Introduction of BRBs Using Welded End-slot Connections

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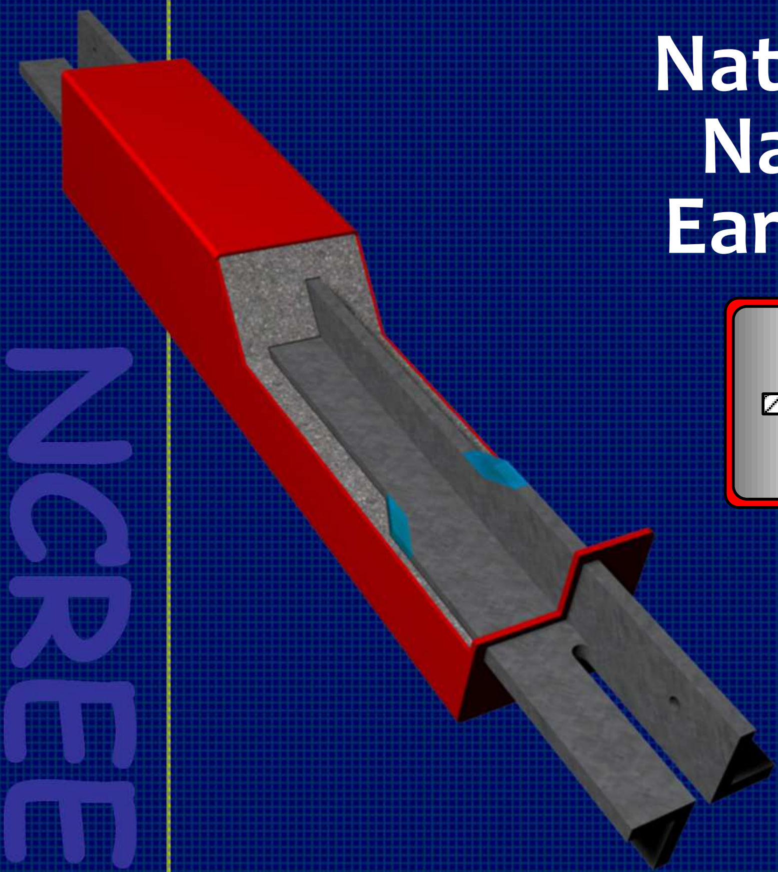

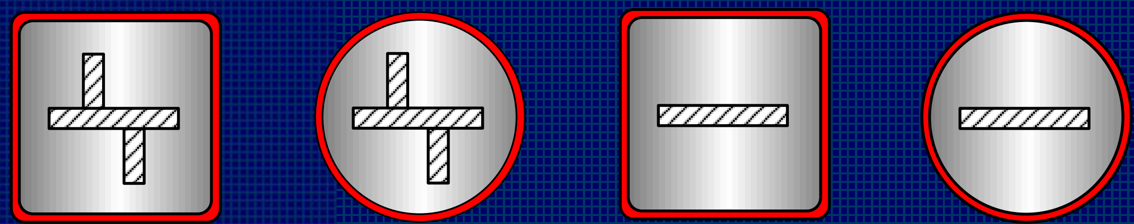

Using WES-BRBs for An Improved Seismic Resisting Performance of Buildings

November 12-14, 2013, New Zealand

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The NARLabs consists of

- National Chip Implementation Center (CIC)
- Instrument Technology Research Center (ITRC)
- National Science and Technology Center for Disaster Reduction (NCDR)
- National Center for High-performance Computing (NCHC)
- National Center for Research on Earthquake Engineering (NCREE)
- National Nano Device Laboratories (NDL)
- National Laboratory Animal Center (NLAC)
- National Space Organization (NSPO)
- Science & Technology Policy Research and Information Center (STPI)
- Taiwan Ocean Research Institute (TORI)
- Taiwan Typhoon and Flood Research Institute (TTFRI)

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Evolution of the NCREE

- NSC project awarded to NTU in 1990
- Merged into NARL as one of the Centers in 2003
- Major experimental facilities have been running since 1997 when the laboratory was completed

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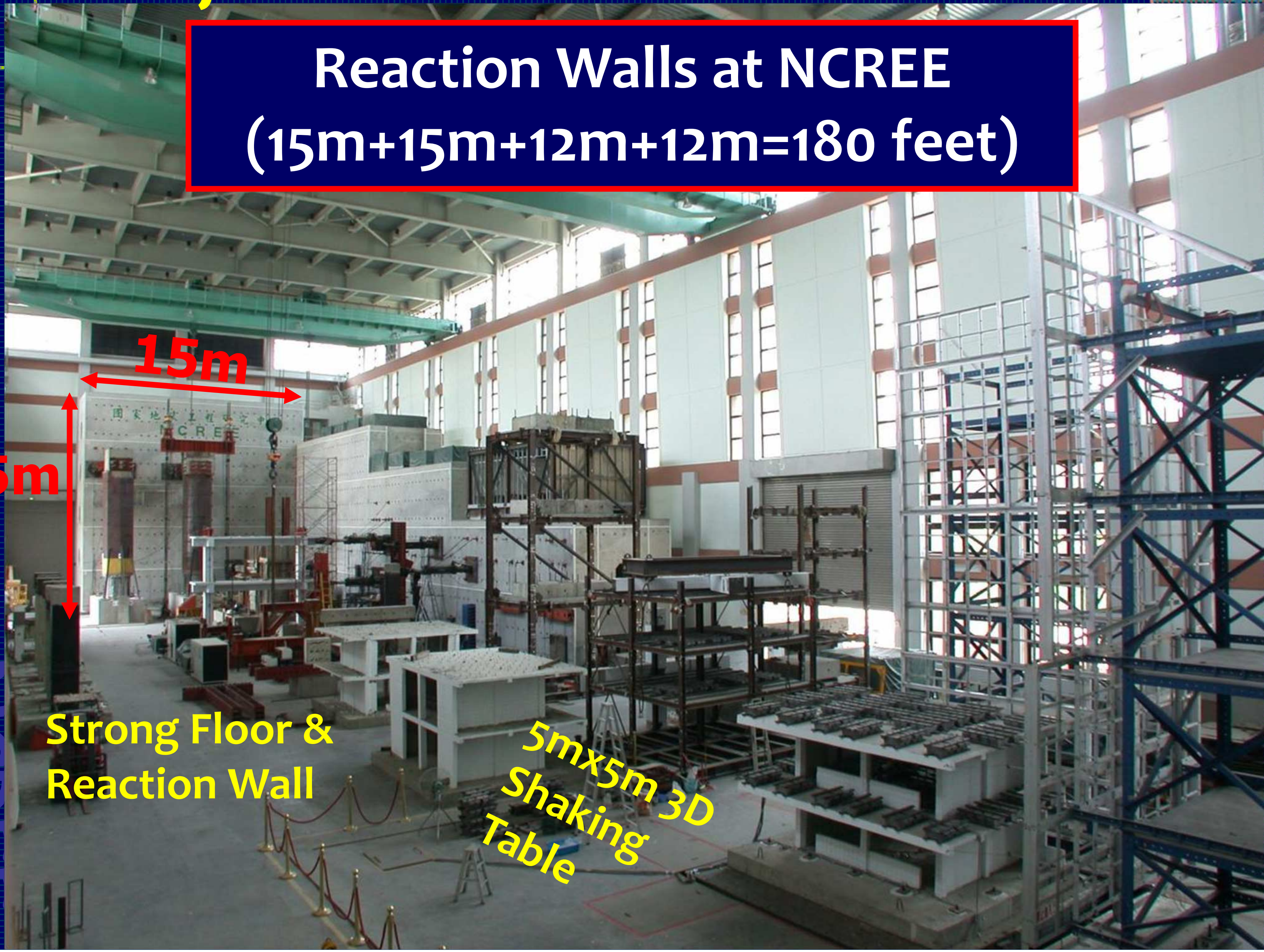
Major facilities in NCREE

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NCREE vision and mission

- Pre-quake preparation, emergency response and post-quake recovery
- Integrate research capacities of various EQ ENG research institutes in Taiwan
- Promote INTL research collaboration on EQ hazard mitigation, and lead a key role in the world EQ ENG research community

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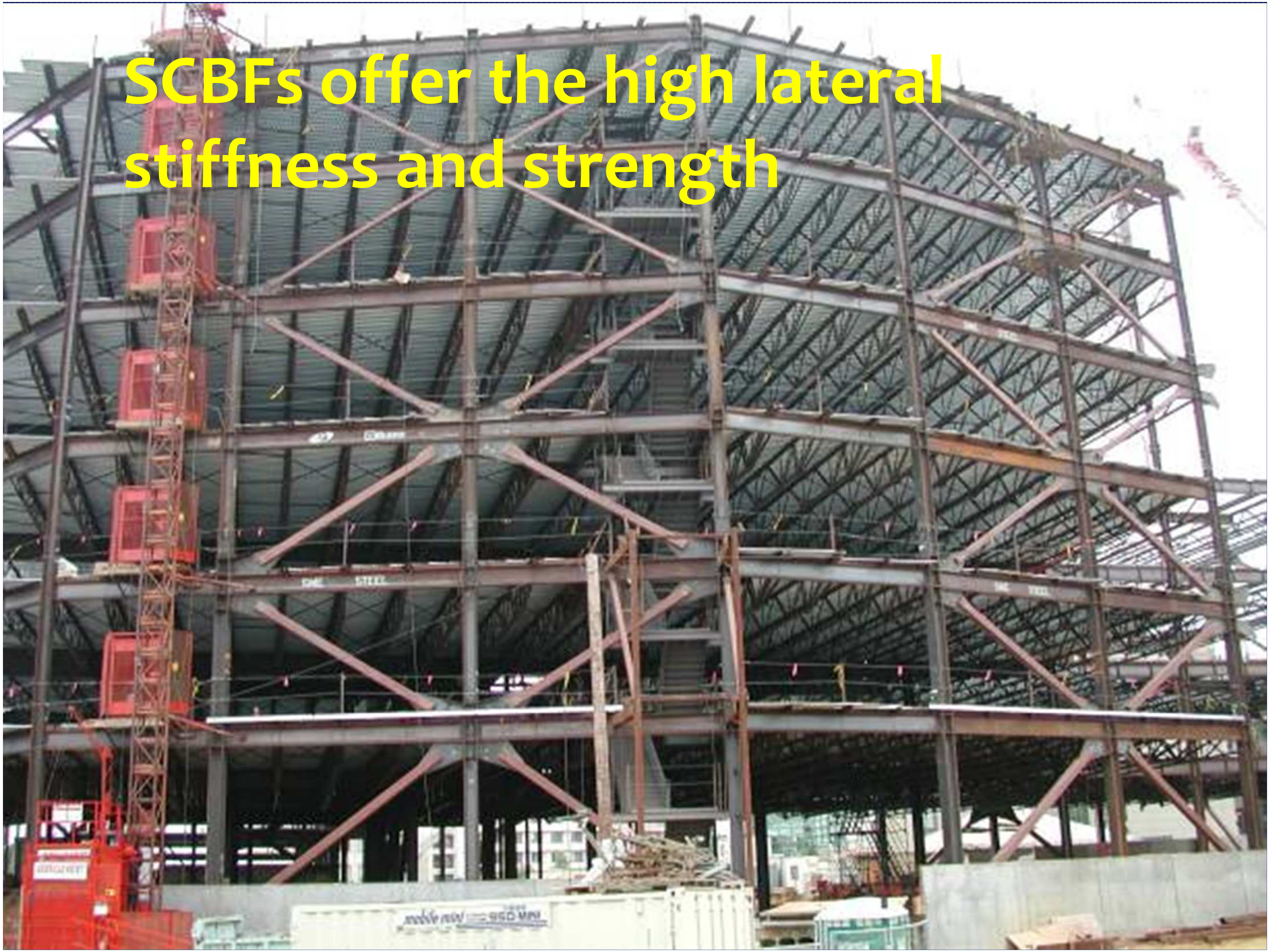
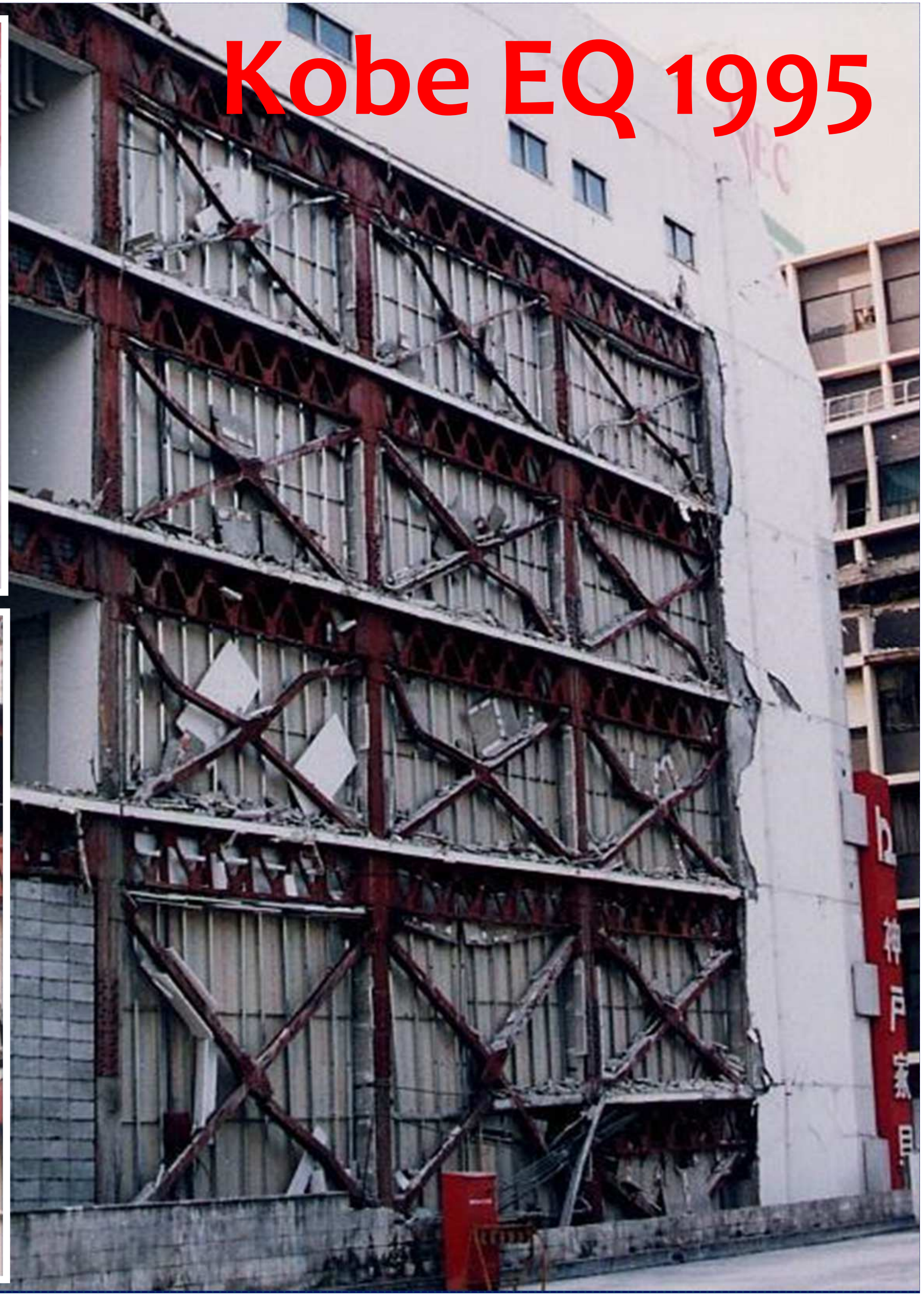
SCBFs offer the high lateral stiffness and strength




Out-of-plane buckling


In-plane buckling


Kobe EQ 1995

Basic LRFD Load Combinations

$1.4D$

$1.2D + 1.6L + 0.5(Lr \text{ or } S \text{ or } R)$

$1.2D + 1.6(Lr \text{ or } S \text{ or } R) + (0.5L \text{ or } 0.8W)$

$1.2D + 1.6W + 0.5L + 0.5(Lr \text{ or } S \text{ or } R)$

$0.9D + 1.6W$

$$\left.\begin{array}{l} 1.2D + 1.0E + 0.5L + 0.2S \\ 0.9D + 1.0E \end{array}\right\} \text{Load Combinations Including } E$$

