Introduction

Use of prestressed FRP fabrics has not developed as widely as that of laminated strips:

- devices effective in seizing and prestressing laminated strips have been produced

- significant problems have been encountered in developing as effective devices for fabrics:
  - difficulty in seizing the fabric for prestressing without ripping the fibres
Summary

• current prestressing methods

• main technical issues

• a new tensioning device suitable for fabrics
  – concept
  – scheme
  – a design procedure
  – remarks
current methods

Two main methods of prestressing external strengthening reinforcement

**indirect**: by cambering the flexural member

![Diagram of indirect method](image)

**direct**: jacking against an external reaction frame or on the beam itself

![Diagram of direct method](image)
Technological issues

The main technological challenge in prestressing FRP fabrics is seizing the fabric itself.

FRP laminated strip
(transverse stiffness)

FRP fabric
(thickness ≈ 0.2mm)

differential strain/prestress
Technological issues

- So far the only reliable way to seize fabric is to wrap it several times around a resin-impregnated steel rod.

- Several applications exist, all of them needing time for the resin to cure before prestressing the fabric.
- The rod remains in place after the prestressing process.
The FRP-prestressing device

mounted under a bridge beam
The FRP-prestressing device
The FRP-prestressing device

- Beam soffit
- FRP fabric
- Sliding sledges
- Rotating cylinder
- Gear(s)
- Fixed teeth
- Hydraulic jack(s)
- Fixed sledge
Design of flexural strengthening with prestressed FRP

- Case of R/C beam with inadequate steel reinforcement

- **Steps** in the analysis:
  1. assess the Existing Moment Capacity
  2. evaluate the Difference Demand - Capacity
  3. **Design** the required amount of strengthening material and prestress level using closed-form equations
**Geometry and material properties**

- $b_c =$ section width
- $h =$ section depth
- $d' =$ concrete cover thickness
- $d = h - d' =$ effective depth
- $A_s =$ tension steel area
- $A'_s = u A_s =$ compressive steel area

### Material Properties

- $f_{ck} =$ concrete characteristic strength
- $f_{cd} = \alpha_{cc} f_{ck} / \gamma_c =$ concrete design strength
- $E_c = 22000 (f_{cm} / 10)^{0.3} =$ concrete modulus
- $f_{cm} = f_{ck} + 8 \text{ MPa} =$ concrete mean strength
- $\varepsilon_{cu} = 0.0035 =$ concrete crush strain
- $f_{yk} =$ steel characteristic strength
- $f_{yd} = f_{yk} / \gamma_s =$ steel design yield strength
- $\varepsilon_{yd} = f_{yd} / E_s =$ steel design yield strain
Non-dimensional formulation

\[ \xi = \frac{\delta}{d} = \text{neutral axis depth} \]
\[ \delta = \frac{d'}{d} = \text{concrete cover ratio} \]
\[ \eta = \frac{h}{d} = 1 + \delta = \text{beam depth ratio} \]
\[ u = \frac{A'}{A_s} = \text{compressive/tensile steel ratio} \]
\[ w = 1 - u = \text{complementary steel ratio} \]
\[ \mu_s = u \mu_s = \text{mechanical steel ratios} \]

\[ \mu_s = \frac{A_s f_{yd}}{f_{cd} b_c d} \]

(compression steel)

\[ \mu_s' = \frac{A_s' f_{yd}}{f_{cd} b_c d} = u \cdot \mu_s \]

(tensile steel)

\[ A_f = \text{area of the FRP sheet/plate} \]
\[ b_f = \text{sheet width} \]
\[ t_f = \text{sheet thickness} \]
\[ f_{fd} = E_f \varepsilon_{fd} = \text{design FRP strength} \]
\[ \varepsilon_{fd} = \text{design ultimate strain of FRP} \]
Non-dimensional formulation

- all moments can be normalized as:

\[
m = \frac{M}{f_{cd} b_c d^2}
\]
1. Moment Capacity

1.1 Compatibility

1.1.1 **Cross section failure** occurs when \( \varepsilon_c = \varepsilon_{cu} \)

