Introduction of BRBs Using Welded End-slot Connections

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Using WES-BRBs for An Improved Seismic Resisting Performance of Buildings
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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)
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
Major facilities in NCREE

Reaction Walls at NCREE
(15m+15m+12m+12m=180 feet)

Strong Floor & Reaction Wall

5mx5m 3D Shaking Table
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
SCBFs offer the high lateral stiffness and strength
## Basic LRFD Load Combinations

1. $1.4D$
2. $1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$
3. $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (0.5L \text{ or } 0.8W)$
4. $1.2D + 1.6W + 0.5L + 0.5(L_r \text{ or } S \text{ or } R)$
5. $0.9D + 1.6W$
6. $1.2D + 1.0E + 0.5L + 0.2S$
7. $0.9D + 1.0E$

} \text{ Load Combinations Including } E
Lateral force vs. deformation

\[ R = R_\mu \times \Omega_0 \]

\[ \frac{\Delta}{R} \]

\[ \frac{\Delta_y}{R_\mu} \]

\[ \frac{\Delta_D}{\Omega_0} \]

\[ \text{\(\Delta\)} \]

\[ \text{\(\Delta_s\)} \]

\[ \text{\(\Delta_y\)} \]

\[ \text{\(\Delta_D\)} \]

\[ \varapprox 0.003 \text{ rad.} \]

\[ \varapprox 0.02 \text{ rad.} \]

\(V\)

\(V_E\)

\(V_y\)

\(V_s\)

\(\Omega_0\)
Braced Frame Deformations

Shear

\[ \theta \neq 0 \]

\[ \varepsilon_{wp} \neq 0 \]

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

Bending

\[ \theta \neq 0 \]

\[ \varepsilon_{wp} = 0 \]
Brace strain and story drift

$$\epsilon_{wp} = \frac{\theta}{2} \times \sin 2\phi$$

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

$$\rightarrow \epsilon_{wp} = 0.01$$
Brace response under cyclic loads

W6x20  $KL/r=80$
The brace buckles at a small strain.
Ductile brace connection details (AISC)
Connection failure under tension
Connection failure under tension
Example of brace connection details
Example of brace connection details

>2t
NG design of connection details
Connection failure under compression
Questionable connection details?
Buckling-restrained brace (BRB)

No Buckling (Yielding)

F

P

Tension

Compression

Core member

Unbonding material

Mortar (Concrete)

Steel casing

Buckling restrainer

BRB

NCREE
Predictable strength properties

- **Nominal yield strength**
  \[ P_y = F_y \times A_c \]

- **Max. compressive strength**
  \[ P_{\text{max}} = P_y \times R_y \times \Omega_h \times \beta \]

- \( R_y \): material overstrength factor
- \( \Omega_h \): strain hardening factor
- \( \beta \): compression strength adjustment factor

<table>
<thead>
<tr>
<th>Material</th>
<th>( R_y )</th>
<th>( \Omega_h )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN490B</td>
<td>1.2</td>
<td>1.3</td>
<td>1.1~1.2</td>
</tr>
<tr>
<td>A572 GR50</td>
<td>1.1</td>
<td>1.3</td>
<td>1.1~1.2</td>
</tr>
<tr>
<td>A36</td>
<td>1.5</td>
<td>1.5</td>
<td>1.1~1.2</td>
</tr>
</tbody>
</table>
Select steel casing to prevent buckling

\[ P_y = F_y \times A_c \rightarrow \]

\[ P_{\text{max}} = P_y \times R_y \times \Omega_n \times \beta \]

\[ P_{\text{max}} \leq P_{e\text{ - tube}} = \frac{\pi^2 E I_{\text{tube}}}{(K L_{\text{tube}})^2} \]
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

\[
L_c \quad L_{wp} \quad L_{b}/2 \quad L_{wp} \quad L_{b}/2
\]
Advantages of Double-core BRBs with Lapped Ends

\[ P_{e_{\text{trans}}} = \frac{\pi^2 E I_{\text{trans}}}{(K L_b)^2} \geq P_{\text{max}} \]

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

**Effective axial stiffness**

\[ K_{\text{eff}} = \frac{1}{\frac{L_c}{EA_c} + \frac{2L_t}{EA_t} + \frac{2L_j}{EA_j}} = \frac{EA_c A_t A_j}{L_c A_t A_j + 2L_t A_c A_j + 2L_j A_c A_t} \]

- Area = \( A_c \)
- Area = \( A_t \)
- Area = \( A_j \)