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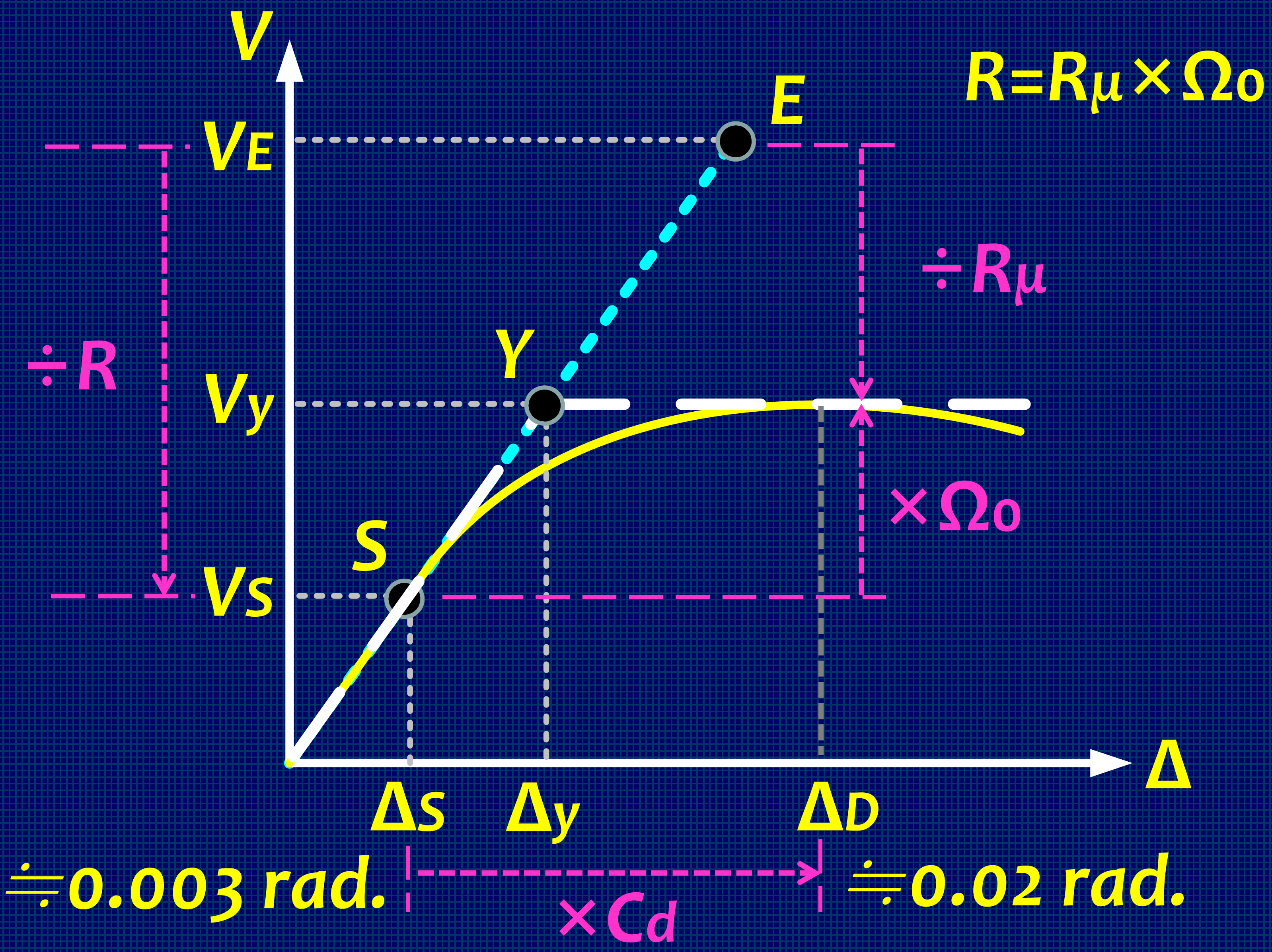
Lateral force vs. deformation



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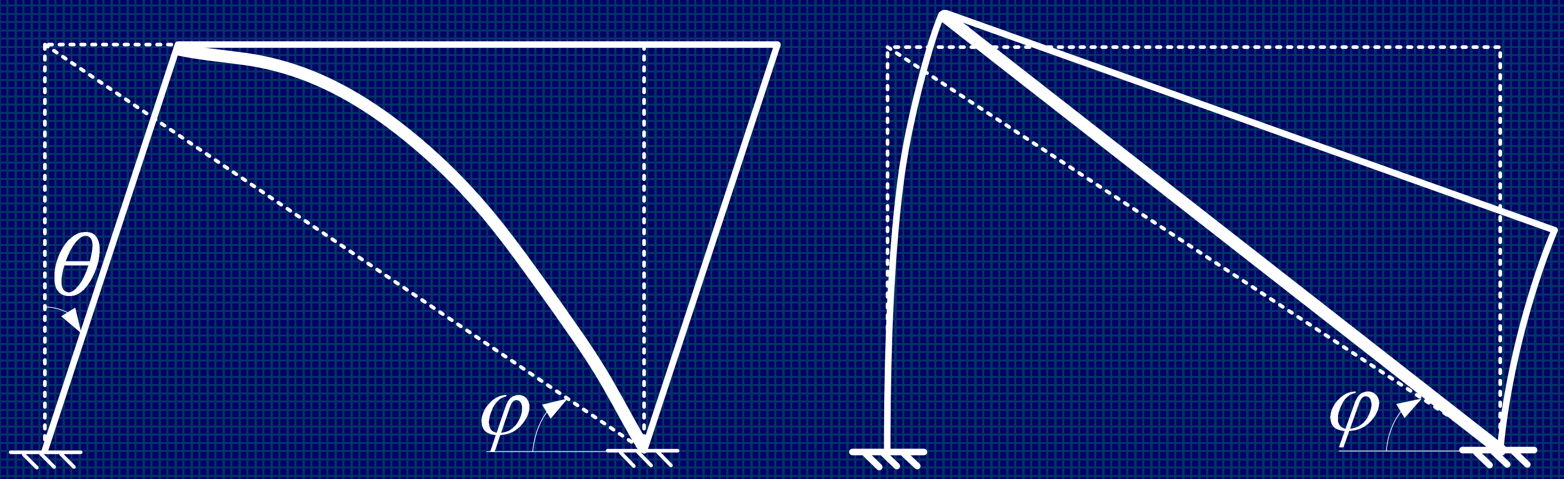
Braced Frame Deformations



Shear	Bending
$\theta \neq 0$	$\theta \neq 0$
$\varepsilon_{wp} \neq 0$	$\varepsilon_{wp} = 0$

$$\varepsilon_{wp} = \frac{\theta}{2} \times \sin 2\varphi$$

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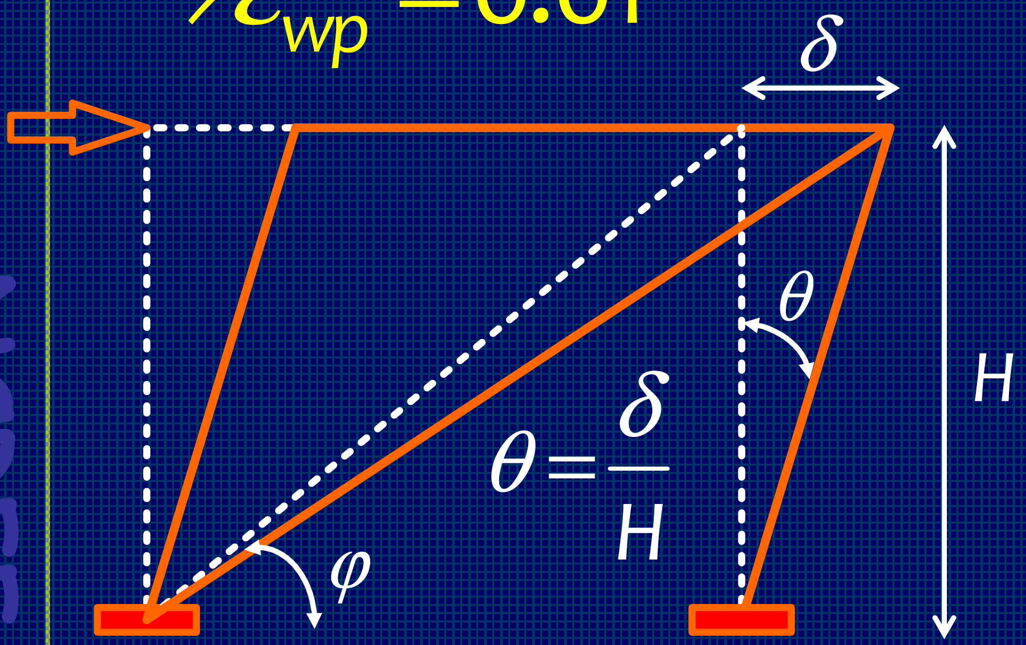
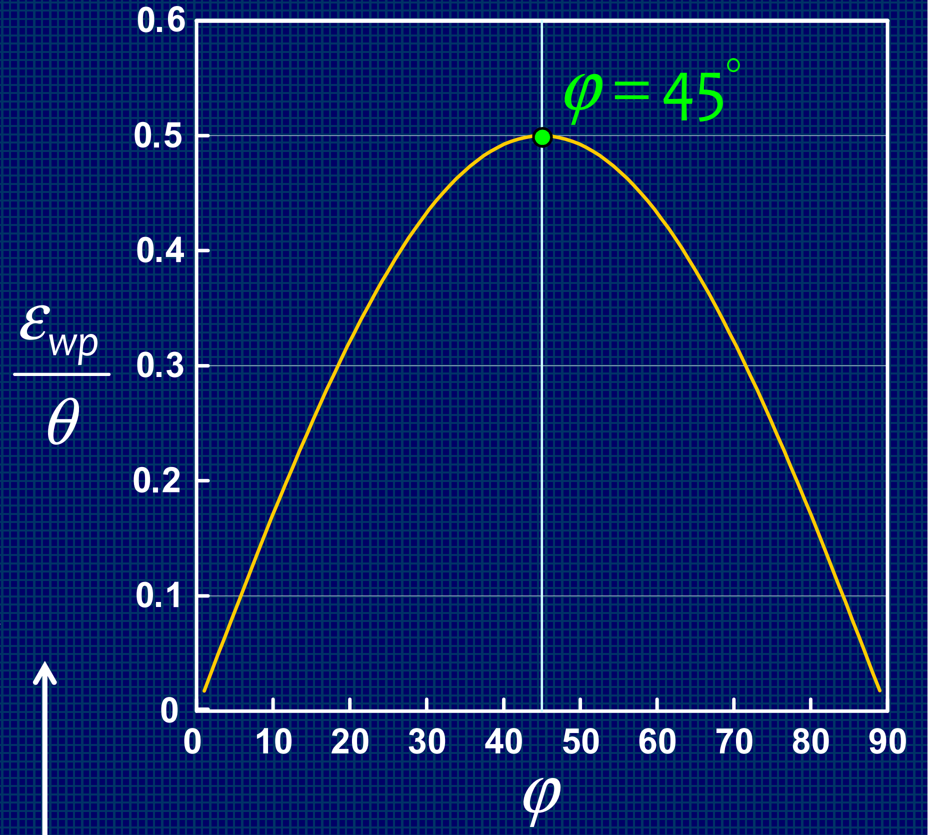
Brace strain and story drift

$$\varepsilon_{wp} = \frac{\theta}{2} \times \sin 2\varphi$$

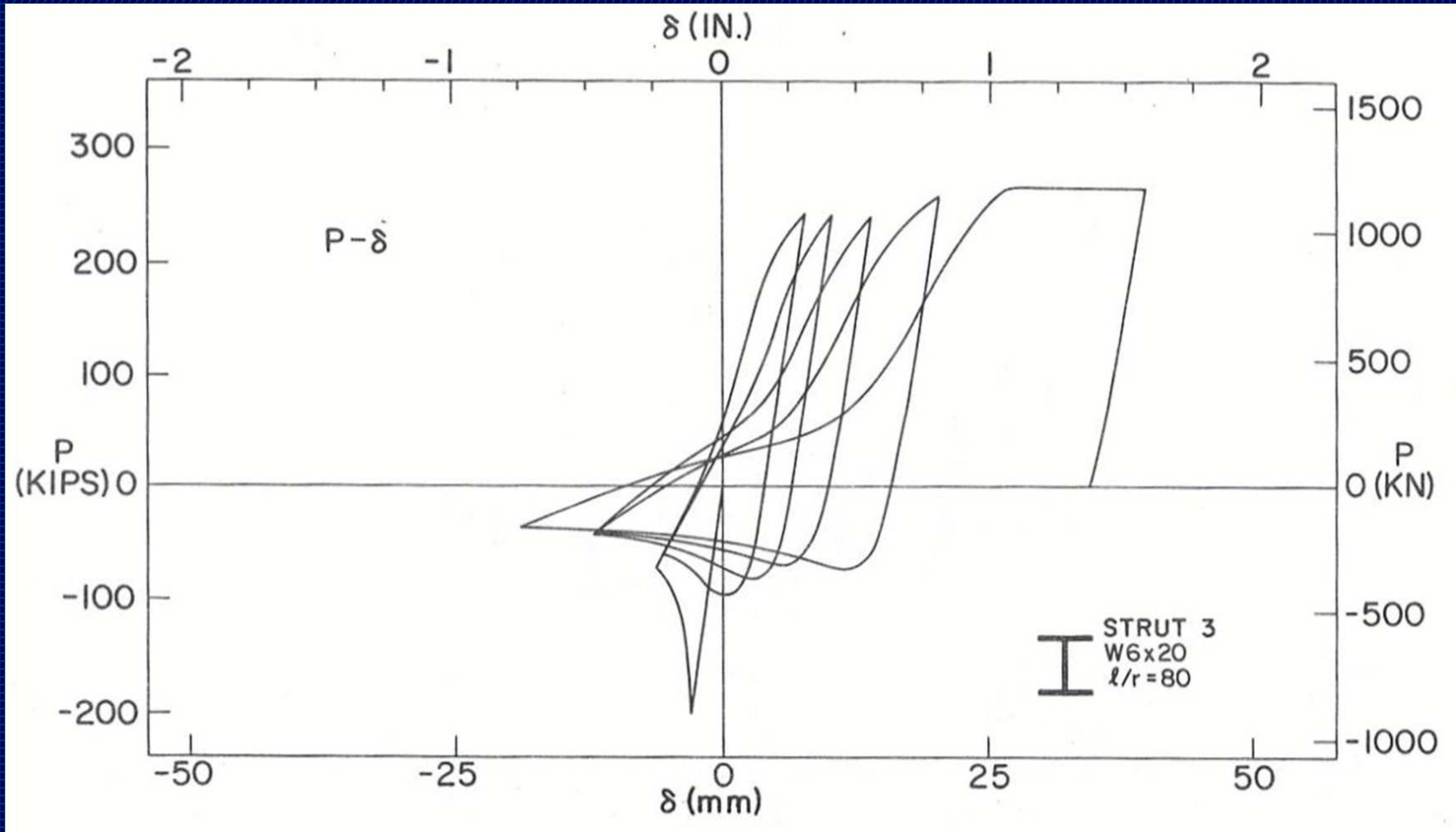
$$\text{If } \varphi = 45^\circ,\ \theta = 0.02\ rad.$$

