BUCKLING-RESTRAINED BRACE
HISTORY, DESIGN and APPLICATIONS

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1.1 Composition of buckling-restrained Braces (BRB)

Concept of Buckling-restrained Brace Mortar

Types of restrainer

Appearance of typical BRB
Chapter 1: Composition and history of Buckling-restrained Braces

Buckling-restrained Braces and Applications

Development of higher buckling mode

Clearance and eccentricity

Hysteresis of well-designed BRB

Restrainer
Core plate

Axial deformation (mm)
Axial force (kN)
1.2 History of Development

1972: Takeda et al. tried to improve the post-buckling behaviour of H-section braces by encasing the steel section in reinforced concrete. However, because no debonding mechanism was provided, the restrainer received a significant compressive force, cracked and ultimately experienced overall buckling.

1979: Motizuki et al. proposed introducing a debonding layer between the core plate and reinforced concrete restrainer. However, the system tended to buckle at the unrestrained core extension.

1988: The first practical buckling-restrained brace was achieved by Saeki, Wada, et al. employed rectangular steel tubes with infilled mortar for the restrainer, and determined the optimal debonding material specifications to obtain stable and symmetric hysteresis behaviour.
1.2 History of Development

The first application of Buckling-restrained Brace (Unbonded Brace, 1987)

Nippon Steel Headquarter No.2 (Tokyo)

BRB experiment 1987

BRB installation

Chapter 1: Composition and history of Buckling-restrained Braces

Plant & Environmental Sciences, UC Davis

Bennett Federal Building Retrofit/ Salt Lake City

Early US applications in 2000’s
1.3 BRB TYPES (Mortar in-filled type)
1.3 BRB TYPES (Dry type)

- Pin End
- Restrainer Tube
- Solid End
- Core Tube
- Bolt End
- Restrainer Tube
- Restrainer Tube
- Core Tube
- Core Plate
- Restrainer
- Unbonded Sheet
- Core Plate
- Bolt
- Core Plate
- Bolt
- Core Plate
- Bolt
- Restrainer
- Core Plate
Quality Requirement for Hysteresis models

- Inappropriate clearance
- Plastic strain concentration
- Local buckling
- Local bulging
- Uneven stiffness
- Uneven strength
- Degradation in compression side

Bulging-induced failure

- Tearing
- Fracture
- Slack (pin connection)

Buckling-induced failure

- Buckling

Uneven strength

Local bulging
Degradation in compression side
2.1 Restrainer Design

1. **Restrainer** successfully suppresses core first-mode buckling (*Chapter 2*)
2. **Debonding mechanism** decouples axial demands and allows for Poisson effects (*Chapter 2*)
3. **Restrainer wall bulging** due to higher mode buckling is suppressed (*Chapter 3*)
4. **Global out-of-plane stability** is ensured, including connection (*Chapter 4*)
5. **Low-cycle fatigue capacity** is sufficient for expected demands (*Chapter 5*)
Chapter 2: Restrainer Design and Clearances

\[ a_c + y_c = \frac{N^E_{cr} \cdot a_c}{N^E_{cr} - N_{cu}} \]

\[ M^B = N_{cu} (a_c + y_c) = \frac{N_{cu} a_c}{1 - N_{cu} / N^B_{cr}} = \frac{N_{cu} (a + 2s + e)}{1 - N_{cu} / N^B_{cr}} \leq M^B_y \]

\( a \): Fabrication tolerances of core and/or brace
\( s \): Clearance or thickness of debonding material (per face)
\( e \): Eccentricity of the axial force
\( M^B_y \): Flexural strength of the restrainer
\( N_{cu} = d a N_y \): Core yield force amplified by overstrength and strain hardening
\( d a = 1.4 \sim 1.5 \)
\( N^B_{cr} \): Euler buckling strength of the restrainer, given by:
\[ N^B_{cr} = \frac{\pi^2 EI_B}{l_B^2} \]

