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Experimental Study and Numerical Modelling on Flexural and Shear Strengthening of RC Beam with Prestressed FRP Bars

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Abstract: The most prevalent and widely used building material in the world is reinforced concrete. The primary building material for the majority of constructions, including buildings, bridges, etc., is reinforced concrete. Because of various factors, some of these buildings or portions of them are failing to perform as designed. The best solution to increase the load carrying capacity and extend the useful life of these inadequate structures is to strengthen them because replacing them would need significant investments and not be an appealing alternative. Even though the effectiveness of other techniques is widely accepted,a new effective and promising technique of strengthening civil engineering structures externally is gaining popularity, where fibre-reinforced polymer (FRP) is used. One of the most popular strengthening methods recently is the use of carbon fibre reinforced polymer (CFRP) to strengthen reinforced concrete beams. It provides a desirable way to improve the shear and flexural strengths of RC beams. The manner in which these composites are bonded to the beam has a significant impact on the behaviour of reinforced concrete beams in shear and flexure. The purpose of this study was to present a three-dimensional nonlinear finite element analysis (FEA) of a reinforced concrete beam (RC beam) reinforced by prestressed carbon fibre plate (CFRP plate). While there are many commercial programmes available for three-dimensional nonlinear FEA, each one has a unique ability to represent complex behaviour of composite materials, such as RC beams strengthened with prestressed CFRP plate and the contact interaction. Because of its reputation for accuracy in simulating the behaviour of a range of materials, including concrete, and its potent contact algorithms, the ABAQUS finite element programme was chosen for this work. Steel reinforcements were modelled as elastic- perfectly plastic materials, while concrete was studied using the concrete damage plasticity (CDP) constitutive model. The CFRP plate was modelled as an entirely elastic substance that breaks under the highest tensile strain. Concrete and steel reinforcement were considered to have a perfect connection, and the behaviour of concrete and CFRP plate was represented using a contact model. The FEA's findings were verified against experiment findings that were published in the literature. In terms of load-deflection behaviour, crack patterns, and mode of failure, the results were compared. The proposed FEA model was able to accurately simulate the behaviour of RC beams strengthened with prestressed CFRP plate based on the validation. To find out the impact of the thickness, width, and length of the CFRP plate, as well as the prestressing levels and steel grades, a parametric research was done. In particular, the strength of the RC beam for the ultimate load was shown to be increased by increasing prestressing of the CFRP plate. However, as prestressing increased, the fracture of the CFRP plate altered the mechanism of failure, preventing the ultimate load from increasing further. The use of higher grade steel improved the ability to support additional weight. Although the general load carrying capability of the CFRP plate was increased by lengthening the plate, it was discovered that strengthening RC beams by 25% of their shear span was sufficient and cost- effective. The load-deflection curve, failure modes, and crack patterns from the experiments are fairly reflected in the FE model.

I. INTRODUCTION

Due to its high strength, low cost, and ease of production, reinforced concrete (RC) is a material that is frequently used in construction. Buildings, bridges, and other large constructions. However, environmental assault, excessive traffic, and earthquakes cause RC members to deteriorate. To reverse this degradation, a variety of rehabilitation treatments using various materials are available. To improve flexural performance, one of these methods involves attaching high tensile strength fibre reinforced polymer (FRP) materials to the tensile face of the RC beam.

FRP composites have gained popularity as desirable retrofitting materials due to their low density, high tensile strength, corrosion resistance, and portability. The flexural and shear performance of RC members are developed using FRP materials.

There are numerous varieties of FRP materials, including glass fibre reinforced polymer (GFRP), aramid fibre reinforced polymer (AFRP), and carbon fibre reinforced polymer (CFRP). CFRP offers the highest tensile strength, highest elastic modulus, and best fatigue performance of any FRP materials. As one of the most popular materials used in the world's infrastructure it is important that cement displays exceptional strength and durability because its failure results in high financial costs and the potential loss of millions of lives. To this end several efforts to improve its properties have been and continue to be studied and implemented. The use of fiber reinforcements is one such mean the types of reinforcements currently used include steel, glass cellulose and carbon fibers. The fibers are used individually or in combination.

Investigation of the behaviour of FRP retrofitted reinforced concrete structures has in the last decade become a very important research field. In terms of experimental application several studies were performed to study the behaviour of retrofitted beams and how various parameters influence the behaviour. The effect of number of layers of CFRP on the behaviour of a strengthened RC beam was investigated [Aghaei, H.R. (2008)].They tested simply supported beams with different numbers of CFRP layers. The specimens were subjected to dead load and horizontal forces. The results showed that the load carrying capacity increases with an increased number of layers of carbon fibre sheets. The model of RC building shown in plan was developed in ANSYS software.

