TENSION STIFFENING BEHAVIOUR OF GFRP-RC

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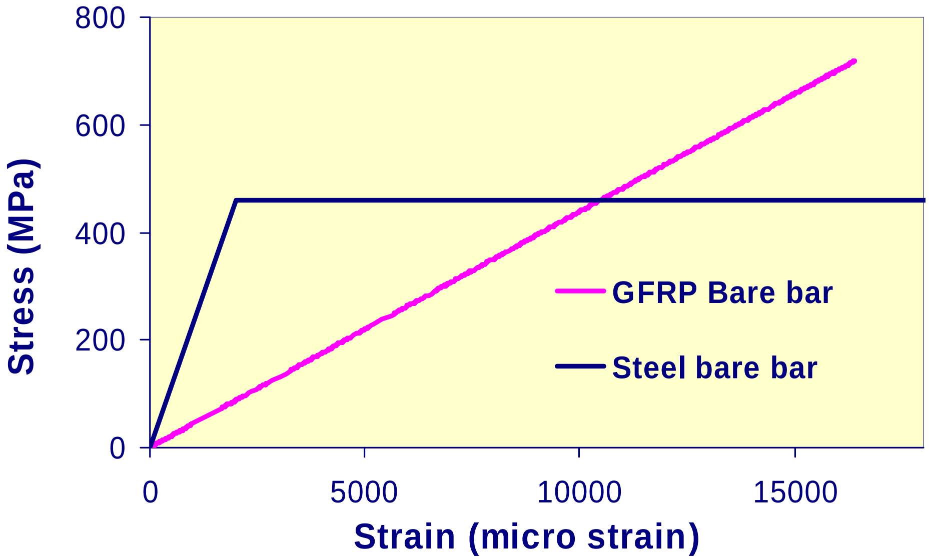
Outline

- Importance of tension stiffening
- Tension stiffening in codes
  - -Deflection calculations
- Direct tension studies
- Parametric studies
- Modelling
- Conclusions

Use of GFRP-RC in Construction

GFRP bars

Use of GFRP for bridge deck construction
(Franklin county bridge Virginia)



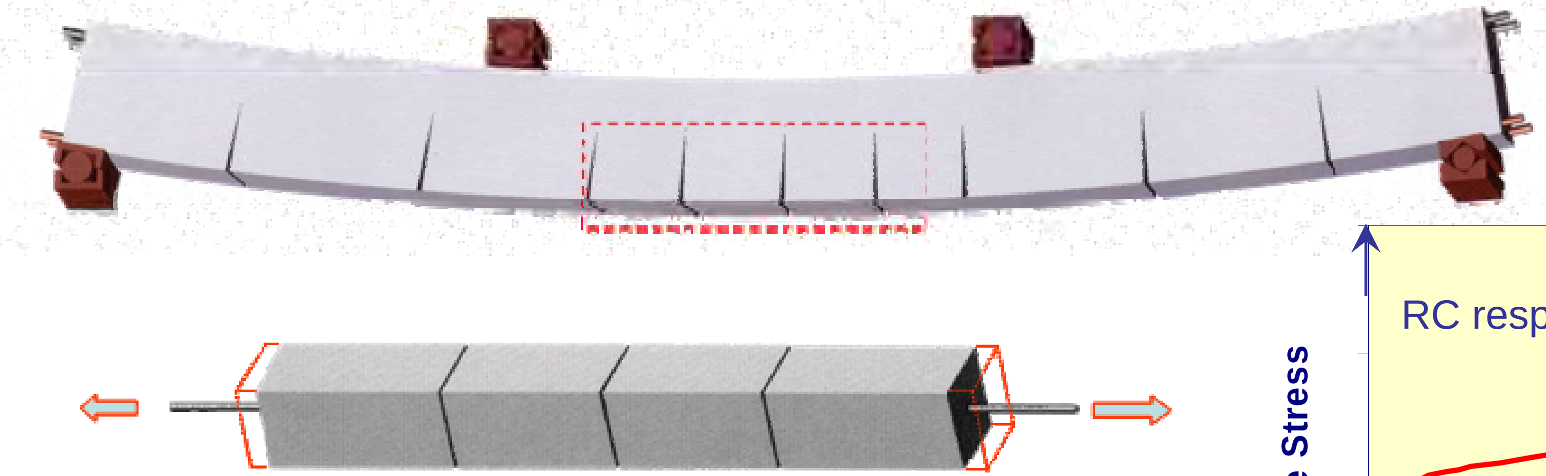
Stiffness of GFRP compared to Steel

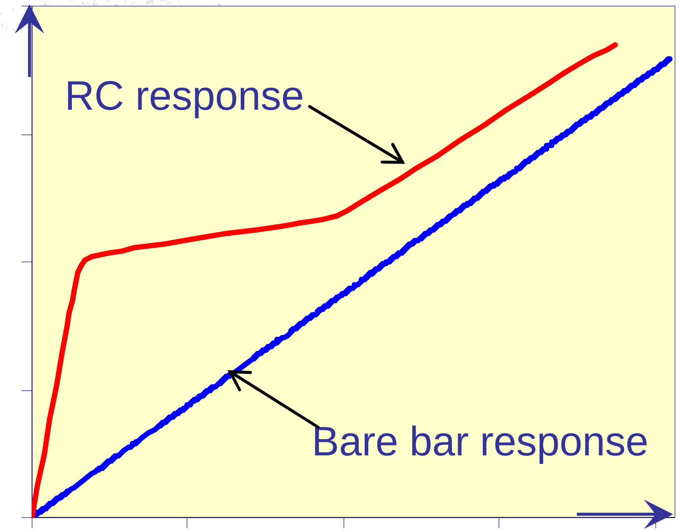
Importance of Tension Stiffening

Tension stiffening of concrete is defined as:

the ability of concrete to carry tension between cracks and provide extra stiffness for RC in tension.

- **Serviceability often governs GFRP-RC design**
- **Tension stiffening is very important for the determination of deflections and crack widths at low load levels**





Tension stiffening effect

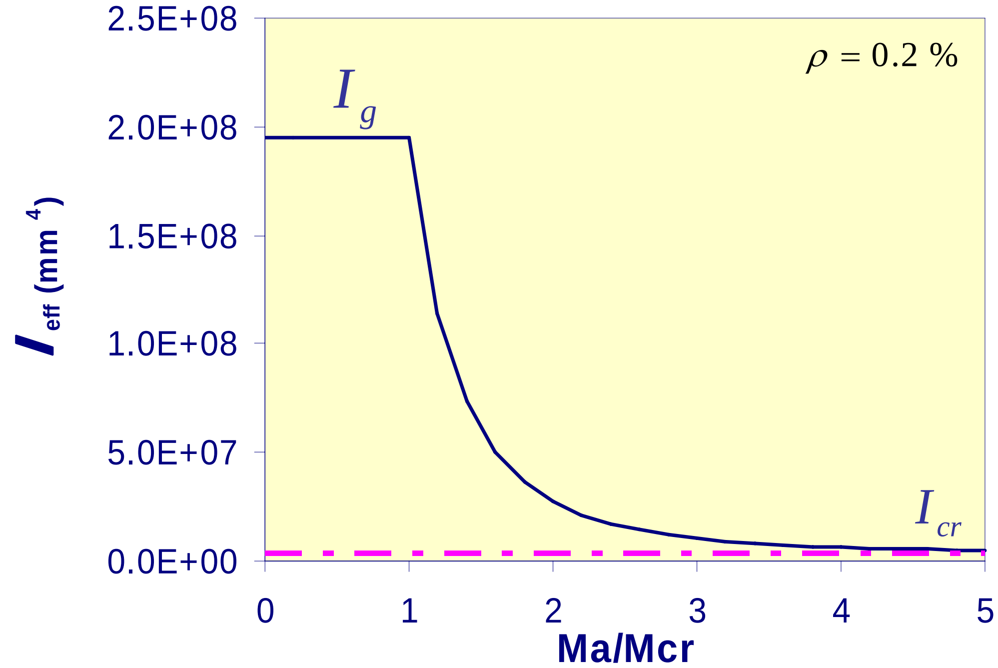
Tension Stiffening in Design Codes

In ACI

$$\Delta = \frac{kPl^3}{EI_{eff}}$$

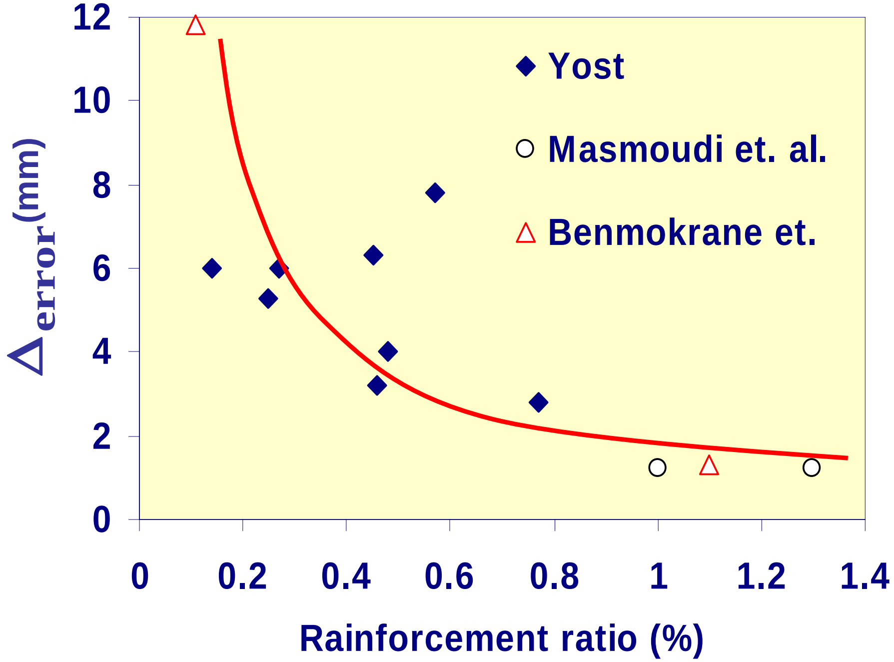
Branson's equation for I_{eff}

$$I_{eff} = I_g \left(\frac{M_{cr}}{M_a}\right)^3 + I_{cr}\left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right]$$



