FRP Seismic Strengthening of Frames

Mihaela-Anca CIUPALA
Kypros PILAKOUTAS

Centre for Cement and Concrete
Department of Civil and Structural Engineering
The University of Sheffield, UK

Acknowledgements of EU projects:
Craft G1ST-CT-2002-50365 – CURVEDNFR
Marie Curie Fellowship HPMF-CT-2001-01279EU TMR
Network ConFibreCrete ERB-FMRX-CT-97-0135
Ecoleader Project
Durability of EBR

Content

- Introduction
- Plastic hinge region
- FRP confinement models
- Test frame
- Predictions
- New ideas
Introduction

- Difference with steel
  - Yielding
  - Stiffness
  - Energy dissipation
- Rectangular sections
- Joints
Stress-strain curve for WC1 and PC1-20 specimens

Volumetric Strain for WC1 and PC1-20 specimens
Conventional Ductility

- Curvature in plastic hinge region in constant
- Plastic hinge region estimated roughly
- Yield penetration at plastic stage only

\[
\mu_{\phi} = 1 + \frac{\mu_{\Delta} - 1}{3(L_p / L)(1 - 0.5L_p / L)} = 1 + \frac{\mu_{\Delta} - 1}{3\lambda_{pl}(1 - 0.5\lambda_{pl})}
\]

\[
L_p = 0.08L + 0.022f_yd_l \geq 0.044f_yd_l
\]
Conventional Ductility

Curvature ductility from Displacement ductility:
Ductility Issues

- Curvature in plastic hinge region varies if bars are fully bonded due to high confinement
- Plastic hinge region depends on moments
- Yield penetration at yield and plastic stage

\[
\mu_f = 1 + \frac{\mu_A - (1 + \lambda_{pl})}{\lambda_{pl} (1.5 - 0.5 \lambda_{pl} )} \\
\lambda_{pl} = 1 - \frac{M_y}{M_{ult}}
\]
Ductility Calculation

Moments and curvatures at yielding

Moments and curvatures at maximum response (ultimate state)
Ductility equations

\[
\mu_\phi = \frac{\mu_\Delta - (1 - 0.5 \lambda_{pl}) \cdot 0.9 \cdot (1 - 15 \alpha)}{(1.3 \lambda_{pl} + 42 \alpha \beta + 294 \alpha^2 \beta^2) \cdot 0.9 \cdot (1 - 15 \alpha)}
\]

where

\[
\alpha = \frac{d}{L} \cdot \frac{f_y}{500}
\]

\[
\beta = \frac{f_{ult}}{f_y}
\]

\[
\varepsilon_{cc,85} = \phi_u \cdot x = \mu_\phi \cdot \phi_y \cdot x
\]
Maximum concrete Strain

\[ \varepsilon_{cu} = \varepsilon_{cc} \left( \frac{E_{sec} (E_c - E_{sec,u})}{E_{sec,u} (E_c - E_{sec})} \right) \frac{E_{sec}}{E_c} \]

\[ f'_{cu} = E_{sec,u} \varepsilon_{cu} \]

\[ \frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1.75 + m \left( \frac{f'_l}{f'_c} \right) \]

\[ \varepsilon_{cu} = 0.0035 + 0.1 \cdot \alpha \omega_{wd} \]

- **Spoelstra and Monti**
- **Lam and Teng (m 10-22)**
- **Model code**
Maximum concrete Strain

Fardis et al., 1981  Miyauchi et al., 1997
Karbhari et al., 1997 Samaan et al., 1998
Toutanji, 1999 Saffi et al., 1999
Speelstra et al., 1999 Lam et al., 2001
Mander et al., 1998 EC8-2001
MECH-1998 Present-Exp.-PC

Normalised ultimate axial strain

\( \alpha \omega \)

Present-Exp.-CC
Present-Exp.-WC
MECH-1998

Normalised ultimate axial strain

\( \alpha \omega \)

Present-Exp.-WC
Present-Exp.-CC
MECH-1998

Normalised ultimate axial strain

\( \alpha \omega \)

