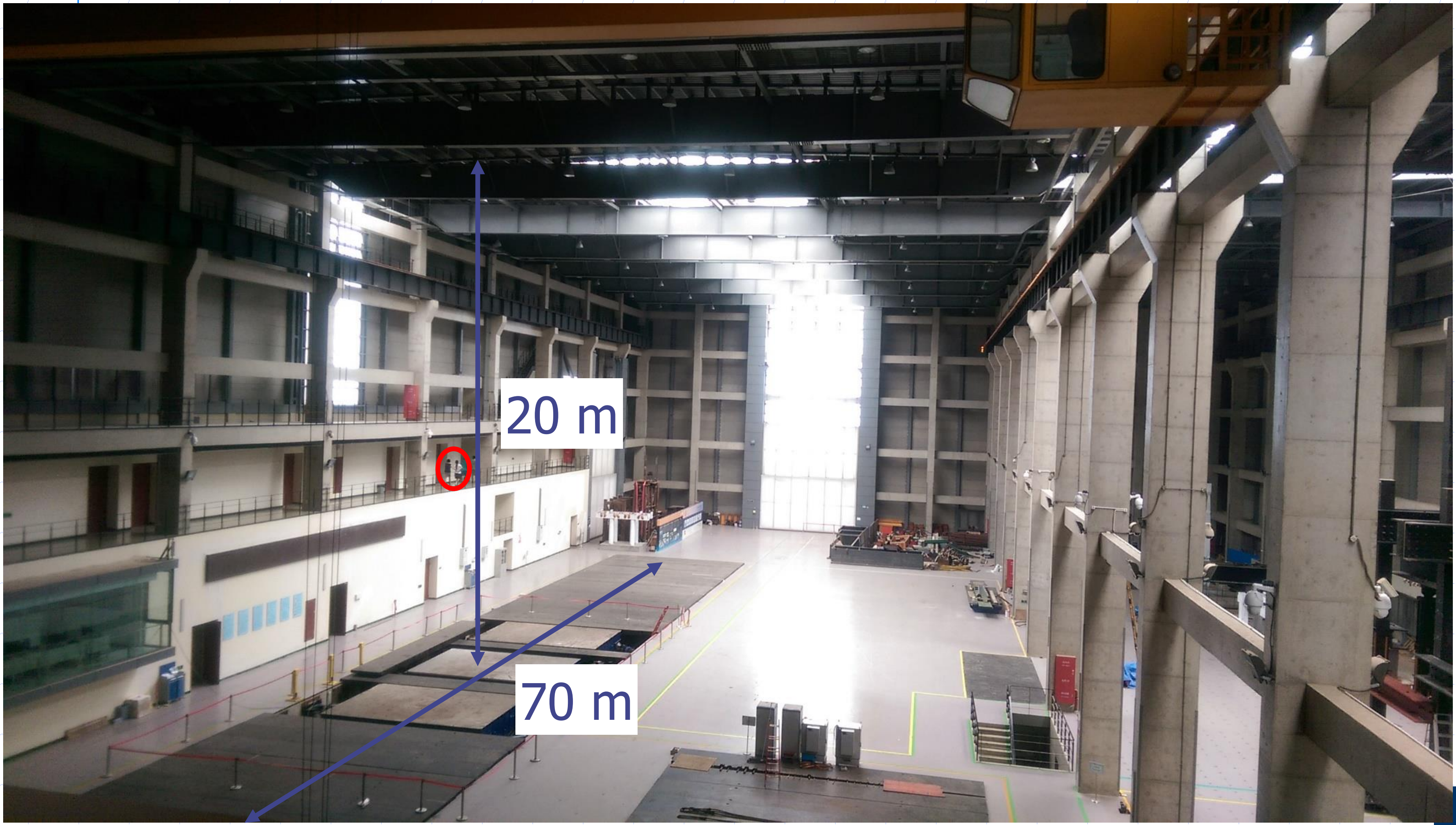
ILEE – International collaboration

ILEE facilities



ILEE facilities

ILEE facilities

ILEE facilities

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- T-shape wall, 30m long 15m high
- Shear strength of 600ton (at the top level of reaction wall)
- Bending moment strength of 9000ton-m.

ILEE facilities

ILEE facilities

ILEE

ILEE board of directors and scientific committee:

X. Gu (China)

S. Mahin (USA)

X. Lu (China)

T. Yang (Canada)

J. Li (China)

Y. Zhou (China)

K. Elwood (New Zealand)

K. Kasai (Japan)

K. Mosalam (USA)

A. Pavese (Italy)

C. Ventura (Canada)

A. Whittaker (USA)

K. Chang (Taiwan)

I. Buckle (USA)

B. Stojadinovic (Switzerland)

ILEE

Objectives of ILEE:

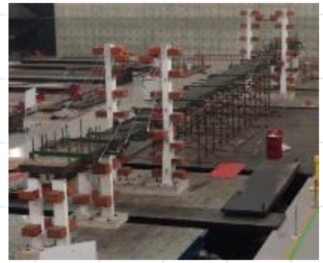
- Achieve earthquake resilience society through international effort using state-of-the-art experimental facilities

Strengths:

- Largest international earthquake engineering research network with the most advanced testing facilities;
- Facilitate the exchange of research personal, share facilities and publish cutting-edge research findings.

ILEE

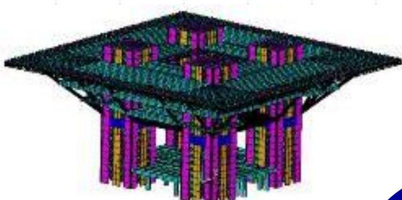
Shanking table test of Shanghai Tower



Shanking table test of cable-stayed bridge model

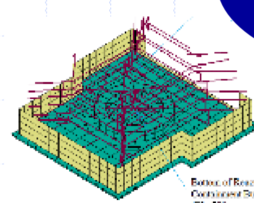
Earthquake engineering

- Building Engineering
- Bridge Engineering
- Lifeline Engineering
- Major Energy Facilities
- Geotechnical Engineering



Numerical calculation model of China Pavilion

Seismic test of super-long immersed tube tunnel of Hong Kong-Zhuhai-Macao Bridge



Seismic isolation model of nuclear power station

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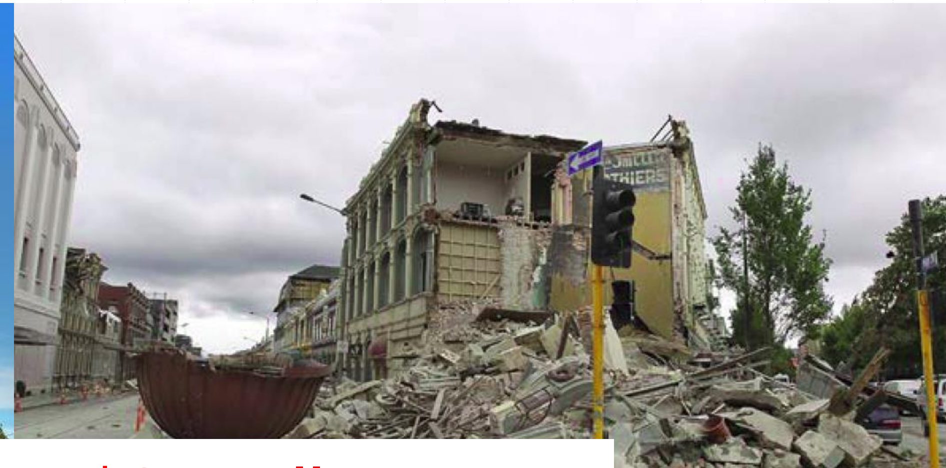
1906 San Francisco Earthquake, USA

- Destroyed 80% of the "golden" city.
- Over 3,000 died and half of the population homeless.

2011 Christchurch earthquake, New Zealand



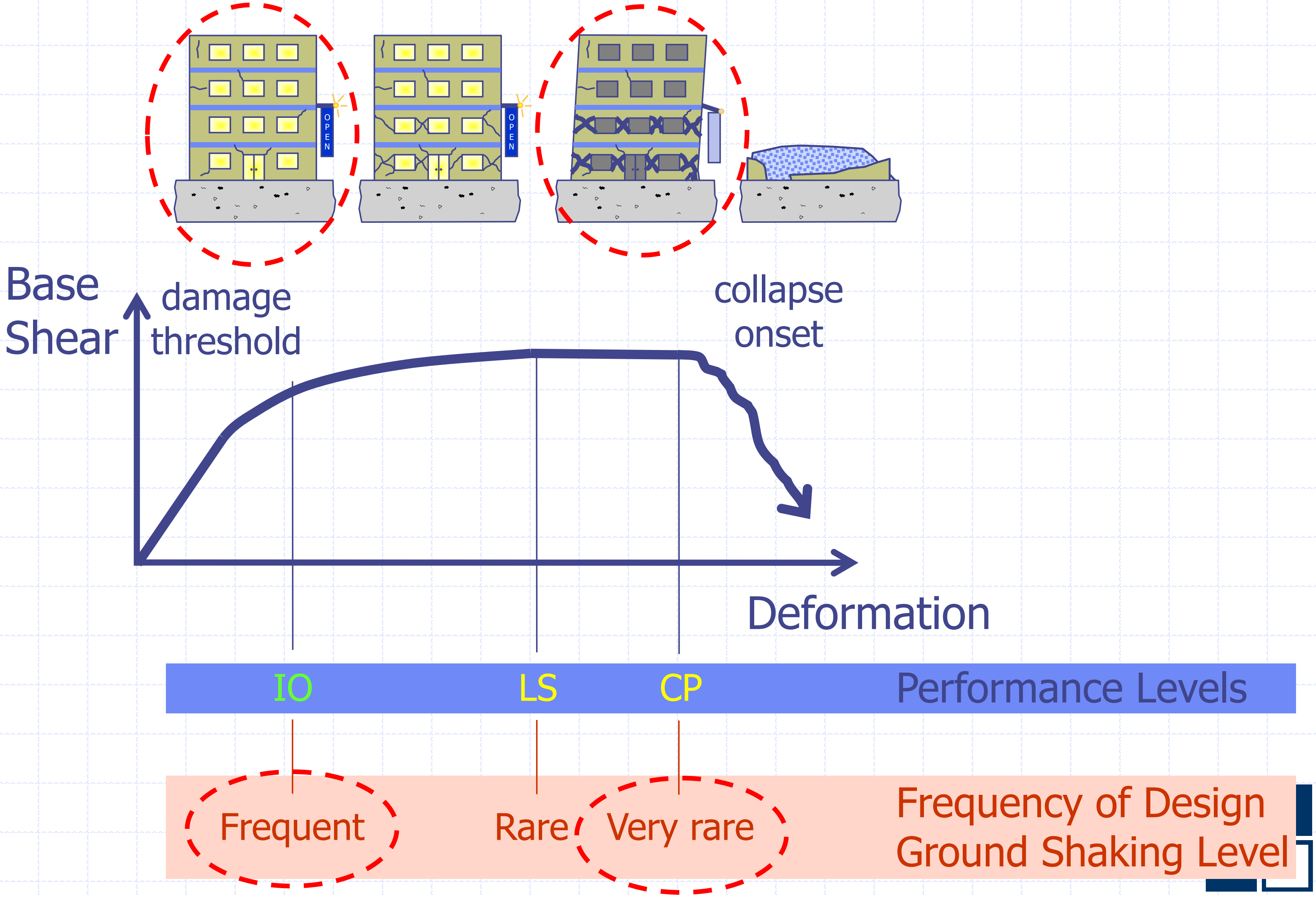
Financial loss: $35 Billion USD

2011 Tohoku earthquake, Japan

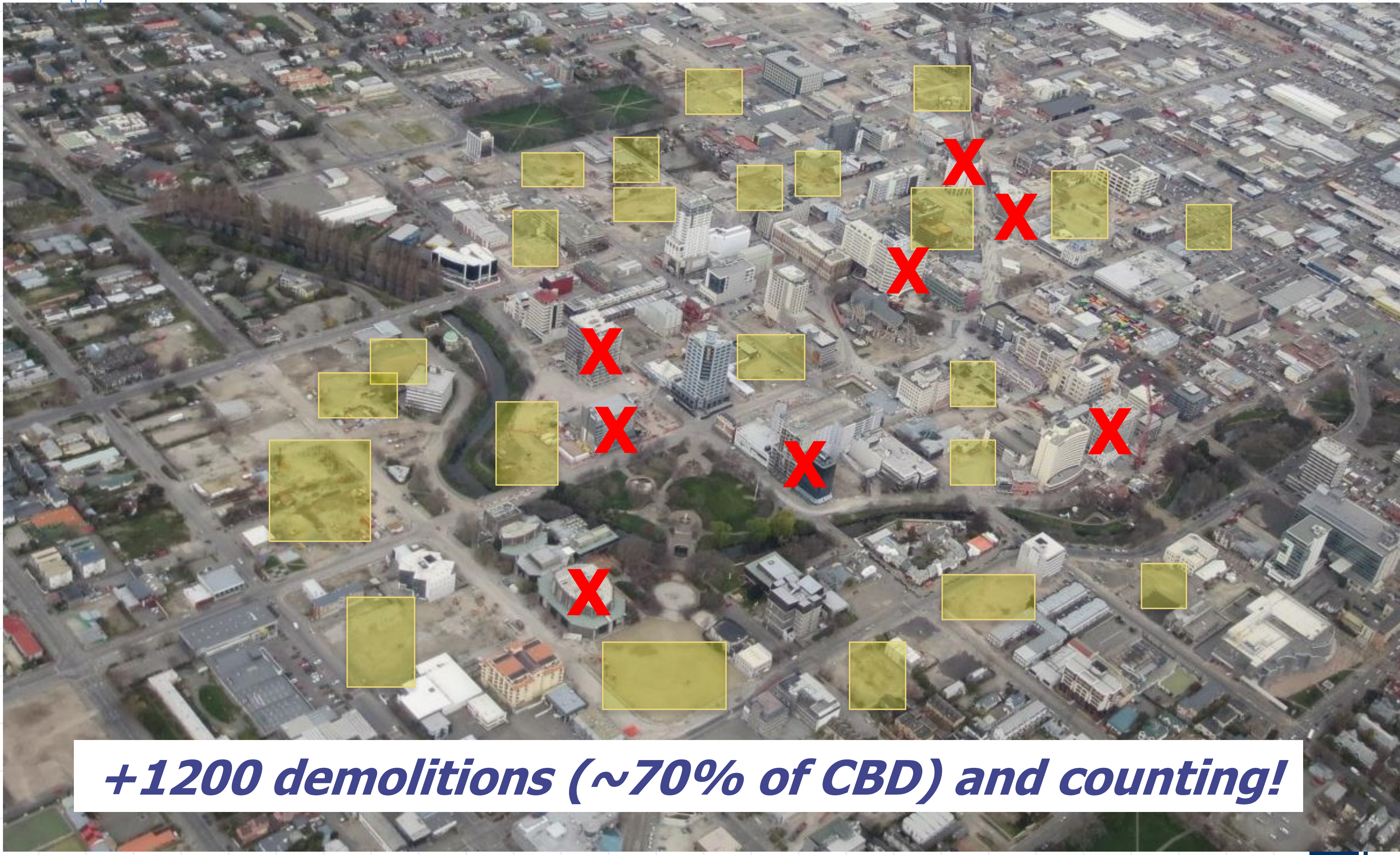
Financial loss: $235 Billion USD

Earthquake engineering

Performance-based design approach



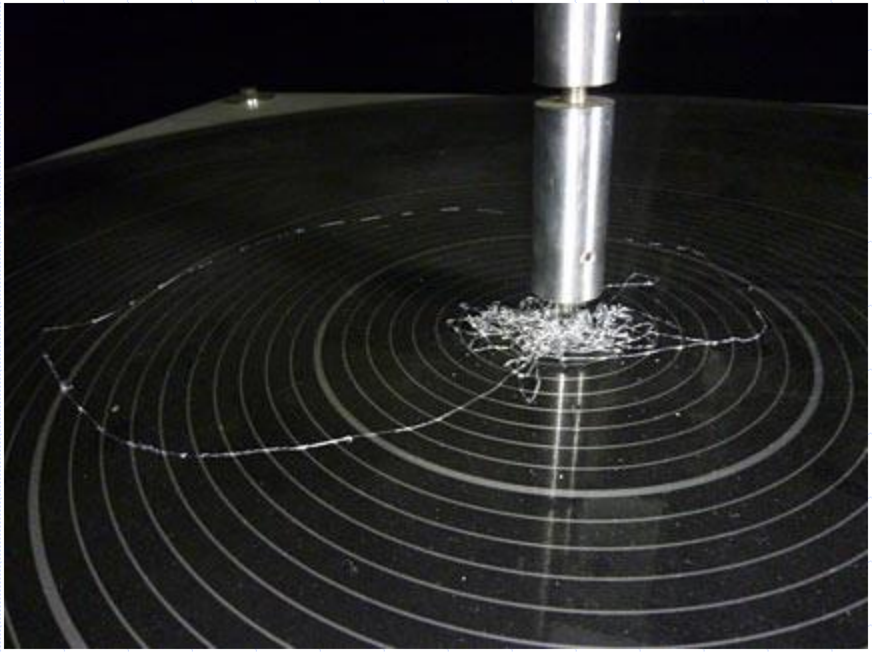
2011 Christchurch earthquake, New Zealand



+1200 demolitions (~70% of CBD) and counting!

High-performance structures

Sendai MT Building remain undamaged during the 2011 Great East Japan Earthquake.

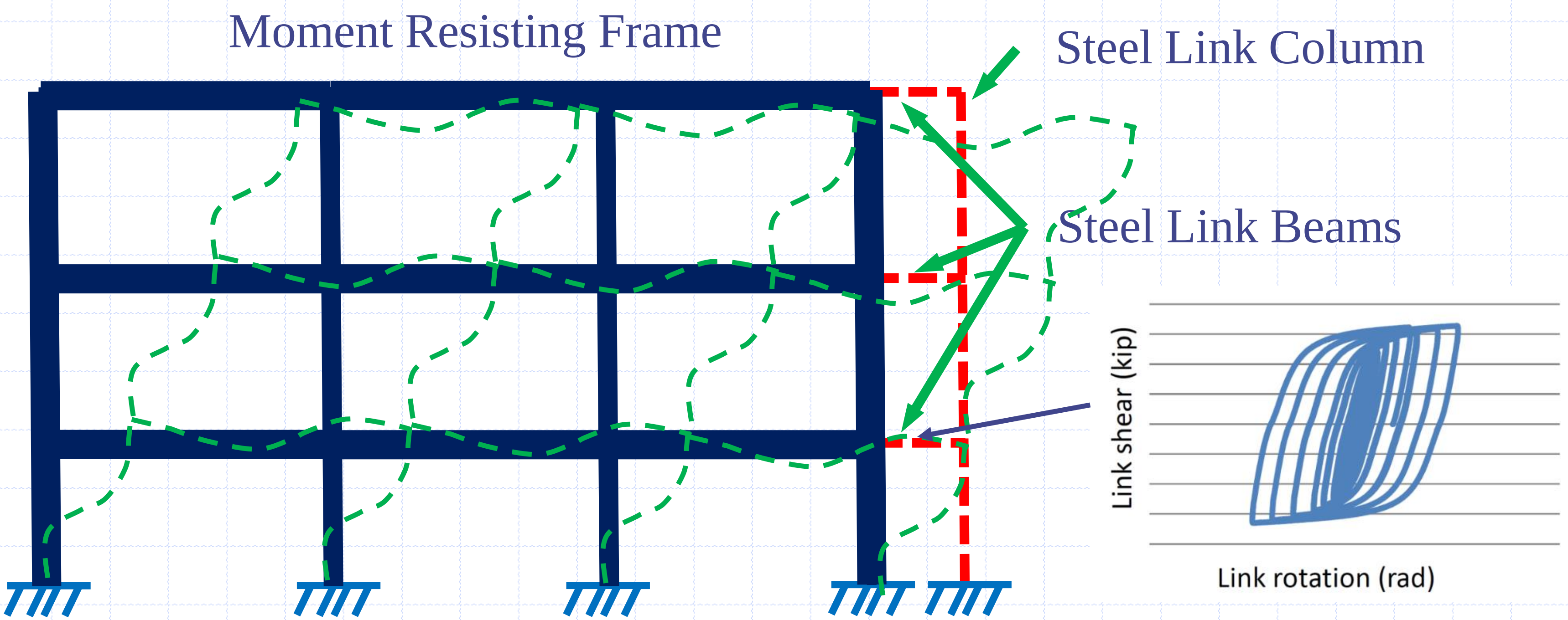


The measurement equipment shows that the building experienced as much as 23 cm of horizontal displacement. (Photo: Mori Trust Co., Ltd.)

