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TENSION STIFFENING BEHAVIOUR OF GFRP-RC

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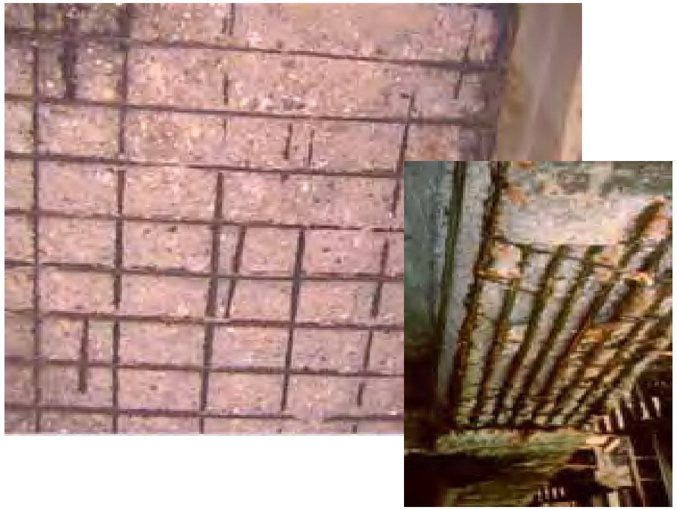
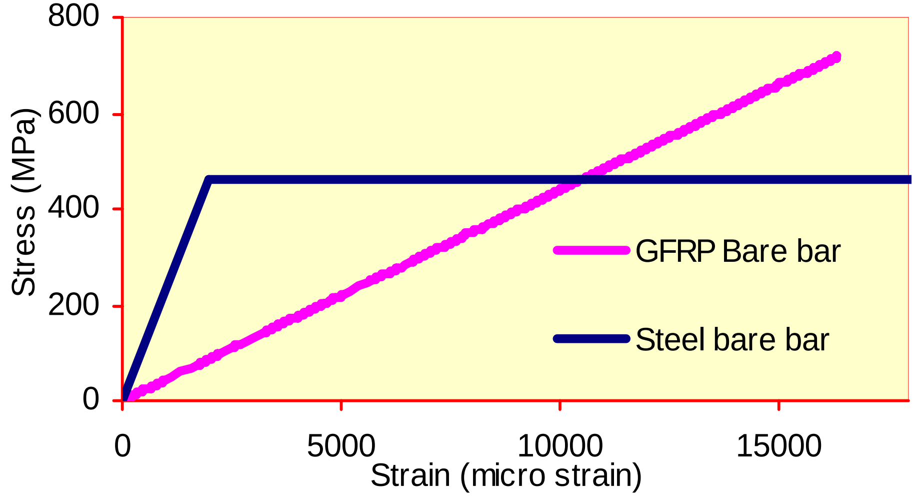
Background and the use of GFRP-RC in construction



Corrosion damaged slab

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

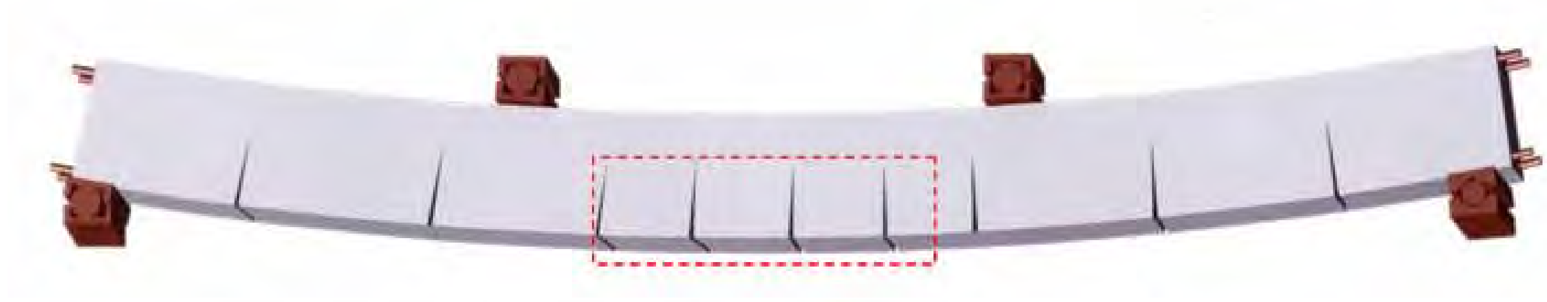
GFRP bars

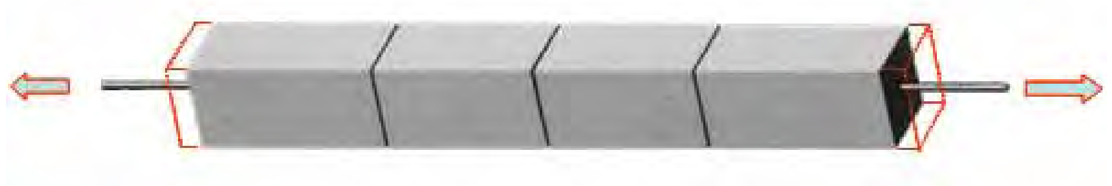


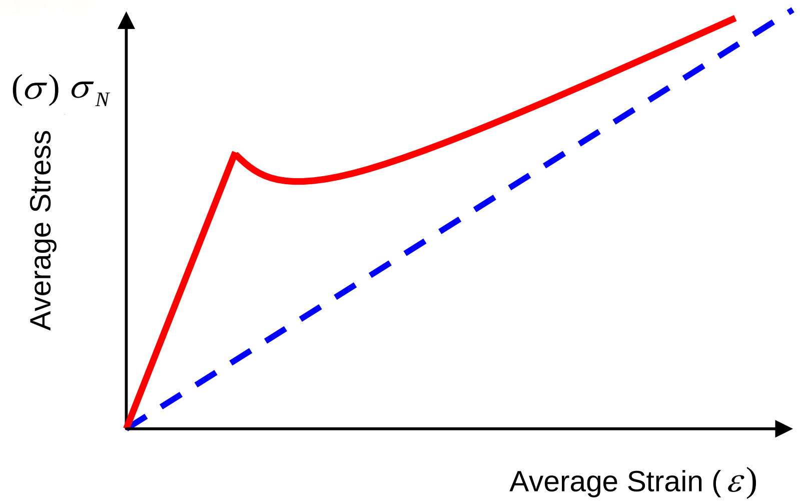
Stiffness of GFRP compared to Steel

Average stress strain behaviour of reinforced concrete in tension

When designing GFRP-RC serviceability limit state (especially deflections at service loads) and not the ultimate limit state govern the design and therefore proper accounting for tension stiffening is very important.