Δ_{error} = Experimental Deflection minus the Deflection by Branson's Equation, both at service level (50% ultimate load)

(Toutanji et al. (2003), Construction and Building Material)



Tension Stiffening for FRP Design

- **No general agreement on tension stiffening**

$$I_{eff} = I_g\left(\frac{M_{cr}}{M_a}\right)^3 + I_{cr}\left[1-\left(\frac{M_{cr}}{M_a}\right)^3\right]$$ *ACI Branson's*

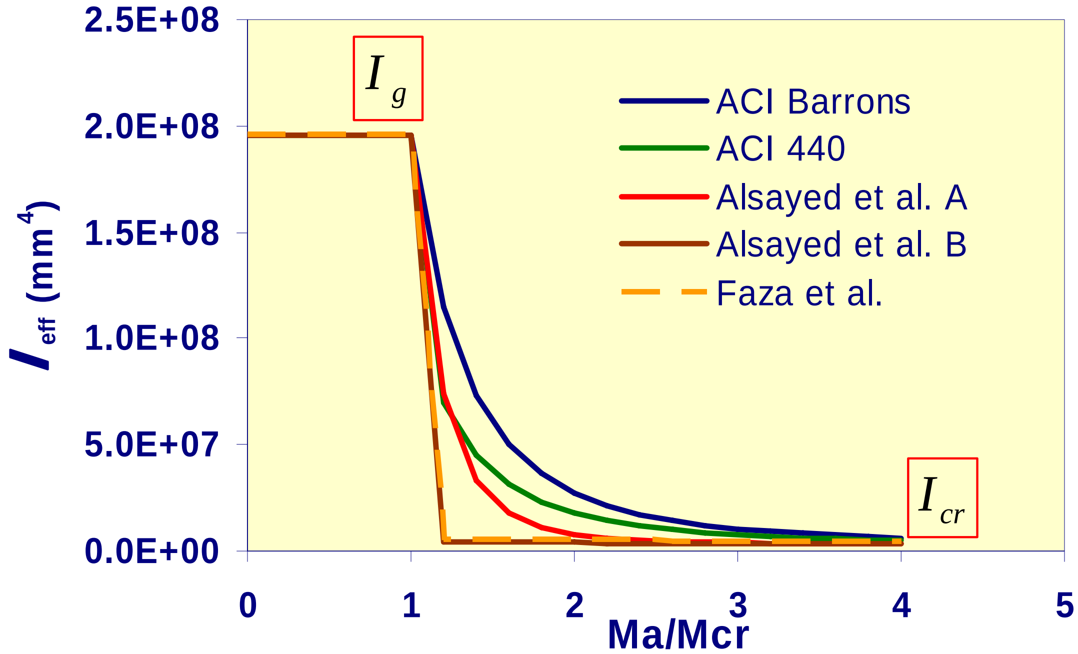
$$I_{eff} = I_g\beta_d\left(\frac{M_{cr}}{M_a}\right)^3 + I_{cr}\left[1-\left(\frac{M_{cr}}{M_a}\right)^3\right]$$ *ACI 440*

$$I_m = \frac{23I_{cr}I_e}{8I_{cr}+15I_e}, \quad I_e = ACI \quad I_{eff}$$ *Faza et. al B*

$$I_{eff} = I_g\left(\frac{M_{cr}}{M_a}\right)^{5.5} + I_{cr}\left[1-\left(\frac{M_{cr}}{M_a}\right)^{5.5}\right]$$ *Alsayed et. al A*

$$1<\frac{M_a}{M_{cr}}<3 \Rightarrow I_{eff} = I_{cr}\left[1.40-\frac{2}{15}\left(\frac{M_a}{M_{cr}}\right)\right]$$ *Alsayed et. al B*

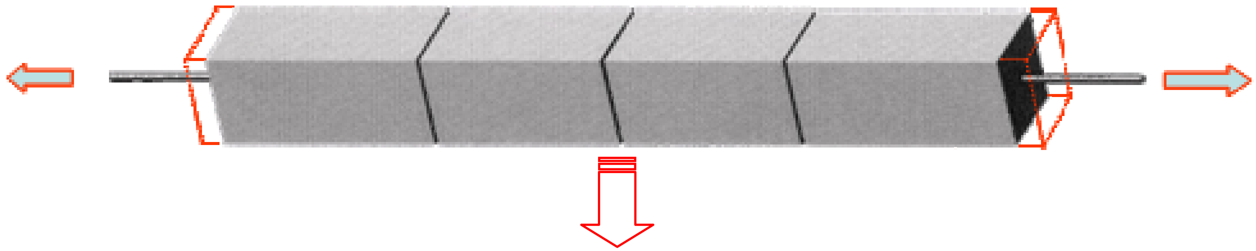
$$I_{eff} = I_{cr}$$



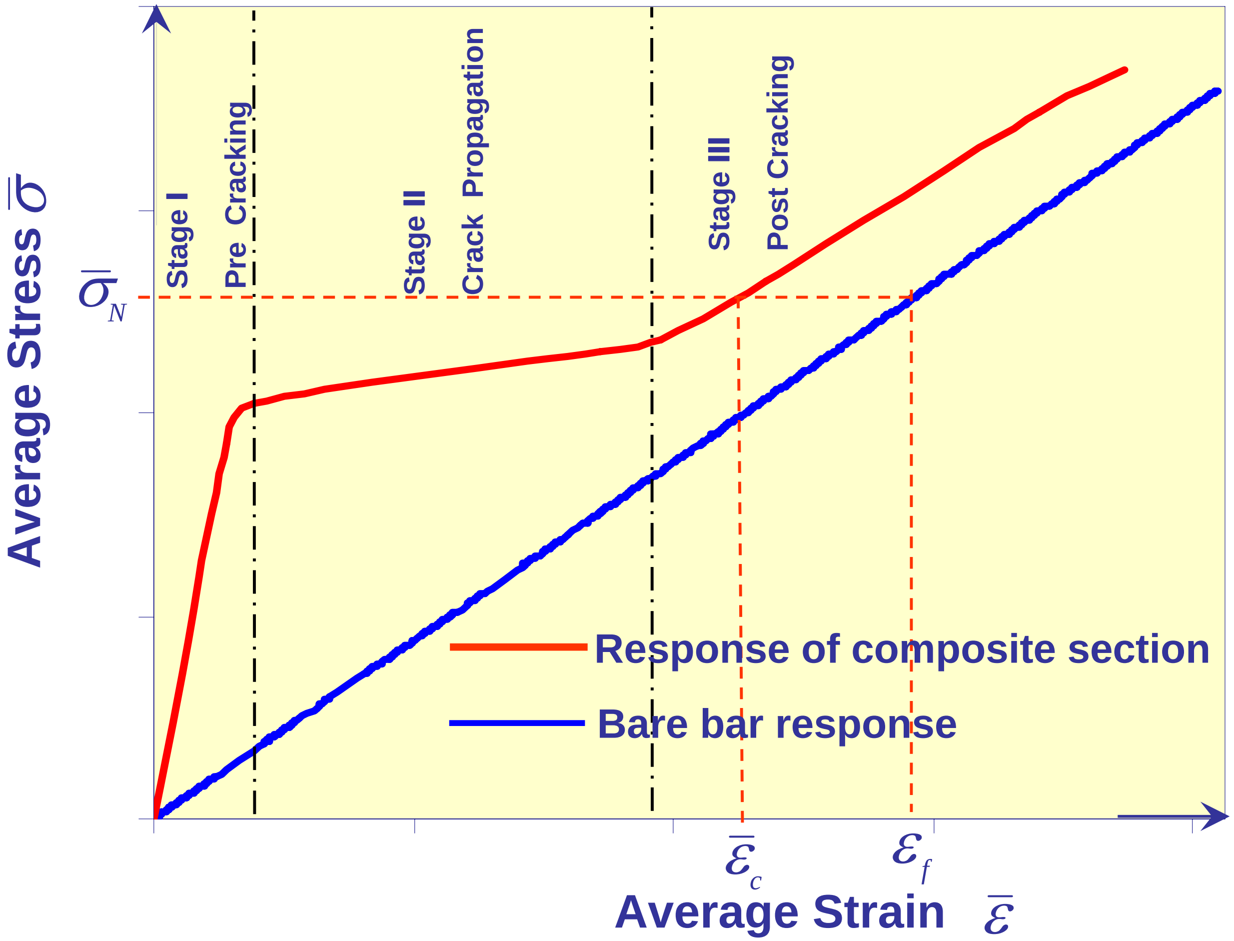
- **Need to develop tension stiffening models for numerical analysis**

