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ScienceDirect
Engineering Structures 29 (2007) 2428–2444
ENGINEERING STRUCTURES
www.elsevier.com/locate/engstruct

Flexural behaviour of reinforced concrete beams strengthened by CFRP sheets

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Received 30 May 2006; received in revised form 23 October 2006; accepted 12 December 2006
Available online 24 January 2007

Abstract

This paper investigates the flexural behaviour of reinforced concrete beams strengthened using Carbon Fibre Reinforced Polymers (CFRP) sheets. The effect of reinforcing bar ratio ρ on the flexural strength of the strengthened beams is examined. Twelve concrete beam specimens with dimensions of 150 mm width, 200 mm height, and 2000 mm length were manufactured and tested. Beam sections with three different reinforcing ratios, ρ, were used as longitudinal tensile reinforcement in specimens. Nine specimens were strengthened in flexure by CFRP sheets. The other three specimens were considered as control specimens. The width, length and number of layers of CFRP sheets varied in different specimens. The flexural strength and stiffness of the strengthened beams increased compared to the control specimens. From the results of this study, it is concluded that the design guidelines of ACI 440.2R-02 and ISIS Canada overestimate the effect of CFRP sheets in increasing the flexural strength of beams with small ρ values compared to the maximum value, ρ_{max}, specified in these two guidelines. With the increase in the ρ value in beams, the ratios of test load to the load calculated using ACI 440 and ISIS Canada increased. Therefore, the equations proposed by the two design guidelines are more appropriate for beams with large ρ values. In the strengthened specimens with the large reinforcing bar ratio, close to the maximum code value of ρ_{max}, failure occurred with adequate ductility.

Keywords: CFRP; Flexural strengthening; Reinforcing bar ratio; Reinforced concrete beams

1. Introduction

Strengthening, upgrading and retrofitting of existing structures are among the major challenges that modern civil engineering is currently facing. One of the most promising answers to these needs is the use of strips made of fibre reinforced polymers (FRP) bonded to the tensile face of the member. Comprehensive experimental investigations conducted in the past have shown that this strengthening method has several advantages over the traditional ones, especially due to the high strength, low weight and improved durability of the composite material.

In FRP-strengthened beams failure may occur due to beam shear, flexural compression, FRP rupture, FRP debonding or concrete cover ripping as presented by Ascione and Feo [1], and Bonacci and Maalej [2,3]. Based on experimental results conducted by Teng et al. [4], the most common failure mode is due to debonding of FRP plate or ripping of the concrete cover. These failure modes are undesirable because the FRP plate cannot be fully utilized. In addition, such premature failures are generally associated with a reduction in deformability of the strengthened members. Premature failure modes are caused by interfacial shear and normal stress concentration at FRP cut-off points and at flexural cracks along the beam.

Extensive testing of such strengthened members has been carried out over the last two decades. A number of failure modes for RC beams bonded with FRP soffit plates have been observed in numerous experimental studies to date (e.g. Ritchie et al. [5], Saadatmanesh and Ehsani [6], Triantafillou and Plevris [7], Chajes et al. [8], Sharif et al. [9], Hefferman and Erki [10], Shahawy et al. [11], Takeda et al. [12], Arduini and Nanni [13], Maalej and Bian [14], Malek et al. [15], Grace et al. [16], GangaRao and Vijay [17], Ross et al. [18],

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0141-0296/$ - see front matter
doi:10.1016/j.engstruct.2006.12.008