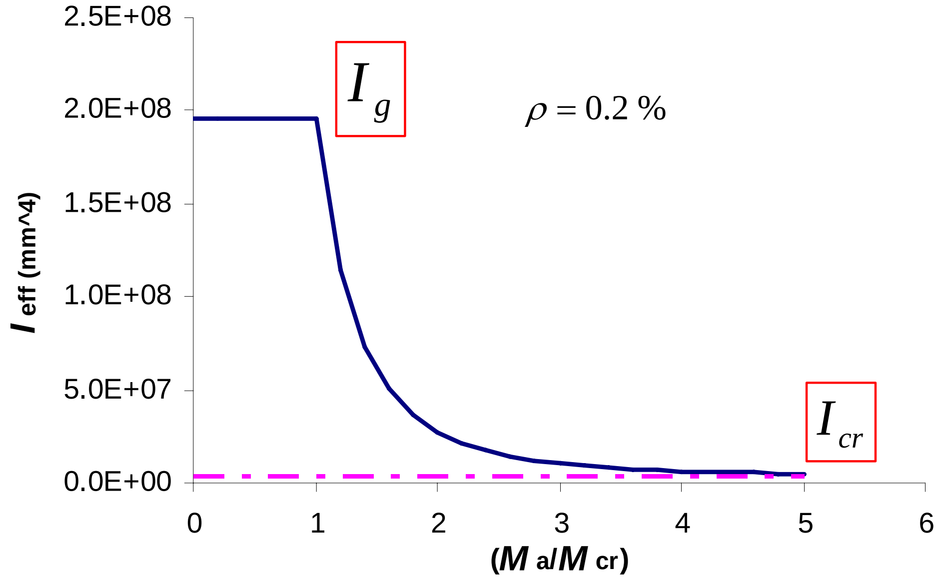
How the tension stiffening is accounted for in design codes

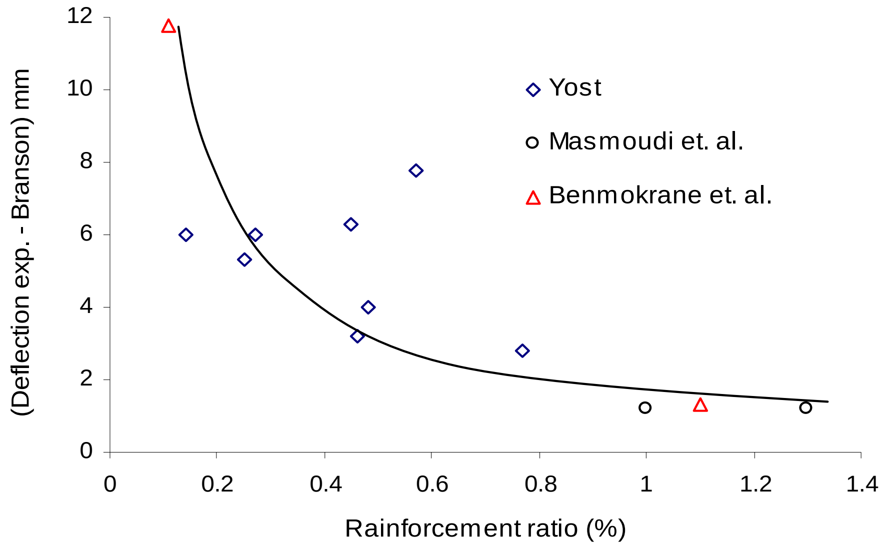
How it is accounted in ACI

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

Branson's equation for I_{eff}

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





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Importance of studying the tension stiffening behaviour of GFRP-RC

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1. **There is no general agreement about how tension stiffening can be accounted for**

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

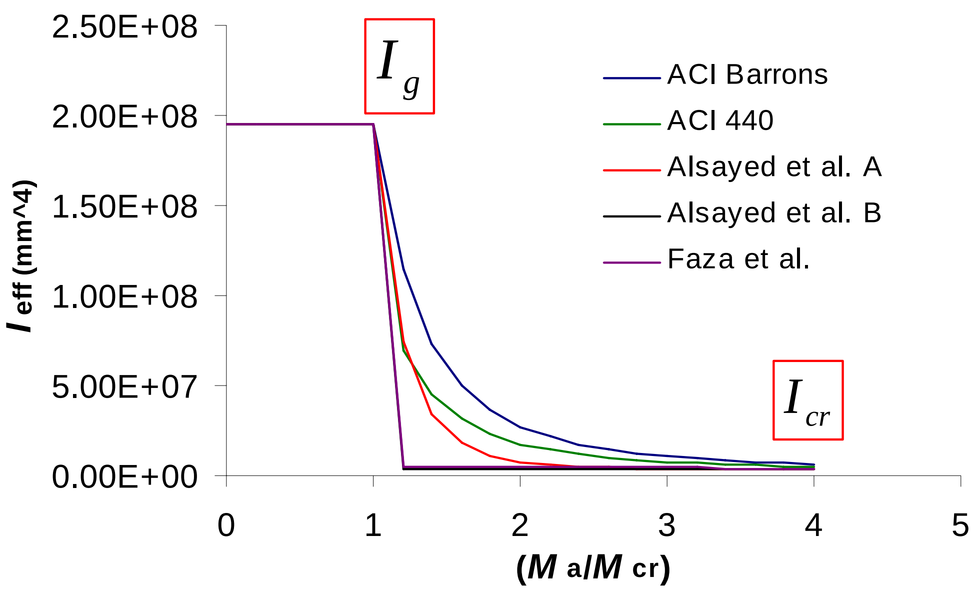
$$I_{eff} = I_g \beta_d \left(\frac{M_{cr}}{M_a}\right)^3 + I_{cr}\left[1-\left(\frac{M_{cr}}{M_a}\right)^3\right]$$ ACI 440

$$I_{eff} = I_g \left(\frac{M_{cr}}{M_a}\right)^{5.5} + I_{cr}\left[1-\left(\frac{M_{cr}}{M_a}\right)^{5.5}\right]$$ 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

