Buckling Restrained Braces and Structural Fuses

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Outline

• Description of Structural Fuse Concept (SFC)
• Description of Buckling Restrained Braces (BRB)
• Applications of BRB and SFC to Bridges
Energy Dissipation

- Earthquake-resistant design has long relied on hysteretic energy dissipation to provide life-safety level of protection.

- Advantages of yielding steel:
  - Stable material properties well known to practicing engineers.
  - Not a mechanical device (no special maintenance).
  - Reliable long term performance (resistance to aging).

- For traditional structural systems, ductile behavior achieved by stable plastic deformation of structural members = damage to those members.

- In conventional structural configurations, serves life-safety purposes, but translates into property loss, and need substantial repairs.
Energy Dissipation
Ductility

Brittle (↓)  (Somewhat) Ductile (↓)
Structural Fuses

- From Energy Dissipation to Structural Fuse
  - Researchers have proposed that hysteretic energy dissipation should instead occur in “disposable” structural elements (i.e., structural fuses)
Analogy

- Sacrificial element to protect the rest of the system.
Weak Link

Brittle (↓) (Somewhat) Ductile (↓)
Capacity Design

\[ P_{\text{MAX}} = P_Y \]

(Special plastic link (only link requiring ductile detailing))
Roeder and Popov (1977)

“Ductile Fuse”

- Ductile seismic behavior
- Concentrating energy dissipation in special elements + capacity design
- Links not literally disposable

Eccentrically Braced Frame

Other studies:
- Fintel and Ghosh (1981)
- Aristizabal-Ochoa (1986)
- Basha and Goel (1996)
- Carter and Iwankiw (1998)
- Sugiyama (1998)
- Rezai et al. (2000)
Eccentrically Braced Frame
(Opening a parenthesis)
Tubular Eccentrically Braced Frame

- EBFs with wide-flange (WF) links require lateral bracing of the link to prevent lateral torsional buckling
- Lateral bracing is difficult to provide in bridge piers
- Development of a laterally stable EBF link is warranted
- Consider rectangular cross-section – No LTB
Proof-of-Concept Testing
Proof-of-Concept Testing
Finite Element Modeling of Proof-of-Concept Testing

Hysteretic Results for Refined ABAQUS Model and Proof-of-Concept Experiment
(Closing a parenthesis)
Structural Fuse Analogy

- EBF (Incomplete Fuse Analogy)
  - Ductile link
  - Maybe not easily replaceable
- Need to configurations that decouple the energy dissipating system from the gravity carrying load system
- BRB is one of many devices that could serve as a structural fuse
What is a Buckling Restrained Brace?

Explained by comparison with regular concentric brace not restrained against buckling
Ductile Design of Steel Structures
CBFs

- KL/r – compression and tension strengths are unequal
  - Less energy dissipation in compression
  - Unbalanced force issues
  - Local buckling and fracture
13.4b. K-Type Bracing

K-type Braced Frames are not permitted for SCBF.
Buckling Restrained Braces

- The disadvantages of the CBF system can be overcome if the brace can yield during both tension and compression without buckling.
- A braced frame that incorporates this type of brace is the buckling restrained brace (BRB) Frame (BRBF)
- BRBF is a special class of CBF that precludes brace buckling
Most of the BRBs developed to date are proprietary, but the concepts are similar

- Ductile steel core, designed to yield during both tension and compression
- Steel core placed inside a steel casing (usually a hollow structure shape)
- Unbonding material wraps steel core
- Casing is filled with mortar or concrete.
- Unbonding material minimizes / eliminates transfer of axial force from steel core to mortar
- Note: Poisson effect causes steel core to expand under compression
Buckling-Restrained Brace Mechanics

- Encasing mortar
- Yielding steel core
- Unbonding material between steel core and mortar
- Steel tube
- Decoupling

Unbonded Brace Type

Buckling Restraint

Ductile Design of Steel Structures
WHAT IS A BUCKLING-RESTRAINED BRACE?
Two Definitions

De-Coupled Stress and Buckling
(Mechanics Definition)

Balanced Hysteresis
(Performance Definition)
Ductile Design of Steel Structures

Axial force-displacement behavior

- typical buckling brace
- buckling-restrained brace
Ductile Design of Steel Structures
Seismic Design of Buckling-Restrained Braced Frames (An SSEC-sponsored seminar)

Speakers:
Walterio A. López, S.E.
and
Rafael Sabelli, S.E.
Ductile Design of Steel Structures

Diagram showing a section of a steel structure with an allowance for contraction. The diagram includes a section of styrofoam for insulation or shock absorption.
Ductile Design of Steel Structures
Ductile Design of Steel Structures
Ductile Design of Steel Structures
Buckling Restrained Braces in Structural Fuse Application

Wada et al. (1992)

**Damage-controlled or Damage-tolerant Structures**

- Ductile elements were used to reduce inelastic deformations of the main structure.
- Concept applied to high-rise buildings \((T > 4 \text{ s})\)

Other studies:
- Connor et al. (1997)
- Shimizu et al. (1998)
- Wada and Huang (1999)
- Wada et al. (2000)
- Huang et al. (2002)
mass, $m$

structural fuse, $d$

braces, $b$

frame, $f$

Ground Motion, $\ddot{u}_g(t)$
Benefits of Structural Fuse Concept:

