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# Bond–slip behaviour of FRP-reinforced concrete beams

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## HIGHLIGHTS

- Experimental study of flexural and bond–slip behaviour of FRP concrete beams.
- Bond–slip behaviour is detected under standard beam test rather than pull-out test.
- Numerical modelling of the flexural and bond–slip behaviour using new elements.
- Further validation of the recently developed elements by the experimental results.
- Parametric study to investigate the structural behaviours with varying parameters.

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## ABSTRACT

Flexural and bond–slip behaviour of fibre reinforced polymer (FRP)-reinforced concrete beams are investigated experimentally and numerically in this paper. Four-point bending tests are carried out to study the flexural and bond–slip behaviour of FRP-reinforced concrete beams reinforced with carbon FRP, glass FRP, and basalt FRP rebars with different surface conditions. The flexural and bond–slip behaviours of the test beams are also studied numerically by employing the recently developed finite element models with and without bond–slip effect. The results obtained from the numerical modelling agree very well with those obtained from experimental studies. Parametric study is carried out to investigate the effects of different rebar surfaces and rebar types on the structural behaviour of the FRP-reinforced concrete beams.



## 1. Introduction

In recent years, fibre reinforced polymers (FRPs) have been increasingly used as substitutes for traditional steel reinforcements in reinforced concrete structures due to their superior material properties, such as high tensile strength, cost-effective fabrication and excellent electrochemical corrosion resistance. However, FRP reinforcing bars (rebars) are elastic brittle and comparatively weak in bonding with the concrete, and thus the study of the structural behaviour of FRP reinforced concrete structures especially the bond–slip effect has attracted great interest.

To date, many experimental tests have been conducted to investigate the flexural behaviour of FRP-reinforced concrete beams [1–7], and the flexural capacities of concrete beams reinforced with FRP bars and comparisons of the structural performance of these beams with that of conventional steel-reinforced concrete beams have been well documented. However, bonding between FRP reinforcing bars and the surrounding concrete, which is known to play an essential role in transferring the stress from the concrete to the reinforcing bars, still needs extensive investigation. Bond–slip has a significant effect on the structural behaviour of FRP-reinforced concrete structures due to the weaker bond characteristics between FRP rebars and concrete comparing with the conventional steel rebars.

So far, pull-out test has been the most common method used for examining bond–slip between FRP rebars and concrete, and some methods for calibrating the parameters of the local bond–slip relationship have been proposed based on the results from pull-out tests [8–14]. However, the higher ultimate bond stresses and greater slips at the loaded and free ends are usually observed in pull-out tests, giving upper bond values for the bond–slip performance of FRP rebars. This is attributed to the absence of flexural cracks in the concrete and the splitting of the concrete being avoided by the thickness of concrete cover and the confining action of the reaction plate on the pull-out specimens [8]. Thus, a pull-out test does not reflect the actual condition of reinforcements in reinforced concrete members under bending [15].

It is generally believed that a beam test under a bending load can realistically report the bond performance of reinforcing bars in concrete. In contrast to the pull-out test, in the beam test, as the concrete surrounding the reinforcing bars is under tension,

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cracking of the concrete may take place under a lower stress level, thereby resulting in a reduction in the bond strength. Nevertheless, very few experimental studies on the bond–slip behaviour of FRP rebars in concrete using the beam test have been reported. In one such study conducted by Tighiouart et al. [16], the test specimens consisted of two rectangular blocks of reinforced concrete joined at the top by a steel ball joint and at the bottom by the reinforcement, with only one part of the reinforcement anchored in each block while the remaining part was isolated from the concrete. In Ehsani et al.'s study [17], each beam specimen contained two bars and was applied with a state of stress similar to that in a concrete beam. In addition, the beam test was conducted on a prismatic concrete specimen embedded with a reinforcing bar in the centre in Pecce et al.'s study [18], and the testing arrangement was a modification of the standard beam test. Although these beam tests closely simulated the conditions of reinforcements in concrete beams under bending and produced better test data than those obtained from pull-out tests, they were still not exactly the same as a real beam test.

Furthermore, it should be noted that assessing the bond stress–slip law by means of the pull-out test or the above-mentioned beam tests is not straightforward because, usually, the values in the bond stress–slip law are obtained by assuming a constant distribution of bond stresses in the embedded portion whereas the slips are actually measured at the free ends. However, while this assumption of constant bond stress distribution is suitable for steel reinforcements, for FRP reinforcing bars, as the measured values at their two ends are normally quite different, it seems to be inappropriate [18].

