FAILURE MODE ANALYSES OF FIBRE REINFORCED POLYMER PLATED REINFORCED CONCRETE BEAMS

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Abstract

Externally-bonded fibre reinforced polymers are now routinely used for increasing the strength of a concrete beam in flexure and this method is very popular for the repair of structures. Nevertheless, this type of reinforcement may cause a premature and brittle failure such as plate end interfacial debonding or concrete cover separation. This paper is concerned with the failure by concrete cover separation; in other words by peeling-off. This mode involves the tearing-off of the concrete cover along the level of tension steel reinforcement starting from a plate end. In this paper, experimental work and numerical analyses of four types of reinforced concrete beams have been carried out. A nonlinear finite element analysis using the commercial program ABAQUS was carried out to predict ultimate loading capacity and the failure mode of RC beams in a four-point bending setup. A series of 4 RC beams strengthened with FRP sheets at the bottom were tested to failure under a four-point bending load. By comparing numerical results with experimental ones, the proposed finite element model has been validated and can be used for further prediction of this type of failure.

Keywords: Concrete cover separation, experimental, finite element, numerical, peeling-off, strengthening

1. Introduction

The flexural strength of a reinforced concrete beam can be increased by bonding a fibre-reinforced polymer sheet or a steel plate to the tension face. The advantage of strengthening by bonding is that it increases the life of reinforced structures and that can limit the stress concentrations in comparison to the assembly by bolting. Nowadays FRP sheets are used more than the steel plates because of numerous advantages such as minimum increases in structural size and weight, high strength-to-weight ratio, ease of site handling and excellent corrosion resistance. A large number of researches show that FRP-plated RC beams may fail by one of these failure modes: a) flexural failure by FRP rupture, b) flexural failure by crushing of compressive concrete, c) shear failure, d) concrete cover separation (also referred
as peeling-off), e) plate end interfacial debonding and f) intermediate crack induced interfacial debonding. Among these failure modes, the first three are roughly the same as those in conventional RC beams while the others are known as premature failures because they prevent the strengthened RC beams from attaining their ultimate flexural capacity; furthermore, these types of failure are brittle and unique to beams bonded with a soffit plate. Figure 1 shows the failure modes of a FRP/steel strengthened reinforced concrete beam.

![Figure 1: Failure modes of a FRP/steel strengthened reinforced concrete beam](image)

Literature review of current attempts to explain the premature plate debonding mechanism shows that the researchers have established some experimental rules to prevent premature failures, for example for strengthening concrete beams with steel plates, it's recommended that the ratio of the plate width to thickness is above 60 [1]. The researchers have also developed some theoretical models to predict the premature failures of reinforced concrete beams or plates strengthened in flexure by gluing steel/FRP plates to their tension sides [2-4]. Among these models, it's easy to distinguish three categories of strength models, namely shear capacity based models, concrete tooth models and interfacial stress based models [5-9]. Although there is a large number of experimental and numerical researches on the fibre-reinforced polymer (FRP) strengthening of concrete structures, a full understanding of the premature failures are somewhat lacking. In other words, a primary technique for analyzing strengthened RC beams has yet to be agreed upon.

This work is concerned with the failure by concrete cover separation which is far more common than plate end interfacial debonding. The first step for a successful, safe and economic design of flexural strengthening using FRP composite is then the prediction of such failure. In this paper, a 3D finite element model using the commercial program; ABAQUS, is presented for the simulation of concrete cover separation failures. Numerical simulation of a peeling-off problem is a highly nonlinear problem with material nonlinearities and large displacements. Numerical analyses are performed to predict the behavior and ultimate load-carrying capacity of RC beams strengthened by FRP applied at the bottom of them. As a part of the present study, experiments were performed on strengthened RC beams to investigate the behavior and to determine the ultimate failure load. 15 RC beams were tested up to failure in a four-point bending set-up. Comparisons between the predictions of the numerical model and test results show a very good agreement. The details of the numerical and experimental work and their results are discussed in following sections.

