ANALYTICAL AND EXPERIMENTAL STUDY ON STEEL BRACES WITH STRONGER MIDDLE LENGTH TREATED BY INDUCTION HARDENING

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Tuesday, June 26 – Friday, June 29
Presentation Outline

1. Introduction – Research Motivation
2. Concept of Proposed Steel Brace
3. Induction Heating and Quenching Technologies
4. Analytical Investigation
5. Experimental Investigation
6. Conclusions
Steel braces constitute the main earthquake-resistant mechanism in structures. They provide very large **strength** and **stiffness** for controlling the lateral drifts.
They buckle suddenly and lose compressive strength – At small axial deformations

High stress concentration leads to middle local buckling – Unstable energy dissipation
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New Design Scenario for Steel Braces

- Conventional

- New design

2. Concept of Proposed Steel Brace

- Conventional Brace
- New design

Axial load (kN) vs. Story Drift (%)

- Buckling

- Delay Buckling

Stress (MPa) vs. Strain (%)

- $2 \sim 4 \times \sigma_y$
New Design Scenario for Steel Braces

- Influence of the middle length strengthening:

A. Middle length remains elastic. Conventional steel parts absorb the deformation.

→ Compression strength can increase

B. Local buckling (plastic hinge) is expected to occur at the conventional steel part

→ Stabilization of Post-buckling behavior
New Design Scenario for Steel Braces

- Post buckling behavior

\[
\begin{align*}
\text{Elastic deformation} & : \quad w_e = \frac{Nl}{EA} \quad \cdots \text{(1)} \\
\text{Geometric deformation} & : \quad w_b = \frac{l}{2} \cdot (a\theta_1^2 + (1-a)\theta_2^2) \\
\text{Plastic deformation} & : \quad w_p = d \cdot \frac{\theta_1 + \theta_2}{2} \quad \cdots \text{(3)} \\
\text{Axial deformation} & : \quad w = w_e + w_b + w_p \quad \cdots \text{(4)}
\end{align*}
\]

Geometrically,
\[
M = N \cdot u = N \cdot a(1-a)(\theta_1 + \theta_2)l \quad \cdots \text{(5)}
\]

From M-N interruption,
\[
\frac{M}{M_p} + \frac{N}{N_y} = 1 \quad \cdots \text{(6)}
\]

Here,
\[
M_p = A \frac{d}{2} \sigma_y = N_y \cdot \frac{d}{2} \quad \cdots \text{(7)}
\]

2. Concept of Proposed Steel Brace

From eq.(5), (6), (7)
\[
\theta_1 + \theta_2 = \frac{1}{2a(1-a)} \cdot d \frac{N_y}{N} - 1 \quad \cdots \text{(7a)}
\]

or \[
\theta_2 = \frac{1}{2(1-a)} \cdot d \frac{N_y}{N} - 1 \quad \cdots \text{(7b)}
\]

Substituting eq.(1), (2), (3), (7) for eq.(4)
\[
\frac{w}{l} = \frac{N}{N_y} \cdot \varepsilon_y + \frac{1}{8a(1-a)} \left( \frac{d}{l} \right)^2 \left( \frac{N_y}{N} - 1 \right)^2 + \frac{1}{4a(1-a)} \left( \frac{d}{l} \right)^2 \left( \frac{N_y}{N} - 1 \right) \quad \cdots \text{(8)}
\]

\[
\frac{w}{l\varepsilon_y} = \frac{N}{N_y} + \frac{1}{4a(1-a)} \frac{2}{\pi^2 \lambda c^2} \left[ \left( \frac{N_y}{N} \right)^2 - 1 \right] \quad \cdots \text{(9)}
\]
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Strength Enhancement

By Induction Heat (IH) Treatment Technology

- Alternate magnetic flux
- Eddy current
- Heating coil
- High frequency power supply
- Heating object

3. Induction heating and quenching technologies

Graph showing tensile stress (MPa) vs. strain.
Induction heat (IH) treatment technology heats up only a selected area of the steel surface over 1000°C, and then, by quenching the steel in water the workpiece obtains the new material properties, such as three-to-four times higher yield stress.
Compression Coupon Tests

3. Induction heating and quenching technologies

<table>
<thead>
<tr>
<th></th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6 x (\sigma_y)</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td></td>
</tr>
<tr>
<td>IHS</td>
<td></td>
</tr>
</tbody>
</table>

Yielding stress (0.2% offset)

<table>
<thead>
<tr>
<th>Material</th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional steel</td>
<td>345 MPa</td>
</tr>
<tr>
<td>Induction heating steel</td>
<td>880 MPa</td>
</tr>
</tbody>
</table>

Short Column tests

Cross-section

- Stain Gauges Location
- Conventional Boundary
- IH steel
- Boundary
Tension Coupon Tests

3. Induction heating and quenching technologies

IH-treated steel provides:
- 2~3 times larger yield stress
- Three times lower ductility

