Performance of CFRP strengthened concrete beam subjected to cyclic temperature

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Abstract

The use of Carbon Fiber Reinforced Polymers (CFRP) for strengthening of structurally deficient reinforced concrete structures is widely gaining appeal. There are many applications in outdoor structures such as bridges. These structures are directly exposed to the environment. Epoxy adhesive used to create the bond between CFRP and concrete is very sensitive to the elevated temperature. It is important to explore the behavior of CFRP strengthened concrete structures under long term exposure to cyclic temperature because of the direct exposure of these structures even for the daily temperature fluctuations. A numerical model was developed to simulate the behavior of CFRP strengthened concrete beam subjected to four point bending. Initially, the composite beam was analysed to evaluate the short term performance and validated with experimental results. Then, the simulations were extended to determine the deterioration of load bearing capacity of the beam under long term exposure to cyclic temperature.

Keywords: CFRP, Concrete, Long term Performance, Elevated temperature, Finite element modeling

1. Introduction

Carbon Fiber Reinforced Polymer (CFRP) is a composite material, consisting of various carbon fibers and thermosetting resins. The properties of CFRP differ so much from that of their matrix material. CFRP materials are distinguished by their extremely high strength and rigidity. Low density, excellent damping properties and a high resistance to impacting combined with exactly modifiable thermal expansion to complement the complex characteristics profile. Unlike Glass Fibre reinforced Plastics (GFRP), CFRP exhibit considerably greater rigidity, sharply enhanced electrical and thermal conductivity and a lower density. Their positive characteristics (relative to the weight) mean that CFRP materials are typically used for applications in aerospace engineering (the wings of the Airbus A350), in the automotive industry, in motor racing (monocoque in formula 1), sport equipment subject to high levels of stress (bicycle frames) and high-strength and high-rigidity parts in industrial applications, such as robot arms, reinforcement and sleeves in turbo molecular pumps or drive shafts. The positive chemical resistance pays off in the case of CFRP vanes in sliding vane rotary pumps used for aggressive media. CFRP material consists of a polymer (usually duroplastics, thermoplastics) employed as a matrix material in which carbon fibres with a diameter of a few micrometers are embedded. Different processes are utilised for the manufacturer of semi-finished products and final products, depending on the geometry and requirement profile involved. These include fibre winding, autoclave pressing, board pressing, resin transfer moulding (RTM, the resin injection method) or manual laminating for individual and small series production. These applications have been proved excellent durability properties. However, the application technique and the construction method used in the Civil Engineering industry shows a slight deviation from these applications. Therefore, it is important to explore durability properties for further applications of this system in the construction industry.

2. Finite Element Analysis (FEA)

The study was focused on the behaviour of CFRP strengthened concrete beam subjected to extreme temperature cycles. A numerical model was developed using commercially available computer software (ANSYS). Verification of the model predicted results for the unconditioned beam was done by comparing with the test results available in literature (Pham and Al Mahaidi, 2005). Therefore, the selected beam details for this analysis are as the same as in Pham's study (Pham, 2005).

2.1 Beam details and Finite element idealization

The geometry and reinforcement details of the beam are shown in Figure 1. The related parameters are listed in Table 1.

