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# FRP Shear Strengthening of RC Beams

**ACI Spring 2011 Convention**
**April 3 - 7, Tampa, FL**

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The audio for this web session will begin momentarily and will play in its entirety along with the slides.

However, if you wish to skip to the next speaker, use the scroll bar at left to locate the speaker's first slide (indicated by the icon in the bottom right corner of slides 10 and 34). Click on the thumbnail for the slide to begin the audio for that portion of the presentation.

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With over 1,300 delegates attending each convention, there is ample opportunity to meet and talk individually with some of the most prominent persons in the field of concrete technology. For more information about ACI conventions, visit www.aciconvention.org.

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# Fall 2011 Seminars

These seminars, cosponsored by ACI and the Portland Cement Association (PCA), will cover all the major changes in the new edition of the **318-11 Building Code**.

| DATE | LOCATION | DATE | LOCATION |
|---|---|---|---|
| September 13 | Chicago, IL | November 3 | Charlotte, NC |
| September 27 | Philadelphia, PA | November 8 | Boston, MA |
| September 29 | Houston, TX | November 10 | Detroit, MI |
| October 4 | Seattle, WA | November 15 | Des Moines, IA |
| October 6 | Los Angeles, CA | November 17 | Portland, OR |
| October 11 | New York, NY | November 29 | Denver, CO |
| October 13 | Minneapolis, MN | December 1 | Phoenix, AZ |
| October 20 | Cincinnati, OH | December 6 | Atlanta, GA |
| October 25 | New Brunswick, NJ | December 8 | Washington, DC |
| October 27 | St. Louis, MO | December 13 | Dallas, TX |
| November 1 | Orlando, FL | December 15 | San Francisco, CA |

For more information, visit ACI seminars.

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# FRP Shear Strengthening of RC Beams

**ACI Spring 2011 Convention**
**April 3 - 7, Tampa, FL**

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**Amir Mofidi** is a PhD candidate in the Department of Construction Engineering, University of Quebec, Ecole de technologie supérieure, Montreal, Quebec, Canada. His research interests include the use of fiber-reinforced polymer composites for strengthening and retrofitting concrete structures.

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# Shear Strengthening of RC Beams with EB FRP: Evolutive Model versus Code

10th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures
(in conjunction with the Spring 2011 ACI Convention)

April 2-4, 2011, Marriott Tampa Waterside & Westin Harbor Island

**Amir Mofidi and Omar Chaallal**

Presented by: Ahmed Godat

Université du Québec
École de technologie supérieure
DRSR

FRPRCS - 10
Tampa, FL April 2-4 2011

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## Influencing Parameters

The following parameters that influence deboning of FRP are studied:

- Bond Model
- Effective Strain
- FRP Effective Anchorage Length
- FRP Effective Width
- Strip-Width to Strip-Spacing Ratio
- Transverse Steel
- Crack Pattern

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## International Design Codes and Guidelines

Status of influencing factors on shear strengthening of RC beams in the current design guidelines.

| | | Influencing factors | | | | | | |
|---|---|---|---|---|---|---|---|---|
| FRP design guidelines | Latest revision | Bond model | Effective strain | Anchorage length | $w_f / s_f$ | Crack angle | Crack pattern | Effect of transverse steel |
| ACI 440-2R | 2008 | YES | YES | YES | NO | NO | NO | NO |
| CSA-S06 | 2006 | YES | YES | YES | NO | YES | NO | NO |
| CSA-S806 | 2002 | NO | YES | NO | NO | NO | NO | NO |
| fib-TG 9.3 | 2001 | NO | YES | NO | NO | YES | NO | NO |
| CNR-DT 200 | 2004 | YES | YES | YES | YES | YES | NO | NO |
| HB 305 (CIDAR) | 2008 | YES | YES | YES | YES | YES | NO | NO |

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## Research Significance

The main impetus to carry out current study are;

- to study the effect of parameters which have been proven to influence the shear resistance of EB FRP, but which have not been sufficiently documented in the guidelines,
- to develop a transparent and evolutive design model for the shear resistance of FRP-strengthened beams which fail by FRP debonding.