Where initial imperfections \( e_c / l_B \leq 1/500 \), a relatively slender restrainer with \( l_B / D_r > 20 \) and with an overall safety factor of \( e \alpha \geq 1.5 \):

\[ N^B_{cr} = \frac{\pi^2 EI_B}{l_B^2} > e \alpha N_{cu} \]
3.1 Failure Caused by High Mode Buckling

in-plane local bulging failure

out-of-plane local bulging failure

(Tokyo Institute of Technology)

(National Center for Research on Earthquake Engineering)
3.1 Failure Caused by High Mode Buckling

![Diagram of steel core and mortar layers with section s-s and w-w]

- **Section s-s**: Steel core (Srs) and mortar layer (Srsw) with debonding layer (Dr) between them.
- **Section w-w**: Steel tube wall (Bc) and steel core (Bc) with mortar layer (Srsw) and debonding layer (Dr).

**Notes**:
- Compression and tension behaviors are shown on the left.
- Axial force vs. core strain graph.
- Dimensions and labels include D_r, B_c, B_r, t_c, and s_r.

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Buckling-restrained Braces and Applications
3.1 Failure Caused by High Mode Buckling

Compression is initially applied.

Flexural buckling waves form in both the in-plane and out-of-plane directions.

(section s-s)

(section w-w)
3.1 Failure Caused by High Mode Buckling

Maximum tensile strain is applied

Clearances increase because of the Poisson effect

\[ \gamma_p = 0.5, \text{Poisson ratio of steel inelastic deformation} \]

\[ s_{rs} + 0.5 \gamma_p B_c \varepsilon_t \]

Section s-s

\[ s_{rw} + 0.5 \gamma_p t_c \varepsilon_t \]

Section w-w
3.1 Failure Caused by High Mode Buckling

Compression reaches yield strength $N_y$

High mode buckling waves form and generating the outward forces.

**section s-s**

$$2s_{rs} + \gamma_p B_c \varepsilon_t$$

**section w-w**

$$2s_{rw} + \gamma_p t_c \varepsilon_t$$
3.1 Failure Caused by High Mode Buckling

Compression reaches maximum compressive capacity $N_{cu}$

High mode buckling wavelengths remain, the maximum outwards are fully developed.

**section s-s**

**section w-w**
3.1 Failure Caused by High Mode Buckling

Local bulging failure when restrainer is too weak in sustaining outward forces

Section s-s

In-plane local bulging failure

Section w-w

Out-of-plane local bulging failure

Diagram showing core strain, in-plane bulging, and out-of-plane bulging.
3.2 Estimation on Outward Force (demand)

Apply moment equilibrium condition on the free body, 

**In-plane outward force** \( P_{d,s} \)

\[
P_{d,s} = \frac{4N_{cu} \left( 2s_{rs} + \nu_p B_c \epsilon_t \right)}{I_{p,s}}
\]

**Out-of-plane outward force** \( P_{d,w} \)

\[
P_{d,w} = \frac{4N_{cu} \left( 2s_{rw} + \nu_p t_c \epsilon_t \right)}{I_{p,w}}
\]
3.4 Estimation on Steel Tube Resistance (capacity)

**out-of-plane bulging failure**

External work = \( P_{c,w} \delta_w \)
3.4 Estimation on Steel Tube Resistance

Yield line patterns

**Condition 1**
(Yoshida et al. 2010)
Internal energy: \( E_9 \) (9 yield lines)
\( \alpha: \) minimizing \( E_9 \)

\[
P_{c,w} = \frac{4}{\sqrt{1 - B_c/B_r}} t_r^2 \sigma_{ry}
\]

\[
P_{c,s} = \frac{1}{\sqrt{1 - t_c/D_r}} \frac{4}{4 - 2t_c/D_r} t_r^2 \sigma_{ry}
\]

(resistance factor)