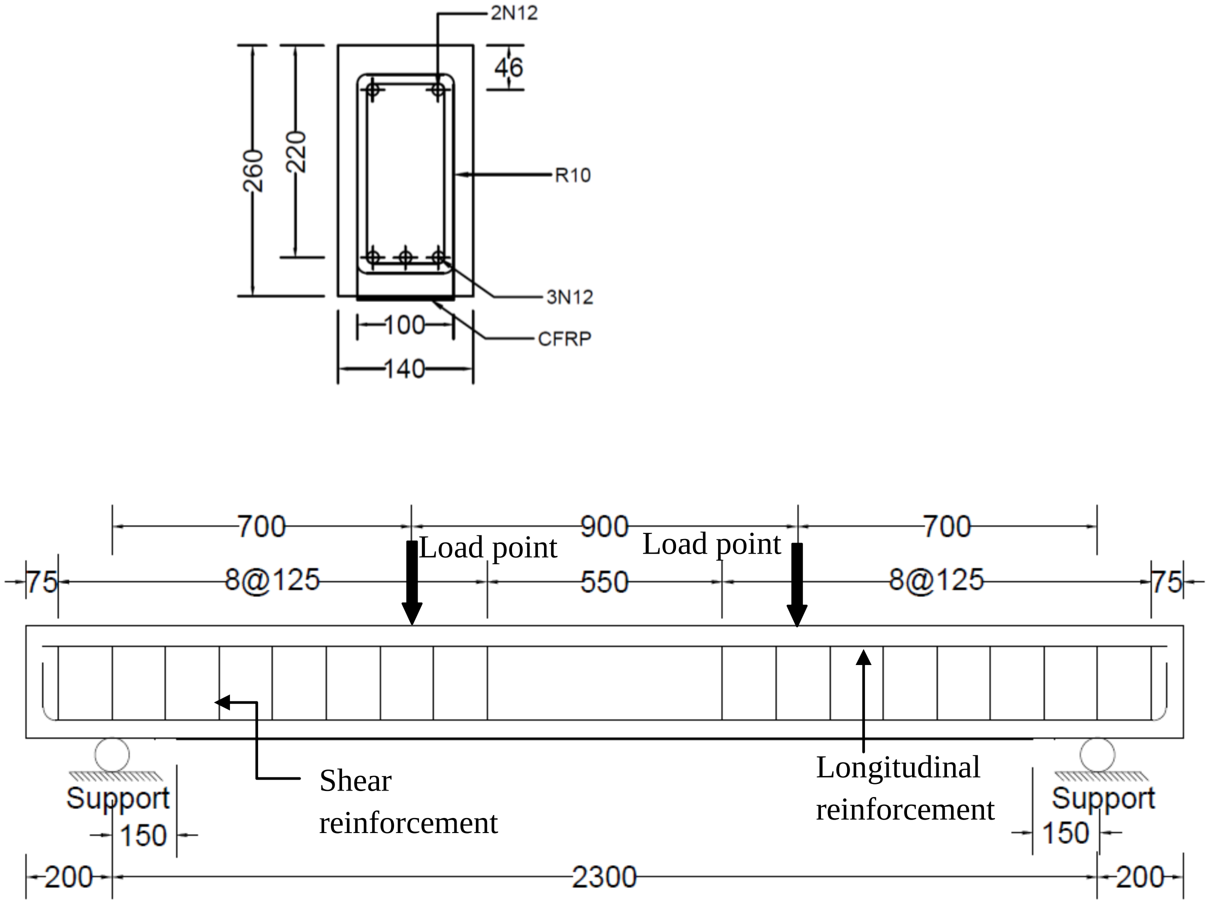

Figure 1: Dimensions of the beam (Pham, 2005)

Table 1: Variables of the beam

Label	N_s x d_b	$D_{b,sv}$ – s	Cover (mm)	t_o	L_o (mm)
E1	3 x 12	10 – 125	24	6 x 0.176	150

N_s x d_b: Number of steel tension bars x bars diameter (mm)

$D_{b,sv}$ – s : Stirrups diameter (mm) – spacing(mm)

Cover: Concrete cover to stirrup

t_o: Ply thickness (mm), L_o: Distance from end of FRP to nearest support

Finite element mesh and boundary conditions are shown in figure 2. The selected aspect ratios (length over height) range approximately around 1.0 to 1.5. Since the beam geometry, loading and boundary conditions were symmetrical about the center line, a half of the beam was modeled using ANSYS version 12.0. The model was supported vertically at the base and horizontally along the centerline with roller supports as shown in figure. An incremental loading was introduced to the beam till failure.