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## Influencing Parameters (cont'd)

### Bond Model:

To study the mechanism of FRP debonding from concrete, a reliable bonding model is required.

$$P_{frp} = w_{frp} \times L_e \times \tau_{eff}$$

| | Advantage | disadvantage |
|---|---|---|
| Holzenkämpfer (1994) | | |
| Maeda et al. (1997) | [illegible] bond model, Calculated $P_{frp}$ and $L_e$ are [illegible] relatively accurate [illegible] concrete strengths. | [illegible] When model produces [illegible] conservative results [illegible] bond length, $L_e$. |
| Khalifa et al. (1998) | | |
| Neubauer and Rostásy (1997) | | |
| Chen and Teng (2001) | | |

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## Influencing Parameters (cont'd)

### Effective Strain:

- Assuming that FRP carries only normal stresses in the principal direction, FRP may be treated by analogy to internal steel.
- All the FRP strips intersected by the selected shear crack are assumed to contribute the same FRP effective strain.
- Most of design models or equations basically use similar design analogy with different definitions of the effective strain.

$$V_f = \frac{2t_f \cdot w_f \cdot \varepsilon_{fe} \cdot E_f \cdot (\cot\theta + \cot\alpha) \cdot \sin\alpha \cdot d_f}{s_f}$$

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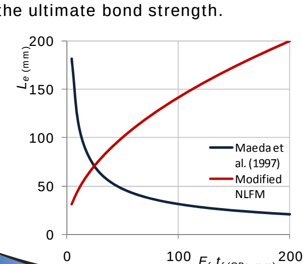
## Influencing Parameters (cont'd)

### FRP Effective Anchorage Length:

- Beyond a certain FRP bond-length threshold, increasing bond length does not result in an increase in the ultimate bond strength.




Note: In NLFM equation $f_c'$ is assumed to be equal to 5 MPa.

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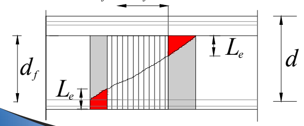
## Influencing Parameters (cont'd)

### FRP Effective Width:

- Only the FRP fibers that have an anchorage length greater than the FRP effective length remain adequately anchored.
- The width of the FRP sheet, $w_f$, is replaced by an effective width, $w_{fe}$.

$$w_{fe} = d_f - L_e$$




Effective width of FRP in RC beam strengthened with side-bonded FRP

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## Influencing Parameters (cont'd)

### Strip-Width to Strip-Spacing Ratio:

- Previous FRP-to-concrete direct pull-out tests have shown that the width of the FRP sheets bonded to a concrete block has a significant effect on the maximum bond strength of the FRP.
- According to experimental research studies as the FRP sheets become narrower, the bond strain increases.

$$k_p = \sqrt{1.125 \times \frac{2 - b_p/b_c}{1 + b_p/400}}$$

Holzenkämpfer (1994) and Neubauer and Rostásy (1997)

$$\beta_w = \sqrt{\frac{2 - w_f/s_f}{1 + w_f/s_f}}$$

Chen and Teng (2001).

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## Influencing Parameters (cont'd)

### Transverse Steel:

- It has been clearly established that the effectiveness of the strengthening contribution of FRP to shear resistance depends on the amount of internal shear-steel reinforcement.
- None of the guidelines has yet considered in their formulae the effect of transverse steel on $V_f$.

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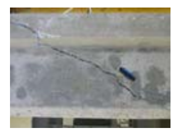
## Influencing Parameters (cont'd)

### Cracking Pattern:

Experimental observations clearly showed that in RC beams with transverse reinforcement the shear-crack pattern tends to be distributed over a large width compared with the pattern in RC beams with no or low shear reinforcement.



No transverse reinforcement

Transverse steel reinforcement

EB U-Jacket FRP sheet

Transverse steel reinforcement + EB U-Jacket FRP sheet

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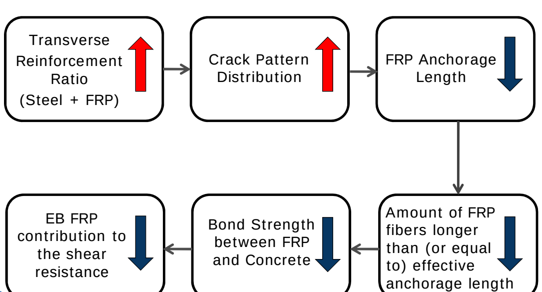
## Influencing Parameters (cont'd)