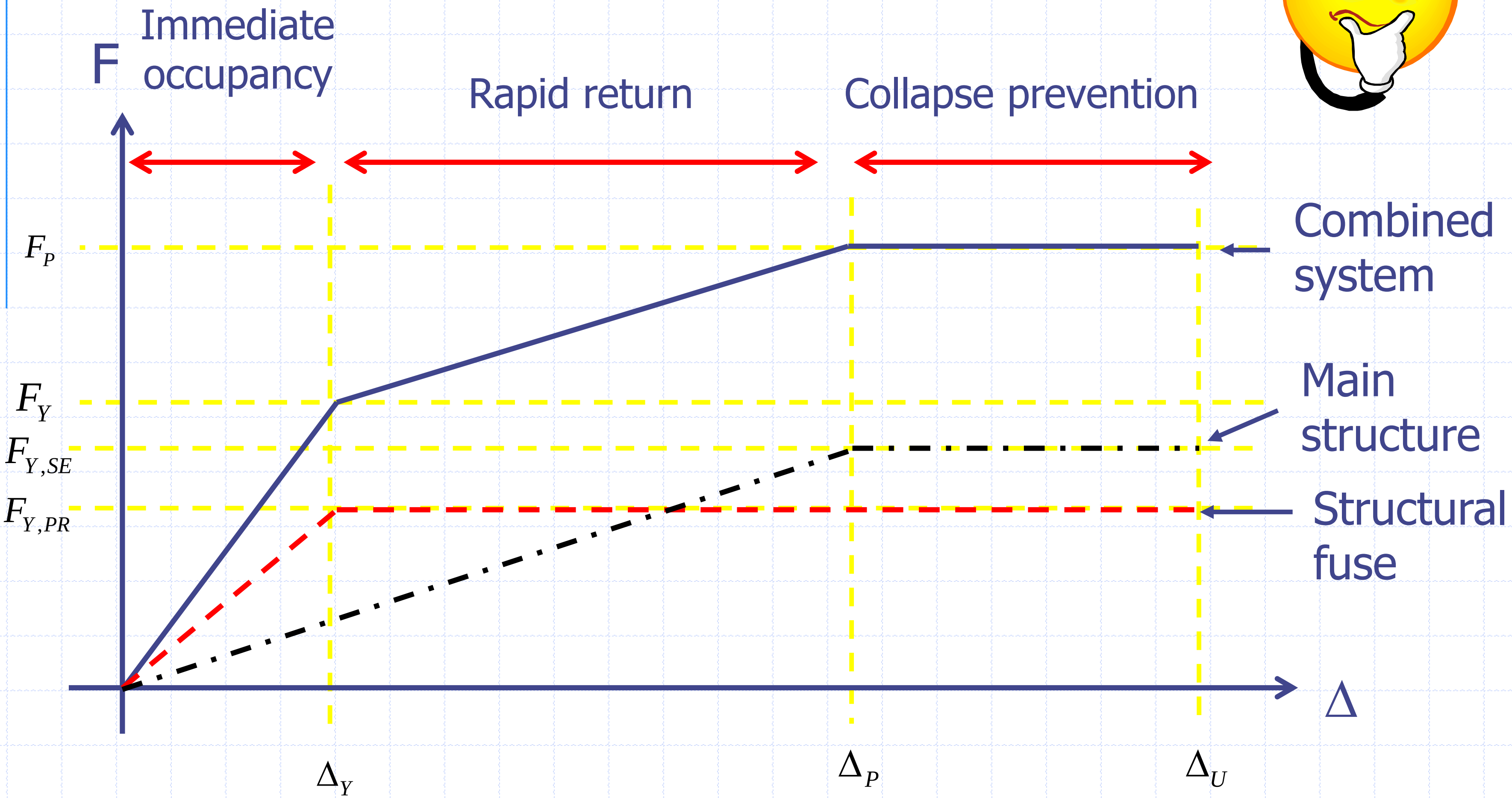
High-performance structures

High-performance structures

Steel Linked Column Frame



High-performance structures

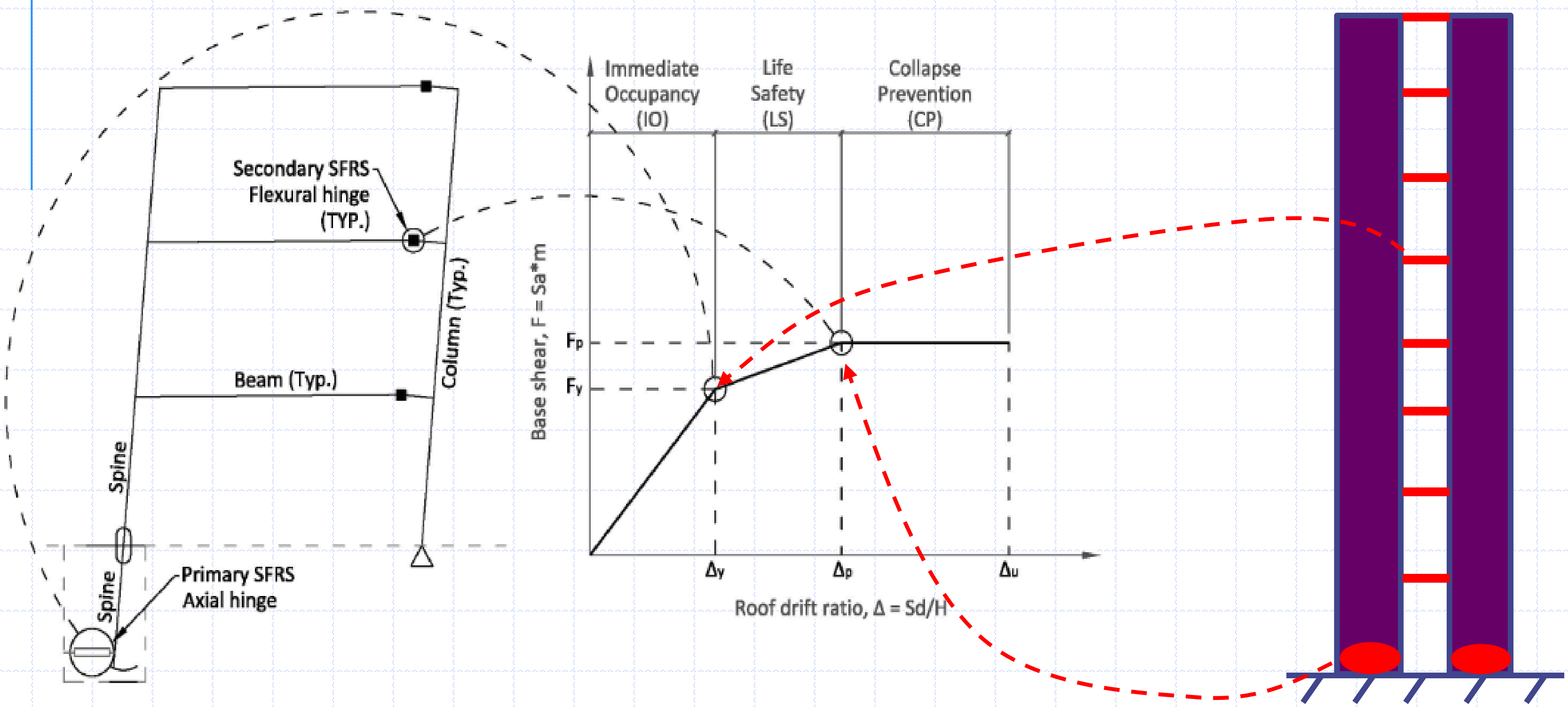


Alternate design methods

Features & requirements	EEDP	DDBD	PBPD	P-spectra	η-chart
Based on nonlinear SDOF responses	✓	✓	✓	✓	✓
Pre-select yielding mechanism & capacity design	✓	✓	✓	✓	✓
Require structural period estimation			✓	✓	✓
Require preliminary member sizes		✓		✓	
Require nonlinear analyses				✓	✓
Require minimum iterations		✓	✓	✓	✓
Consider multiple shaking intensities	✓			✓	
Achieve multiple performance objectives	✓			✓	

Equivalent energy design procedure (EEDP)

- Energy-based design procedure.
- Allows designers to select a plastic mechanism to dissipate EQ energy.



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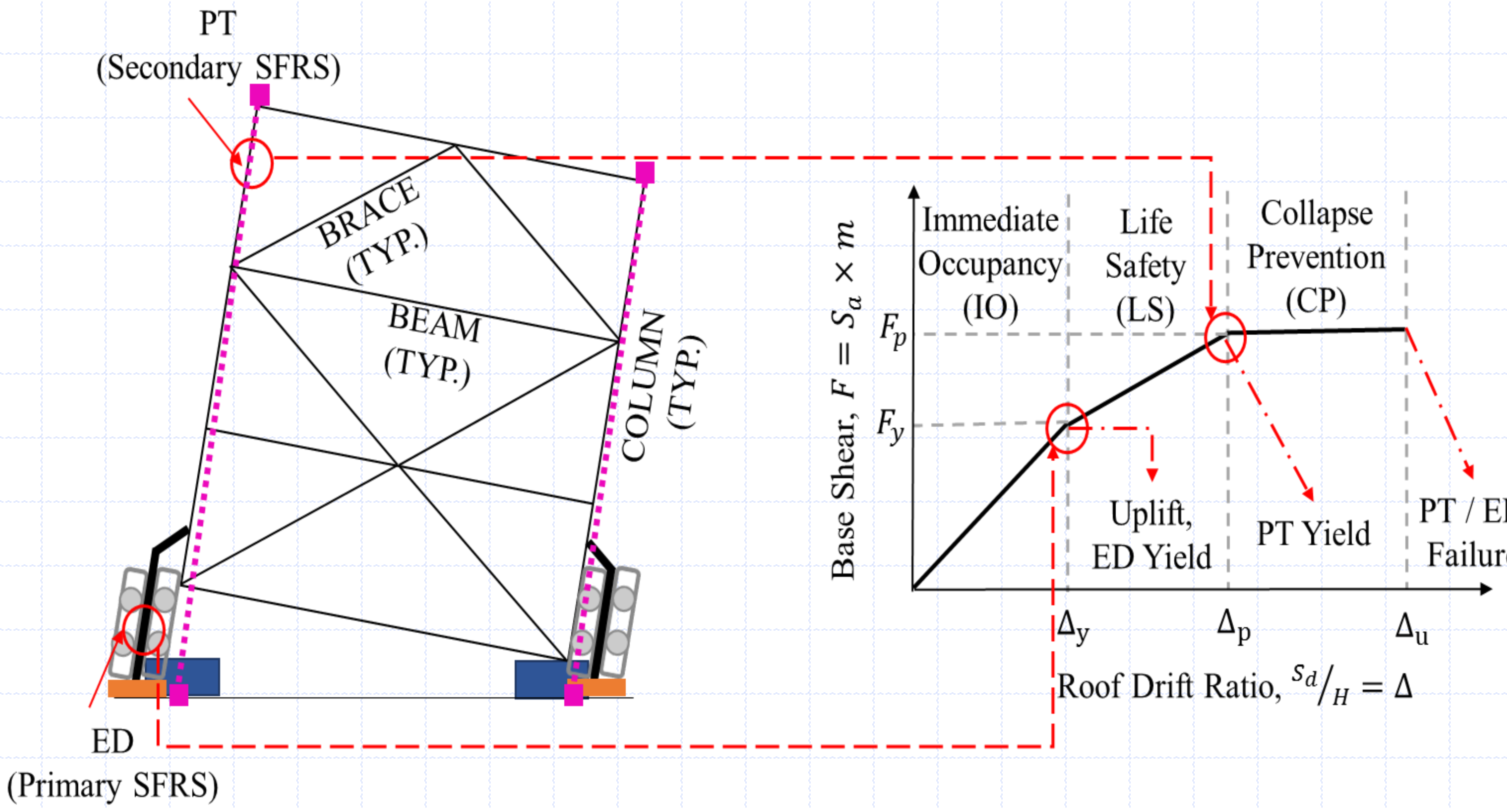


Equivalent energy design procedure

- Energy-based design procedure.
- Allows designers to select a plastic mechanism to dissipate EQ energy.
- Targeted to achieve different performance objectives at multiple earthquake shaking intensities.
  - SLE: No or minimum damage ➔ "Immediate occupancy".
  - DBE: Only damage to the structural fuses. No damage to the main structure ➔ "Rapid return".
  - MCE: Not collapse ➔ "Collapse prevention".
- Designers can select the member sizes to satisfy both the strength and drift limits without iteration!!
- Can be applied to different structural systems. Including new systems.
  - No need to assume R_d R_0 values.

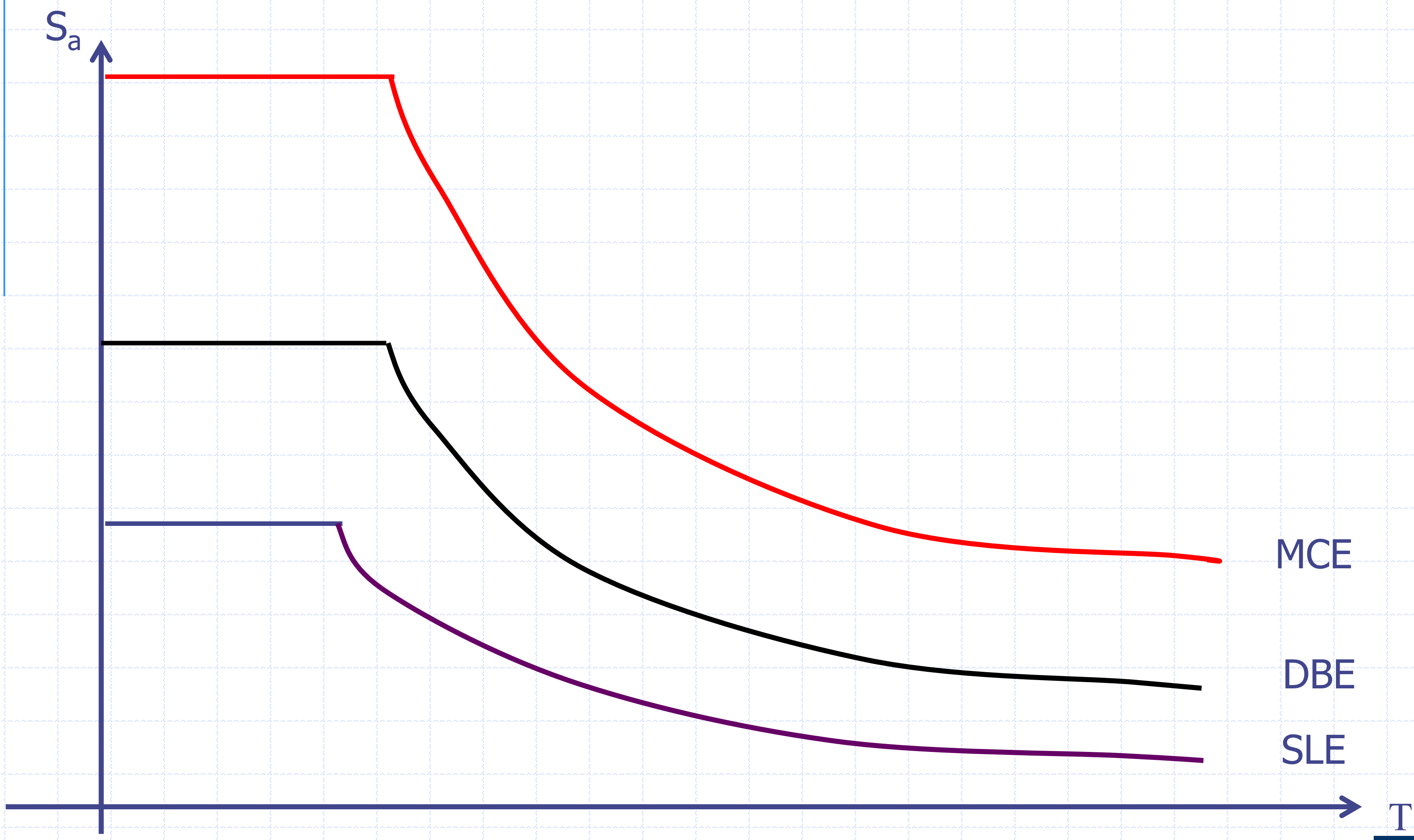
Equivalent energy design procedure

1. Define the performance objectives of the structure, by selecting the target shaking intensities and target drifts.
2. Calculate the base shear for the whole system.
3. Calculate the yield force for the primary and secondary system.
4. Select the plastic mechanism.
5. Distribute the yield force vertically on the primary and secondary systems.
6. Size the yielding elements.
7. Capacity design the non-yielding elements.

➔ Able to achieve the target performances without iteration!!!

Equivalent energy design procedure

- 1.0: Select the seismic hazards:



