FE MODELING OF CFRP STRENGTHENED CONCRETE BEAM EXPOSED TO CYCLIC TEMPERATURE, HUMIDITY AND SUSTAINED LOADING

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Abstract: Need for strengthening of civil engineering structures has been growing in recent times due to many reasons such as improper design, increased loading and environmental deterioration. Use of Carbon Fiber Reinforced Polymers (CFRP) has become a most promising and affordable solution for strengthening of structures due to their superior properties. The major challenge of this composite application in outdoor structures is the long term durability of the bond between CFRP sheet and the concrete substrate. Therefore, the understanding of performance of this system in different service conditions is very important.

A finite element model was developed to simulate the behaviour of CFRP strengthened concrete beams. The short term and long term behavior of a composite member was predicted and validated with experimental results. The results showed that the bond between CFRP and concrete is sensitive to the environmental conditions, such as temperature and humidity fluctuations.

Keywords: CFRP, Concrete, Durability, Humidity, Finite Element Modeling

1. Introduction

CFRP (Carbon Fiber Reinforced Polymer) 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, that a relationship is barely discernible any more. 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 manufacture 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.

With successful applications in Aerospace and Automobile industry, Civil Engineers drove this technology towards the construction industry successfully. The adhesive being used in the construction industry has different properties and also application procedure is completely different to the adhesive and process used in Aerospace and Automobile industries. Therefore, it is important to explore the short term and long term performance of strengthened members. Majority of research has been focused on short term behaviour and design guidelines have also been developed. However, the service behaviour of these members is still not fully explained. This paper presents the approach to simulate the bond behaviour when the composite is exposed to humidity and temperature fluctuations.

2. Test Program

The test program conducted by Pham (2005) was selected to verify the simulations presented in this paper. In his study, two experimental programs were carried out to investigate the behaviour of reinforced concrete (RC) beams retrofitted with CFRP fabrics using a wet layup method. The aim of the test program was to study the failure mechanisms and the influence of a number of parameters on bond performance. A total of eighteen RC beams were tested under four point bending. In this test program, two of them were unstrengthened control beams and sixteen were retrofitted with CFRP fabrics. The variables of the beams were the CFRP bond length, CFRP thicknesses, steel tension reinforcement amount, concrete cover and stirrups spacing. To simulate the behaviour under service, the beam named as E1 was selected. The geometrical properties and reinforcement details are illustrated in Table 1 and Figure 1.

Table 1: Variables of the beam

Label	Reinforcements	Stirrups	Cover (mm)	CFRP thickness (mm)
E1	3 T 12	10 R @ 125	24	0.176

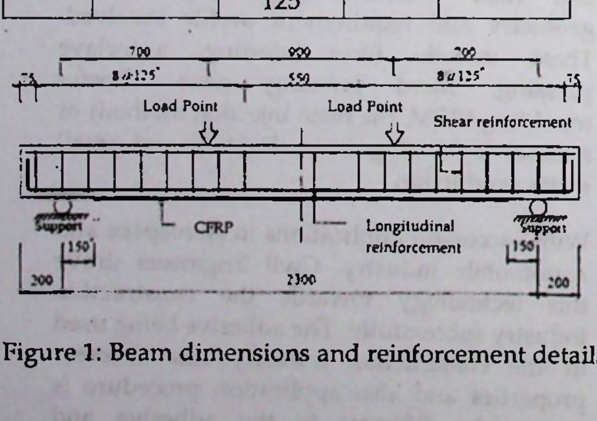
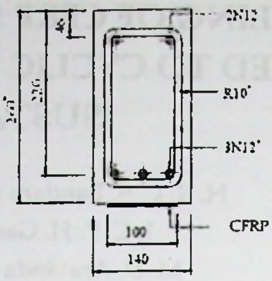


Figure 1: Beam dimensions and reinforcement details



A two dimensional (2D) model was developed to simulate the behaviour of CFRP strengthened concrete members. Since the beam geometry, loading and boundary conditions were symmetrical about the center line, only 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 the Figure 2. Loading was applied to nodes as defined on the steel plate on the top of the beam. The aspect ratios (length over height) of elements were selected in the range approximately around 1.0 to 1.5. The concrete, epoxy and CFRP sheet were modeled using shell elements (shell 93). The type 93 is uniaxial tension-compression element with two degrees of freedom at each node. In the model we have entered the non linear properties for both concrete and epoxy in accordance with BS8110 and epoxy properties were also included. The reinforcements were modeled using line elements.