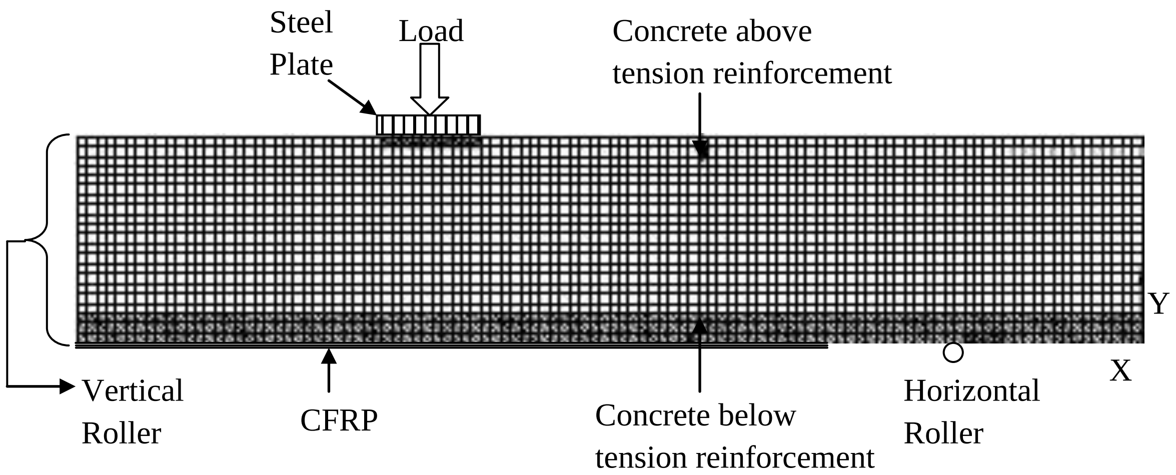

Figure 2: Two dimensional meshes of beams loaded in four point bending

The concrete was modeled using shell elements (shell 93). It is also used for Carbon Fiber Reinforce Polymer (CFRP) and Epoxy. The reinforcement was modeled using link elements (link1). This element can use to model the behaviour under uniaxial tension-compression with two degrees of freedom at each node. The non linear properties for both concrete and epoxy layer was used (Fiedler, 2005). Reinforcement details of the beam are shown in Figure 3.

All dimensions are in millimeters

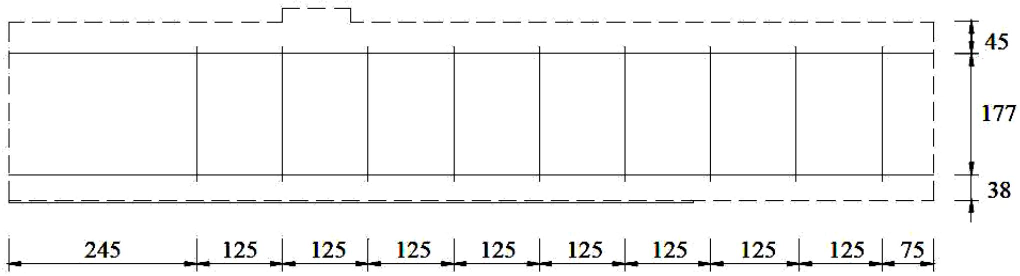

Figure 3: Reinforcement details

Anchorage failure of steel reinforcement was not observed in his research, the bonded portions of the tension bars were not modeled. The longitudinal bar locations were simplified as straights lines extending from one ends to the other end. At the longitudinal tension reinforcement level, the thickness of the concrete was reduced to account for the reduction of concrete due to presence of the bar. This was achieved by reducing the thickness of the concrete elements just below the tensile beam elements such that the concrete area lost was equivalent to the area of tension reinforcement as shown in figure 4. By doing this we have made sure that the weakest shear plane is present at just below the tension reinforcement. In this model we have assumed that the bond between epoxy and concrete is perfect but we have input the nonlinear properties to the epoxy layer as well as for the concrete layer. By doing that we were able to track the failure of the layers from stress failures. To prove the models that we have done, we checked the values of the deflections that were obtained from the practical results done by Huy Binh Pham (2005).

In the finite element models, 20 mm thick steel plate, modeled using shell 93, were added at the load location. There were assumed both the steel plate element and concrete elements around the load points and support have linear elastic properties.