1.1.2 Through compatibility the corresponding strains of tensile and compression steel are:

\[
\varepsilon_s(\xi) = \varepsilon_{cu} \frac{d - y}{y} = \varepsilon_{cu} \left( \frac{1}{\xi} - 1 \right) \quad \text{(tension)}
\]

\[
\varepsilon_s'(\xi) = \varepsilon_{cu} \frac{y - d'}{y} = \varepsilon_{cu} \left( 1 - \frac{\delta}{\xi} \right) \quad \text{(compression)}
\]

1.1.3 **stress** in the compression steel in non-dimensional form is

\[
s'(\xi) = \frac{\sigma_s'}{f_{yd}} = \min \left[ \frac{\varepsilon_{cu}}{\varepsilon_{yd}} \left( 1 - \frac{\delta}{\xi} \right), 1 \right]
\]
1. Moment capacity

1.2. Condition assessment

1.2.1 In non-dimensional form, the *existing* resisting moment is found by solving the equilibrium equation for the neutral axis depth $\xi$

$$0 = \alpha \cdot \xi + s'(\xi) \cdot u \cdot \mu_s - \mu_s$$

where $\alpha = 0.8 = \text{concrete resultant coefficient}$

1.2.2 The non-dimensional resisting moment is found by replacing $\xi$ in the equation

$$m_{Rd} = s'(\xi) \cdot u \cdot \mu_s (\nu \cdot \xi - \delta) + \mu_s (1 - \nu \cdot \xi)$$

where $\nu = 0.4 = \text{concrete resultant centroid coefficient}$
1. Moment capacity
1.3. Initial conditions before FRP-strengthening

1.3.1 Before applying the FRP strengthening, it is necessary to know the strain state at the beam soffit.

In case of propped beam, this is equal to zero.

1.3.2 If the beam is left under the permanent load $G_k$, the initial strain $\varepsilon_0$ is evaluated as

$$\varepsilon_0 = \min(\varepsilon_{0,cr} , \varepsilon_{0,id})$$

and can be found as:

$$\varepsilon_0 = \frac{M_{G_k}}{E_c I_{(cr \ or \ id)}}(h - y)$$
2. Demand – Capacity Gap

2.1 FRP-strengthening design target

2.1.1 The aim of the strengthening procedure is to obtain

\[ m_{Rd, f} = incr \cdot m_{Rd} \geq m_{Sd} \]

2.1.2 FRP strain must not exceed the design maximum strain, reduced by a efficiency (uncertainty) factor \( r \), based on the prestressing device used

\[ \varepsilon_f(\xi) = \varepsilon_{fm}(\xi) + \varepsilon_{fp} \leq r \cdot \varepsilon_{fd} \]

where \( \varepsilon_{fm}(\xi) = \) mechanical strain, found based on compatibility as

\[ \varepsilon_{fm}(\xi) = \varepsilon_{cu} \left( \frac{\eta}{\xi} - 1 \right) - \varepsilon_0 \]

and \( \varepsilon_{fp} = \) prestress strain
2. Demand – Capacity Gap

2.2 Strengthening with prestressed FRP

2.2.1 First step: choose the appropriate FRP material only on the basis of the design ultimate strain \( \varepsilon_{fd} \).

2.2.2 The device efficiency (or uncertainty) factor can then be expressed as:

\[
r = \frac{\varepsilon_{fm}(\xi)}{\varepsilon_{fd}} + p_f \leq 1
\]

where \( p_f = \frac{\varepsilon_{fp}}{\varepsilon_{fd}} \) is the FRP prestress ratio wrt its ultimate strain \( \varepsilon_{fd} \), \( p_f \) is the objective of the design,

