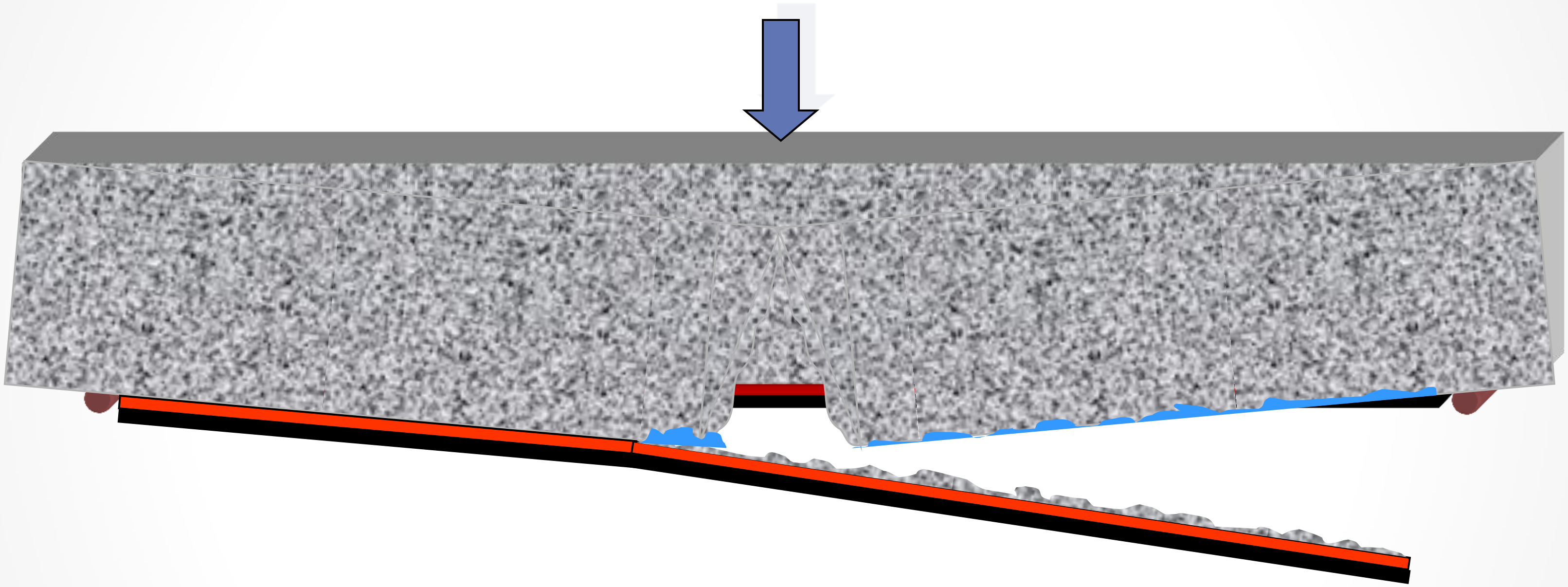
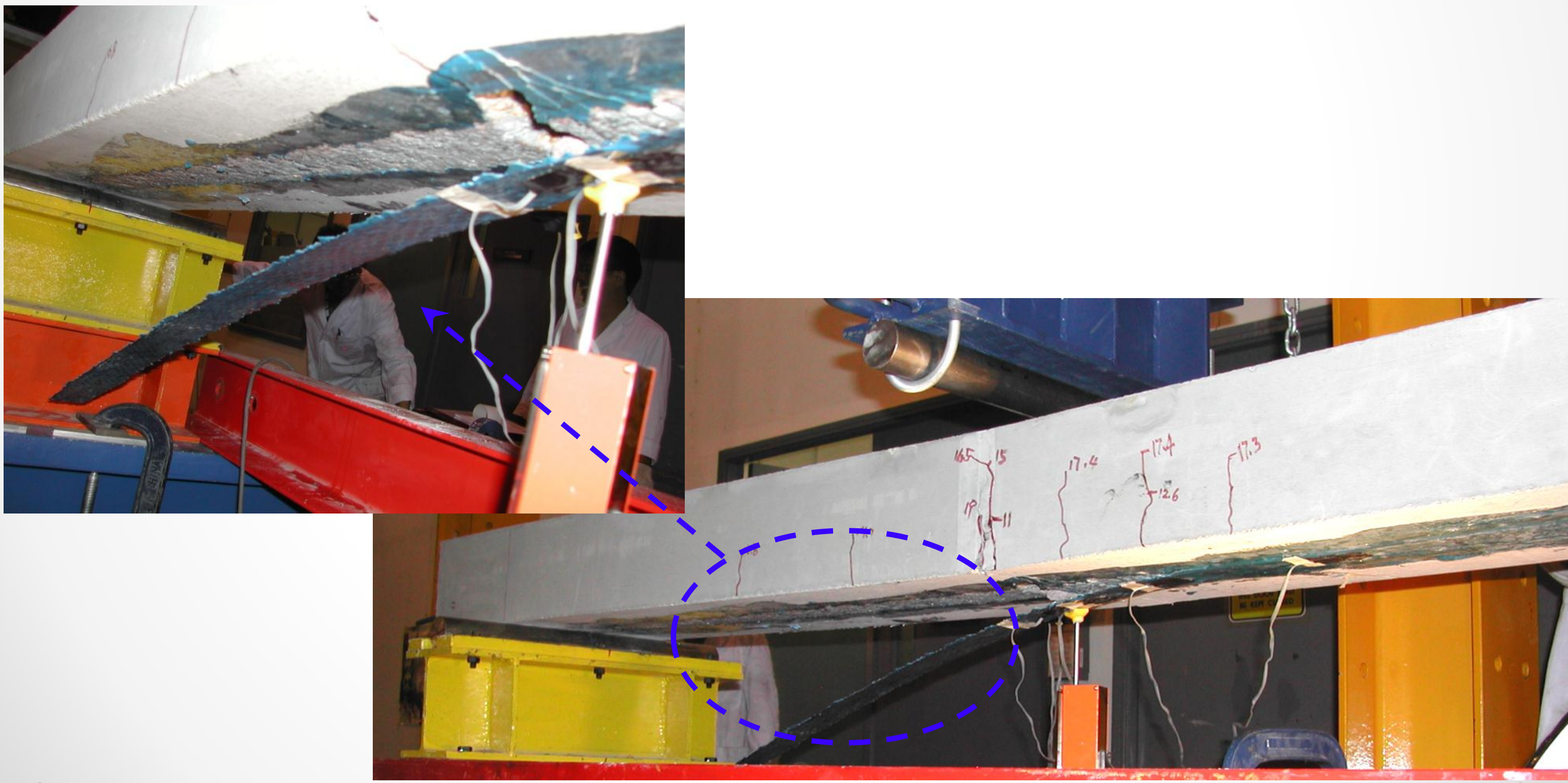
Critical problem in EB-FRP technique



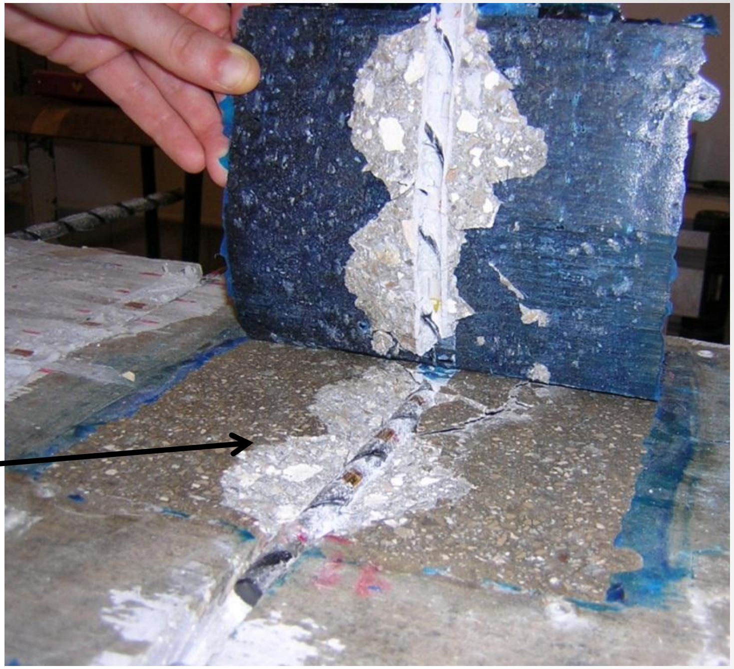
Unless only a small amount of FRP is used, full utilization of FRP materials' tensile strength cannot be realized.

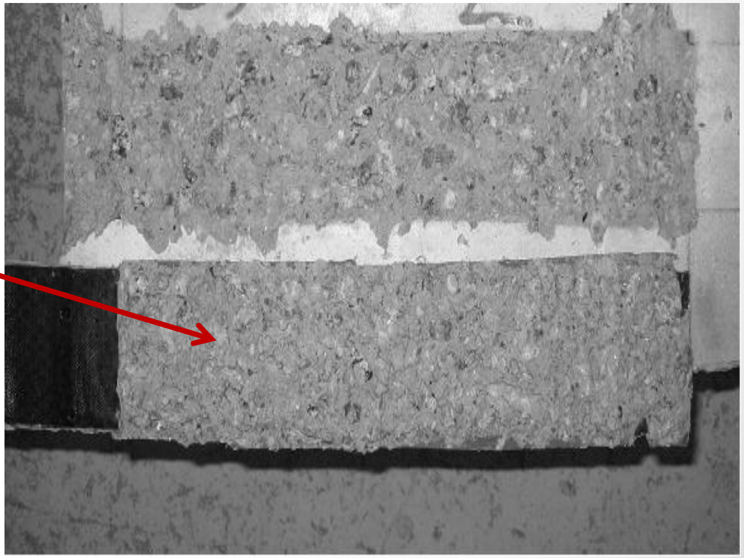
- Failure of a strengthened member - a premature, sudden and brittle detachment of FRP from the concrete substrate.
- This weakest link of bond fundamentally limits the efficacy level and reliability of the method.



Current Technology:

- FRP strength transmitted into concrete through adhesion.
- Weak interface by surface adhesion
- Problem remains when a stronger adhesive used - peeling off a thin concrete layer.
- Low strength utilization ratio - lower than 20% of the FRP strength.
- Limited applications due to limited increase in strength.