2. Experimental work

The test specimens consisted of 15 RC beams classified into 5 groups according to the different characteristics namely width and height of the beam and thickness of external reinforcement (FRP sheet). Among these beams, 1 group was not strengthened and used as reference specimens and 4 groups were strengthened externally with carbon FRP composite
strips glued with epoxy adhesive to the tension face of the RC specimens. In each group the beams have the same characteristics in order to have reproducible tests. All the beams were 1200 mm long and they were designed in a way that the failure mode would be peeling-off. They were internally reinforced in flexure with two bars of 6 mm diameter on the bottom side of the beam. Shear reinforcement for the beams consisted of FRP composite plates glued to the sides of the beams in the shear span. Beams geometry are shown in Table 1 where a, t, d, Φ, b_p and t_p denote the width and depth of RC beam, distance from beam tension face to the centre of steel tension reinforcement, diameter of tension steel reinforcement, FRP width and FRP thickness.

Table 1: Characteristics of concrete beams

<table>
<thead>
<tr>
<th>Group No</th>
<th>No</th>
<th>a (mm)</th>
<th>t (mm)</th>
<th>d (mm)</th>
<th>f'_c [MPa]</th>
<th>f'_t [MPa]</th>
<th>Φ (mm)</th>
<th>t_p (mm)</th>
<th>b_p (mm)</th>
<th>F_{rup} (kN)</th>
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<tr>
<td>1</td>
<td>1.2.3</td>
<td>100</td>
<td>150</td>
<td>24</td>
<td>45.0</td>
<td>3.1</td>
<td>Φ6</td>
<td>1.2</td>
<td>100</td>
<td>50.1</td>
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<td>2</td>
<td>4.5.6</td>
<td>100</td>
<td>150</td>
<td>24</td>
<td>42.3</td>
<td>2.7</td>
<td>Φ6</td>
<td>0.6</td>
<td>100</td>
<td>48.8</td>
</tr>
<tr>
<td>3</td>
<td>7.8.9</td>
<td>100</td>
<td>150</td>
<td>24</td>
<td>42.6</td>
<td>2.4</td>
<td>Φ6</td>
<td>-----</td>
<td>-----</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>10.11.12</td>
<td>70</td>
<td>105</td>
<td>24</td>
<td>37.5</td>
<td>2.7</td>
<td>Φ6</td>
<td>1.2</td>
<td>70</td>
<td>26.3</td>
</tr>
<tr>
<td>5</td>
<td>13.14.15</td>
<td>80</td>
<td>120</td>
<td>24</td>
<td>37.5</td>
<td>2.7</td>
<td>Φ6</td>
<td>0.6</td>
<td>80</td>
<td>29.8</td>
</tr>
</tbody>
</table>

Specimens were simply supported and tested under four-point bending with a net span of 1.0 m and a pure flexural span of 0.4 m. Compression and Brazilian tests were carried out in order to define the compressive and tensile strength of concrete beams. All the beams were loaded up to complete failure. Test setup including beam geometry and reinforcement as well as the loading and support arrangement before and after the failure are illustrated in Figure 2. The load-deflection curves of all beams are presented in the fourth section of this paper.

![Figure 2: test setup before and after failure](image)

3. Numerical study

It has been always difficult to develop a definitive technique for analyzing reinforced concrete which is the most used composite materials in construction. For many structural materials such as steel and aluminium which have well-defined constitutive properties, the finite
element method works very well but when the constitutive behavior is not so straightforward like concrete in which discrete cracking occurs, the task is more difficult. The objective of this part of the study is to establish a reliable, convenient and accurate methodology for analyzing FRP strengthened RC beams which can correctly represent global beam behavior and accurately predict stress and strain distribution through the thickness of beams. The numerical analysis consists of a three dimensional-nonlinear finite element analysis by the means of the commercial FE program ABAQUS.

3.1 Geometry and hypotheses of numerical model

The numerical analysis herein is a three dimensional-nonlinear finite element analysis of the experimental set-up by the means of the commercial FE program ABAQUS. Figure 3 shows a typical three-dimensional model containing the geometry, boundary conditions, the load and the mesh used in this study. Double symmetry of load and geometry were used to model just a quarter of the beams and appropriate boundary conditions are imposed. The geometrical nonlinearity is taken into account in calculus. Full bond is assumed between FRP and concrete. It's also assumed that there is no slip between the steel reinforcement and the concrete. The mesh is more refined in the area susceptible to peeling-off and also in the vicinity of steel bars and it's coarser in other areas. The concrete and the steel bars are modelled using twenty-node solid elements with quadratic approximation of displacements. Eight-node shell elements with six transitional degrees of freedom per node with quadratic approximation of displacements are used to simulate the behavior of FRP sheets.