2.2.3 together with the FRP-strengthening ratio

\[
\mu_f = \frac{A_f f_{fd}}{f_{cd} b_c d}
\]

where \( f_{fd} \) is the FRP design strength.
2. Demand – Capacity Gap

2.2 Strengthening with prestressed FRP

2.2.4 The cross-section equilibrium equations are in this case:

\[ 0 = \alpha \cdot \xi + s'(\xi) \cdot u \cdot \mu_s - \mu_s - r \cdot \mu_f \]

\[ m_{Rd,f} = s'(\xi) \cdot u \cdot \mu_s (1 - \nu \xi) + \mu_s (1 - \nu \xi) + r \cdot \mu_f (\eta - \nu \xi) \]

where:

– the target value \( m_{Rd,f} \) depends on the chosen increment \( incr \)
– and \( \eta = h/d = 1 + \delta \)

By solving both above equations, with the limitation given by the efficiency factor \( r \), the three unknowns \( \xi, P_f, \mu_f \) are found
3. Required strengthening

3.1. Design through closed-form equations

3.1.1 Simple design equations can be obtained by making the assumption that the stress in the compressive steel is \( s'(\xi) = 1 \) (low contribution from the yielded compressive steel).

3.1.2 The two (translational and rotational) equilibrium equations become

\[
0 = \alpha \cdot \xi - w \cdot \mu_s - r \cdot \mu_f \\
\eta = \frac{h}{d} = 1 + \delta \quad u = \frac{A_s'}{A_s} \\
w = 1 - u
\]

\[
m_{Rd,f} = \mu_s \cdot (1 - u \cdot \delta - w \cdot \nu \cdot \xi) + r \cdot \mu_f (\eta - \nu \cdot \xi)
\]

3.1.3 From the first equation the neutral axis depth is found by

\[
\xi = \frac{w \cdot \mu_s + r \cdot \mu_f}{\alpha}
\]

by substituting it in the latter, one obtains

\[
m_{Rd,f} = \mu_s (1 - u \cdot \delta) + r \cdot \mu_f \cdot \eta - \frac{\nu}{\alpha} (w \cdot \mu_s + r \cdot \mu_f)^2
\]
3. Required strengthening

3.1. Design through closed-form equations

Then:

3.1.4 the amount of FRP is found

\[
\mu_f = \frac{1}{2\nu r} \left[ \alpha \cdot \eta - 2\nu w \cdot \mu_s - \sqrt{\alpha^2 \cdot \eta^2 - 4\nu \alpha [m_{Rd,f} - \mu_s (u - \delta)]} \right]
\]

3.1.5 along with the prestress to be applied

\[
p_f = r - \frac{\varepsilon_{cu}}{\varepsilon_{fd}} \left( \frac{\alpha \cdot \eta}{w \mu_s + r \mu_f} - 1 \right) + \frac{\varepsilon_0}{\varepsilon_{fd}}
\]
3. Required strengthening

3.2 Actual amount of FRP

Once determined the amount of FRP in non-dimensional terms, one has:

3.2.1 the FRP area

\[ A_f = \frac{\mu_f f_{cd} b_c d}{f_{fd}} \]

by selecting the FRP design strength and (implicitly) the FRP modulus

\[ E_f = \frac{f_{fd}}{\varepsilon_{fd}} \]

3.2.2 the applied prestress:

\[ \sigma_{fp} = p_f \cdot r \cdot f_{fd} \]

3.2.3 and the prestressing force to apply to the FRP

\[ P_{fp} = \sigma_{fp} \cdot A_f \]
the device allows for varying prestress level along the beam

Multiple prestressed layers: prestress level in first layers decreases

Single prestressed layer: prestress level controlled

max: debonding strength

min: debonding length
Conclusions

• New device developed to properly seize and accurately prestress FRP fabric layers

• Easily handled, reusable and adjustable to local working conditions and design needs

• Prestress level and total stress in the fabric continuously monitored and easily adjustable

• Simple design procedure proposed allowing, by use of *closed-form equations*, to determine the amount of FRP and the prestressing level to obtain the required bending resistance increase
Thank you for listening!

Marco.menegotto@uniroma1.it