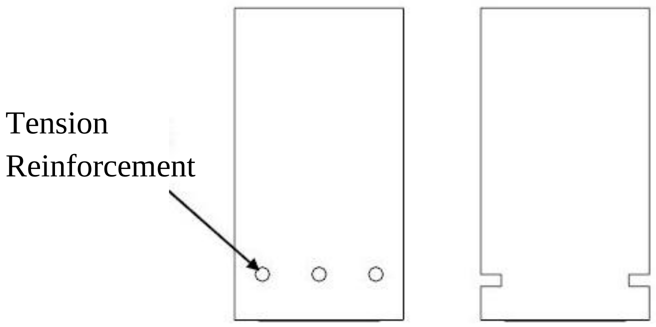

Figure 4: Reduced concrete width (Pham and Al-Mahaidhi, 2005)

2.2 Material properties

Concrete properties were selected in a similar manner as those used in modeling of shear laps specimens. The properties adopted are shown in below table.

Table 2: Properties of concrete

Property	Value
Elastic modulus (kN/m^2)	29400000
Poisson's ratio	0.2
Grade	30

The main flexural and shear steel reinforcements in the finite element models were assumed to be an isotropic linear elastic material up until the yield point. The module and yield stresses are summarized in below table. The steel plates were assumed to be linear elastic material. Poisson's ratio was taken as 0.25.

Table 3: Properties of steel

Bar type	Elastic modulus (kN/m^2)
Main flexural reinforcement(12 mm)	205000000
Shear reinforcement (10 mm)	204000000
Shear reinforcement	238000000
Steel plate	200000000

Epoxy adhesive used to create the bond between CFRP and steel was modeled with following properties:

Table 4: Properties of epoxy layer

Property	CFRP
Elastic modulus(kN/m^2)	8500000
Poisson's ratio	0.3
Maximum tensile stress	3500 kN/m^2

The interface strength reduction properties of conditioned CFRP/concrete composites were obtained from research data by Gamage (2008). Their test program was based on small scale concrete blocks strengthened with CFRP and conditioned in the environmental chamber before testing for failure. The modeling was done in ATENA/GID interface and had found the deteriorated interface properties and validations were made with experimental results. In this study, these deteriorations of interfaces are introduced to the numerical model and the behaviour of strengthened beam subjected to temperature cycles was simulated. Further, the validation was done with unconditioned beam testing done by Pham and Mahaidhi (2005).

3. Model results and validations

Initially, the behaviour of unconditioned beam strengthened with CFRP was simulated. This study showed the failure load as 75.99kN and maximum deflection was observed as 9.975 mm. Pham (2005) test results and FEA results showed similar failure loads ((70.7 kN, 76 kN experiments),(75.99 kN FEA) and deflections for this beam. Therefore, the model accuracy was confirmed. The strain distribution on CFRP sheet along the bond length at different load levels is shown in Figure 5. The deflection of beam with applied loading is shown in Figure 6.