$$\rightarrow \varepsilon_{wp} = 0.01$$

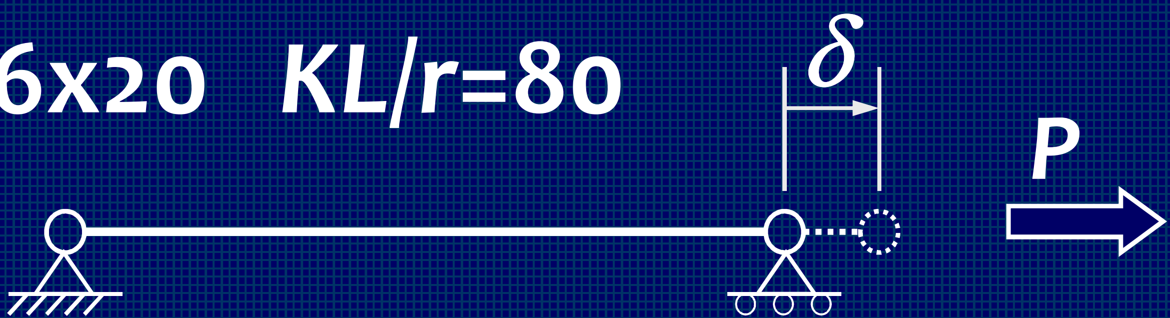




Brace response under cyclic loads



W6x20 *KL/r*=80



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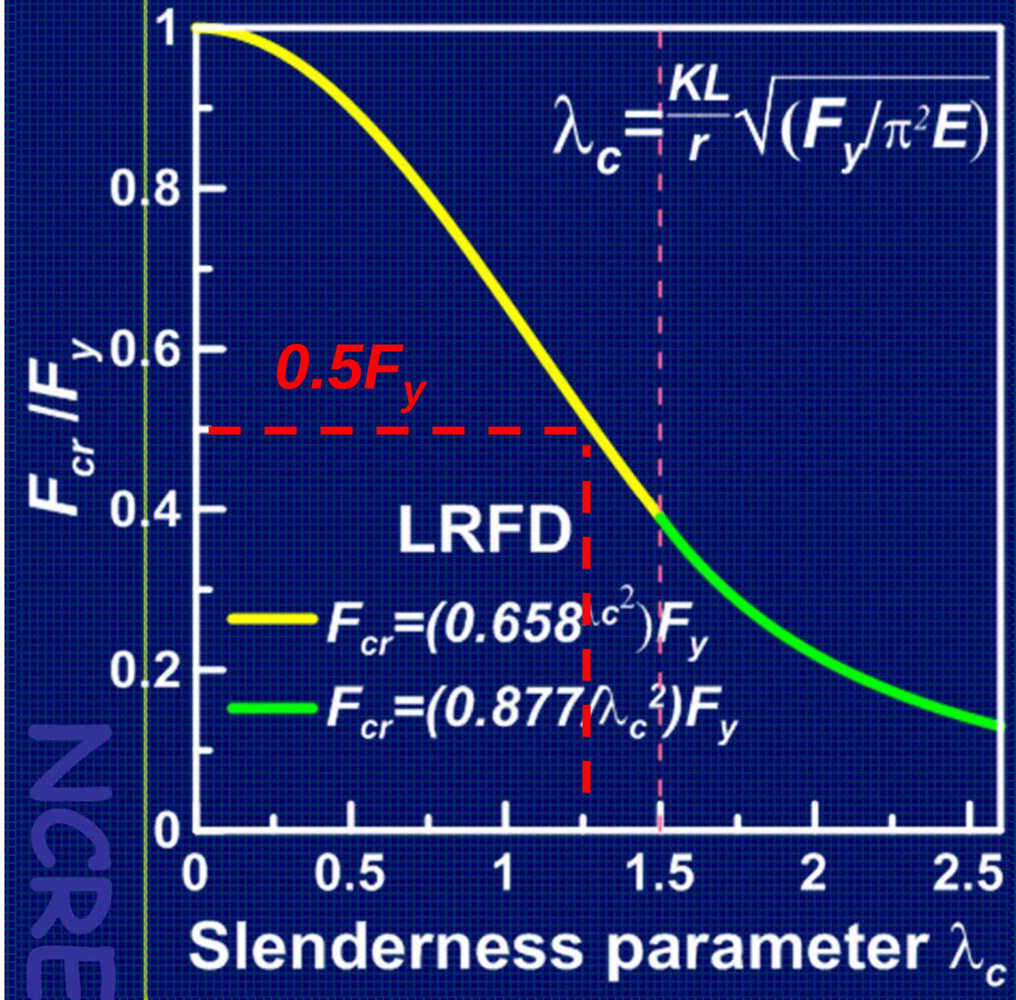
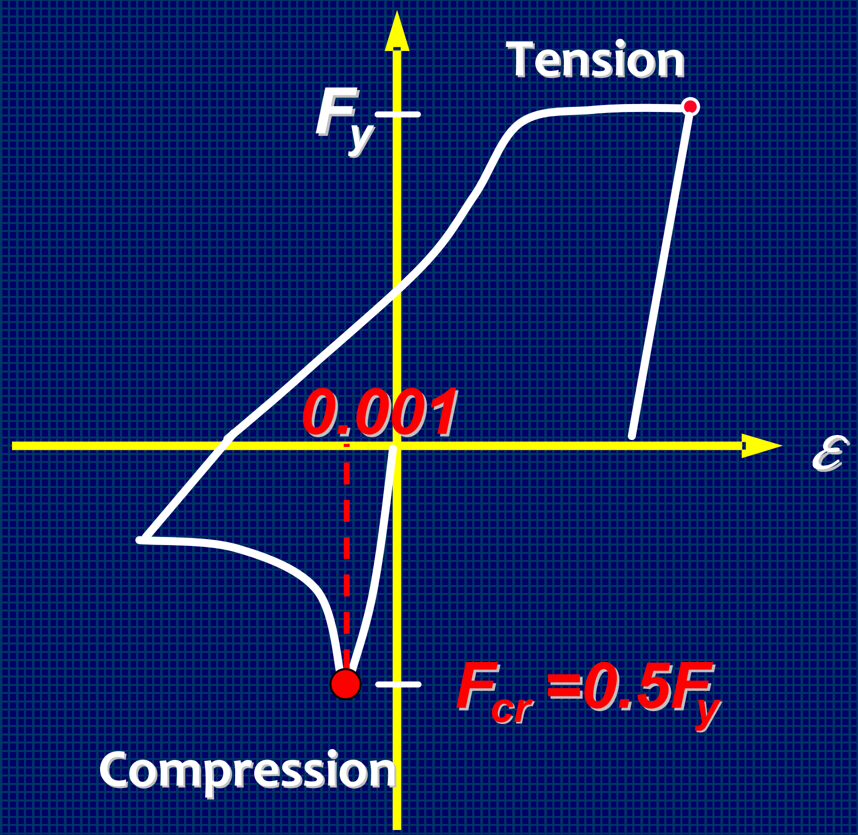
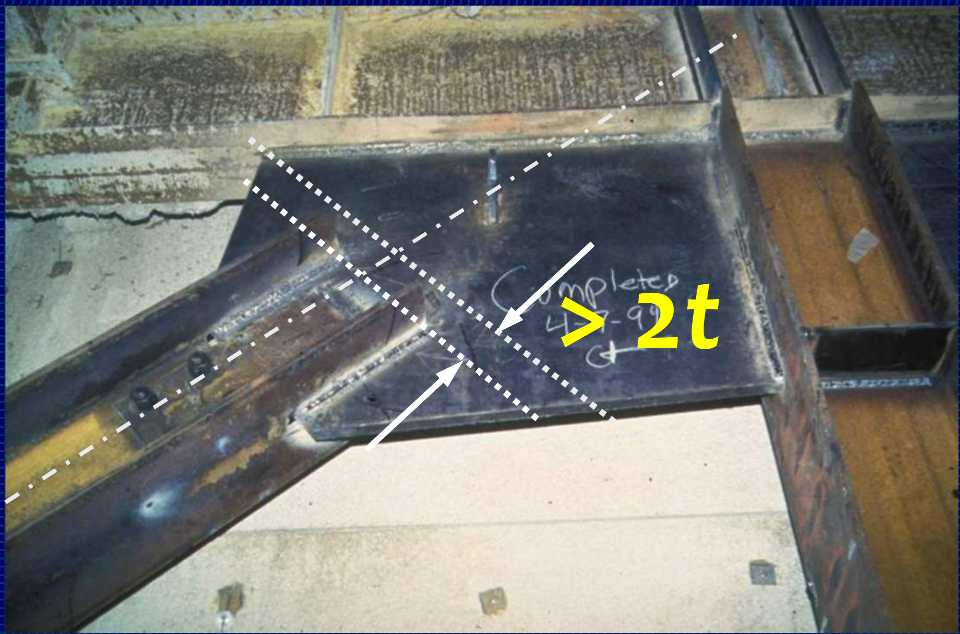
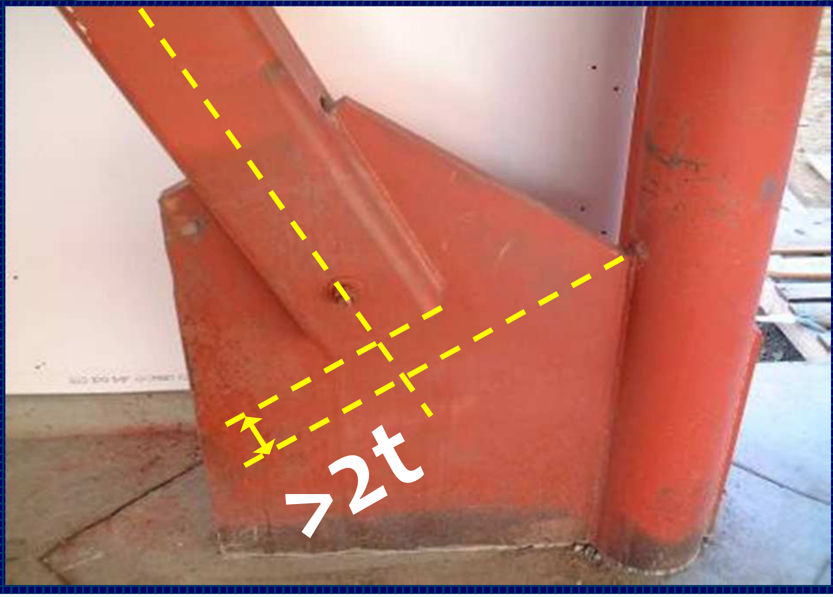
The brace buckles at a small strain

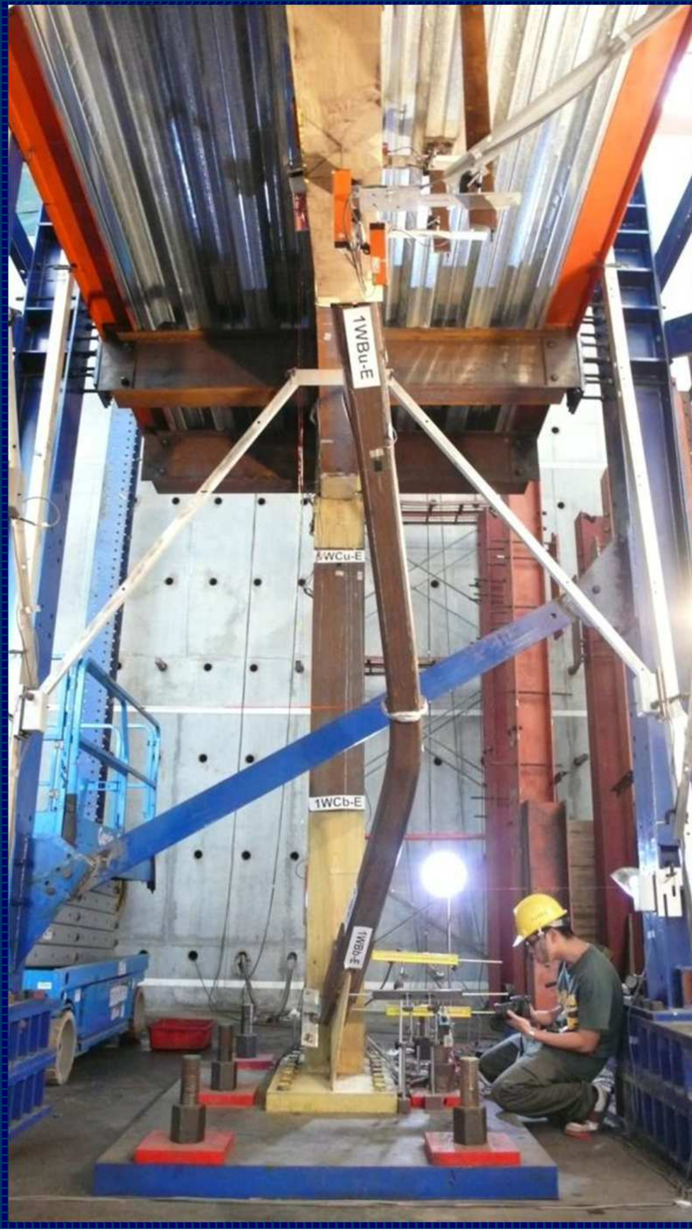




Ductile brace connection details (AISC)







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Connection failure under tension

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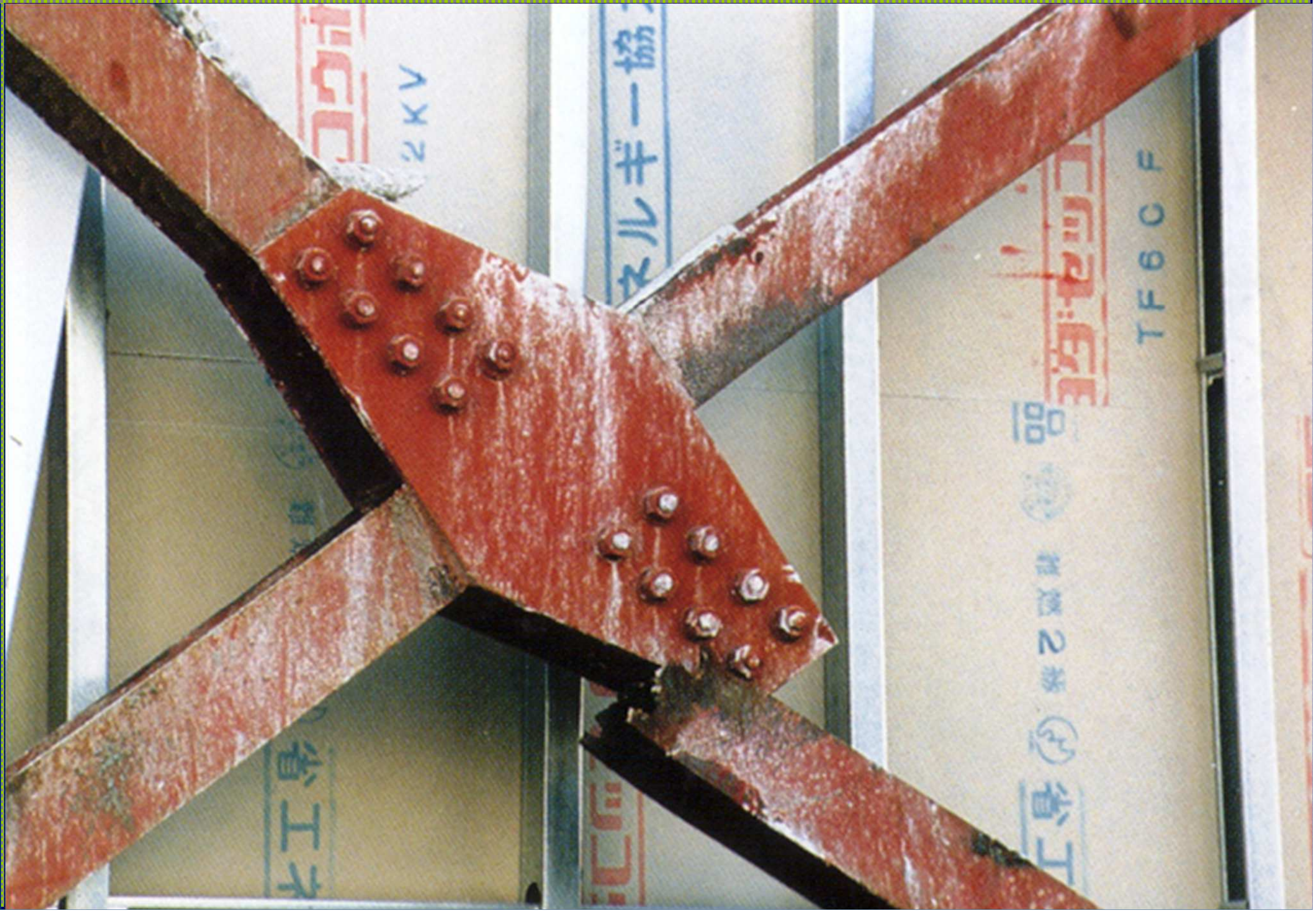
Connection failure under tension



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Example of brace connection details

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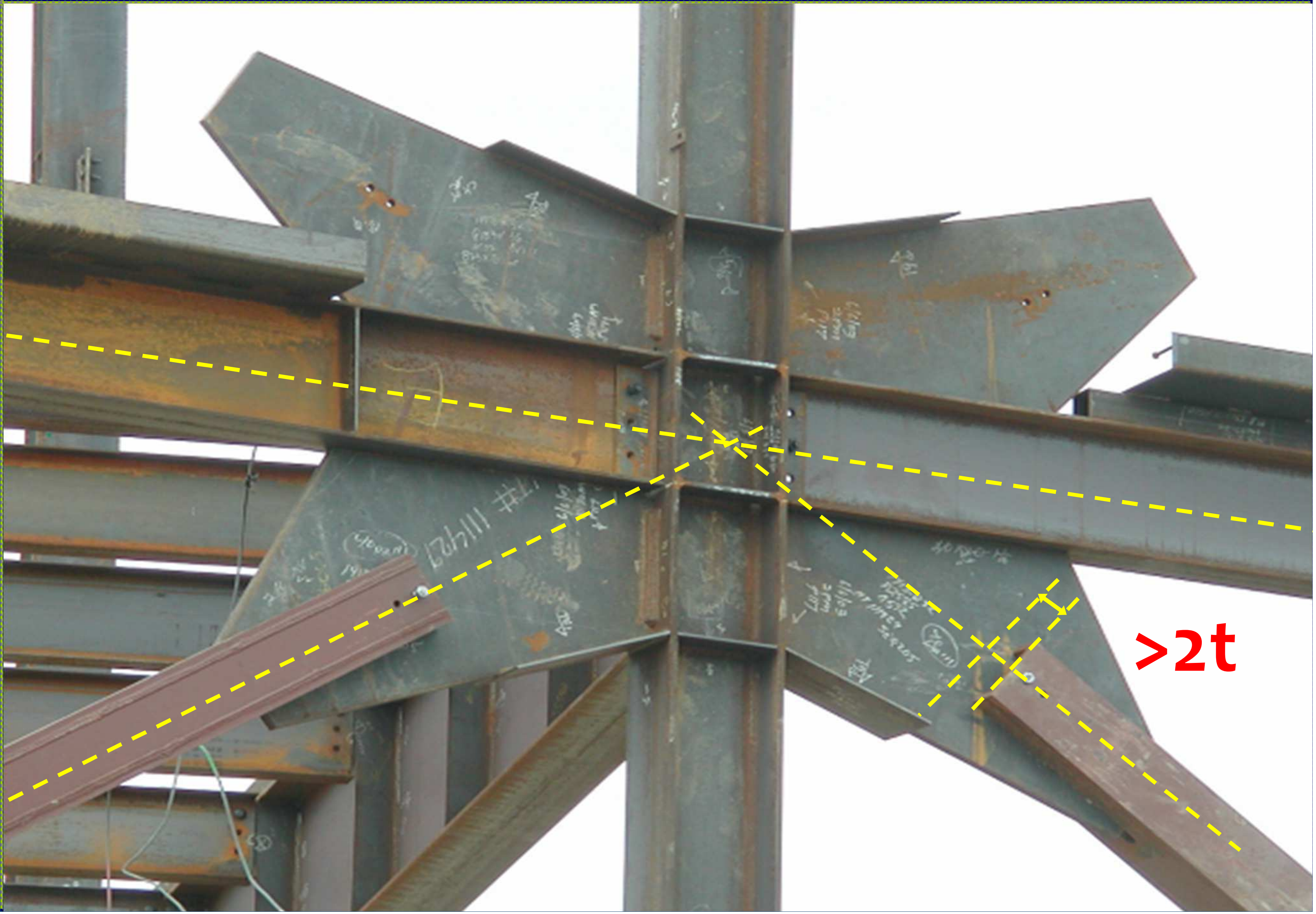
Example of brace connection details