Tension Stiffening Study of GFRP-RC

Reinforced concrete in tension



Typical Test Results

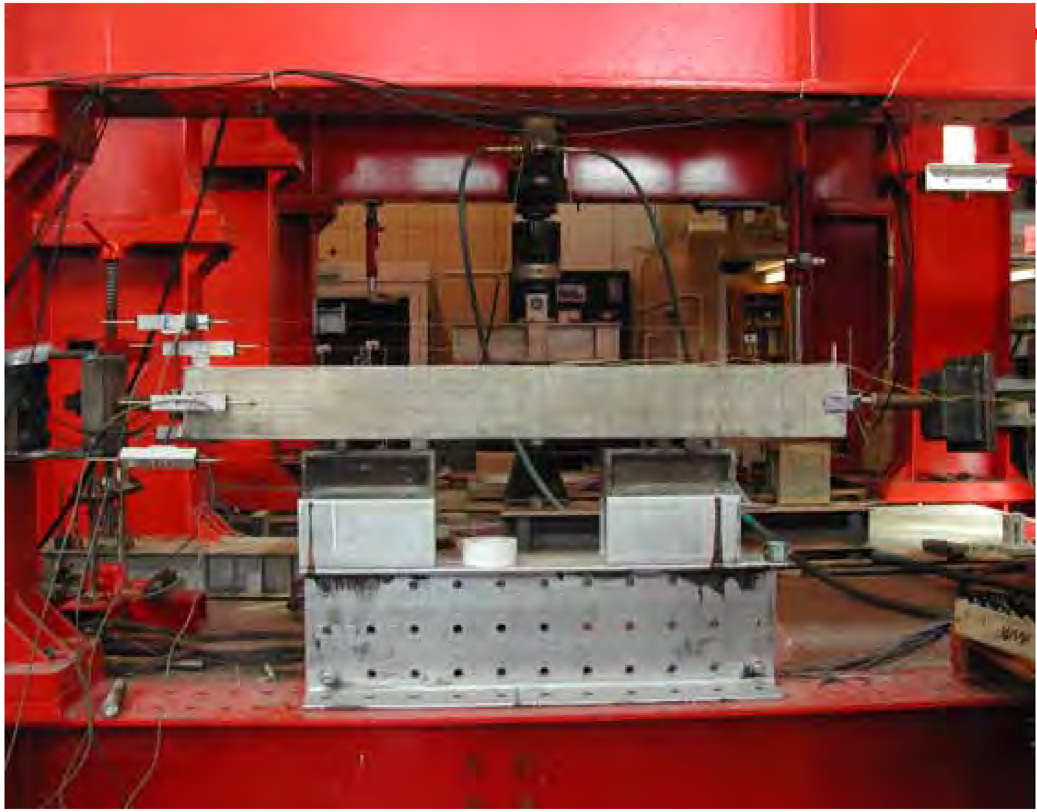


$\bar{\varepsilon}_c$ Strain of the composite specimen at $\bar{\sigma}_N$

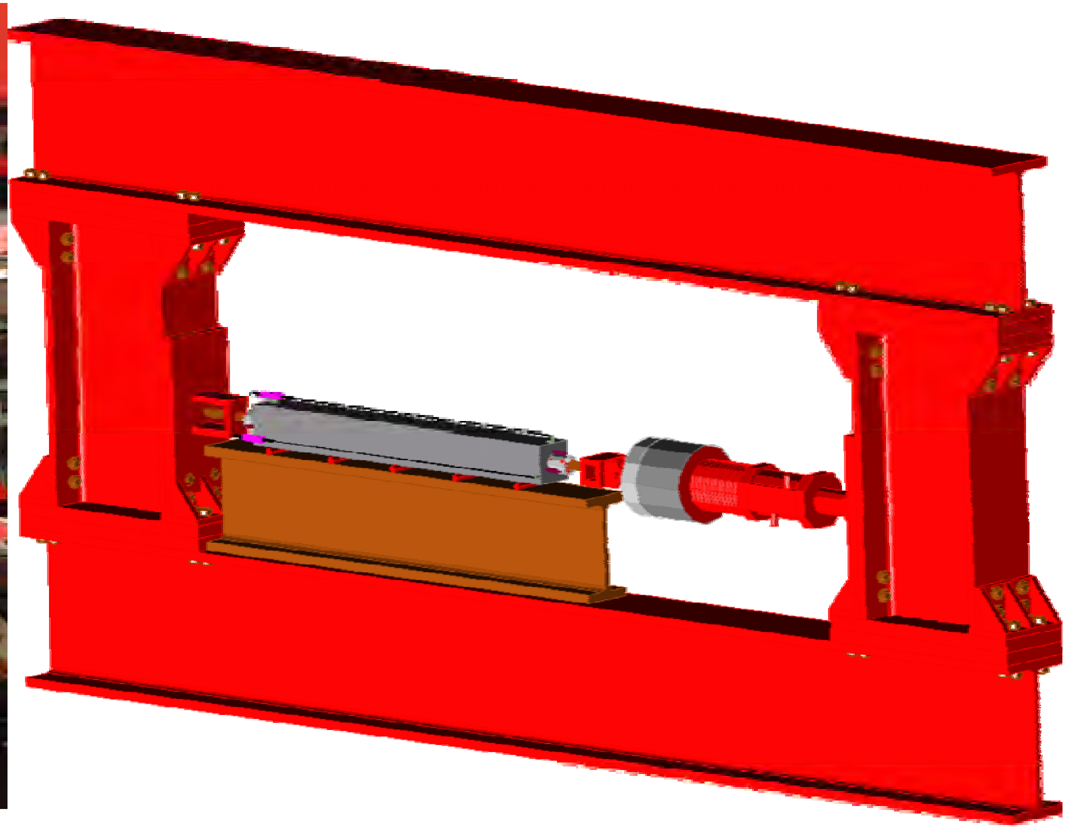
ε_f Strain of the bar at crack $\bar{\sigma}_N$