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

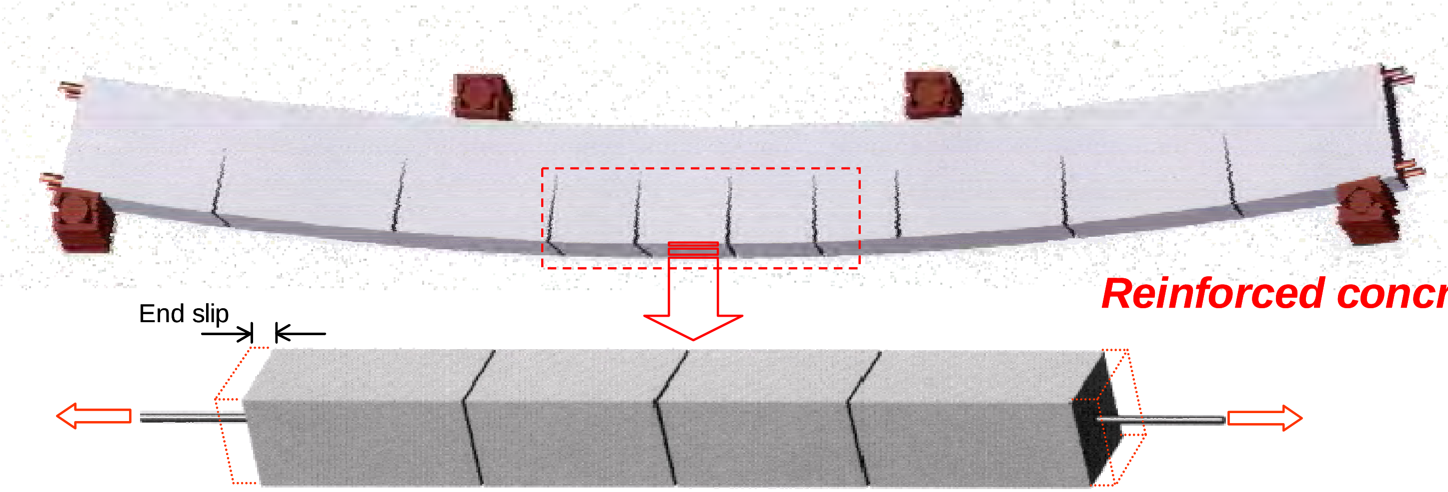
$$\frac{M_a}{M_{cr}} > 3 \Rightarrow I_m = \frac{23 I_{cr} I_e}{8 I_{cr} + 15 I_e}$$ Faza et. al B



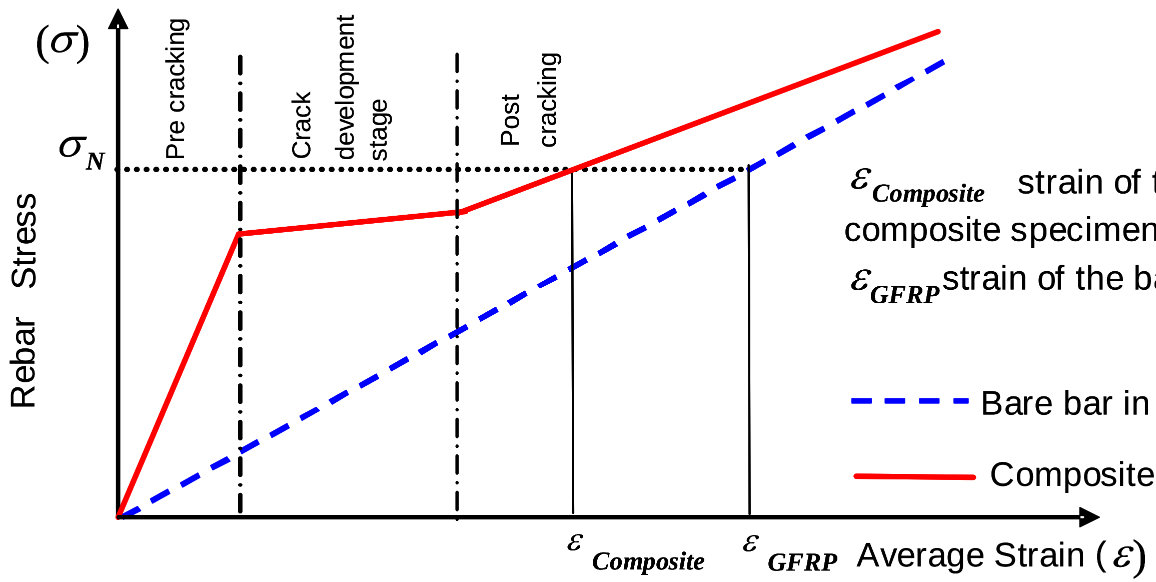
2. **With the increasing use of Modified Compression Field Theory (MCFT) and Softened Truss Model Theory (STMT) in FE analysis for reinforced concrete, there is a need to characterise average stress strain behaviour of concrete in tension in order to analyse GFRP-RC using common FE packages.**

Experimental investigation of tension stiffening effect GFRP-RC

The ability of concrete to carry tension between cracks and provide extra stiffness into RC in tension is defined as tension stiffening effect of concrete.



Reinforced concrete in tension



Typical test results

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Experimental set-up for measuring tension stiffness using direct tension test