Previous solution to the problem

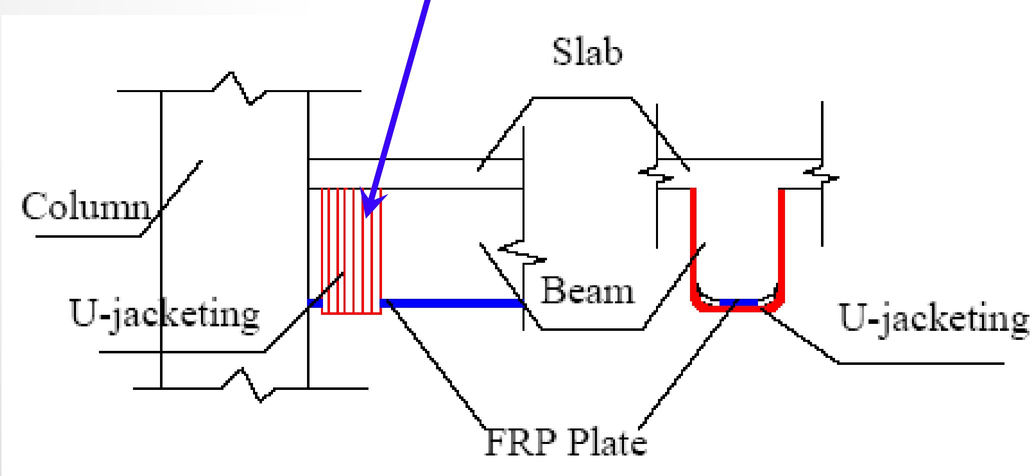
Additional U-jacket FRP strips bonded to beam sides at the plate end

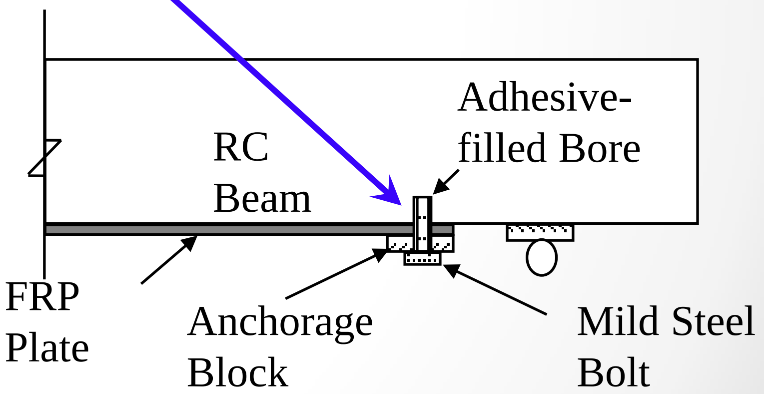
- Brena et al. (2003), Ritchie et al. (1991), Swamy and Mukhopadhyaya (1999), Smith and Teng (2003), Teng et al. (2002).

End anchorage

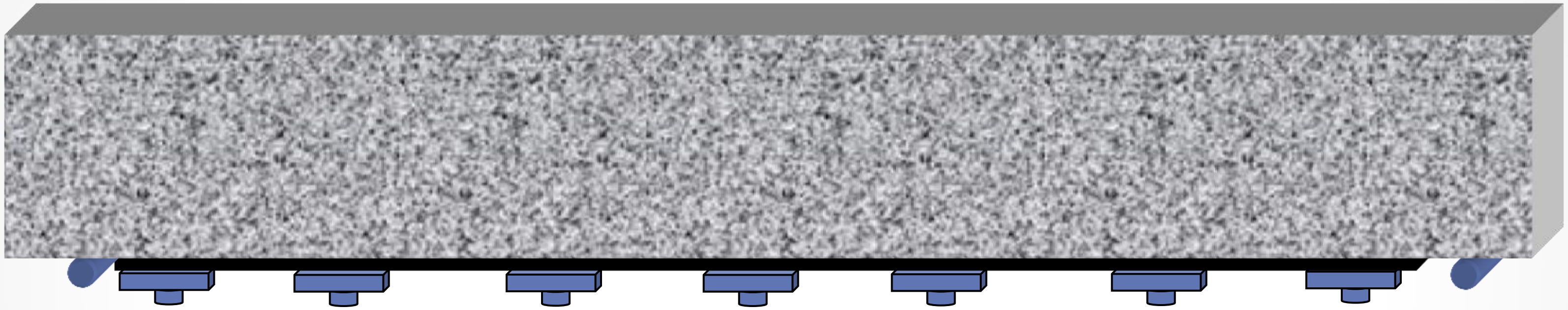
Anchoring FRP strips at ends with

- large mechanical anchors, or
- FRP U-jacket





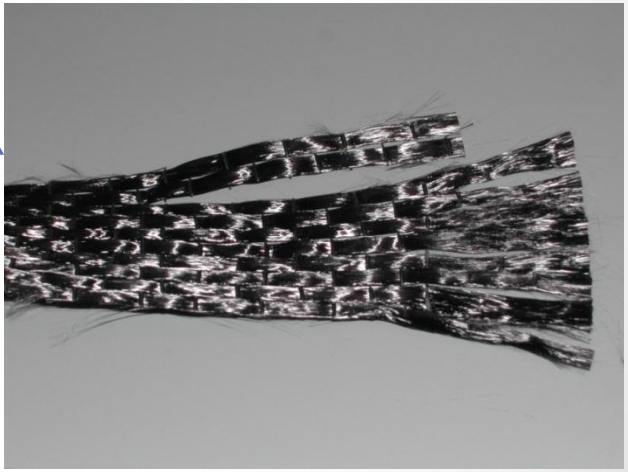
Mechanically Fastened (MF) FRP system

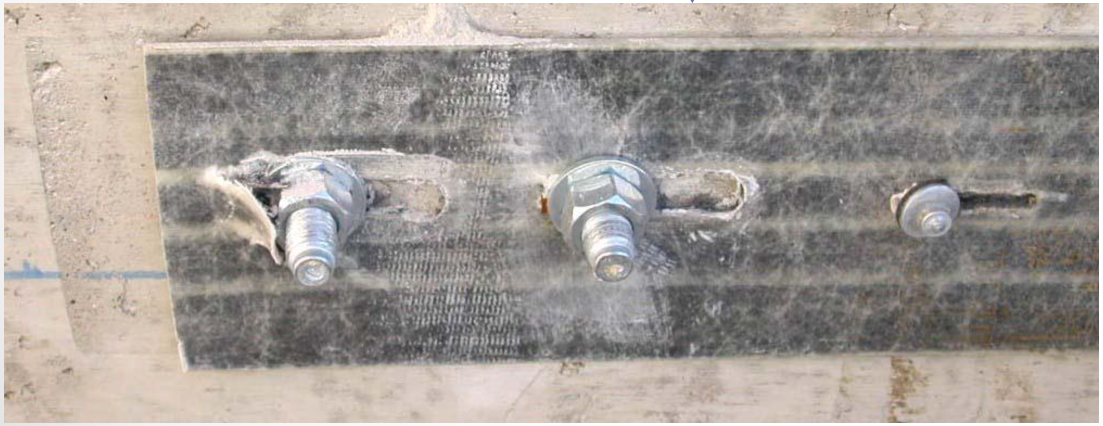


- Lamanna et al. (2001, 2002, 2004).

Mechanical fastening of FRPs (MF-FRP)

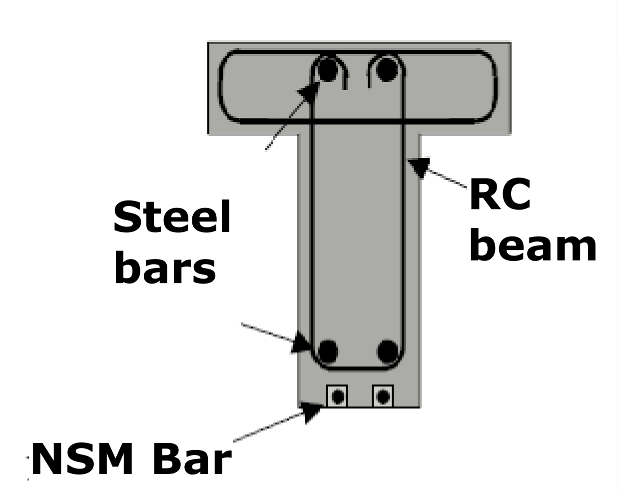
- Mechanical fastening - a conventional and effective way.
- Not applicable to normal FRP fabric/laminates, due to low bearing strength.
- A special FRP – <u>SafStrip™</u> – that posses certain bearing strength – but for temporary strengthening





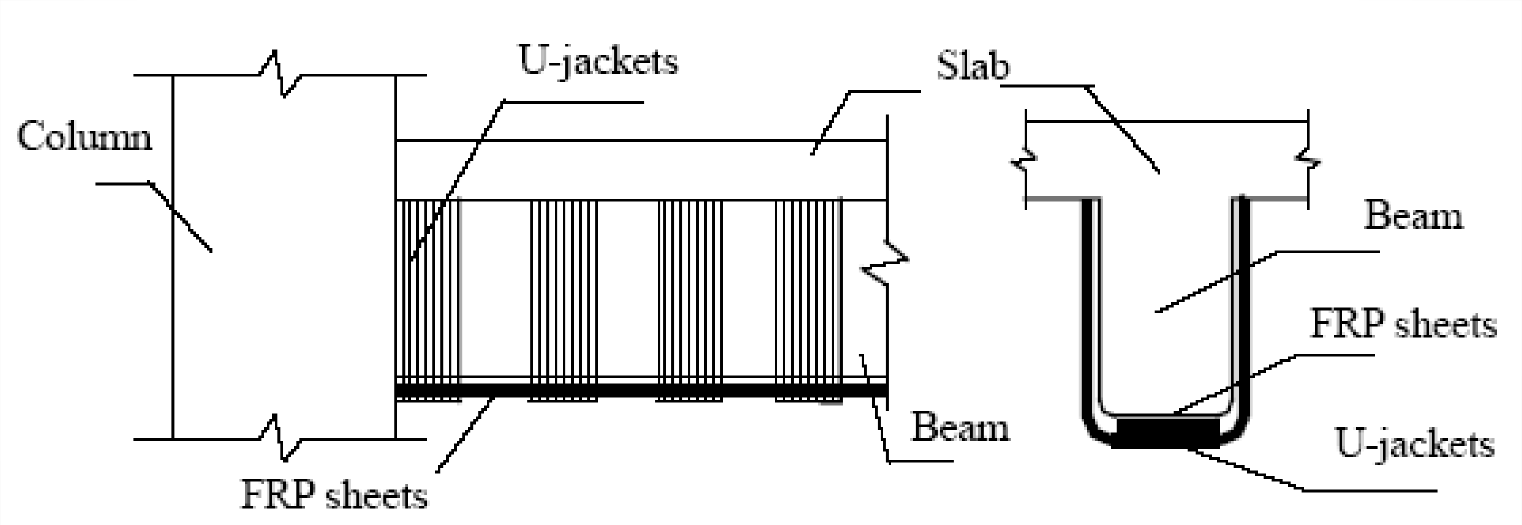
Near-surface mounting (NSM)

- Inserting FRP bars or strips into concrete cover.
- Saw-cutting may cut existing reinforcement bars.
- Limited increase in bond strength.