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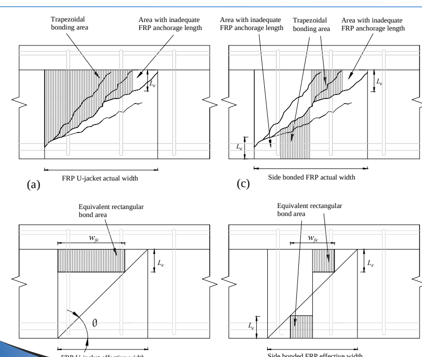
## Proposed Model (cont'd)

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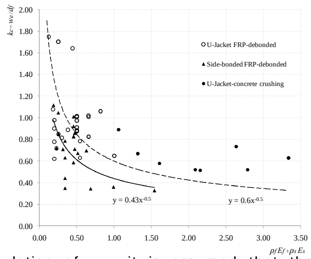
## Proposed Model (cont'd)




- In the calculation of $w_{fe}$, it is assumed that the cracking pattern changes with the amount of internal steel and external FRP shear reinforcement as measured by their respective rigidities.

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## Proposed Model (cont'd)

- The effective width is then calibrated as a function of $(\rho_f \cdot E_f + \rho_s \cdot E_s)$ for beams strengthened with a continuous U-jacket and side-bonding configurations.

$$w_{fe} = \frac{0.6}{\sqrt{\rho_f \cdot E_f + \rho_s \cdot E_s}} \times d_f \quad \text{for U-Jacket}$$

$$w_{fe} = \frac{0.43}{\sqrt{\rho_f \cdot E_f + \rho_s \cdot E_s}} \times d_f \quad \text{for side bonded}$$

- The cracking modification factor can then be calculated as:

$$k_c = \frac{w_{fe}}{d_f} = \frac{0.6}{\sqrt{\rho_f \cdot E_f + \rho_s \cdot E_s}} \quad \text{for U-Jackets}$$

$$k_c = \frac{w_{fe}}{d_f} = \frac{0.43}{\sqrt{\rho_f \cdot E_f + \rho_s \cdot E_s}} \quad \text{for side bonded}$$

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## Proposed Model (cont'd)

- The effects of $k_c$ to consider the effect of cracking pattern and that of $k_w$ to incorporate the $w_f / s_f$ ratio of the FRP strips are considered in the equation for effective strain:

$$\varepsilon_{fe} = \frac{k_c \cdot k_L \cdot k_w \cdot \tau_{eff} \cdot L_e}{t_f . E_f} = 0.31 k_c \cdot k_L \cdot k_w \sqrt{\frac{\sqrt{f_c'}}{t_f E_f}} \leq \varepsilon_{fu}$$

- The shear contribution of FRP, $V_f$, can be calculated as a function of $\varepsilon_{fe}$ using the following equation:

$$V_f = \frac{2 t_f \cdot w_f \cdot \varepsilon_{fe} \cdot E_f \cdot (\cot\theta + \cot\alpha) \cdot \sin\alpha \cdot d_f}{s_f}$$

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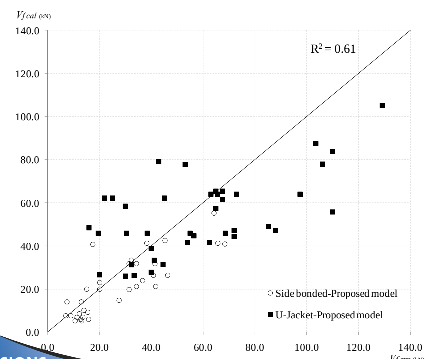
## Validation of the Proposed Model

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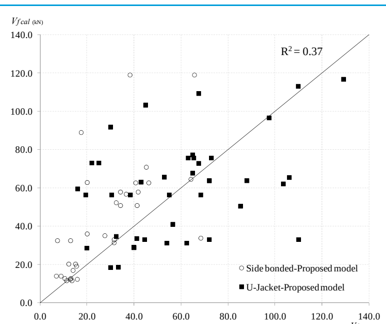
## Validation of the Proposed Model

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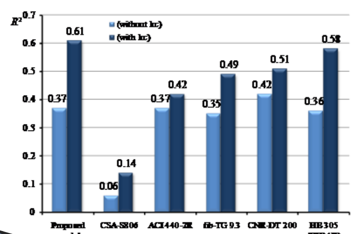
## Validation of the Proposed Model (cont'd)

Applying $k_c$ to $V_f$ calculated using the ACI 440.2R 2008, *fib* -TG 9.3 2001, CAN/CSA-S806 2002, HB 305 2008 (CIDAR 2006), and CNR-DT200 2004 guidelines resulted in a significant improvement on the accuracy of the calculated results for all the mentioned guidelines .