**Condition 2**
Internal energy: \( E_9 \) (9 yield lines)
\( \alpha = 45^\circ \)

\[
P_{c,w} = \frac{4 - 2B_c/B_r}{1 - B_c/B_r} t_r^2 \sigma_{ry}
\]

\[
P_{c,s} = \frac{2}{\sqrt{1 - t_c/D_r}} \frac{4 - 2t_c/D_r}{2} t_r^2 \sigma_{ry}
\]

(resistance factor)

**Condition 3**
Internal energy: \( E_5 \) (5 yield lines)
\( \alpha: \) minimizing \( E_5 \)
\( \alpha = 45^\circ \)

\[
P_{c,w} = \frac{2}{\sqrt{1 - B_c/B_r}} t_r^2 \sigma_{ry}
\]

\[
P_{c,s} = \frac{2}{1 - t_c/D_r} \frac{2 - t_c/D_r}{2} t_r^2 \sigma_{ry}
\]

(resistance factor)

**Condition 4**
(Lin et al. 2010)
Internal energy: \( E_5 \) (5 yield lines)
\( \alpha = 45^\circ \)

\[
P_{c,w} = \frac{2 - B_c/B_r}{1 - B_c/B_r} t_r^2 \sigma_{ry}
\]

\[
P_{c,s} = \frac{2 - t_c/D_r}{1 - t_c/D_r} t_r^2 \sigma_{ry}
\]

(resistance factor)
3.5 Test Results and Evaluations

Experimental resistance factor

\[
\text{out-of-plane: } \frac{4N_{cu,exp}(2s_{rw} + v_p t_c \varepsilon_t)}{I_{p,w} t_r^2 \sigma_{ry}}
\]

\[
\text{in-plane: } \frac{4N_{cu,exp}(2s_{rs} + v_p B_c \varepsilon_t)}{I_{p,s} t_r^2 \sigma_{ry}}
\]

**Example:**

- **Conservative:** bulging is in expectation but did not occur in test
- **Appropriate:** bulging occurred in test and was in expectation
- **Dangerous:** bulging occurred in test but was not in expectation
- **Appropriate:** bulging did not occur in test and was not in expectation

---

[Graph showing experimental resistance factor vs. Bc/Br or tc/Dr]

- ● 15 specimens without bulging
- × 14 out-of-plane bulged specimens
- ▲ 5 in-plane in-plane bulged specimens

**Condition 1**

(9 dangerous estimation)

**Condition 2**

(9 dangerous estimation)

**Condition 3**

(recommended)

**Condition 4**

(over-conservative)
### 3.5 Test Results and Evaluations

**Proposed design method:**

\[
DCR_w = \frac{P_{d,w}}{P_{c,w}} = \frac{(B_r - B_c)}{(2B_r - B_c)\tau^2\sigma_{ry}} \cdot \frac{4N_{cu}\left(2\sigma_{ru} + \nu_p t_c \varepsilon_t\right)}{l_{p,w}} < 1.0
\]

\[
DCR_s = \frac{P_{d,s}}{P_{c,s}} = \frac{(D_r - t_c)}{(2D_r - t_c)t_r^2\sigma_{ry}} \cdot \frac{4N_{cu}\left(2\sigma_{ru} + \nu_p B_c \varepsilon_t\right)}{l_{p,s}} < 1.0
\]

- **Out-of-plane bulging**
  \[
  \frac{t_c}{D_r} \leq 0.85
  \]
- **In-plane bulging**
  \[
  \frac{B_c}{B_r} \leq 0.85
  \]

- ● 15 specimens without bulging
- × 14 out-of-plane bulged specimens
- ▲ 5 in-plane in-plane bulged specimens

![Graph showing resistance factor vs. Bc/Br or tc/Dr]
3.6 Required Mortar Strength for Local Pressure

\[
\frac{P_{d,w}}{l_c B_c} < f'_c
\]