U-jacket

Wrapping FRP strips with U-shaped strip that may increase the bond strength by 30% (Ye et al. 2005)



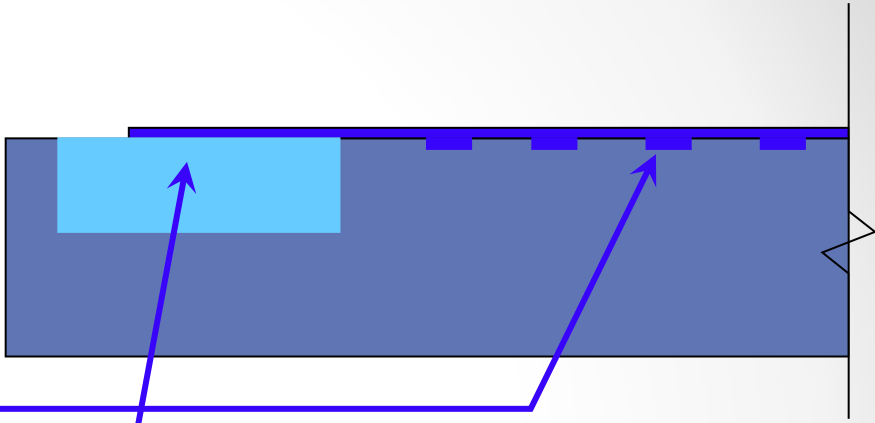
Ye, LP, Lu XZ, and Chen, JF. “Design proposals for the debonding strengths of FRP strengthened RC beams in the Chinese design code”. Proc. International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005), Hong Kong, pp 45-54.

Fiber anchoring

- Fiber anchor spikes can increase the flexural capacity of strengthened beam by 35% (Ekenel et al. 2006).
- Construction inconvenient

Ekenel, M., Rizzo, A., Myers, J.J., and Nanni, A. Flexural fatigue behavior of reinforced concrete beams strengthened with FRP fabric and precured laminate systems, *J. Composite for Construction* 2006; 10(5): 433-442.

Interlocking-anchorage



- Interlocking keys - cutting transverse shallow grooves and filled with epoxy.
- U-jacket at the end.
- Increasing bond strength by 11% (Grace 2001)

Grace, N.F. Improved anchoring system for CFRP strips, *Concrete International* ACI, 2001; 23(10): 55-60.

The state-of-the-art

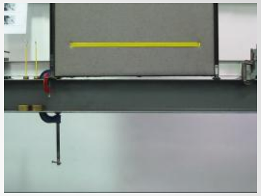
After more than one decade of extensive R&D works all over the world, international leading experts conclude:

"No efficient method is available yet to avoid IC debonding failure…"

(Ye et al. 2005)

Ye, LP, Lu XZ, and Chen, JF. "Design proposals for the debonding strengths of FRP strengthened RC beams in the Chinese design code". Proc. International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005), Hong Kong, pp 45-54.

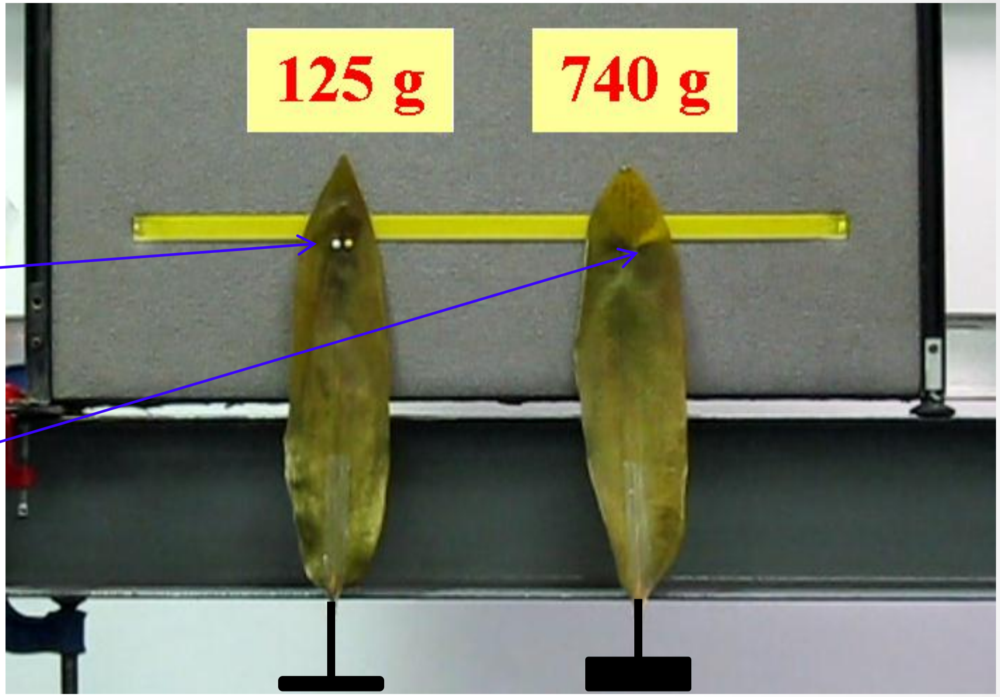
No solution for the problem?



A simple test:

A leaf mounted
by two pins

A leaf mounted
by a staple

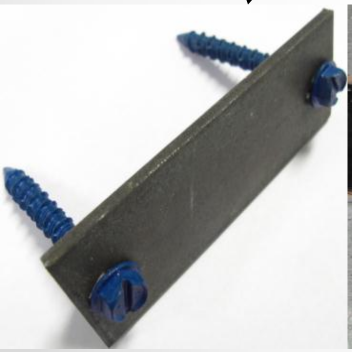


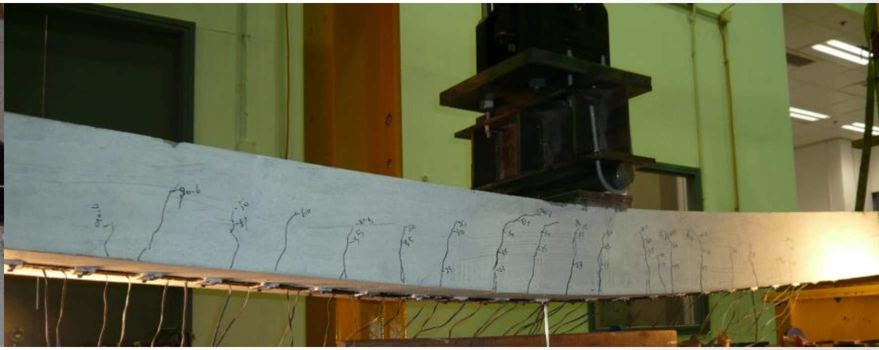
Increase in bond strength by replacing two pins with a staple:

$740/125*100\% = 592\%$

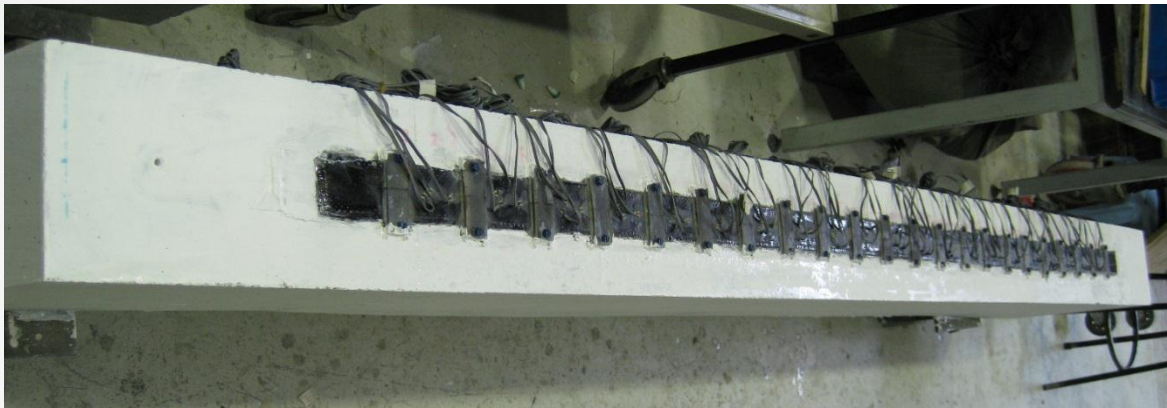
A New Patented Technology – HB-FRP

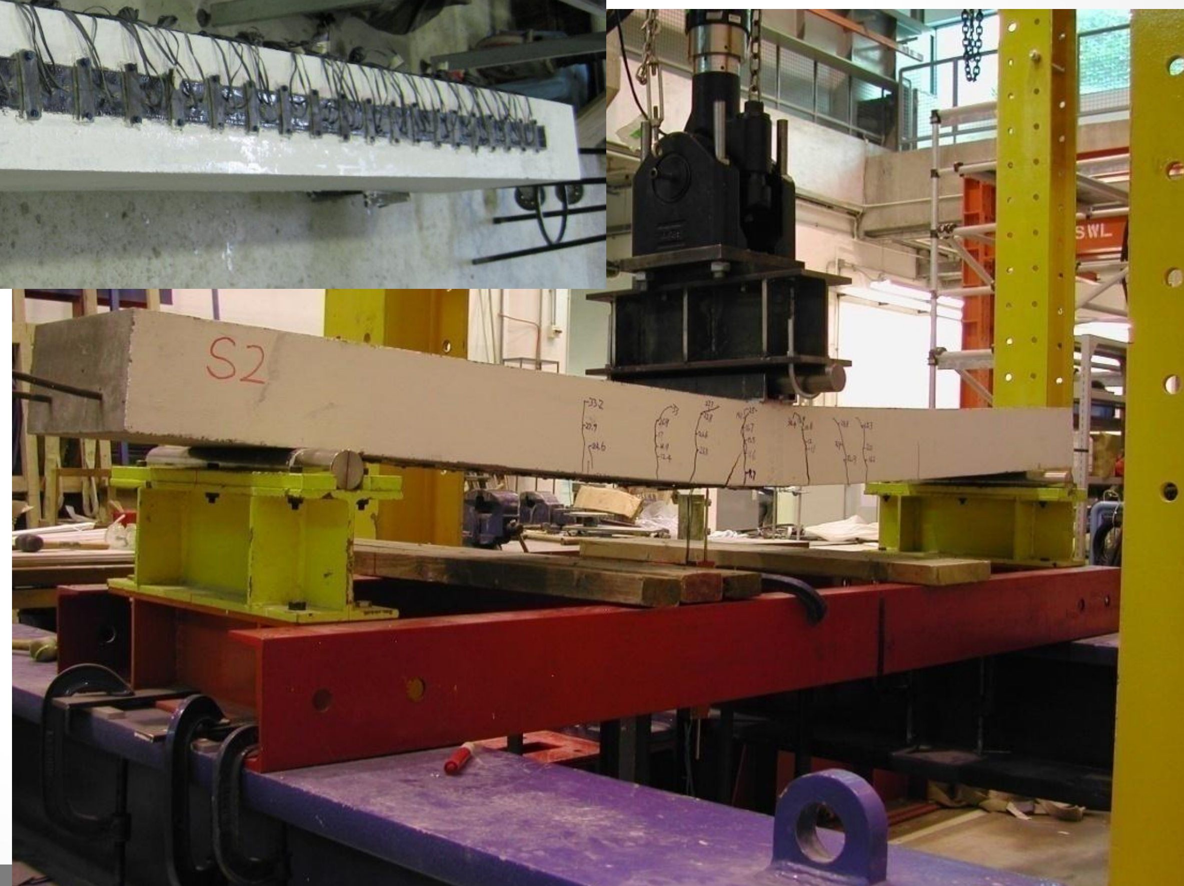
- Normal adhesive bond augmented by a specially mechanical fastener
- Conventional anchors replaced by "staples"



