AN IMPROVED CREEP AND SHRINKAGE BASED MODEL FOR DEFLECTIONS OF COMPOSITE MEMBERS REINFORCED WITH CARBON FIBER REINFORCED BARS

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ABSTRACT

Corrosion of steel and resulting degradation of concrete severely affects the serviceability and safety of structures. Millions of dollars are spent every year for the repair and rehabilitation of such structures. Carbon fiber reinforced polymers (CFRP) provide excellent choice to resist corrosion. In this paper an improved analytical model to predict the creep and shrinkage based deflections of CFRP reinforced concrete flexural members is presented. Deflection values are compared with experimental data from literature and commonly used models. Our results show that the proposed model correlates well with the experimental results and provides much better prediction than the American Concrete Institute's (ACI) procedure and a common literature model.

Keywords: model, structures, steel, concrete, CFRP reinforcement, flexural member, creep, shrinkage, deflection.

1. INTRODUCTION

Reinforced concrete structures, exposed to atmosphere are susceptible to corrosion of reinforcing steel. This subsequently affects the serviceability and safety of structures. Exposure to severe and harsh climatic conditions aggravates the situation. Retrofitting measures for the rehabilitation of structures can incur huge cost. Fiber Reinforced Polymers (FRP) provides excellent resistance to corrosion. Long term deflection and curvature are governed by creep and shrinkage. Sometimes these time-dependent deformations can be so large that it could pose a severe threat to the serviceability of the structure.

In this paper, an improved analytical model to predict the creep and shrinkage based deflections of CFRP reinforced concrete flexural members is presented. Deflection values are assessed with experimental data from literature, a commonly used literature model, and ACI procedure.

2. PROPOSED APPROACH

Experimental data [1] on deflection and common analytical approaches [1, 2] for predicting the time dependent behavior of CFRP reinforced concrete beams have been used as a comparison in this research. The applicability of these common models is limited due to their inability to account for relative humidity.

This basic research consists of two parts. First part involves the development of a proposed analytical model and the second part compares the model values with the experimental data and other models.

2.1 Proposed model

Symbols used in the model are listed in the nomenclature section. Total deflection at any particular time is the sum of instantaneous and time dependent deflections. The instantaneous deflection is computed by elastic analysis. Time dependent curvature and deflections have been determined using creep and shrinkage coefficients. Section properties have been determined using age adjusted elastic modulus method.

Mean curvature at the end of loading period is:

$$\psi(t_0) = (1-\lambda_1)\psi_1 + \lambda_1\psi_2 \qquad [1]$$

$$\lambda_1 = \begin{cases} 1-0.75\left(\dfrac{M_{cracked}}{M_{applied}}\right) \\ 0 \end{cases}$$

For a cracked and uncracked section

$$\psi_1 = M_a / E_c I_{gross}$$

$$\psi_2 = M_a / E_c I_{effective}$$

Parabolic variation is assumed for instantaneous central deflection. The approximate instantaneous maximum deflection at center is provided by:

$$\Delta_i = \frac{\psi(t_0)L^2}{50} \qquad [2]$$

Mean curvature at time t_s is provided by:

$$\psi(t_s) = (1-\lambda_2)(\psi_1 + \Delta\psi_1) + \lambda_2(\psi_2 + \Delta\psi_2) \qquad [3]$$

$$\lambda_2 = \begin{cases} 1-0.25\left(\dfrac{M_{cracked}}{M_{applied}}\right)^2 \\ 0 \end{cases}$$

Change of curvature is provided by:

$$\Delta\psi_1 = \alpha\left[\varphi(t,t_s)\psi_1 + \varepsilon_{cs}(t,t_s)y_c / r_c^2\right] \qquad [4]$$

$$\Delta\psi_2 = \alpha\left[\varphi(t,t_s)\psi_2 + \varepsilon_{cs}(t,t_s)y_c / r_c^2\right] \qquad [5]$$

