Shear and Flexural Ultimate Behavior of Concrete Members Jacketed by Fiber Sheet with Large Fracture Strain

Jian-Guo DAI¹ and Tamon UEDA²

1. Assistant Professor, Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, China
2. Professor, Division of Built Environment, Graduate School of Engineering, Hokkaido University, Japan
The Hong Kong Polytechnic University
Outline of this presentation

• Mechanical properties of large rupture strain (LRS) fiber reinforced polymer (FRP) composites

• Behavior of LRS FRP-jacketed RC bridge piers subjected to cyclic loading

• Behavior and modeling of LRS FRP-confined concrete

• Shear behavior of LRS FRP-fully wrapped RC beams

• Practical applications and cost-effectiveness

• Concluding remarks
LRS FRP composites are usually made of recycled materials.
LRS FRP composites

Polyethylene Naphthalate (PEN)

Polyethylene Terephthalate (PET)

Favorable bi-linear tensile property.
Behavior of LRS FRP Jacketed RC Bridge Piers

New Retrofit Method
(Duplex Jacketing)
Behavior of LRS FRP Jacketed RC Bridge Piers

19 tests in total (major parameter: shear/flexure strength ratio)
Behavior of LRS FRP Jacketed RC Bridge Piers

As-built

SP-2 AFRP

SP-4 PET FRP

Achieved the same ductility ($>10\delta_y$) with a smaller stiffness of FRP
Behavior of LRS FRP Jacketed RC Bridge Piers

Progressive bulking of steel reinforcement precedes the ultimate state but is suppressed by FRP jackets.
Behavior of LRS FRP Jacketed RC Bridge Piers

No rupture at the corner

AFRP JACKET

PET FRP JACKET
Behavior of LRS FRP Jacketed RC Bridge Piers

- PET shows good performance
  - Confining cover concrete
  - No fracturing

In a specimen fracture of transverse steel reinforcement occurred but no fracture of PET sheet was found.
Behavior of LRS FRP Jacketed RC Bridge Piers

\[ \theta_u = \theta_m + \eta \left( 1 - \frac{M_u}{M_{\text{max}}} \right) \]

\[ \theta_u = \theta_{\text{me}} + \theta_{\text{mp}} \]

\[ \theta_{\text{mp}} = \frac{0.021 k_s K_0 \rho_w + 0.013}{0.79 \rho_t + 0.153} \]

\[ K_0 = 0.0019 E_{\text{frp}} \cdot \rho_{\text{frp}} + 3.65 \]

\[ \eta = 1.22 K_u + 0.04 \]

\[ K_u = \frac{V_w + V_c}{V_{\text{mu}}} \cdot \frac{E_{\text{frp}} \cdot \rho_{\text{frp}}}{E_w \cdot \rho_w} \]

where:
- \( \theta_u \): total drift ratio at ultimate state
- \( \theta_m \): total drift ratio at maximum load
- \( M_u \): ultimate moment which can be considered as same value of yield moment
- \( M_{\text{max}} \): moment at peak load
- \( \eta \): factor to consider the gradient of linear softening of members

Ductility prediction (Danny et al. 2006)
Cement and Concrete Composites

Research Group in Emerging Structural Materials and Systems (ESMS) Oct. 10-12, 2010
Behavior of LRS FRP Jacketed RC Bridge Piers

Simulation of shear/Flexure Interaction: a big challenge
**Flexure:** FRP confinement, post-buckling behaviour; interaction between FRP and longitudinal and transverse reinforcement within the hinge zone;

**Shear:** A generic shear model is needed to consider the interaction among concrete, FRP and shear reinforcement at different deformation levels.
Behavior and modeling of LRS FRP confined-concrete
No explosive failure
Behavior and modeling of LRS FRP confined-concrete

\[ \frac{\varepsilon_c}{\varepsilon_{c0}} = f(\frac{\varepsilon_l}{\varepsilon_{c0}})(\alpha + \beta \frac{\sigma_1}{f_{c0}}) \]

\[ f(\frac{\varepsilon_l}{\varepsilon_{c0}}) = a(\frac{\varepsilon_l}{\varepsilon_{c0}})^b + c(\frac{\varepsilon_l}{\varepsilon_{c0}}) \]

\[ \alpha = 1; \beta = 8; \]
\[ a = 1.024; b = 0.350; c = 0.089 \]

\[ \frac{\sigma_c}{f_{cc}^*} = \frac{(\varepsilon_l / \varepsilon_{cc}^*)m}{m - 1 + (\varepsilon_l / \varepsilon_{cc}^*)^m} \]

\[ m = \frac{E_c}{E_c - f_{cc}^* / \varepsilon_{cc}^*} \]
\[ f_{cc}^* = f_{co}^* + 3.5\sigma_1 \]
\[ \varepsilon_{cc}^* = \varepsilon_{co} [1 + 17.5(\frac{\sigma_1}{f_{co}})^{1.2}] \]