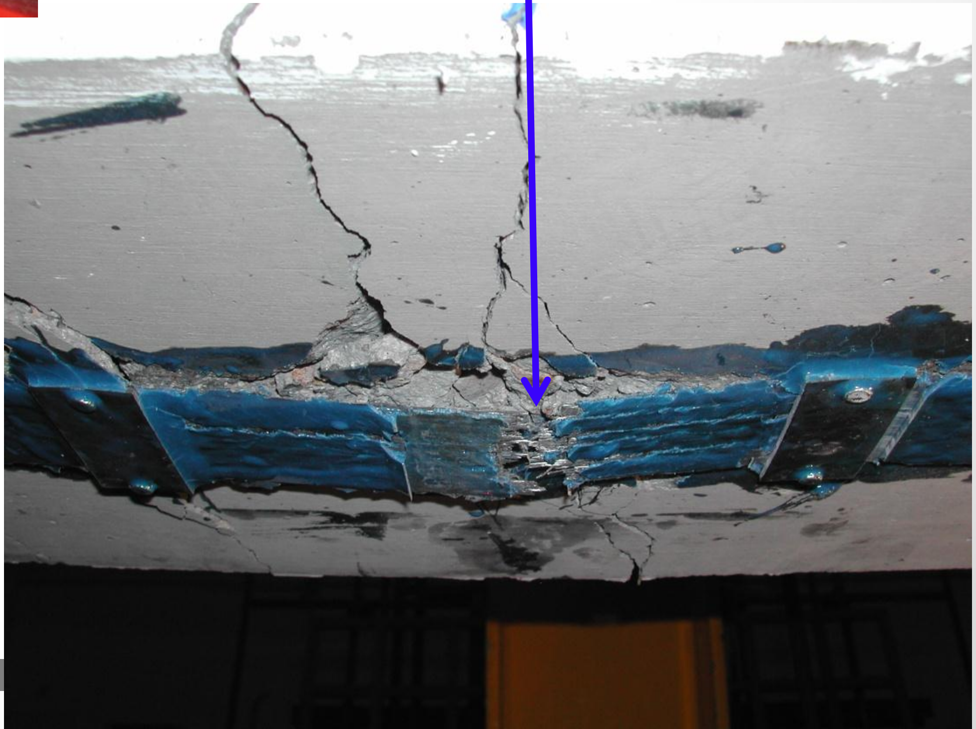


Laboratory Testing





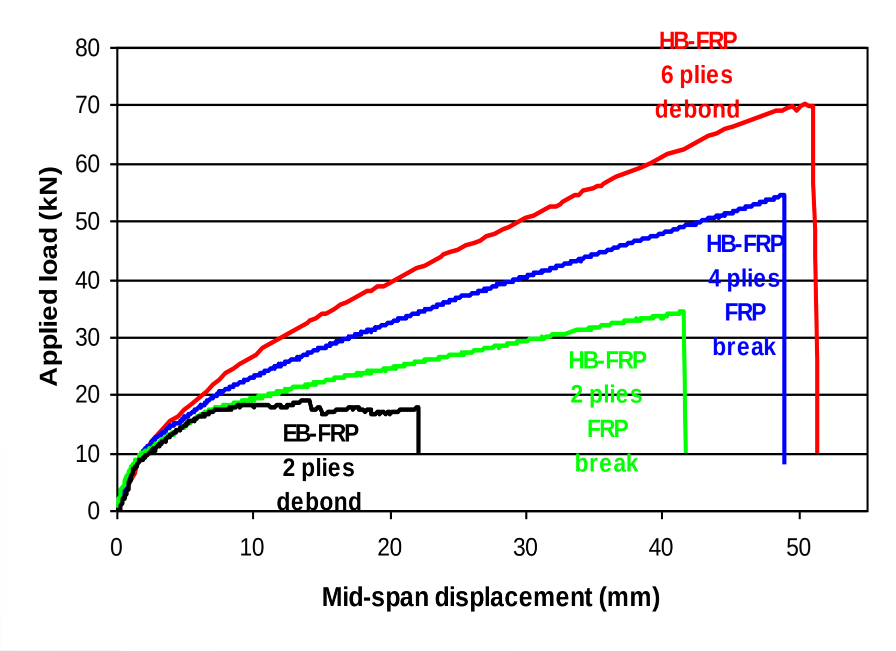
With the fasteners
- FRP rupture



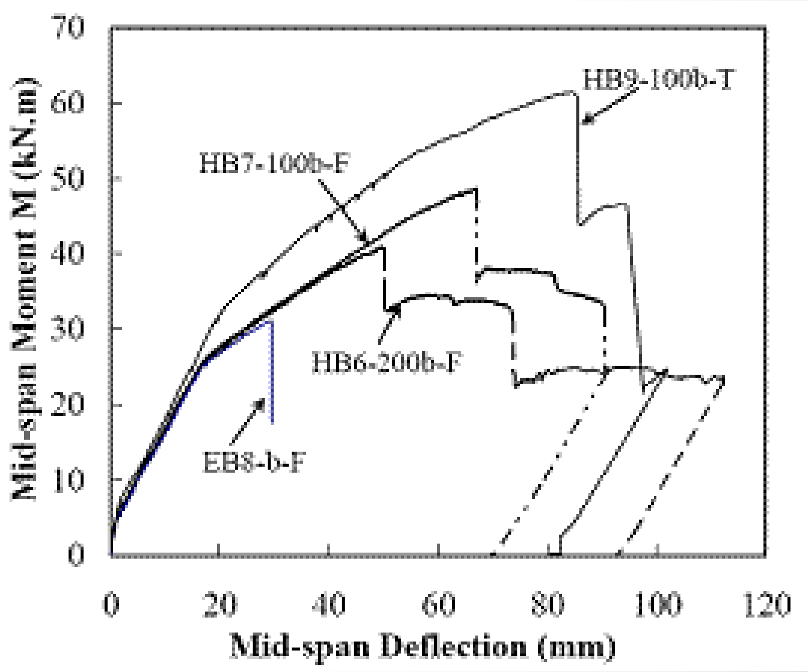
No fastener –
FRP debonding

Test results

- Flexural strength increase: > 4 times
- Bond strength increase: > 6 times
- Additional bond: proportional to fastener number
- Higher increase expected

