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Structural behaviour of RC beams with external flexural and flexural–shear strengthening by FRP sheets

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ABSTRACT

This paper presents experimental research on reinforced concrete (RC) beams with external flexural and flexural–shear strengthening by fibre reinforced polymer (FRP) sheets consisting of carbon FRP (CFRP) and glass FRP (GFRP). The work carried out has examined both the flexural and flexural–shear strengthening capacities of retrofitted RC beams and has indicated how different strengthening arrangements of CFRP and GFRP sheets affect behaviour of the RC beams strengthened. Research output shows that the flexural–shear strengthening arrangement is much more effective than the flexural one in enhancing the stiffness, the ultimate strength and hardening behaviour of the RC beam. In addition theoretical calculations are developed to estimate the bending and shear capacities of the beams tested, which are compared with the corresponding experimental results.

1. Introduction

Strengthening techniques for building structures have been developed for many years to lengthen the service period and retrofit the damaged structures. There are many structures, due to original design limits and construction errors or an aggressive environment conditions [1,2] such as disastrous earthquakes in China and Japan in recent years, that need to be retrofitted to meet the demand usage in a more economic and effective way [3,4]. The techniques based on the externally bonded fibre reinforced polymer (FRP) materials are the most widely used ones for retrofitting damaged existing structures [5]. The reason for that is due to their high strength-to-weight ratio, high stiffness, easy installation and stable geometry during the service life [6–8].

Many studies [1–4,7–10] have been undertaken on the RC beams retrofitted in flexural by FRP sheets through experimental, finite element and analytical approaches. The studies have shown that the beams strengthened with FRP in flexural strengthening would avoid the debonding failure mode when a carefully designed anchorage is applied [1,7,10–13], which gives a good flexural performance in terms of strength and ductility. Although a lot of research has been undertaken on the flexural strengthening by using of FRP materials bonded onto the tension face of the beam, the main focus was on the influence of FRP type, thickness and width on the failure modes of RC beams strengthened [2,8,9,11–18]. There were few of these studies covering the effect of beam size [19] and concrete cover thickness [20] on the flexural strength of beams strengthened.

Recently, there is increasingly widespread interesting on strengthening RC beams using externally bonded FRP materials to enhance their shear capacities [21–26]. Shear failure has different characters as compared to bending failure, in which the former is more brittle and often occurs without any forewarning [27]. Research was also carried out to investigate the effects of longitudinal tensile reinforcement ratio [15,21,28], shear span to effective depth ratio [21,28,29], spacing of CFRP strips, and amount and orientation of CFRP strips on the shear capacity of the precracked and non-precracked beams [28]. Further experimental tests were undertaken to investigate the effect of cross section depth and concrete strength on the shear performance of FRP strengthened RC beams [15,30–36].

However, a lot of research focused on either the flexural or shear failure, with few studies investigating the combined failures [37]. The existing experimental [5,6] and analytical [7] research demonstrated that FRP sheets and strips could enhance strength and improve ductility of a beam more effectively if a combined flexural and shear strengthening configuration was applied. Costa and Barros [6] undertook research on the shear capacity of RC beams and found that the load carrying capacity increased 50% when the flexural strengthening was combined with the U or O (full wrapping) shear strengthening.

The research work presented here focuses on the strengthening efficiency of RC beams with different layers of CFRP sheets, and un-

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der different pre-crack width, concrete cover thickness and the flexural reinforcement ratio and shear reinforcement configurations. A detailed experimental programme provides evaluations of structural behaviour of the combined flexural–shear retrofitting of RC beams by using CFRP sheets prebonded on the tension face of the beam for flexural strengthening, and then reinforced in shear by GFRP or CFRP sheets in U or L configurations. Other experimental parameters have been covered, which include the cross section depth, the stirrups reinforcement ratio and the concrete strength in the flexural–shear retrofitting tests. Research output shows that the flexural–shear strengthening arrangement is much more effective than the flexural one in enhancing the stiffness, the ultimate strength and hardening behaviour of the beam. In addition theoretical calculations on estimating the bending and shear capacities of the beams tested are presented and compared with the corresponding experimental results in a reasonably good agreement.

2. Experimental work

2.1. Materials

Table 1 shows the material properties of the concrete, steel rebars and FRP (CFRP and GFRP) sheets which were used to make specimens. Concrete mixes were designed with the grades of compressive strength according to the Chinese Standard [38]. The mix was made of ordinary Portland cement 32.5R, natural sand and gravels with aggregate size between 10 and 31 mm. The average compressive strengths (f_c) were obtained from cube crush tests on cubes with 150 mm side length at 28 days.