- Seismically induced damage is concentrated on the fuses.
- Following a damaging earthquake only the fuses would need to be replaced.
- Once the structural fuses are removed, the elastic structure returns to its original position (self-recentering capability).
\[ \alpha = 0.05 \]
\[ \mu_{\text{max}} = 10 \]

Drift Limit (Suggested)

\[ \mu_f = \frac{\mu_{\text{max}}}{\Delta y_f} \]

\[ \eta = 0.2 \]

\[ \eta = 1.0 \]
Model with Nippon Steel BRBs

Eccentric Gusset-Plate
Test 1
(PGA = 1g)
Test 1 (Nippon Steel BRB Frame)
First Story Columns Shear

1st Story Columns Shear (kN)

Inter-Story Drift (mm)
Static Test - Nippon Steel BRBs
Note: Replacement is to re-center the building
(not due to BRB fracture life)
BRB and SFC in Bridges

- Ductile Diaphragms
  - BRB SFC in end-diaphragms
- Rocking Trusses (Rocking Braced Frames)
  - SFC with BFB at base
- ABC Piers
  - BRB SFC between dual columns
Ductile Diaphragms with Structural Fuses


Inelastic Behavior of Proposed and Existing End-Diaphragm
3-D Deflected Shape
SEISMIC LOAD PATHS

TOP LOAD PATH
- Top Chords & Top Laterals
- End Cross Frames

BOTTOM LOAD PATH
- Interior Cross-Frames
- Side Diagonals
- Lower Chords & Lower Laterals
Ductile Retrofit Strategies

Continuous Deck

Retrofitted Panels

Eccentrically Braced Frame

TADAS

Vertical Shear Link
Implementation of Concept
Minato Bridge (Hanshin Expressway Corporation)

Ductile Cross-Frames implemented as part of a comprehensive seismic rehabilitation process


Figure-7 Steel Damper bracing and hysteretic loops

Figure-8 Optimal Layout of damper bracings
BRB and SFC in Rocking Truss Piers

Controlled Rocking/Energy Dissipation System

- Absence of base of leg connection creates a rocking bridge pier system partially isolating the structure.

- Installation of steel yielding devices (buckling-restrained braces) at the steel/concrete interface controls the rocking response while providing energy dissipation.
Static, Hysteretic Behavior of Controlled Rocking Pier

FPED = 0
FPED = w/2

Global Response
Device Response
General Design Constraints for Controlled Rocking System

- (1) Deck-level displacement limits need to be established on a case-by-case basis
  - Maintain pier stability
  - Bridge serviceability requirements

- (2) Strains on buckling-restrained brace (uplifting displacements) need to be limited such that it behaves in a stable, reliable manner

- (3) Capacity Protection of existing, vulnerable resisting elements considering 3-components of excitation and dynamic forces developed during impact and uplift

- (4) Allow for self-centering of pier
Design Procedure

- **Design Constraints**
  - **Acceleration**
    Limit forces through vulnerable members using structural “fuses”
  - **Velocity**
    Control impact energy to foundation and impulsive loading on tower legs by limiting velocity
  - **Displacement Ductility**
    Limit $\mu_L$ of specially detailed, ductile “fuses”
  - $\beta<1$ Inherent re-centering (Optional)
Experimental Testing

- Artificial Mass Simulation Scaling Procedure
  - $\lambda_L > 5$ (Crane Clearance)
  - $\lambda_A = 1.0$ (1-g Field)
  - $W_m = 70\text{kN}$ ($W_e = 76\text{kN}$)
  - $T_{om} = 0.34\text{sec}$ ($T_{oe} = 0.40\text{sec}$)

- Loading System
  - Phase I
    - 5DOF Shake Table
  - Phase II
    - 6DOF Shake Table
Synthetic EQ 150% of Design
Free Rocking

Synthetic EQ 150% of Design
TADAS Case $\eta_L = 1.0$
Synthetic EQ 150% of Design – Free Rocking
Synthetic EQ 175% of Design - Viscous Dampers
ABC Bridge Pier with Structural Fuses

Simulate ABC Construction
Simulate ABC Construction
New “Short Length” BRB
Developed by Star Seismic
Specimen S2-1
Experimental versus Analytical Results for Specimen S2-1
Specimen with BRB Fuses
Pushover Comparison of Frame with Different Structural Fuses

![Graph showing comparison of total force vs. top displacement for different structural fuses: BRB, SPSL (with Restraints), SPSL (no Restraints), and Bare Frame. The graph illustrates the maximum total force and corresponding top displacements for each case.](image)

- **BRB**
- **SPSL (with Restraints)**
- **SPSL (no Restraints)**
- **Bare Frame**

**Graph Details**
- Total Force (kN) on the y-axis
- Top Displacement (mm) on the x-axis
- Maximum total force: $F_{\text{max}} = 3.3$ kN
- Top displacement at $F_{\text{max}}$: $u_{\text{max}} = 100$ mm
- Percentage comparisons: 30% and 60%
Conclusions

- Recently developed options for seismic design and retrofit illustrated (BRB with Fuse, TEBF, Rocking)
- Instances for which replacement of sacrificial structural members (considered to be structural fuses dissipating hysteric energy) was accomplished, in some cases repeatedly.
- Article/Clauses for the design of some of these systems are being considered by:
  - CSA-S16 committee for 2009 Edition of S16
  - AISC TC9 Subcommittee for the 2010 AISC Seismic Provisions
- Emerging field: opportunities to develop structural fuse concepts still exist
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Questions?