Equivalent energy design procedure

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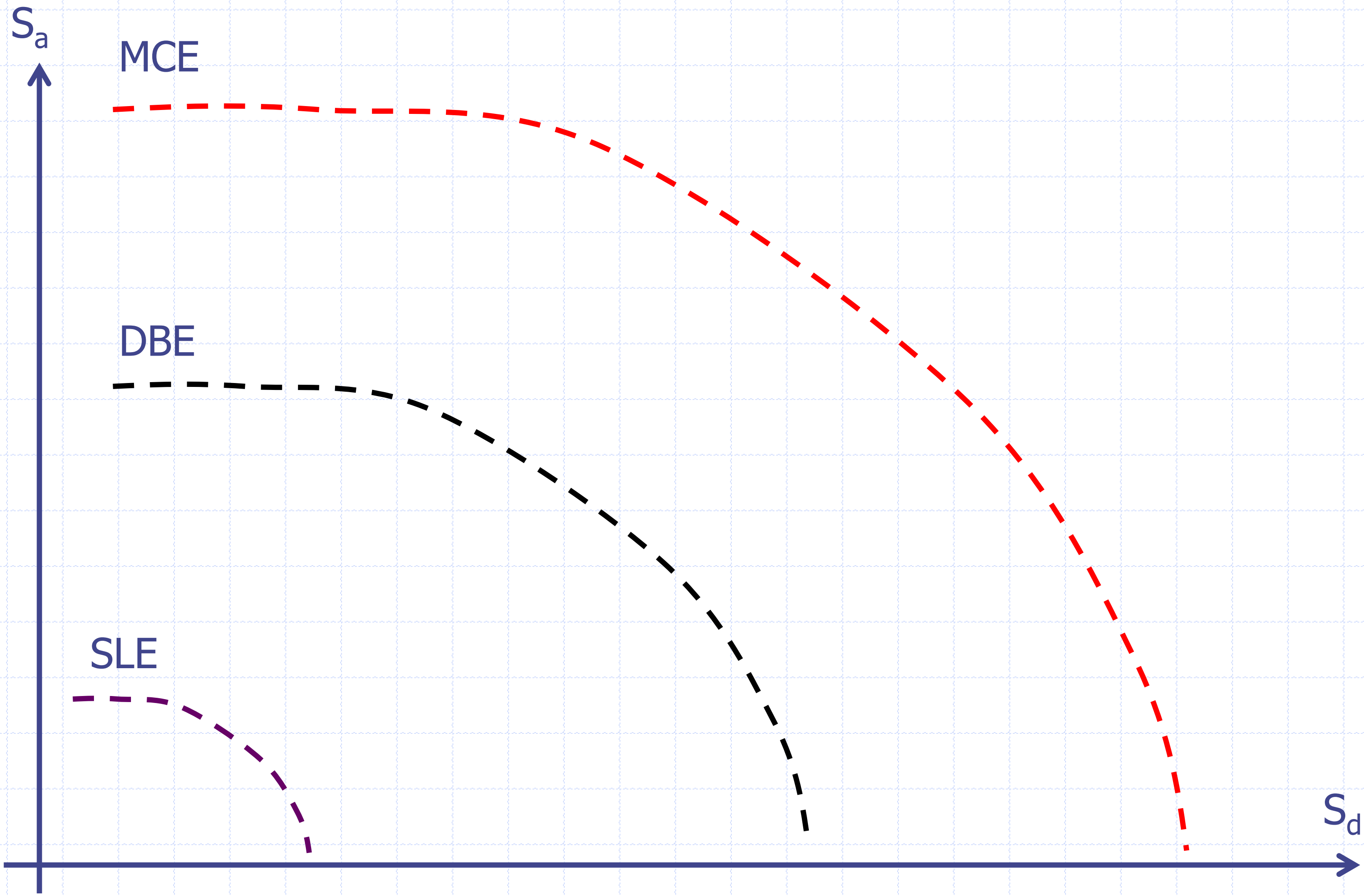
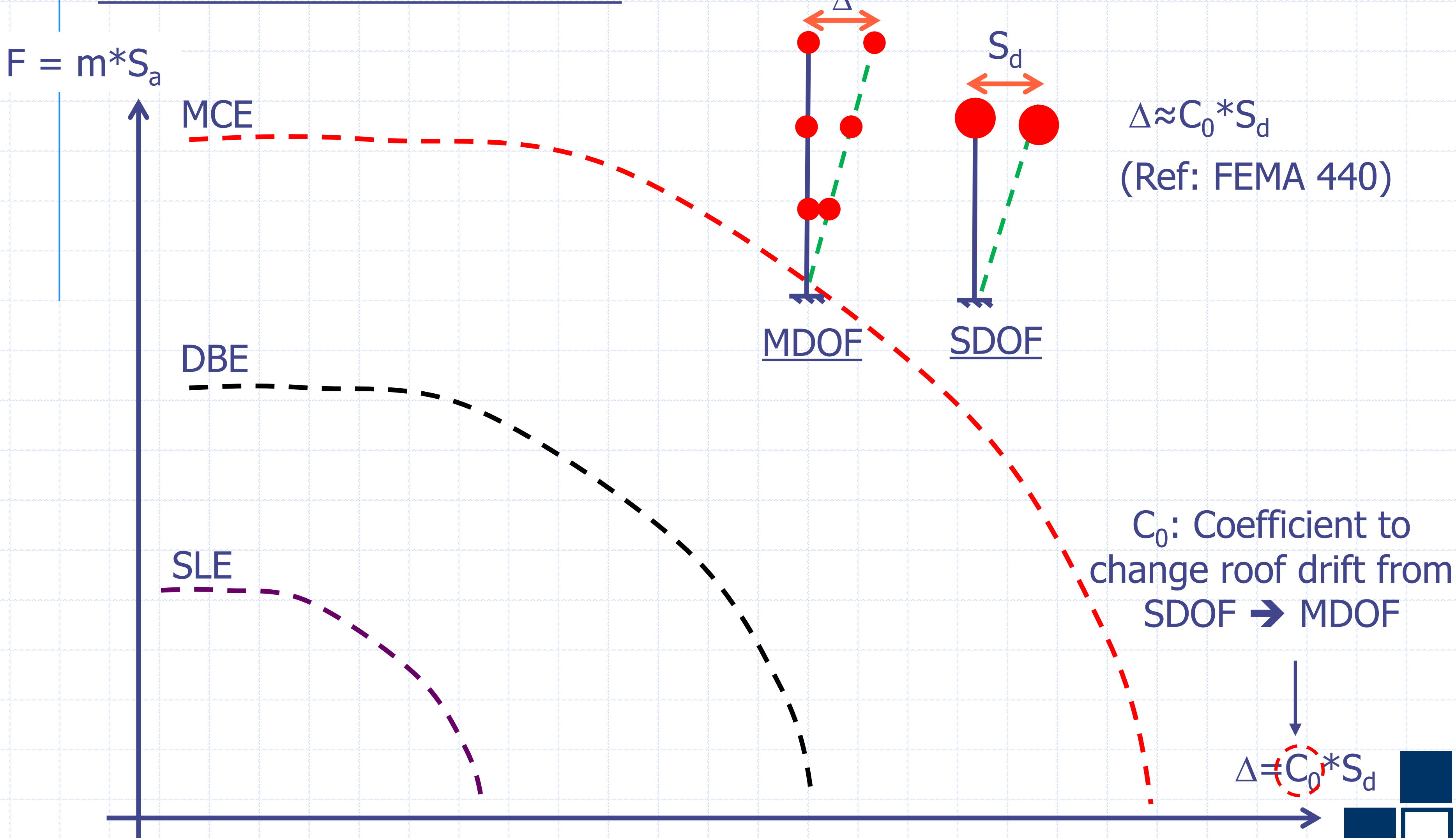


Equivalent energy design procedure

- 1.0: Select the seismic hazards:



Equivalent energy design procedure

- 2.0: Calculate the base shear:

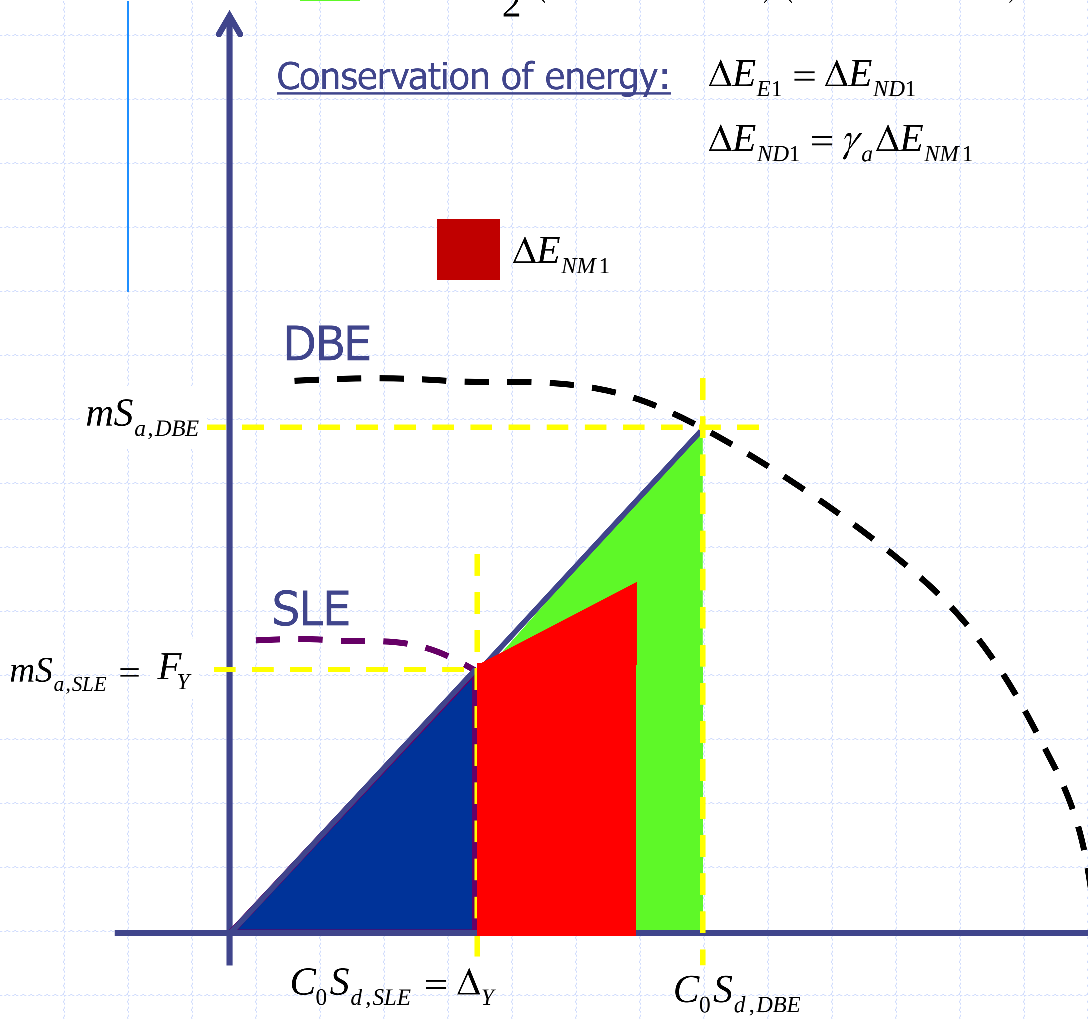
$F = m*S_a$

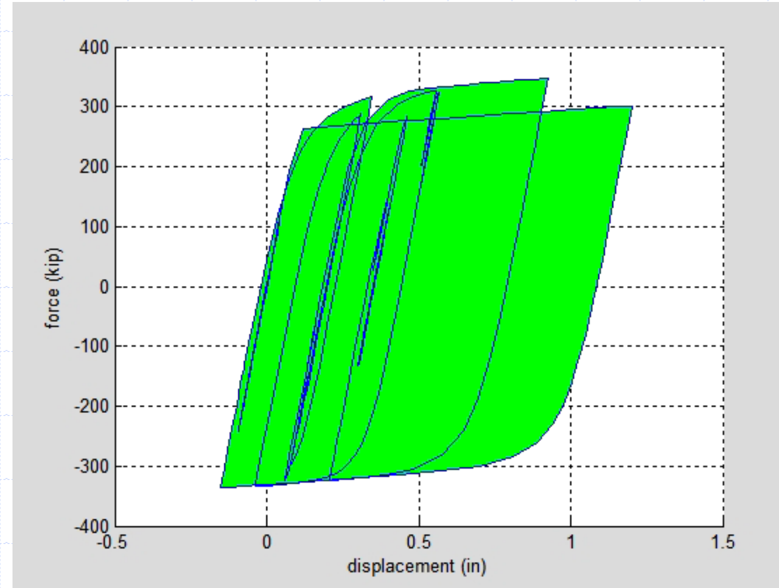
$$\Delta E_{E1} = \frac{m}{2}\left(S_{a,SLE} + S_{a,DBE}\right)\left(C_0 S_{d,DBE} - \Delta_Y\right)$$

Conservation of energy: $\Delta E_{E1} = \Delta E_{ND1}$

$$\Delta E_{ND1} = \gamma_a \Delta E_{NM1}$$

ΔE_{NM1}





T is constant, once SLE and Δ_Y is defined.

$$\left.\begin{array}{l} S_{a,SLE} = \dfrac{F_Y}{m} \\ S_{d,SLE} = \dfrac{\Delta_Y}{C_0} \end{array}\right\} \Rightarrow T = 2\pi\sqrt{\frac{S_d}{S_a}} = 2\pi\sqrt{\frac{\Delta_Y m}{C_0 F_Y}}$$

Equivalent energy design procedure

- <u>2.0: Calculate the base shear:</u>

F = m*S_a

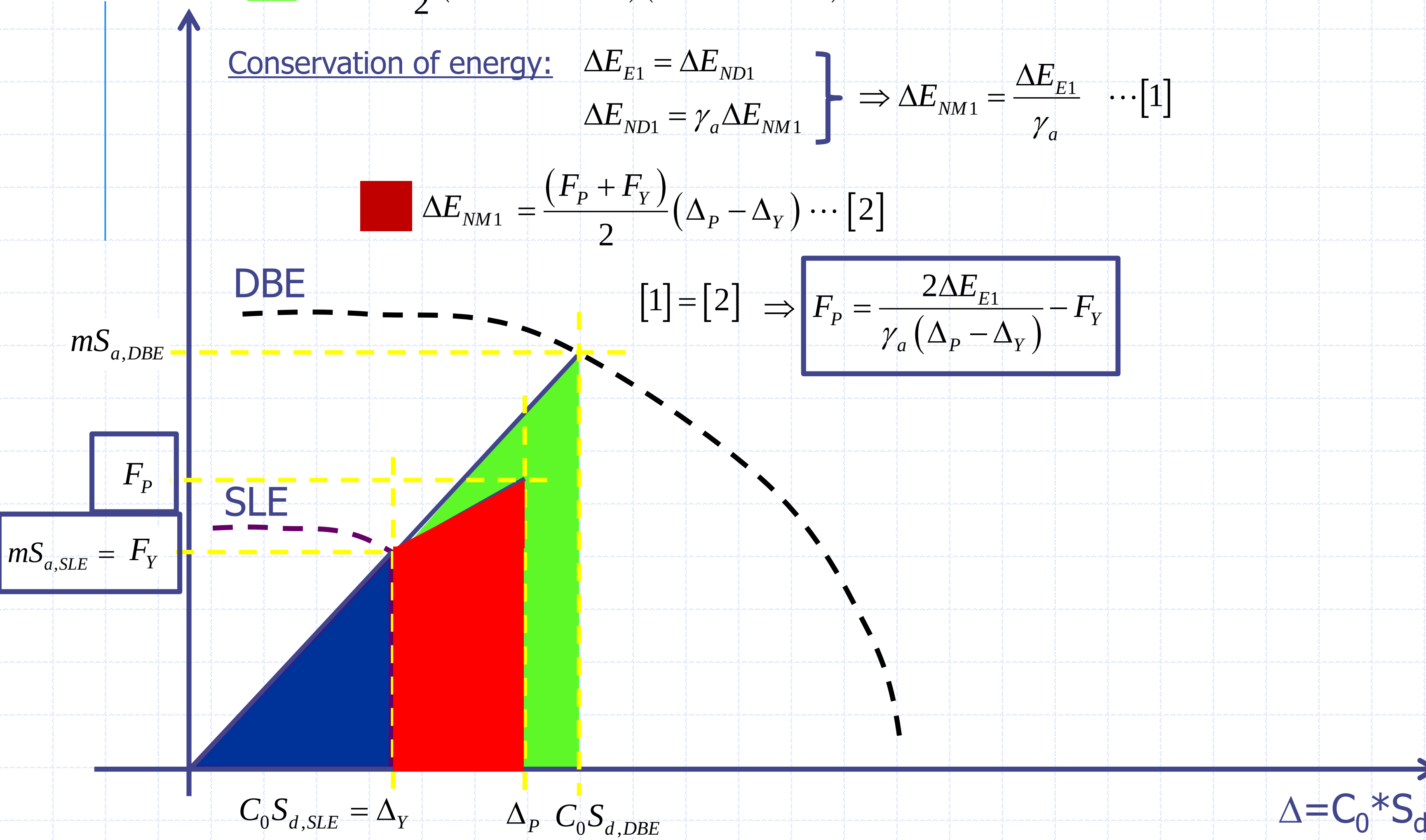
$$\Delta E_{E1} = \frac{m}{2}\left(S_{a,SLE} + S_{a,DBE}\right)\left(C_0 S_{d,DBE} - \Delta_Y\right)$$

<u>Conservation of energy:</u>

$$\left.\begin{aligned} \Delta E_{E1} &= \Delta E_{ND1} \\ \Delta E_{ND1} &= \gamma_a \Delta E_{NM1} \end{aligned}\right\} \Rightarrow \Delta E_{NM1} = \frac{\Delta E_{E1}}{\gamma_a} \quad \cdots [1]$$

$$\Delta E_{NM1} = \frac{\left(F_P + F_Y\right)}{2}\left(\Delta_P - \Delta_Y\right) \cdots [2]$$

$$[1] = [2] \quad \Rightarrow \quad F_P = \frac{2\Delta E_{E1}}{\gamma_a\left(\Delta_P - \Delta_Y\right)} - F_Y$$



Equivalent energy design procedure

- 2.0: Calculate the base shear:

$$\Delta E_{E2} = \frac{mC_0}{2}\left(S_{a,MCE} + S_{a,DBE}\right)\left(S_{d,MCE} - S_{d,DBE}\right)$$

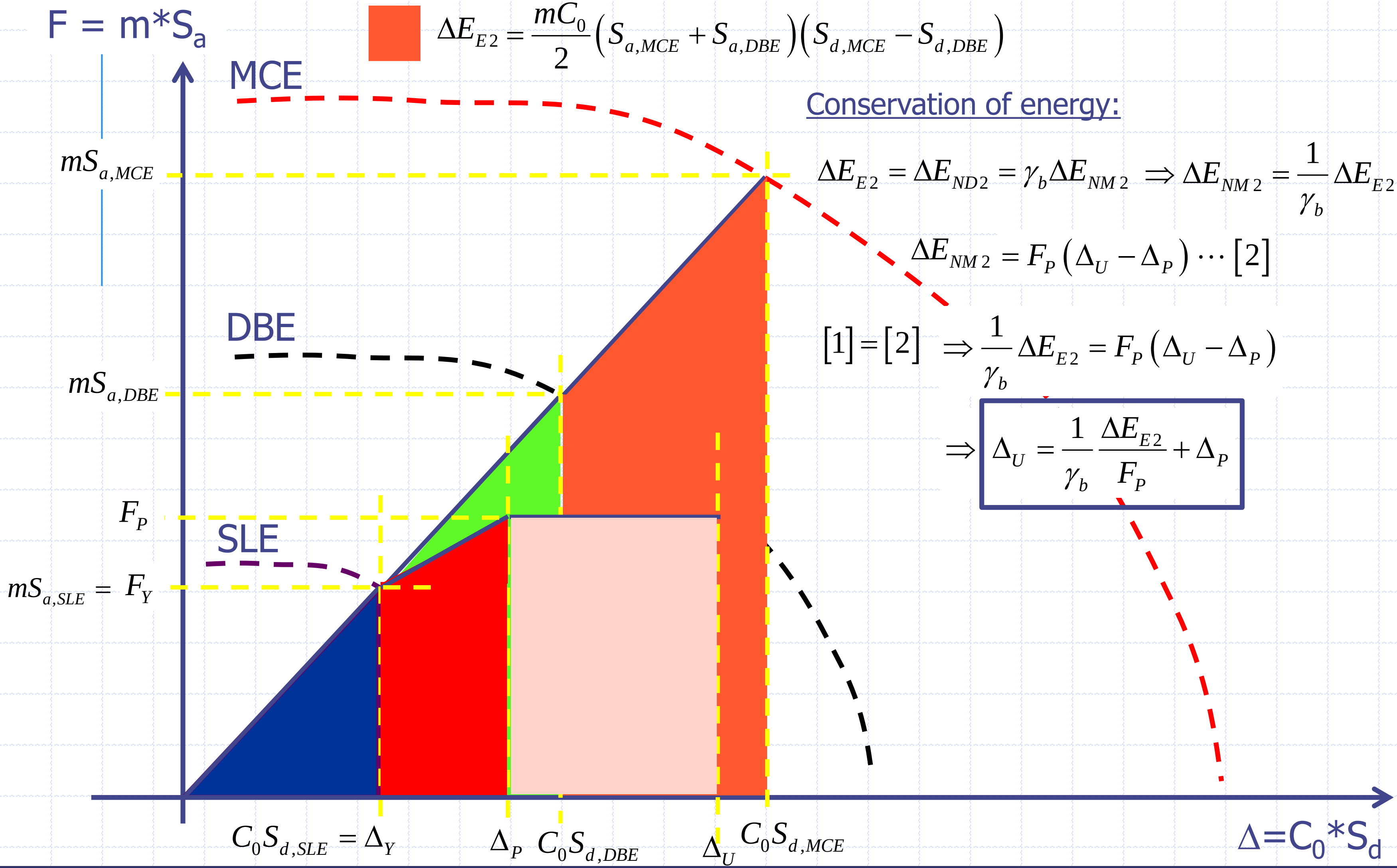
Conservation of energy:

$$\Delta E_{E2} = \Delta E_{ND2} = \gamma_b \Delta E_{NM2} \Rightarrow \Delta E_{NM2} = \frac{1}{\gamma_b}\Delta E_{E2} \cdots [1]$$

$$\Delta E_{NM2} = F_P\left(\Delta_U - \Delta_P\right) \cdots [2]$$

$$[1] = [2] \Rightarrow \frac{1}{\gamma_b}\Delta E_{E2} = F_P\left(\Delta_U - \Delta_P\right)$$

$$\Rightarrow \Delta_U = \frac{1}{\gamma_b}\frac{\Delta E_{E2}}{F_P} + \Delta_P$$



