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Effect of steel and synthetic fibers on flexural behavior of high-strength concrete beams reinforced with FRP bars

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ABSTRACT

Six high-strength concrete beam specimens reinforced with fiber-reinforced polymer (FRP) bars were constructed and tested. Three of the beams were reinforced with carbon FRP (CFRP) bars and the other three beams were reinforced with glass FRP (GFRP) bars as flexural reinforcements. Steel fibers and polyolefin synthetic fibers were used as reinforcing discrete fibers. An investigation was performed on the influence of the addition of fibers on load-carrying capacity, cracking response, and ductility. In addition, the test results were compared with the predictions for the ultimate flexural moment. The addition of fibers increased the first-cracking load, ultimate flexural strength, and ductility, and also mitigated the large crack width of the FRP bar-reinforced concrete beams.

1. Introduction

Recently, there has been a rapid increase in the use of fiber-reinforced polymer (FRP) bars substituting for conventional steel bars for concrete structures. Because FRP materials are nonmagnetic and noncorrosive, the problem of electromagnetic interference and steel corrosion can be avoided with FRP bars. In addition, FRP bars have the advantages of high strength and light weight, and a number of design guides and national standards have been published to provide recommendations for the analysis, design, and construction of concrete structures reinforced with FRP bars [1–3]. However, due to the substantial differences in the physical and mechanical properties between FRP and conventional steel, the use of FRP bars is still a formidable challenge for engineers.

The elastic modulus of FRP bars is much less than that of steel bars. Glass fiber-reinforced polymer (GFRP) bars and aramid fiber-reinforced polymer (AFRP) bars have an elastic modulus of between 35 and 50 GPa, and the elastic modulus of carbon fiber-reinforced polymer (CFRP) bars is between 120 and 150 GPa. This low elastic modulus leads to higher deflection and larger crack width in FRP bar-reinforced concrete beams that have an equivalent reinforcement ratio to steel-reinforced concrete beams; therefore, both deflection and crack width must be checked for the serviceability limit state. In addition, while steel bars behave inelastically after yield strength, FRP bars show perfect elastic behavior up to failure. Since FRP bars are linear elastic to failure and fail in a brittle manner, a ductile steel-like failure does not occur in FRP bar-reinforced concrete beams. To avoid brittle failure, failure by concrete crushing (over-reinforced beams), which is generally avoided in steel-reinforced concrete design, is preferred in FRP bar-reinforced concrete design [1–4]. However, because concrete itself is a brittle material and high-strength concrete is even more brittle, the ductility of FRP bar-reinforced high-strength concrete beams is less than that of steel-reinforced concrete beams.

In order to overcome the problems in terms of deformability and ductility of concrete beams reinforced with FRP bars, an alternative solution using fiber reinforced concrete (FRC) was proposed. It is now well established that the addition of steel fibers improves the mechanical properties of concrete members. Steel fibers offer increased toughness, durability, and impact resistance, and control the initiation and growth of cracks [5]. Many researchers have proven that the addition of steel fibers increases the ductility of over-reinforced steel reinforced beams and high-strength steel reinforced beams [6,7]. However, few studies have been carried out on the effects of fibers on the behavior of concrete beams reinforced with FRP bars. It is likely that the efficiency of fibers for the FRP bar-reinforced beams, which have a large crack width and deep crack propagation, can be higher than that for steel-reinforced beams. In particular, because the failure of over-reinforced beams with FRP bars is controlled mainly by the concrete compressive strain, the increased and softened postpeak strain of FRC may considerably improve the ductility of FRP beams.

In this study, six high-strength concrete beam specimens were constructed and tested to investigate the effect of fibers on the behavior of FRP bar-reinforced concrete beams. Carbon FRP (CFRP) bars and glass FRP (GFRP) bars were used as flexural reinforcements, and not only steel fibers but also recently developed polyolefin synthetic fibers [8] were considered as reinforcing discrete