<table>
<thead>
<tr>
<th>Steel</th>
<th>Yielding Stress (MPa)</th>
<th>Ultimate Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>354.0</td>
<td>0.217</td>
</tr>
<tr>
<td>IH-treated</td>
<td>778.0</td>
<td>0.069</td>
</tr>
</tbody>
</table>
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In order to evaluate the effect of the IH treatment, three design parameters were evaluated analytically by OpenSees:

1. Slenderness ratio

   \[ n = \left( \frac{L_{IH}}{L_t} \right) \]

2. Yield stress of IH steel

   \[ \frac{\sigma_{y,\text{IH}}}{\sigma_{y,\text{CS}}} \]

3. Length ratio of IH portion.

   \[ L_{IH} : \text{IH part length} \]
   \[ L_t : \text{entire length} \]

\[ n\% \]
4. Analytical Investigation

- Evaluation of post buckling behavior

The evaluation parameter: the storey drift where the brace reaches ‘80% of the buckling load’.

![Graph showing the evaluation parameter: the storey drift where the brace reaches 80% of the buckling load.](chart.png)
Analytical Investigation - Results

- **Slenderness ratio** – results for $n=0.6$

For a slenderness ratio $0.5 < \lambda < 1.5$

Buckling load **increased** by 10%

IH brace provides with **bi-linear** behavior until 0.5% drift

Compression strength exhibits **less deterioration** in post-buckling region especially for **small values of slenderness ratio**
**Analytical Investigation - Results**

- **Yield Stress** – results for $\lambda=0.72$

IH-to-conventional steel yielding ratio

$$1 < \frac{\sigma_{IH}}{\sigma_{CS}} < 4$$

Buckling load and post-buckling behavior remain the same for values of yielding ratio more than two.
Length of IH portion – results for $\sigma_{IH}/\sigma_{CS} = 4$

$0.46 < n < 0.80$

As the ratio $n$ increases the strength exhibits less deterioration in the post-buckling behavior.

→ Need to check the maximum and cumulative strain
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Test Plan

1. Conventional Steel Brace (CBB)
   - Slenderness (norm.) 0.70
   - Gusset plate connections (AISC, 2010)

1. Induction Heated (IH-CBB)
   - Slenderness 0.70
   - Gusset plate connections (pin)
   - IH-to-conv. steel yield ratio = 2.6
   - Length ratio of IH = 60%
Test Set-up

Hydraulic Jack

Specimen

Dimensions: mm

4. Experimental Investigation

Drift Angle (% rad.)

No. of Cycles

0.1 0.25 0.5 0.75 1 1.5 2 3 4

0 2 4 6 8 10 12 14 16 18
Specimen Overview

4. Experimental Investigation
Test results: Overall deformation and local buckling

4. Experimental Investigation

**CBB**
- Compression -0.5% 1st
- Compression -1.5% 1st

**IHCBB**
- Compression -0.5% 1st

**Graphs:**
- Deformation vs. Location (mm)
  - CBB: 0.25%, 0.50%, 0.75%, 1.00%
  - IHCBB: 0.25%, 0.50%, 0.75%, 1.00%, -0.50% (2nd)
Test results: Cyclic behavior

Comparison with CBB test.
Normalized by yield strength.
No data measured in the dotted red line.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$K_e$ (kN/mm)</th>
<th>$P_{y,tension}$ (kN)</th>
<th>$P_c$ (kN)</th>
<th>$P_u$ (kN)</th>
<th>Global buckling</th>
<th>Local buckling</th>
<th>Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBB</td>
<td>62.3</td>
<td>119.1</td>
<td>-219.6</td>
<td>298.8</td>
<td>1\textsuperscript{st} -0.5 %</td>
<td>2\textsuperscript{nd} -1.0 %</td>
<td>2\textsuperscript{nd} 2.0 %</td>
</tr>
<tr>
<td>IHCBB</td>
<td>61.5</td>
<td>128.4</td>
<td>-257.1</td>
<td>315.3</td>
<td>1\textsuperscript{st} -0.5 %</td>
<td>1\textsuperscript{st} -0.5 %</td>
<td>2\textsuperscript{nd} 1.0 %</td>
</tr>
</tbody>
</table>
Global Buckling in IHCBB

4. Experimental Investigation

[Diagram showing out frame components: out frame, tension, main frame, roller, gusset plate, brace tube, compression, easy to rotate, loading frame, out-of-plane imperfections]
4. Experimental Investigation

Test results: Stress-strain relationships

IH steel
Conventional steel
Conclusions

Analytical study

- An increase of buckling load and an improved post-buckling behavior was observed for intermediate values of slenderness ratio.
- The improvement was capped at the values of IH-to-conventional yield stress ratio more than two.
- As the length of IH portion increases the negative slope in post-buckling region becomes less steep moderating the strength deterioration.

Experimental study

- Buckling observed in a compressive load almost 20% larger than the corresponding conventional brace.
- A severe local buckling took place within the unheated portions which led to an earlier than expected global failure.
THANK YOU FOR YOUR KIND ATTENTION

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