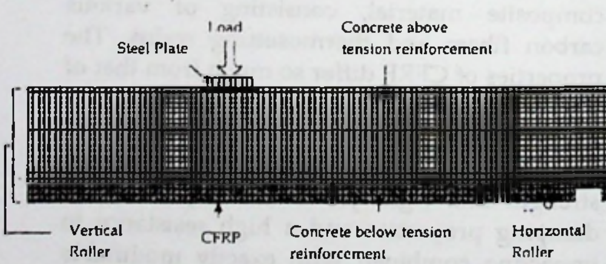


Figure 2: Finite Element Mesh

In the finite element model, a 20 mm thick steel plate, modeled using shell 93 element type, were added at the load location. It was assumed that both the steel plate and concrete elements around the load points and support have linear elastic properties. The material properties used for modeling the concrete substrate is listed in Table 2.

Table 2: Properties of concrete

Property	Value
Elastic modulus (kN/m²)	29400000
Poisson's ratio	0.2

The main flexural and shear steel reinforcements in the finite element models were assumed to be an isotropic linear elastic material until the yield point. The module and yield stresses are summarized in Table 3. The steel plates were assumed to be linear elastic material. The Poisson's ratio of steel was taken as 0.25.

Table 3: Steel properties

Bar type	Elastic modulus (kN/m²)
Main flexural reinforcement (12 mm)	205000000
Shear reinforcement (10 mm)	204000000
Shear reinforcement	238000000
Steel plate	200000000

Properties listed in Table 4 were used to model the CFRP sheet.

Table 4: Properties of CFRP

Property	CFRP
Elastic modulus(kN/m²)	8500000
Poisson's ratio	0.3
Maximum tensile stress	3500 kN/m²

Initially, the model was analysed to simulate the short term performance of the system. The model predicted behaviour of the composite was validated with FE and test results in literature (Pham 2005). In general, environmental testing is not economical. Long term performance of the bond between CFRP and concrete was studied by Gamage (2008) using small scale CFRP strengthened concrete specimens. The deterioration of interface properties was determined for different exposure conditions as shown in Table 5. The main objective of this finite element modeling was to determine the long term performance of CFRP strengthened concrete beam. The properties listed in Table 5 was introduced to the interface between CFRP and concrete to simulate the performance of CFRP strengthened concrete beam in service when exposed to the exposure conditions listed in Table 5.

Table 5: Properties at interface between CFRP and concrete

Beam	Sustained Loading	Interface		
		F_c (kN/m²)	Tensile strength (kN/m²)	Elastic modulus (kN/m²)
20-50C cyclic temperature, 90%constant humidity				
B-2	25%e	25000	2265	36095000
20-50C cyclic temperature, 60%constant humidity				
C-2	25%	31500	2617	26165058
20-50C cyclic temperature, 60%constant humidity				
D-2	25%	25000	2265	14194181

4. Model Results and Validations

The test and FE results of Pham (2005) showed the failure load as 70.7 kN and 76 kN respectively. The current FE results showed the failure load of 75.99 kN as shown in Figure 3 for identical specimens, that lies within the same range showing accuracy of the numerical model.

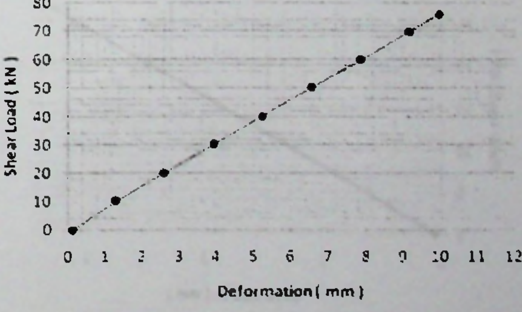


Figure 3: Shear load Vs Deformation of Beam E-1

According to the non linear finite element analysis done for the unstrengthened beam, it was found that the failure load of the beam is

66.56 kN. The latter for the strengthened beam was 75.99 kN. This shows a 14.16% increment of failure load for CFRP strengthened beam.