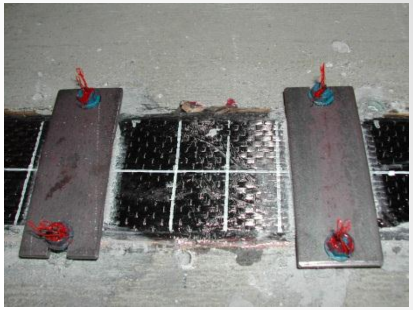


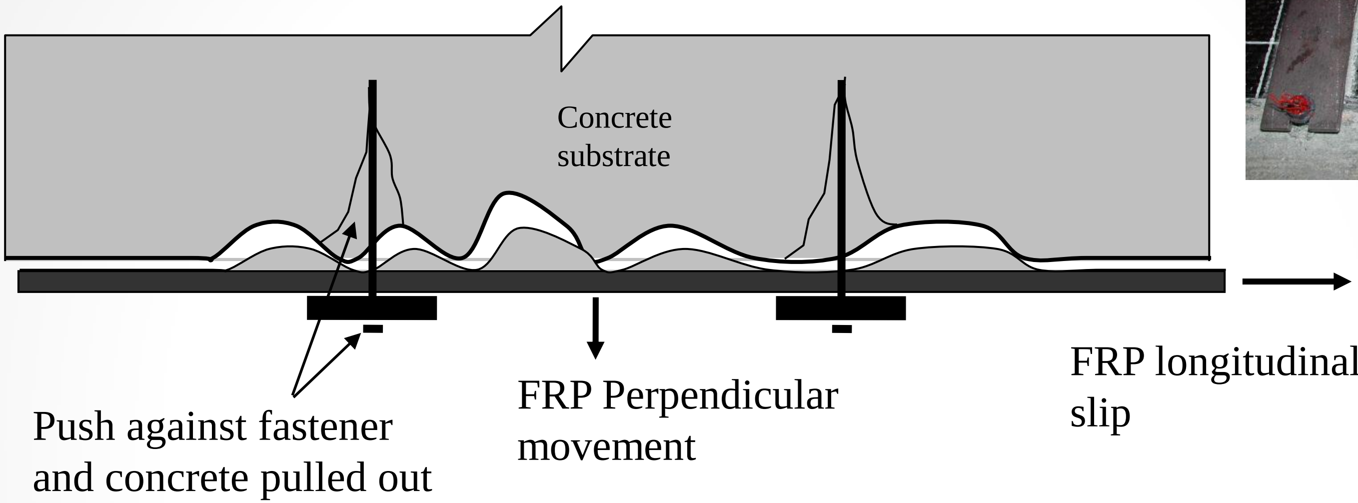
Batch A tests



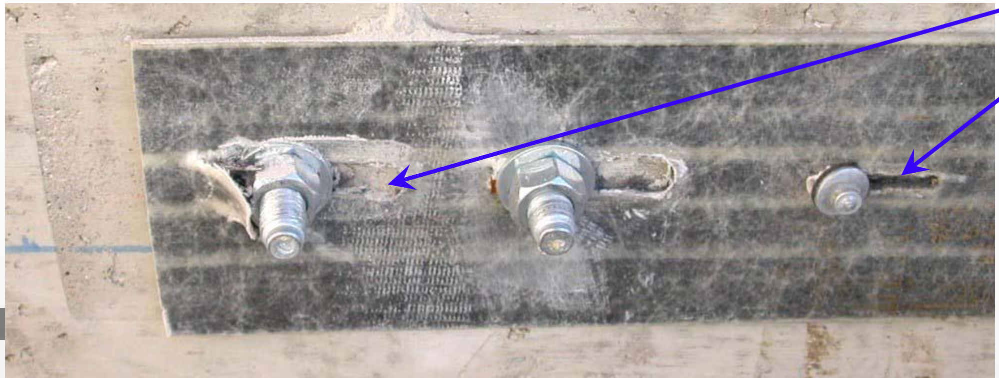
Batch B tests

Mechanism

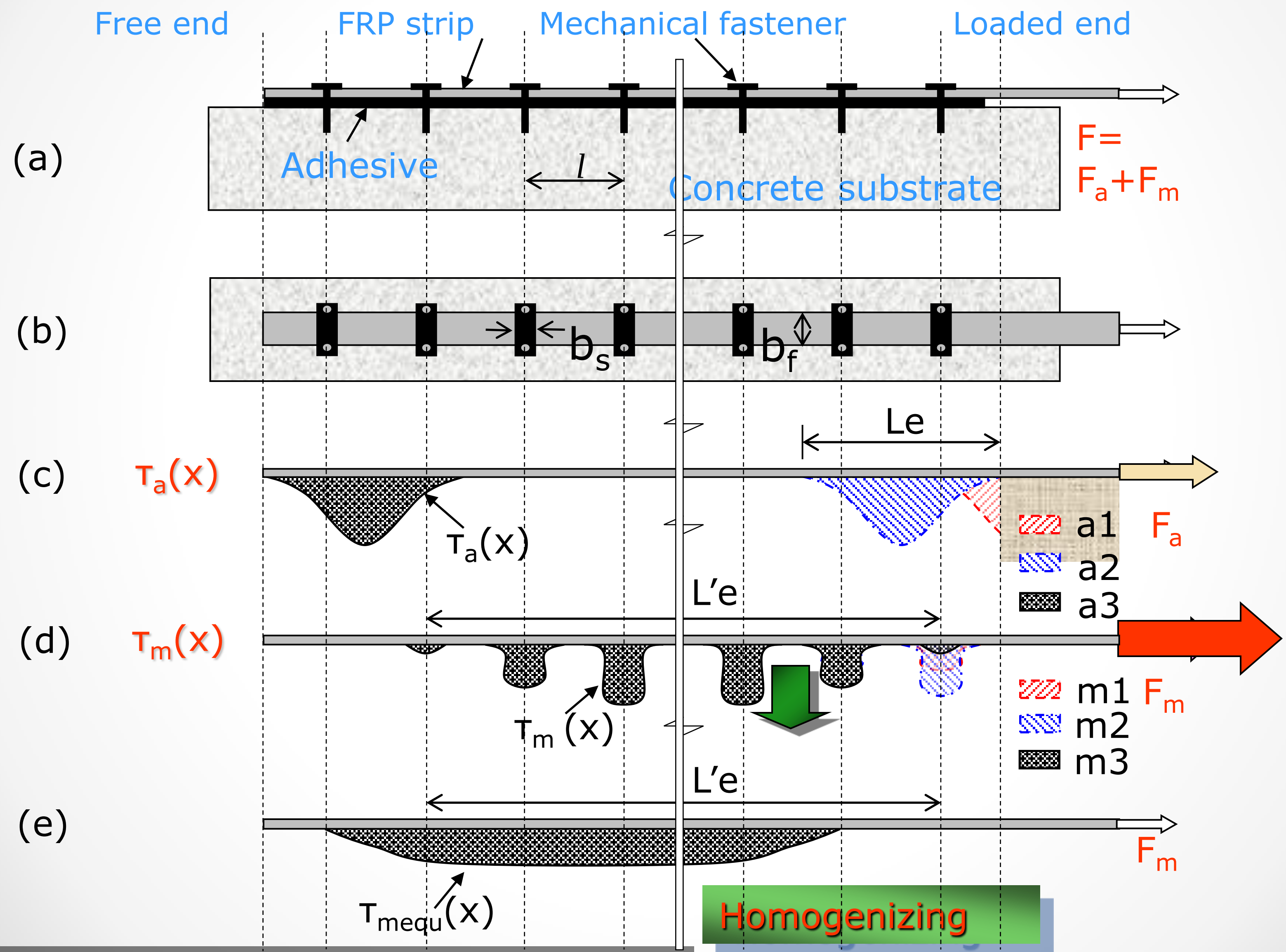




- HB – FRP: slip causes passive pressure, hence friction
- No bearing resistance is required for FRP, hence applicable to any FRP laminates
- Different from the mechanism for SafStrip - <u>bearing</u>



Mechanism of HB-FRP joints



Load-slip response for HB-FRP joints

Based on equilibrium, constitutive and compatibility conditions, governing equations for adhesive joints can be expressed as follow

Homogenizing

$$s'' = \frac{\alpha}{\beta^2} \cdot e^{-\frac{s}{\alpha}} \cdot \left(1 - e^{-\frac{s}{\alpha}}\right) + \begin{cases} \dfrac{\tau_{\max}}{E_f \cdot t_f} \cdot \left(\dfrac{s}{s_1}\right)^{\gamma_1} & (s \le s_1) \\ \dfrac{\tau_{\max}}{E_f \cdot t_f} & (s_1 < s \le s_2) \\ \dfrac{\tau_{\max}}{E_f \cdot t_f} \cdot \left(\dfrac{s - s_3}{s_2 - s_3}\right)^{\gamma_2} & (s_2 < s \le s_3) \\ 0 & (s > s_3) \end{cases}$$

$$\begin{cases} s = s_f \\ \varepsilon = 0 \end{cases}$$

when x=0,

$$\begin{cases} s = s_l \\ \varepsilon = \dfrac{\overline{F}}{E_f \cdot b_f \cdot t_f} \end{cases}$$

when x=L

Energy Method

Load-slip response for HB-FRP joints

Energy Method

$$\overline{F} = \begin{cases} \sqrt{2 \cdot E_f \cdot b_f^2 \cdot t_f \cdot \left(B_1 + C_{meq} \cdot \frac{\tau_{\max} \cdot s_1}{\gamma_1 + 1} \cdot \left(\left(\frac{s_l}{s_1} \right)^{\gamma_1 + 1} - \left(\frac{s_f}{s_1} \right)^{\gamma_1 + 1} \right) \right)} & s_l \le s_1 \\ \sqrt{2 \cdot E_f \cdot b_f^2 \cdot t_f \cdot \left(B_1 + C_{meq} \cdot \left(B_2 + \tau_{\max} \cdot (s_l - s_1) \right) \right)} & s_1 < s_l \le s_2 \\ \sqrt{2 \cdot E_f \cdot b_f^2 \cdot t_f \cdot \left(B_1 + C_{meq} \cdot \left(B_2 + B_3 + \frac{\tau_{\max} \cdot (s_2 - s_3)}{\gamma_2 + 1} \cdot \left(\left(\frac{s_l - s_3}{s_2 - s_3} \right)^{\gamma_2 + 1} - 1 \right) \right) \right)} & s_2 < s_l \le s_3 \\ \sqrt{2 \cdot E_f \cdot b_f^2 \cdot t_f \cdot \left(B_1 + C_{meq} \cdot (B_2 + B_3 + B_4) \right)} & s_l > s_3 \end{cases}$$

where,

$$B_1 = \frac{1}{2} \cdot E_f \cdot t_f \cdot \frac{\alpha^2}{\beta^2} \cdot \left(\left(1 - e^{-\frac{s_l}{\alpha}} \right)^2 - \left(1 - e^{-\frac{s_f}{\alpha}} \right)^2 \right)$$

$$B_2 = \frac{\tau_{\max} \cdot s_1}{\gamma_1 + 1} \cdot \left(1 - \left(\frac{s_f}{s_1} \right)^{\gamma_1 + 1} \right)$$

$$B_3 = \tau_{\max} \cdot (s_2 - s_1)$$

$$B_4 = \frac{\tau_{\max} \cdot (s_3 - s_2)}{\gamma_2 + 1}$$

Load capacity of HB-FRP joints

Infinite bond length

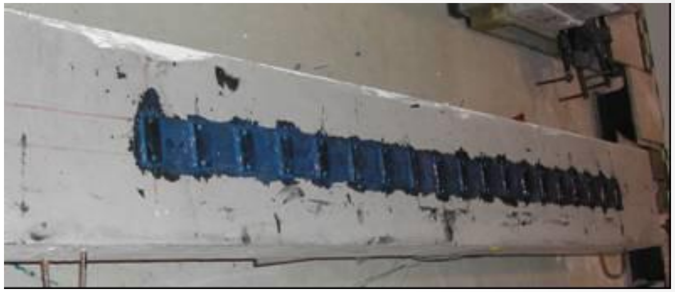
$$P_u = \lim_{\substack{s_l \to \infty \\ s_f \to 0}} \overline{F} = \sqrt{2 \cdot E_f \cdot b_f^2 \cdot t_f \cdot \left(\frac{1}{2} \cdot E_f \cdot t_f \cdot \frac{\alpha^2}{\beta^2} + C_{meq} \cdot \tau_{\max} \cdot \left(\frac{s_1}{\gamma_1 + 1} + (s_2 - s_1) + \frac{(s_3 - s_2)}{\gamma_2 + 1} \right) \right)}$$

Finite bond length

No closed-form solution but can be obtained numerically by solving the second order differential equation (governing equation).