Direct Tension Tests

Testing Rig



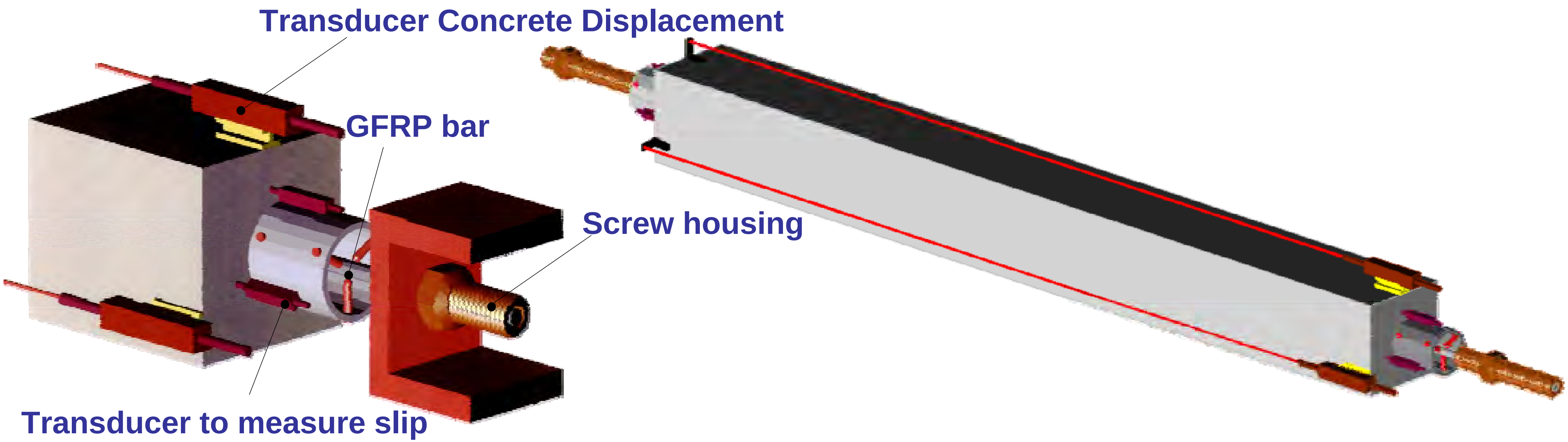
Photograph of the testing rig

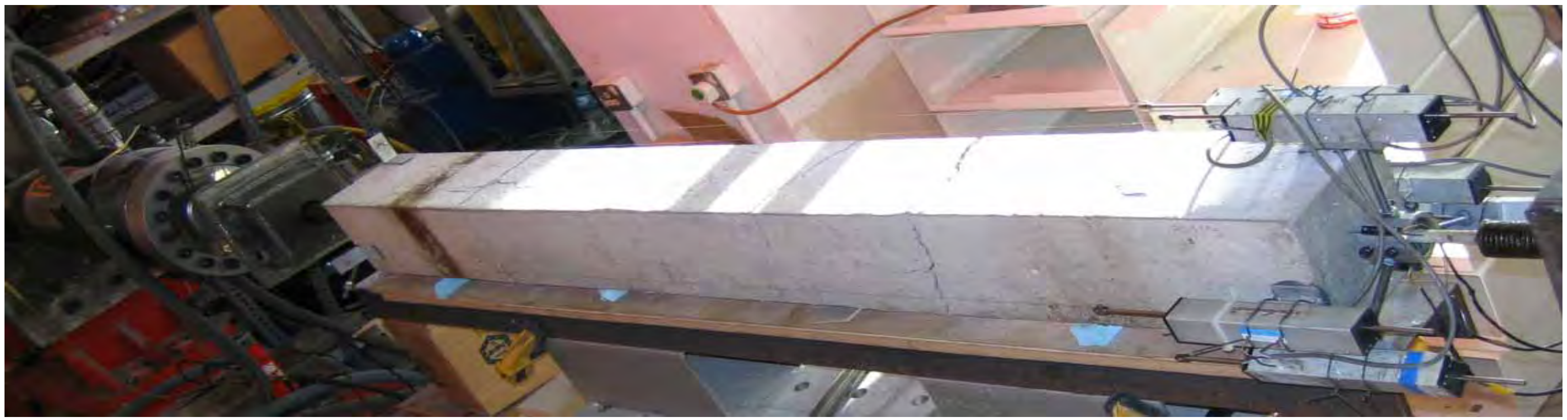


Schematic representation of the rig

Direct Tension Measurements

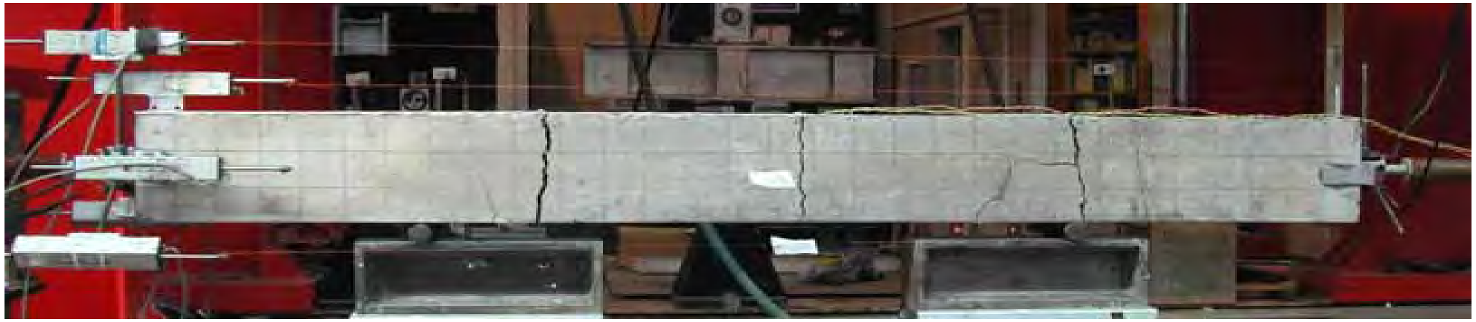
Measuring Arrangement

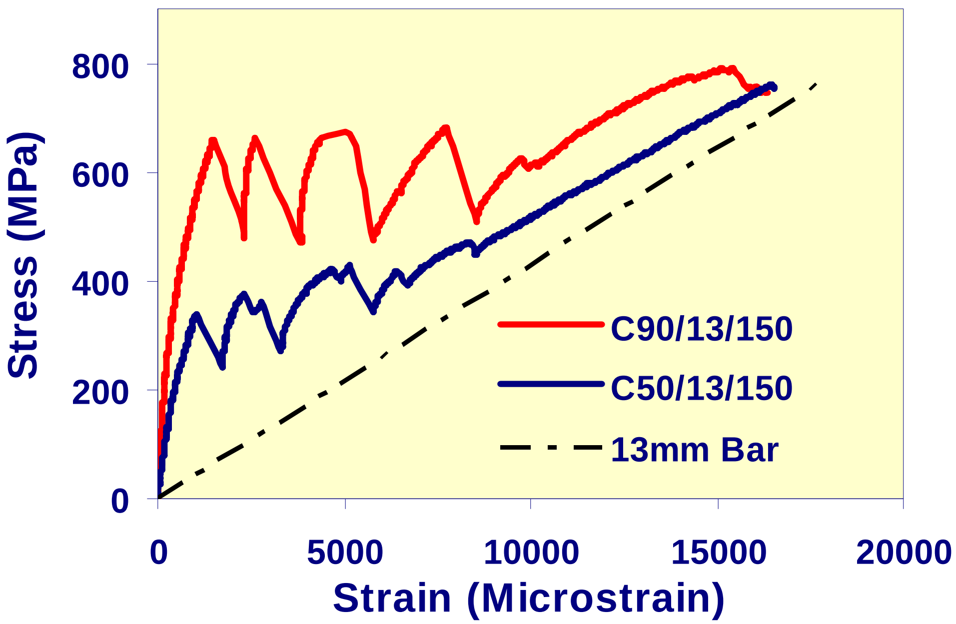




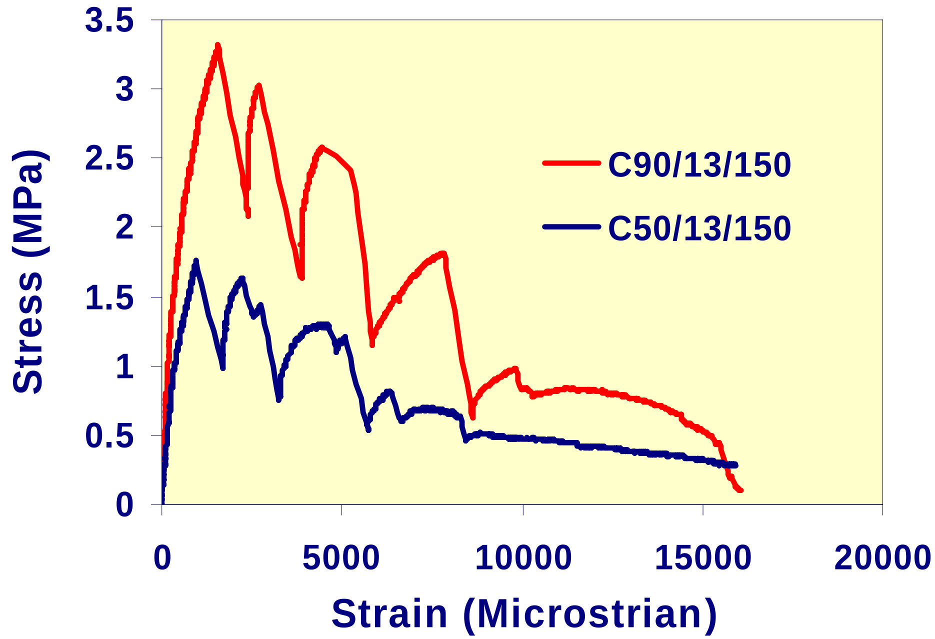
Experimental Set-up

Strain Softening Behaviour Concrete



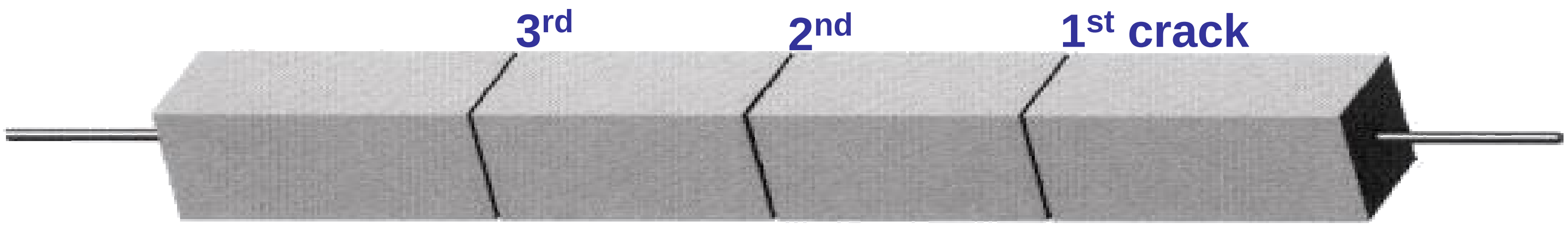


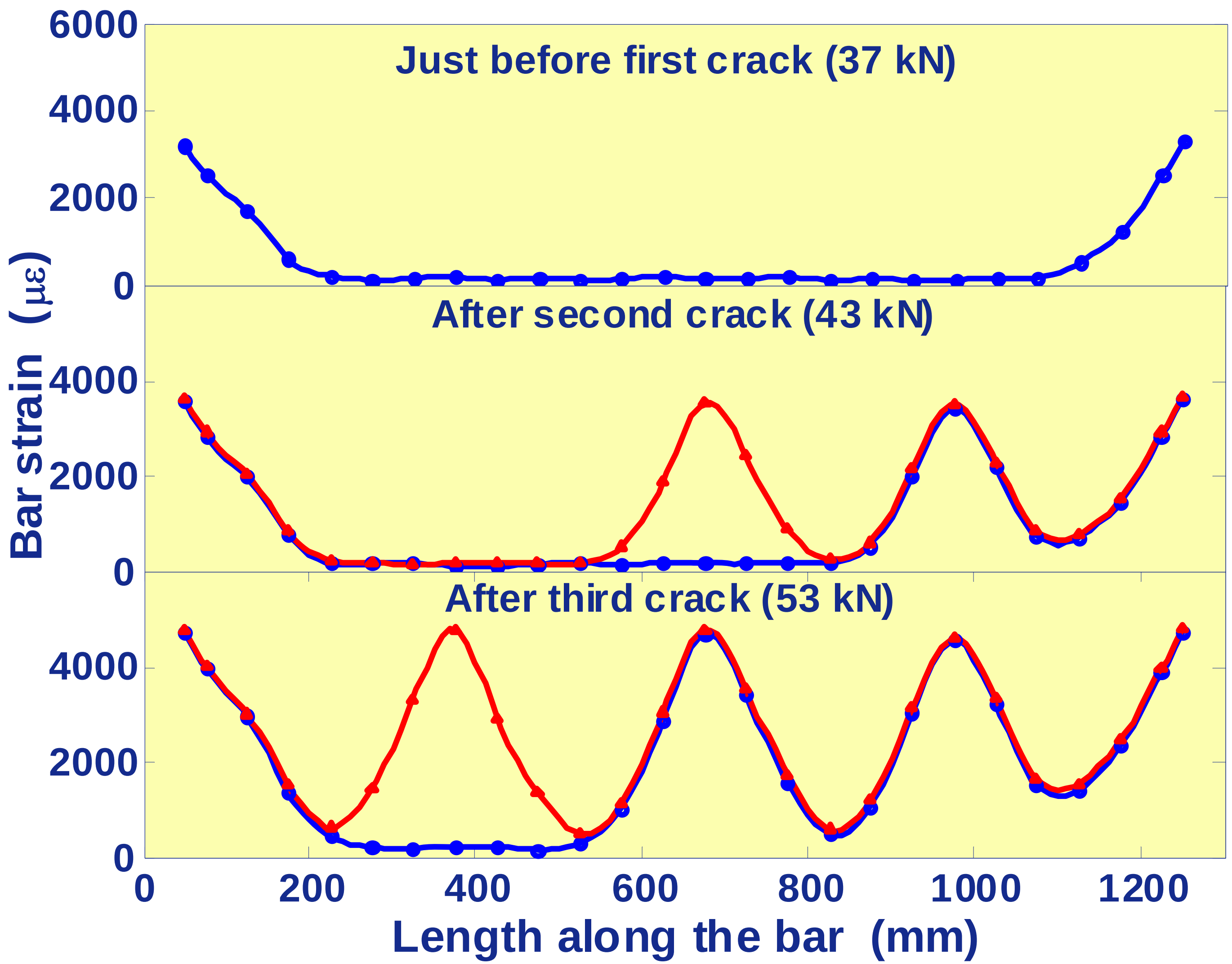
Test results bar stress Vs overall strain