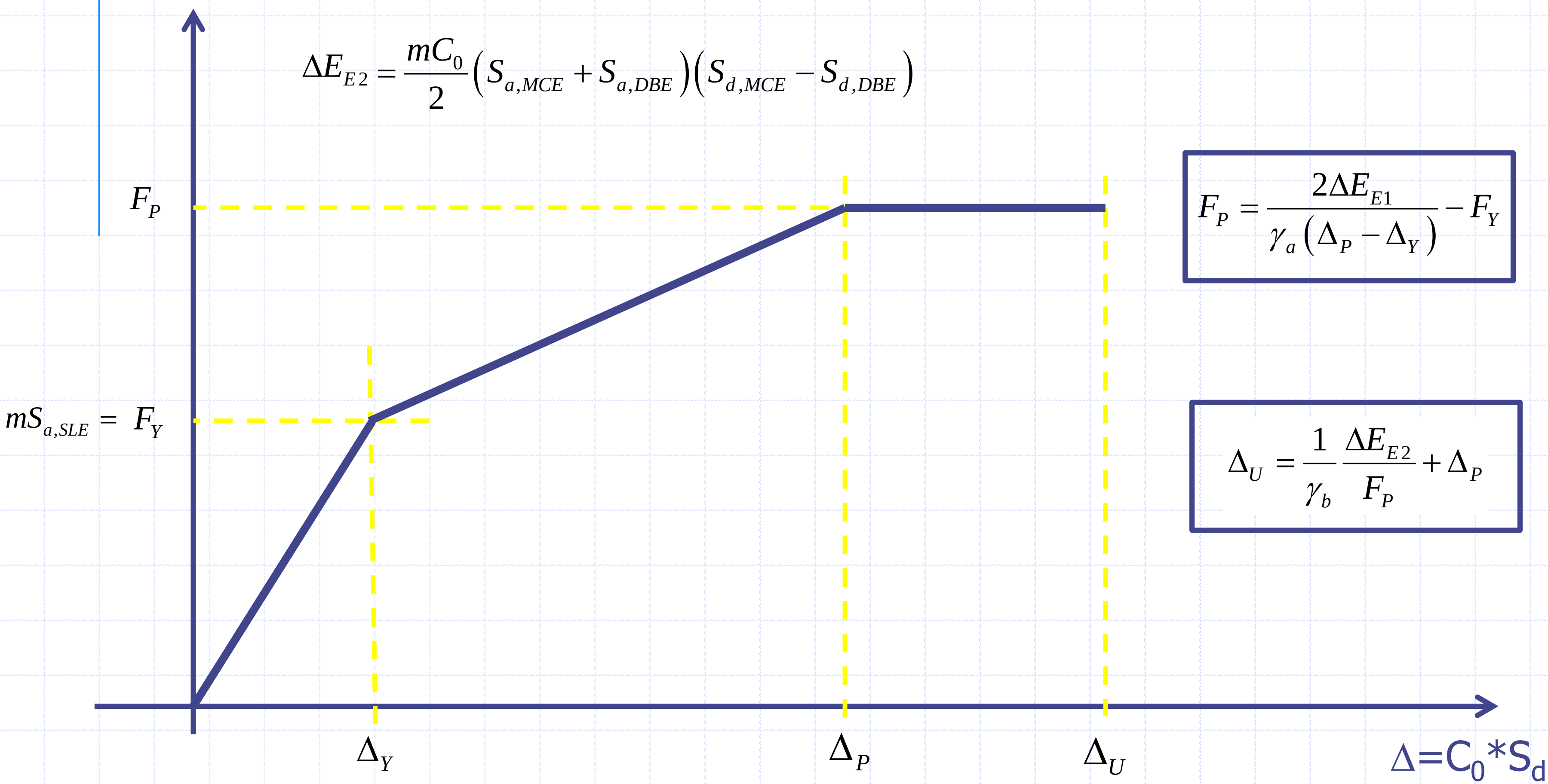
Equivalent energy design procedure

- 2.0: Calculate the base shear:

F = m*S$_a$

$$\Delta E_{E1} = \frac{m}{2}\left(S_{a,SLE} + S_{a,DBE}\right)\left(C_0 S_{d,DBE} - \Delta_Y\right)$$

$$\Delta E_{E2} = \frac{mC_0}{2}\left(S_{a,MCE} + S_{a,DBE}\right)\left(S_{d,MCE} - S_{d,DBE}\right)$$



$$F_P = \frac{2\Delta E_{E1}}{\gamma_a\left(\Delta_P - \Delta_Y\right)} - F_Y$$

$$\Delta_U = \frac{1}{\gamma_b}\frac{\Delta E_{E2}}{F_P} + \Delta_P$$

Equivalent energy design procedure

- 3.0: Distribute the base shear:

F = m*Sa

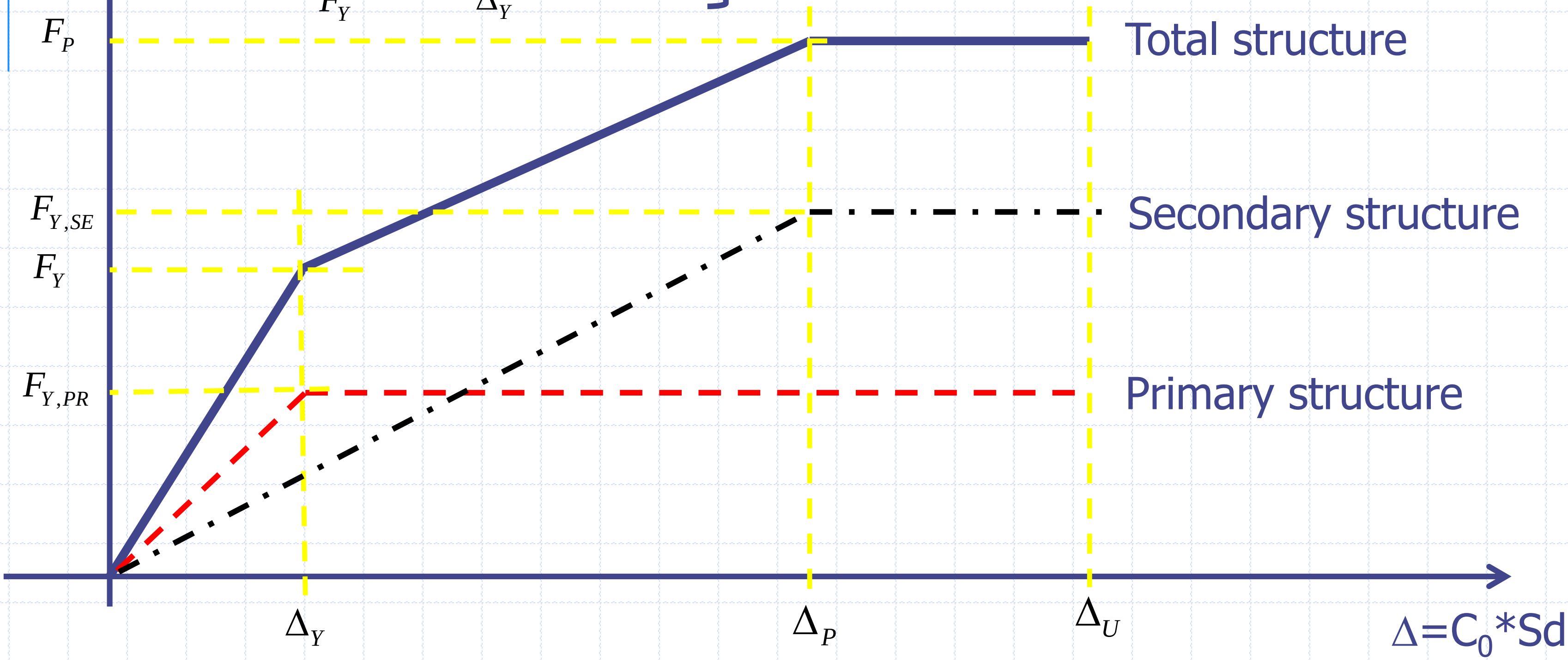
$$F_{Y,PR} + F_{Y,SE}\left(\frac{\Delta_Y}{\Delta_P}\right) = F_Y \quad \cdots [1]$$

$$F_{Y,PR} + F_{Y,SE} = F_P \quad \cdots [2]$$

$$\text{Let } \lambda = \frac{F_P}{F_Y}; \qquad \mu = \frac{\Delta_P}{\Delta_Y};$$

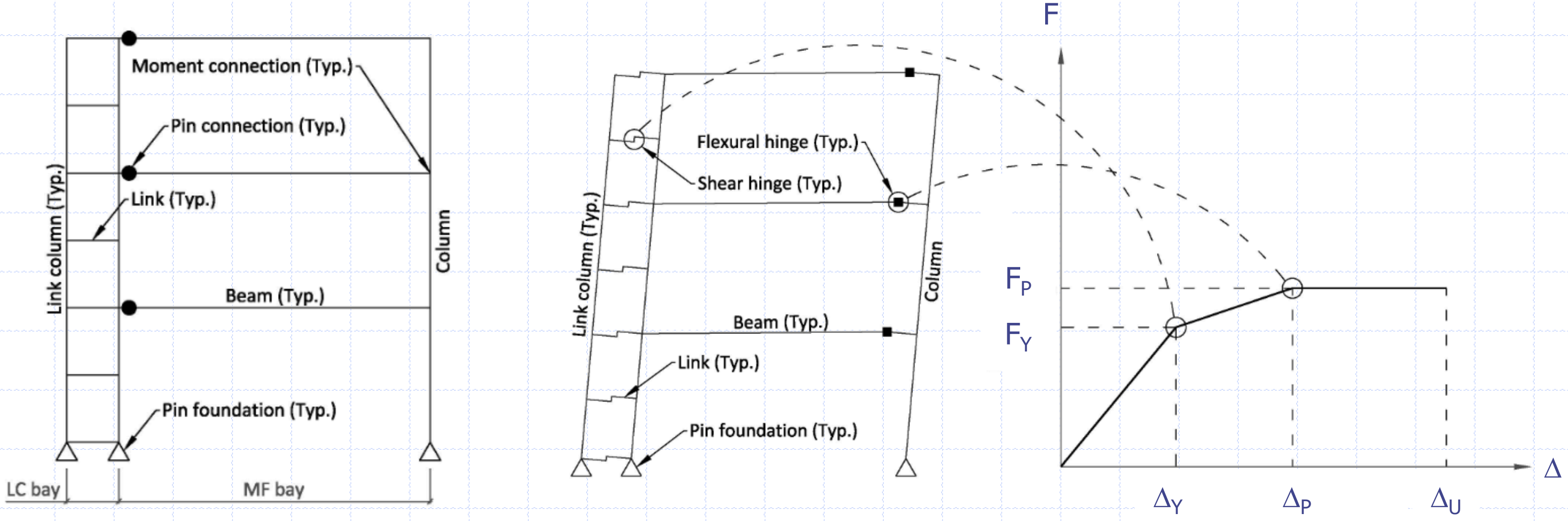
$$\Rightarrow F_{Y,PR} = F_Y \frac{(\lambda - \mu)}{(1-\mu)}$$

$$\Rightarrow F_{Y,SE} = \frac{(1-\lambda)\mu F_Y}{(1-\mu)}$$



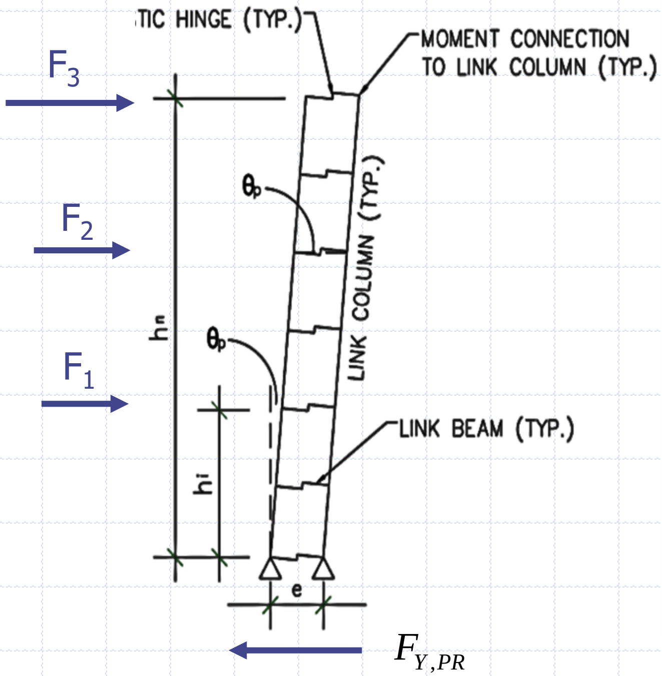
Equivalent energy design procedure

- 4.0: Select the plastic mechanism (system dependent):



Equivalent energy design procedure

- 6.0: Size the yielding elements: Link beams in LC bays



$$W_{ext} = \sum_{i=1}^{n} F_{link,i}\left(h_i\theta_p\right)$$

$$W_{\text{int}} = 2\sum_{i=1}^{n} \beta_i V_{pr}\left(e\theta_p\right) + \beta_1 V_{pr}\left(e\theta_p\right)$$

$$W_{ext} = W_{\text{int}} \Rightarrow \theta_p \sum_{i=1}^{n} F_{link,i} h_i = V_{pr} e\theta_p \left(2\sum_{i=1}^{n}\beta_i + \beta_1\right)$$

$$V_{pr} = \frac{\sum_{i=1}^{n} F_{link,i} h_i}{e\left(2\sum_{i=1}^{n}\beta_i + \beta_1\right)}$$ ← Shear demand at roof

$$V_{pi} = \beta_i V_{pr}$$ ← Shear demand at i[th] floor

Assume no gravity load on LC bay!

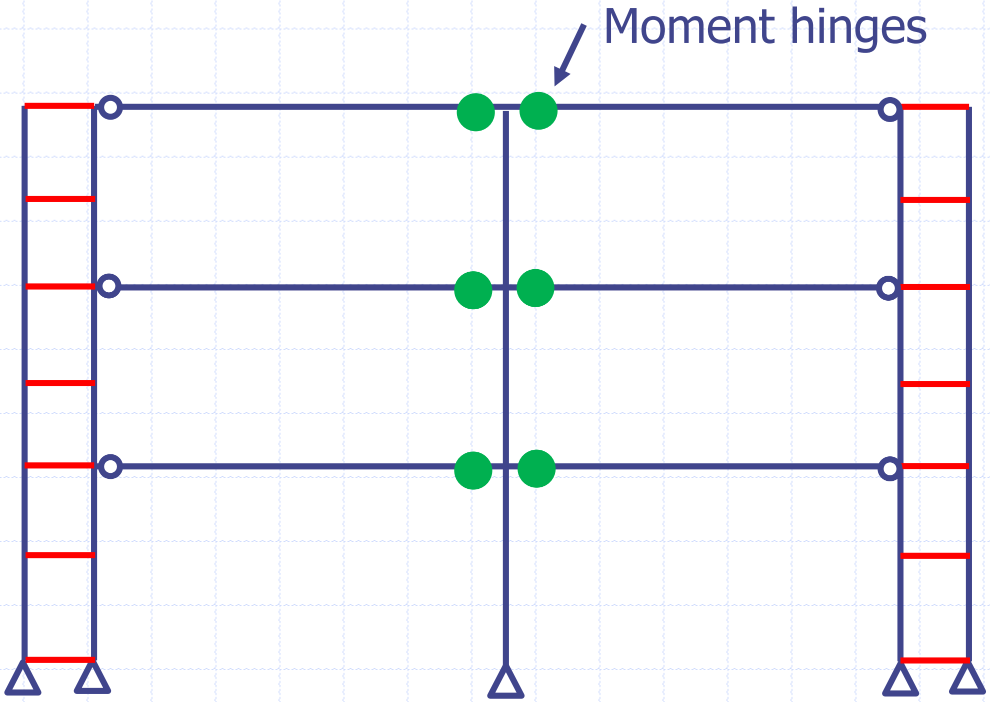
Capacity $$V_{pi,capacity} = \phi 0.6 F_y d_b t_w \geq \beta_i V_{pr}$$

Check the link is shear controlled: $1.5 V_{pi,capacity} \leq 2\frac{1.2 M_{pi}}{e}$

Strength hardening

Equivalent energy design procedure

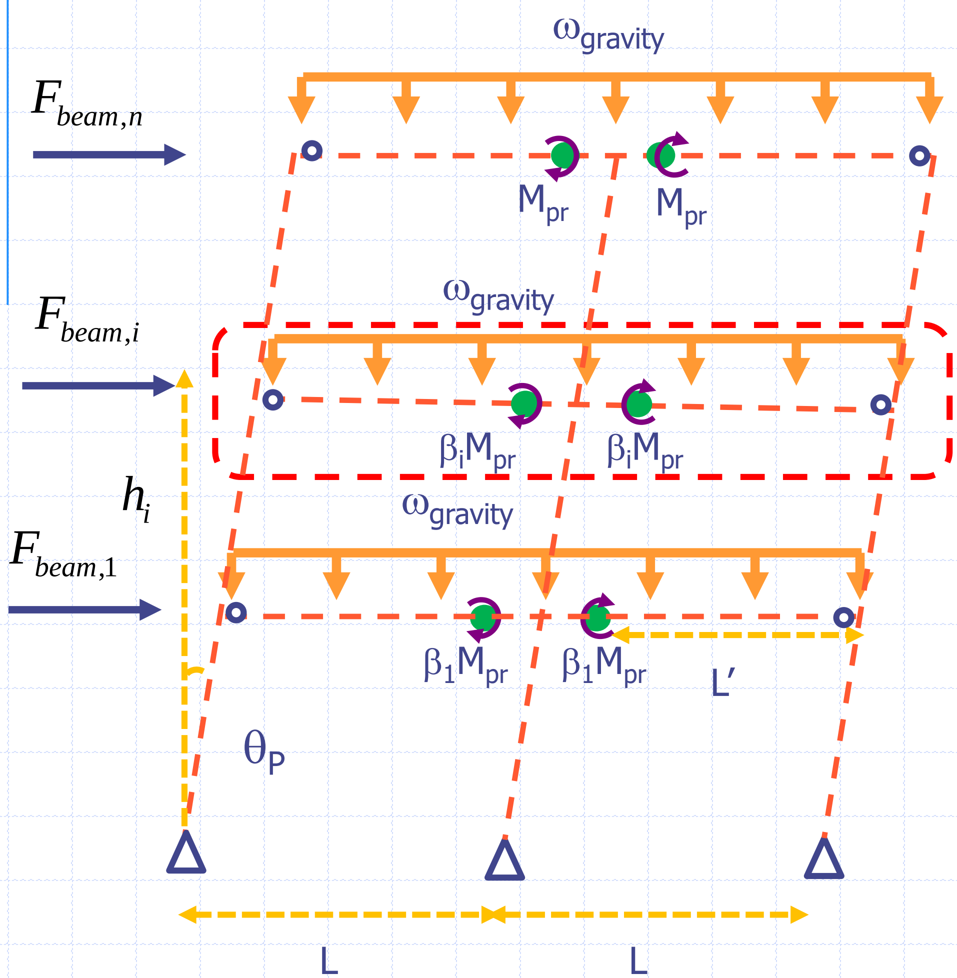
- 6.0: Size the yielding elements: Beam hinges in MF bays



Equivalent energy design procedure

- 6.0: Size the yielding elements: Beam hinges in MF bays

Plastic mechanism



$$W_{ext} = \sum_{i=1}^{n} F_{beam,i}\left(h_i\theta_p\right)$$

$$W_{\text{int}} = \sum_{i=1}^{n} \beta_i M_{pr}\frac{L}{L'}\theta_p$$

$$W_{ext} = W_{\text{int}}$$

$$\Rightarrow \theta_p \sum_{i=1}^{n} F_{beam,i}h_i = \sum_{i=1}^{n} \beta_i M_{pr}\frac{L}{L'}\theta_p$$