Numerical Modeling of the hybrid bonding scheme

Hybrid bonding scheme



Modeling

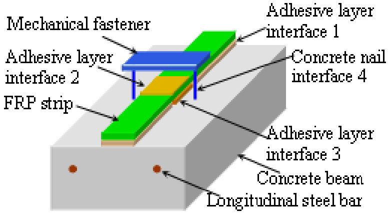
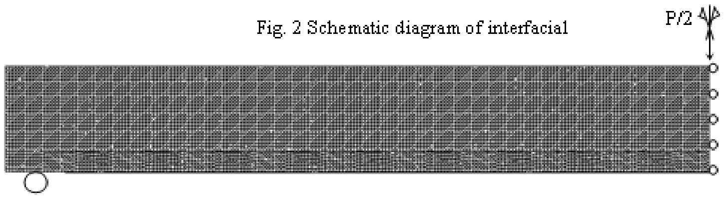


Fig. 2 Schematic diagram of interfacial



FE mesh and boundary conditions

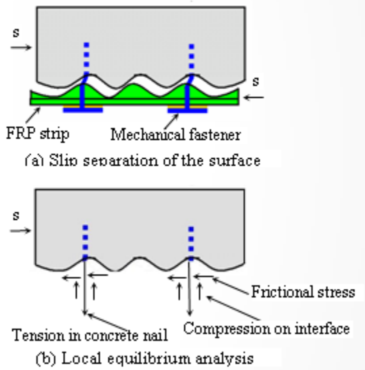


Fig. 6 Shear friction analogy

Numerical results

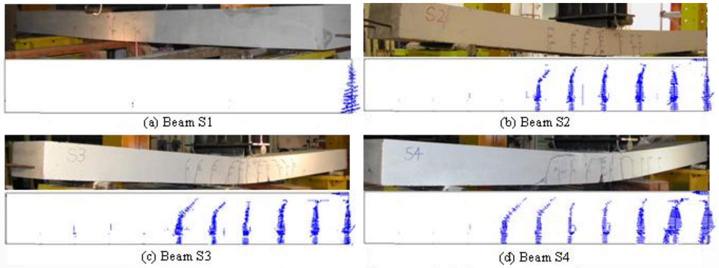
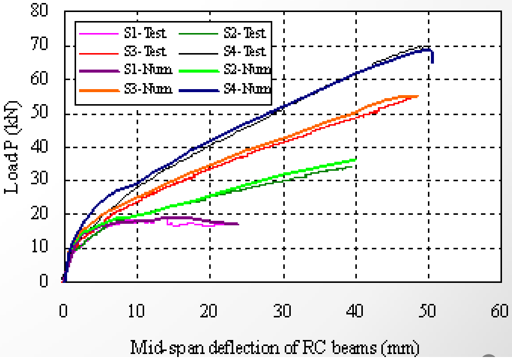


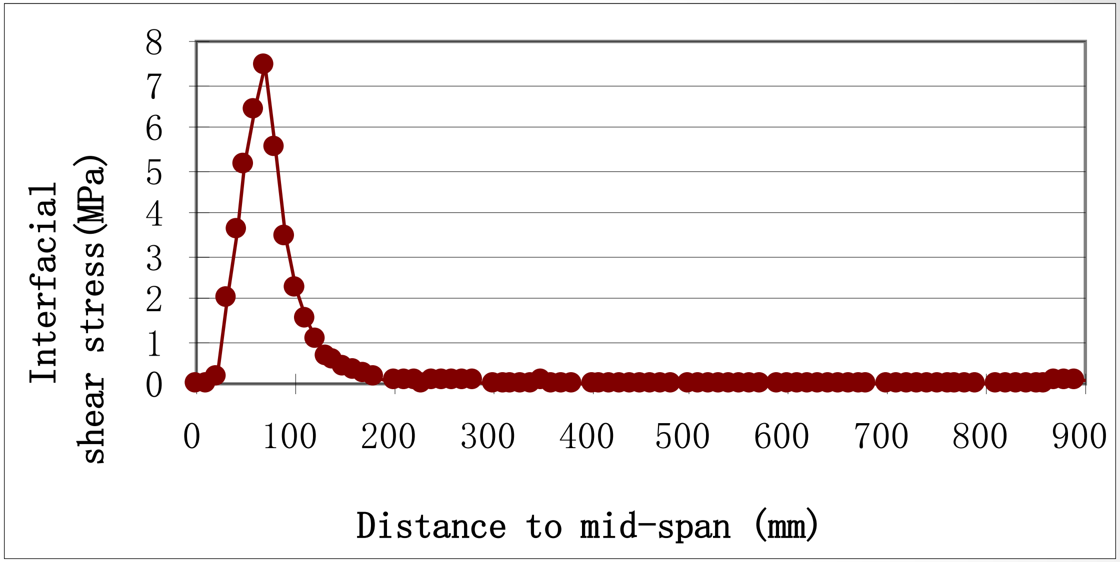
Fig. 13 Test and numerical crack patterns for the beams



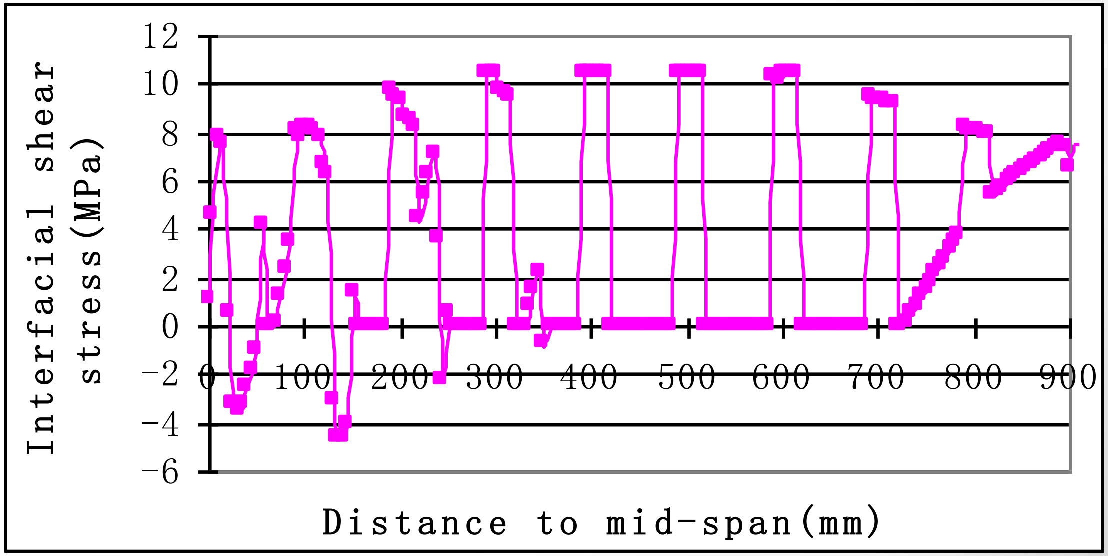
Load-deflection response curves

Numerical simulation results

- EB-FRP: one bond stress block, moving to plate end at debonding



- HB-FRP: many bond stress blocks, one for each anchor.



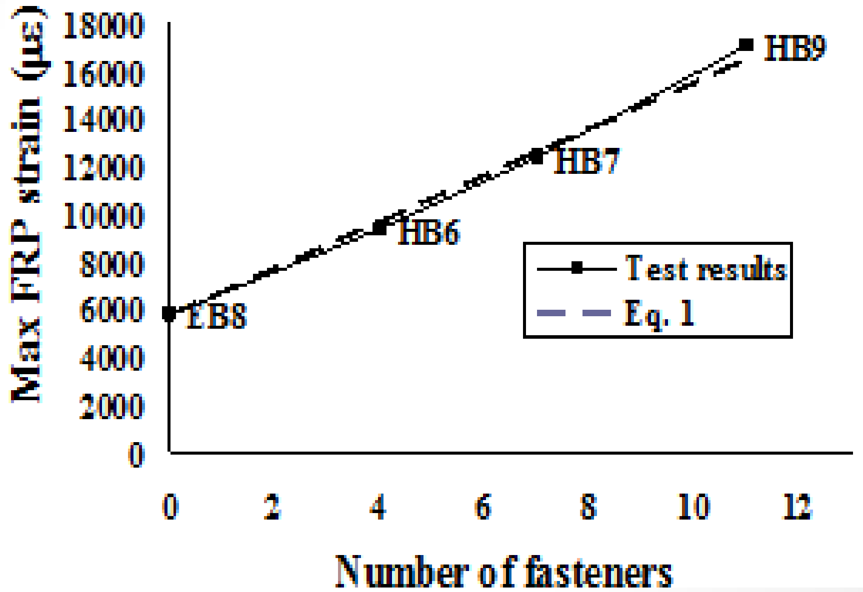
Design Equations

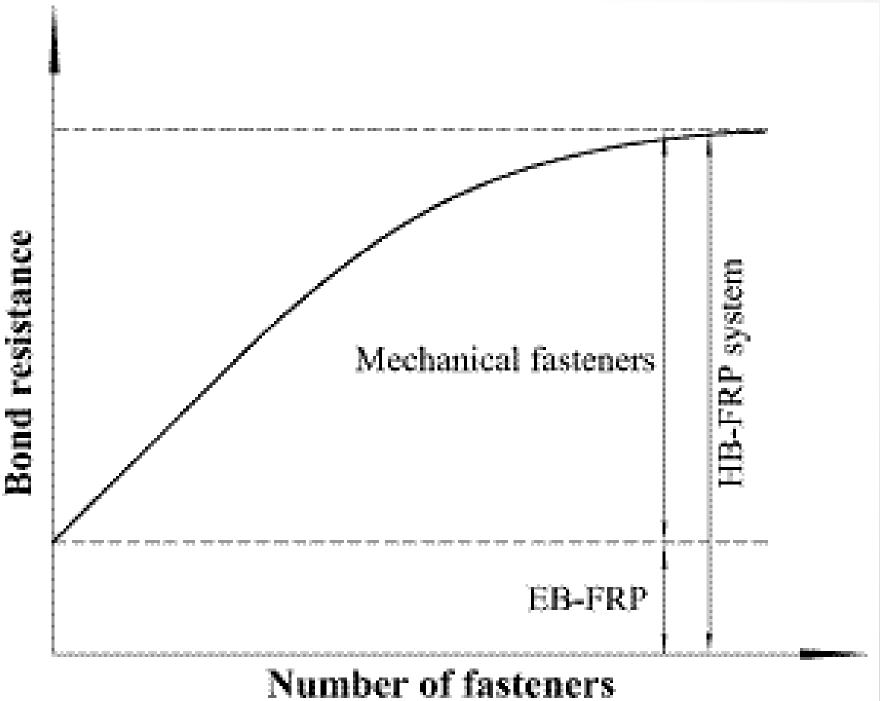
$$P_u = P_a + P_f + P_d \qquad (1)$$

where
P_u - total bond strength;
P_a - adhesive bond strength;
P_d - dowel strength; and
P_f - frictional bond strength given by

$$P_f = \mu \cdot N_a \cdot m$$

in which
μ- frictional coefficient, = 0.96;
N_a - vertical pullout resistance of one fastener; and
m – number of fasteners.





Conclusions

- The current adhesive bond technology relies on the tensile strength of concrete which is weak and unreliable. Furthermore, it cannot significantly increase the strength of strengthened structures.
- One feasible, and probably the only fundamental, solution to this problem is to ensure that the FRP “takes root” in the concrete substrate
- The new HB-FRP technology can increase the bond strength by many times. It can be applied to structure where large increase in strength is needed.
- It is applicable to any existing commercially available FRP fabrics, plates, laminates or sheets.