Average stress strain behaviour of concrete

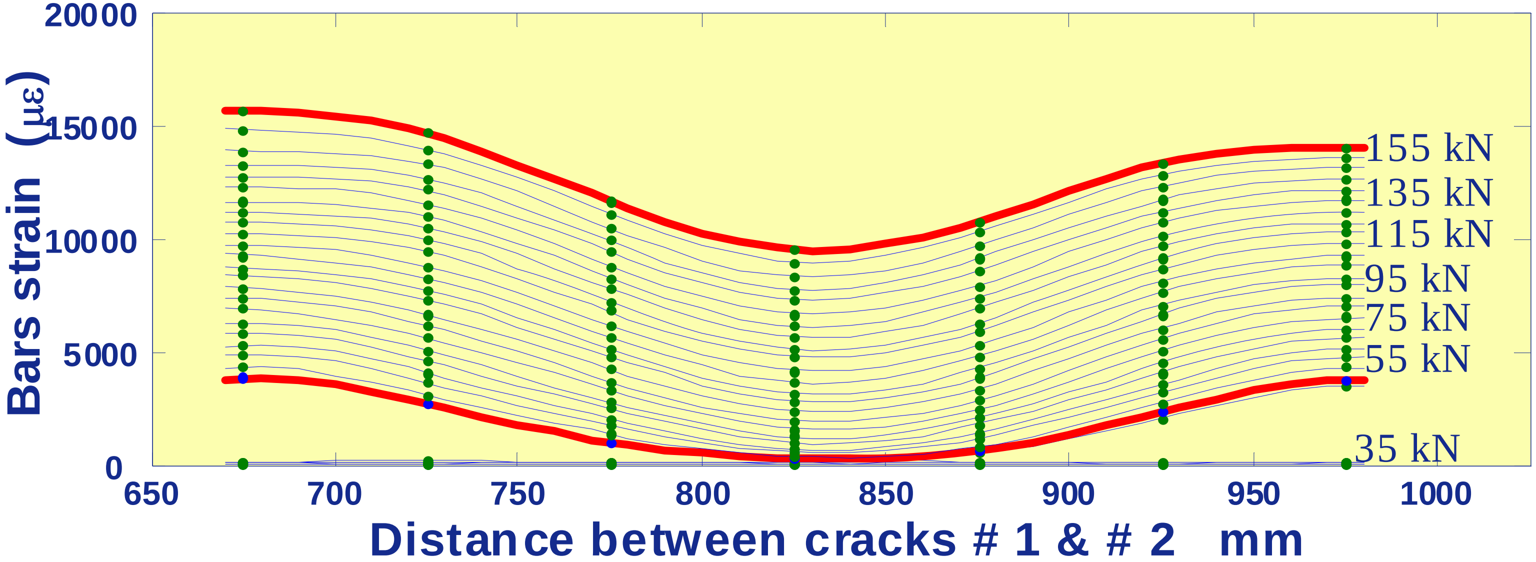
Strain Distribution during Cracking

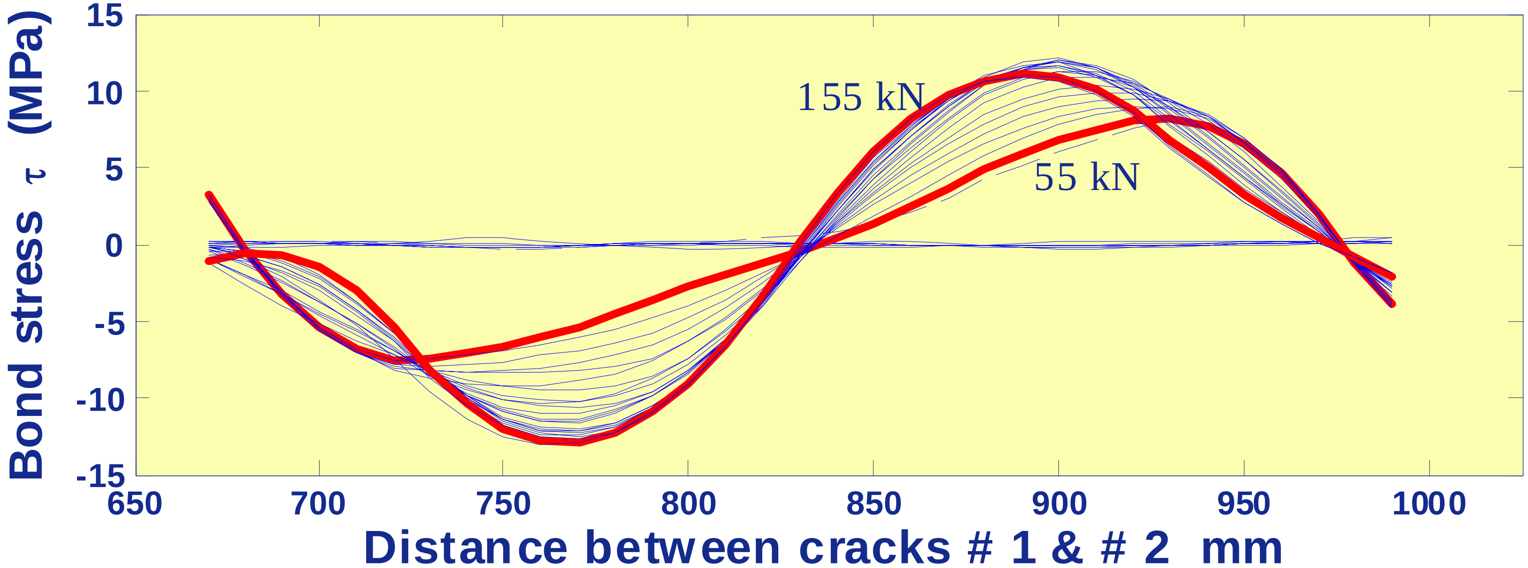




Internally strain gauged bar

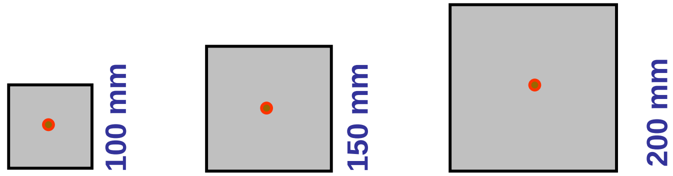
Post Cracking Strain Profile





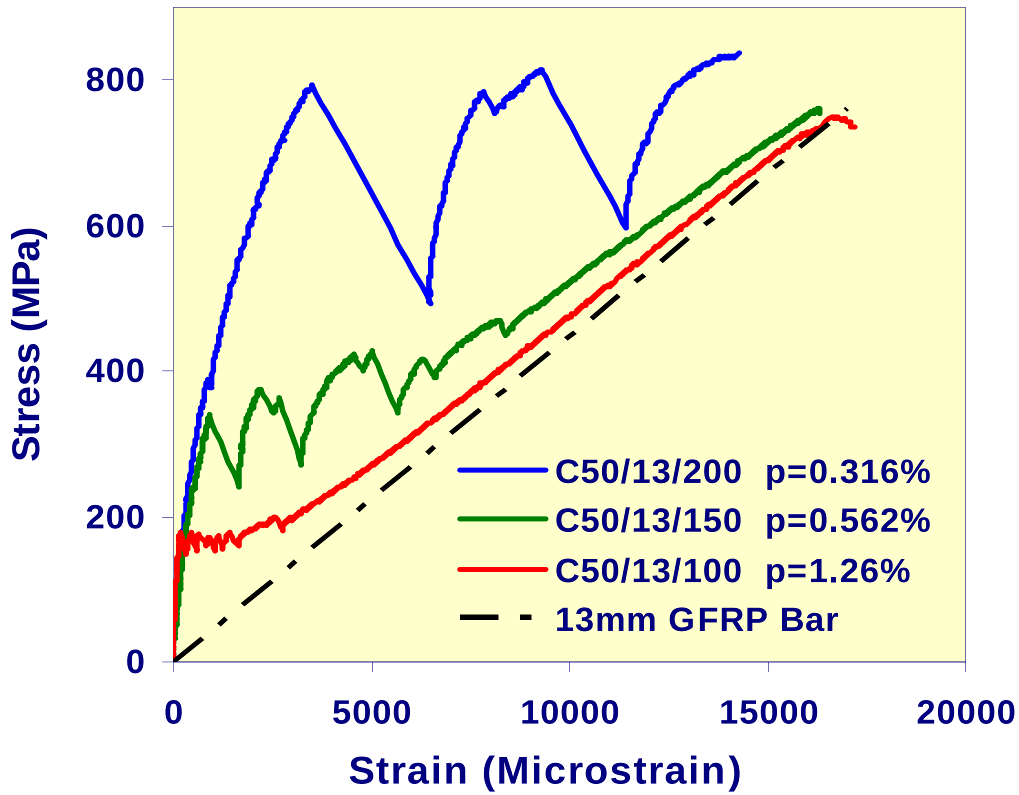
Typical strain and bond stress distribution between cracks

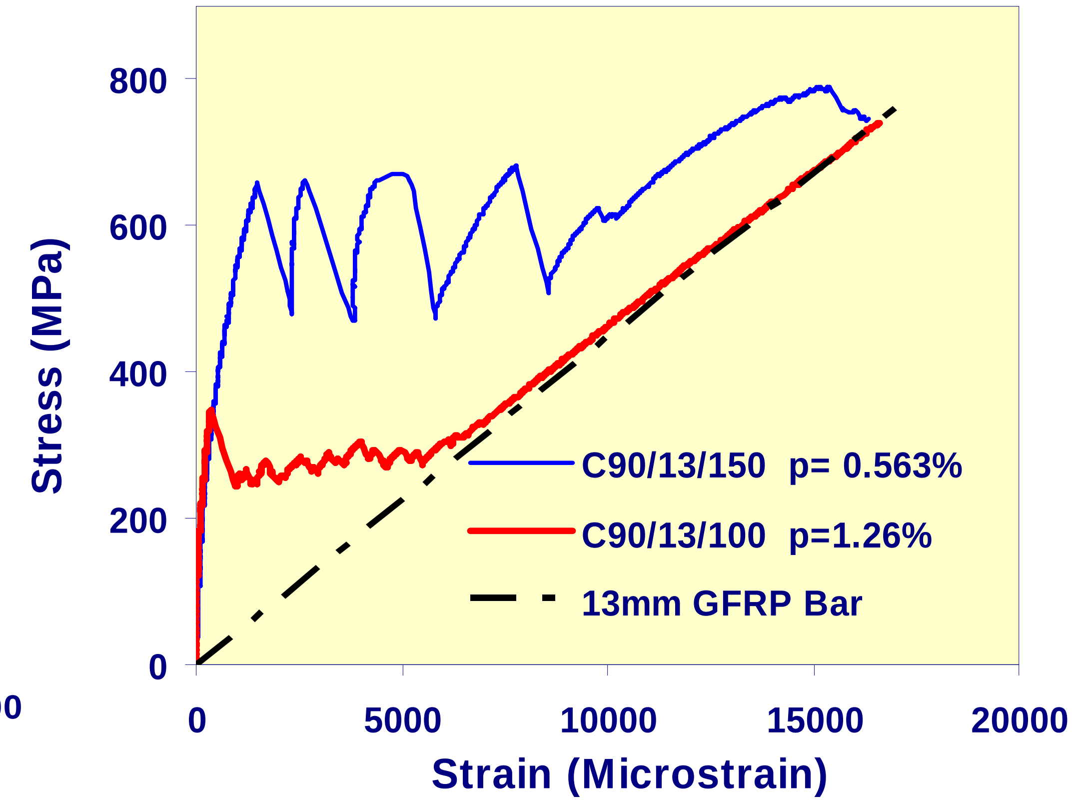
Parametric Study



Specimen	Concrete strength (f_c')	Bar Diameter (ϕ)	Dimension *b×d×l*	Reinforcement ratio (ρ)
C50/13/100	52	12.7	100×100×1500	1.26
C50/13/150	52	12.7	150×150×1500	0.56
C50/13/200	52	12.7	200×200×1500	0.32
C90/13/100	91	12.7	100×100×1500	1.26
C90/13/150	91	12.7	150×150×1500	0.56
C50/19/150	52	19.1	150×150×1500	1.27
C50/19/200	52	19.1	200×200×1300	0.72
C90/19/150	52	19.1	150×150×1300	1.27
C90/19/200	91	19.1	200×200×1300	0.72
C50/19/200N	91	19.1	200×200×1300	0.72