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## Conclusions

- A new design approach has been proposed for calculating the shear contribution of FRP, taking into consideration the effect of transverse steel on the EB FRP contribution in shear.
- The proposed model showed an acceptable correlation with experimental results in comparison with the current guidelines.

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## Acknowledgement


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- The Fonds québécois de la recherche sur la nature et les technologies (FQRNT),
- The Ministère des Transports du Québec (MTQ).


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Thanks for your attention

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*FIBER-REINFORCED POLYMER REINFORCEMENT FOR CONCRETE STRUCTURES*
*FRP-RCS10 April 2-4, 2011 - Tampa, Florida, USA*

## PARAMETRIC STUDIES OF THE NSM FRP STRIPS SHEAR STRENGTH CONTRIBUTION TO A RC BEAM


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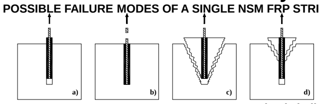
## MECHANICAL MODEL : 1 – Physical Aspects

POSSIBLE FAILURE MODES OF A SINGLE NSM FRP STRIP



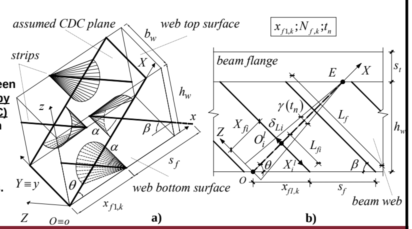

Loss of bond (debonding) | Strip Rupture | Concrete semi-conical fracture | Mixed shallow semi-cone-plus debonding

In analogy with the fastening technology, 4 possible failure modes can be foressen.

SCHEMATIZATION OF R.C. BEAM WEB AND NSM FRP STRIPS

The strengthened web can be seen as a prism divided in two parts by the Critical Diagonal Crack (CDC) which can be schematized as an inclined plane intersecting the strips.

The two resulting web parts are sawn together by the FRP strips.

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Parametric studies of the NSM FRP strips shear strength contribution to a RC beam