3.7 Local Bulging Criteria for Circular Restrainer

\[
DCR_{sc} = \frac{P_{d,s}}{P_{c,s}} = \frac{(B_r - 2t_r)}{(c_m t_m + t_c) \pi t_r B_r \sigma_{ry}} \cdot \frac{4N_{cu} (2s_{rs} + v_p B_c \varepsilon_t)}{l_{p,s}} < 1.0
\]
Chapter 4: Connection Design and Global Stability

4.2 Design Concepts

The AIJ Recommendations provide rigorous evaluation methods for BRB connection out-of-plane buckling. **Two concepts below are presented:**

1: Cantilevered gusset
2: Restrainer end continuity

BRB configurations

BRB configurations in frame

(a) One-way
(b) Chevron

Type A
(a) low stiffness
(US/NZ details)

Type B
(b) high stiffness
(JP details)

Type C

Not rotationally braced
Stability assessment

Tsai and Nakamura’s proposal (2002)

\[ \lambda_r = \frac{L_0^2}{i_c^2} \]

Koetaka and Inoue’s proposal (2008)

\[ N_{cr} = \frac{(1-2\alpha_N \xi)l}{(l+d^*-\alpha_N \xi l)(d^*+\alpha_N \xi l)} \cdot K_R \]

\[ N_{cr} = \frac{1-\xi_1-\xi_2}{(1-\xi_1) \cdot \xi_2 L_0} \cdot K_R \]
Hikino and Okazaki’s proposal (2013)

\[ N_{cr} = \frac{K_R L_1}{L_1 + L_2} \frac{1-2\xi - d^*}{1-\xi} = \frac{1-\xi_1 - \xi_2}{(1-\xi_1) \cdot \xi_2 L_0} \cdot K_R \]

Takeuchi’s proposal (2013)

\[ N_{lim1} = \frac{(M_p^r - M_0^r)}{(M_p^r - M_0^r) / (a_r N_{cr}^r)} + 1 > N_{cu} \]

\[ N_{cr}^r = \frac{\pi^2 (1-2\xi) \gamma J EI_B}{(2\xi L_0)^2} \cdot \frac{\kappa_{Rg}}{\xi \kappa_{Rg}} + \frac{24 / \pi^2}{(1-2\xi) \xi \kappa_{Rg}} \]

\[ \lambda_r = \frac{2\xi L_0}{i_c} \cdot \sqrt{\frac{\kappa_{Rg} + 24 / \pi^2}{(1-2\xi) \xi \kappa_{Rg}}} \]

a) mortar-filled BRB

b) steel tube-in-tube BRB

[Buckling-restrained braces and applications]
**Takeuchi’s proposal (cont’d)**

In case of plastic hinges produced at joint ends

\[
N_{\text{lim2}} = \frac{\left[ \left(1 - 2\xi \right) M_p^g - M_0^r \right] + \left( M_p^r - M_0^r \right) }{a_r} \left[ \left(1 - 2\xi \right) M_p^g - M_0^r \right] + \left( M_p^r - M_0^r \right) \right] / \left( a_r N_{\text{cr}}^B + 1 \right) > N_{\text{cu}}
\]

\( (a_r \text{ is the maximum imperfection along the restrainer}) \)

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**Ultimate strength**

- Stable: \( N = N_{\text{cr}} + \frac{M_p^r - M_0^r}{y_r + a_r} \)
- Stable: \( N = N_{\text{cr}} + \frac{M_p^r - M_0^r}{y_r + a_r} \)

**Stability limit** \( N_{\text{lim}} \)

**Maximum axial strength of core plate** \( N_{\text{cu}} \)

**Elastic buckling path**

**Plastic collapse path**
4.6 In-plane pinching

(a) Frame pinching  (b) Frame opening

Expected Failure  Recommended Proposal
Cumulative energy-dissipation capacity

(a) Ordinary Tube Brace

(b) Incomplete Buckling-restrained Brace

(c) Complete Buckling-restrained Brace

Local Buckling Mechanism

Plastic stress concentration

Friction

Mild local buckling and averaged strain distribution along plastic zone

Local buckling distribution until fracture
Chapter 5: Cumulative Deformation Capacity until Fracture