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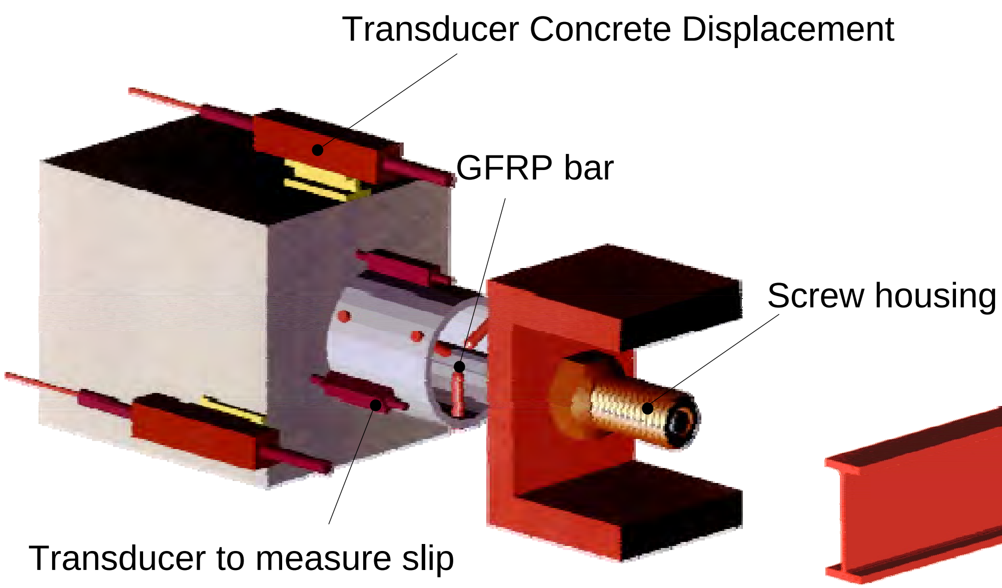
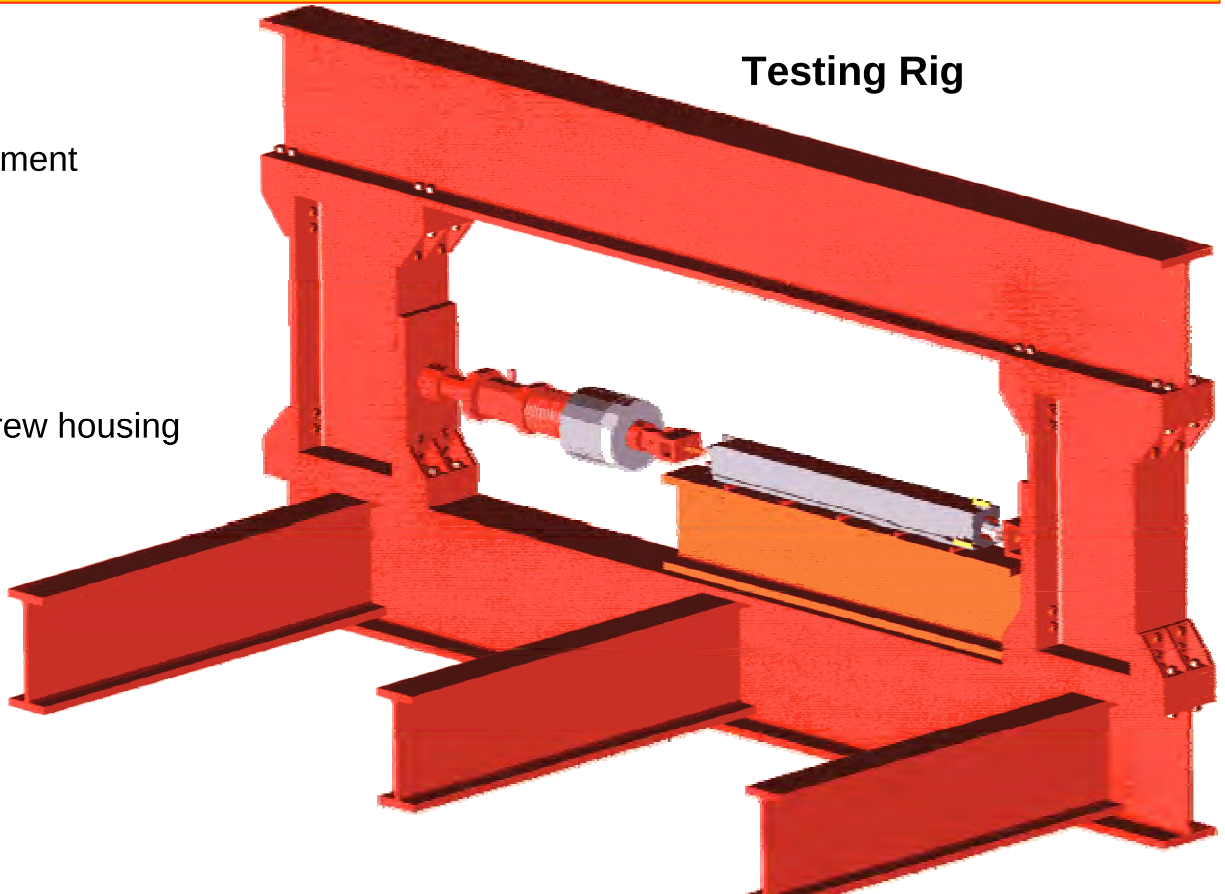
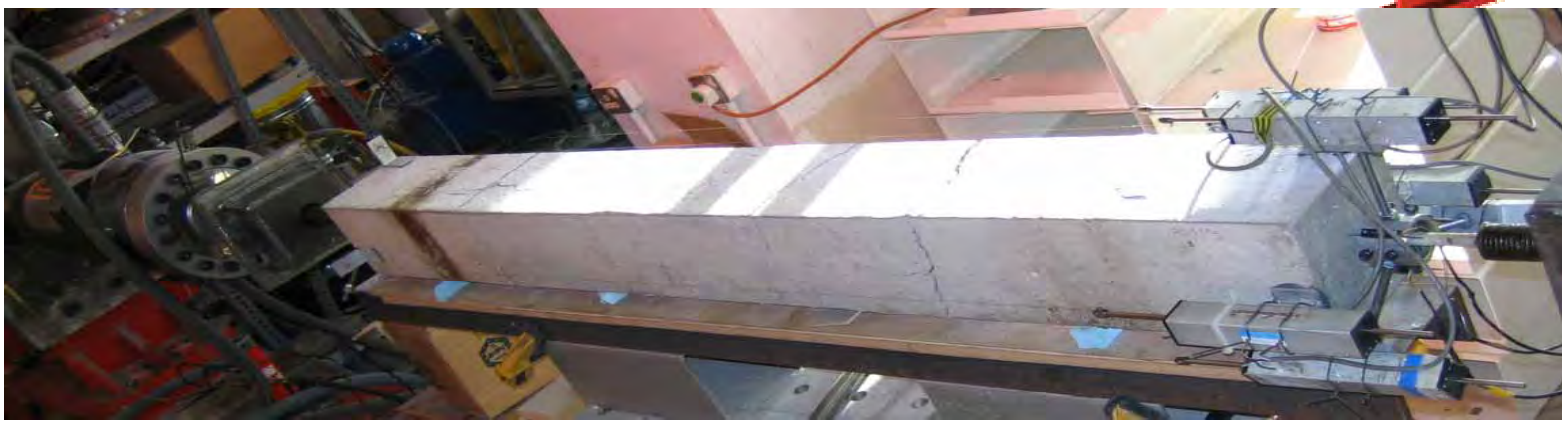
Measuring Arrangement



