FRP Seismic Strengthening of Columns in Frames

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  – EU Ecoleader project
  – University of Sheffield
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is also gratefully acknowledged.
Outline

- Introduction and Context of work
- Design procedure
- FRP confinement models
- Test frame
- Strengthening design example
- Conclusions
Context of work

- Centre of Cement and Concrete - The University of Sheffield, UK
- EU TMR Network ConFibreCrete
- EU Ecoleader research project

- Full scale 3D – two storey RC frames
- Tamaris Laboratory, CEA Saclay, France
Introduction

- Use of FRP in columns
- Confinement objective
- Difficulties:
  - most existing models for confined concrete and strengthening design guidelines are based on steel confinement
  - confinement of rectangular sections is not always dealt properly by models developed for circular sections
  - joint confinement is not always easy to achieve
Design procedure for plastic hinge confinement

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

\[
L_p = 0.08L + 0.022f_yd_i \geq 0.044f_yd_i
\]
Conventional ductility

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

![Diagram showing moments and curvatures at yielding and ultimate response.](image-url)
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

\[ \lambda_{pl} = 1 - \frac{M_y}{M_{ult}} \]

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

\[ \beta = \frac{f_{ult}}{f_y} \]
Design procedure for plastic hinge confinement

Target

\[ \mu_{\Delta} \]

Required thickness of FRP
- Confinement model

\[ \varepsilon_{cu} = \mu_{\phi} \cdot \phi_y \cdot x \]
Models for FRP-confined rectangular columns

• **Wang & Restrepo**
  \[ f'_{cc} = \alpha_1 \alpha_2 f'_{co} \]

• **Spoelstra & Monti**
  \[ \varepsilon_{cu} = \varepsilon_{cc} \left[ \frac{E_{sec}(E_c - E_{sec,u})}{E_{sec,u}(E_c - E_{sec})} \right]^{\frac{E_{sec}}{E_c}} \]
  \[ f'_{cu} = E_{sec,u} \varepsilon_{cu} \]

• **Lam & Teng**
  \[ \varepsilon_{cc} / \varepsilon_{co} = 1.75 + m(f'_1 / f'_{co}) \]
  \[ f'_{cc} / f'_{co} = 1 + 2f'_1 / f'_{co} \]

• **CEB-FIB Model Code 1990**
  \[ \varepsilon_{c,85}^* = 0.0035 + 0.1 \cdot \alpha \omega_{wd} \]
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 ’90* model simple
RC frame

- 3 RC frames to be tested by the Ecoleader project

- Designed using old standards
- Strengthening with FRP after damaging on shaking table

Pushover analysis of the frame was carried out to determine the failure mechanism

![Diagram of RC frame with dimensions and design details]

Graph showing base shear vs. top displacement with markers indicating first yielding and collapse points.
Design procedure for plastic hinge confinement

Target

\[ \mu_\Delta \]

\[ \mu_\phi \]

Required

\[ \varepsilon_{cu} = \mu_\phi \cdot \phi_y \cdot x \]

Required thickness of FRP
- Confinement model
Strengthening design example for columns

- Confinement of plastic hinge region
- Jacket thickness of 1, 2, 3 fibre sheets

Table 1. Fibre properties

<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>
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<tbody>
<tr>
<td>CFRP</td>
<td>0.117</td>
<td>240000</td>
<td>3900</td>
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<tr>
<td>GFRP</td>
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<td>1700</td>
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</table>

- Strengthening objective  \( \mu_\Delta = 8 \)
- Effective column length is 1.65 m and the expected  \( L_p = 301 \) mm
- Required curvature ductility is  \( \mu_\phi = 15 \) resulting in a required  \( \varepsilon_{cu} = 0.01 \)
Axial stress for 1L of CFRP confinement

Rectangular

Circular

- Normalised axial stress (fcc/fco)
- Axial strain

- Models:
  - Wang & Resprepo
  - Spoelstra & Monti
  - Lam & Teng
  - Model Code 1990
  - Unconfined concrete

- Test
Normalised strength enhancement \( (f'_c / f'_o) \)

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<tr>
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## Ultimate strain $\varepsilon_{cu}$ (%)

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## Estimated displacement ductility $\mu_{\Delta}$

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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