BRB Fatigue Performance under Cyclic Loading

Steel material fatigue performance\(^4\)

\[
\Delta \varepsilon_i = C_1 N_f^{-m_1} + C_2 N_f^{-m_2}
\]

Manson-Coffin Fatigue Formula


Steel material fatigue performance\(^4\)

Elastic region

Plastic region

BRB < Steel Material
Chapter 5: Cumulative Deformation Capacity until Fracture

Fatigue Performance of BRB using Plastic Strain Concentration Mechanism

Fatigue performance of BRB decreases as clearance between core plate and restrainer increases.

Chapter 5: Cumulative Deformation Capacity until Fracture

Estimation by Miner’s Method

Fatigue Curve under Constant Amplitude

Accuray by Miner’s Method

Gradually Increasing
Fatigue
Shaking Table

Evolutionary Dynamics

34 Buckling-restrained Braces and Applications
Chapter 6: Performance Test Specification for BRB

6.1 Test Configurations

1) Uniaxial test

Single Brace test

Oil Jack or Dynamic Actuator

Load Dir.

BRB

Sliding Base

Eccentric Loading of Brace

Single Brace test with rotational deformation
(ANSI/AISC 341-05)

Loading of Brace with Constant Imposed Rotation
2) Inclined test

Inclined layout with column

Inclined layout with initial out-of-plane drift
3) In-frame test

![Diagram of in-frame test setup](image_url)
## Example BRB testing protocol

(a) ANSI/AISC 341-05 and US practice

<table>
<thead>
<tr>
<th>Cycle (Story drift angle)</th>
<th>Inelastic Deformation ($\Delta_{bm} = 4\Delta_{by}$)</th>
<th>Cumulative strain ($\Delta_{by} = 0.25%$)</th>
<th>Cumulative Inelastic strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_{by} \times 2$</td>
<td>$2 \times 4 \times (\Delta_{by} - \Delta_{by}) = 0\Delta_{by}$</td>
<td>$2 \times 4 \times 0.25 = 2%$</td>
<td>$2 \times 4 \times 0 = 0%$</td>
</tr>
<tr>
<td>$0.5\Delta_{bm} \times 2$</td>
<td>$2 \times 4 \times (2\Delta_{by} - \Delta_{by}) = 8\Delta_{by}$</td>
<td>$2 \times 4 \times 0.5 = 4%$</td>
<td>$2 \times 4 \times 0.25 = 2%$</td>
</tr>
<tr>
<td>$1.0\Delta_{bm} \times 2$</td>
<td>$2 \times 4 \times (4\Delta_{by} - \Delta_{by}) = 24\Delta_{by}$</td>
<td>$2 \times 4 \times 1.0 = 8%$</td>
<td>$2 \times 4 \times 0.75 = 6%$</td>
</tr>
<tr>
<td>$1.5\Delta_{bm} \times 2$</td>
<td>$2 \times 4 \times (6\Delta_{by} - \Delta_{by}) = 40\Delta_{by}$</td>
<td>$2 \times 4 \times 1.5 = 12%$</td>
<td>$2 \times 4 \times 1.25 = 10%$</td>
</tr>
<tr>
<td>$2.0\Delta_{bm} \times 2$</td>
<td>$2 \times 4 \times (8\Delta_{by} - \Delta_{by}) = 56\Delta_{by}$</td>
<td>$2 \times 4 \times 2.0 = 16%$</td>
<td>$2 \times 4 \times 1.75 = 14%$</td>
</tr>
<tr>
<td>$1.5\Delta_{bm} \times 4$</td>
<td>$4 \times 4 \times (6\Delta_{by} - \Delta_{by}) = 80\Delta_{by}$</td>
<td>$4 \times 4 \times 1.5 = 24%$</td>
<td>$4 \times 4 \times 1.25 = 20%$</td>
</tr>
</tbody>
</table>

