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Effectiveness factor of strut-and-tie model for concrete deep beams reinforced with FRP rebars

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ABSTRACT

This paper focuses on the shear strength of a fiber reinforced polymer (FRP) reinforced concrete deep beam without any web reinforcement, and proposes a new effectiveness factor for concrete struts for its design using the strut-and-tie model. A total of fifteen deep beam specimens reinforced with steel, AFRP, and CFRP rebar were tested by considering the effective beam depth, shear-span-to-depth ratio, and reinforcement ratio as test variables. The general behavior of the test specimens was examined and the effects of the test parameters on the shear strengths of the test specimens were investigated. The derivation of the new effectiveness factor of concrete struts was based on the test results performed in this work and the well-known effect of concrete specimen geometry on effective compressive strength. The experimental data obtained from the test results of this study was compared with the suggested prediction and other available proposals. It showed that the proposed effectiveness factor is able to provide highly accurate predictions on the shear strength of FRP reinforced deep beams without any web reinforcement.

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1. Introduction

Unlike steel reinforcement, fiber reinforced polymer (FRP) rebar possess several outstanding properties such as corrosion resistance, light weight, insensitivity to magnetic fields, non-conductivity, and increased strength. These advantages have led FRP rebar to become a widely used alternative to steel reinforcement in reinforced concrete structures. However, although the high tensile strength of FRP rebars enhances the flexural capacity of reinforced concrete beams, the relatively low modulus of elasticity of FRP may cause increased crack width, reduced dowel action, and decreased aggregate interlock. This may eventually result in reduced shear strength capacity of the beam [10,13,14]. Moreover, when subjected to tensile force, FRP shows a tendency to suddenly rupture without a noticeable yield point. As a consequence, the use of FRP rebar may lead to a less optimal design in terms of safety, and its application to structural design may also be limited.

There have been many studies on the shear behavior of FRP reinforced slender beams with shear span-to-depth ratios higher than 2.5, and several design formulas have been proposed which provide reasonable estimates of the shear strengths of FRP reinforced concrete beams [5,6,11,12]. In contrast, relatively few studies have been performed regarding the evaluation of shear strengths of concrete deep beams reinforced with FRP rebars, of which the shear span-to-depth ratio is less than 2.5, and its design standards are still under development.

It is possible to apply the general shear theory to slender beams reinforced with steel rebar, but this is not the case with the deep beams. This is because the entire member of a deep beam is classified as a disturbed region (D-region) in which localized stress concentration occurs. According to the current ACI building code [1], a steel reinforced concrete deep beam should be designed using the strut-and-tie model, which takes into account the complicated force flow in D-regions, instead of simply relying on an empirical formula for its design. In order to apply this approach to the design of FRP reinforced concrete deep beams, modification of several design factors is required due to the differences between the material properties of steel and FRP reinforcement.

Based on the above discussions, this study aims to experimentally investigate the shear behavior of FRP reinforced concrete deep beams, and proposes a new effectiveness factor to use in the strut-and-tie model in the design of FRP reinforced concrete deep beams. The effectiveness factor is a parameter that plays an important role in the strut-and-tie design of reinforced concrete deep beams and shear strength estimation. Tests were performed on fifteen FRP reinforced concrete deep beam specimens by considering the shear span-to-depth ratio, reinforcement ratio, effective depth, and rebar type as test variables. Their shear strengths were measured, the shear failure characteristics of each specimen were examined,

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Nomenclature

a/d	shear span-to-depth ratio
b	width of the deep beam section
d	effective depth of the deep beam section
z	width of the inclined concrete strut
f_c'	compressive strength of the concrete
f_{fu}	tensile strength of FRP bars
f_y	tensile yield strength of reinforcing steel bars
F_{cu}	compressive force of the inclined strut
P_{test}	faliure load measured from the test
P_{ACI}	failure load predicted by the ACI strut-and-tie model (ACI 318-11)
P_{Nehdi}	failure load predicted by the strut-and-tie model with the effectiveness factor proposed by Nehdi et al.
$P_{Razaqpur}$	failure load predicted by the shear strength equation of FRP reinforced concrete deep beams proposed by Razaqpur et al.
P_{CSA}	failure load predicted by CSA S806-02
P_{JSCE}	failure load predicted by JSCE 97
V_u	applied shear force
α	angle between the inclined strut and horizontal tie
β_s	effectiveness factor provided by the ACI strut-and-tie model (ACI 318-11)
β_s^*	target effectiveness factor
ρ	longitudinal reinforcement ratio
ϕ	strength reduction factor

and the effects of the test variables on the shear strengths of the test specimens were investigated.