Notations

A_s	Cross-sectional area of tension steel reinforcement
A'_s	Cross-sectional area of compression steel reinforcement
A_f	Cross-sectional area of FRP plate
b	Width of rectangular crosses section
h	Beam height
C_E	Environmental-reduction factor
d', d	Depth of centroid of tensile and compression steel reinforcement from extreme compression fibre
d_f	Depth of FRP shear reinforcement
E_f	Modules of elasticity of FRP material
E_c	Modules of elasticity of concrete
E_s	Modules of elasticity of steel
f'_c	Compressive strength of concrete
F_c	The axial forces in concrete
F_p	The axial forces in FRP material
F_{st}	The tensile axial forces in steel
F_{sc}	The compressive axial forces in steel
K_m	Bond-dependent coefficient for flexure
P_{ACI}	Calculated ultimate strength of beam according to ACI440.2R-02
$P_{cont.}$	Calculated ultimate strength of the control specimen
P_{ISIS}	Calculated ultimate strength of beam according to ISIS Canada
P_{test}	The maximum applied load to the specimens
t_f	Thickness of CFRP plate
M_c	The bending moments on the cross-section due to axial stress in concrete
M_{sc}	The bending moments on the cross-section due to axial stress in compression steel bars
M_{st}	The bending moments on the cross-section due to axial stress in tension steel rears
M_p	The bending moments on the cross-section due to axial stress in FRP plates
β_1	Ratio of the depth of the equivalent rectangular stress block to the depth of the neutral axis
ε_c	Concrete strain at extreme compression fiber at particular load
$\varepsilon_{c\,max}$	Maximum compressive strain of concrete
ε_0	Concrete strain corresponding to maximum concrete stress
ε_{fe}	Effective design strain for CFRP plate
ε_{fu}	Specified rupture strain for CFRP plate
ε_s	Strain level in the steel reinforcement
ε_y	Strain corresponding to the yield strength of steel reinforcement
ε_{frp}	Strain in FRP plate
γ	Multiplier on f'_c to determine the intensity of an equivalent rectangular stress distribution for concrete
φ_s	Strength reduction factor for reinforcing bar
φ_{frp}	Strength reduction factor for FRP
σ_s	Stress in tensile steel at ultimate condition
σ'_s	Stress in compressive steel at ultimate condition
σ_p	Stress in tensile FRP at ultimate condition

Bonacci and Maalej [2], Nguyen et al. [19], and Rahimi and Hutchinson [20]). Based on existing studies, a schematic representation of typical failure modes observed in tests is shown in Fig. 1. These failure modes are termed: Type (1) flexural failure by crushing of compressive concrete which could happen before or after yielding of tensile steel reinforcement; Type (2) rupture of the FRP laminate after yielding of the steel in tension; Type (3) cover delamination at the end of FRP (shear delamination of the concrete cover); Type (4) debonding of the FRP from the concrete substrate: Type (4-a) plate end interfacial debonding, Type (4-b) inter-facial debonding induced by flexural crack, Type (4-c) interfacial debonding induced by flexural shear crack and Type (5) shear failure.

Failure types (3) and (4-a) have been studied experimentally and analytically by Maalej and Bian [14], Malek et al. [15], Ye [21], Ascione and Feo [1], Lau et al. [22]. These types of failure are common in cases where the ends of the FRP sheets are not properly anchored. Failure Types (4-b) and (4-c) depend on the bond-slip behaviour between FRP sheets and concrete. According to Sebastian [23] and Teng et al. [4], the corrosion of longitudinal steel bars and the change of the reinforcing bar ratio in the vicinity of large bending moments and shear forces increase the probability of these types of failures.

When FRP reinforcement is being used to increase the flexural strength of a member, it is important to verify that the member will be capable of resisting the shear forces associated with the increased flexural strength. To avoid failure type 5, the potential for shear failure of the section should be considered by comparing the design shear strength of the section to the required shear strength. If additional shear strength is required, FRP laminates oriented transversely to the section can be used to resist the applied shear forces.

In spite of many recent studies on the behaviour of reinforced concrete beams strengthened using FRP composites, the effect of the reinforcing bar ratio on the behaviour and the strength of these beams has not yet been explored. The reinforcing bar ratio of beams affects the pattern and the width of cracks due to the effect of bending and shear. The influence of the FRP composites on flexural strengthening of reinforced concrete beams should depend on the width and spacing of these cracks. The ductility of beams, also, depends on the reinforcing bar ratio. This paper presents the test results of twelve beam specimens strengthened by carbon FRP sheets. The main variable parameter in these tests is the reinforcing bar ratio. The types of failure of these beams are also investigated.

2. Experimental study

2.1. Materials

For the beam specimens, the design compressive strength of 25 MPa was used. The concrete mixture proportions are presented in Table 1. For each series of casting, the specified compressive strength is measured by testing five concrete cylinders.

Different sizes of reinforcing bars, 8, 10, 12, 16 and 20 mm were used in specimens. For each bar size, three samples