Reference papers

1. Wu YF, Huang Y. Hybrid bonding of FRP to Reinforced Concrete Structures. *Journal of Composites for Constructions* 2008; 12(3): 266-273.
2. Wu YF, Wang ZY, Liu K, He W. Numerical Analyses of Hybrid-Bonded FRP Strengthened Concrete Beams, *Computer-Aided Civil and Infrastructure Engineering* 2009; 24: 371–384.
3. Yun YC, Wu YF, Tang WC. Performance of FRP bonding systems under fatigue loading. *Engineering Structures* 2008; 30(11): 3129-3140.
4. Wu YF, Yan JH, Zhou YW, Xiao Y. The ultimate strength of reinforced concrete beams retrofitted with hybrid bonded FRP, *ACI Structural Journal* July/August 2010; 107(4).

CityU patents

- One US patent - granted
- One China patent – filed

Design guideline

- Recommended in the proposed "Hong Kong Guide for the Strengthening of Concrete Structures using FRP Composites".

Better solution?

Brittleness of FRP material often causes problems in engineering applications.

A strong, light, yet <u>ductile</u> material possesses great advantages.

Thanks to the advances in materials science, such materials are nowadays available.

Example: nanostructured steel material.

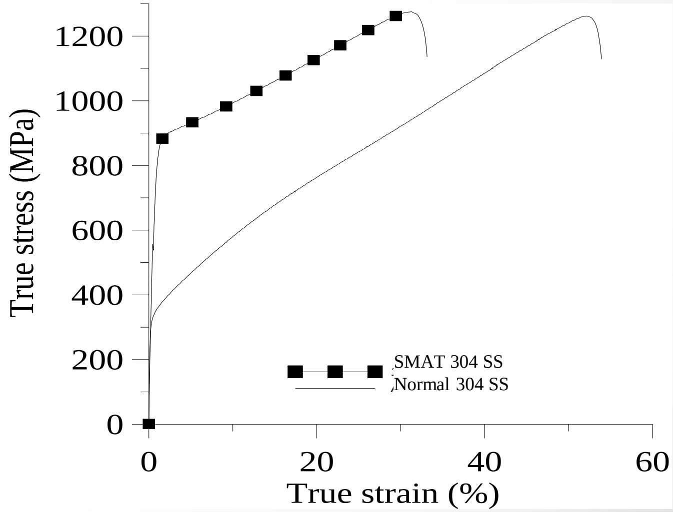
Surface Nanocrystallization Technology

Surface Mechanical Attrition Treatment (SMAT) (Lu and Lu, 1999; Tong et al., 2003) is a recently developed processes to form nanocrystallized surface layer.

*S*MAT process

Current possible strength of SMATed SS
σ_y = 1700 MPa.

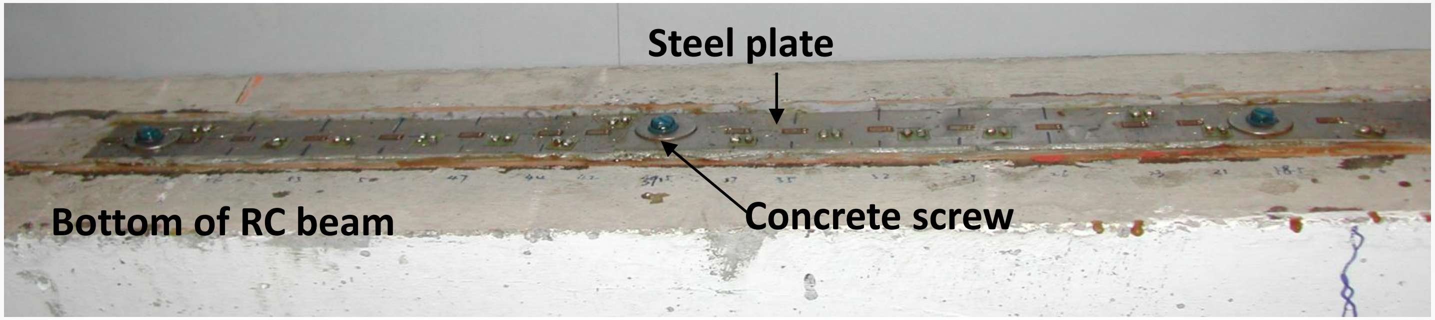
Actual strength of a two-ply CFRP strip (t ≈ 1mm)
σ_u = 4300x0.165x2=1419 MPa



SMATed 304 stainless steel

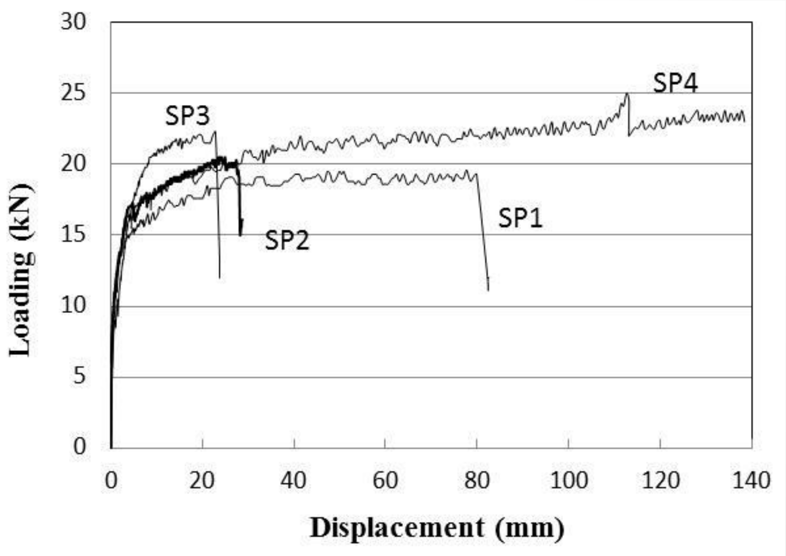
<u>Conclusion</u>: SMATed SS can have a higher strength than CFRP, yet with a ductile post-yield behavior
- ideal for structural rehabilitation

Flexural Strengthening Using SMATed steel



Strengthened bottom face of beam

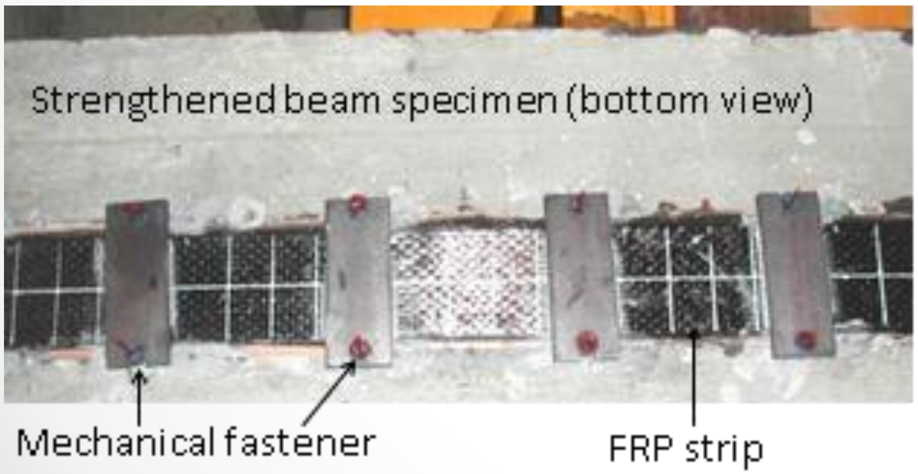
Test setup



Response curves

Advantages

- With the strength of FRP, and the ductility of steel
- No debonding by making use of hybrid bond mechanism without additional steel capping plates.



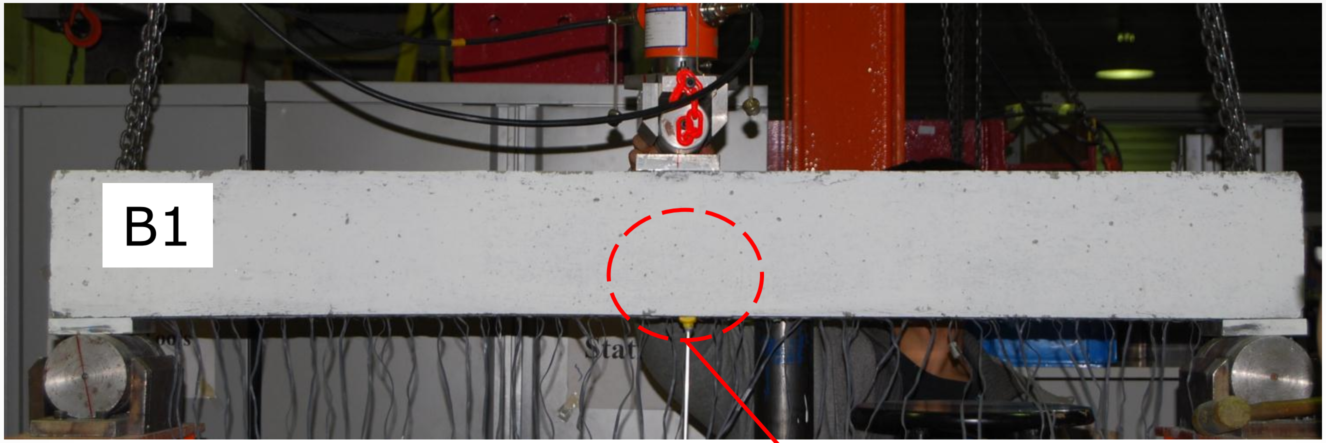
HB-FRP

Steel plating

Additional advantage –

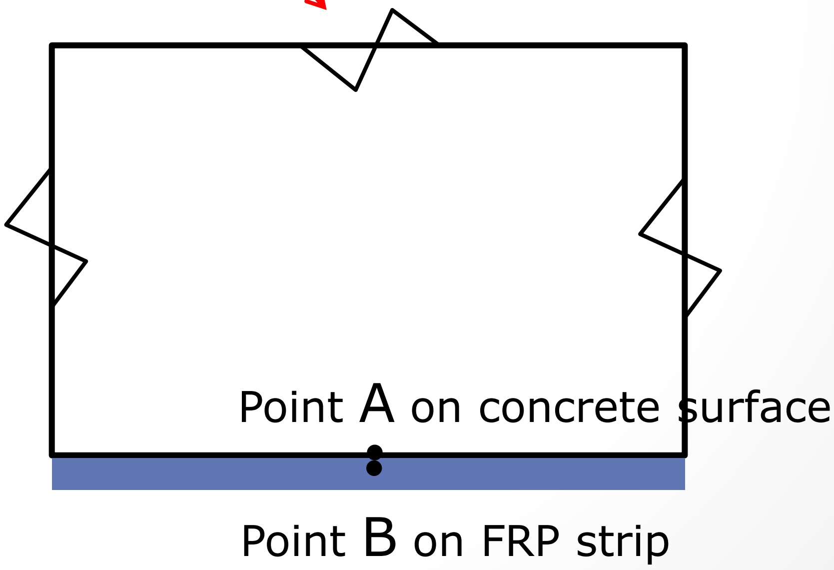
Avoiding detachment of externally bonded reinforcement using
<u>the nano-treated material</u>