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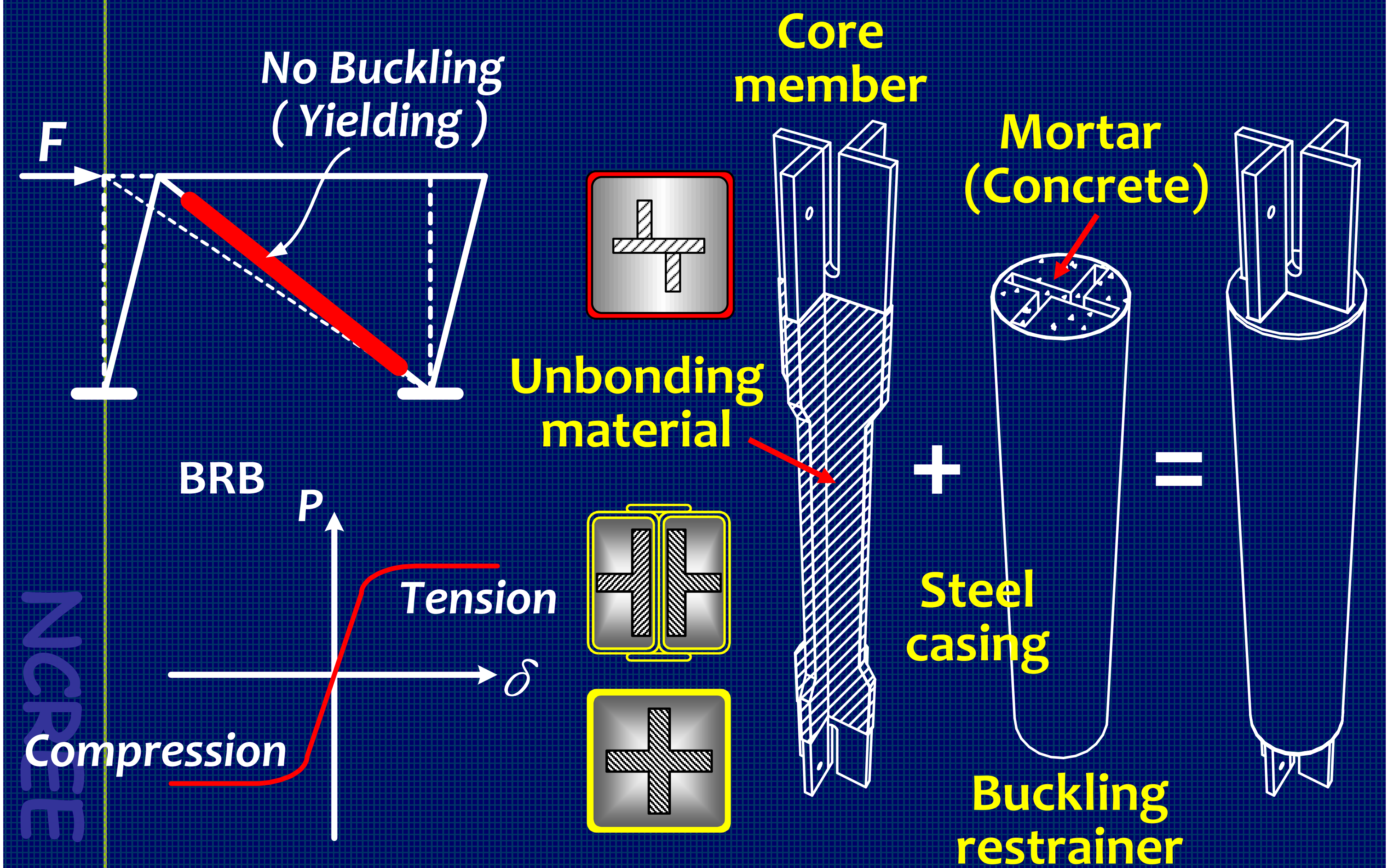
NG design of connection details

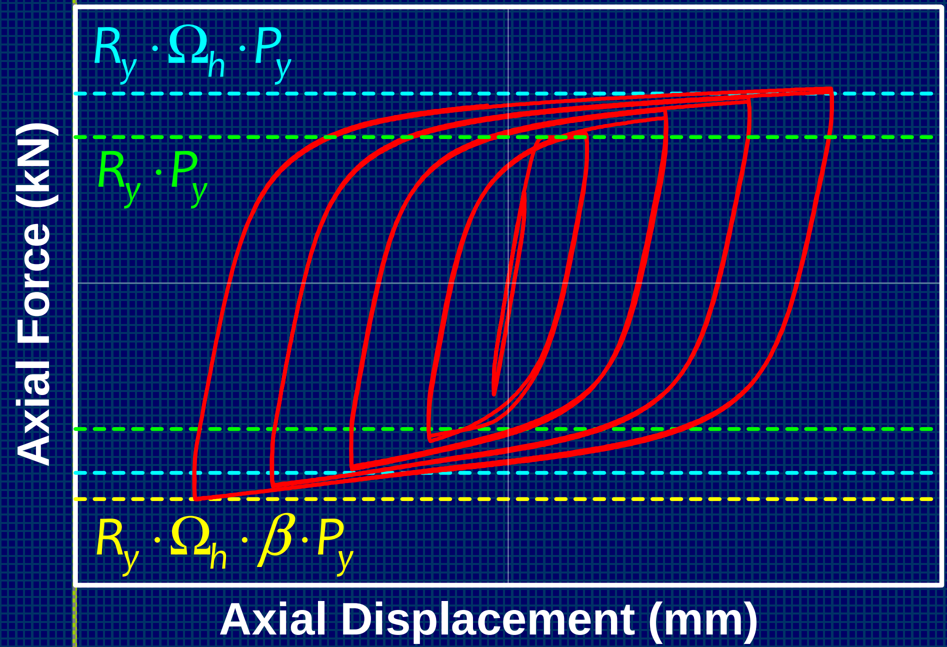
Connection failure under compression

Questionable connection details ?

Buckling-restrained brace (BRB)



Predictable strength properties



- **Nominal yield strength**

$$P_y = F_y \times A_c$$

- **Max. compressive strength**

$$P_{max} = P_y \times R_y \times \Omega_h \times \beta$$

R_y : *material overstrength factor*

Ω_h : *strain hardening factor*

β : *compression strength adjustment factor*

Material	R_y	Ω_h	β
SN490B	1.2	1.3	1.1~1.2
A572 GR50	1.1	1.3	1.1~1.2
A36	1.5	1.5	1.1~1.2

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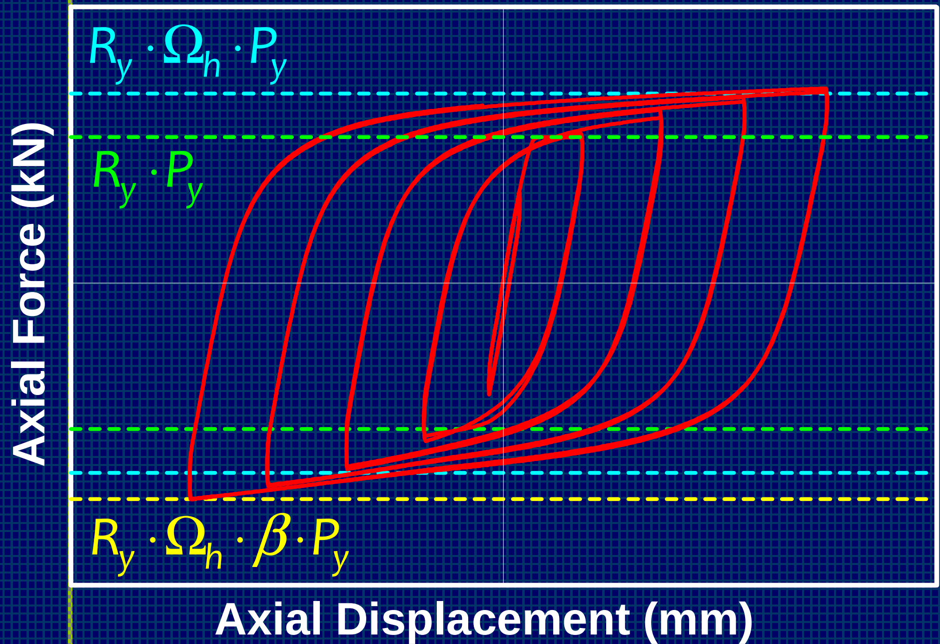
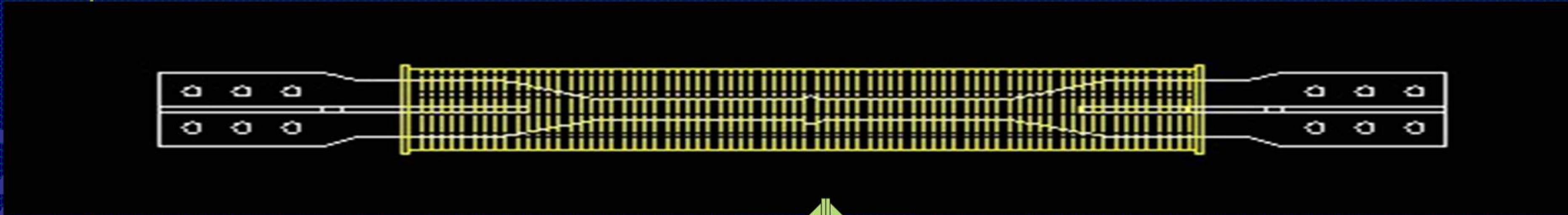
Select steel casing to prevent buckling

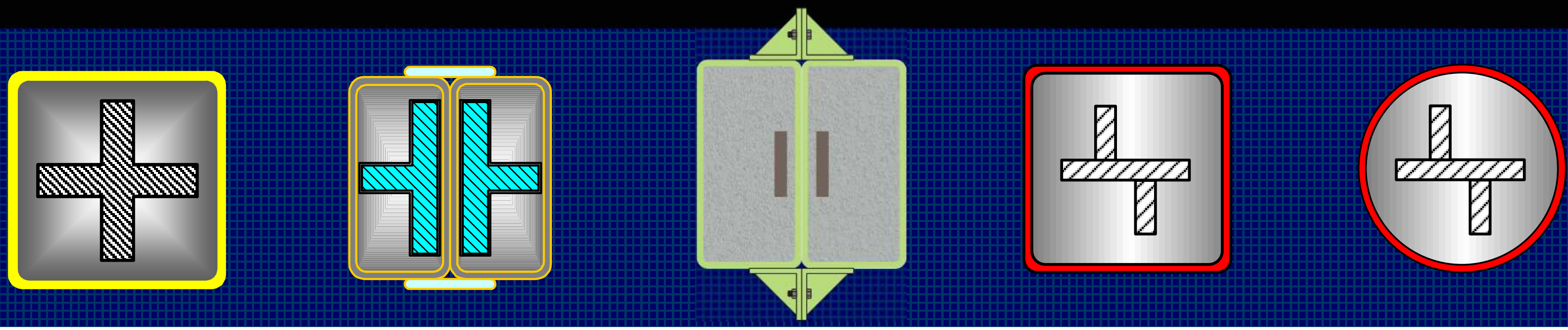


$$P_y = F_y \times A_c \rightarrow$$

$$P_{max} = P_y \times R_y \times \Omega_h \times \beta$$

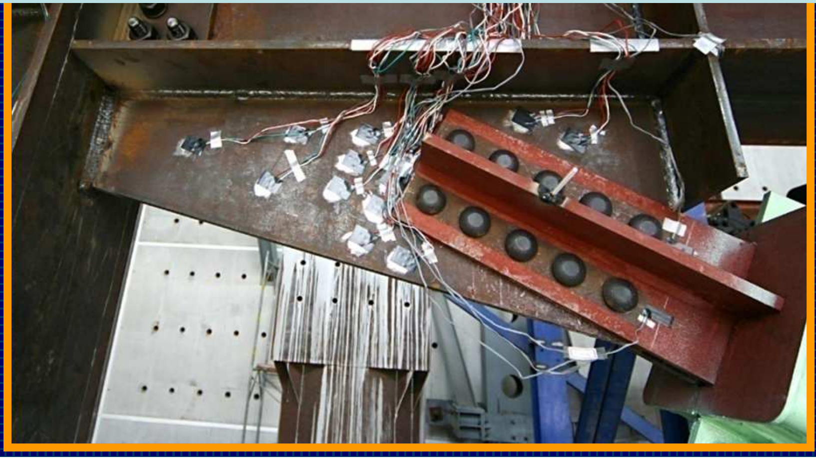
$$P_{max} \leq P_{e\_tube} = \frac{\pi^2 EI_{tube}}{(KL_{tube})^2}$$





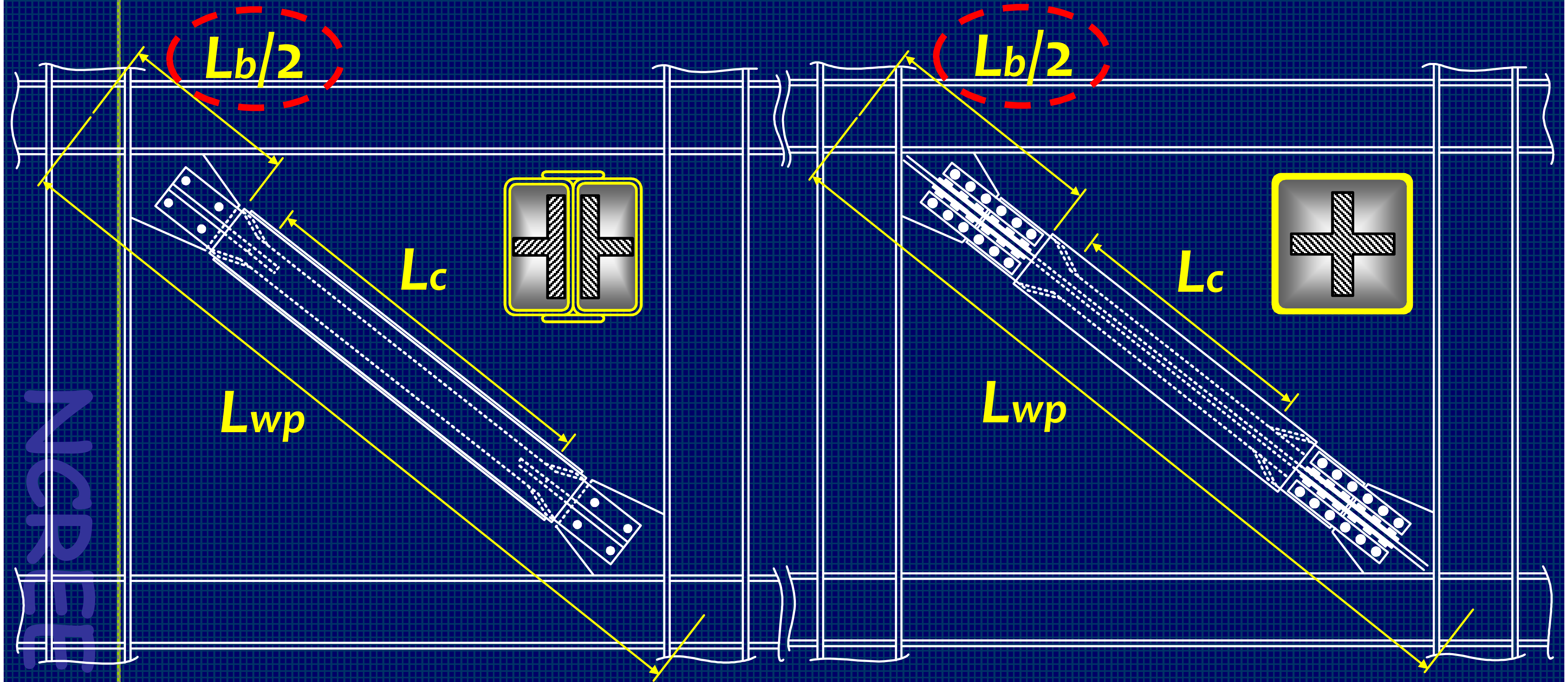
Lap vs. Butt BRB end connections

- Reduce the length and the number of bolts
- Conveniently connected to the gusset plate