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Nomenclature

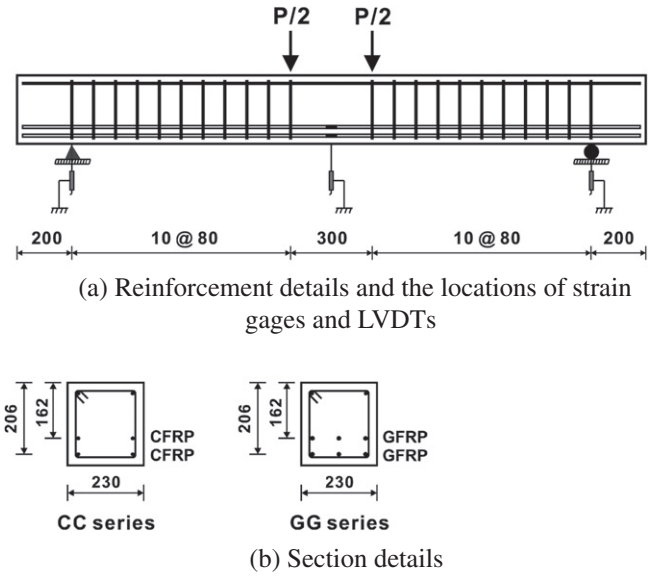
A'_s	area of compressive steel reinforcement, mm^2
A_r	area of flexural reinforcements, mm^2
A_{r1}, A_{r2}	area of outer layer and inner layer flexural reinforcements, respectively, mm^2
b	width of beam section, mm
c	distance from extreme compression fiber to the neutral axis, mm
C_c, C'_s	compressive force of concrete and compressive steel reinforcement, respectively, kN
d_f	fiber diameter, mm
d_1, d_2	effective depth of outer layer and inner layer flexural reinforcements, respectively, mm
D'	depth of compressive steel reinforcement, mm
D_f	bond factor of steel fiber
e	distance from extreme compression fiber to top of tensile stress block of fibrous concrete, mm
E_{ct}	elastic modulus of concrete in tension, GPa
E_{el}	elastic energy released upon failure, kN m
E_r	modulus of elasticity of reinforcement, GPa
E_{tot}	total energy stored in the system, kN m
f_c	compressive stress of concrete, MPa
f'_c	specified compressive strength of concrete, MPa
f^D_{150}, f^D_{600}	residual strength of FRC at net deflection of L/150 and L/600, respectively, MPa
f_r	modulus of rupture of concrete, MPa
f_{r1}, f_{r2}	stress in outer layer and inner layer flexural reinforcements, respectively, MPa
f'_s	stress in compressive steel reinforcement, MPa
f_{sp}	splitting tensile strength of concrete, MPa
f_t	maximum tensile strength of concrete, MPa
f_u	ultimate tensile strength of reinforcement, MPa
f_y	specified yield strength of reinforcement, MPa
F_{be}	bond efficiency of the fiber which varies from 1.0 to 1.2 depending upon fiber characteristics
h	overall height of beam, mm
l_f	fiber length, mm
M_u	ultimate moment, kN m
P_{cr}	first cracking load, kN
P_u	ultimate load, kN
S	average slope of the load deflection curve
T^D_{150}	toughness of FRC, area under the load vs. net deflection curve 0 to L/150, Nm
T_f	tensile force of fibrous concrete, kN
T_{r1}, T_{r2}	tensile force of outer layer and inner layer flexural reinforcements, respectively, kN
v_f	percentage by volume of fibers, %
V_f	fiber volume content
w_f	percentage by weight of fibers, %
β	bond factor of fiber
β_1	factor relating the depth of equivalent rectangular compressive stress block to the neutral axis depth
γ	multiplier on f'_c to determine the intensity of an equivalent rectangular stress distribution for concrete
Δ_{cr}	deflection at first cracking load, mm
Δ_u	deflection at ultimate load, mm
ε_c	compressive strain in concrete
ε'_c	strain corresponding to the peak stress of FRC
ε_{cu}	ultimate compressive strain in concrete
ε_{r1}, ε_{r2}	strain in outer layer and inner layer flexural reinforcements, respectively
ε'_s	strain in compressive steel reinforcement
ε_f	tensile strain in fibers at theoretical moment strength of beam
μ_e	ductility index
σ_t	tensile stress in fibrous concrete, MPa
τ	interfacial bond stress between fiber and matrix, MPa

fibers. This is because the large crack width and deep crack propagation in FRP bar-reinforced concrete beams have a high potential for the corrosion of steel fibers at cracks, even if crack widths of less than 0.1 mm do not allow the corrosion of steel fibers passing across the crack [9]. This study focused on the flexural behavior of these beams in terms of load-carrying capacity, cracking pattern, and ductility. In addition, the experimental results presented in this paper were compared with the results from flexural strength prediction models proposed by various researchers [10–12].

2. Experimental program

2.1. Test specimens

Fig. 1 and Table 1 show the details of six beam specimens. All specimens were 2300 mm long with a rectangular cross section of 230 × 250 mm. These were reinforced with two layers of reinforcement, and the effective depths of the outer layer (d_1) and the inner layer (d_2) were 206 mm and 162 mm, respectively. The main variables were the material of the flexural reinforcement and the fiber. The specimens can be divided into two series: a beam series reinforced with CFRP bars (CC Series) and a beam series reinforced with GFRP bars (GG Series). In order to provide similar nominal flexural strength for the two series, four 9 mm CFRP bars were used in the CC Series beams, and six 13 mm GFRP bars were used in the GG Series beams. Each specimen was made of different types of concrete, i.e. plain concrete, steel fiber reinforced concrete (SFRC), and synthetic fiber reinforced concrete (SNFRC). The letters ST and SN in the specimen names indicate steel fiber and synthetic fiber, respectively. The steel fibers and synthetic fibers were added to the SFRC in the percentage of v_f = 1.0% by volume and to the SNFRC in the percentage of v_f = 2.0% by volume. A 25 mm concrete cover



(a) Reinforcement details and the locations of strain gages and LVDTs

(b) Section details

Fig. 1. Details of test specimens and test setup (dimensions in mm).