![Figure 3: FRP Strengthened RC beams: geometry, boundary conditions and loads, mesh](image)

3.2 Material properties and constitutive models

3.2.1 Concrete

The quasi-brittle behavior of concrete is very difficult to model because of many parameters like concrete heterogeneity, different behavior of concrete in traction and compression, randomly distributed microcracks and etc. Describing the mechanical behavior of concrete is presented today in many ways like discrete or smeared crack approaches, plasticity, damaged plasticity and fracture mechanics [4,10,11].

Concrete in compression: It is known that under multiaxial compression, concrete behaves like a ductile material and can flow on the yield or failure surface before reaching its crushing strains [12] and thus one of the commonly used constitutive models for concrete is an elastic-plastic material by using a yield function [13,14] but it's important to notice the fact that at local level, the mechanisms involved in this case corresponds to the microcracking. The material model for concrete is developed within the framework of the theory of plasticity, in detail; the Drucker-Prager yield function formulated in stress space with associated flow is adopted. An important advantage of this approach is its robustness and the facility of calculation convergence. Classically, the stress field can be expressed by two components: hydrostatic pressure (p) and Mises equivalent stress (q), the expression of these components are defined in Eq. (1) and (2) where \( \sigma_i \) is a component of stress in the general stress tensor. These two stresses define the elastic and plastic domains in p-q plane.
The yield criterion is represented by $F_{DP}$ in Eq. 3 in the p-q plane, which demarcates the stress states that cause elastic and plastic deformation. In this model, the yield surface is defined by two material parameters: the internal angle of friction of the material ($\varphi$) and the cohesion ($d$).

We have calibrated the parameters of this model by means of compression and Brazilian tests: $\varphi=69.2^\circ$ and $d=2$ MPa. The elastic mechanical properties of concrete are: $E=37$ GPa, $\nu=0.2$.

**Tensile behavior of concrete:** In design of concrete sections with steel bars, the concrete tensile strength is often neglected but it is naturally expected that the reinforcement could have a great effect on tension stiffening and on the development of deflections. Tension Stiffening in reinforced concrete represents the capacity of the concrete to carry the tensile forces after the crack and it’s due to the development of tensile stresses in the concrete between the neighboring cracks. Therefore, it is better to use the constitutive models including tension-stiffening for concrete especially in FRP-plated RC beams. There exist a large number of models for representing this effect. Figure 4 shows some of concrete tension stiffening models [11,15]. In order to model the behavior of concrete in tension, researches have adopted two main approaches: the first one consists of the full modeling of constitutive law and the second one is based on the use of fracture energy. In the present study the second approach which has more advantages than the first one is taken into account to determine the total failure of concrete beams by peeling-off.

![Figure 4: Tension-stiffening law for concrete in tension](image)

In Figure 4 the hatched area ($g_f$) shows the fracture energy in mode I ($G_I$) per unit width of crack. The fracture energy of concrete $G_f$ is the energy required for a tensile crack of unit area to propagate. According to the model code of CEB-FIP [16] in the absence of empirical values $G_f$ can be estimated from Eq. 4:

$$G_f = G_{f0} \left( \frac{f_c}{10} \right)^{0.7}$$

where $f_c$ is the compressive strength of concrete (MPa) and $G_{f0}$ is the base value of fracture energy and it depends on the maximum aggregate size of concrete. In the tests presented before, the maximum aggregate size was equal to 16 mm, thus $G_{f0}=0.03$ and $G_{f0}=0.08$ N.mm/mm².

### 3.2.2 Steel reinforcing bar and Fibre-reinforced plastics

The most commonly used model for steel reinforcement is the linearly elastic-perfectly plastic type. A uniaxial stress-strain relationship is sufficient for the constitutive model of steel
reinforcement because it is generally assumed that the steel reinforcement transmits force axially. The mechanical properties of steel are as follows: $E = 200$ GPa, $\sigma_e = 500$ Mpa, $\nu = 0.3$. The behavior of the FRP laminates is considered as elastic linear up to failure. Mechanical properties of FRP shear reinforcements and flexural FRP reinforcements are evaluated as follows: $E_L=160$ GPa, $E_T$, $E_N=6$ GPa, $G_{LT}$, $G_{LN}=4$ GPa, $G_{TN}=2.4$ GPa; $E_L=120$ GPa, $E_T$, $E_N=8$ GPa, $G_{LT}$, $G_{LN}=4.5$ GPa, $G_{TN}=3.2$ GPa.