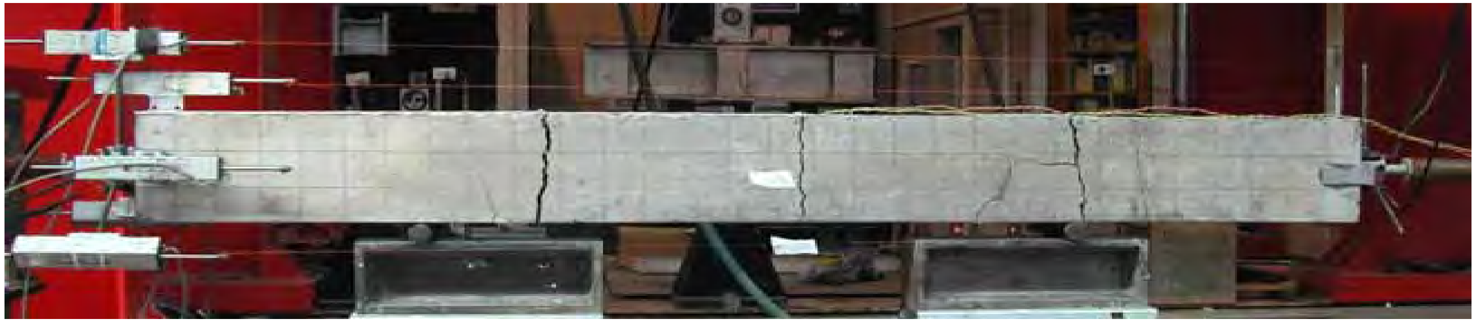
Testing Rig

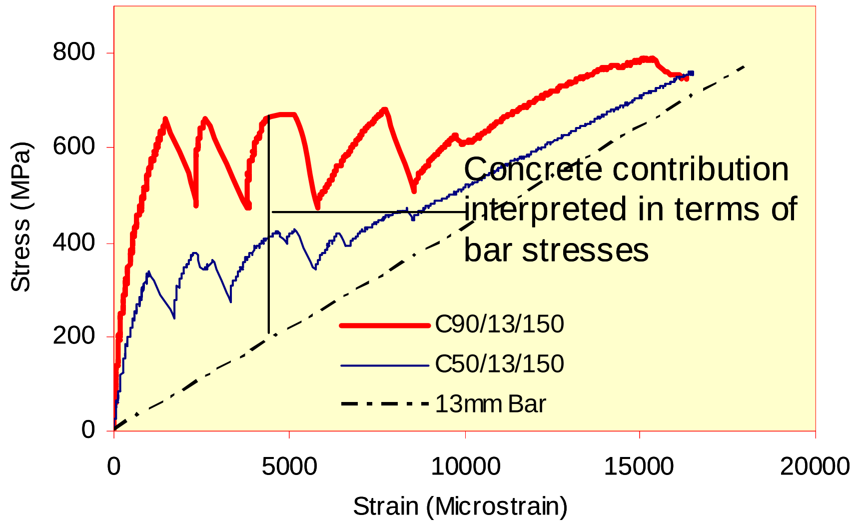




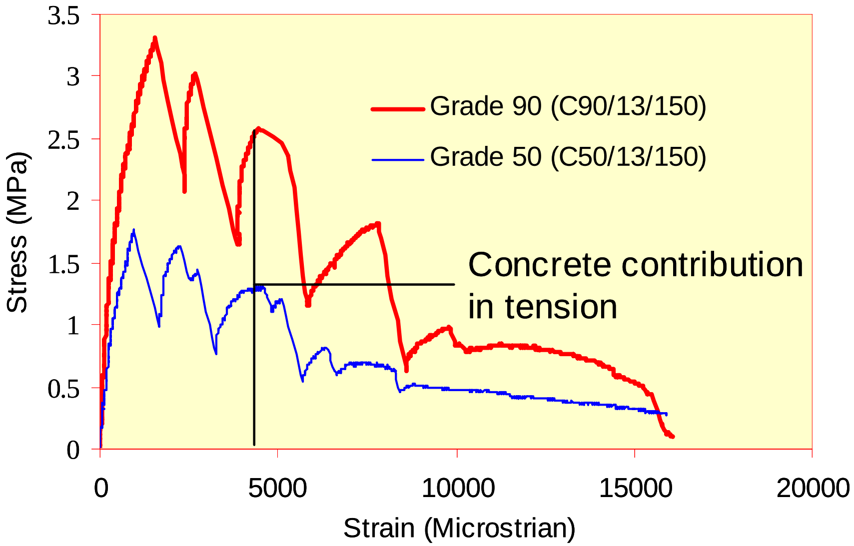
Experimental Set-up

Conversion of direct tension test results into concrete softening behaviour





Test results bar stress Vs overall strain



Average stress strain behaviour of concrete

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Details of the specimens tested in the parametric study

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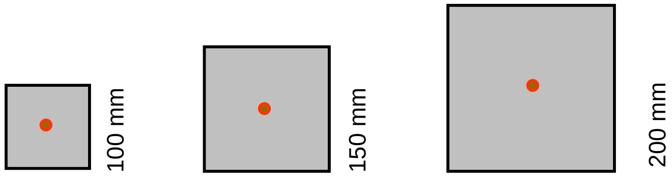
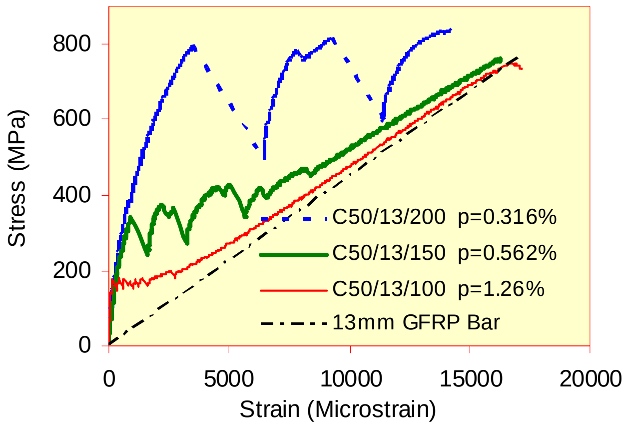
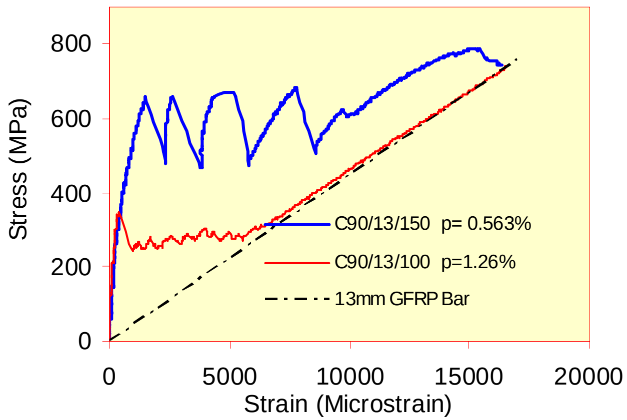


