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Flexural behaviour of reinforced concrete beams strengthened with prestressed carbon composites

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ABSTRACT

In this study, a total of 13 FRP-strengthened reinforced concrete beams were tested in flexure and analyzed using the finite element method. The various variables included bonding or no bonding of the FRP, the anchorage system, the amount of prestressing, and the span length. The experiments consisted of one control beam, two non-prestressed FRP-bonded beams, four prestressed FRP-unbonded beams, four prestressed FRP-bonded beams, and two prestressed FRP-unbonded beams with different span lengths. All the beams were subjected to three-point and four-point bending tests under deflection control, with the loading, deflection and failure modes recorded to the point of failure. A nonlinear finite element analysis of the tested beams was also performed using the DIANA software; this analysis accounted for the nonlinear concrete material behaviour, the reinforcement, and an interfacial bond-slip model between the concrete and CFRP plates.

The aim of this investigation was to study the flexural performance of reinforced concrete members strengthened using CFRP plates, employing different FRP bonding and prestressing methods. The failure mode of the prestressed CFRP-plated beams was not debonding, but FRP rupture. For the reinforced concrete members strengthened with externally bonded prestressed CFRP plates, debonding of the composite laminates occurred in two stages. After the debonding of the CFRP plates that occurred in the bonded cases, the behaviour of the bonded CFRP-plated beams changed to that of the unbonded CFRP-plated beams due to the effect of the anchorage system. The flexural test results and analytical predictions for the CFRP-strengthened beams were compared and showed very good agreement in terms of the debonding load, yield load, and ultimate load. The ductility of the beams strengthened with CFRP plates having the anchorage system was considered high if the ductility index was above 3.

1. Introduction

The bonding of steel plates for the strengthening and rehabilitation of reinforced concrete structures was a popular strengthening method in the past. In recent years, there has been extensive research on the use of fibre reinforced polymer (FRP) composites for the replacement of steel plates in plate bonding. FRPs have also been widely used as external wrapping for column strengthening and prestressed bonding for reinforced concrete members. Indeed, there is considerable interest worldwide in the field of FRPs for civil engineering infrastructure and much research has been carried out on a variety of important topics [1–18].

The widely used strengthening method of simply bonding FRPs, such as carbon fibre, aramid and glass fibre, for strengthening a structure generally produces a debonding failure prior to the attainment of the tensile strength of the FRP being used [6,11,13]. In fact, the debonding strain of the composite differs according to the material used, and this debonding occurs at about 30–50% of the FRP tensile strength [8].

A reinforced concrete member strengthened with prestressed FRPs is a combination of the FRP bonding and external prestressing methods. This leads to a more efficient use of the FRP; the method can be used to compensate for prestressing losses of existing reinforced concrete or prestressed concrete members, to enhance the strengthening performance, and to improve the serviceability of cracked or deflected members.

The focus of this paper is to study the flexural performance of reinforced concrete members strengthened by CFRP plates, using FRP bonding and prestressing methods. Flexural tests were performed with respect to the bonding method, the anchorage system, the amount of prestressing, and the span length as experimental variables. A total of 13 beams, including a control beam, were subjected to flexural tests. A nonlinear finite element analysis of the beams was also performed for each flexural test using the DIANA software package, incorporating the plasticity of concrete and

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interface elements between the FRP and concrete. The analytical results for the CFRP-strengthened reinforced concrete are compared to the flexural test results. The strengthening effect, failure mode, and load-deflection behaviour were considered for each experiment, and the ductility was evaluated as the ratio of the ultimate load for each tested beam to the deflection at yielding.

2. Experimental program for reinforced concrete beams strengthened with CFRP plates

2.1. Variables of the experiments and beams

In this investigation, flexural tests were performed with the experimental variables being bonding or no bonding of the FRPs, the anchorage system, the amount of prestressing, and the span length (240 cm, 450 cm and 600 cm). Flexural tests were conducted on a control beam without strengthening, on beams strengthened with bonded CFRP plates with one and two laminates in the width direction, and on beams strengthened with CFRP plates prestressed with 0%, 20%, 40%, and 60% of the ultimate tensile strength of the CFRP plates.

