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Evaluation of the flexural strength and serviceability of concrete beams reinforced with different types of GFRP bars

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ABSTRACT

The current available glass-fiber-reinforced polymer (GFRP) bars have a modulus of elasticity ranges from 40 to 60 GPa in accordance with CSA S807-10 Canadian standard. The surface profile of GFRP bars, however, can be smooth, sand-coated, deformed, grooved, or ribbed. This study aimed at investigating the flexural behavior and serviceability performance of concrete beams reinforced with different types of GFRP bars. The test parameters were: (i) modulus of elasticity (46.4–69.3 GPa); (ii) surface profile (sand-coated and helically-grooved), and (iii) reinforcement ratio. The study included testing of 17 full-scale beams measuring 4,250 mm long × 200 mm wide × 400 mm deep reinforced with GFRP bars. The test results are presented and discussed in terms of deflection, crack width, strain, and load-carrying capacity. The cracking behavior of the tested beams tends to confirm that sand-coating of GFRP bars enhances the bond performance in concrete more than the helically-grooved profile. The curvature limit of $0.005/d$ seems to be feasible in controlling the serviceability of GFRP-reinforced concrete (GFRP-RC) beams. In addition, ACI 440.1R-06 and ACI 440.1R-15 underestimated the deflection, while ISIS M-03 and CSA S806-12 provided conservative deflection values at 0.30 of nominal moment capacity, M_n.

1. Introduction

Glass fiber-reinforced-polymer (GFRP) bars have been extensively used as alternatives to steel bars for the last two decades. Recent advances in FRP technology led to the development of GFRP bars with modulus of elasticity exceeds 60 GPa which is expected to reduce the reinforcement amounts and yields cost-effective designs. In addition, the GFRP bars have a variety of surface profiles such as smooth, deformed, sand-coated, and grooved to enhance the bond with the surrounding concrete.

Since GFRP bars have a lower modulus than steel bars, the design of GFRP-reinforced concrete (GFRP-RC) is often governed by the serviceability limit state (deflection and cracking) rather than the ultimate state. Consequently, increasing the tensile properties—especially the modulus of elasticity—is expected to enhance the serviceability of GFRP-RC members. In addition, surface profile may play a role in the cracking performance and consequently crack width. Thus, the performance of GFRP bars with different modulus of elasticity and surface profiles needs to be studied, considering the serviceability and ultimate limit states. Consequently, the GFRP-RC structures may cost more than the steel-RC structures since GFRP bars are more expensive than steel bars and satisfying the serviceability limit state may require more bars. The optimization of the structural design, however, may help in reducing the total cost of GFRP-RC structures such as in case of La Chancelière Parking Garage, Quebec City, Canada [3]. In this project, the 50 tons steel bars, priced at $125,000 CAD, were replaced with 42,160 linear meters of GFRP, priced at $210,800 CAD (1.7 times the cost of steel). The total cost, however, was dropped by 5% when GFRP was used since the asphalt layer was replaced with an anti-friction chemical layer due to the non-corrodible nature of GFRP reinforcing bars [3].

Bischoff and Gross [7,8] reported that the abrupt loss of stiffness at

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Nomenclature

A	effective tension area of concrete surrounding the flexural tension reinforcement and bearing the same centroid as the reinforcement, divided by the number of bars (mm^2)
a	shear span (mm)
A_f	area of FRP tension reinforcement (mm^2)
b	effective beam width (mm)
c	neutral-axis depth (mm)
d	distance from the extreme compression fiber to the centroid of tension force (mm)
d_b	bar diameter (mm)
d_c	distance from extreme tension fiber to the center of the longitudinal bar or wire located closest thereto according to the code or guideline (mm)
E_c	modulus of elasticity of concrete (MPa)
E_f	modulus of elasticity of longitudinal reinforcement (MPa)
E_s	modulus of elasticity of longitudinal steel reinforcement (MPa)
f'_c	compressive strength of the concrete (MPa)
f_f	stress in FRP reinforcement under specified loads (MPa)
f_{fu}	ultimate strength of FRP longitudinal reinforcement (MPa)
f_r	modulus of rupture (MPa)
f_s	stress in bars at serviceability limit state and calculated on the basis of a cracked section
f_t	tensile strength from cylinder-splitting test (MPa)
h_1	distance from neutral axis to center of tensile reinforcement (mm)
h_2	distance from neutral axis to extreme tension fiber (mm)
I_{cr}	transformed moment of inertia of cracked reinforced-concrete section (mm^4)
I_e	effective moment of inertia (mm^4)
I_g	gross moment of inertia of uncracked section (mm^4)
k_b	bond-dependent coefficient
L	length of clear span (mm)
L_g	length of the uncracked section (mm)
M_a	applied moment (kN·m)
M_{cr}	cracking moment (kN·m)
M_n	nominal moment of the reinforced-concrete section (kN·m)
P	applied load (kN)
s	spacing between the longitudinal reinforcement bars (mm)
SD	standard deviation
w	maximum crack width (mm)
y_t	distance from centroid axis of cross-section to the extreme fiber in tension (mm)
δ	mid-span deflection (mm)
ε_{cu}	ultimate strain of concrete
ρ_f	longitudinal reinforcement ratio
ρ_{fb}	balanced longitudinal reinforcement ratio
ψ	curvature