Age adjusted section properties are:

$$\alpha = I_{cr} / I_{effective} \qquad [6]$$

$$I_{cr} = bc_{tr}^3/3 + A'^{tr}_f(c_{tr} - d')^2 + A^{tr}_f(d - c_{tr})^2 \qquad [7]$$

c_{tr} values are obtained by setting the following equation to zero:

$$bc_{tr}^2/2 + A'^{tr}_f(c_{tr} - d') - A^{tr}_f(d - c_{tr}) = 0$$

$$A'^{tr}_f = \{2\eta'(t,t_s) - 1\}A'_f$$

$$A^{tr}_f = \eta'(t,t_s)A_f \qquad [8]$$

$$\eta'(t,t_s) = E_{CFRP} / E'_c(t,t_s)$$

$$E'_c(t,t_s) = 57000\sqrt{f'_c(t_s)}$$

$$f'_c(t_s) = f_c(28)\{t_s/(4 + 0.85t_s)\}$$

$$y_c = c_{tr}/2; r_c^2 = I_{cr}/A_c; A_c = bc_{tr}$$

$$I_{effective} = (M_{cr}/M_a)^3 I_{gross} + \left[1 - (M_{cr}/M_a)^3\right]I_{cr}$$

Creep calculations are as follows:

$$\varphi(t,t_s) = \varphi_0\beta_c(t,t_s)$$

$$\varphi_0 = \varphi_{RH}\beta(f_{cm})\beta(t_0)$$

$$\varphi_{RH} = 1 + \left\{(1 - RH/RH_0)/0.46(h_e/h_0)^{1/3}\right\} \qquad [9]$$

$$h_e = 2A_g/u$$

$$\beta(f_{cm}) = 5.3/(f_{cm}/f_{cmo})^{0.5}$$

$$\beta(t_0) = 1/\left\{0.1 + (t_0/t_1)^{0.2}\right\}$$

$$\beta_c(t,t_s) = \left[\{(t_s - t_0)/t_1\}/\{\beta_H + (t_s - t_0)/t_1\}\right]^{0.3}$$

$$\beta_H = 150\left[1 + (1.2RH/RH_0)^{18}\right](h_e/h_0) + 250 \le 1500$$

Shrinkage calculations are as follows:

$$\varepsilon_{cs}(t,t_s) = \varepsilon_{cso}\beta_s(t,t_s)$$

$$\varepsilon_{cso} = \varepsilon_s(f_{cm})\beta_{RH}$$

$$\varepsilon_s(f_{cm}) = 1.2\left[160 + \beta_{sc}(9 - f_{cm}/f_{cmo})\right]10^{-6} \qquad [10]$$

$$\beta_{sc} = 50 \text{ for type I cement}$$

$$\beta_{RH} = -1.55\left[1 - (RH/RH_0)^3\right]$$

Long term deflection at mid-span is provided by:

$$\Delta_l = \psi(t_s)L^2 \times 10^3/30 + \ln(t_s)(RH)0.20 \qquad [11]$$

3. COMPARISON OF DEFLECTION VALUES

Figure-1 and Table-1 summarize the results of beam B1, while Figure-2 and Table-2 summarize the results of beam B2. To accommodate common humidity ranges in this area, lower and upper values of 50% and 80% were considered. For beam B1, the proposed ratios range from 1.02 to 1.16 as compared to 2.66 to 5.97 for common models. In the case of beam B2, the proposed ratios range from 0.98 to 1.29 as compared to 2.61 to 7.55 range for other models. Figures 1 and 2 show similar conclusions.