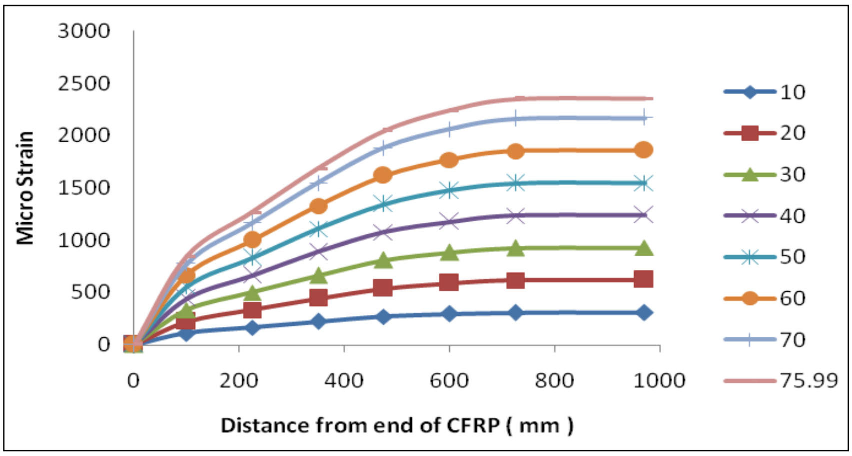

Figure 5: CFRP strain distributions along the bond length

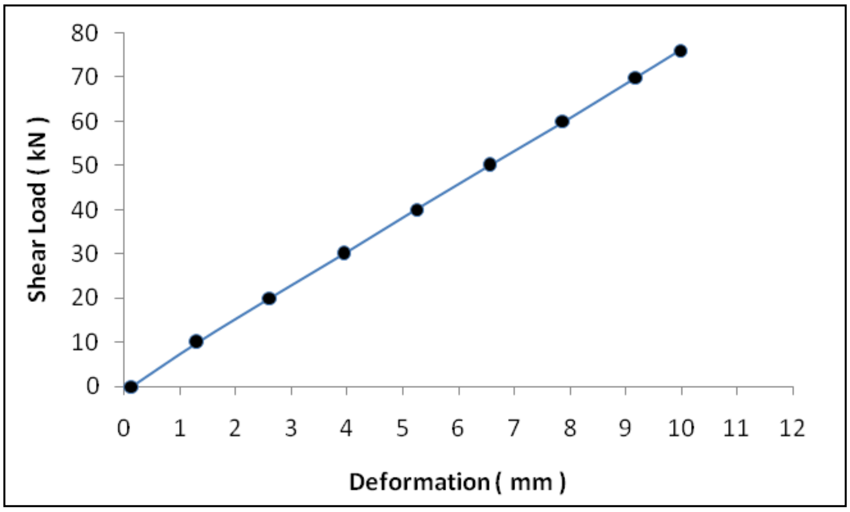

Figure 6: Load deflection curve

After verifying the accuracy of the model, simulations were carried out to determine the long term performance of the Carbon Fiber Reinforced Polymer (CFRP) strengthened concrete beam.

4. Behaviour of conditioned beams

The conditioning period was 3 months. The composite was simultaneously exposed to 60% humidity, 20oC – 50oC temperature cycles (600 cycles within 3 months) and sustained loading. Beams C-1, C-2 and C-3 were subjected to no sustained loading, 25% and 35% loading respectively. At the end of exposure period, the beams were tested at room temperature (Gamage, 2008). This study shows the degree of interface deterioration when the system subjected to this studied exposure condition. The simulations were further carried out to determine the behaviour of CFRP strengthened beam considering the interface deterioration found in this experimental study.

According to the non linear finite element analysis done for the beam C-1 failure load was obtained as 26.5 kN and it is a reduction of 65.13% compared to the control beam. Maximum deflection obtained was 3.282 mm and it is also a value reduced by 67.1% compared to the control beam maximum deflection. Load deflection curve for beam C-1 is in Figure 7.

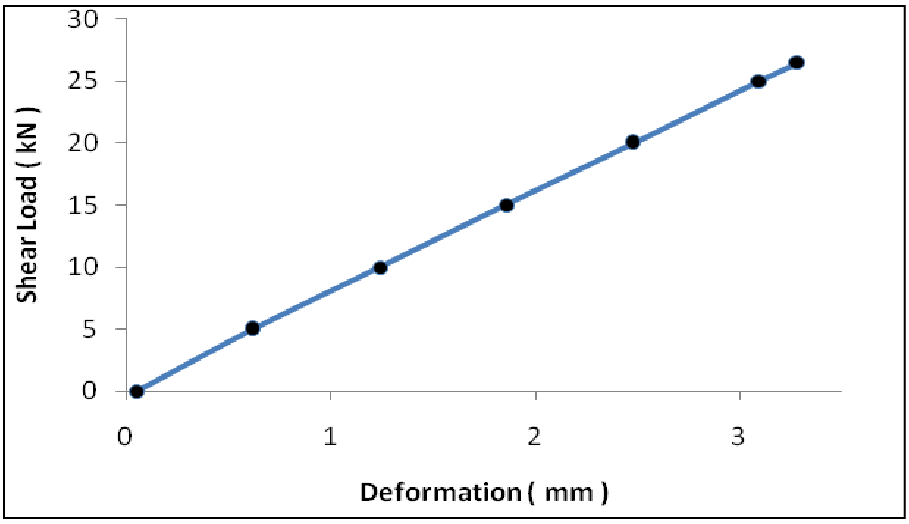

Figure 7: Shear load Vs Deformation of Beam C-1

According to the analysis the maximum micro strain obtained in the CFRP layer was 772.69 at the middle of the beam which is 970 mm away from the end of the CFRP sheet. That value is a reduction of 67.20% compared to the maximum strain obtained for the control beam and the Strain distributions are shown in figure 8.