The peak load observed from the beam notated as B - 2 was 19.00 kN. This is a reduction of 75% compared to the control beam. This indicates severe bond deterioration when the system exposed to extreme environmental cycles while subjected to 25% of sustained loading. Maximum deflection of the beam was obtained as 2.355 mm and it is a reduction of 76.39% compared to control beam. The relationship between the load and deflection is shown in Figure 4.

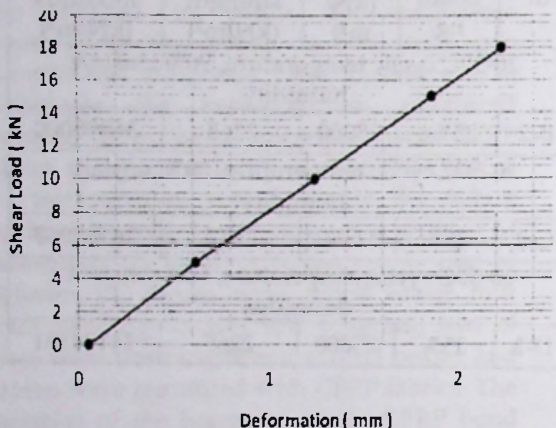


Figure 4: Shear load Vs Deformation of Beam B-2

The model predicted failure load for beam C - 2 is 26.99 kN and the maximum deflection was 3.355 mm. Load deflection curve is shown in Figure 5.

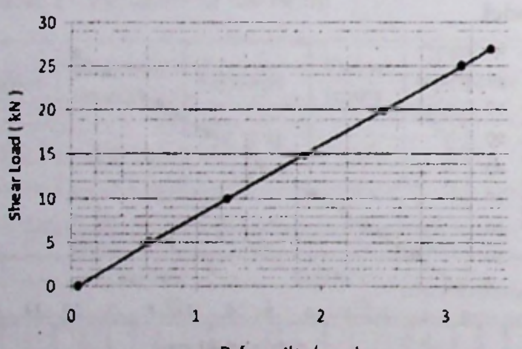


Figure 5: Shear load Vs Deformation of Beam C-2

The simulations of beam notated as D-2 showed the failure load of 38.74 kN. It is a 49.02% of reduction when compared to the control beam. Maximum deflection of this beam was obtained at the failure load as 4.831 mm and compared to control beam, it is a reduction of 51.57% and the load deflection curve obtained for beam D-2 is in Figure 6.

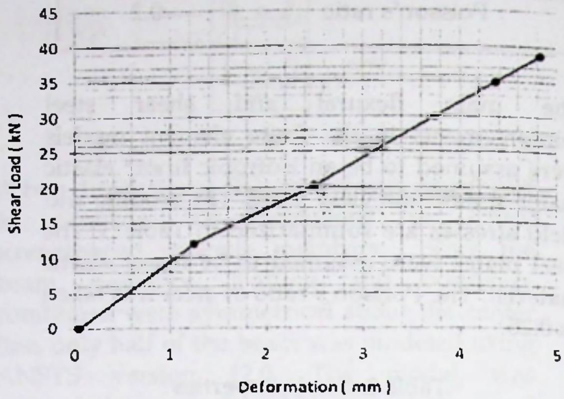


Figure 6: Shear load Vs Deformation of Beam D-2

5. Conclusions

Endurance of CFRP strengthened concrete members under its operating environment is one of the most important characteristics for structural elements. However, the study showed that the behaviour of composites is mainly influenced by the environmental factors such as humidity and temperature. Other important characteristic is to be able to withstand mechanical stresses that are acting on it with the variance of these environmental conditions. Therefore evaluation of the system performance for these effects simultaneously is one of the main requirements before recommending them.

When the system is exposed to severe environmental conditions, a 75% reduction in load bearing capacity was observed. However, this environmental condition is unlikely in Sri Lanka when compared with past weather data. In the range of normal exposure, the system showed a reduction in load bearing capacity between 64% and 49%. Therefore, it is important to introduce a strength reduction factor for service conditions for designing of CFRP strengthened concrete members.

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