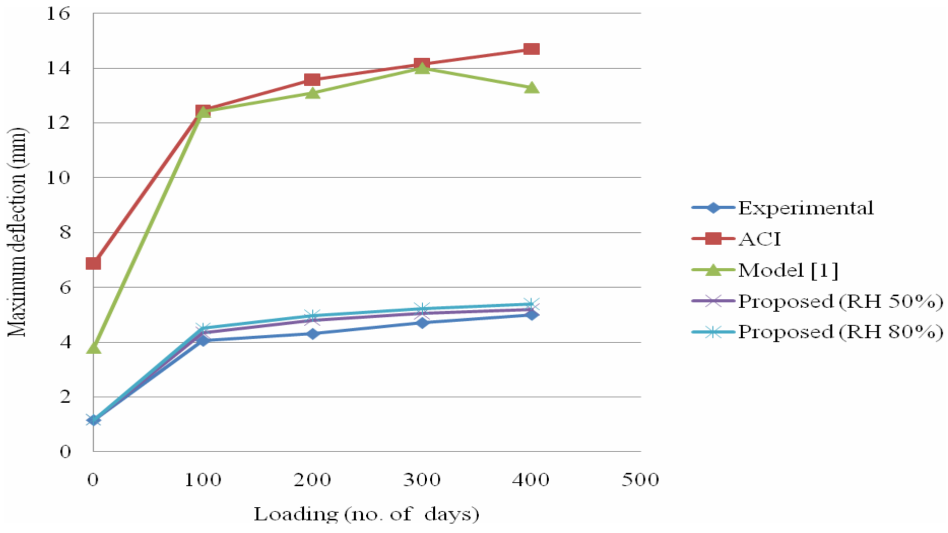

Figure-1. Graphical comparison of deflection values for beam B1.

Table-1. Comparison of deflection ratios for beam B1.

Days	Δ_{ACI}/ Δ_{Exp}	$\Delta_{Model\ [1]}$/ Δ_{Exp}	$\Delta_{Prop\ [50\%]}$/ Δ_{Exp}	$\Delta_{Prop\ [80\%]}$/ Δ_{Exp}
0	5.97	5.09	1.02	1.02
100	3.08	3.00	1.07	1.11
200	3.16	3.05	1.12	1.16
300	3.01	2.98	1.07	1.11
400	2.94	2.66	1.04	1.08

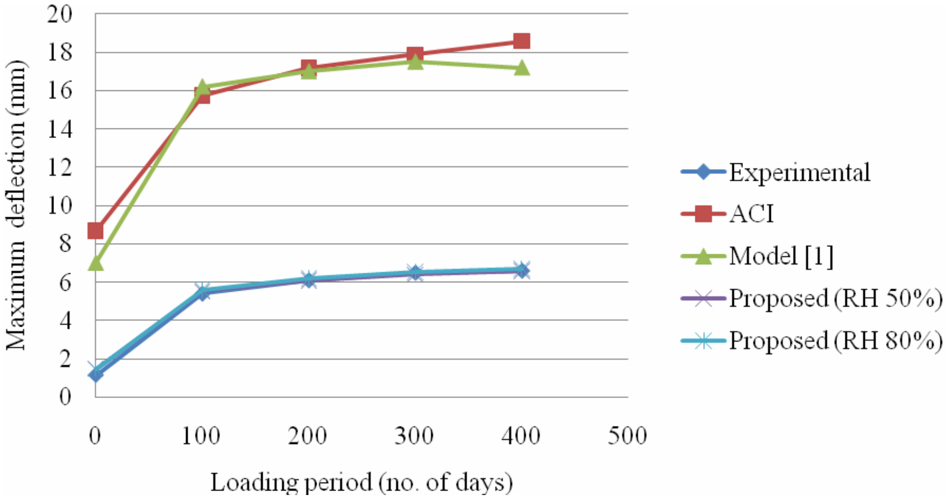

Figure-2. Graphical comparison of deflection values for beam B2.

Table-2. Comparison of deflection ratios for beam B2.

Days	Δ_{ACI}/ Δ_{Exp}	Δ Model $_{[1]}$/ Δ_{Exp}	$\Delta_{Prop\ [50\%]}$/ Δ_{Exp}	$\Delta_{Prop\ [80\%]}$/ Δ_{Exp}
0	7.55	6.43	1.29	1.29
100	2.92	3.00	1.02	1.04
200	2.81	2.79	1.00	1.02
300	2.75	2.69	0.98	1.00
400	2.82	2.61	1.00	1.02

4. CONCLUSIONS AND FUTURE WORK

In this paper an improved analytical model to predict the creep and shrinkage based deflections of CFRP reinforced flexural concrete members is presented. Deflection values are assessed with experimental data from literature, a commonly used literature model and ACI procedure. Based on this study, the following conclusions can be drawn:

- Comparison of analytical predictions with the experimental data and other models show that the proposed model correlates better with the experimental values.
- The rate of increase of deflection is higher in the initial loading period and tends to reduce with respect to long-term.