Specimen	Concrete Strength (MPa)	Bar Diameter D *(mm)*	Dimensions *b×d×l (mm)*	Reinforcement Ratio ρ %
C50/13/100	52	12.7	100×100×1500	1.26
C50/13/150	52	12.7	150×150×1500	0.56
C50/13/200	52	12.7	200×200×1500	0.32
C90/13/100	91	12.7	100×100×1500	1.26
C90/13/150	91	12.7	150×150×1500	0.56
C50/19/150	52	19.1	150×150×1500	1.27
C50/19/200	52	19.1	200×200×1300	0.72
C90/19/150	91	19.1	150×150×1500	1.27
C90/19/200	91	19.1	200×200×1300	0.72
C50/19/200N	52	19.1	200×200×1300	0.72

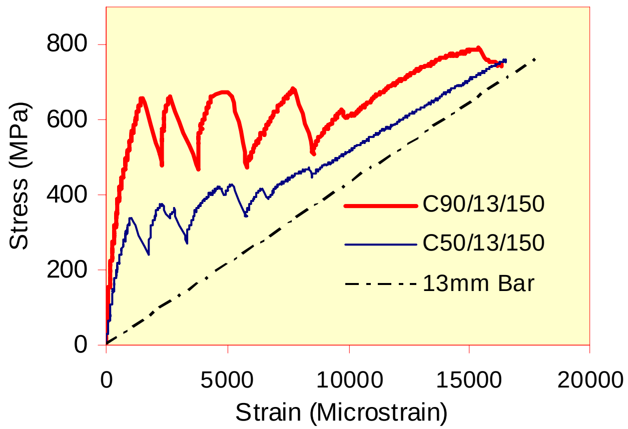
Factors influencing tension stiffening behaviour results of parametric study

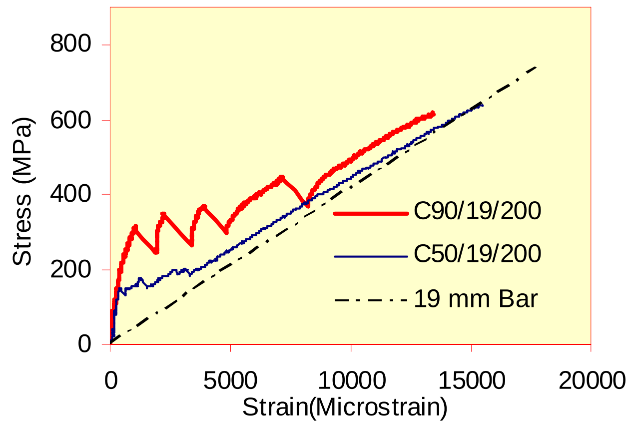
Reinforcement ratio



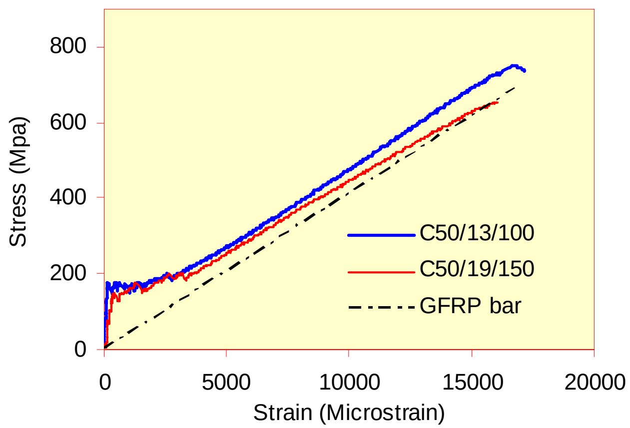


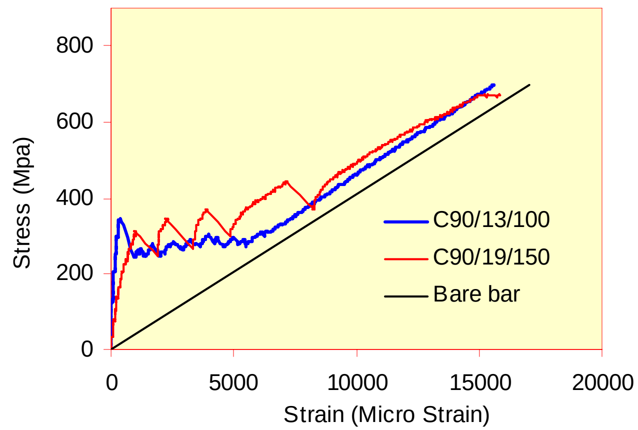
Concrete strength





Bar diameter





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Experimental results compared with existing models

