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Review

Retrofitting of reinforced concrete beams using composite laminates

Yasmeen Taleb Obaidat [a,*], Susanne Heyden [a], Ola Dahlblom [a], Ghazi Abu-Farsakh [b], Yahia Abdel-Jawad [b]

[a] Division of Structural Mechanics, Lund University, Lund, Sweden
[b] Jordan University of Science and Technology, Irbid, Jordan

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A B S T R A C T

This paper presents the results of an experimental study to investigate the behaviour of structurally damaged full-scale reinforced concrete beams retrofitted with CFRP laminates in shear or in flexure. The main variables considered were the internal reinforcement ratio, position of retrofitting and the length of CFRP. The experimental results, generally, indicate that beams retrofitted in shear and flexure by using CFRP laminates are structurally efficient and are restored to stiffness and strength values nearly equal to or greater than those of the control beams. It was found that the efficiency of the strengthening technique by CFRP in flexure varied depending on the length. The main failure mode in the experimental work was plate debonding in retrofitted beams.

Contents

1. Introduction

There are many existing structures, which do not fulfill specified requirements. This may for example be due to upgrading of the design standards, increased loading, corrosion of the reinforcement

* Corresponding author.
E-mail address: Yasmeen.Obaidat@construction.lth.se (Y.T. Obaidat).

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bars, construction errors or accidents such as earthquakes. To remedy for insufficient capacity the structures need to be replaced or retrofitted.

Different types of strengthening materials are available in the market. Examples of these are ferrocement, steel plates and fibre reinforced polymer (FRP) laminate. Retrofitting of reinforced concrete (RC) structures by bonding external steel and FRP plates or sheets is an effective method for improving structural performance under both service and ultimate load conditions. It is both environmentally and economically preferable to repair or strengthen structures rather than to replace them totally. With the development of structurally effective adhesives, there have been marked increases in strengthening using steel plates and FRP laminates. FRP has become increasingly attractive compared to steel plates due to its advantageous low weight, high stiffness and strength to weight ratio, corrosion resistance, lower maintenance costs and faster installation time.

Earlier research has demonstrated that the addition of carbon fibre reinforced polymer (CFRP) laminate to reinforced concrete beams can increase stiffness and maximum load of the beams. In a study by Toutanj et al. [1] beams retrofitted with CFRP laminates showed an increased maximum load up to 170% as compared to control beams. Another study by Kachlakev and McCurry [2] shows an increase of 150% when beams were strengthened in both flexure and shear with CFRP and glass FRP laminates respectively. Other studies have also been conducted by David et al. [3], Shahawy et al. [4], Khalifa and Nanni [5], Shehata et al. [6], Khalifa et al. [7] in an attempt to quantify the flexural and shear strengthening enhancements offered by the externally bonded CFRP laminates. Ferreira [8] showed that when a beam is strengthened with CFRP sheets the stiffness increase and the tension cracking is delayed to higher loads, and Karunasena et al. [9] showed that an externally bonded composite, of either CFRP or GFRP materials, improved the moment capacity of deteriorated concrete beams.

In spite of many studies of the behaviour of retrofitted beams, the effect of the length of CFRP on the behaviour of pre-cracked beams retrofitted by CFRP in flexure and the behaviour of retrofitted beams in shear after preloading have not been explored. This study examined experimentally the flexural and the shear behaviours of RC-beams retrofitted or strengthened with CFRP laminates. To accomplish this, laboratory testing was conducted on full-size beams. The main variables in this study are the reinforcement steel ratio and CFRP length.

2. Materials and methods

The experimental work undertaken in this study consisted of four point bending tests of 12 simply supported RC beams. In addition, material tests were carried out to determine the mechanical properties of the concrete, reinforcement steel and CFRP which were used in constructing the beams.

2.1. Materials

An ordinary strength concrete mix was prepared using Ordinary Portland cement (Type I). The aggregate used consisted of coarse limestone, crushed limestone and silica sand. The gradation of coarse and fine particles met the ASTM specification (C136) [10].

The concrete mix was designed according to ACI method 211 [11], to have slump 50 mm and 28 days cylinder compressive strength of 30 MPa. The maximum aggregate size was 10 mm and the free water cement ratio was 0.55. The concrete mix is shown in Table 1.

The mean compressive strength was determined in compressive tests 28 days after casting of three 300 mm by 150 mm diameter cylinders. The average concrete compressive strength was 29 MPa. The failure of a specimen is shown in Fig. 1.

The steel bars used for longitudinal reinforcement were tested in uniaxial tension. Details of the material properties for the reinforcing steel are given in Table 2. The average elastic modulus was 209 GPa. The stirrups were fabricated using steel with nominal diameter 8 mm. This steel was not tested in the experimental work.

The CFRP used in this study was supplied by FOSROC [12]. The laminate had a thickness of 1.2 mm, a width of 50 mm and the elastic modulus 165 GPa according to the manufacturer. The plates were supplied in a roll form as shown in Fig. 2. Three specimens were prepared and tested using a tension testing machine at a rate of 2 mm/min, to determine the ultimate stress. The mean ultimate stress of the

Table 1
Concrete mix proportions, kg/m^3 concrete.

Materials	kg/m^3
Cement	332
Water	206
Coarse aggregate (5 mm $\leqslant d \leqslant$ 10 mm)	830
Fine aggregate (d < 5 mm)	662

Fig. 1. Concrete specimen in cylinder compression test.

Table 2
Mechanical properties of steel bars.

Nominal diameter (mm)	Elastic modulus (GPa)	Yield Stress (MPa)	Ultimate stress (MPa)	Ultimate strain
10	211	520	741	0.151
12	207	495	760	0.167
18	209	512	739	0.131

Fig. 2. Roll of CFRP plate.