An improved analytical model to predict the creep and shrinkage based deflections of CFRP reinforced concrete members is introduced. Good agreement is observed between analytical predictions and experimental results. This model can be used as a design tool to predict the long term deflections of CFRP reinforced concrete members. However, more experimental and analytical work is needed to further validate this approach. Future research may include:

- Use of ambient atmospheric temperature and shape coefficients for different fiber reinforced polymers in the model.

Nomenclature

L	Length of beam
$M_{applied}$	Applied bending moment
$M_{cracked}$	Cracking moment
t_0	28 days (curing period of the CFRP reinforced concrete beams)
t_s	Number of days after the curing period is over
t_1	day 1
E_c	Modulus of elasticity of concrete
E_{CFRP}	Modulus of elasticity of CFRP
$E_c^{'}(t,t_s)$	Age adjusted modulus of elasticity of concrete
C_{tr}	Neutral axis depth of the age adjusted cracked section
y_c	Half of the neutral axis depth of the age adjusted cracked section
r_c^2	Radius of gyration of the age adjusted cracked section
I_{gross}	Gross moment of inertia of the section
I_{cr}	Moment of inertia of the age adjusted cracked section
$I_{effective}$	Effective moment of inertia of the age adjusted cracked section
b	Width of the section
d	Depth of the tension reinforcement from the top of the section
$d^{'}$	Depth of the compression reinforcement from the top of the section
A_g	Gross area of the cross section
u	Perimeter of the cross section
A_f	Area of tension CFRP reinforcement
$A_f^{'}$	Area of compression CFRP reinforcement
A_f^{tr}	Transformed area of the equivalent tension CFRP reinforcement
$A_f^{'tr}$	Transformed area of the equivalent compression CFRP reinforcement
A_c	Area of concrete in compression
h_0	Parameter that takes into account cross-sectional dimension at t_0
λ_1	Coefficient of instantaneous curvature
λ_2	Coefficient of long time curvature
ψ	Instantaneous curvature of bending
$\psi(t_0)$	Mean curvature at time t_0
$\psi(t_s)$	Curvature of the member at time t_s
ψ_1	Instantaneous curvature for a cracked section
ψ_2	Instantaneous curvature for an uncracked section
$\Delta\psi$	Time dependent change in curvature due to creep and shrinkage
$\Delta\psi_1$	Change in curvature for a cracked section
$\Delta\psi_2$	Change in curvature for an uncracked section
$\varphi(t,t_s)$	Time dependent creep coefficient
$\varepsilon_{cs}(t,t_s)$	Time dependent shrinkage coefficient
$\eta'(t,t_s)$	Age adjusted modular ratio
$f_c^{'}(t,t_s)$	Age adjusted mean compressive strength of concrete
ε_{cso}	Shrinkage strain for a particular concrete strength and relative humidity
$\varepsilon_s(f_{cm})$	Coefficient that accounts for 28 day concrete compressive strength
$\beta(f_{cm})$	Coefficient that accounts for 28 day concrete compressive strength
$\beta_s(t,t_s)$	Coefficient that accounts for shrinkage
$\beta_c(t,t_s)$	Coefficient that accounts for creep
β_H	Coefficient that takes into account the effect of relative humidity for creep
β_{RH}	Coefficient that takes into account the effect of relative humidity for shrinkage
β_{sc}	Coefficient that accounts for cement type
$\beta(t_0)$	Coefficient that accounts for time t_0
f_{cm}	Mean compressive strength of concrete at 28 days
f_{cmo}	10 MPa (constant value)
h_0, h_e	Parameters that takes into account cross-sectional dimension
φ_0	Basic creep coefficient
φ_{RH}	Relative humidity coefficient
α	Curvature reduction factor
RH	Relative humidity
Δ_i	Instantaneous deflection
Δ_L	Long term deflection
RH_0	100% relative humidity

REFERENCES

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[2] 2008. American Concrete Institute, Committee 209, Detroit, MI.