Present-Exp.-WG
Present-Exp.-CG
MECH-1998

Normalised ultimate axial strain

\( \alpha \omega \)
Rectangular columns

- *Mander’s model* modified by several researchers
- Lateral stress is not calculated and effective stress not properly addressed
- Energy approach!
- *Spoelstra and Monti* calculate lateral stress
- Model code model simple

Effectively confined concrete core
Unconfined concrete

b' = b - 2r

FRP jacket

r

b

d

d' = d - 2r
• 3 RC frames to be tested by the Ecoleader project
• Frames designed to old standards
• Strengthening with FRP after damaging on Shake-table
• Participants: Roma, Ghent, Patras, Sheffield
Push-over analysis

- Target displacement ductility of $\mu_\Delta = 8$
## Data

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>$t_j$ (mm)</th>
<th>$E_j$ (MPa)</th>
<th>$f_{ju}$ (MPa)</th>
<th>$\varepsilon_{ju}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP</td>
<td>0.117</td>
<td>240000</td>
<td>3900</td>
<td>1.55</td>
</tr>
<tr>
<td>GFRP</td>
<td>0.068</td>
<td>65000</td>
<td>1700</td>
<td>2.80</td>
</tr>
<tr>
<td>AFRP</td>
<td>0.280</td>
<td>120000</td>
<td>2000</td>
<td>1.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plastic hinge length</th>
<th>Curvature ductility</th>
<th>Ultimate concrete strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_p$ (mm)</td>
<td>$\mu_\phi$</td>
<td>$\varepsilon_{cc,85}$ (%)</td>
</tr>
<tr>
<td>Conventional</td>
<td>Eq.2 340</td>
<td>Eq.1 13.66 1.00</td>
</tr>
<tr>
<td>Proposed</td>
<td>Eq.4 400</td>
<td>Eq.5 12.22 0.925</td>
</tr>
</tbody>
</table>
Results – Layers Required

CFRP

<table>
<thead>
<tr>
<th>No of layers</th>
<th>Ultimate concrete strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L</td>
<td>Mander &amp; al.</td>
</tr>
<tr>
<td>2L</td>
<td>Spoelstra &amp; Monti</td>
</tr>
<tr>
<td>3L</td>
<td>Lam &amp; Tang</td>
</tr>
<tr>
<td></td>
<td>EC8</td>
</tr>
</tbody>
</table>

GFRP

<table>
<thead>
<tr>
<th>No of layers</th>
<th>Ultimate concrete strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L</td>
<td>Mander &amp; al.</td>
</tr>
<tr>
<td>2L</td>
<td>Spoelstra &amp; Monti</td>
</tr>
<tr>
<td>3L</td>
<td>Lam &amp; Tang</td>
</tr>
<tr>
<td></td>
<td>EC8</td>
</tr>
</tbody>
</table>

AFRP

<table>
<thead>
<tr>
<th>No of layers</th>
<th>Ultimate concrete strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L</td>
<td>Mander &amp; al.</td>
</tr>
<tr>
<td>2L</td>
<td>Spoelstra &amp; Monti</td>
</tr>
<tr>
<td>3L</td>
<td>EC8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No of layers</th>
<th>Ultimate concrete strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L</td>
<td>Mander &amp; al.</td>
</tr>
<tr>
<td>2L</td>
<td>Spoelstra &amp; Monti</td>
</tr>
<tr>
<td>3L</td>
<td>Lam &amp; Tang</td>
</tr>
<tr>
<td></td>
<td>EC8</td>
</tr>
</tbody>
</table>
Results – Layers Required

**CFRP**

- Mander & al.
- Spoelstra & Monti
- Lam & Tang
- EC8
- Target displacement ductility

**AFRP**

- Mander & al.
- Spoelstra & Monti
- Lam & Tang
- EC8
- Target displacement ductility

**GFRP**

- Mander & al.
- Spoelstra & Monti
- Lam & Tang
- EC8
- Target displacement ductility
Conclusions

- FRP strengthening differs in behaviour (and design) from steel jacketing.
- FRP jacketing can enhance bond slip characteristics and lead to different plastic hinge lengths.
- The main design parameter for confinement strengthening is maximum concrete axial strain.
- Many models, but not enough accuracy.
- Results of design dominated by the model inaccuracy.
- More research to be done at the element and structural level.