Moment demand at roof

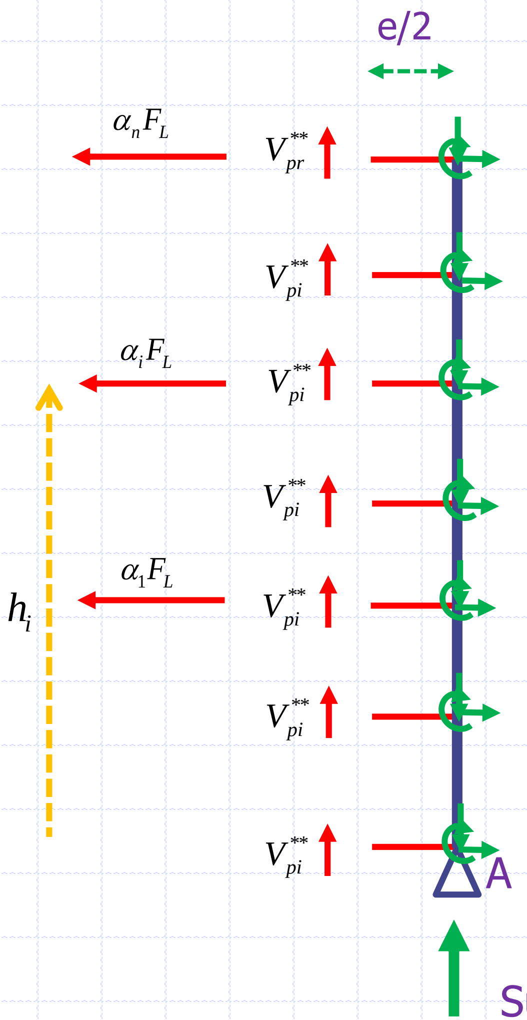
$$\Rightarrow M_{pr} = \frac{\sum_{i=1}^{n} F_{beam,i}h_i}{\frac{L}{L'}\sum_{i=1}^{n}\beta_i}$$

Moment demand at ith floor

$$M_{pi} = \beta_i M_{pr}$$

Equivalent energy design procedure

- 7.0: Capacity design the non-yielding elements: (Exterior column in LC bays)



The column tree is not in equilibrium ➔ need to find the "equivalent" lateral force profile to keep the column in equilibrium.

$$\sum M_A = 0 \Rightarrow \sum_{i=1}^{n} \alpha_i h_i F_L = \frac{e}{2} V_{pr}^{**} \left(2\sum_{i=1}^{n} \beta_i + \beta_1 \right)$$

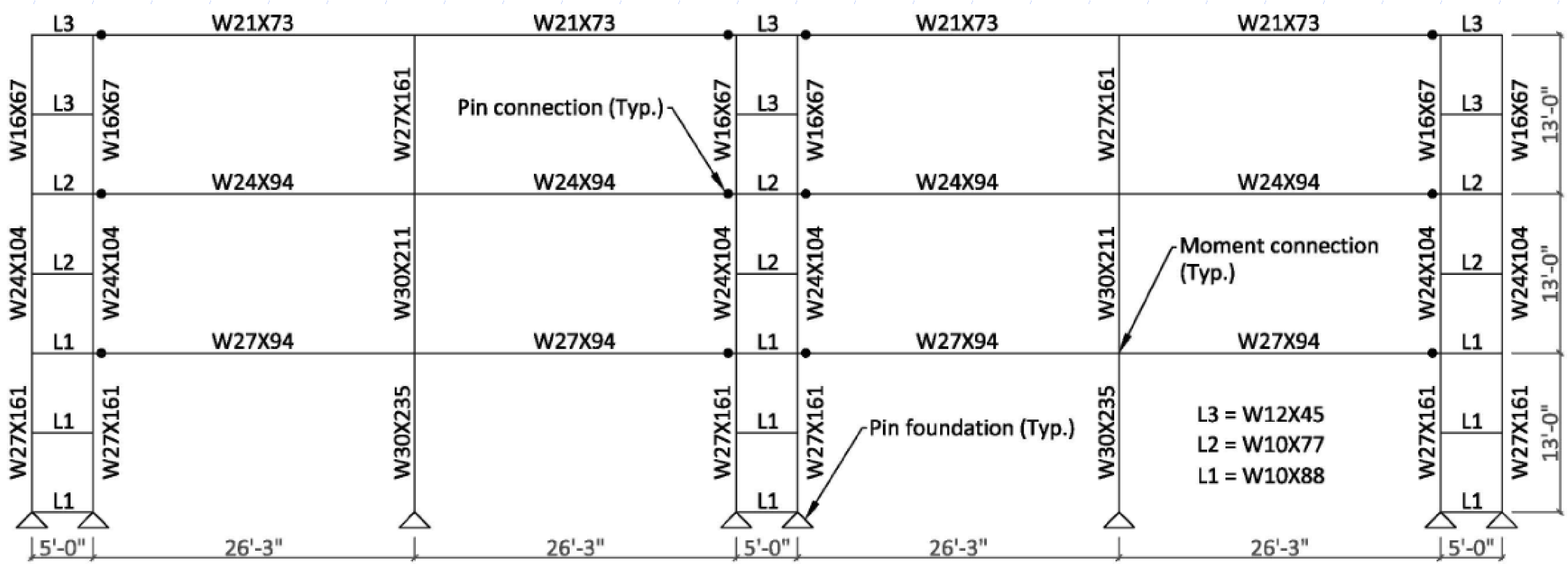
$$\Rightarrow F_L = \frac{\frac{e}{2} V_{pr}^{**} \left(2\sum_{i=1}^{n} \beta_i + \beta_1 \right)}{\sum_{i=1}^{n} \alpha_i h_i}$$

$$\Rightarrow \alpha_i = \frac{(\beta_i - \beta_{i+1})}{\sum_{i=1}^{n} (\beta_i - \beta_{i+1})}; \text{ When } i = n, \beta_{n+1} = 0;$$

Support needed to be capacity designed.

Prototype building

- 3-storey LCF building designed using EEDP



Prototype building

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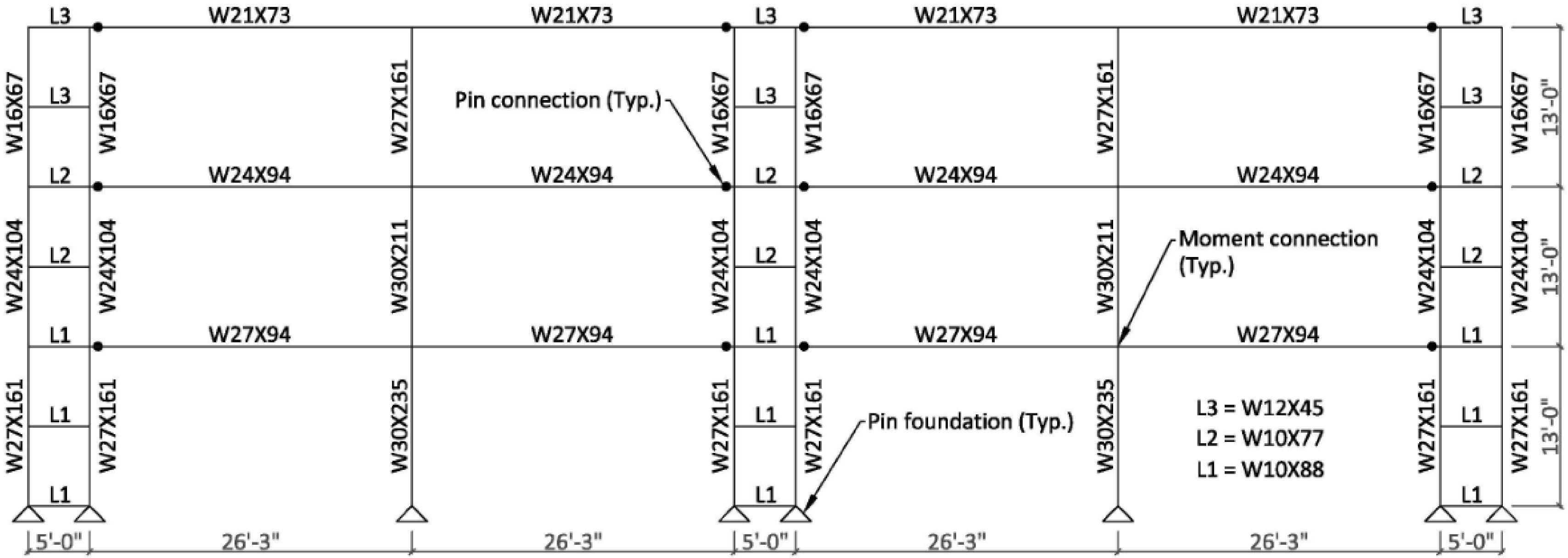
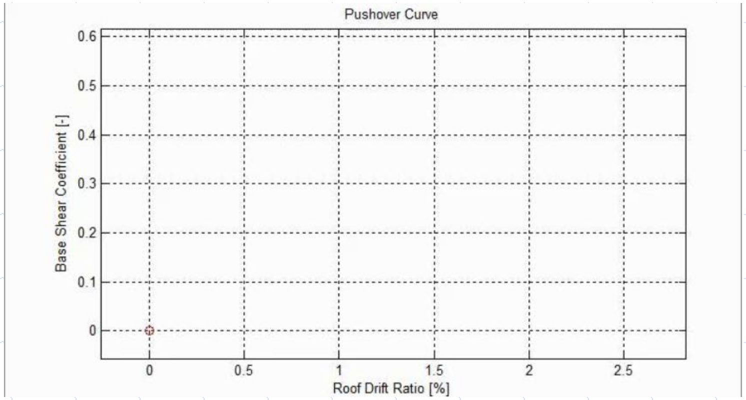
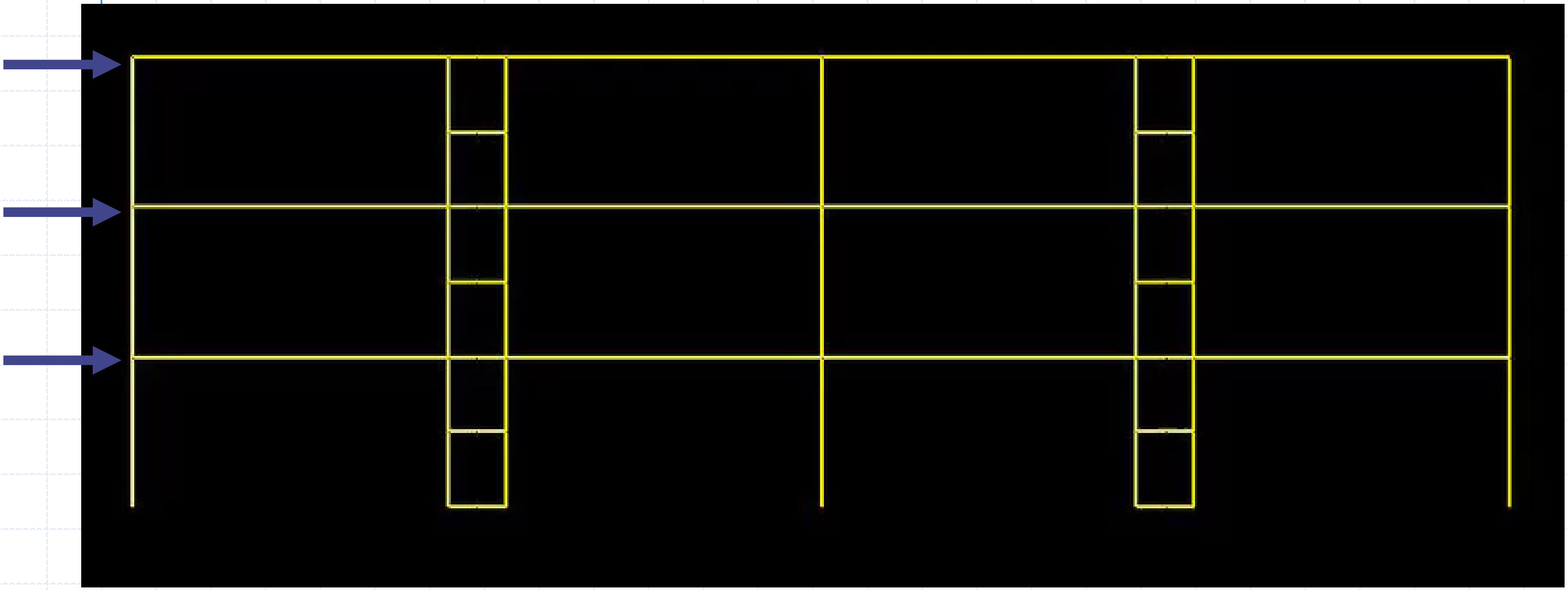


High-performance structures

Steel Linked Column Frame

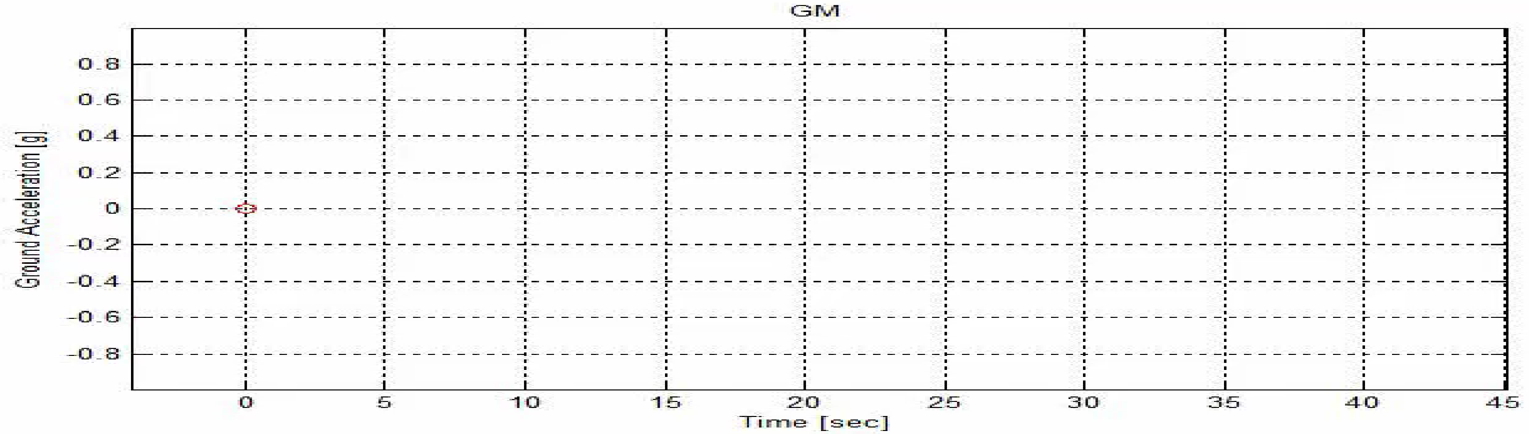
$\Delta_y = 0.5$; $\Delta_p = 2.0$;

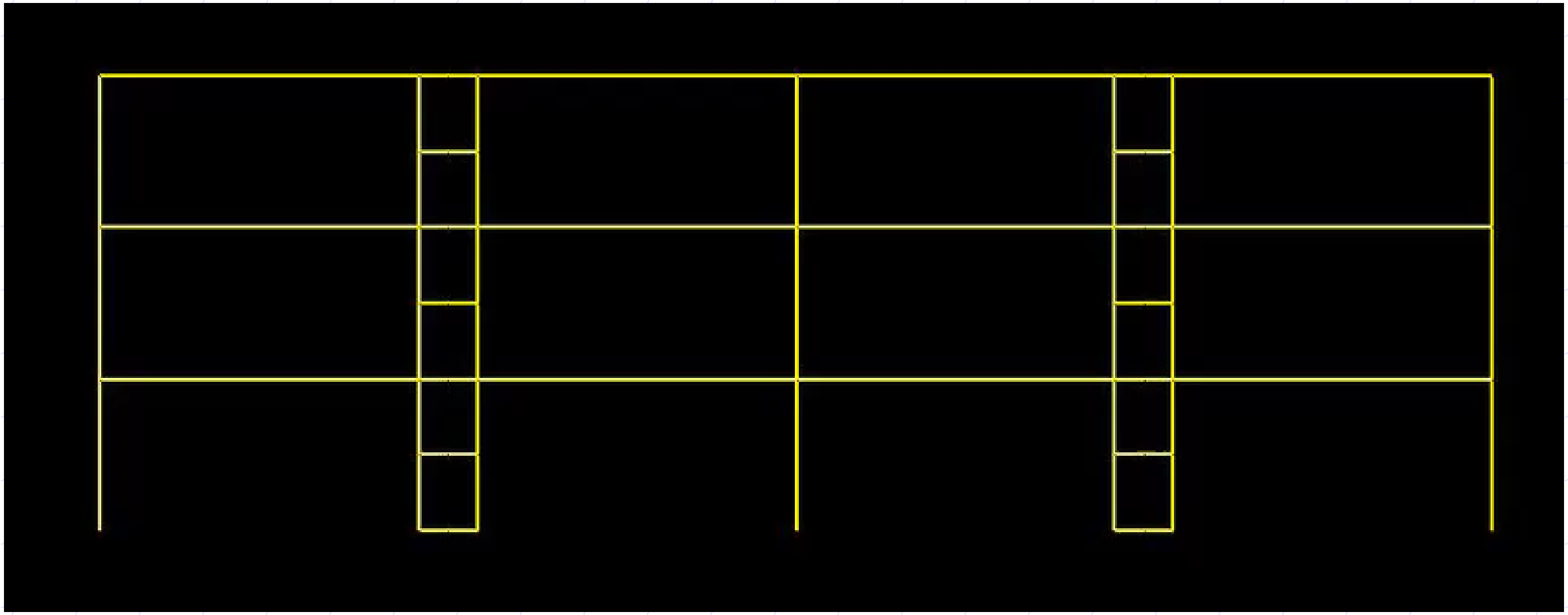




High-performance structures

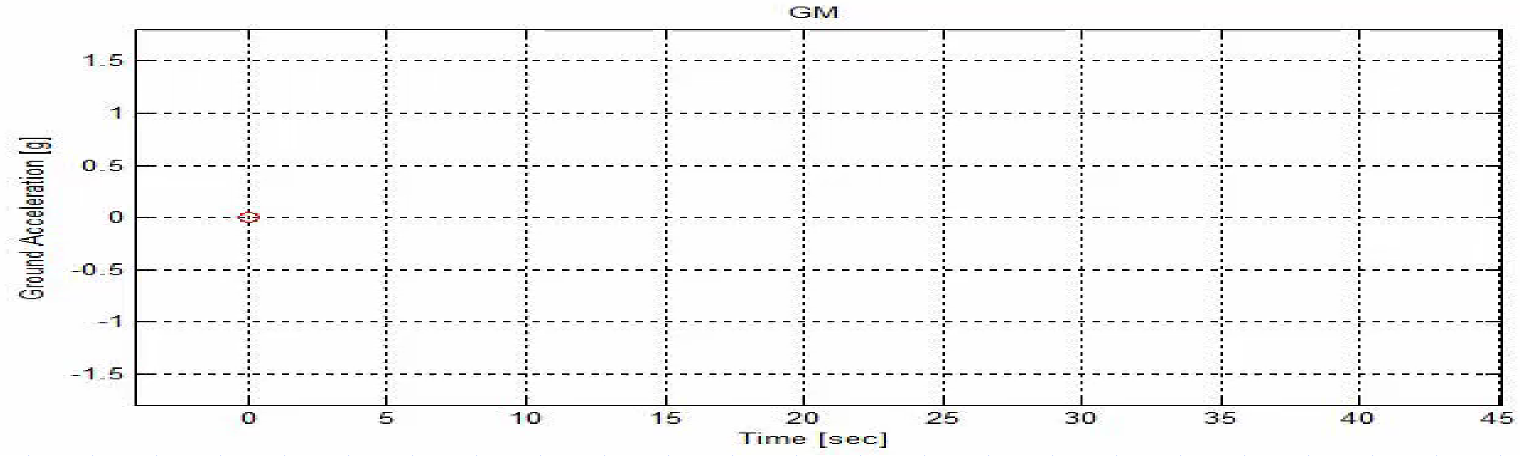
Steel Linked Column Frame (DBE → IO)