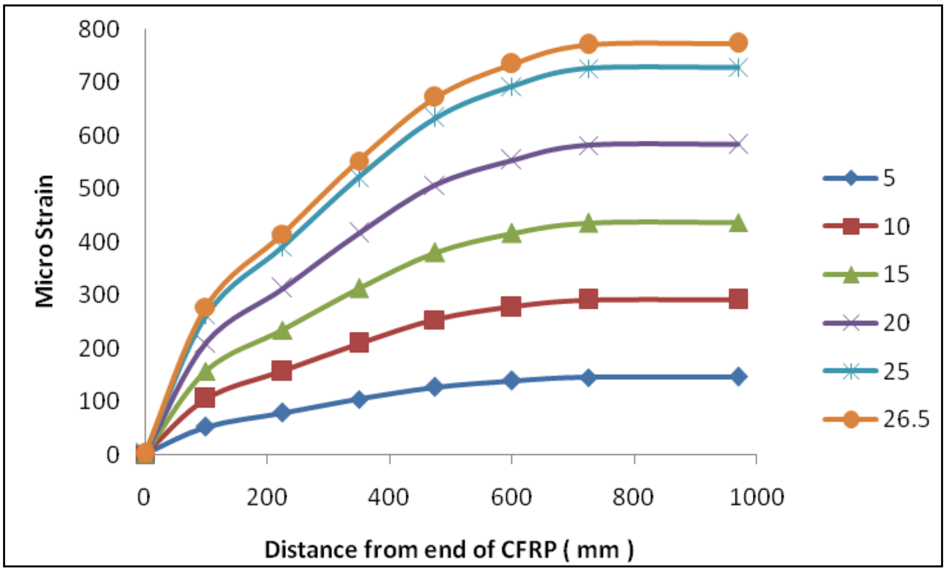

Figure 8: CFRP Strain distribution in Beam C-1

The beam C-2 and C-3 showed the failure loads as 26.39 kN, 26.74 kN respectively. The average reduction of the failure load is 64%. Maximum deflection obtained from the analysis is 3.355 mm, 3.318 mm for C-2 and C-3 respectively and it is an average reduction of 66% compared to the maximum deflection obtained in the control beam. Maximum CFRP micro strain (970 mm from end of CFRP) was obtained in the beam as 790.96 and it is a value which is a reduction of 66.42% compared to control beam maximum CFRP Strain (970 mm from end of CFRP) along the CFRP sheet.

The summary of numerical results is listed in Table 5.

Table 5: Summary of numerical results

Beam	Maximum Deflection (mm)	Failure load (kN)	Maximum Micro strain (970 mm from end of CFRP)
C-1	3.282	26.5	772.69
C-2	3.355	26.99	790.96
C-3	3.318	26.74	781.65

Table 6: Results comparison

Beam	Reduction Compared to Control Beam %		
	Maximum Deflection (mm)	Failure load (kN)	Maximum Strain (970 mm from end of CFRP)
C-1	67.10	65.13	67.20
C-2	66.37	64.48	66.42
C-3	66.74	64.81	66.82

5. Conclusions

Endurance of CFRP strengthened concrete members is one of the most important characteristics in its operating environment. But this factor is mainly influenced by environmental factors like humidity and temperature. Other important thing is it should be able to withstand for the mechanical stresses on it with the variance of these environment conditions. Therefore evaluation of the system for these effects simultaneously is one of the main requirements for the modern world.

On average, 64% reduction in failure loads when compare with the short term strength were observed for these conditioned beams. However, it is important to develop a probabilistic model to convert the period of acceleration to equivalent life span of the member. In this regards, more experimental and numerical investigations for this system subjected to similar conditioning are required.

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