In this method the cross section is subdivided in to small sub-elements, the deflections are considered constant within each sub-element. The deflections at each sub-element can be traced clearly and hence the gradual spread of yielding can be predicted. The plastic zone method eliminates the need for separate member capacity check, hence this method accepted to provide exact solution. constructions due to structural deficiency, material deterioration, unlooked-for over loadings or physical damage. Premature material deterioration will arise from variety of causes, the foremost common being once the development specifications are profaned or once the ability is exposed to harsher service setting than those expected throughout the design and style stages. Physical damage may also arise from fireplace, explosion – as well as from restraints, each internal and external, against structural movement. Except in extreme cases, most of the structures need restoration to satisfy its purposeful necessities by acceptable repair techniques.

II. LITERATURE

The FRP laminate in the RC beams is fastened to the concrete with adhesive. The transfer of load from concrete to the FRP laminate depends critically on the bond between the two materials (Diab & Wu, 2007). Because the strength and stiffness of adhesive materials (bonding) directly affect how adhesive they are, it is important to understand their qualities. Due to the materials' organic behaviour, the bonding between the FRP plates and RC members is categorised as anisotropic. As an example, the anisotropic behaviour of FRP results from differences in the longitudinal behaviour, which is dominated by the fibres, and the transverse behaviour, which is under the control of the resin (Cosenza et al., 1997). Epoxies and viny ester are just a couple of the adhesives that can be used between the RC concrete and CFRP laminate. Bond failure is defined as the loss of the bonding materials; section 3.5 will describe a variety of failure types. There have been numerous studies done to look into FRP laminate delamination from concrete members. Based on the duration of the prestressing, there are two different ways to apply it. Pretension is the term used to describe the first prestressing procedure, which involves introducing the prestressing force before any contact between concrete and FRP or steel. One type of prestressing is the attachment of FRP plates to concrete elements as external reinforcement for prestressing (Hajihashemi et al., 2011). The second method, prestressing of internal reinforcement, uses embedded reinforcement but has the same fundamental concepts as the previous one (Lou et al., 2016). The second form of prestressing is known as posttensioning. After casting concrete, this method of stressing may be employed with both FRP and steel reinforcements, and it would increase the structure's total load carrying capacity (Ma et al., 2016). Failure Modes of RC Strengthened with FRP Laminate. To investigate the durability characterizations of the interfacial bond between concrete and FRP sheet, Toutanji and Gomez (1997) tested fifty-one RC beams under four-point bending. Numerous factors were investigated, including various FRP sheet kinds, extreme weather conditions, and epoxy systems. In comparison to wet/dry circumstances, it was found that using different types of FRP (carbon and glass) greatly enhanced flexural performance in dry and normal settings. Debonding of the FRP sheet was the only failure mode, and choosing the right epoxy kinds was crucial, particularly in wet/dry conditions. To examine the flexure response of RC beams strengthened by prestressing CFRP plate, Yang et al. (2009) conducted an experimental research as well as a 3D finite-element (FE) analysis using DIANA. Pretressing levels (0%–60%), anchorage systems, bonding and non- bonding of FRP plates, and span length were also examined. The performance of RC beams enhanced by prestressed CFRP plate was found to be unaffected by bonding. Additionally, bonded CFRP plate-strengthened RC beams without anchorage systems exhibit less ductility. The outcomes of 3D FE shown good agreement with experimental findings.

Externally bonded FRP sheets can effectively improve the shear strength and ductility of beam column joints but the magnitude of effectiveness depends how the sheets were attached to joints and whether mechanical anchorage was used or not. The effect of two different schemes of rehabilitation was studied in upgrading the joint. In the first scheme, CFRP sheets were epoxy bonded to the joint, beams, and part of the column regions. In the second scheme, however, sheets were epoxy bonded to the joint region only but they were effectively prevented against any possible de-bonding through mechanical anchorages. It was observed that Scheme 1 is an efficient scheme because it upgrades both the joint and the beam. However, due to the absence of any mechanical anchorages in this scheme, at higher stages of loading de-bonding bulging of externally bonded CFRP sheets occurred, which allowed cracks to form and widen under the fibre sheets. Scheme 2 is an economical and effective scheme for joint strengthening, as in this scheme CFRP sheets were applied in such a way that the possibility of de-bonding is eliminated. Moreover, this scheme makes the joint so strong that failure is directed to the beams. The effectiveness of the two above-mentioned schemes of strengthening was also examined through shear distortion hysteretic curves and it was observed that externally bonded CFRP sheets make the joint stiffer against distortion. The results of the present study infer that, for field applications, it is very much necessary to decide judiciously and carefully which scheme is suitable for strengthening a deteriorated or deficient beam-column joint. This is because strengthening of a joint and its adjacent members with CFRP sheets at one place can substantially improve the shear strength and ductility of the joint but at the same time it may also shift the failure mode from the joint to the adjacent member e.g., beam or column or vice versa.