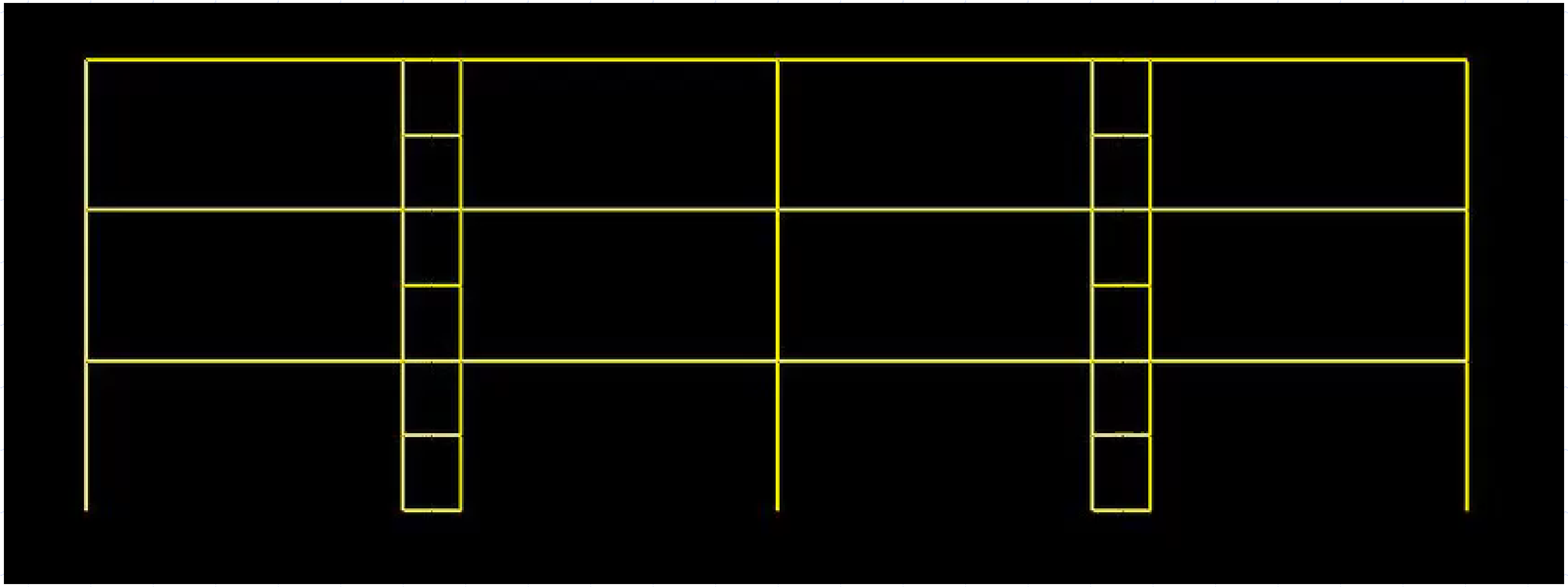




High-performance structures

Steel Linked Column Frame (MCE → CP)

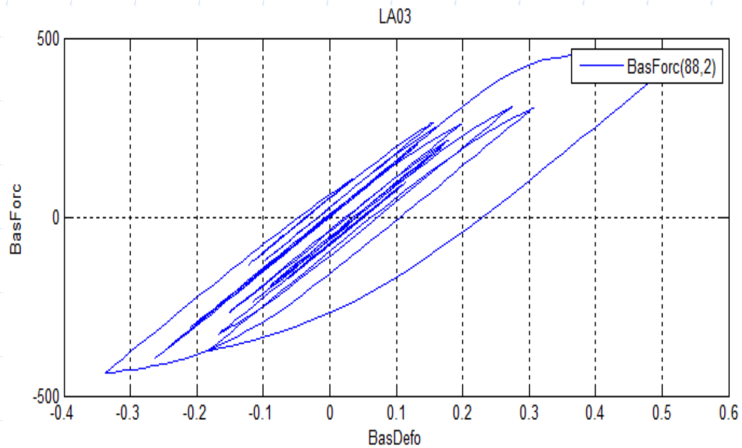




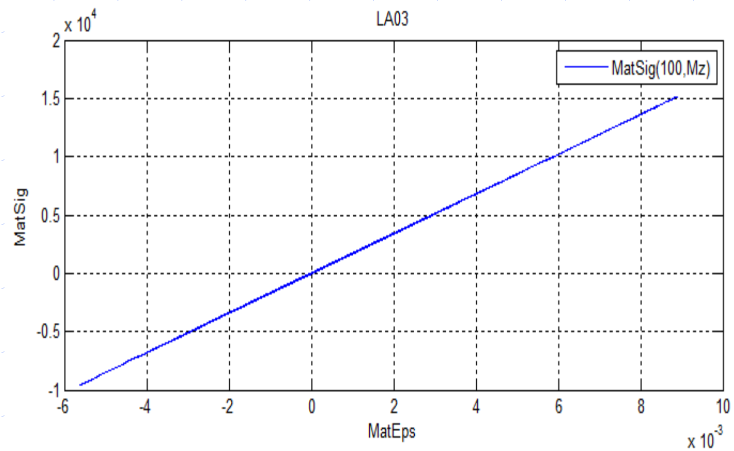
High-performance structures

DBE:

LC

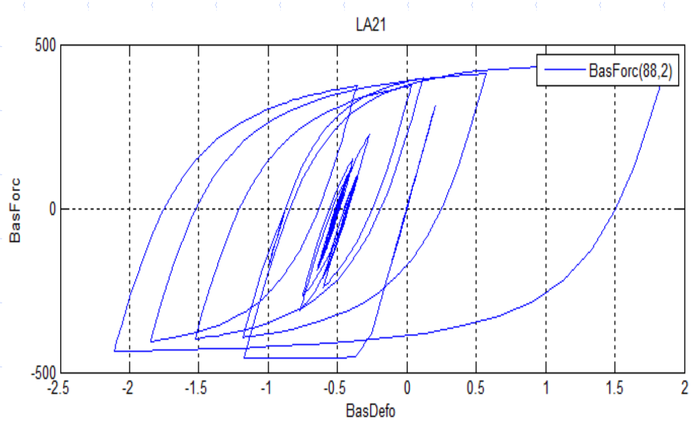


MF

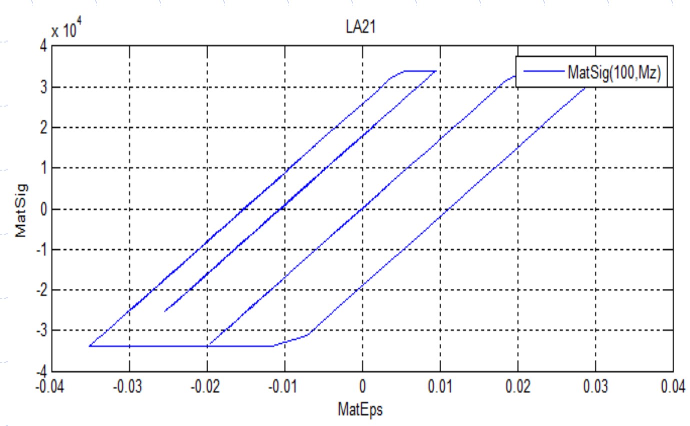


MCE:

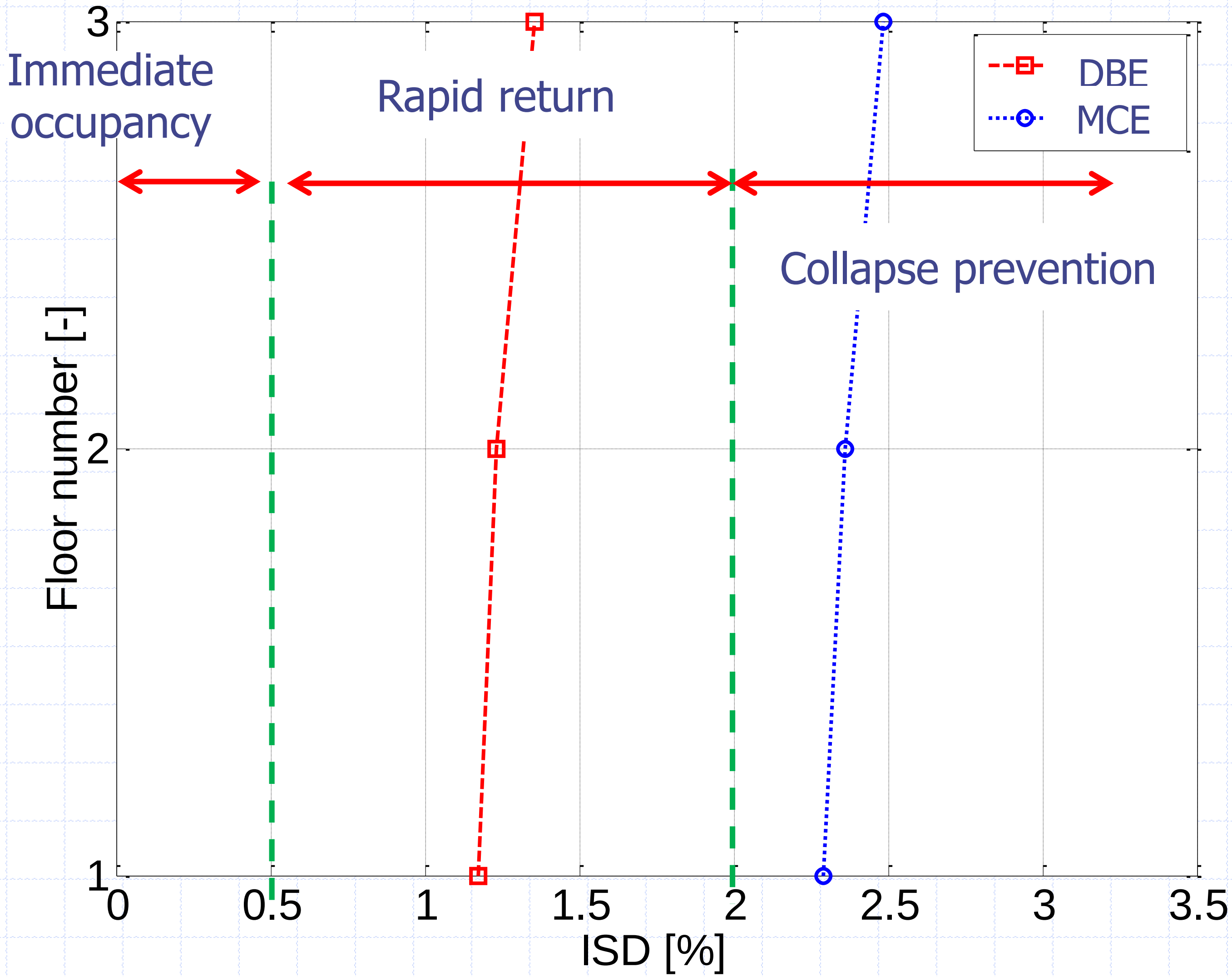
LC



MF

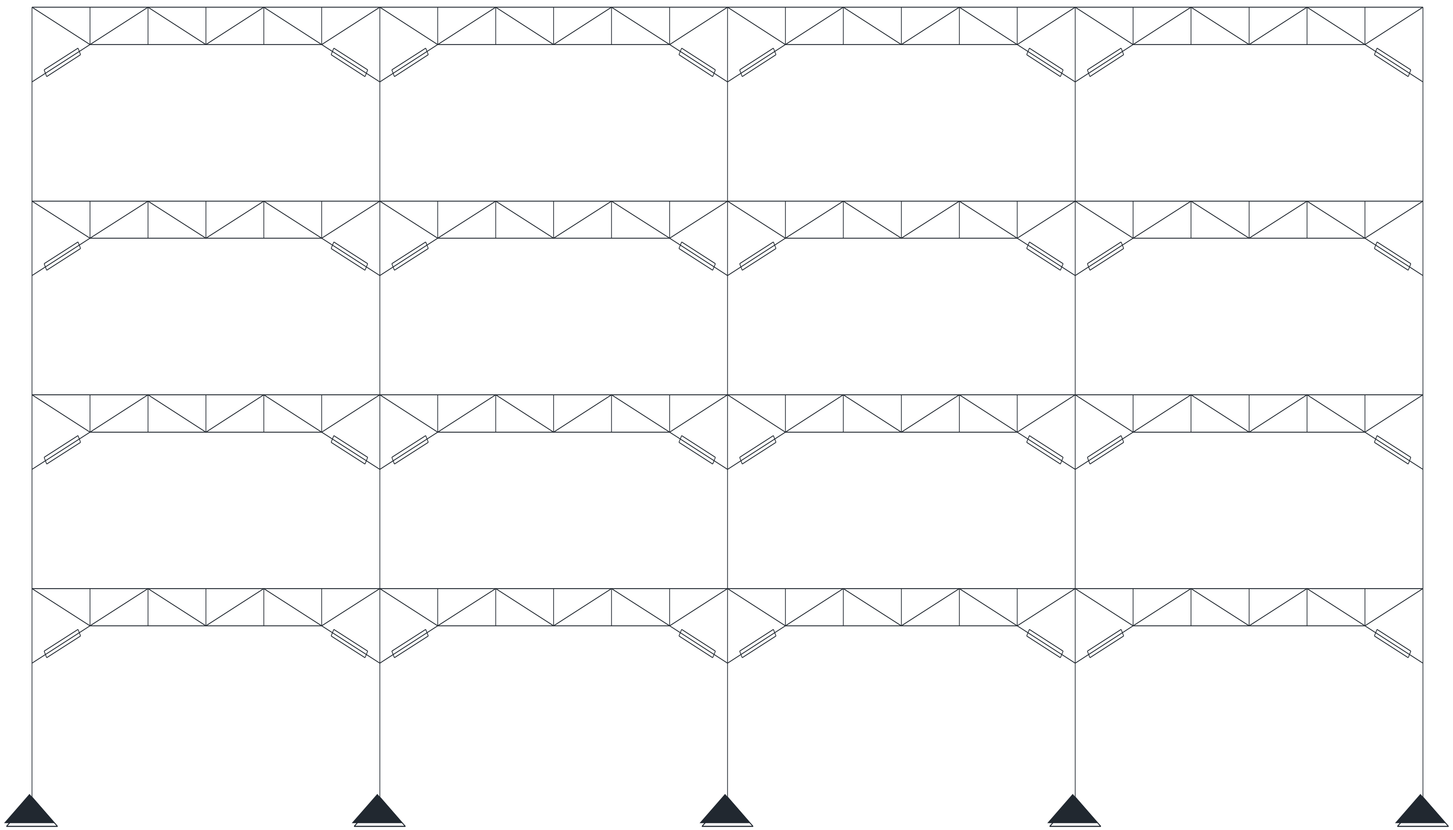


High-performance structures



High-performance structures

Buckling Restrained Knee Braced Truss MF (BRKBTMF):



UBC | Univ. of Michigan | King Mongkut's Univ. of Tech. | IIT, Kanpur

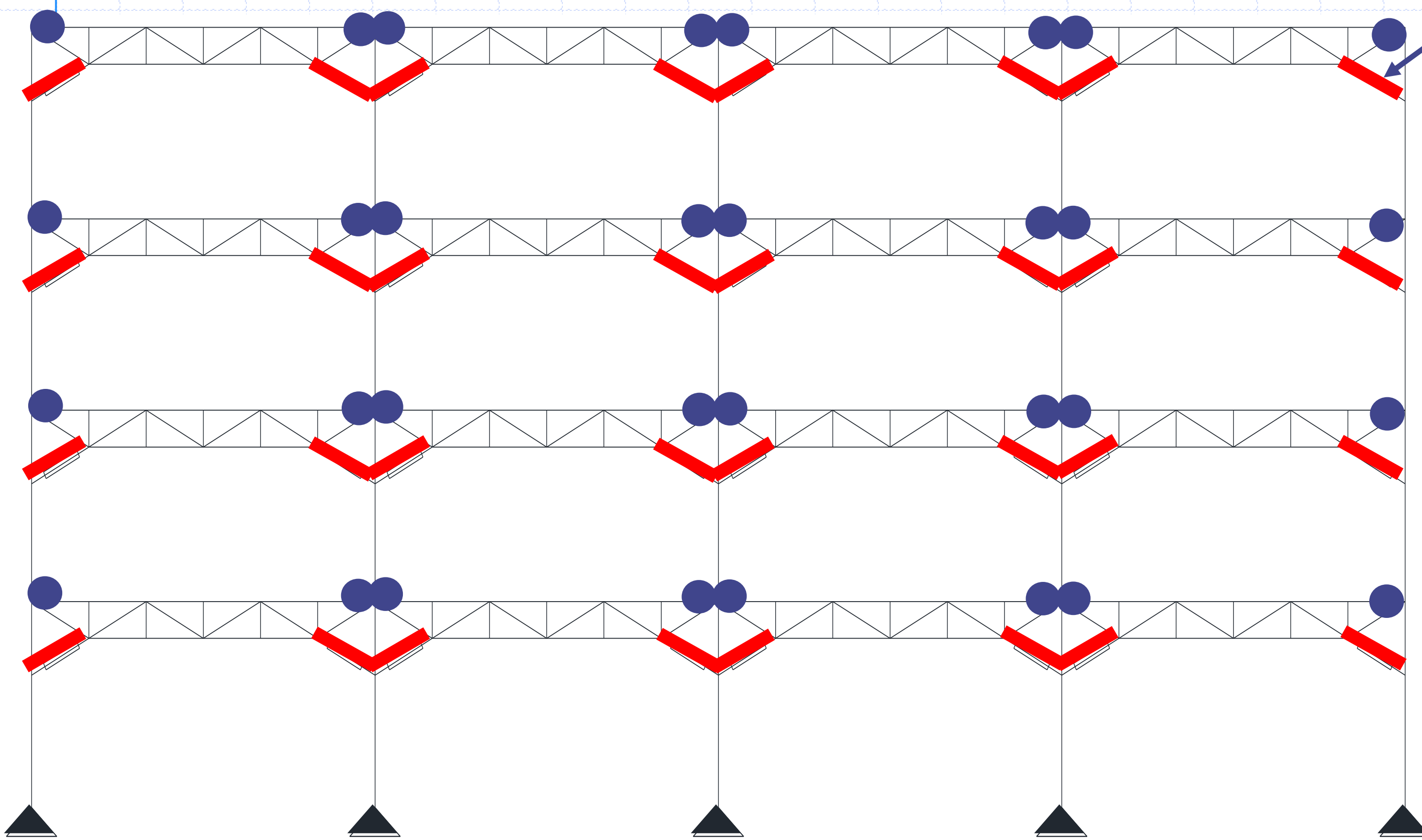
High-performance structures

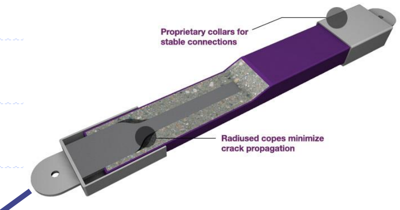
Buckling Restrained Knee Braced Truss MF (BRKBTMF):

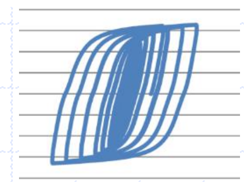
UBC | Univ. of Michigan | King Mongkut's Univ. of Tech. | IIT, Kanpur

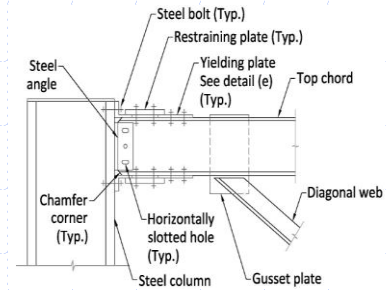
High-performance structures

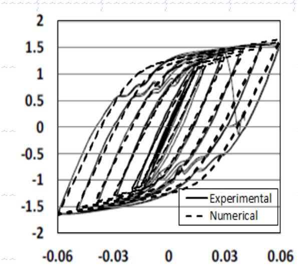
Buckling Restrained Knee Braced Truss MF (BRKBTMF):