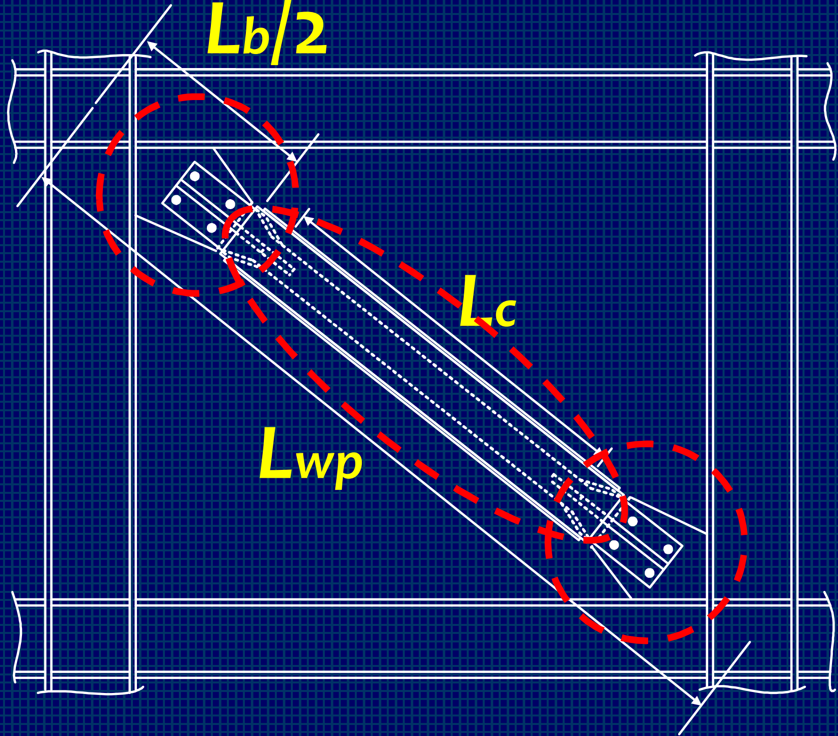
A shorter connection is better

Increase the BRB fatigue life and end connection stability



Advantages of Double-core BRBs with Lapped Ends

$$P_{e\_trans} = \frac{\pi^2 EI_{trans}}{(KL_b)^2} \geq P_{max}$$



- Compact end connections enhance the stability
- Increases the core region length, reduces the brace strain and improves the BRB fatigue life

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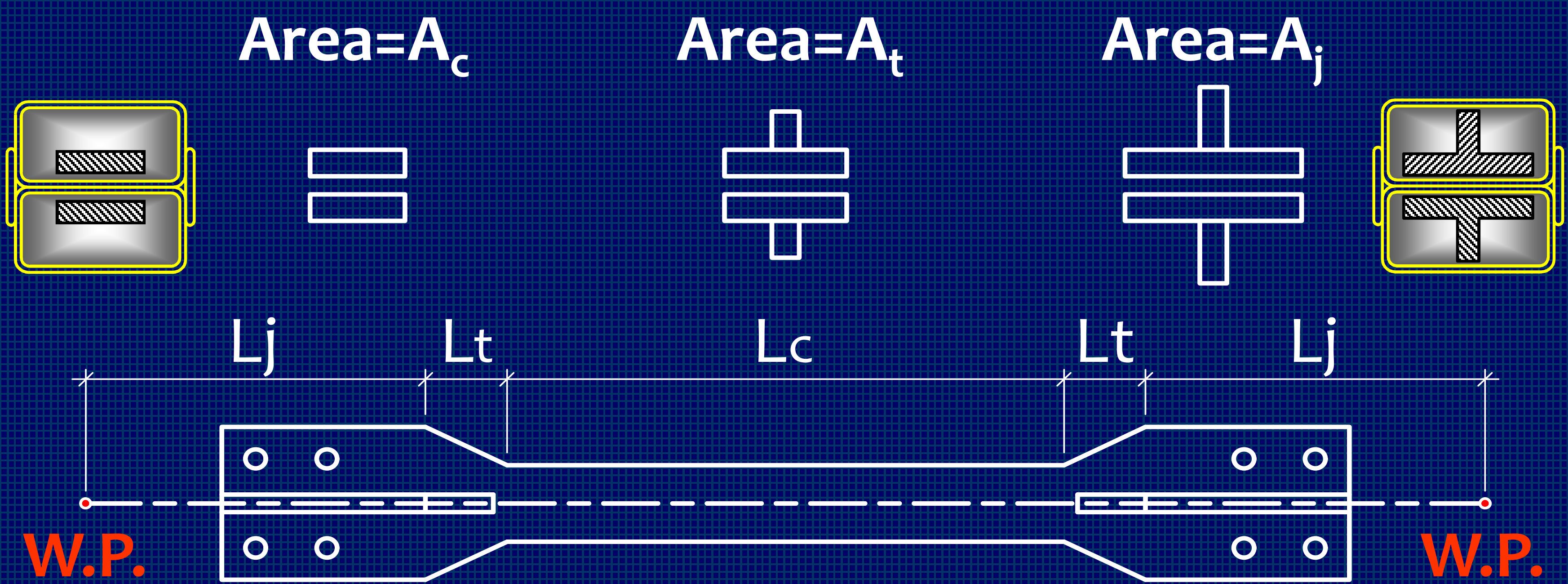
Predictable Effective Stiffness

- **Effective axial stiffness**

$$K_{eff} = \frac{1}{\dfrac{L_c}{EA_c} + \dfrac{2L_t}{EA_t} + \dfrac{2L_j}{EA_j}} = \frac{EA_c A_t A_j}{L_c A_t A_j + 2L_t A_c A_j + 2L_j A_c A_t}$$



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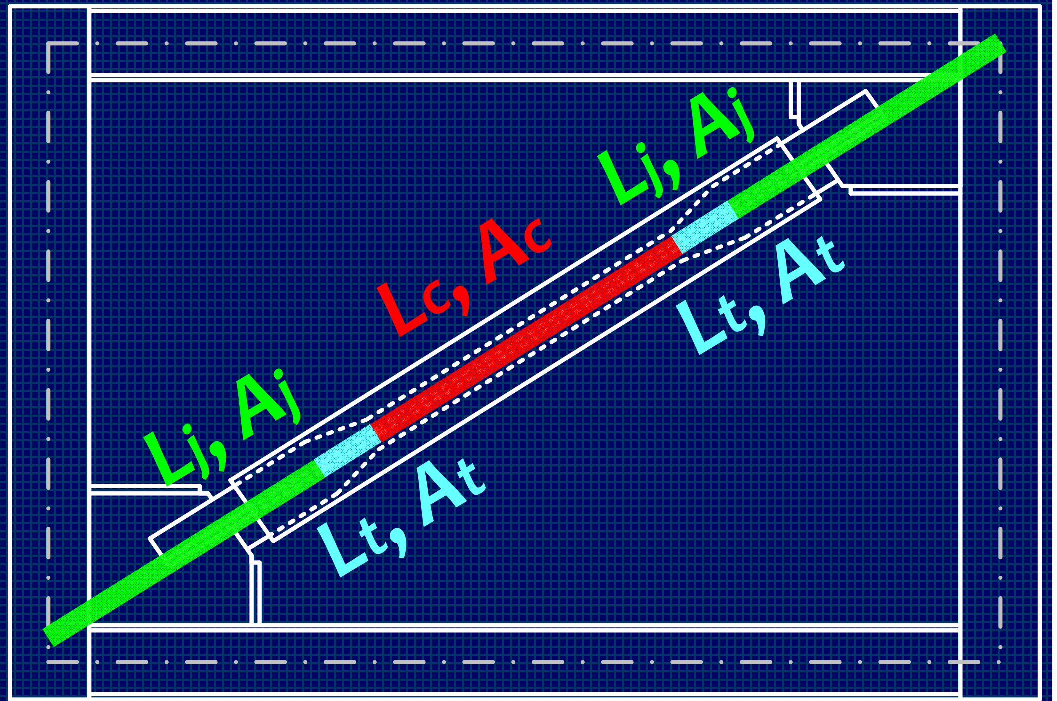
Effective stiffness factor Q

- **Length ratio** $L_c = \alpha_c L_{wp},\ 2L_t = \alpha_t L_{wp},\ 2L_j = \alpha_j L_{wp}$

$$\alpha_c + \alpha_t + \alpha_j = 1.0$$



- **Area ratio**

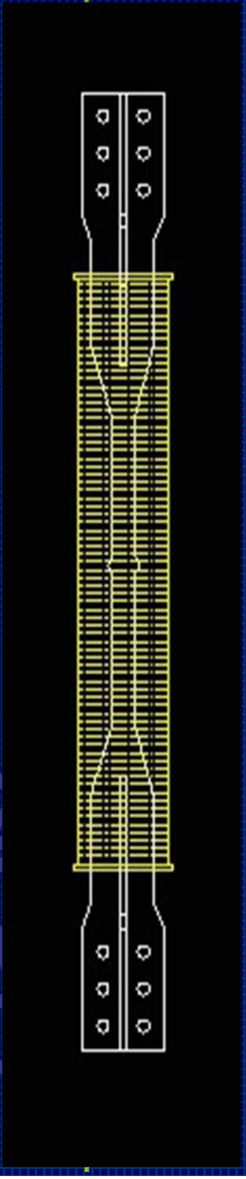
$$A_t = a_t A_c,\ A_j = a_j A_c$$

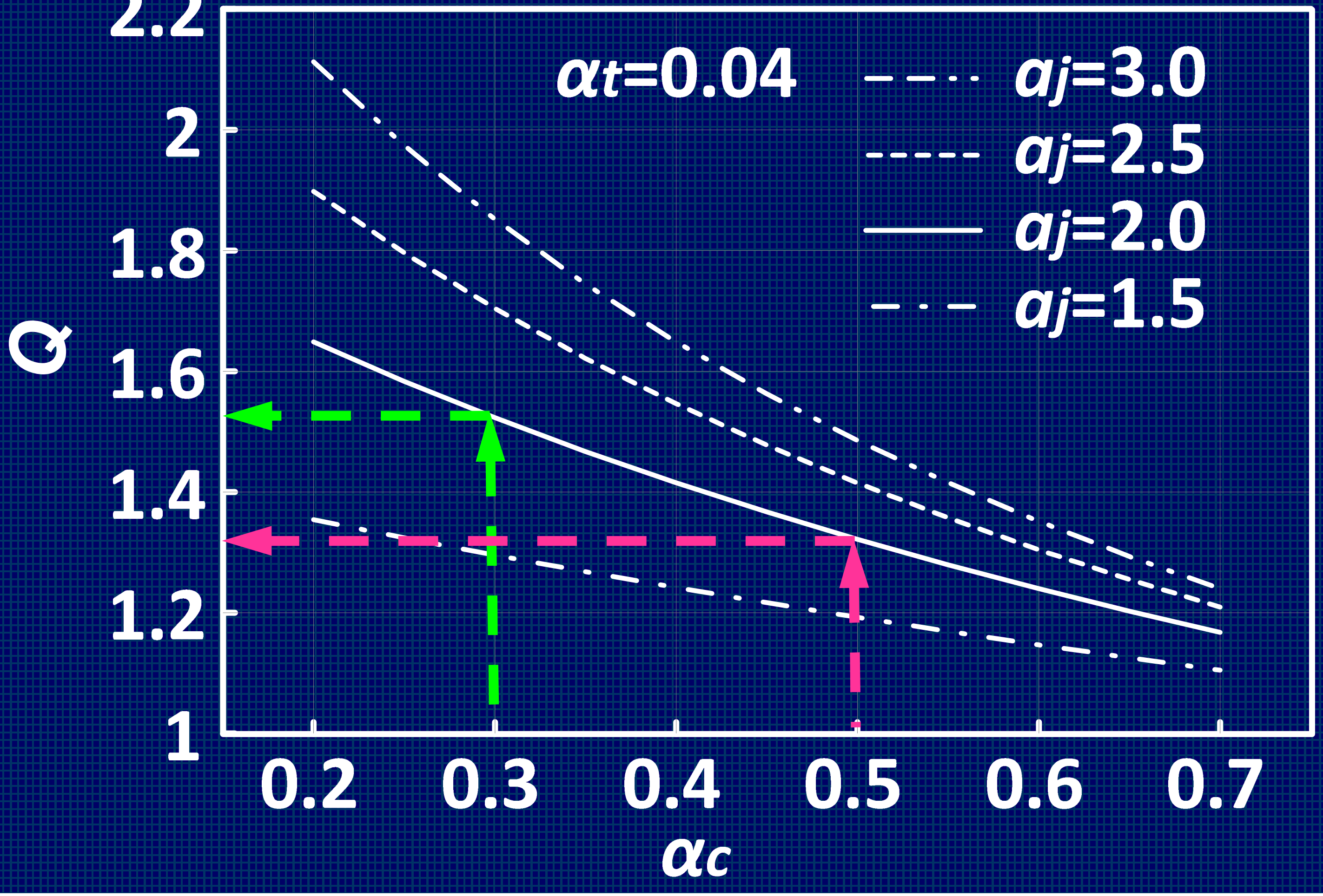
- **Effective stiffness**

$$K_{eff} = \frac{a_t a_j}{\alpha_c a_t a_j + \alpha_t a_j + \alpha_j a_t} \frac{EA_c}{L_{wp}} = Q \frac{EA_c}{L_{wp}}$$

Q value is ranging from 1.2~1.5

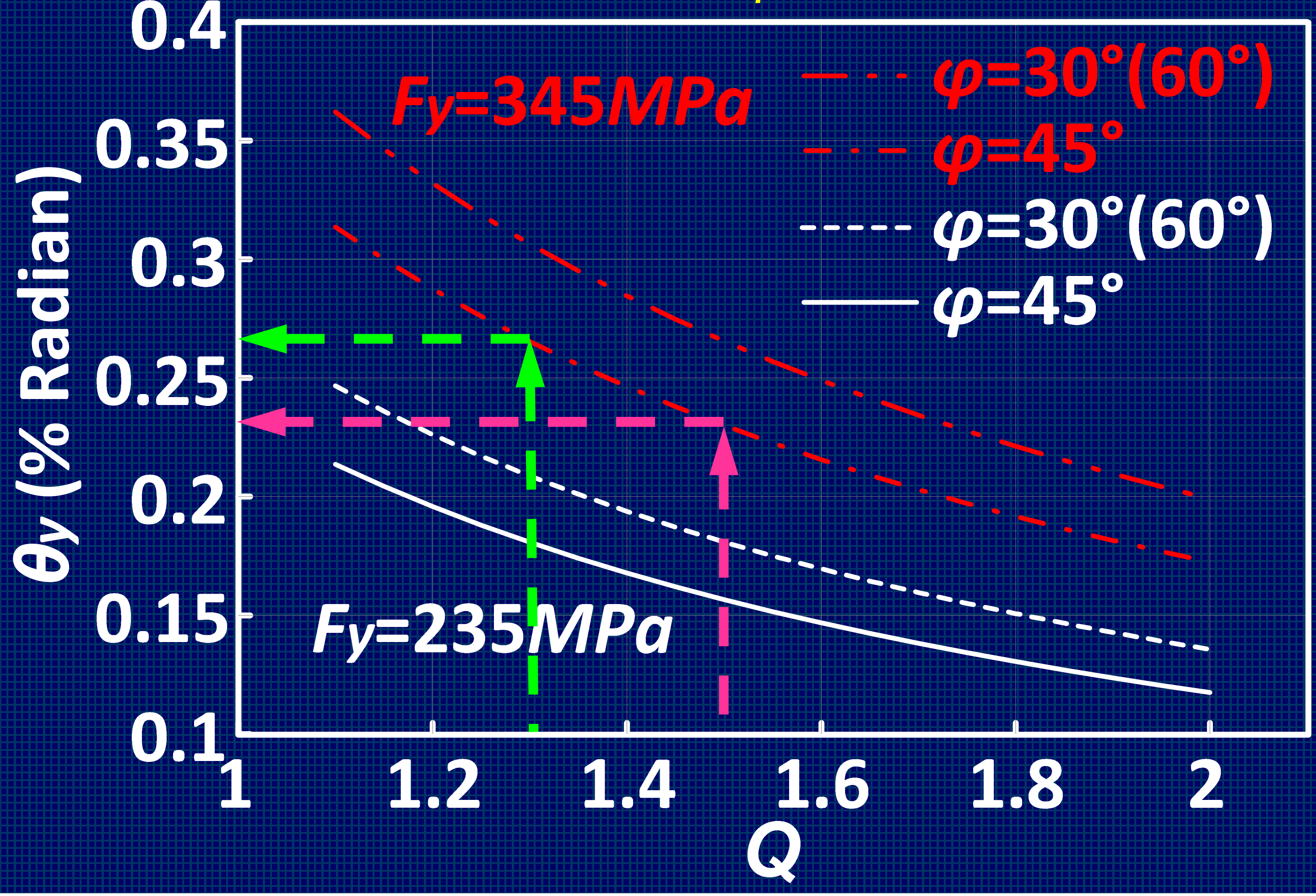
$$K_{eff} = \frac{a_t a_j}{\alpha_c a_t a_j + \alpha_t a_j + \alpha_j a_t} \frac{EA_c}{L_{wp}} = Q\frac{EA_c}{L_{wp}}$$





Q value and yield story drift θ_y

$$\varepsilon_{wp} = \frac{\theta}{2}\sin 2\varphi \rightarrow \theta_y = \frac{2P_y / K_{eff}}{L_{wp}\sin 2\varphi} = \frac{2F_y / QE}{\sin 2\varphi}$$