cracking affects the post-cracking behavior and deflection. Mousavi et al. [21] investigated the deflection of GFRP-RC beams, claiming that the low elastic modulus of GFRP bars accounts for the abrupt loss of concrete stiffness. In addition, they reported that the bond-dependent coefficient and the modulus of elasticity of the FRP bars were the main factors affecting the behavior of the GFRP-RC beams. Arivalagn [4] compared stainless-steel, GFRP, and conventional steel bars in simply supported concrete beams. The results showed that once the concrete cracked, the GFRP-RC beams lost their stiffness at a faster rate than those reinforced with steel. This is due to the low modulus of elasticity of the GFRP bars compared to that of steel.

Jakubovskis et al. [18] investigated the effect of distributing the tensile bars on three layers in GFRP-RC beams. The results indicated that the deformation behavior, tension stiffening, and crack pattern and width were related to the arrangement of the tensile bars within the beam section. Based on a statistical analysis of 173 flexural tests of GFRP-RC beams from literature, Xue et al. [24] concluded that the reinforcement ratio of 1.5 ρ_b (where ρ_b is the balanced reinforcement ratio) can be considered as the upper bound for beams in the transition region. On the other hand, Vijay and GangaRao [23] stated that the reinforcement ratio should be higher than 1.4 ρ_b to satisfy the serviceability requirements for GFRP-RC beams.

This paper investigates the flexural behavior and serviceability performance of concrete beams reinforced with GFRP bars with different modulus of elasticity and surface profiles. A total of 17 full-scale GFRP-RC were tested to failure in four-point bending over a clear span of 3750 mm. The test results are reported in terms of deflection, crack width, strains in concrete and reinforcement, flexural capacity, mode of failure, and deformability. The design provisions are assessed and the predicted results are compared with the measured values.

2. Experimental program

Seventeen full-scale GFRP-RC beams were tested under four-point bending until failure. The beams were designed to fail in compression (over-reinforced), which is the common design concept for FRP-RC members, as recommended in design guides and standards. Some results concerning the bond-dependent coefficient are presented elsewhere [12].

2.1. Materials

The beams were reinforced with three commercially available GFRP bars referred to as GFRP-1, GFRP-2, and GFRP-3. GFRP bars sizes No. 13 to No. 25 (12.9–25.4 mm diameters) of each type were used. GFRP-1 and GFRP-2 bars had a sand-coated surface and manufactured by Pultrall Inc. (Thetford Mines, QC, Canada), while GFRP-3 had a helically-grooved surface and manufactured by Fiberline Composites Inc. (Kitchener, ON, Canada). Fig. 1 shows the GFRP reinforcing bars. The tensile properties of the GFRP bars were determined by testing representative specimens in accordance with ASTM D7205 [5] and the bond performance was determined in accordance with the pullout test of ASTM D7913 [6]. Table 1 summarizes the properties while Figs. 2 and 3 show the pullout test details and the typical bond stress-slip relationships of the GFRP bars. In accordance with Canadian standard CSA [11], the three types of GFRP bars were classified as: (1) Grade I (E_f < 50 GPa); (2) Grade II (50 GPa ≤ E_f < 60 GPa) for GFRP-1; and (3) Grade III (E_f ≥ 60 GPa) for GFRP-2 and GFRP-3. The beam

Fig. 1. GFRP reinforcing bars.