A review of some significant experimental investigations conducted using steel plates is presented to demonstrate some of the structural implications of external plating. Research work into the performance of members strengthened with steel plates was pioneered simultaneously in South Africa and France in the 1960s. Continued development of suitable adhesive and the increased use of the technique in practice stimulated further research work [ACI Committee 440 (1996)].

The effect of widening the plate whilst maintaining its cross-sectional area constant was studied. It was found that the plated as-cast and the pre-cracked beams gave similar load/deflection curves, demonstrating the effectiveness of external plating for strengthening purposes [Chalioris, C.E.(2007a)].

III. OBJECTIVE OF THE STUDY

The development of FE models that accurately represent the behaviour of RC beams strengthened with various levels of CFRP plate prestressing is the main goal of this study. The particular goals of this study include:

1) Develop a FE model to depict the flexural behaviour of the prestressed CFRP-plate- enhanced RC beams.
2) Validate the FE models using experimental results.
3) Execute a parametric research to examine the impact of the level of prestressing, the steel's strength, and the parameters of the CFRP plate, including its length, width, and depth.

IV. DEVELOPMENT OF FEM

Due to its effectiveness and respectable accuracy in studying concrete's structural behaviour under various loading circumstances, finite element (FE) modelling has been widely used. Even though experiment tests are the most accurate, there are a few disadvantages to them, including the difficulty of implementing some loading and boundary conditions, the lengthy preparation and testing period, and the high cost. The ABAQUS FE package was chosen because of its capacity to model the assembly of these components using cutting- edge interfacial models between concrete and CFRP plate as well as simulate various concrete, steel, and CFRP components.

The model development processes are discussed in this chapter. This covers the geometry of the beam, the material properties of each component, the boundary condition, the choice of the element, the mesh, the contact modelling between the parts, and the application of prestressed force.The characteristics of the materials were covered in detail. The characteristics of the concrete material were described in depth since it displayed complex nonlinear behaviour that changed between compression and tension stresses. Additionally, in order to appropriately depict the delamination process at the contacting nodes, some interfacial characteristics are needed at the contact between the CFRP plate and the concrete.

V. METHODOLOGY

A. Boundary Condition

Boundary conditions and loading used for modeling the prestressed CFRP plate with concrete are shown in Figure 3.18.

For boundary conditions, in the experimental test, a simply supported beam were tested. Also, based of the symmetric configuration of the tested beam, only half of the beam was modeled. Therefore, to model the support conditions located at 150 mm from the ends of the beam as shown in Figure 3.16, displacement was restricted in directions X and Y, and represented by $U2 = U3 = 0$. On the other hand, the symmetry boundary condition was applied at the symmetry line located at 1650 mm as shown in Figure 3.16. They included the restriction of the movement in horizontal axis (directions Z), and the rotation about out of planes axis (direction X, and Y) represented by $U3 = 0$, $UR1 = 0$, and $UR2 = 0$ respectively. For loading, displacement-controlled loading was applied. To illustrate, a specific value of displacement was applied in the middle of the beam, this value was 90 mm to simulate three bending tests. To model these loading, allowable displacement was set to 90 mm in vertical axis (direction Y), $U2 = -90\ mm$ and was located at 1650 mm

B. Comparison Between Flexure and Shear Strength Results of Prestressed Frp

The flexural and shear strength of controlled RC beam is reported as 40.50 MPa and 55.70 MPa which further increases to 70.90 MPaand 84.17 MPa for RC beam with 30% prestressed CFRP plate. The strength of RC beam increases with the CFRP plate. The prestressing of CFRP plate enhances further the flexural as well as the shear strength of RC beam. The experimental results of flexureand shear strength of RC beam with CFRP plate and with Prestressing 5%, 20% and 30% is mentioned below

Specimen	Flexural trength(MPa)	Shear Strength (kN)	Percentage of increase in Flexural Strength (%)	Percentage of increase in Shear Strength (%)
Controlled RC beam	40.50	55.70	-	-
RC beam strengthened with CFRP plate	55.25	69.41	36.42	24.61
RC beam strengthened with prestressed CFRP plate (5%)	59.62	75.94	47.21	36.34
RC beam strengthened with prestressed CFRP plate (20%)	67.38	80.65	66.37	44.79
strengthenedwith d CFRP plate(30%)	70.90	84.17	75.06	51.11

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VI. CONCLUSION

The proposed FE model was created and validated based on experimental behaviour. Some conclusions can be made as follows.