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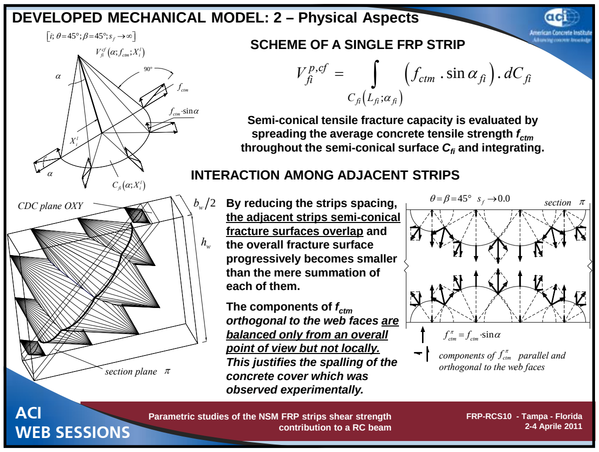
DEVELOPED MECHANICAL MODEL: 2 – Physical Aspects
SCHEME OF A SINGLE FRP STRIP
Semi-conical tensile fracture capacity is evaluated by spreading the average concrete tensile strength $f_{ctm}$ throughout the semi-conical surface $C_{fi}$ and integrating.
INTERACTION AMONG ADJACENT STRIPS
By reducing the strips spacing, the adjacent strips semi-conical fracture surfaces overlap and the overall fracture surface progressively becomes smaller than the mere summation of each of them.
The components of $f_{ctm}$ orthogonal to the web faces are balanced only from an overall point of view but not locally. This justifies the spalling of the concrete cover which was observed experimentally.
CDC plane OXY
section plane π
components of $f_{ctm}^{\alpha}$ parallel and orthogonal to the web faces
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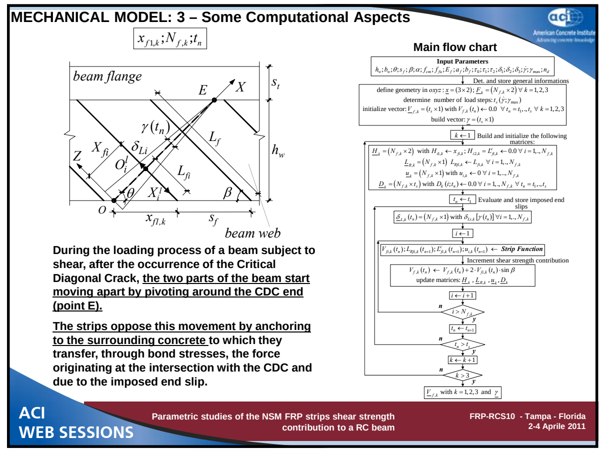
MECHANICAL MODEL: 3 – Some Computational Aspects
Main flow chart
beam flange
beam web
During the loading process of a beam subject to shear, after the occurrence of the Critical Diagonal Crack, the two parts of the beam start moving apart by pivoting around the CDC end (point E).
The strips oppose this movement by anchoring to the surrounding concrete to which they transfer, through bond stresses, the force originating at the intersection with the CDC and due to the imposed end slip.
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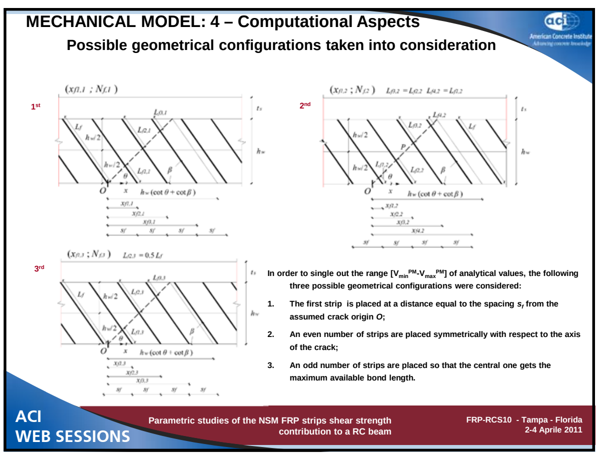
MECHANICAL MODEL: 4 – Computational Aspects
Possible geometrical configurations taken into consideration
1st
2nd
3rd
In order to single out the range [Vmin PM - Vmax PM] of analytical values, the following three possible geometrical configurations were considered:
1. The first strip is placed at a distance equal to the spacing $s_f$ from the assumed crack origin O;
2. An even number of strips are placed symmetrically with respect to the axis of the crack;
3. An odd number of strips are placed so that the central one gets the maximum available bond length.
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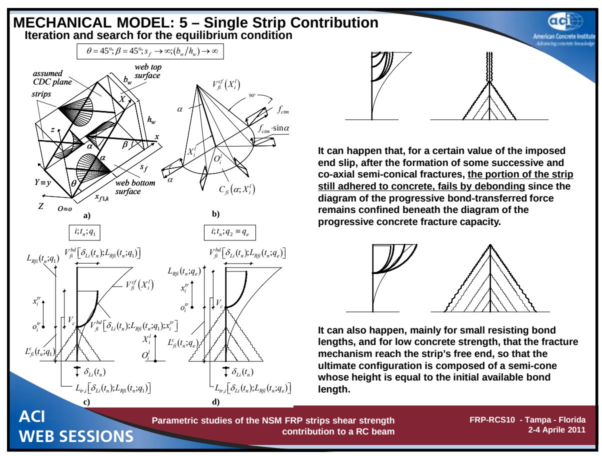
MECHANICAL MODEL: 5 – Single Strip Contribution
Iteration and search for the equilibrium condition