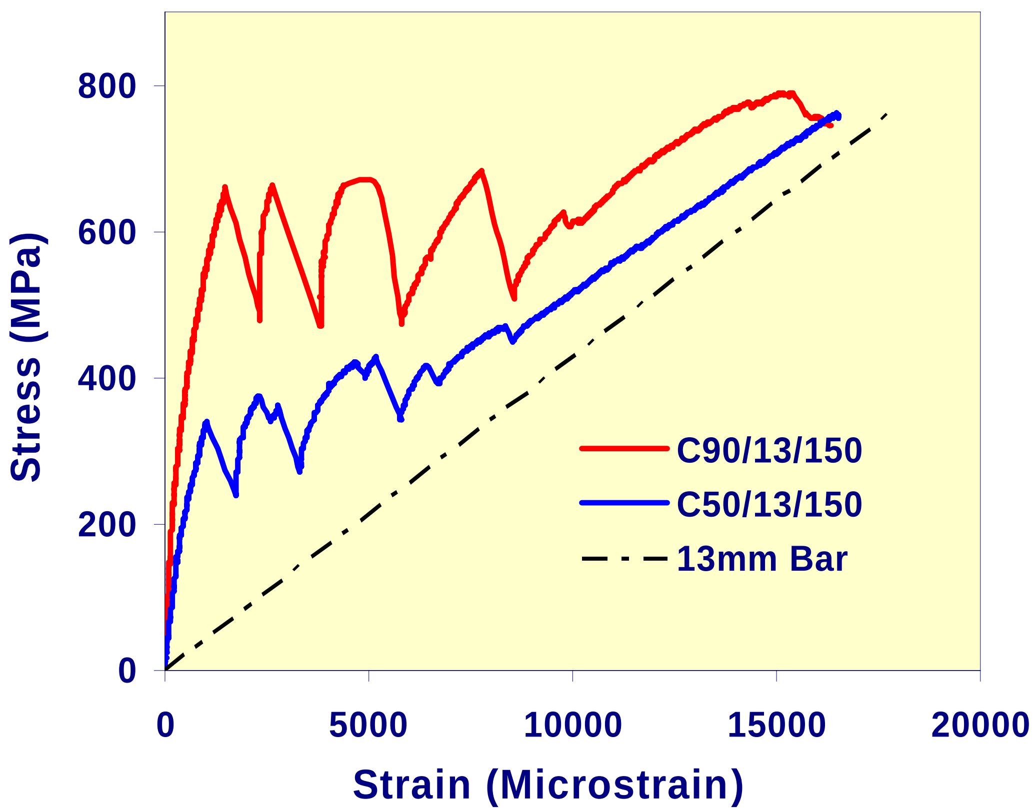
Reinforcement Ratio

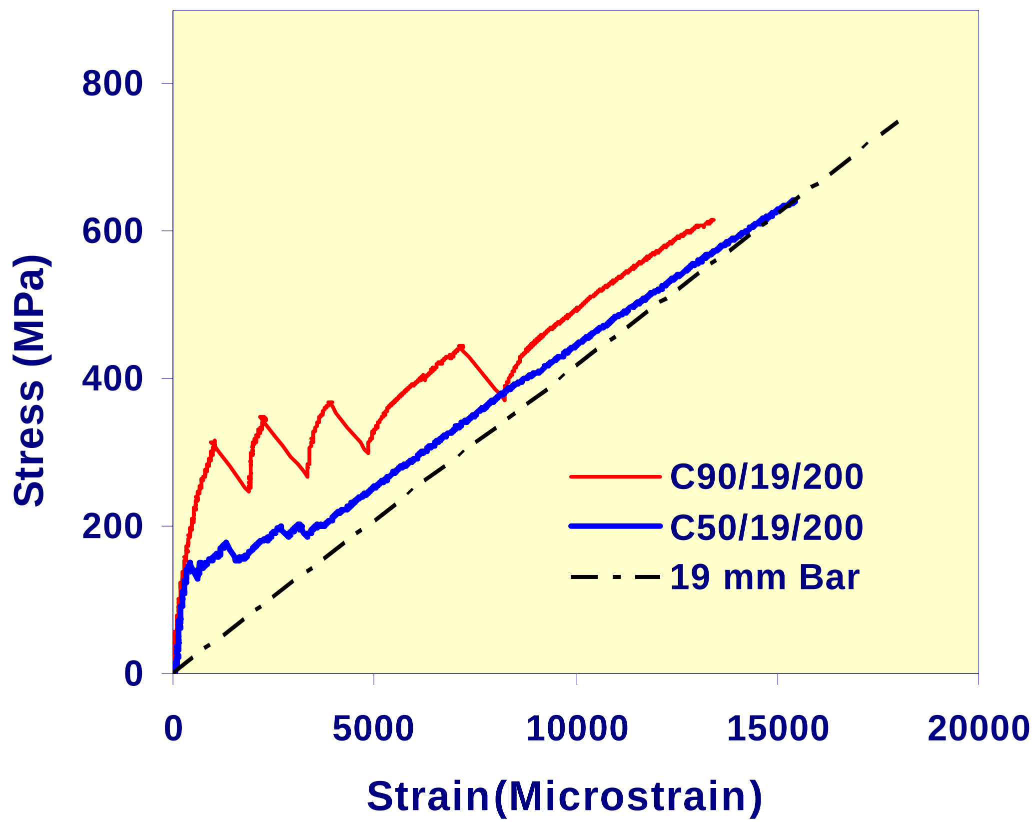




- Direct influence on tension stiffening effect

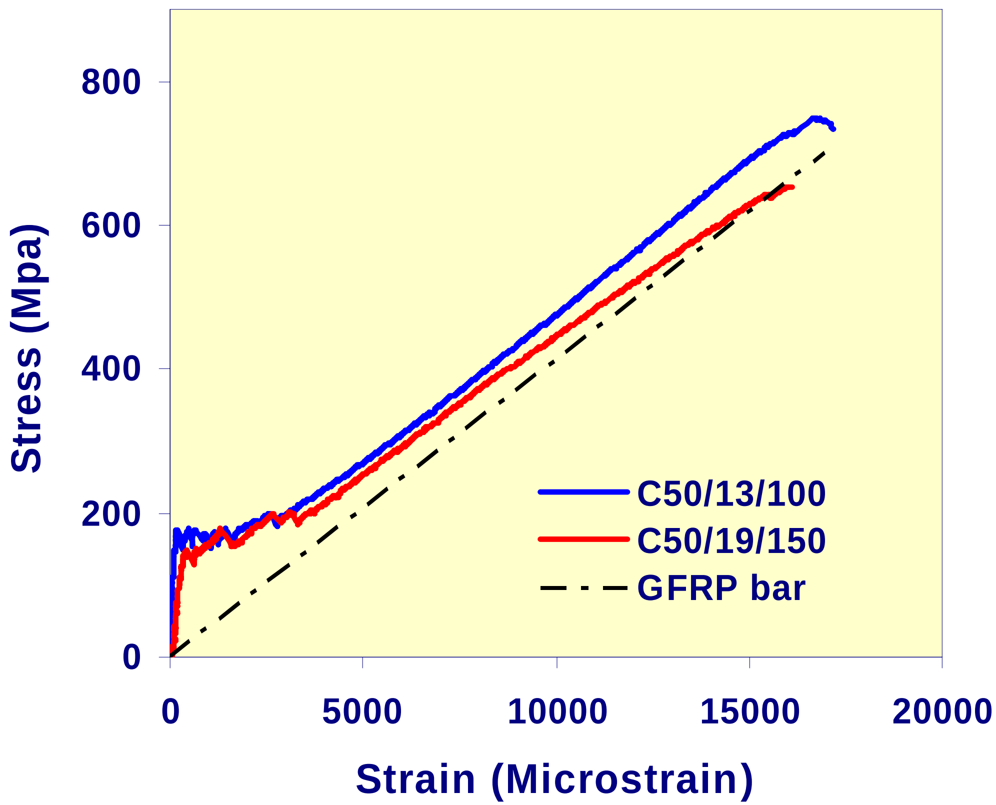
Concrete Strength

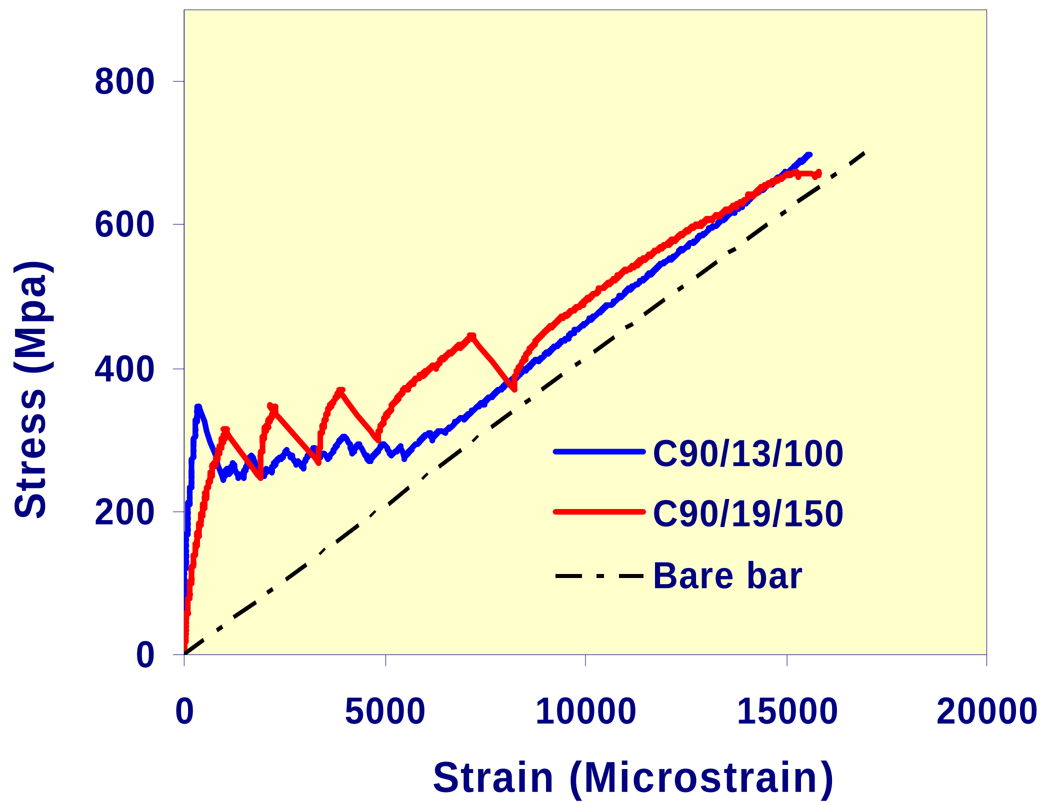




- Direct influence on tension stiffening effect

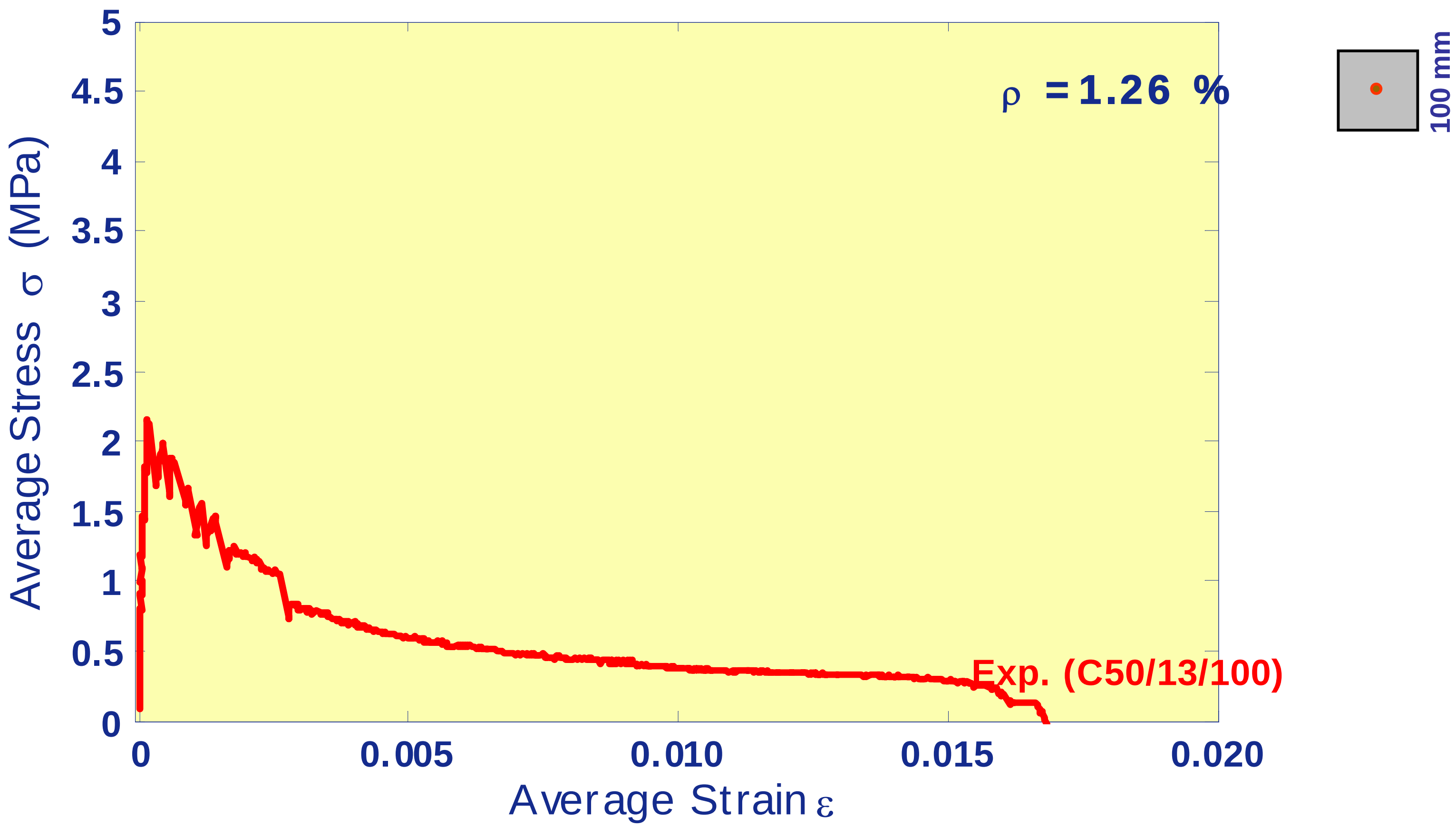
Bar Diameter





- **Bar diameter when compared at same reinforcement ratio has no significant influence of tension stiffening effect**

Existing Model Predictions