1) In addition to the model of failure, the proposed models were assessed based on the behaviour of load deflection under load and the patterns of cracks. The yield and ultimate loads were dramatically increased when RC beams were strengthened with CFRP plate, both with and without prestressing.
2) For the yield load, the percentages of difference between FE and experimental data for controlled RC beam, RC beam strengthened with standard CFRP plate, prestressed 5% CFRP plate, 20% CFRP plate, and 30% CFRP plate, respectively,were 14.8%, 15.1%, 12.5%, 13.85%, and 10.03%.
3) For the ultimate load, the experimental and FE results for the controlled RC beam, RC beam strengthened with ordinary CFRP plate, prestressed 5% CFRP plate, 20% CFRP plate, and 30% CFRP plate, respectively, differed by 0.34%, 8.68%, 9.47%, 7.82%, and 8.25%.
4) The optimum flexural and shear strength of 70.90 MPa and 84.17 Kn is obtained with the RC beam strengthened with 30% prestressed CFRP plate.
5) Displacement-controlled loading was able to represent the flexural behaviour of the RC beam strengthened with prestressed CFRP plate.

6) Increasing prestressing level showed a significant influence only on the ultimate load.

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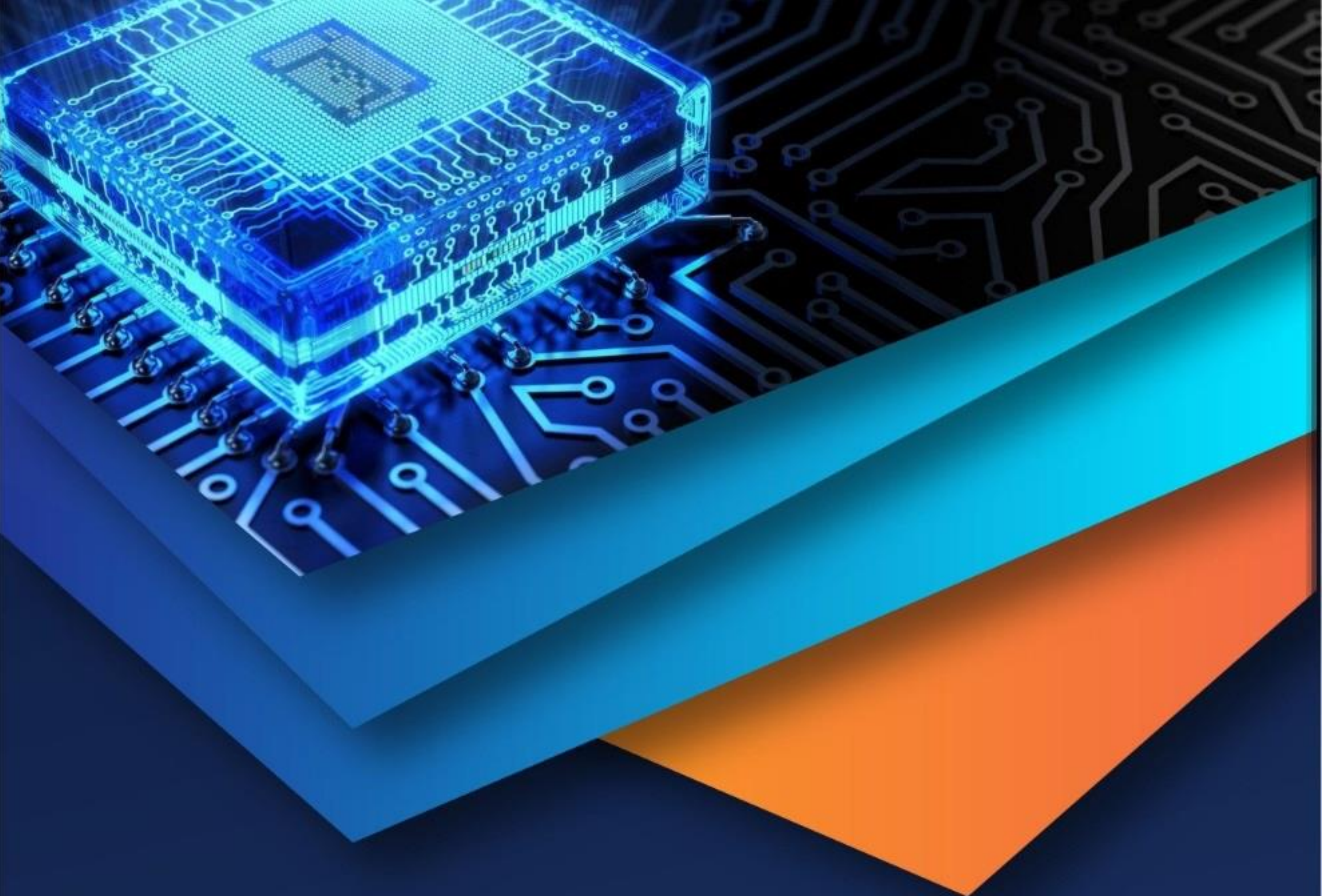

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