Ultimate strength analysis of CFRP confined concrete using finite element method (FEM)

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Abstract. This paper presents a comparison with experimental data of CFRP confined concrete column damage. The study investigates the behaviour of CFRP confined concrete beams against the experimental results. It also investigates the influence of different parameters on the behaviour of the FRP confined concrete column. The ABAQUS code was used to develop finite element models for simulation of the damage behaviour of the beams. The concrete was modelled using a plastic-damage model which is a perfect bond model and were evaluated for the concrete-FRP confinement interface. The results showed that when the thickness of carbon-fibre reinforced plastics (CFRP) proportional to the load capacity of the beam for both shear and compressive strength. The maximum load increases with an incremental of CFRP thickness. From the simulation results, the load-deflection relationships have been analysed and the FEM results agreed well with the experiments data. Finally, the study shows that the differences between the results of finite element analysis and experimental tests are in an acceptable range.

1. Introduction

Fibre reinforced plastics (FRP) is one of the most used strengthening techniques to reinforced concrete beams due to advantages, such as high strength to self-weight ratio, high tensile strength, large fatigue resistance capacity and high durability, [1-2]. Carbon and glass Fibre reinforced plastics (CFRP and GFRP) composites offer the solution to enhance shear and flexural capacities and ductility, as well as improve the mode of rupture, [3-4].

Study of the behaviour of CFRP reinforced concrete structures has become a very important. In terms of experimental application, several studies were performed to study the behaviour of retrofitted
beams and how various parameters can influence its behaviour [5-6]. While experimental methods of investigation are very useful in obtaining collapse behaviour of FRP and reinforced concrete. The use of numerical models helps in developing a good understanding of the behaviour at lower costs, [7].

In this research, nonlinear finite element analysis models for strengthening of reinforced concrete beams with carbon fibre reinforced plastics (CFRP) have been presented. The collapse behaviour in shear and flexure of reinforced concrete beams strengthened with carbon Fibre reinforced plastics (CFRP) is highly affected by the way in which these composites are applied (bonded) to the beam, [3,4,6].

The influence of some important parameters on the overall response of the strengthened RC beams has been investigated in order to achieve the optimum utilization of such strengthening technique in terms of load capacity and possible deflection values. The research investigate nonlinear finite element models of reinforced concrete beams externally strengthened with carbon Fibre reinforced plastics (CFRP) using the finite element modelling software (ABAQUS). Finally, validate the finite element models by comparing with experimental tests available in the literature.

2. Characterizations Of Material

Experimental data was obtained from previous research[8] and the parameter setting for beam modelling have been set as follows:

| Particular               | Parameter                        |
|--------------------------|----------------------------------|
| High × Width × Length    | 300 mm × 150 mm × 1960 mm        |
| Tension Reinforced       | 12 mm × 2                        |
| Compression Reinforced   | 10 mm × 2                        |
| Shear Reinforced         | 8 mm / 100 mm                    |

2.1 Mechanical Properties of Material

There are three types of material such as concrete, steel and cfrp that had been modeled using Abaqus. Concrete is composed of coarse aggregate, fine aggregate, cement and water. CFRP materials generally have much higher strength than the yield strength of steel [9]. The CFRP materials are not homogeneous and their properties are dependent on many factors. Below are the mechanical properties that have been applied for finite element analysis:

| Particular            | Concrete  | Steel    | CFRP      |
|-----------------------|-----------|----------|-----------|
| Mass Density, ρ       | 2400 kg/m³| 7800 kg/m³| 1600 kg/m³|
| Young’s Modulus, E    | 25084 MPa | 205000 MPa| 165000 MPa|
| Poisson’s Ratio, ν     | 0.15      | 0.3      | 0.25      |
3. Methodology

ABAQUS software was employed to model and simulate damage collapse of the CFRP beam columns. Finite element analysis looking at load–deflection curves of retrofitted beams and control beams. The result from a control beam will be validated by comparing with experimental results. The analysis of linear finite element simulation output results will be compared with all cases and the control beam.

3.1 Finite Element Modeling (FEM)

Finite element failure analysis was performed to model the nonlinear behaviour of the beams. The FEM package Abaqus/standard was used for the analysis. There are also numbers of study have been done by many researchers using Finite Element Analysis (FEA) software to predict and validate material behaviour. Concrete is modelled using a solid eight-node element, [10]. The elastic response of concrete is considered linear by referring to Hooke’s Law:

\[ \{\sigma\} = [E]\{\varepsilon\} \]  

(1)

Where \( \{\sigma\} \) is the stress tensor, \([E]\) is the constitutive matrix of elasticity, \( \{\varepsilon\} \) is the strain tensor and superscript ‘e’ indicates elastic strain.

