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

- GFRP Bare bar
- Steel bare bar

Strain (micro strain):
- GFRP: 0 to 15000
- Steel: 0 to 10000

Stress (MPa):
- GFRP: 0 to 800
- Steel: 0 to 600
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 it is accounted in ACI

\[ \Delta = \frac{kPl^3}{EI_{eff}} \]

Branson’s equation for \( I_{eff} \)

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

\( \rho = 0.2 \% \)
1. There is no general agreement about how tension stiffening can be accounted for

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

ACI Branson’s

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

ACI 440

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

Alsayed et. al A

\[ 1 < \frac{M_a}{M_{cr}} < 3 \Rightarrow I_{\text{eff}} = I_{cr} \left[ 1.40 - \frac{2}{15} \left( \frac{M_a}{M_{cr}} \right)^{15} \right] \]

Alsayed et. al B

\[ \frac{M_a}{M_{cr}} > 3 \Rightarrow I_{m} = \frac{23I_{cr}I_c}{8I_{cr} + 15I_c} \]

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

Measuring Arrangement

- Transducer Concrete Displacement
- GFRP bar
- Screw housing
- Transducer to measure slip

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
Details of the specimens tested in the parametric study

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Concrete Strength (MPa)</th>
<th>Bar Diameter D (mm)</th>
<th>Dimensions b×d×l (mm)</th>
<th>Reinforcement Ratio ρ %</th>
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<td>12.7</td>
<td>100×100×1500</td>
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Factors influencing tension stiffening behaviour
results of parametric study

Reinforcement ratio

Concrete strength

Bar diameter

Factors influencing tension stiffening behaviour
results of parametric study

Reinforcement ratio

Concrete strength

Bar diameter

Factors influencing tension stiffening behaviour
results of parametric study
Experimental results compared with existing models

Average Stress (MPa)

Average Strain

Reduce cross sectional area

Original

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

Modified to account for weak FRP bond

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

Composite strain for the given bar strain

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

\[ f_{scr} = \frac{P_{cr}}{A_f} = f_t \left( \frac{1}{\rho} - 1 + n_f \right) \]
Strain distribution at different stages of cracking

![Diagram showing strain distribution](image)

Strain profiles during first two stages of cracking

- **Before 1st crack (37 kN)**
- **After the 2nd cracking**
- **2nd crack (43 kN)**
- **Before the 2nd crack**
- **3rd crack (53 kN)**

Post cracking strain profile

- **Internally strain gauged bar**
- **Bond stress**
- **Distance between cracks** (mm)
- **Bar strain** (Microstrain)
- **Length along the bar** (mm)

Strain profiles during first two stages of cracking:

(a) Before 1st crack (37 kN)
(b) After the 2nd cracking
(c) 2nd crack (43 kN)
(d) Before the 2nd crack
(e) 3rd crack (53 kN)
Modelling tension stiffening using a cosine strain distribution function

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

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

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

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