A total of 13 beams were subjected to flexural tests. Rectangular normal-weight concrete beams were cast with dimensions of 200 mm (b) $\times$300 mm (h). The characteristics of all the beams, as well as their steel reinforcement details, are shown in Fig. 1 and Table 1.

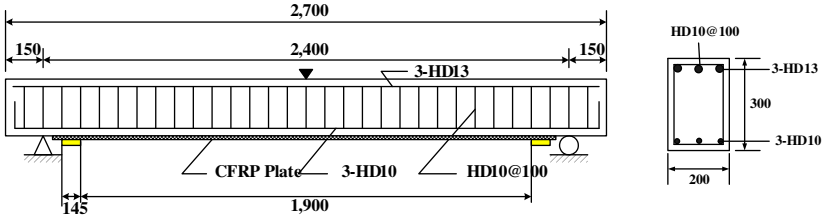
Table 1
Details of the tested beams

Beams	Variables of experiment		Content	Span length
Control	–		Not strengthened	240 cm
NFCB1	No anchorage system		1 laminate	
NFCBW2			2 laminate of width direction	
PFCU1-0R	Prestressing	No bond	Prestressing 0% + anchorage	
PFCU1-2R			Prestressing 20% + anchorage	
PFCU1-4R			Prestressing 40% + anchorage	
PFCU1-6R			Prestressing 60% + anchorage	
PFCB1-0R		Bond	Prestressing 0% + anchorage	
PFCB1-2R			Prestressing 20% + anchorage	
PFCB1-4R			Prestressing 40% + anchorage	
PFCB1-6R			Prestressing 60% + anchorage	
PFCU1-4L	L/h_f		Unbond + prestressing 60% + anchorage	450 cm
PFCU1-6L			Unbond + prestressing 60% + anchorage	600 cm

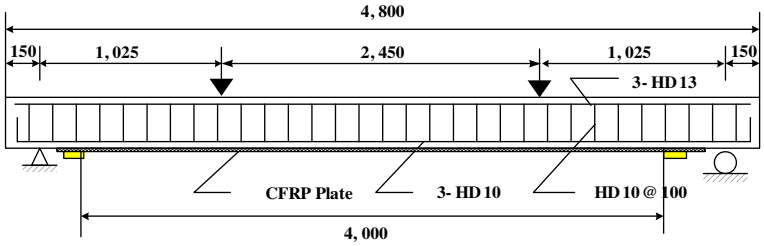
2.2. Materials

The type of concrete used in the flexural tests was a ready-mixed concrete, which had been aged for 28 days, with a specified concrete strength of 18.0 MPa, measured compressive strength of 16.4 MPa, and slump of 120 mm. All the beams were reinforced with three D13 bars (diameter of 13 mm) and three D10 bars (diameter of 10 mm) in the compression and tension zone, respectively. The beams were provided with 10 mm diameter shear reinforcements, with a 100 mm spacing; they were all designed to prevent shear failure. The design yield stress of the 10 mm and 13 mm diameter reinforcing bars were 475.2 MPa and 466.2 MPa, respectively.

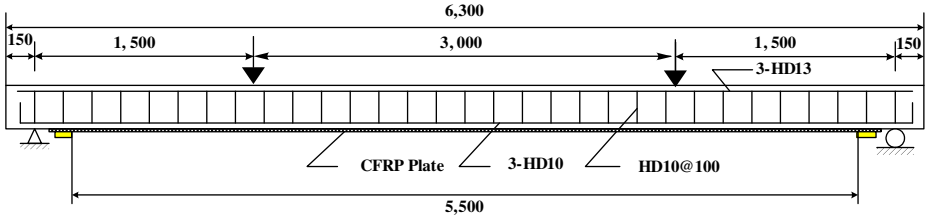
The composite material used in this test program consisted of a three-layer component with a bi-directional CFRP sandwiched between two unidirectional CFRP plates. This was done during the general moulding process so as to prevent cracking in the unidirectional layers due to the prestressing load. The material properties of the CFRP used in the flexural tests are given in Table 2.



(a) Beams of span length 240cm



(b) Beams of span length 450cm



(c) Beams of span length 600cm

Fig. 1. Beam details (units: mm).