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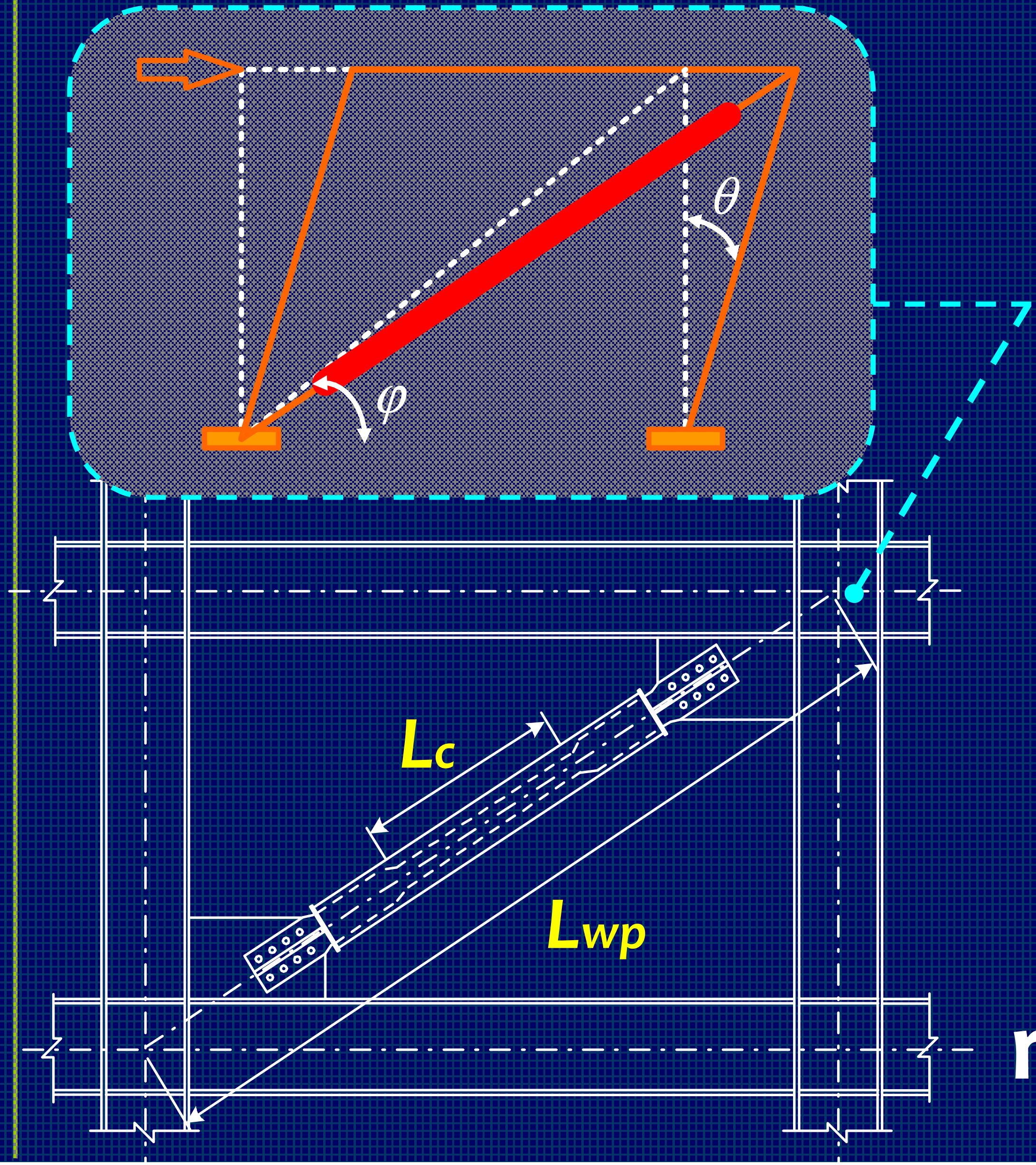
BRB core strain and story drift



$$\varepsilon_{wp} = \frac{\theta}{2} \times \sin 2\varphi$$

$$\alpha_c = \frac{L_c}{L_{wp}}, \ \varepsilon_c = \frac{\varepsilon_{wp}}{\alpha_c}$$

θ=0.02 rad.

φ=45°

α_c=0.5

ε_c=0.02

α_c>0.3 is recommended

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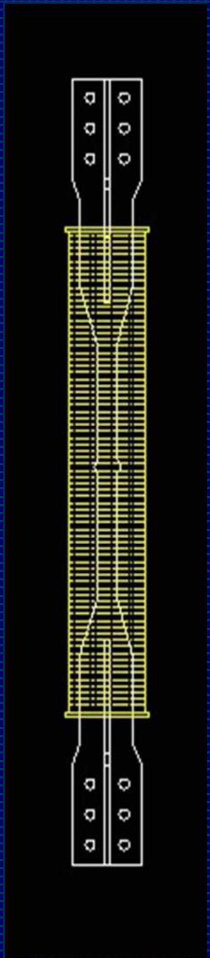
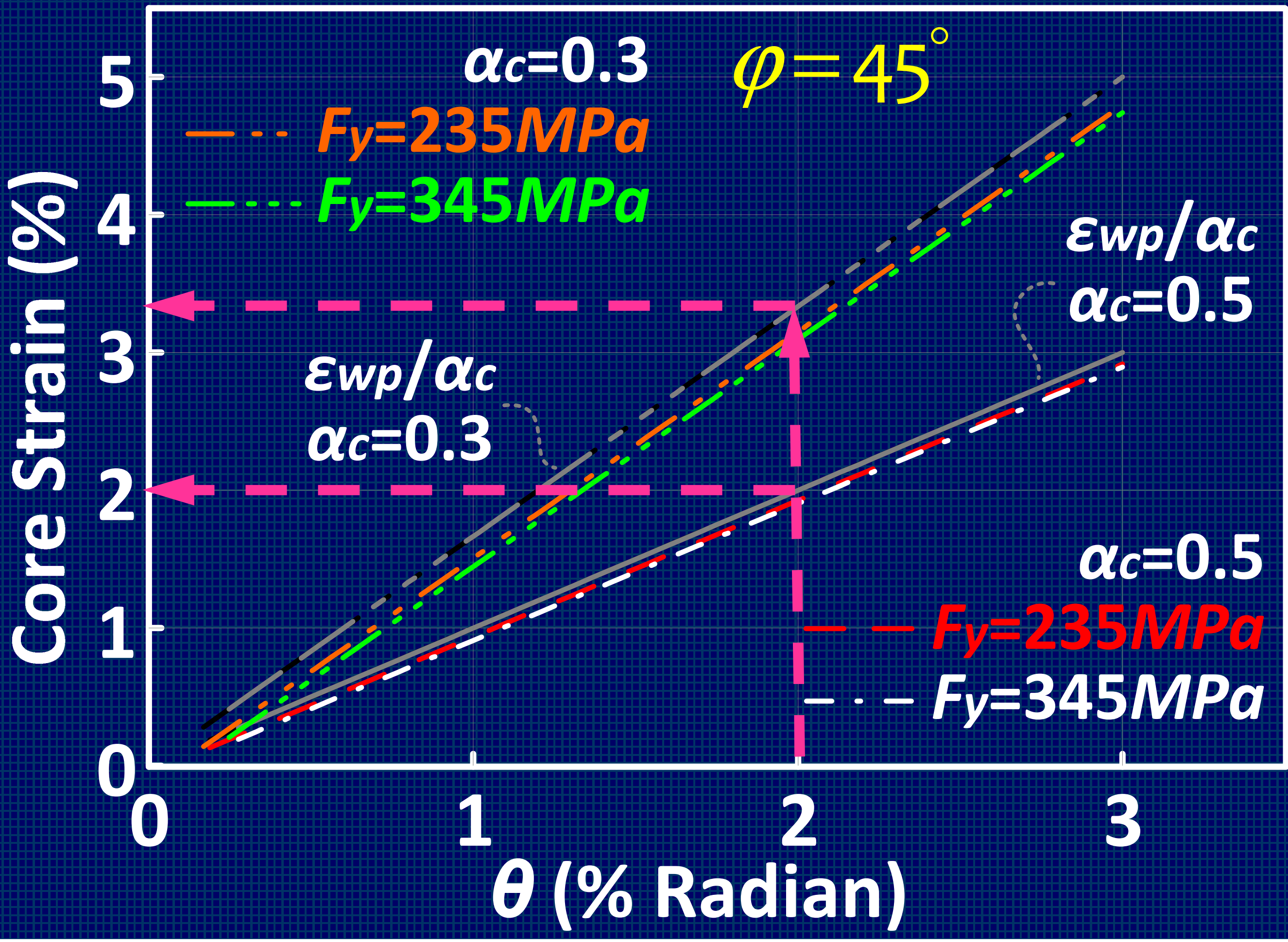
Smaller αc results in a larger εc

$$\varepsilon_c = \frac{\Delta_{wp} - \Delta_t - \Delta_j}{L_c} = \frac{\varepsilon_{wp}}{\alpha_c} - \cancel{\frac{P}{EA_c}\left(\frac{\alpha_j}{\alpha_c a_j} - \frac{\alpha_t}{\alpha_c a_t}\right)} = \frac{\theta \sin 2\varphi}{2\alpha_c}$$





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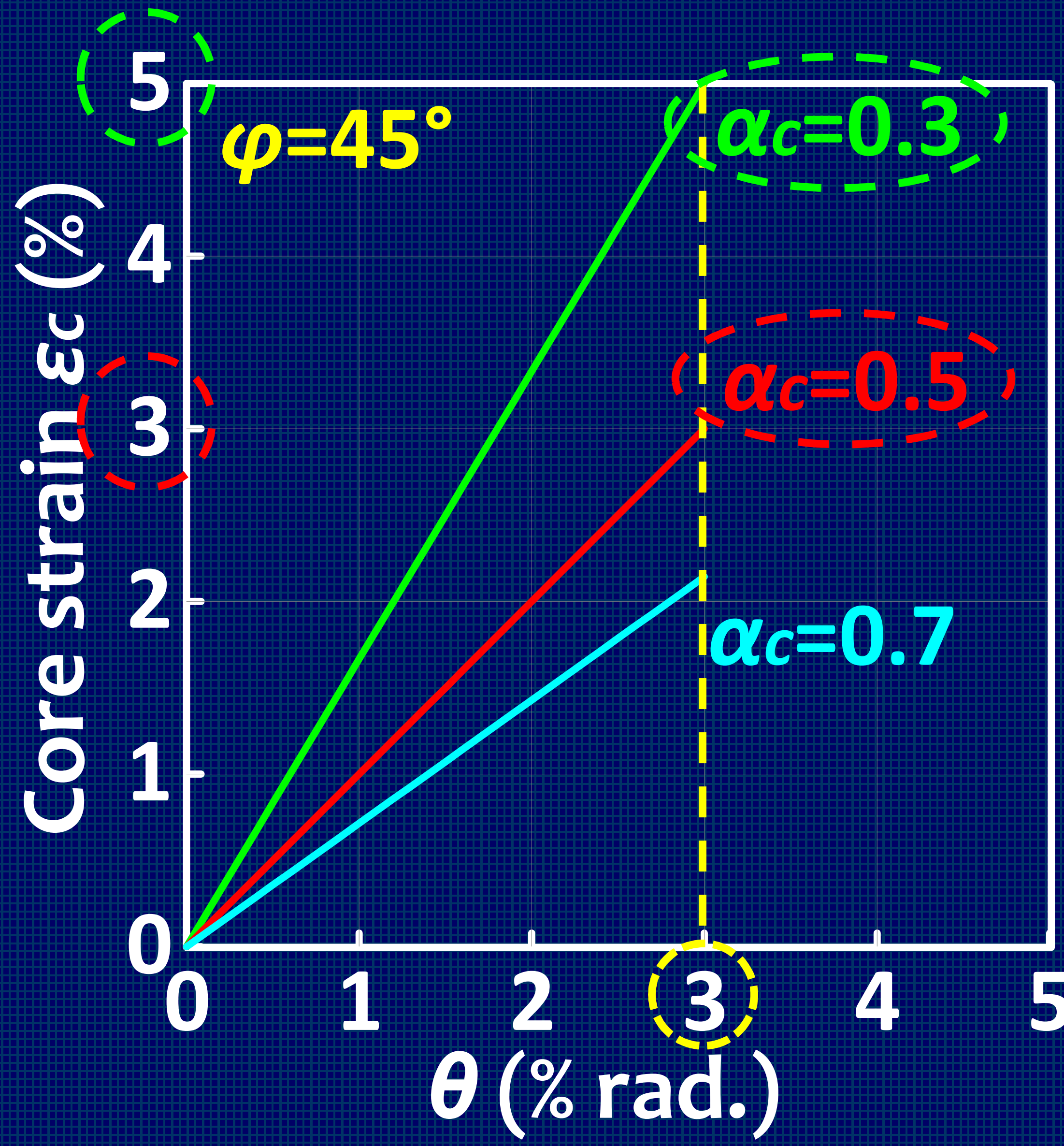
Smaller αc results in a larger εc

$$\varepsilon_{wp} = \frac{\theta}{2} \times \sin 2\varphi$$

$$\alpha_c = \frac{L_c}{L_{wp}}, \ \varepsilon_c = \frac{\varepsilon_{wp}}{\alpha_c}$$



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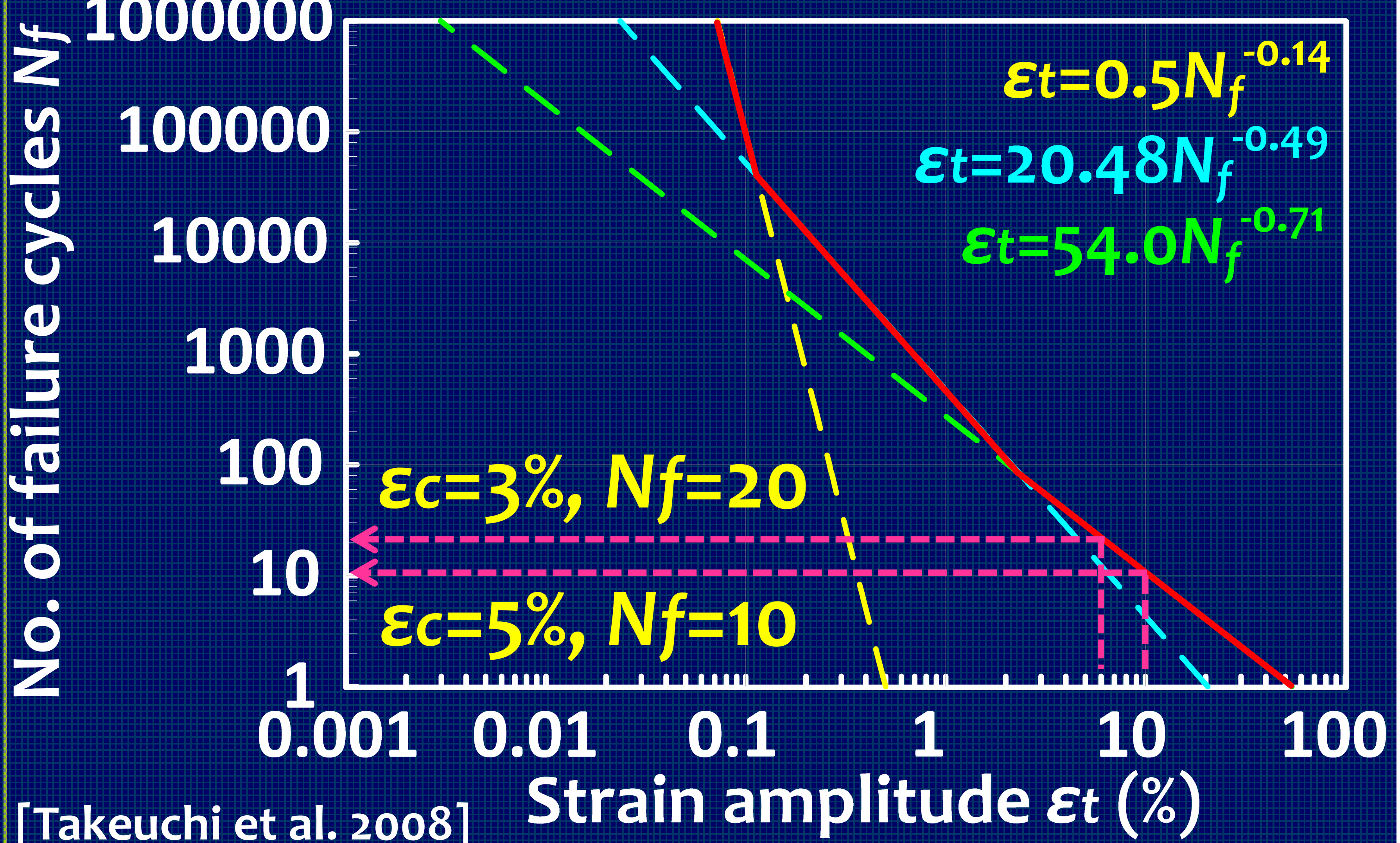
A smaller ε_c results in a Larger N_f

N_f=number of cycles before fracture



[Takeuchi et al. 2008]