It can happen that, for a certain value of the imposed end slip, after the formation of some successive and co-axial semi-conical fractures, the portion of the strip still adhered to concrete, fails by debonding since the diagram of the progressive bond-transferred force remains confined beneath the diagram of the progressive concrete fracture capacity.
It can also happen, mainly for small resisting bond lengths, and for low concrete strength, that the fracture mechanism reach the strip's free end, so that the ultimate configuration is composed of a semi-cone whose height is equal to the initial available bond length.
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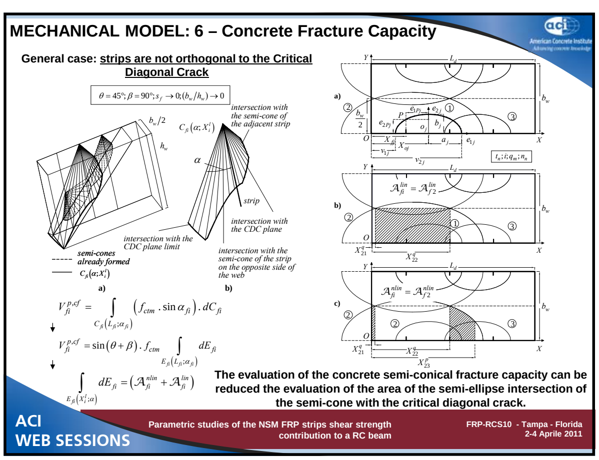
MECHANICAL MODEL: 6 – Concrete Fracture Capacity
General case: strips are not orthogonal to the Critical Diagonal Crack
semi-cones already formed
The evaluation of the concrete semi-conical fracture capacity can be reduced the evaluation of the area of the semi-ellipse intersection of the semi-cone with the critical diagonal crack.
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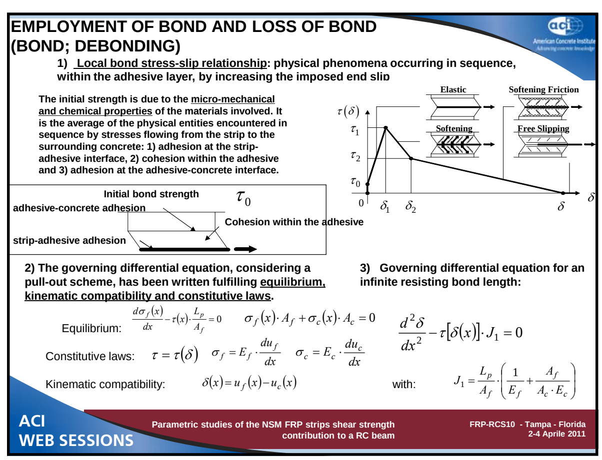
EMPLOYMENT OF BOND AND LOSS OF BOND (BOND; DEBONDING)
1) Local bond stress-slip relationship: physical phenomena occurring in sequence, within the adhesive layer, by increasing the imposed end slip
The initial strength is due to the micro-mechanical and adhesive properties of the materials involved. It is the average of the physical entities encountered in sequence by stresses flowing from the strip to the surrounding concrete: 1) adhesion at the strip-adhesive interface, 2) cohesion within the adhesive and 3) adhesion at the adhesive-concrete interface.
Elastic
Softening Friction
Softening
Free Slipping
Initial bond strength
adhesive-concrete adhesion
Cohesion within the adhesive
strip-adhesive adhesion
2) The governing differential equation, considering a pull-out scheme, has been written fulfilling equilibrium, kinematic compatibility and constitutive laws.
3) Governing differential equation for an infinite resisting bond length:
Equilibrium:
Constitutive laws:
Kinematic compatibility:
with:
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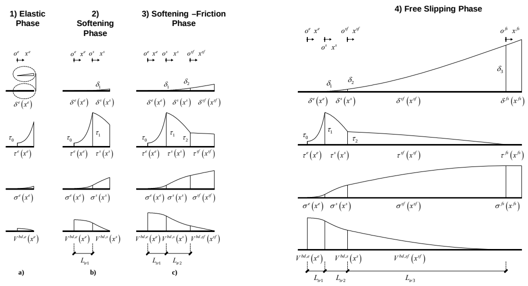
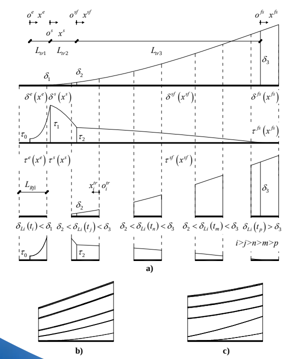
## PROCESS OF LOSS OF BOND FOR AN INFINITE RESISTING BOND LENGTH