(1.5$\Delta_{bm}$ until fracture)

Total: $=208\Delta_{by}$ =56% =52%

(b) BCJ and Japanese practice

<table>
<thead>
<tr>
<th>Cycle (Plastic length strain)</th>
<th>Inelastic Deformation ($\Delta_{by} = 0.25%$)</th>
<th>Cumulative strain ($\Delta_{by} = 0.25%$)</th>
<th>Cumulative Inelastic strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_{by} \times 3$</td>
<td>$3 \times 4 \times (\Delta_{by} - \Delta_{by}) = 0\Delta_{by}$</td>
<td>$3 \times 4 \times 0.25 = 3%$</td>
<td>$3 \times 4 \times 0 = 0%$</td>
</tr>
<tr>
<td>$0.5% \times 3$</td>
<td>$3 \times 4 \times (2\Delta_{by} - \Delta_{by}) = 8\Delta_{by}$</td>
<td>$3 \times 4 \times 0.5 = 6%$</td>
<td>$3 \times 4 \times 0.25 = 3%$</td>
</tr>
<tr>
<td>$1.0% \times 3$</td>
<td>$3 \times 4 \times (4\Delta_{by} - \Delta_{by}) = 36\Delta_{by}$</td>
<td>$3 \times 4 \times 1.0 = 12%$</td>
<td>$3 \times 4 \times 0.75 = 9%$</td>
</tr>
<tr>
<td>$2.0% \times 3$</td>
<td>$3 \times 4 \times (8\Delta_{by} - \Delta_{by}) = 84\Delta_{by}$</td>
<td>$3 \times 4 \times 2.0 = 24%$</td>
<td>$3 \times 4 \times 1.75 = 21%$</td>
</tr>
<tr>
<td>$3.0% \times 3$</td>
<td>$3 \times 4 \times (12\Delta_{by} - \Delta_{by}) = 132\Delta_{by}$</td>
<td>$3 \times 4 \times 3.0 = 36%$</td>
<td>$3 \times 4 \times 2.75 = 33%$</td>
</tr>
</tbody>
</table>

(3.0% until fracture)

Total: $=264\Delta_{by}$ =81% =66%
6.4 Post Earthquake Inspection

Koriyama Big-Eye, a 24-story, 133m building complete in 1998 in Fukushima experienced Tohoku Earthquake 2011 at 234km from epicenter. The cumulative deformation measurements and earthquake record were used to calibrate a finite element model, indicated a peak ductility demand of \( \mu \approx 4 \) and a cumulative plastic strain of \( \sum \varepsilon_p \approx 20\% \) \( (\sum \delta_p / \delta_y \approx 100) \) in the Y direction, still 6% of their capacity.

Inaba Y, Morimoto S, Tsuruta S, Takeuchi T, Matsui R. Damage record of buckling restrained braces that received actual ground motion. *AIJ Kanto Branch Research Report Collection 2017*
### 7.1.1 Damage Tolerant Concepts

**Damage Tolerant Structure**

Earthquake Ground Motion and Seismic Design in Japan

<table>
<thead>
<tr>
<th>Static Design</th>
<th>Dynamic Design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Likely earthquake ground motion during building life span</strong></td>
<td><strong>Maximum Velocity of Grand Motion</strong></td>
</tr>
<tr>
<td><em>Static Lateral Force for Elastic Design defined on the code.</em></td>
<td>= 25 cm/s.</td>
</tr>
<tr>
<td><em>Allowable Stress Design.</em></td>
<td><em>Interstory Deflection Angle &lt;= 1/200.</em></td>
</tr>
<tr>
<td><em>Interstory Deflection Angle &lt;= 1/200.</em></td>
<td><em>Ductility Factor &lt;= 1.0.</em></td>
</tr>
<tr>
<td><strong>Possible Largest earthquake ground motion</strong></td>
<td><strong>Maximum Velocity of Grand Motion</strong></td>
</tr>
<tr>
<td><em>No Criteria for High Rize Steel Buildings.</em></td>
<td>= 50 cm/s.</td>
</tr>
<tr>
<td><em>1.5 times lateral shear capacity to the elastic design force around 1/100.</em></td>
<td><em>Interstory Deflection Angle &lt;= 1/100.</em></td>
</tr>
<tr>
<td><em>Interstory Deflection Angle for Reinforced Concrete High Rize Buildings.</em></td>
<td><em>Ductility Factor &lt;= 2.0.</em></td>
</tr>
</tbody>
</table>