Design Procedures for BRBF

- **Fundamental BRBF period** $T = 0.070 h_n^{3/4}$

  h_n= building height (m)
- **Compute base shear, using Response Modification Factor (R=8, ASCE7-10)**
- **Distribute the base shear vertically and estimate the brace axial load**
- **Select BRB core cross-sectional area** $A_c = \dfrac{P_{BRB}}{0.9F_y}$
- **Construct analytical model using truss elements for BRBs (Q<1.6)**

$$K_{eff} = Q \cdot \frac{EA_c}{L_{wp}}$$

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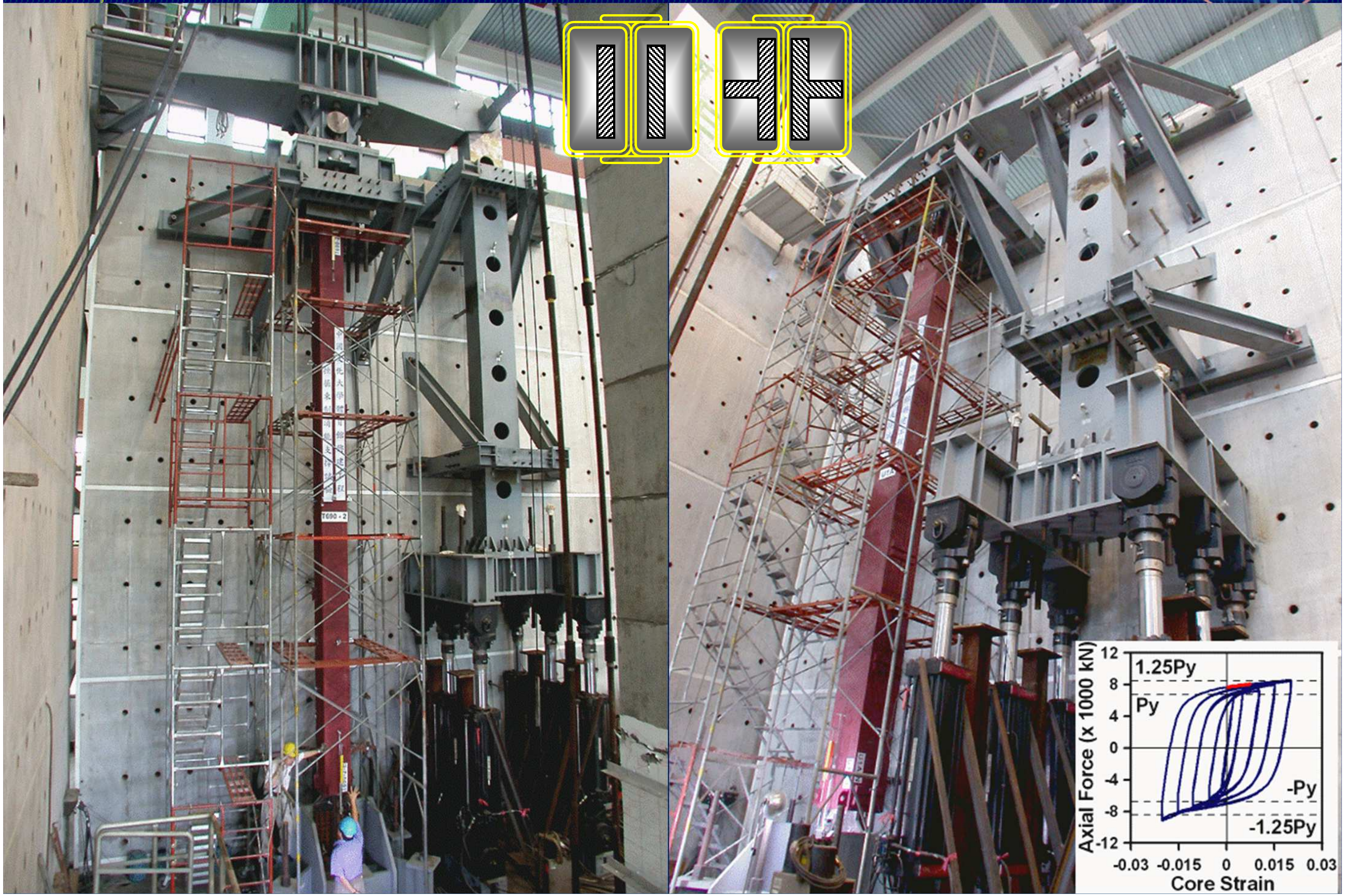
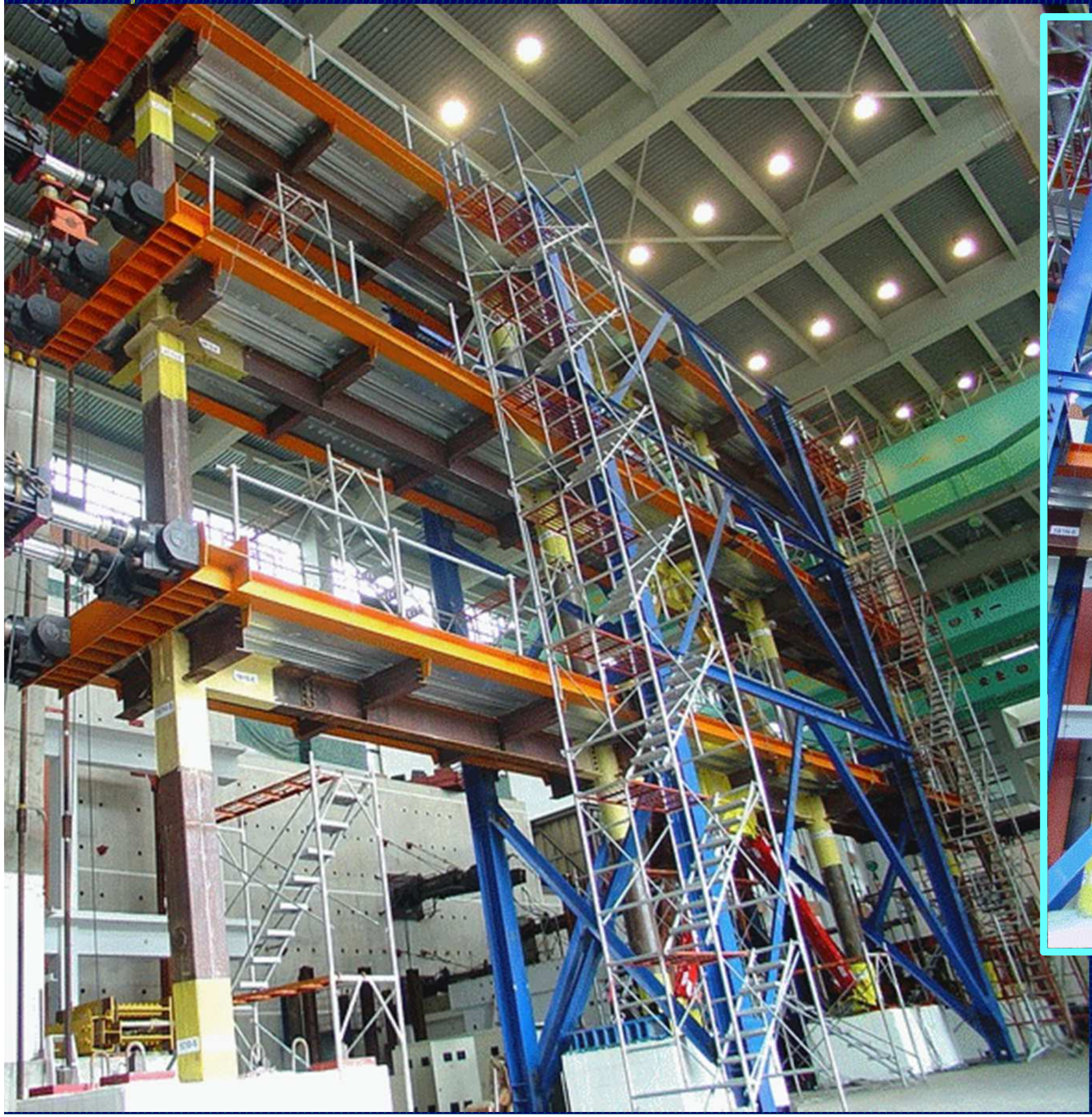
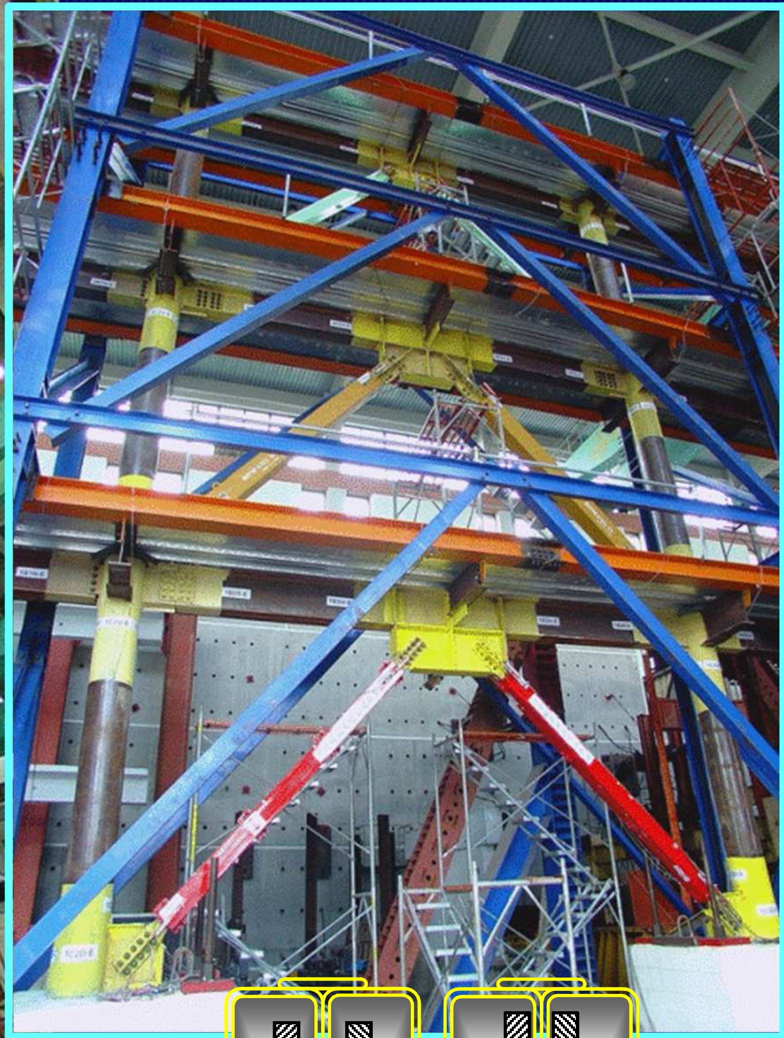
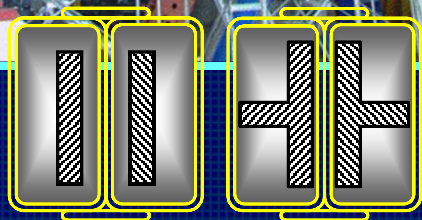
Full-scale DC-BRB component test



Full-scale DC-BRB frame test

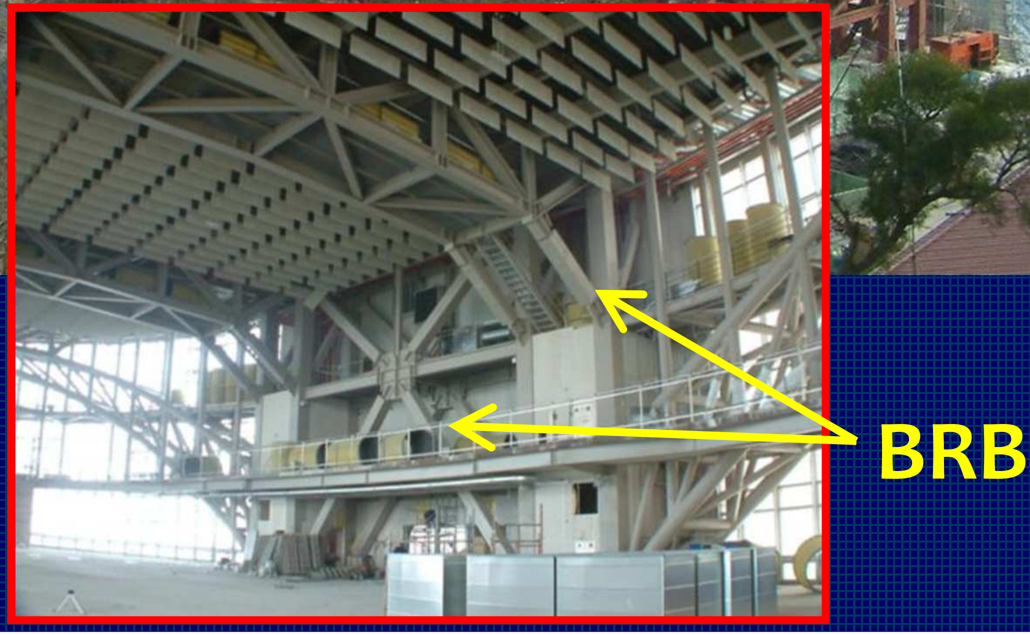






Seismic retrofit of RC frame

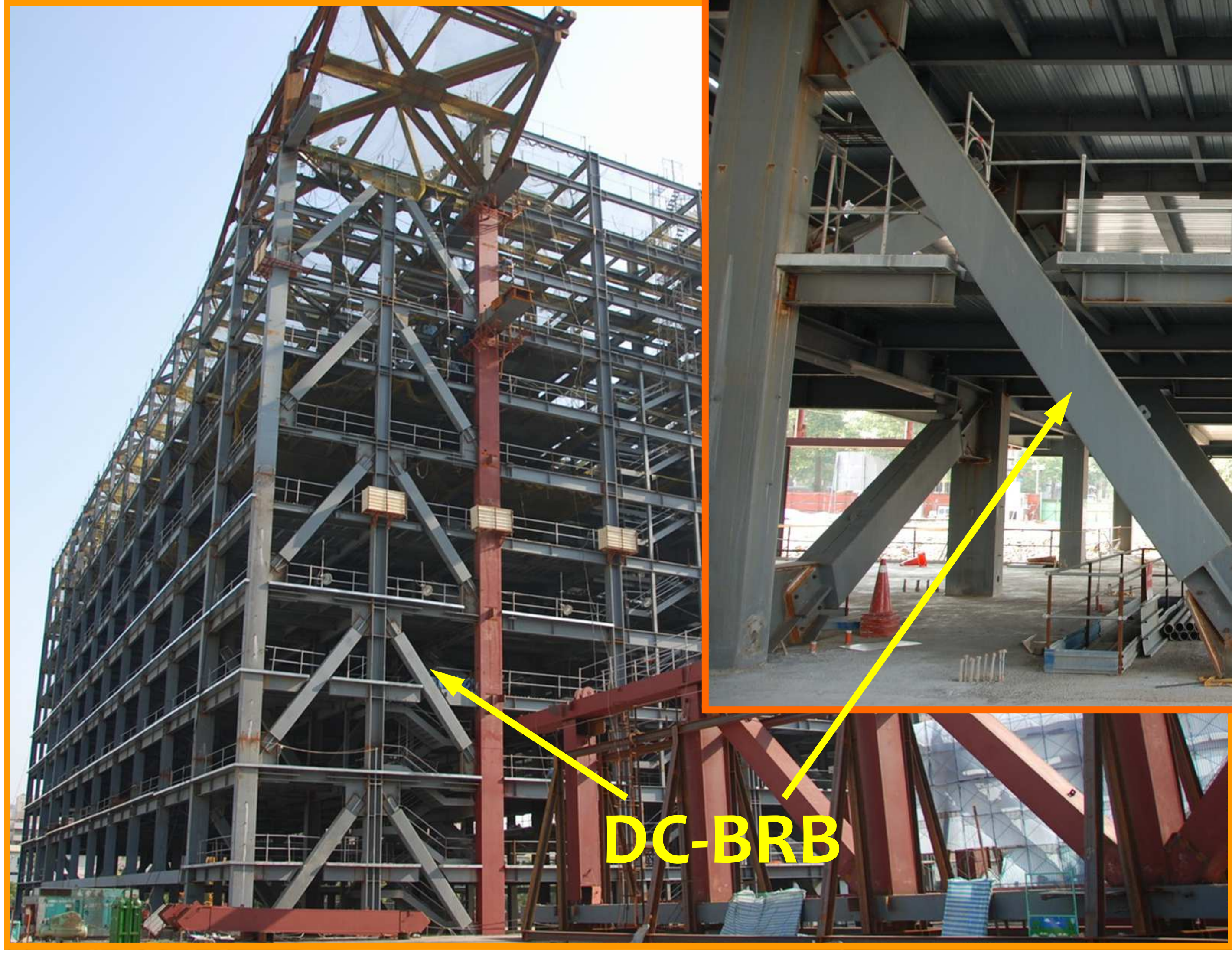
Stadium in Taipei

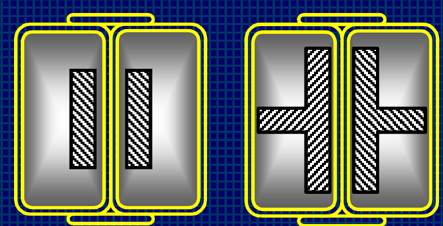


NTU Children's Hospital

City hall of Taichung

$P_{y,max}$=20000kN





Seismic retrofit of RC building using all-steel DC-BRBs

Seismic retrofit of an RC building

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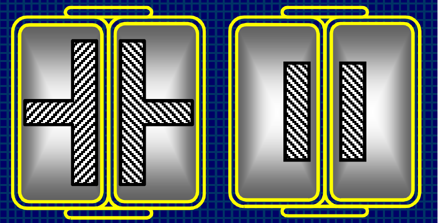
Applications of DC-BRBs

- 15 fabricators were licensed



- Adopted by more than 25 engineering consulting companies
- More than 12,000 BRBs have been installed in more than 60 buildings
- Buildings' seismic performance is improved cost-effectively

Challenges faced

- Very large load carrying capacity
- Application in fast track projects
- Reducing the steel material usage
- Reliable and cost-effective fabrication procedures for unbonding mechanism
- Economical on-site BRB-to-frame connections

More researches have been conducted.