Reduced cross sectional area

Original
$$A_e = \left[\frac{P_{cr}}{P_a}\right]^3 A_g + \left[1 - \left(\frac{P_{cr}}{P_a}\right)^3\right] A_{cr}$$

Modified to account for weak FRP bond
$$A_e = \left[\frac{P_{cr}}{P_a}\right]^3 \beta_d A_g + \left[1 - \left(\frac{P_{cr}}{P_a}\right)^3\right] A_{cr}$$

→ ACI

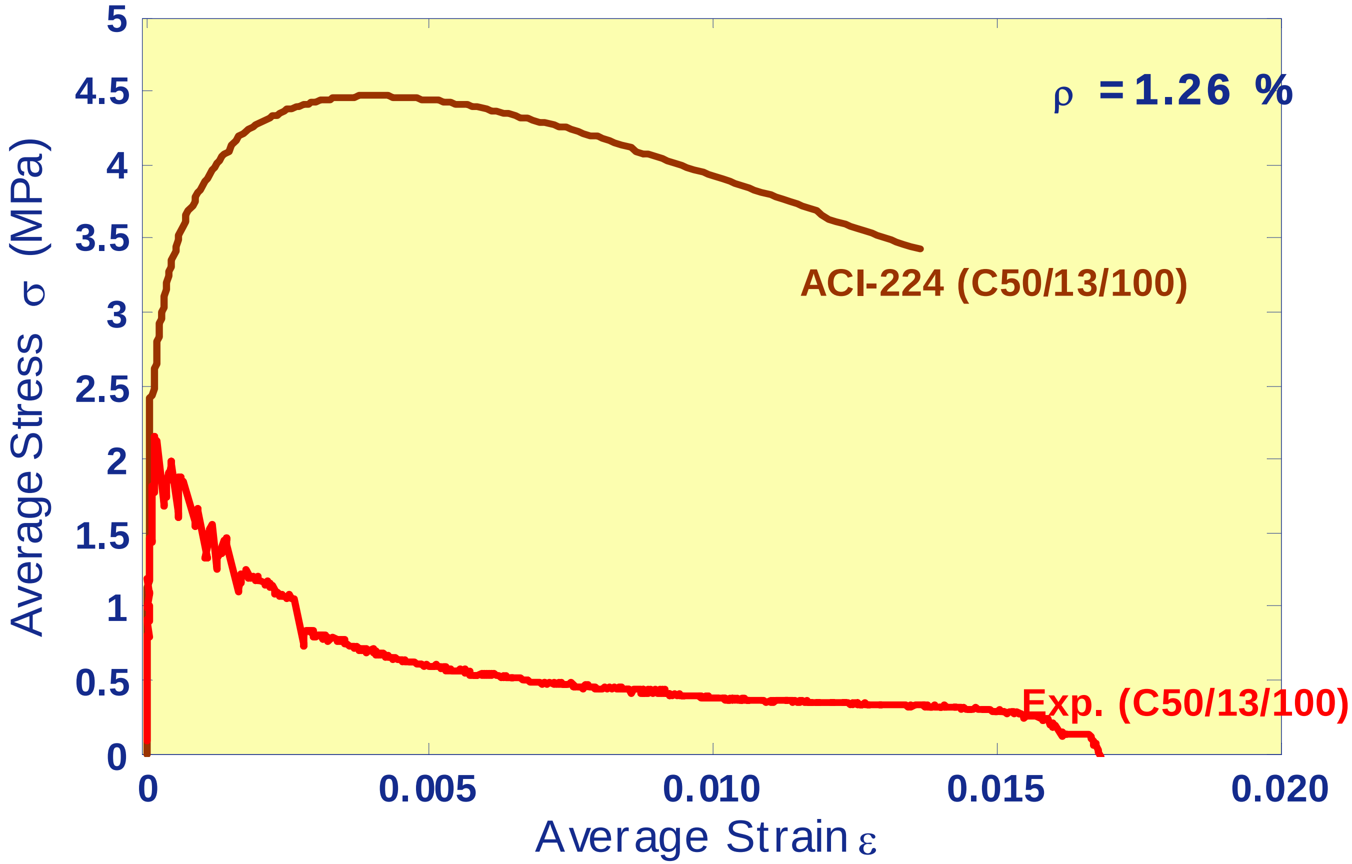
Composite strain for given bar strain

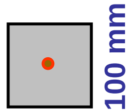
$$\varepsilon_m = \varepsilon_s \left[1 - K\left(\frac{f_{scr}}{f_f}\right)^2\right]$$