Chapter 7.1: Damage Tolerant Concept

### Strain Distribution along the beam

- SS400
- SM490
- HT590 & HT780

### System of Main Structure and Damper

- **Main Structure**
- **Damper**

#### BRB Energy Dissipation Zone
- **Main Frame**
- **Damage Zone**

#### Shear Force-Story Drift Relationship

- **(a) Ordinary Concept**
- **(b) Damage Tolerant Concept**

**Shear force-Story Drift Relationship of Damage Tolerant Structure**

- **Max Response**
- **Main Frame (Normal Steel)**
- **BRB**

**Shear Force**
- **Story Drift Angle**
  - 0.00125 (1/800)
  - 0.005 (1/200)
  - 0.01 (1/100)

**Main Frame (High-strength Steel)**

- **Max Response**
- **BRB**

**Shear Force**
- **Story Drift Angle**
  - 0.00125 (1/800)
  - 0.01 (1/100)
Chapter 7.1: Damage Tolerant Concept

Triton Square Project

Buckling-restrained Braces and Applications
Chapter 7.1: Damage Tolerant Concept

Following Damage Tolerant Projects

Grand Tokyo North Tower

Election of Large BRBF
Grid-skin structures with BRBs

BRB is suitable for Grid-skin structures

Ductile elements, Less bending loss,
Free internal space, Design with facades
Energy-dissipation Skins with Solar Cells
Energy-dissipation Skins with Solar Cells

- Solar-panel Envelope Structure
  Flexible and Lightweight structure over the main frame

- Main Frame
  Spiral Layout of Energy-dissipation Fuses around Perimeter zones

- Open Space

- Energy Dissipation Brace
Midorigaoka-1st Building Retrofit concept

- 5F: Continuously Occupied
- 4F: Laboratory Offices
- 3F: Adding Damper only
- 2F: Drawing Rm.
- 1F: Class Rm.
- B1F: Laboratories

Inner Work in Summer Vacation
Carbon-fiber Reinforcement + Additional Damper
Chapter 7.3: Seismic retrofit with BRBs

Reduced mock-up test for 2nd floor frame

(a) Before retrofit

(b) After Retrofit
Chapter 7.3: Seismic retrofit with BRBs

(a) Before Retrofit

Maximum story drift obtained by time-history analyses

(b) After Retrofit

No damage on Main Structure

Detail for the connections between frame and BRB
Chapter 7.3: Seismic retrofit with BRBs

Environmental effect of outer skins

summer spring/fall winter

Buckling-restrained Braces and Applications
Chapter 7.3: Seismic retrofit with BRBs

Perimeter work process

Carbon fiber reinforcement

BRB Attachment
Chapter 7.3: Seismic retrofit with BRBs
Chapter 7.3: Seismic retrofit with BRBs

Retrofit with Diagonal BRB Louver

(a) Exterior appearance                             (b) Interior view

Application for Seismic retrofit (Administer Build. Tokyo Tech)

7.4.1 BRB application on RC frame with elastic steel frame
Chapter 7.3: Seismic retrofit with BRBs

Typical RC school building in Turkey
Chapter 7.3: Seismic retrofit with BRBs

Inter-story displacement (mm)

- RC only
- RC + BRB
- RC + BRB + SF

Time (sec)