Dilation property of concrete
Behavior and modeling of LRS FRP confined-concrete

Research Group in Emerging Structural Materials and Systems (ESMS) 
Oct. 10-12, 2010
Shear Behavior of LRS FRP-fully Wrapped RC Beams

10 specimens tested:

Major parameters: FRP reinforcement ratio, steel reinforcement ratio, longitudinal reinforcement ratio, shear span to depth ratio, section height

Research Group in Emerging Structural Materials and Systems (ESMS) Oct. 10-12, 2010
Shear Behavior of LRS FRP-fully Wrapped RC Beams

Shear deformation measurement
Displacement transducers, image analysis
### Details of Specimens

<table>
<thead>
<tr>
<th></th>
<th>SP1～SP6</th>
<th>SP7</th>
<th>SP8</th>
<th>SP9</th>
<th>SP10</th>
</tr>
</thead>
<tbody>
<tr>
<td>h×b (mm)</td>
<td>270×250</td>
<td>500×250</td>
<td>270×250</td>
<td>150×100</td>
<td></td>
</tr>
<tr>
<td>d (mm)</td>
<td>240</td>
<td>450</td>
<td>240</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>a (mm)</td>
<td>600</td>
<td>1125</td>
<td>750</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>a/d</td>
<td>2.5</td>
<td>3.13</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ρ_s (%)</td>
<td>4.22</td>
<td>4.5</td>
<td>4.22</td>
<td>3.38</td>
<td>4.22</td>
</tr>
<tr>
<td>ρ_v (%)</td>
<td></td>
<td>0.17</td>
<td></td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>ρ_frp (%)</td>
<td>0</td>
<td>0.11</td>
<td>0.17</td>
<td>0.22</td>
<td>0.34</td>
</tr>
<tr>
<td>Vtd (kN)</td>
<td>205</td>
<td>249</td>
<td>270</td>
<td>292</td>
<td>324</td>
</tr>
<tr>
<td>Mud (kN·m)</td>
<td>339</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vtd·/M</td>
<td>0.7</td>
<td>0.73</td>
<td>0.8</td>
<td>0.86</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Shear Behavior of LRS FRP-fully Wrapped RC Beams

Shear failure before flexural yielding

Post-yielding shear failure

Shear failure is no longer brittle
Shear Behavior of LRS FRP-fully Wrapped RC Beams

Research Group in Emerging Structural Materials and Systems (ESMS)  
Oct. 10-12, 2010
Practical applications and cost effectiveness

• There are practical applications.
  – Seismic retrofit of railway viaduct

Tobu Line near Tokyo
JR Line at Osaka station
JR Line at Shin-Sapporo station
Cost-effectiveness

Competitive to conventional fiber material (carbon and aramid)

- A&P Jacketing
- Jacketing with Aramid

Direct construction cost (Yen/m²)

Shear span to depth ratio, $L_a/D$

800 × 800 mm section
$\rho_t=1.00\%$  $\rho_w=0.21\%$  $\sigma_N=1.0\text{MPa}$

1000 × 1000 mm section
$\rho_t=0.86\%$  $\rho_w=0.17\%$  $\sigma_N=1.0\text{MPa}$

Research Group in Emerging Structural Materials and Systems (ESMS)  
Oct. 10-12, 2010
Concluding remarks

• Large rupture strain FRP composites could provide better confinement effects given the same stiffness of FRP to confine concrete. In other words, to achieve the same ductility, less stiffness of LRS FRP composites is needed, and as a consequence, LRS FRP can be a more economic solution for seismic retrofit.

• Dilation behavior of concrete at large lateral strain levels is a key to the understanding of behavior of LRS FRP-confined concrete;
Concluding remarks

• In RC piers jacketed with LRS FRP composites, the initiation of buckling of steel reinforcement usually proceeds the ultimate state of the piers, the effect of LRS FRP jackets on the progressive buckling of steel reinforcement needs to be well understood for a better prediction of the flexural ductility.

• The potential shear strength of a member is a function of stiffness of tension and shear reinforcement at a given deformation of the member, the preferable mechanical property of shear reinforcement to obtain a high ultimate shear strength and deformability is the linearity with a LRS.
The Hong Kong PhD Fellowship Scheme

✓ Stipend of HK$20,000 per month
✓ Tuition fees waived by PolyU
✓ Travel grants of HK$10,000 per year
✓ Dynamic international city and combination of western and eastern culture.
✓ High quality research in engineering field.
✓ Application deadline: 1 December 2010
Thank you very much for your kind attention.

Jian-Guo DAI
cejgdai@polyu.edu.hk