UBC

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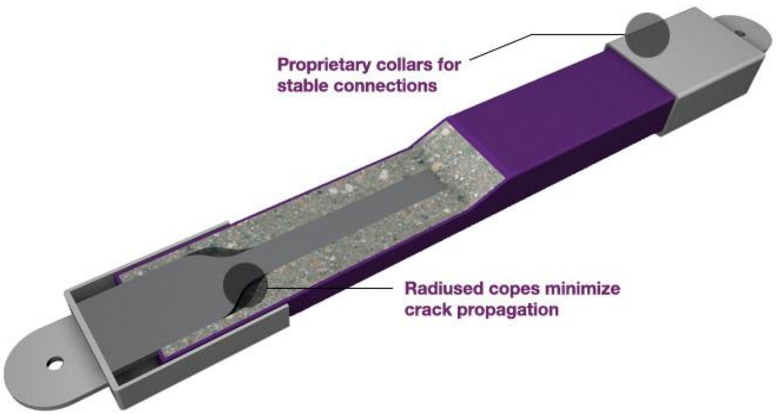
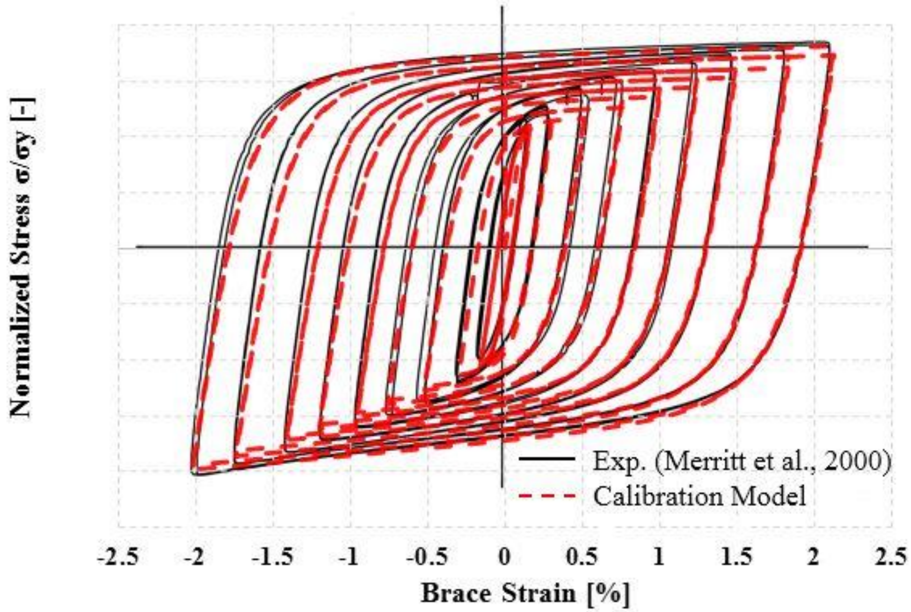
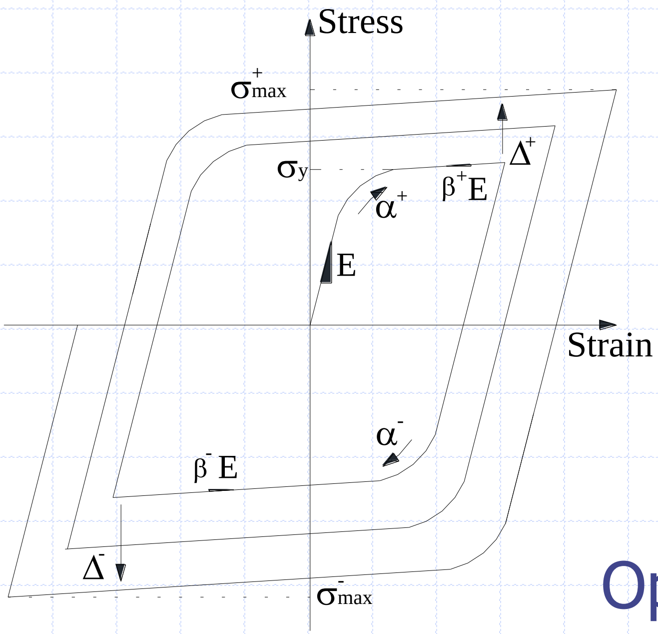
IIT, Kanpur

Force-deformation response of BRB



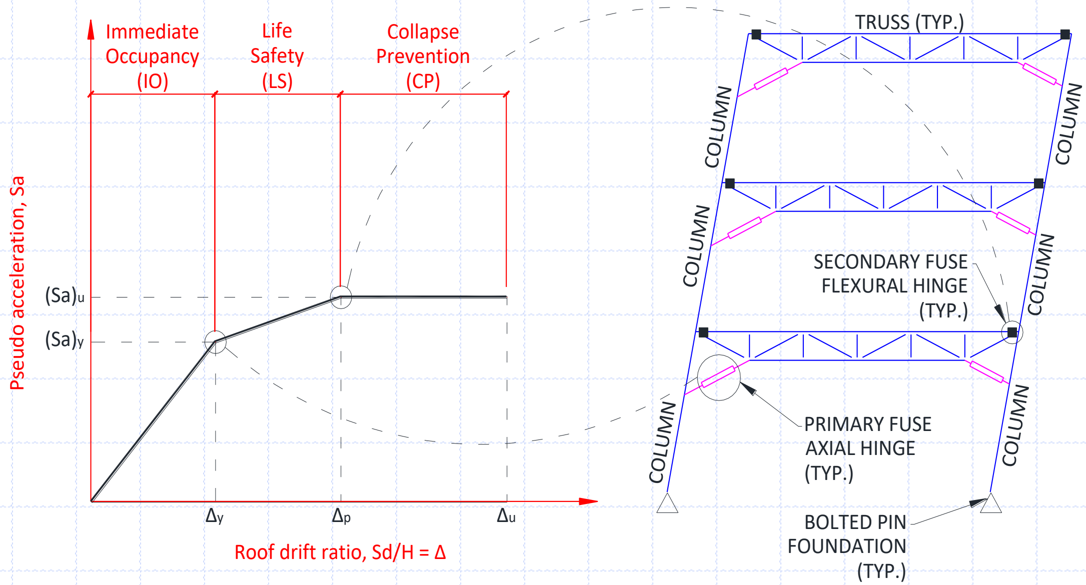




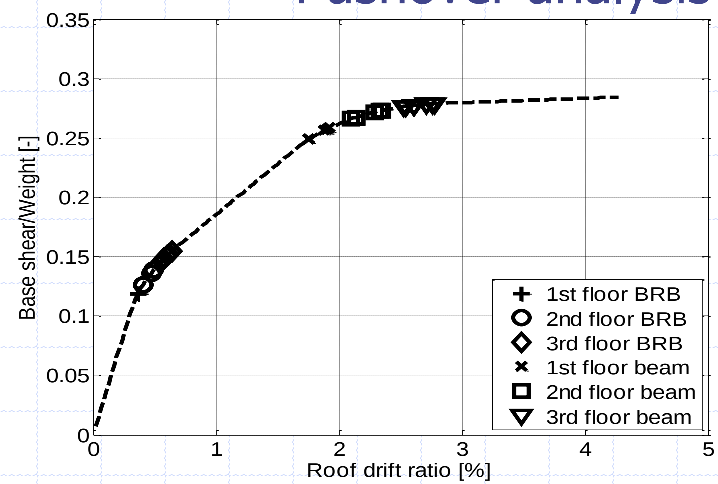
OpenSees model

High-performance structures

Lateral System – multiple performance objectives

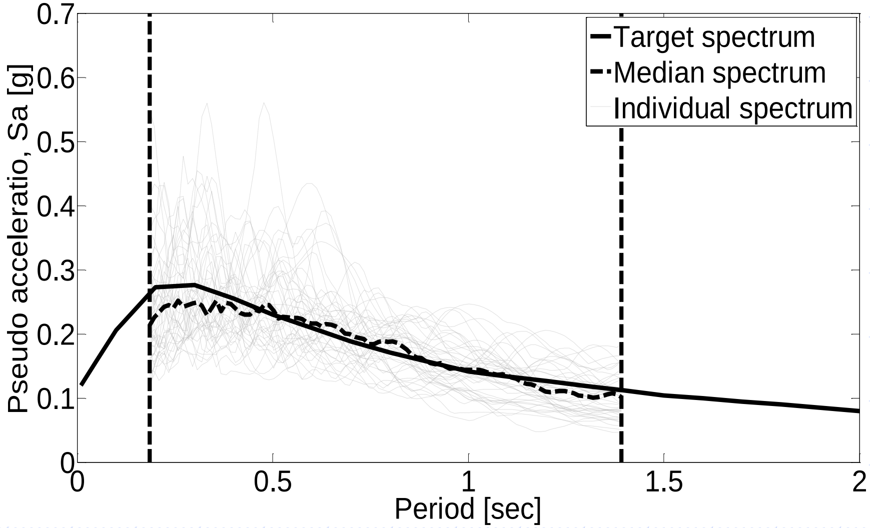


Pushover analysis



High-performance structures

SLE



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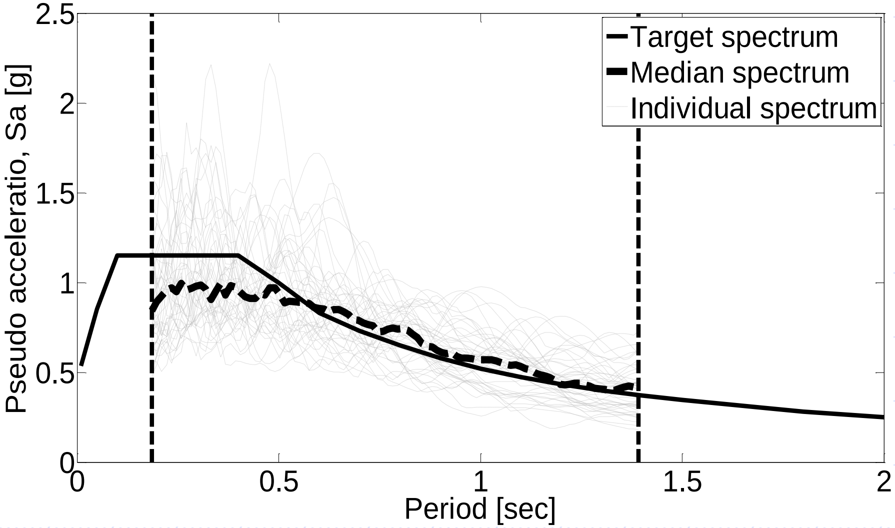

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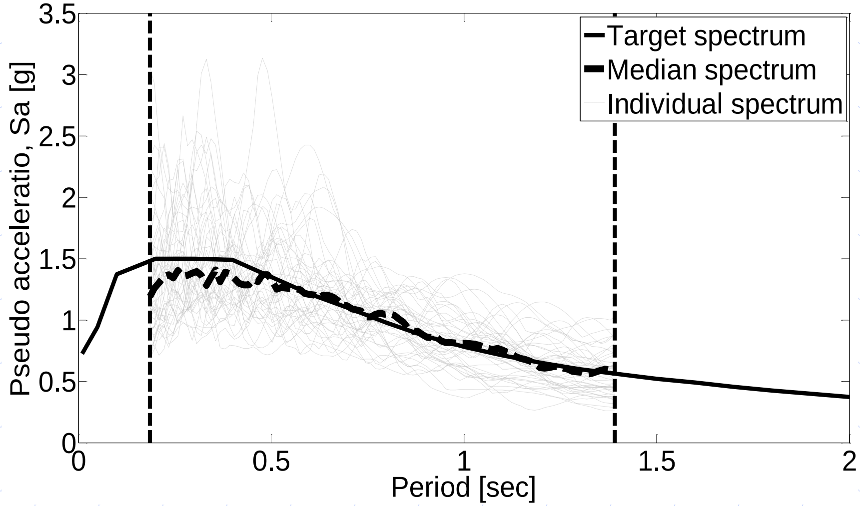
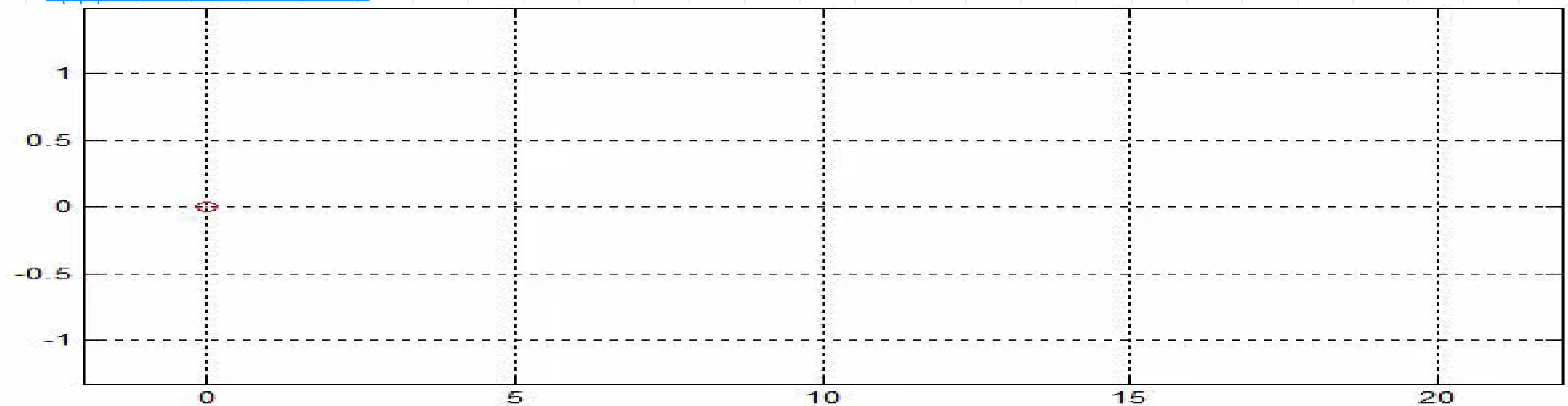
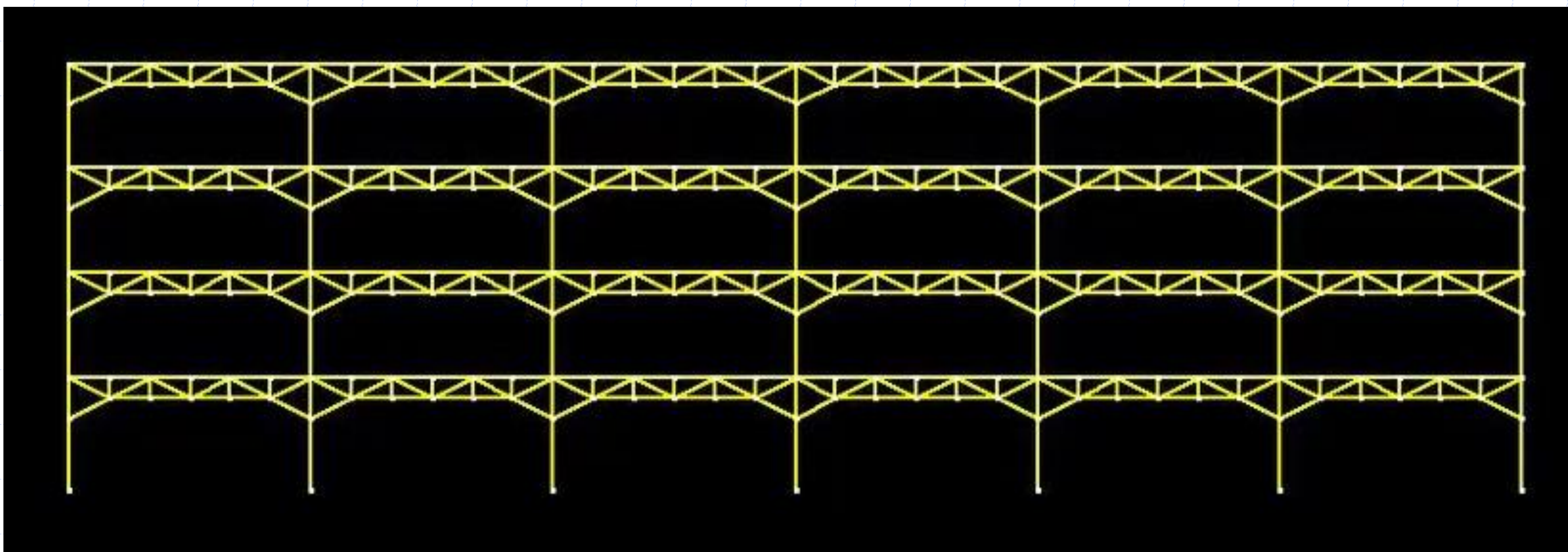
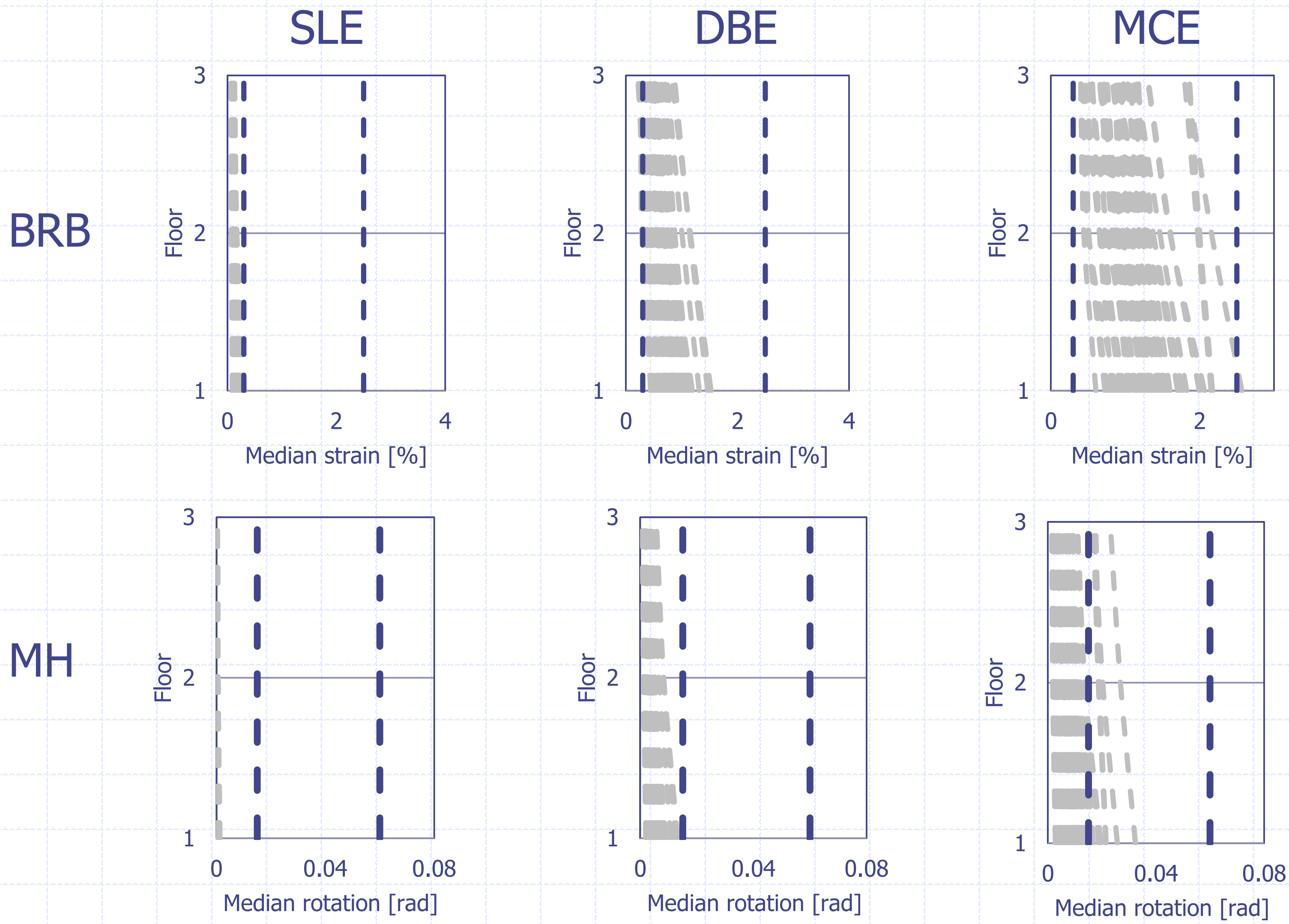