Residual displacement

≈1/1000 story drift

≈1/30 story drift

≈1/3000 story drift

≈1/1000 story drift

≈1/1000 story drift
Chapter 7.3: Seismic retrofit with BRBs

Increment Dynamic Analyses curves

(a) "First Mode" Spectral Acceleration $S_A (T_1, 5%) (g)$
- RC only
- RC+CB+SF
- RC+BRB+SF
- Target drift (1/150)

(b) "First Mode" Spectral Acceleration $S_A (T_1, 5%) (g)$
- RC+CB+SF
- RC+BRB
- RC+BRB+SF

Maximum inter-story drift (rad)
Maximum Residual Drift (rad)
Cyclic Loading Test for RC retrofit with BRB+SF
(Istanbul Technological University)
Chapter 7.6: Applications for truss and spatial structures

7.5.2 Types of Spatial Structure Applications

a) Truss structures

Response Control for Truss Structures

Device Layout Types for Response-controlled Truss Structures
Chapter 7.6: Applications for truss and spatial structures

Seismic Response of Raised Roof

(R-1) Roof with Dampers
(R-2) Base Isolated
(R-3) Substructure with Dampers
(R-4) Entire Base Isolation

Device Layout for Response-controlled Roof Structures
Seismic retrofit of communication towers

BRBs

Existing Tubular Members
Chapter 7.6: Applications for truss and spatial structures

Buckling-restrained Braces and Applications

Toyota Stadium

Shimokita Dome
7.5.3 Applications to Bridge Structures

Seismic retrofit of steel arch bridge with BRBs

Retrofit of Hanshin highway bridge

Bridge girder with BRBs on RC peer

7.6.2. Dual spine system

(a) Conventional BRB distribution

(b) Dual spine concept

Retrofit of Suzukake G3
Tokyo Tech 2010
Akira Wada, Qu Zhe et al.

7.6.4. Non-uplifting Hinged Spine Frame System (Material Research Building)
Chapter 7.7: Spine frame concepts

7.6.5. Comparison of Spine Frame Systems

(a) Conventional BRBF (SD)  
(b) Lift-up Rocking Frame (LU)  
(c) Non-uplifting Spine Frame (NL)

Chapter 7.7: Spine frame concepts

- **Shear Damper System**

- **Lift-up Spine System**

- **Non Lift-up Spine System**

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**Residual Story Drift Angle (%)**

- 0.8% rad. (1/125)
- 0.05% rad. (1/2000)

**Max. Story Drift Angle (%)**

- 0.8% rad. (1/125)
- 0.05% rad. (1/2000)
Chapter 7.7: Spine frame concepts

7.6.7 Application Examples
Retrofit of Steel Frame with RC core wall spine

680 Folsom Street, SF, US

Damped Outrigger concept

Wilshire Grand Tower, LA, US

Chapter 7.7: Spine frame concepts

Optimization Method

Exclusive Optimization

\[ \alpha_{opt} \approx \frac{3.28 S_{tr}^2 R_{at}^2 + 0.75 S_{tr}^2 (1 + R_{at}) R_{at} + 0.57(1 + R_{at})^2}{6.75 S_{tr}^2 R_{at}^2 + 1.81 S_{tr}^2 (1 + R_{at}) R_{at} + 0.63(1 + R_{at})^2} \]

\[ R_{at, opt} \approx \sqrt{\frac{0.20 \alpha^2 - 0.59 \alpha + 0.61}{2.01 \alpha^4 S_{tr}^2 + S_{tr}^2 \alpha(\alpha - 2)^2}} , \quad c_{d, opt} = \frac{k_b R_{at, opt}}{\omega} \]

The latest knowledge is overviewed in

**Buckling-Restrained Braces and Applications**

T. Takeuchi and A. Wada, Japan Society of Seismic Isolation, 2017

mail to contactjssijssi.or.jp

30-years from the first application, BRBs are still actively researched and expanding applications. I am looking forward to further development in the future.
Thank you very much for your kind attention