L_j \quad L_t \quad L_c \quad L_t \quad L_j
Effective stiffness factor $Q$

- **Length ratio**
  \[ L_c = \alpha_c L_{wp}, \quad 2L_t = \alpha_t L_{wp}, \quad 2L_j = \alpha_j L_{wp} \]
  \[ \alpha_c + \alpha_t + \alpha_j = 1.0 \]

- **Area ratio**
  \[ A_t = a_t A_c, \quad A_j = a_j A_c \]

- **Effective stiffness**
  \[ K_{eff} = \frac{a_t a_j}{\alpha_c a_t a_j + \alpha_t a_j + \alpha_j a_t} \]
  \[ \frac{E A_c}{L_{wp}} = Q \frac{E A_c}{L_{wp}} \]
$Q$ value is ranging from $1.2 \sim 1.5$

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

\[ \alpha_t = 0.04 \quad \alpha_j = 3.0 \]
\[ \alpha_j = 2.5 \]
\[ \alpha_j = 2.0 \]
\[ \alpha_j = 1.5 \]
The value and yield story drift $\theta_y$ can be calculated using the following equations:

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

A graph is shown with lines for different values of $F_y$: $345 \text{ MPa}$ and $235 \text{ MPa}$, and angles $\varphi$: $30^\circ (60^\circ)$ and $45^\circ$. The graph illustrates how $\theta_y$ varies with $Q$.
\[ \varepsilon_{wp} = \frac{\theta}{2} \times \sin 2\varphi \]

\[ \alpha_c = \frac{L_c}{L_{wp}}, \quad \varepsilon_c = \frac{\varepsilon_{wp}}{\alpha_c} \]

\[ \theta = 0.02 \text{ rad.} \]
\[ \varphi = 45^\circ \]
\[ \alpha_c = 0.5 \]
\[ \varepsilon_c = 0.02 \]

\[ \alpha_c > 0.3 \] is recommended
Smaller $\alpha_c$ results in a larger $\varepsilon_c$

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

$\phi = 45^\circ$

- $\alpha_c = 0.3$
- $\varepsilon_{wp}/\alpha_c$
- $F_y = 235\,\text{MPa}$
- $F_y = 345\,\text{MPa}$

Core Strain (%) vs. $\theta$ (% Radian)

$\alpha_c = 0.5$

$\alpha_c = 0.3$
Smaller $\alpha_c$ results in a larger $\varepsilon_c$.

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

\[ \alpha_c = \frac{L_c}{L_{wp}} \], \hspace{1cm} \varepsilon_c = \frac{\varepsilon_{wp}}{\alpha_c} \]
A smaller $\varepsilon_c$ results in a larger $N_f$.

$N_f =$ number of cycles before fracture

$\varepsilon_t = 0.5N_f^{-0.14}$

$\varepsilon_t = 20.48N_f^{-0.49}$

$\varepsilon_t = 54.0N_f^{-0.71}$

$\varepsilon_c = 3\%$, $N_f = 20$

$\varepsilon_c = 5\%$, $N_f = 10$

[Takeuchi et al. 2008]
Design Procedures for BRBF

- Fundamental BRBF period
  \[ T = 0.070 h_n^{3/4} \]
  \[ h_n = \text{building height (m)} \]

- Compute base shear, using Response Modification Factor \((R=8, \text{ ASCE7-10})\)

- Distribute the base shear vertically and estimate the brace axial load

- Select BRB core cross-sectional area
  \[ A_c = \frac{P_{BRB}}{0.9 F_y} \]

- Construct analytical model using truss elements for BRBs \((Q<1.6)\)

  \[ K_{eff} = Q \cdot \frac{E A_c}{L_{wp}} \]
Full-scale DC-BRB component test
Full-scale DC-BRB frame test
Seismic retrofit of RC frame
Stadium in Taipei
NTU Children’s Hospital

BRB
City hall of Taichung

\[ P_{y,\text{max}} = 20000 \text{kN} \]
Seismic retrofit of RC building using all-steel DC-BRBs
Seismic retrofit of an RC building
# 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.
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
End-slot detail is very common
Welded end-slot BRB (WES-BRB)
## 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

Gusset

Column

Middle girder

BOD
Brace On Demand
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

\[
\delta = 0.02L_c
\]

\[
L_x \geq 2L_n
\]

\[
L_n = \delta + 25
\]

\[
L_t
\]

\[
L_w
\]

(75) min

(50) min

Slab
Thanks for your attention