By imposing the boundary conditions and solving the differential equation for the several phases of the bond constitutive law, we obtain: slip distribution; distribution of tangential stresses; distribution of the strip axial stress and of the progressive force transferred to the surrounding concrete.






## PROCESS OF LOSS OF BOND FOR A FINITE RESISTING BOND LENGTH




Once the Debonding Process has been solved for an infinite resisting bond length, <u>debonding propagation is schematized as an invariant wave that, increasing the imposed end slip, progresses from the loaded end to the free end.</u>

Thus, with geometrical relations, the trend of slip, tangential stress, axial stress in both the strip and surrounding concrete can be determined for whatever value of both resisting bond length and imposed end slip.

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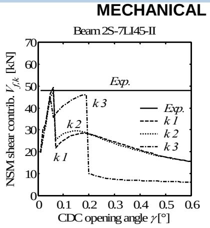
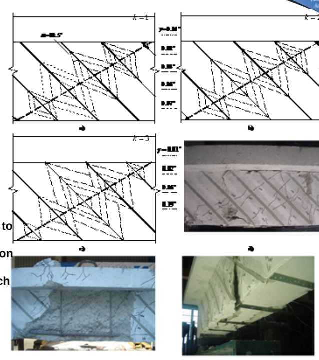
## MECHANICAL MODEL: APPRAISAL (1)




The typical trend of the contribution to the shear strength provided by a system of NSM FRP strips, as function of the CDC opening angle, is characterized by abrupt decays which correspond to the strips failure.



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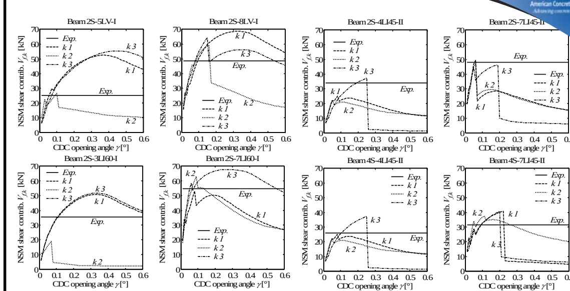
## MECHANICAL MODEL: APPRAISAL (2)




The developed mechanical model allows the maximum contribution to the shear strength provided by a system of NSM FRP strips to be predicted with a <u>satisfactory level of accuracy and regardless of: amount of existing steel stirrups, concrete mechanical properties, number and inclination of the strips.</u>

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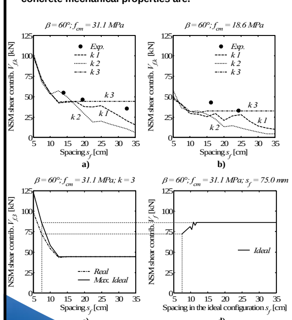
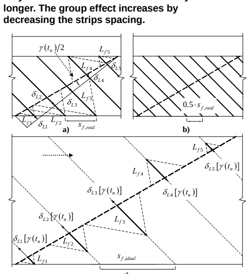
## MECHANICAL MODEL: APPRAISAL (3)

Reducing the strips spacing, the NSM FRP strips shear strength contribution increases, the more as higher the concrete mechanical properties are.




***<u>Group effect</u>***: the reduction of the shear strength contribution provided by a <u>real system</u> of NSM strips with respect to an <u>ideal system</u> in which the same system of strips, subjected to the same system of imposed end slips, are spaced out at such an extent that they do not interact with each other any longer. The group effect increases by decreasing the strips spacing.

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## PARAMETRIC STUDIES: RANGE OF VALUES ASSUMED FOR EACH PARAMETER

Table 1 — Range of values of the parameters whose influence was investigated.