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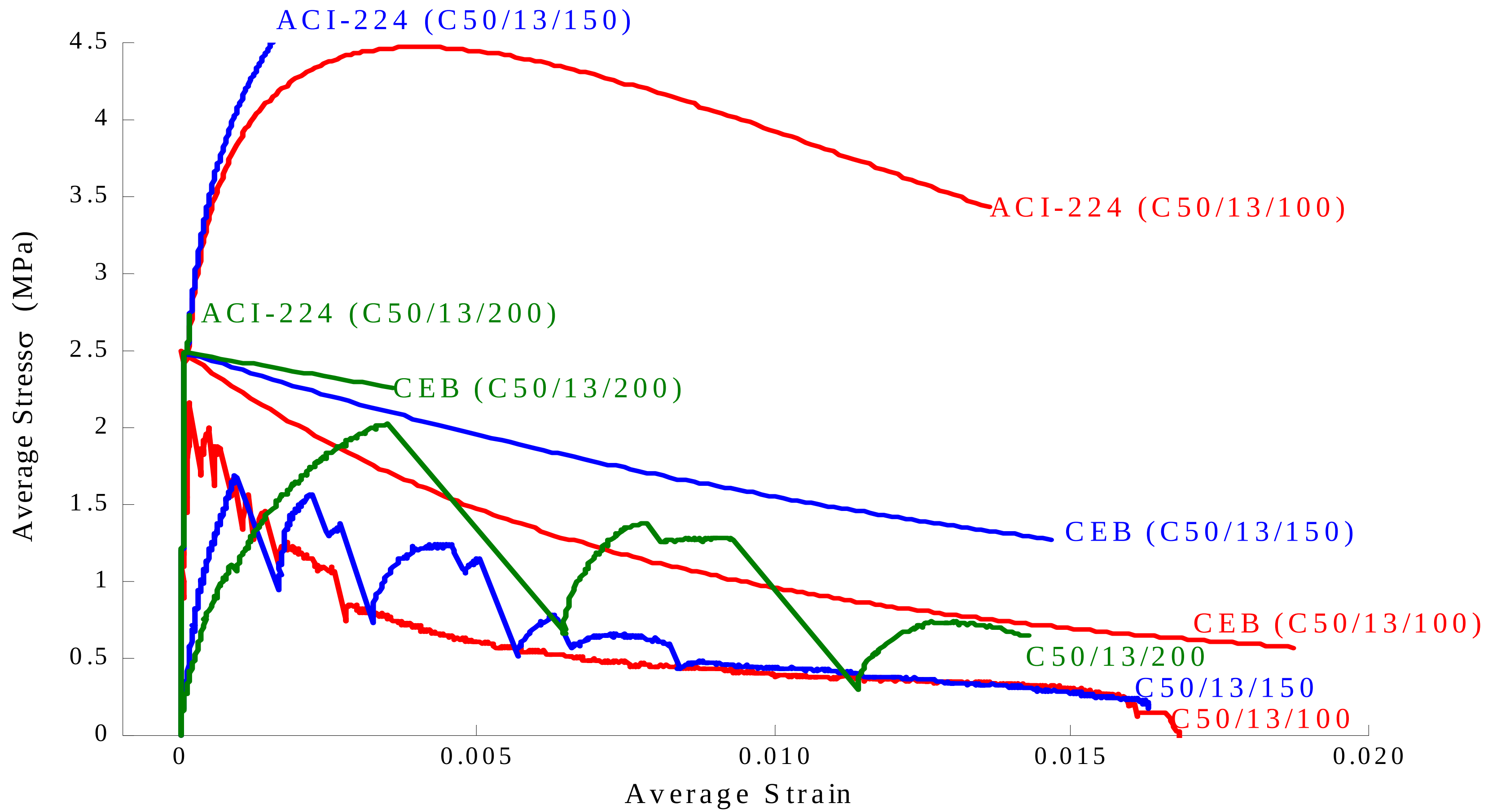


Reduce cross sectional area

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

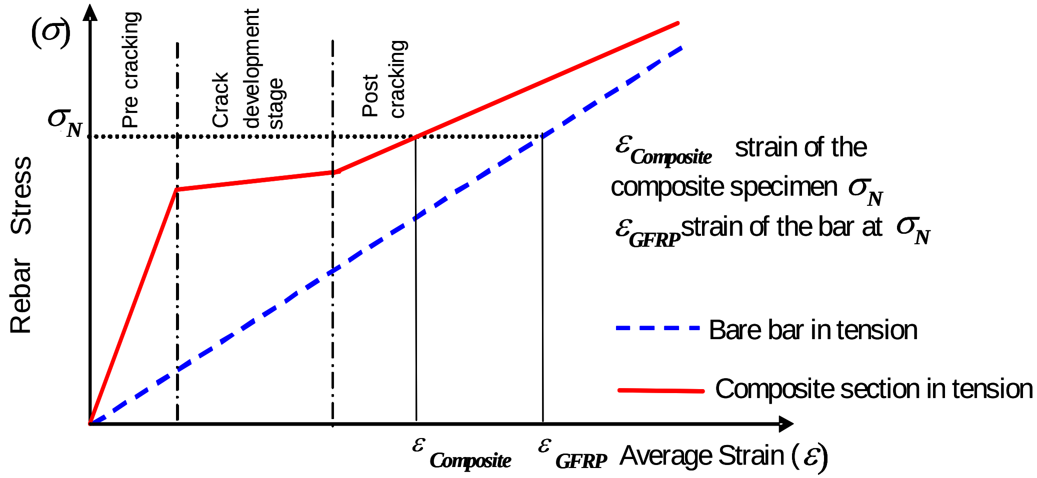
Composite strain for the given bar strain

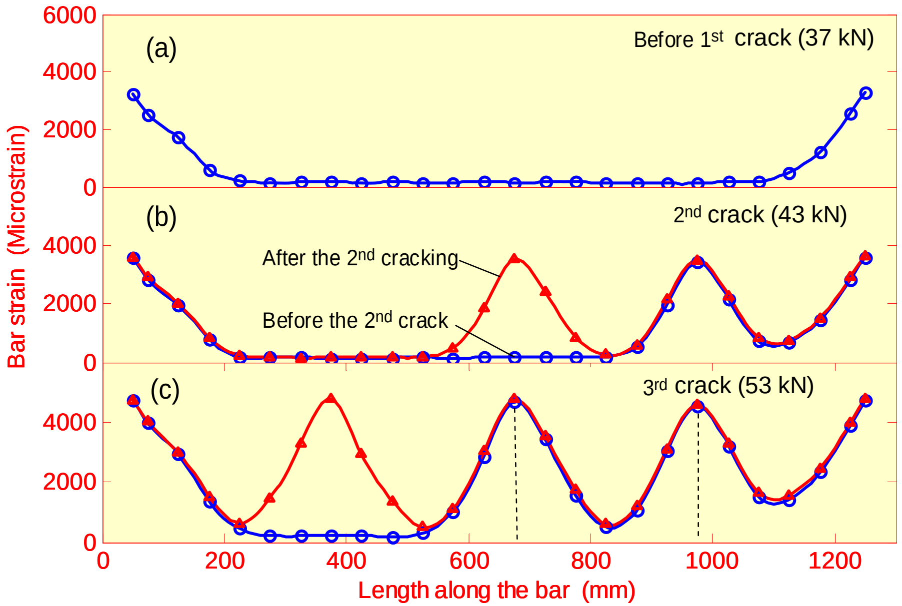
$$\varepsilon_m = \varepsilon_s \left[1 - K\left(\frac{f_{scr}}{f_f}\right)^2\right]$$