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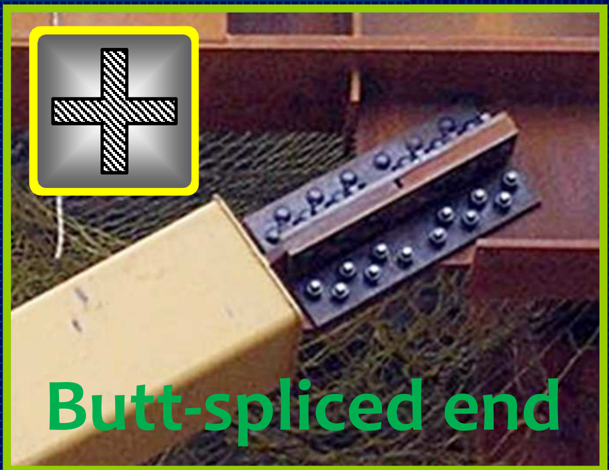
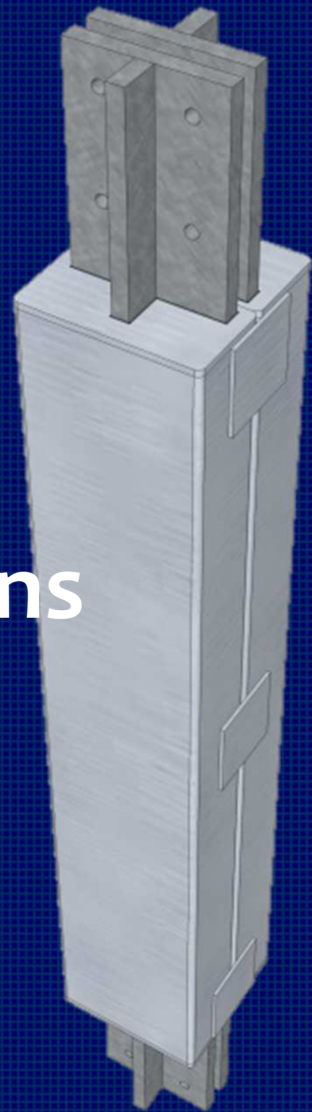
Benefits of Lapped End Connections

- Shorten the connection length
- Enhance the out-plane stability
- Reduce the brace core strain
- Reduce the BRB axial stiffness
- Allow welded & bolted connections



Butt-spliced end

Lapped end



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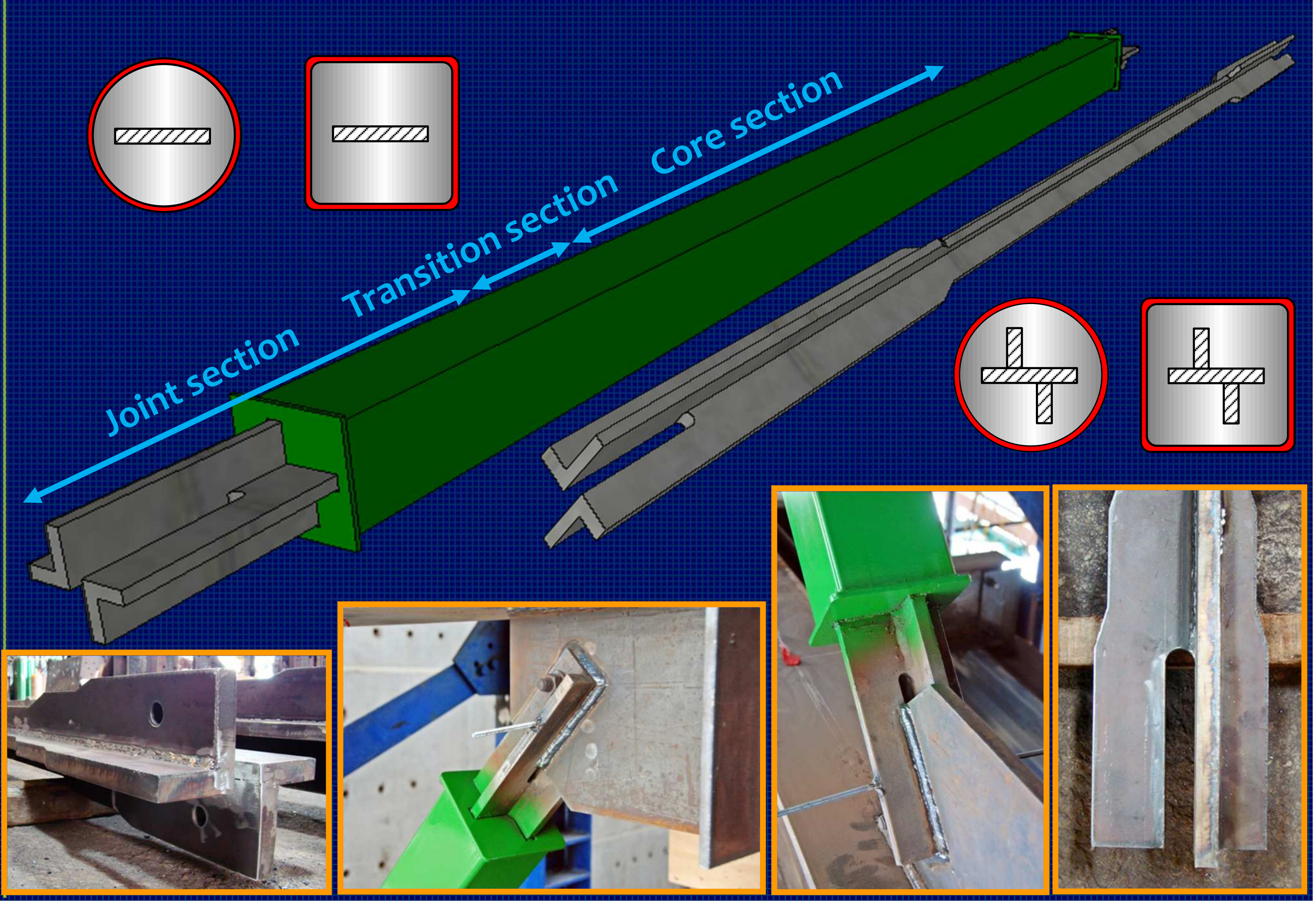
End-slot detail is very common

Welded end-slot BRB (WES-BRB)



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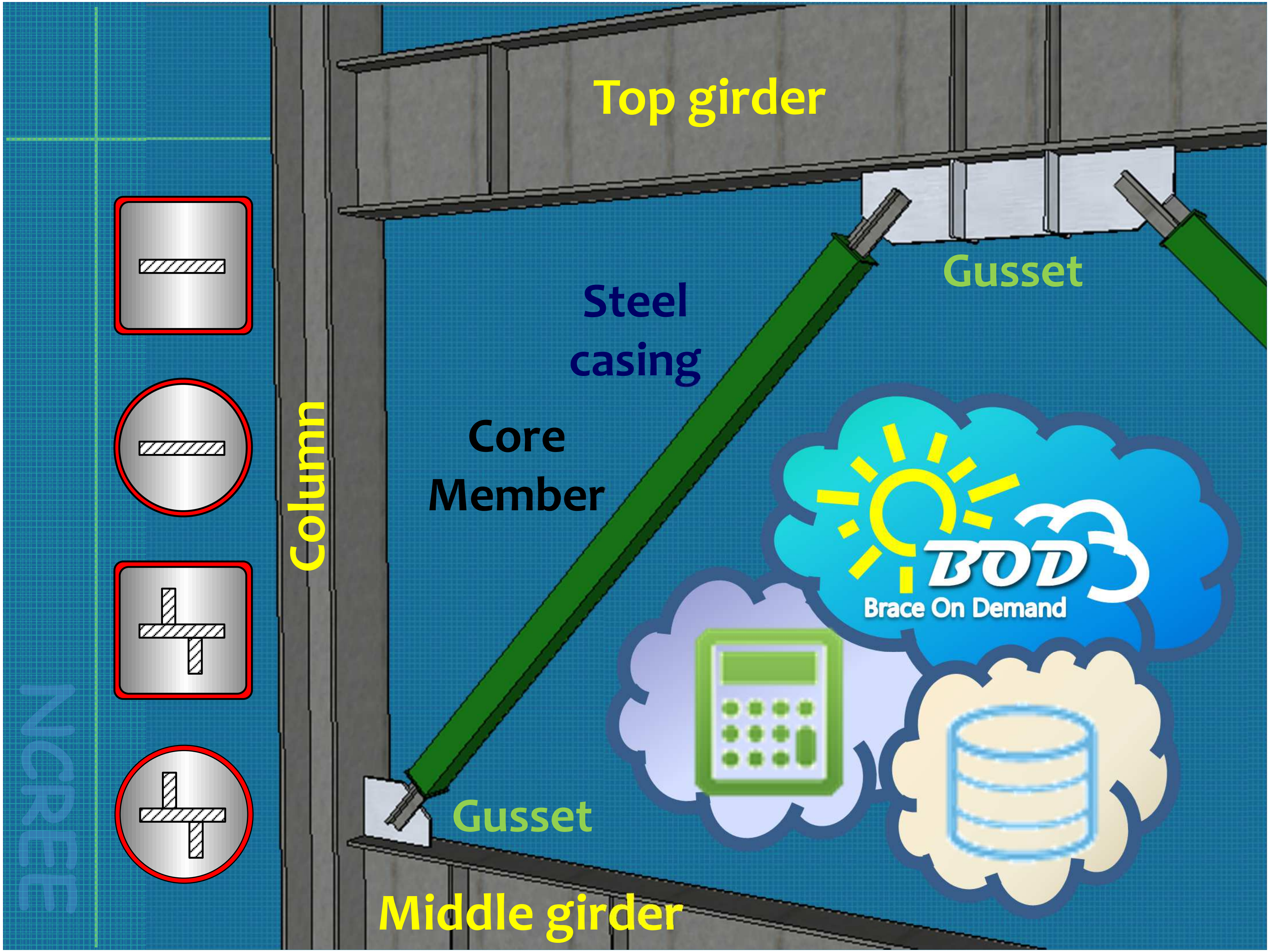
Conclusions

WES-BRB can achieve:

- Compact and stable end connection
- Reduce the BRB core strain
- Reduce the BRB axial stiffness
- Economical on-site BRB-to-frame connections
- Improve the building seismic performance
- Cost-effective in BRBF construction

Today's presentations

- Experimental performance of welded end-slot BRB (An-Chien Wu)
- Seismic design of WES-BRB and gusset connections (Pao-Chun Lin)
- A cloud service for seismic design of buckling restrained braces and connections (Ming-Chieh Chuang)


Top girder
Gusset
Steel casing
Core Member
Column
BOD
Brace On Demand
Gusset
Middle girder
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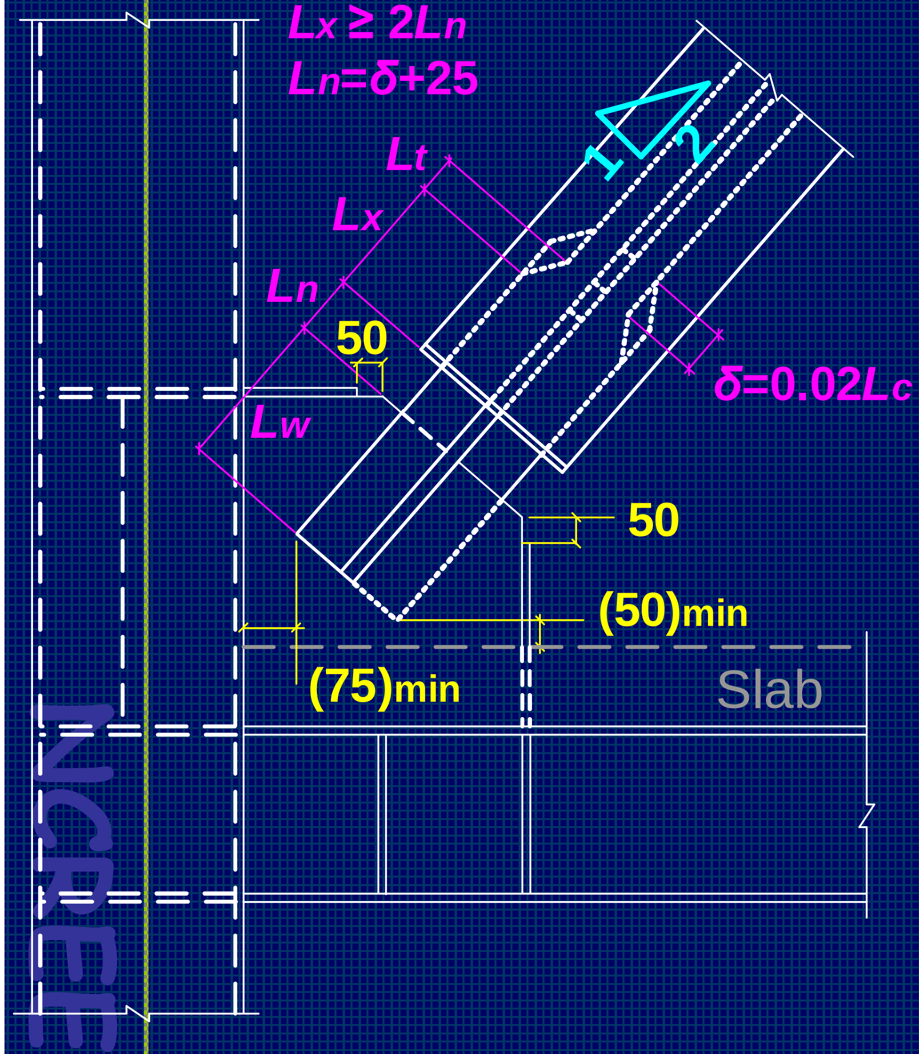
WES-BRB and Connection Designs



Limit States：

(1) Steel casing buckling

(2) Joint region yielding

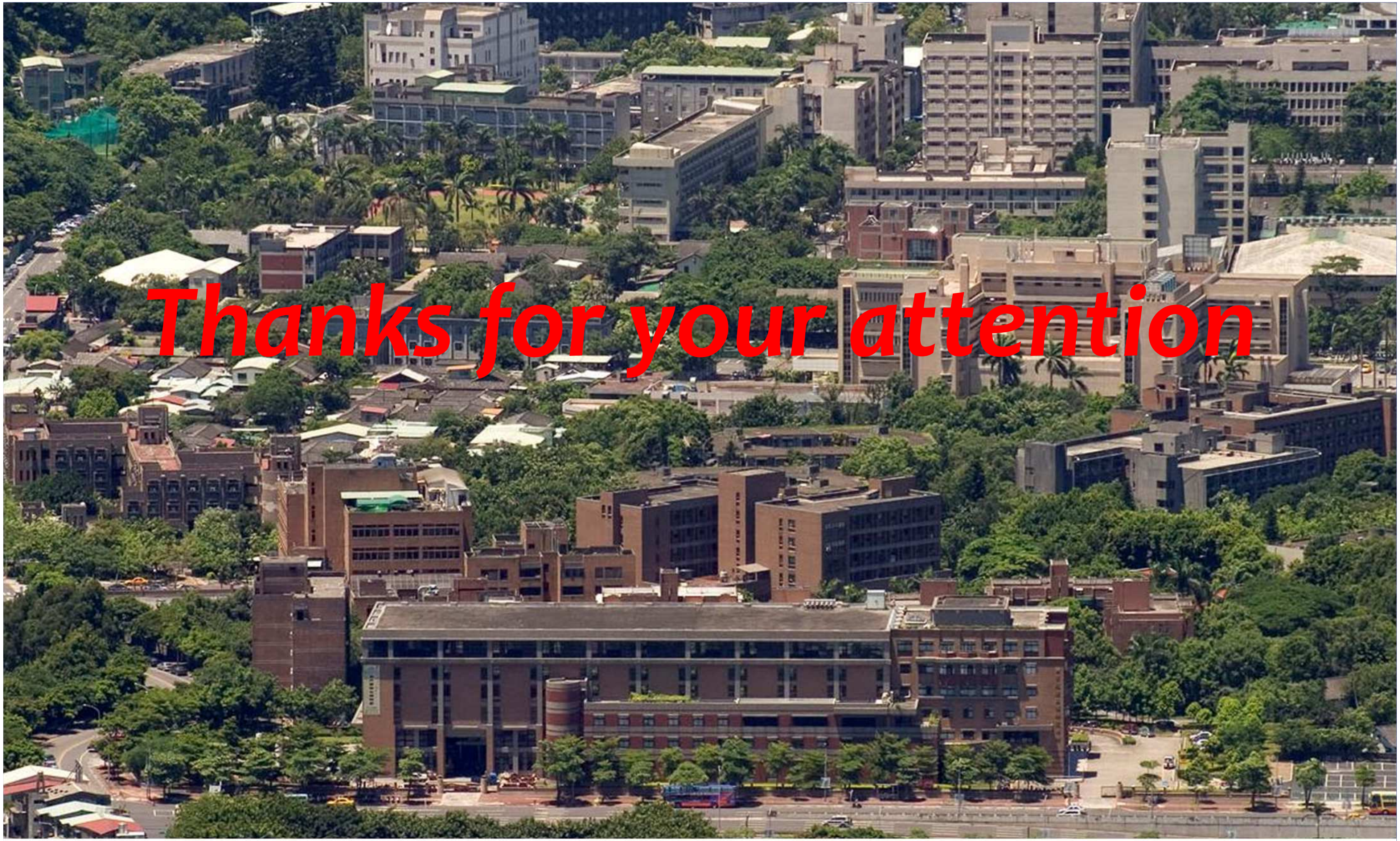
(3) Joint region buckling

(4) Gusset block shear

(5) Gusset yielding

(6) Gusset buckling

(7) Gusset to beam/column interface strengths



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