The longitudinal reinforcements are consisted of two steel rebars of 10 mm or 14 mm in diameter placed on the bottom and two rebars of 8 mm in diameter on the top of the beam. For shear reinforcement, stirrups of 6 mm in diameter were used. The yield strength (f_y), ultimate strength (f_u), elastic modulus (E) and the ultimate elongation (η) of the steel reinforcement (supplied by the Shanxi Zhongyu Ironsteel Co. Ltd.) are also shown in Table 1. Material properties of the CFRP and GFRP sheets (supplied by the Shanghai keep strong in building technology engineering Co. Ltd.) are shown in Table 1 as well.

2.2. Sample preparation

Table 2 shows seven concrete beams for flexural strengthening, in which six beams were strengthened with either single layer or two layers of CFRP sheets and one without retrofitting as a control beam. The reason to attach either one layer or two layers of CFRP sheets is to investigate how effective of the one extra layer is on the crack load, ultimate load, strains and deflection of the beams strengthened. Two strips of the U-shaped CFRP sheets were bonded onto both sides of the beam near the supports as external anchorage to reduce the edge stresses and to prevent the delamination of other CFRP sheets [39,40]. Table 2 also shows test variables covering reinforcement ratio, the longitudinal tensile reinforcement ratio, shear span to effective depth ratio, and the concrete cover thickness. The beam dimensions and reinforcing arrangements are shown in Fig. 1.

Table 3 shows RC beams strengthened in the combined shear and flexural manner, with two beams (SR1 and SR6) made with different concrete strengths for control purpose. The beam SR2 was strengthened with one layer of GFRP sheets in a vertical U-shape configuration. Four beams, SR3, SR4, SR5 and SR7, were strengthened with two layers of CFRP sheets in a diagonal L-shape configuration. The beams strengthened were all prebonded with one layer of CFRP sheets of 100 mm in width and 1500 mm in length on the tensile face of the beam for flexural strengthening. The main parameters studied in the flexural–shear tests were the strengthening material (GFRP or CFRP), the number of FRP layer, the stirrups ratio, the beam height and the concrete strength. The beam dimensions and reinforcing arrangements are shown in Fig. 2.

2.3. Test setup and loading procedures

All the beams were simply supported over a clear span of 1500 mm and tested under four-point bending, as shown in Fig. 3. The load was applied using a servo controlled Shimadzu hydraulic actuator (200 kN capacity) with a loading rate of 1 kN/min. All beams were instrumented to measure strains on the main tensile steel at mid-span, loading points and mid-shear span, strains on the orthogonal internal stirrups and strains on the FRP sheets. In addition, strains on the concrete over the depth of the beams were measured in the mid-span section and three linear voltage displacement transducers (LVDTs) were used to measure deflections at the mid-span and loading points. The locations of strain gauges on the steel, FRP sheets and concrete, as well as the LVDTs are shown in Figs. 1–3. A hand held microscope with a resolution of 0.02 mm was used to measure the width of cracks. For the beams with a pre-crack, the crack widths were the cracks newly developed during the test. The load was applied monotonically up to the failure. Four steel plates (100 mm wide and 20 mm thick) were placed above the supports and underneath the loading points to avoid local crushing on the beams tested.

3. Results and discussion

3.1. Beams with flexural strengthening

3.1.1. Failure modes

The representative failure patterns for all beams tested are shown in Fig. 4. The failure mode of the control beam CR1 (Fig. 4a) is a typical bending failure pattern. For the beams strengthened with one or two layers of CFRP sheets, appearance of cracks was delayed, also the width of those cracks and the inter-space between cracks were reduced. There were two major failure modes for the beams strengthened, i.e. snapping and debonding of CFRP sheets, and shear cracks propagated toward the loading point accompanied by debonding of the CFRP sheets

Table 1
Material properties of concrete, steel rebars and FRP sheets.

Material	Dimensions (mm)	f_c (MPa)	f_y (MPa)	f_u (MPa)	E (GPa)	η (%)
Concrete	C20	22.8	–	–	–	–
	C30	31.3	–	–	–	–
Steel reinforcing	$D = 6$	–	240	420	210	30
	$D = 8$	–	330	490	210	28
	$D = 10$	–	340	480	210	28
	$D = 14$	–	410	555	200	28.5
CFRP sheets	$t_f = 0.111$	–	–	4103	242	1.7
GFRP sheets	$t_f = 0.273$	–	–	3400	73	2.7