ABAQUS is allowing user to specify a method of analysis to be applied. Concrete Damaged Plasticity is one of the common method to be used in analysing elastic concrete behaviour. The stress-strain relations under uni-axial tension and compression are taken into account according to equations below [11]:

\[ \sigma_t = (1 - d_t) \cdot E_0 \cdot (\varepsilon_t - \varepsilon_t^{pl}) \]  

(2)

\[ \sigma_c = (1 - d_c) \cdot E_0 \cdot (\varepsilon_c - \varepsilon_c^{pl}) \]

Where \( \sigma_t \) = stress in tension, \( \sigma_c \) = stress in compression, \( \varepsilon_t \) = strain in tension, \( \varepsilon_c \) = strain in compression, \( E_0 \) = Initial (Undamaged) elastic stiffness, \( \varepsilon_t^{pl} \) = plastic strain in tension, \( \varepsilon_c^{pl} \) = plastic strain in compression.

The 4-Node linear tetrahedral elements method were used for the reinforced concrete, steel reinforcement and also CFRP in this model. The element configuration is shown in Figure 1 and Figure 2. The Node 3-D cohesive elements were used to model the interface layer. To show the effect of the bond model and the behaviour of CFRP, five combinations of bond model and CFRP model were analyses by using the orthotropic material model. One quarter of the beam was modelled and a fine mesh with 3 mm size is set to obtain results of sufficient accuracy [12]. Sample of elements applied in the numerical analysis by using ABAQUS are as follows:

Figure 1. 4-node linear tetrahedral element.  
Figure 2. 8-node 3-D cohesive element.
A trust element was used to model steel reinforcement. CFRP composites can be modelled either using isotropic linear elastic model or orthotropic linear elastic model, [13]. In this study, the properties of the CFRP composites were nearly the same in any direction perpendicular to the fibres. Orthotropic linear elastic model for CFRP composites was used throughout this study.

Normally, the two parameters needed to describe the elastic behaviour of concrete are the Poisson’s ratio and the modulus of elasticity. The Poisson’s ratio of concrete under uniaxial tension and compressive stress ranges from 0.15 to 0.22. For this study, a value of 0.15 for concrete was adopted to perform the finite element analysis.

4. Result and Discussion

In this section, the load–deflection curves obtained for control beam and retrofitted beams from experiments and finite element analysis will be shown and discussed. For control beam, the comparison of FEA and experimental result for Load-Deflection Curve can be shown in Figure 4. From the result and graph below (figure 3), there is good agreement between FEM and experimental results for the control beam. The FEM analysis predicts the beam to be slightly stiffer and stronger, probably because of the assumed perfect bond between concrete and reinforcement. The good agreement indicates that the constitutive models used for concrete and reinforcement can capture the fracture behaviour well.

![Figure 3. Load-Deflection Comparison.](image)

When comparing all the results, it can be seen that the thickness of the CFRP significantly influences the behaviour of the beam. The thicker CFRP, the higher is the maximum load. The perfect bond models increasingly overestimate the stiffness of the beam. This is due to the fact that the perfect bond does not take the shear strain between the concrete and CFRP into consideration. This shear strain increases when cracks appear and causes the beam to become less stiff.

The maximum load for 1mm and 2mm thickness of CFRP before break are 228,143 N and 252,395 N. For 3mm and 4mm thicknesses, the maximum load before break are 260,470 N and 264,790 N. Lastly, the highest maximum load is 267,664 N and it is for 5mm of CFRP thickness.

5. Discussion and Conclusion

A finite element method was used to analyses the beams retrofitted with CFRP. Elastic orthotropic behaviours were used to represent the CFRP behaviour. A cohesive model was used to address the interfacial behaviour between CFRP and concrete. The following conclusions can be drawn from this study:
The behaviour of the retrofitted beams is significantly influenced by the thickness of CFRP. This characteristic show in the experimental results as well as in simulation analysis. The ultimate load is found proportional with the thickness of the CFRP. It shows a good agreement compared [8] to the experimental of a full scale beam column.

Finite element models using ABAQUS were successfully verified comparing with previously published experimental test results. Therefore, ABAQUS can be confidently used in analysis of RC Beams externally strengthened with Carbon Fiber Reinforced Plastics (CFRP) lamination. However, the finite element analysis show that the concrete beam slightly stiffer than the test data.

Finally, environmental factors that may affect the efficiency of RC beams strengthened with CFRP as seasonal temperature variation, creep, and shrinkage were not considered. The effect of these parameters during the beam life span can be studied.

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