Till now, very few numerical studies which considered bond–slip effect on the structural behaviour of FRP-reinforced concrete beams have been reported although many steel-reinforced concrete beams with bond–slip were analysed numerically, and perfect bond has been assumed in most of the reported research for the FRP-reinforced concrete beams. Achillides and Pilakoutas' work [19] is one of the few studies that considered the bond–slip of FRP rebars, in which nonlinear springs were used to model the bond behaviour at the bar–concrete interface in the analyses of GFRP-reinforced concrete cubes and beams. In addition, a one-dimensional composite beam element with bond–slip for nonlinear finite element analysis of steel/FRP-reinforced concrete beams was recently developed by the authors [20], where additional nodal degrees of freedom were introduced to represent the axial displacements of the reinforcements to account for the bond–slip effect.

In order to investigate the bond–slip behaviour of FRP rebars in concrete beams and the effect of bond–slip on the structural behaviour, both experimental studies and numerical analysis are conducted in this research. In experimental studies, standard four-point bending beam tests on FRP-reinforced concrete beams are conducted to determine physically the structural behaviour of reinforced concrete beams, including flexural behaviour and bond–slip behaviour. The flexural behaviour and bond–slip effects of the FRP-reinforced concrete beams are also studied numerically in this paper by employing the composite beam elements [20,21] recently developed by the authors, which have been validated against the experimental results and numerical analysis results reported in the literature. Parametric studies are also carried out using the finite element models to study the effects of parameters such as the type of rebars and the rebar surface conditions on the structural behaviour.

The paper is constructed as follows. The materials, geometry and design of the test beams are introduced in Section 2. Test methods for the material properties, flexural behaviour and bond–slip behaviour are described in Section 3 and the test results are presented in Section 4. The results of the flexural behaviour and bond–slip behaviour of the beams from finite element analyses are shown in Section 5 and the computed results are compared with those obtained from experimental studies. Parametric studies are conducted in Section 6 and the effects of the parameters are investigated. Finally conclusions are drawn.

## 2. Test specimens

In experimental study, to reduce the cost and also due to the availability of the materials at testing, a total of six concrete beams reinforced with CFRP, GFRP and BFRP rebars are tested. The CFRP and GFRP rebars have smooth surfaces while the BFRP rebars are spirally wrapped by strands around their outside diameters which produce spiral indentations in the rebars. The six beams are named as BC1, BG1 and BG2, and BB1, BB2 and BB3 respectively. The first letter 'B' represents 'Beam', the second the type of reinforcing material and the Arabic numeral the number of the sample; for example, 'BB2' means the second sample of a BFRP-reinforced concrete beam. As a large number of experimental tests on concrete beams reinforced with CFRP and GFRP rebars have been reported in the literature and also to reduce cost in experiment, in this study, only one and two samples are tested for CFRP and GFRP-reinforced concrete beams respectively while three specimens are tested for BFRP-reinforced concrete beams.

Each test beam is 1060 mm long with a rectangular cross section of 100 mm × 200 mm, and a 25 mm concrete cover is used all around the beam. Material properties of reinforcing bars are listed in Table 1. The results from tensile tests on these FRP rebars are provided by the manufacturer. Identical concrete mix as shown in Table 2 is used for all beams, and the target design cylinder compressive strength for the concrete is 40 MPa.

Since, unlike steel rebars, FRP rebars do not have a yielding stage, the flexural failure of a FRP-reinforced concrete beam is caused by either concrete crushing or FRP rupture. As FRP rebars show linear behaviour up to failure and make the structural behaviour brittle, thus the concrete becomes the ductile component of FRP-reinforced concrete beams. In order to achieve concrete failure first, FRP-reinforced concrete beams are designed as over-reinforced. Each test beam is reinforced with three FRP bars in the tension zone and two steel bars on the compression face. In order to resist shear failure, 8 mm-diameter stirrups are used throughout the shear span at centre-to-centre spaces of 50 mm. Details of the longitudinal section and cross section are shown in Figs. 1a and 1b respectively.

The concrete beams are cast in a wooden mould. PVC tubes are placed at the ends of the centre rebar and one of the corner rebars

**Table 1**
Material properties of reinforcing bars.

| Bar type | Diameter $d$ (mm) | Elastic $E$ (GPa) | Ultimate strength $f_u$ (MPa) | Elongation (%) |
|---|---|---|---|---|
| CFRP | 10 | 140 | 2000 | 1.6 |
| GFRP | 10 | 30 | 500 | 2.0 |
| BFRP | 8 | 40 | 800 | 2.0 |
| Steel | 6 | 200 | 400 | 0.2 |

**Table 2**
Constituents of concrete mix.

| | |
|---|---|
| Water (W) | 228 kg/m$^3$ |
| Cement (C) | 380 kg/m$^3$ |
| W/C ratio | 0.6 |
| Coarse aggregate (10 mm) | 816 kg/m$^3$ |
| Sand | 856 kg/m$^3$ |