$$f_{scr} = \frac{P_{cr}}{A_f} = f_t'\left(\frac{1}{\rho} - 1 + n_f\right)$$

→ CEB

Existing Model Predictions





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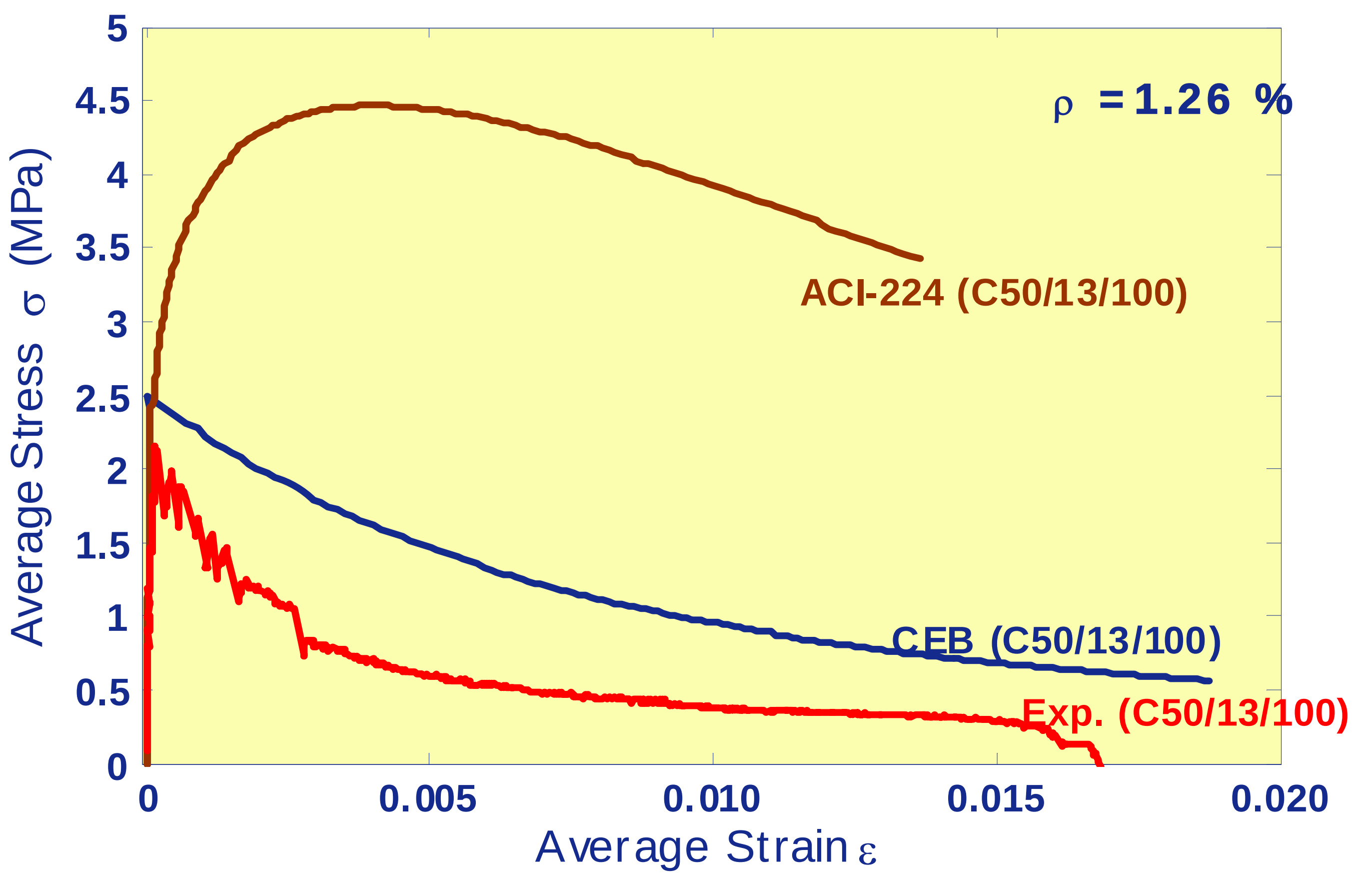

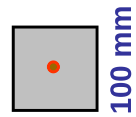

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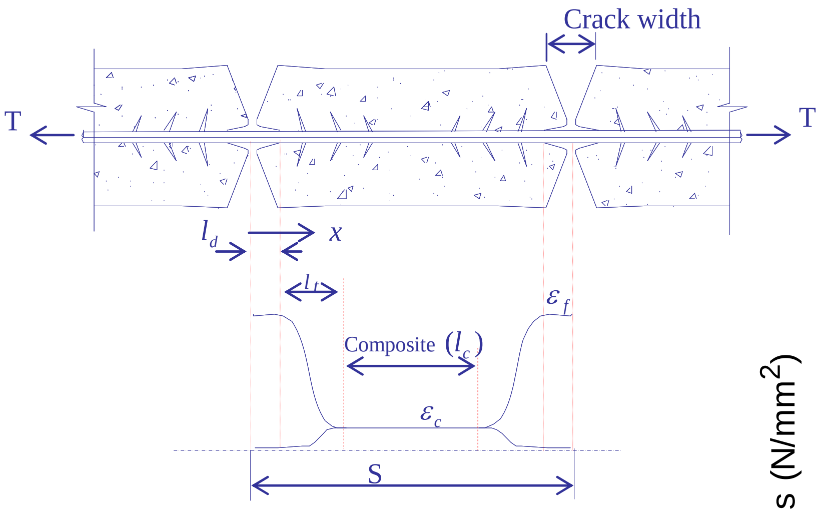
→ **CEB**

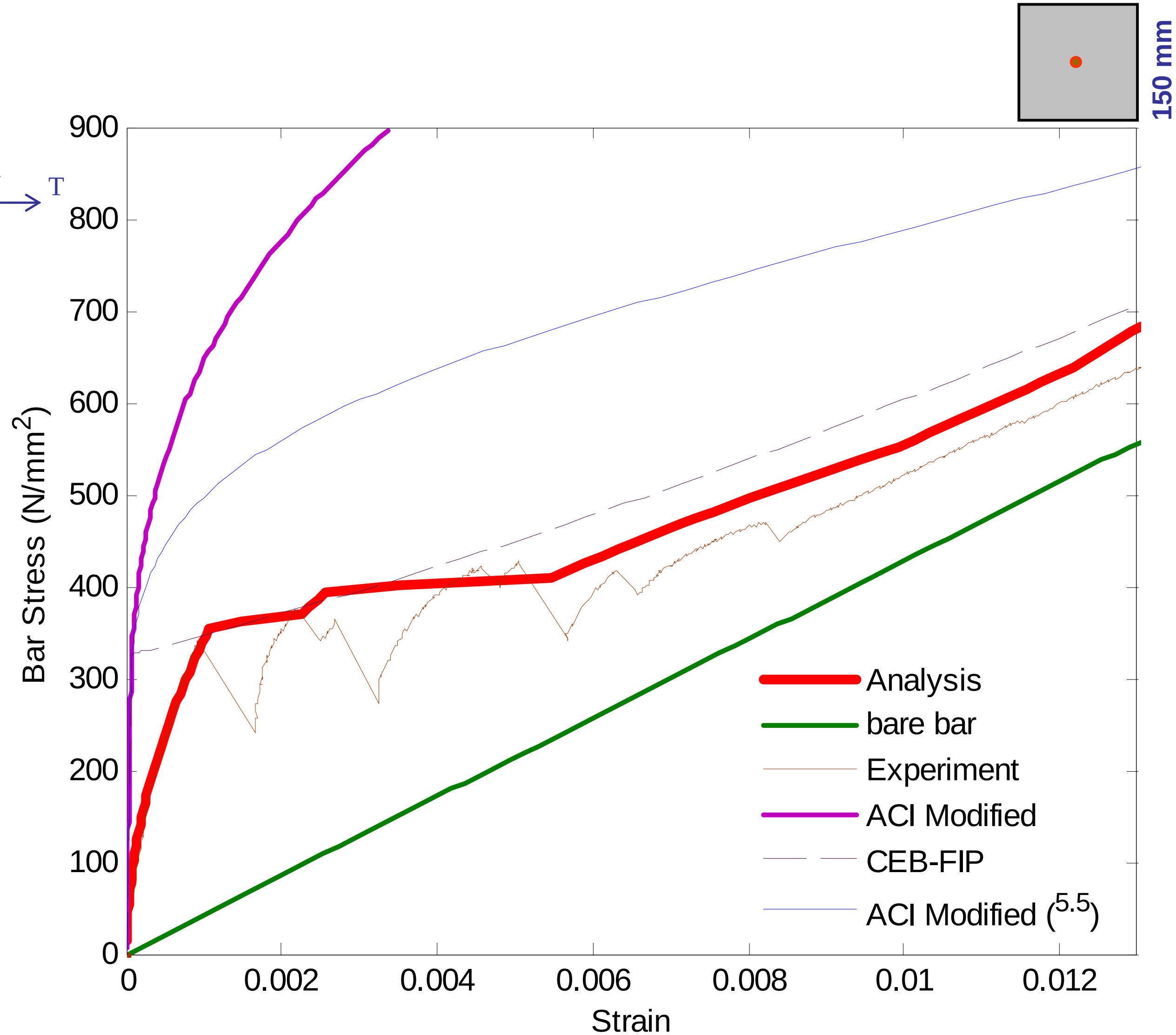
Modelling of Tension Stiffening Effect



$$\varepsilon_s = \left(\frac{p}{A_s E_s}\right)$$

$$\varepsilon_s(x) = 0.5\left(\cos\left(\frac{\pi x}{lt}\right) + 1\right)(\varepsilon_s - \varepsilon_c) + \varepsilon_c$$

$$\varepsilon_s(x) = \varepsilon_c(x) = \left(\frac{p}{A_s E_s + A_c E_c}\right)$$



Experimental result of 13mm bar in 150 square section compared with various models

Conclusions

- Existing tension stiffening models unconservative for GFRP-RC
- Deflections of GFRP-RC underestimated
- Three distinctive stages of tension stiffening behaviour corresponding to different stages of cracking identified.
- Substantial loss of composite action and early stages of bond deterioration in GFRP-RC
- Reinforcement ratio and concrete strength have direct influence on tension stiffening behaviour of GFRP-RC but not bar diameter
- Strain distribution functions used for modelling tension stiffening behaviour of GFRP-RC.