Dynamic response



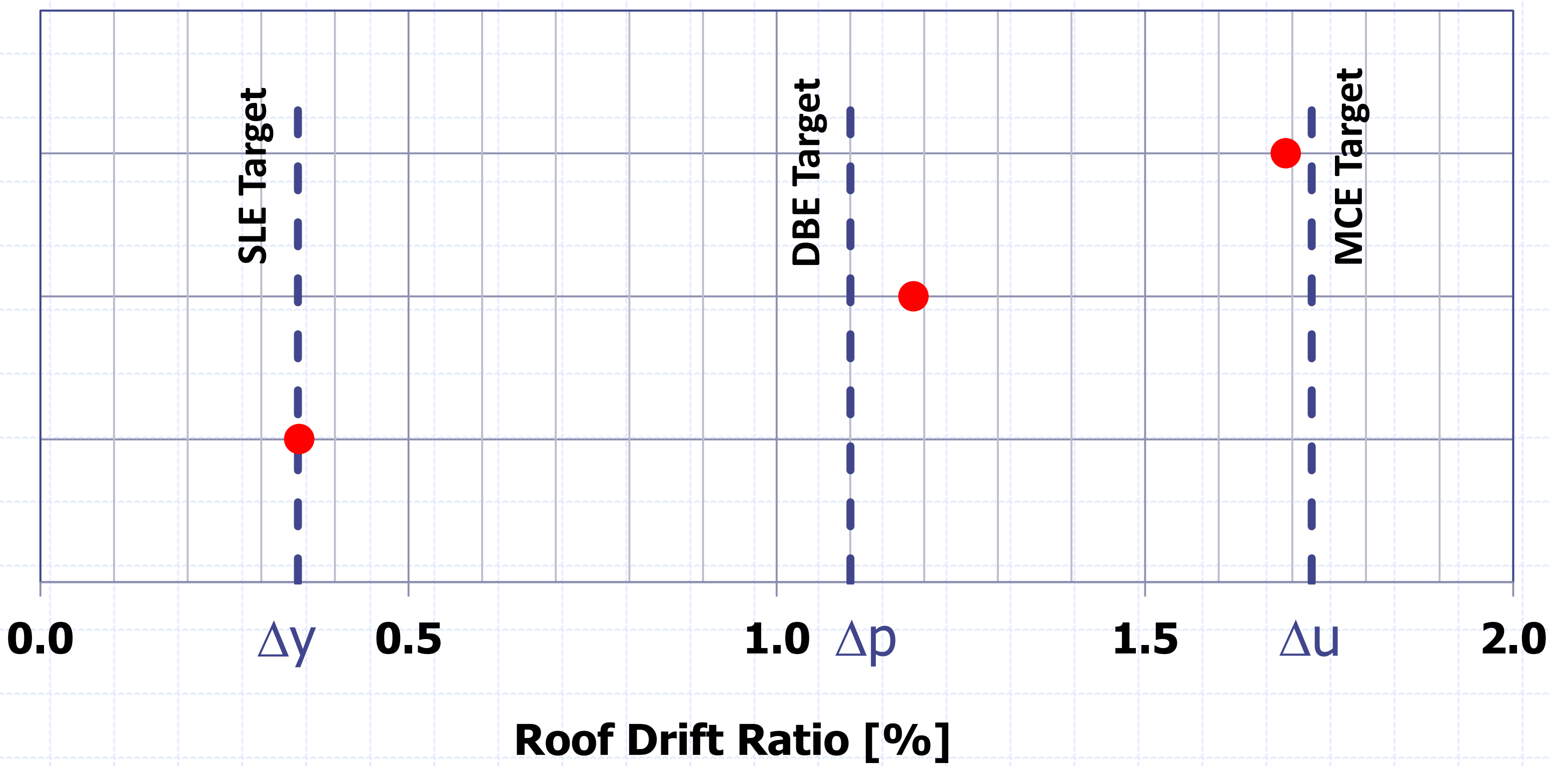


High-performance structures



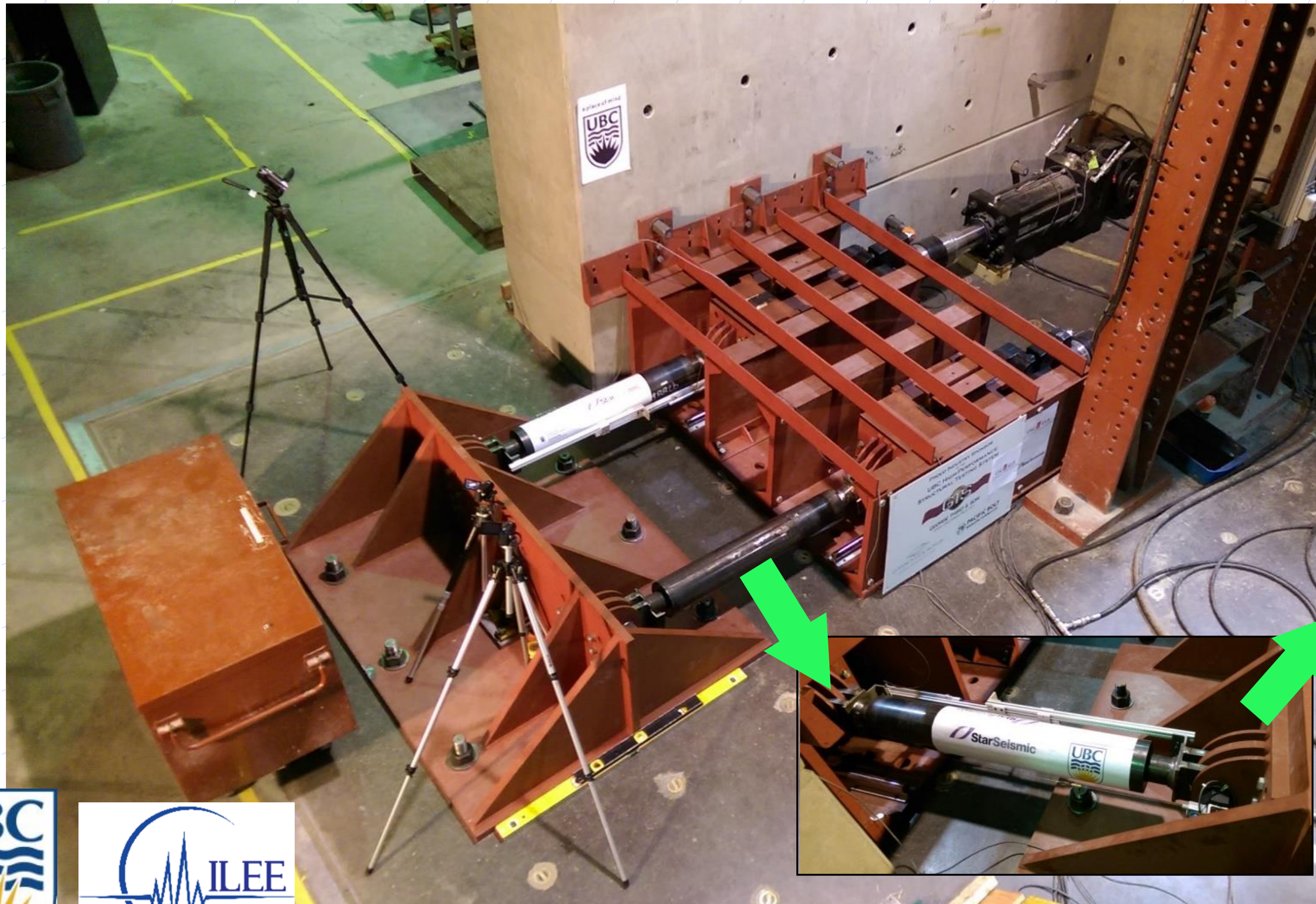
High-performance structures

Lateral System – multiple performance objectives

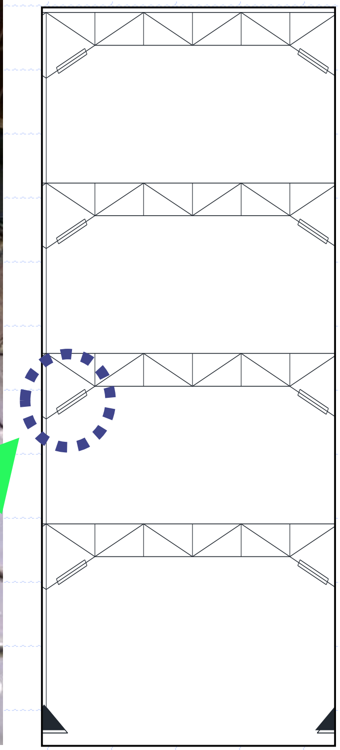


High-performance structures

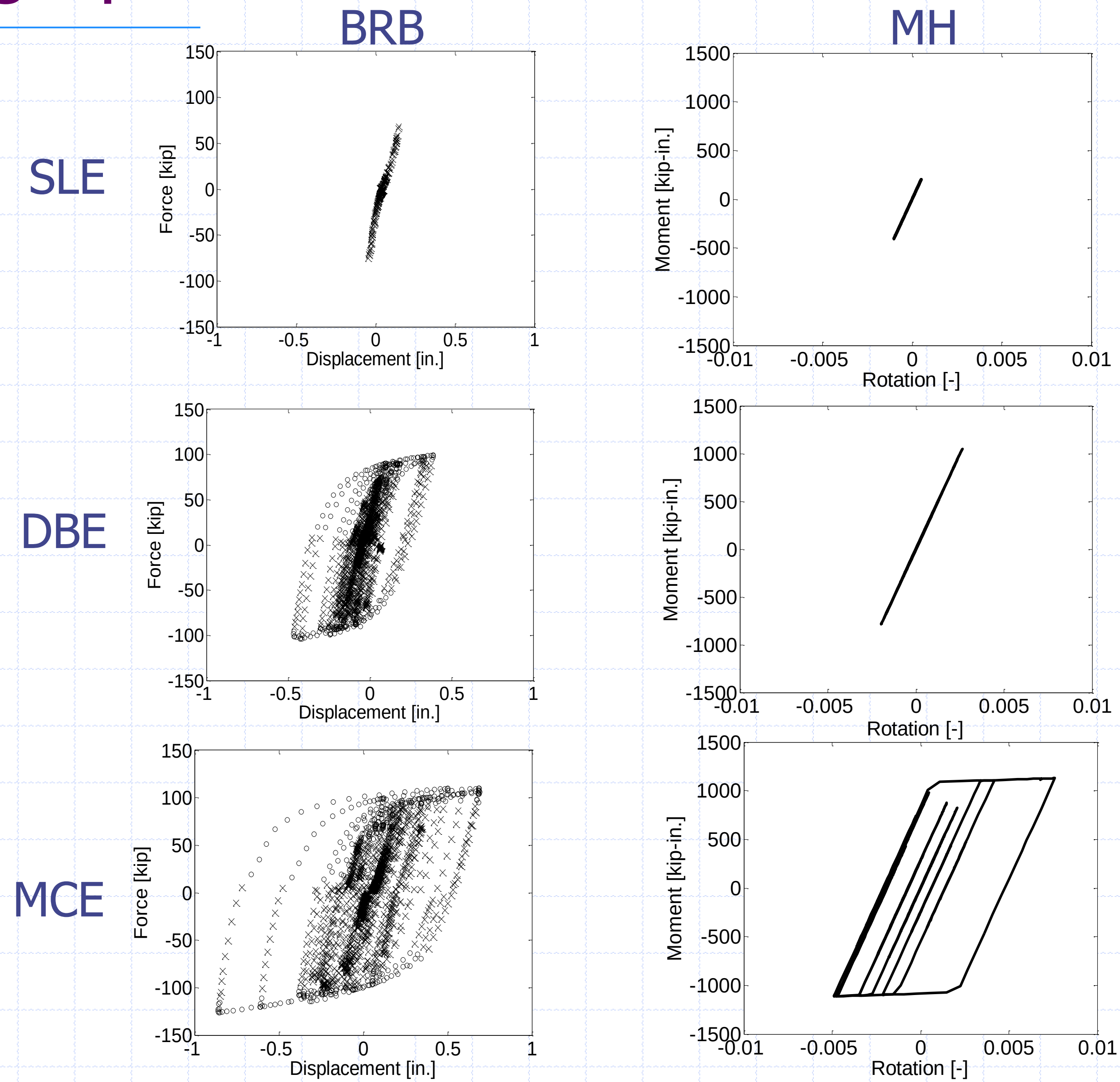
Hybrid simulation testing



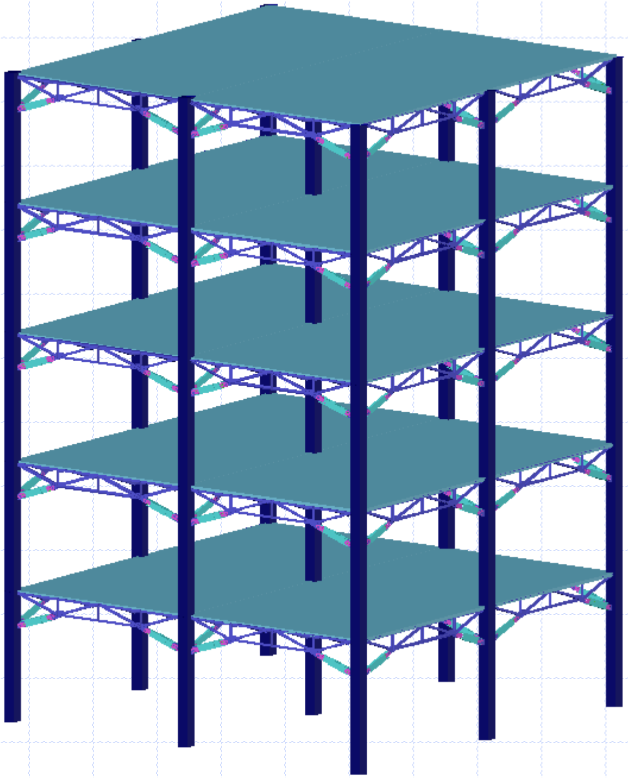
BRKBTMF



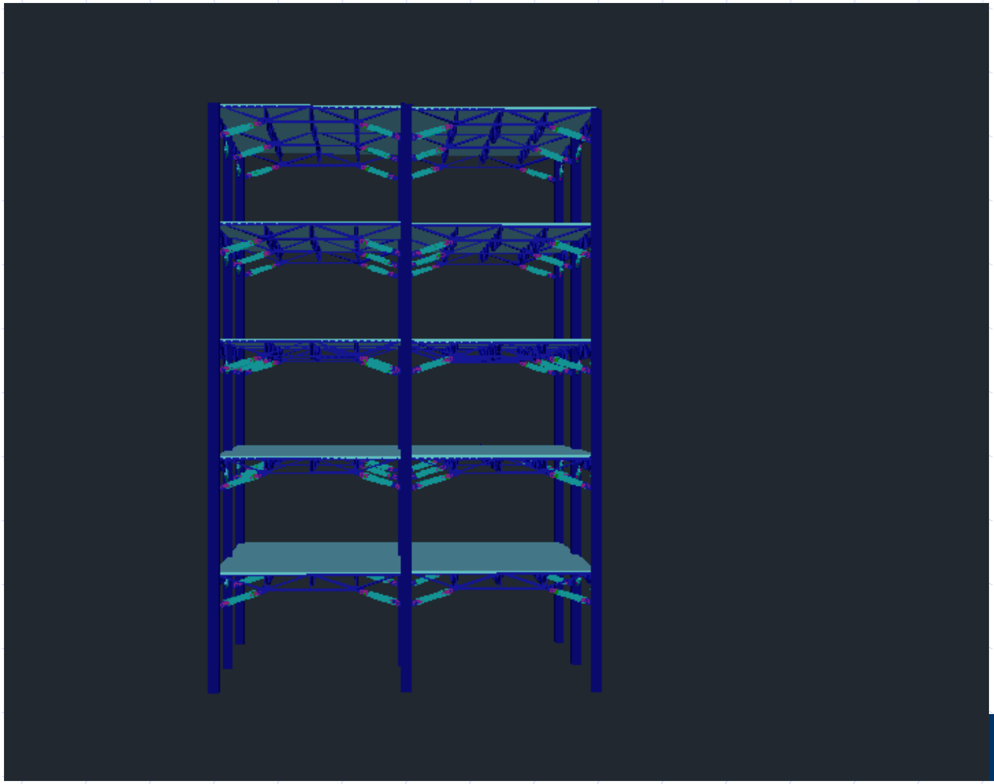
High-performance structures



UBC-GTS Smart Modulus Structure



- Light weight
- Fast construction
- Earthquake resilient



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Summary and conclusions

- Earthquake is one of the most devastating natural hazards.
- Advanced technologies both in simulations and experimental testing have been developed.
- Novel resilient structures are being developed.
  - Lower initial cost:
    - Not significantly affected by the architecture layout.
  - Higher structural performance:
    - Lower structural demand (floor acceleration and ISD).
    - Lower repair cost and downtime.
- Together, we can develop high performance structural systems that is more economical, efficient and robust towards future earthquake design.

Thank you for your attention!

Question?

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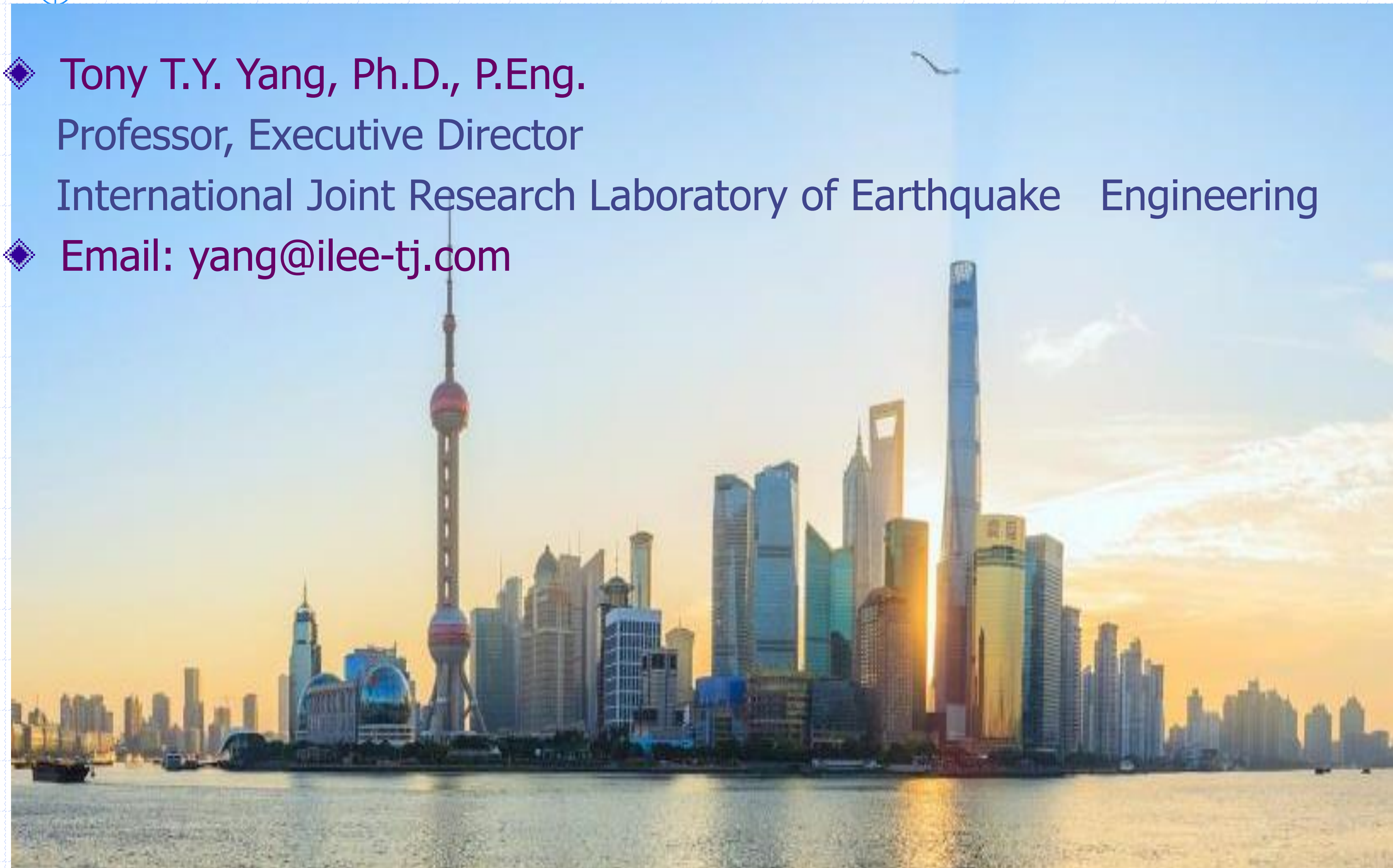

Vancouver, Canada

- I look forward to welcoming you to beautiful British Columbia
- Prof. Tony T.Y. Yang, Ph.D., P.Eng.

Email: yang@civil.ubc.ca