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

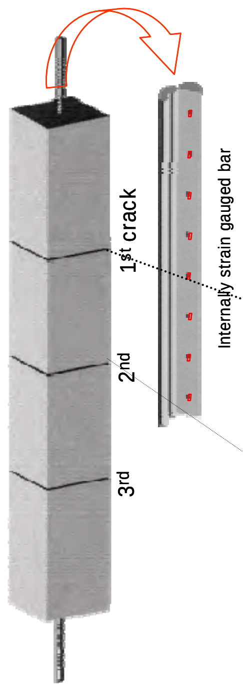
→ CEB

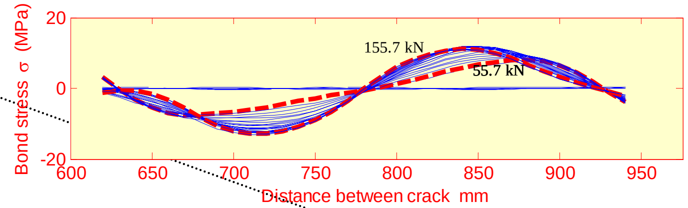
Strain distribution at different stages of cracking

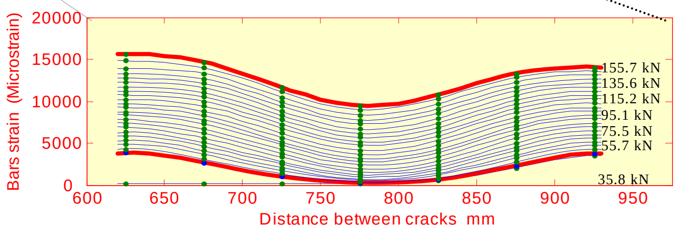




Strain profiles during first two stages of cracking







Post cracking strain profile

Modelling tension stiffening using a cosine strain distribution function

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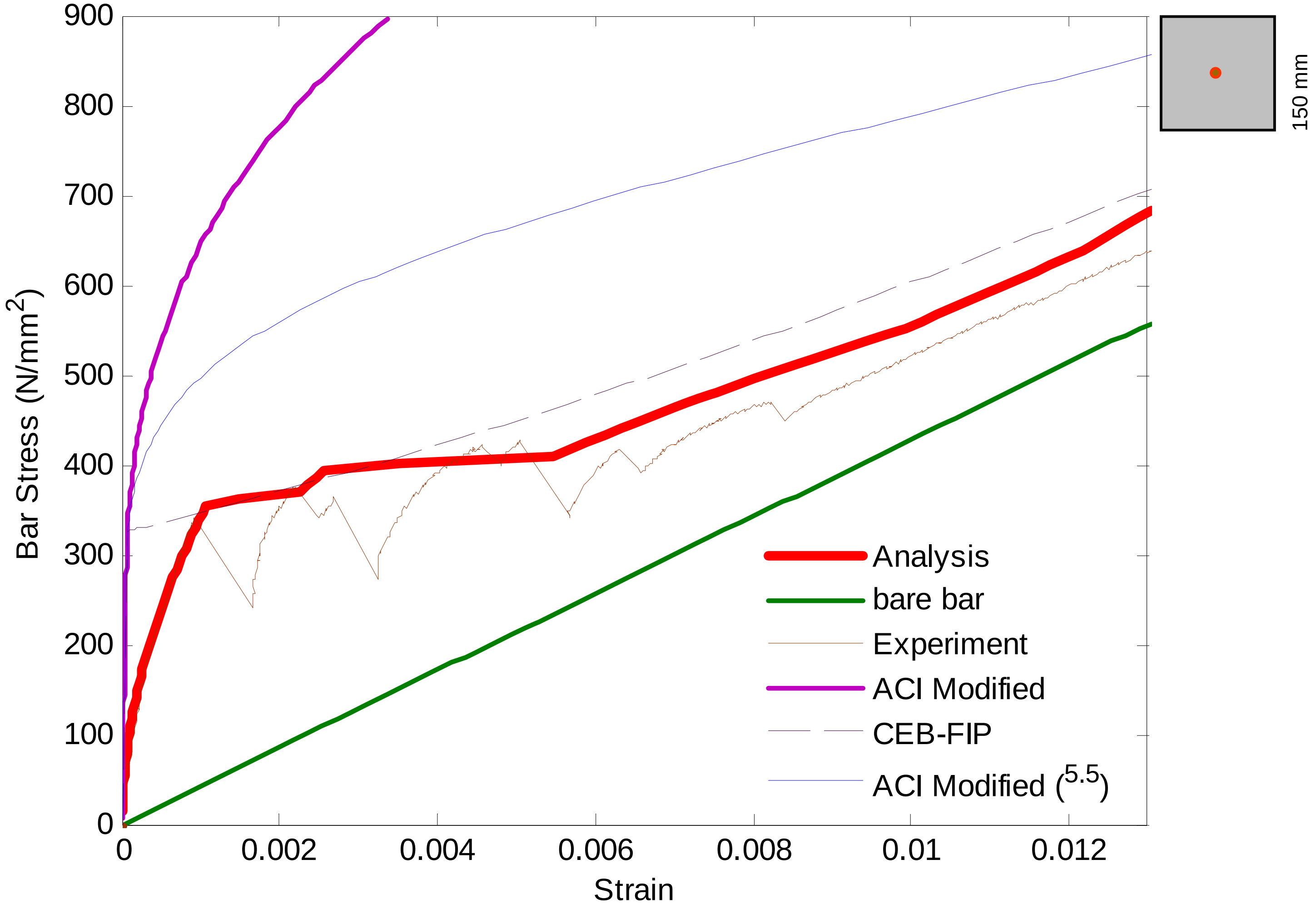
$$\varepsilon_s = \left(\frac{p}{A_s E_s}\right)$$

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

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



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

Conclusions

- Three distinctive stages of tension stiffening behaviour corresponding to different stages of cracking have been identified.
- Substantial loss of composite action and early stages of bond deterioration of GFRP-RC have been observed during direct tension tests.
- Reinforcement ratio and concrete strength have been found to have a direct influence on tension stiffening behaviour of GFRP-RC whilst bar diameter has been found not to have a direct effect.
- Existing models have been found to be unconservative in predicting tension stiffening effect of GFRP-RC. This explains why deflections of GFRP-RC are underestimated when equations of deflections are derived based on these concepts.
- Use of strain distribution functions to model tension stiffening behaviour has been found promising in modelling tension stiffening behaviour of GFRP-RC.

Thank You