Debonding caused by cracking

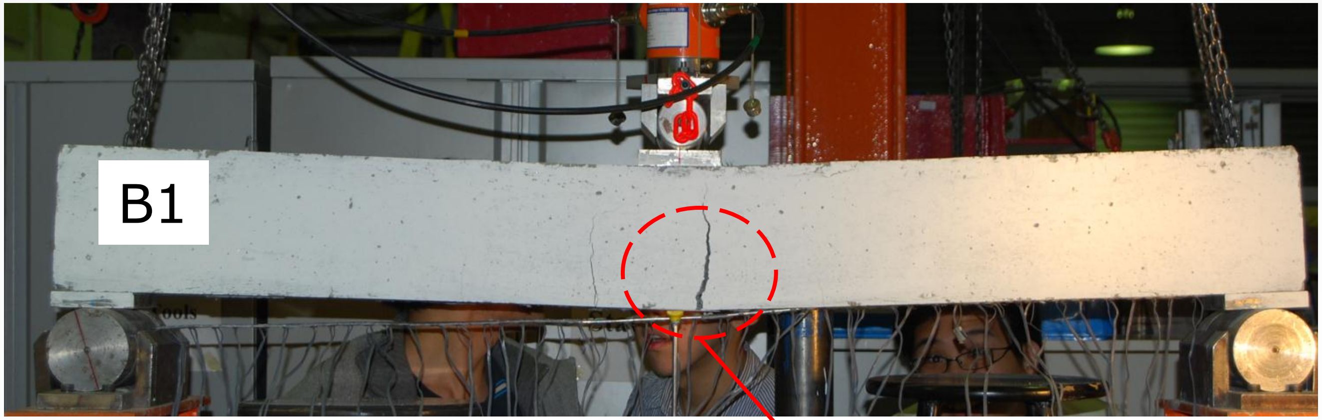


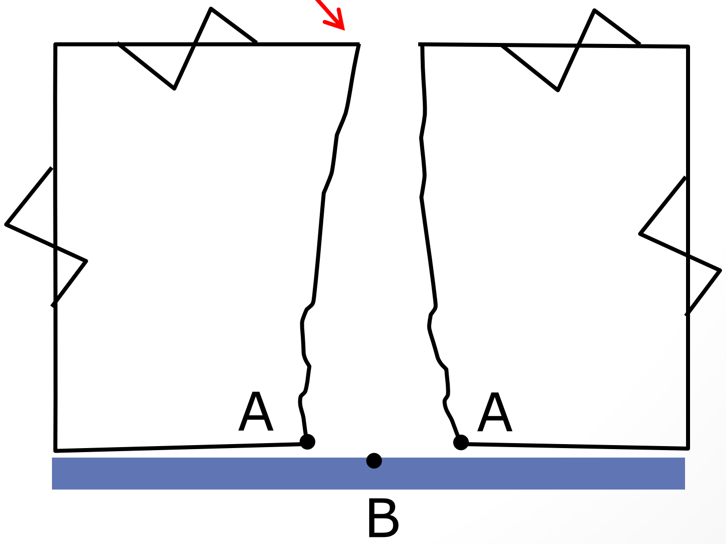
<u>Before cracking</u>:

Points A and B are bonded together



Debonding caused by cracking



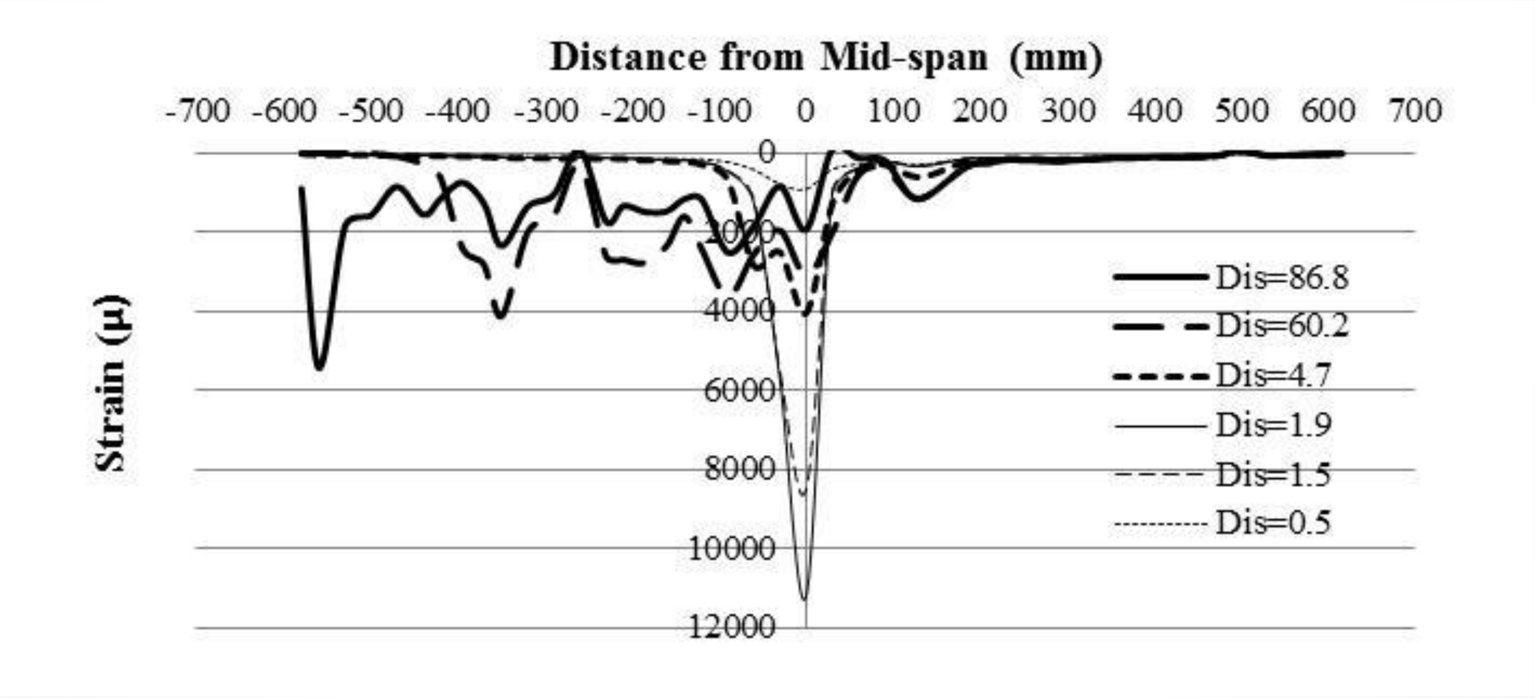


After cracking:

Points A and B separated causing relative movement hence debonding

Debonding process

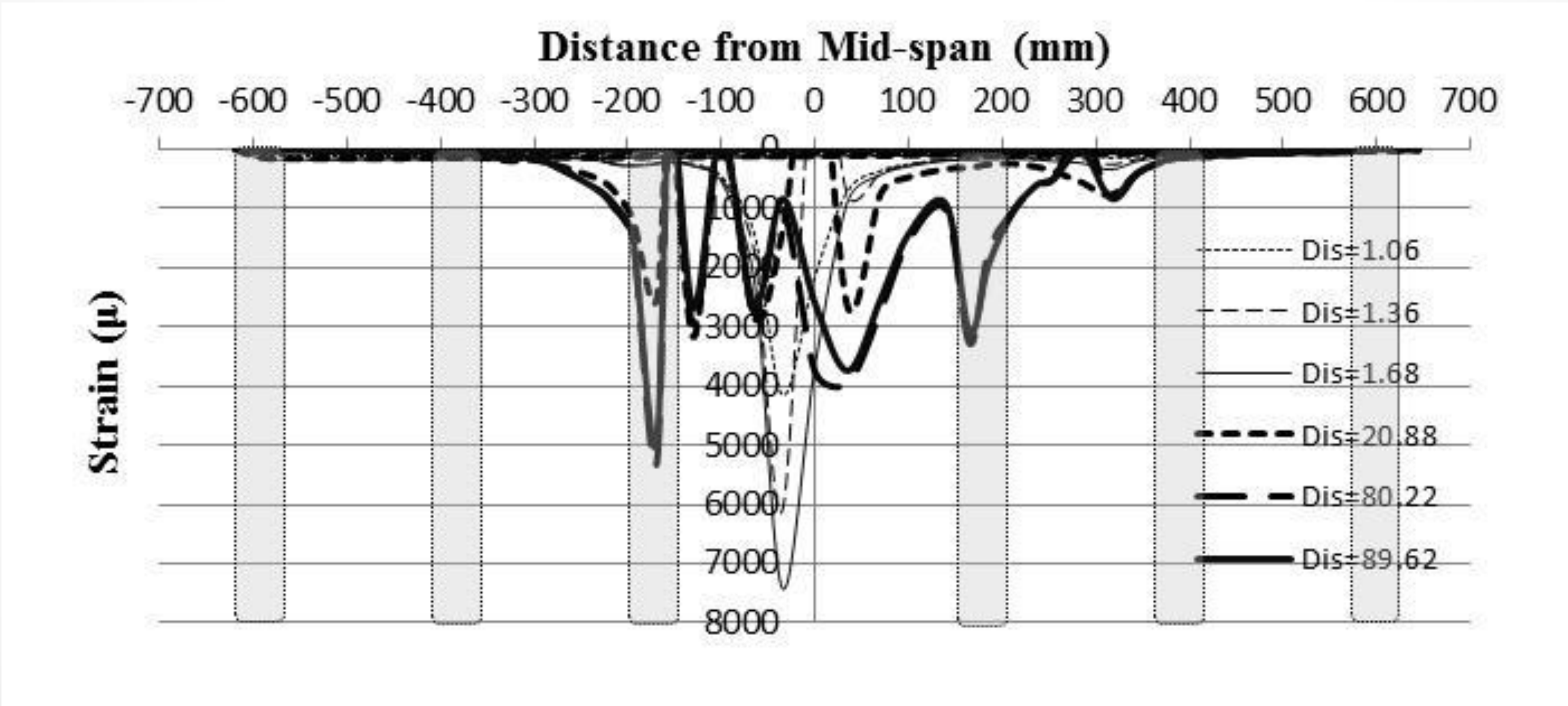
SP5 without nano-treatments debonded in the test



Steel plate strain distributions for SP5

Debonding process

SP6 with nano-treatments did not debond



Steel plate strain distributions for SP6

Conclusions

- High strength steel sheet can replace FRP for RC rehabilitation with much increased ductility.
- Nano-treatment can be utilized to avoid debonding

Thank you !

Email: yfwu00@cityu.edu.hk