| Study | $\gamma$ ° | $\theta$ ° | $h_w$ mm | $b_w$ mm | $a_f$ mm | $b_f$ mm | $s_f$ mm | $\beta$ ° | $E_f$ GPa | $f_{fu}$ GPa | $f_{cm}$ MPa | $\alpha$ ° | $\tau_0$ MPa | $\tau_1$ MPa | $\tau_2$ MPa | $\delta_1$ mm | $\delta_2$ mm | $\delta_3$ mm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RB | 0.01 | 45.0 | 500.0(19.70) | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 1 | **1-10** | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 2 | 0.01 | **20-50** | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 3 | 0.01 | 45.0 | **200-700** | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 4 | 0.01 | 45.0 | 500.0 | **50-400** | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 5 | 0.01 | 45.0 | 500.0 | 200.0 | **1.0-5.5** | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 6 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | **5-35** | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 7 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | **50-800** | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 8 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | **45-90** | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 9 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | **100-250** | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 10 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | **1.0-5** | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 11 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | **10-60** | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 12 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | **10-45** | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 13 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | **0.5-5** | 20.1 | 9.0 | 0.07 | 0.83 | 14.1 |
| 14 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | **9.5-35** | 9.0 | 0.07 | 0.83 | 14.1 |
| 15 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | **3.0-19** | 0.07 | 0.83 | 14.1 |
| 16 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | **0.05-0.8** | 0.83 | 14.1 |
| 17 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | **0.2-10** | 14.1 |
| 18 | 0.01 | 45.0 | 500.0 | 200.0 | 1.4 | 10.0 | 200.0 | 45.0 | 150.0 | 3.0 | 35.0 | 28.5 | 2.0 | 20.1 | 9.0 | 0.07 | 0.83 | **2.0-20** |

(1 mm = 0.0394 in - 1 N = 0.2248 lb - 1000 psi = 6.9 MPa).

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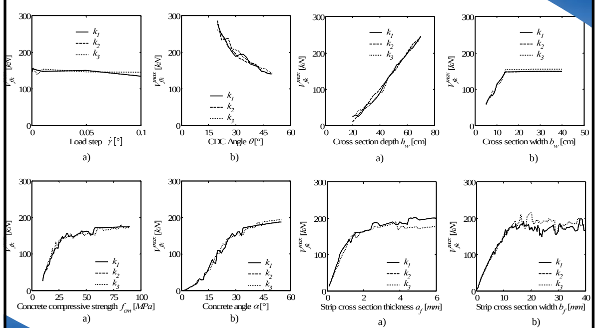
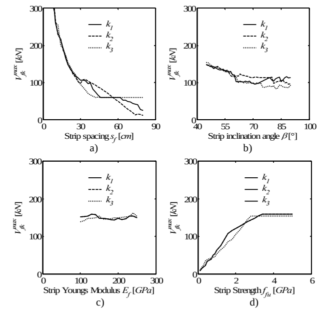
## MECHANICAL MODEL: PARAMETRIC STUDIES (1)



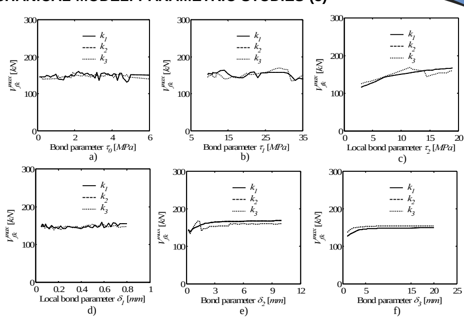



## MECHANICAL MODEL: PARAMETRIC STUDIES (2)






## MECHANICAL MODEL: PARAMETRIC STUDIES (3)




Due to both the high-performance of the currently available structural adhesives and the premature occurrence of other failure modes such as either concrete tensile fracture or strip rupture, a variation of each of the bond parameters does affect the peak NSM shear strength contribution.



**Thank you for your attention**



**Let me invite you to attend the 6th International Conference on FRP Composites in Civil Engineering – CICE2012 which will be held in the "Eternal City" of Rome, in ITALY**

Further information at www.cice2012.it




**Thank you for your attention**

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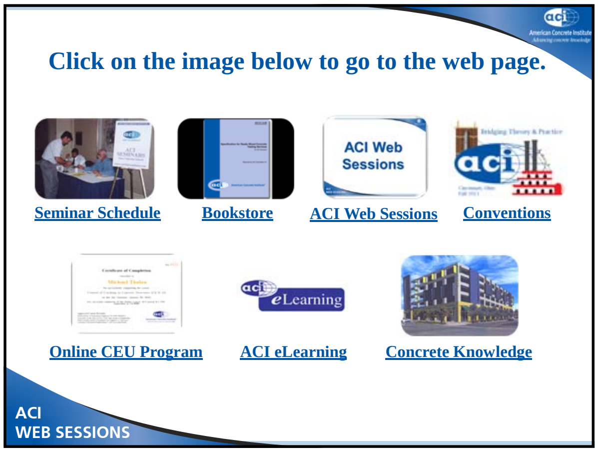
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