2. Experimental program

2.1. Materials

The compressive strength of concrete was measured in accordance with the standards of [3], and the measured average strength was found to be 26.1 MPa. The FRP rebars used in the test specimens were made of aramid fiber reinforced polymer (AFRP), carbon fiber reinforced polymer (CFRP), and deformed steel bars, and their material properties are listed in Table 1.

2.2. Specimen details

For this study, a total of fifteen deep beam specimens were manufactured and tested. Seven were reinforced with AFRP rebars, another seven with CFRP rebars, and one with steel deformed bars. The total length of each specimen was 2000 mm, and the clear span of the beam was 1500 mm. To prevent the end anchorage failure of longitudinal rebars, the specimens had an anchorage length of 210 mm beyond the center of the support and an additional concrete cover of 40 mm. This is sufficiently greater than the development length required by the current ACI building code, thus anchorage failure at deep beam end regions can be prevented. The width of all beam specimens was kept constant at 200 mm, and the size of all bearing plates was 100 mm × 200 mm.

Test parameters included the shear span-to-depth ratio (1.4, 1.7 and 2.1), reinforcement ratio (0.38%, 0.51% and 0.64%), effective depth of the beam (190 mm, 250 mm and 310 mm), and types of rebars (AFRP, CFRP and steel). The notation used to indicate each set of the test parameters is illustrated in Fig. 1. In order to prevent flexural failure and to induce shear failure, no shear reinforcement was provided in any specimens. In addition, the specimens were reinforced in excess of the balanced reinforcement ratio specified in ACI 440.1R-06 [2] to avoid brittle failure by rupture of FRP rebars. The specimens were singly or doubly reinforced depending on the number of rebars. The details of each specimen are listed in Table 2.

Table 1
Properties of rebars.

Bar type	Bar diameter (mm)	Sectional area (mm^2)	Tensile strength (MPa)	Modulus of elasticity (MPa)
Steel	10	78.54	400.0	200,000.0
AFRP	9	63.62	1826.9	80,697.0
CFRP	9	63.62	1955.8	120,214.0

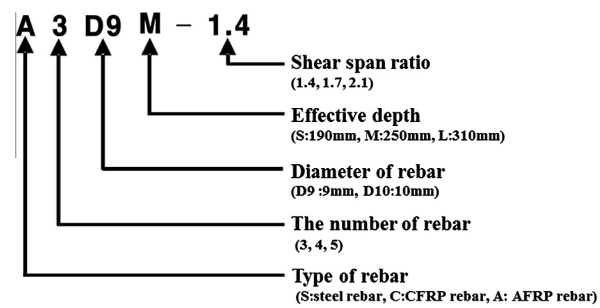

Fig. 1. Notation to indicate the type of each specimen.

Table 2
Specimen details.

Specimen	d (mm)	a/d	Reinforcement ratio (%)		
			ρ	ρ_b	$\rho_{\min}$
A3D9M-1.4	250	1.4	0.38	0.12	0.12
A3D9M-1.7		1.7	0.38		
A3D9M-2.1		2.1	0.38		
A4D9M-1.7		1.7	0.51		
A5D9M-1.7			0.64		
A3D9S-1.7	190		0.50		
A5D9L-1.7	310		0.51		
C3D9M-1.4	250	1.4	0.38	0.15	0.11
C3D9M-1.7		1.7	0.38		
C3D9M-2.1		2.1	0.38		
C4D9M-1.7		1.7	0.51		
C5D9M-1.7			0.64		
C3D9S-1.7	190		0.50		
C5D9L-1.7	310		0.51		
S4D10-1.7	250	1.7	0.63	2.87	0.32

2.3. Test setup and procedures

The details of the test setup are illustrated in Fig. 2. Load was applied to each specimen at a rate of 15 kN/min using a hydraulic cylinder with a maximum capacity of 1000 kN. The force gener-

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