4. Results and discussions

The numerical and experimental results in the following sections are presented in terms of the ultimate load carrying capacities, modes of failure and deformational characteristics of the beams when using the presented model. Figure 5 shows the load-deflection curve of the control beams. As seen in this figure the numerical curve shows the ductile flexural failure as in test control beams. We've calibrated the parameters of Drucker-Prager criterion by using the experimental data of reference beams.

![Figure 5: Experimental and numerical load-deflection curves of control beams](image)

According to numerical results all strengthened RC beams failed by peeling-off as seen in Figure 6 which is in consistent with experimental results (Figure 2).

![Figure 6: Failure by concrete cover separation](image)

Figure 7 shows numerical and experimental load-deflection relationships of strengthened RC beams. As seen there is a very good agreement between numerical and experimental results in terms of the ultimate load carrying capacities and modes of failure. It's easy to distinguish 3 phases in load-deflection curves. Initially, the displacement increases almost linearly with the load, the slopes of curves are similar and Young's modulus has its greatest value. In addition, micro-cracks exist in the aggregate-mortar interface but they are controlled by friction. In the second stage, the cracks propagate and steel bars take the traction and we notice here the non-linearity and irreversibility in beam property. Furthermore, the displacement increases faster than load which means a drop in Young's modulus in other words, a reduction in the beam stiffness. At third level, there is less increase in load because of steel yielding and at last there is the total failure of the beam which is explosive and brittle.

Table 2 refers to the numerical results based on the proposed model. In this table, the ratio of the numerical-to-experimental load capacity and deflection is given for each beam group. The maximum error in the prediction of failure load is equal to 14.1% which is surely acceptable.
for concrete simulation. The maximum error in deflection is 17.9% which may be due to the overestimation of concrete strength in traction after the formation of cracks. The average numerical-to-experimental load and deflection ratios and failure modes indicate the validation of the proposed model which can be used widely for the prediction of concrete cover separation failure.

Table 2: Comparison between the numerical and Experimental results

<table>
<thead>
<tr>
<th>Group</th>
<th>No.</th>
<th>Failure deflection (mm)</th>
<th>Failure load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1, 2, 3</td>
<td>4.46</td>
<td>3.66</td>
</tr>
<tr>
<td>2</td>
<td>4, 5, 6</td>
<td>5.92</td>
<td>5.35</td>
</tr>
<tr>
<td>4</td>
<td>10, 11, 12</td>
<td>7.61</td>
<td>7.22</td>
</tr>
<tr>
<td>5</td>
<td>13, 14, 15</td>
<td>7.15</td>
<td>6.41</td>
</tr>
</tbody>
</table>

5. Conclusions

The work presented here focuses on the study of concrete cover separation failure in FRP strengthened RC beams. Test results of 12 RC beams with external FRP laminates and 3 control beams (non-strengthened) in 4-point bending set-up have been presented. The scatter in the test results was small, indicating a good quality control and repeatability of the experiments. A 3D nonlinear numerical model using the finite element commercial package; ABAQUS, has been developed to predict the flexural load capacity of beams. Based on the work described in this paper, the following conclusions are drawn:

- All strengthened beams exhibited a higher load capacity and a lower ductility compared with their respective control beams (Figure 7a, b vs. Figure 5)
- The failure mode of all strengthened beams was peeling-off which is brittle and explosive.
- The more thick the FRP sheets are, the higher is the stiffness of the beam but the lower is the load capacity of the beam regarding concrete cover separation failure.
The nonlinear 3D FEA model proposed herein provides researchers and designers a computational tool for design of FRP strengthened beams. Through FEA modeling, the failure location, the failure mode and the maximum improvement in strength due to the configuration of FRP layers can be obtained. Thus, with the proposed FEA modeling, it is possible to do trial and error to find an effective and reasonable retrofit scheme.

References


