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Structural performance and serviceability of concrete beams reinforced with hybrid (GFRP and steel) bars

Ahmed El Refai [a,*], Farid Abed [b], Abdullah Al-Rahmani [b]

[a] Department of Civil and Water Engineering, Laval University, Québec City, Québec G1V 0A6, Canada
[b] Civil Engineering Department, American University of Sharjah, Sharjah, United Arab Emirates

HIGHLIGHTS

- Flexural response of hybrid-reinforced concrete beams was investigated.
- Parameters included the reinforcement ratio and the ratio of steel to GFRP bars.
- Code equations were assessed against the experimental test results.
- New bond coefficient proposed to predict the crack width of the hybrid beams.
- New deformability factor proposed to assess the deformability of the hybrid beams.

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ABSTRACT

This paper reports on the structural performance of concrete beams reinforced with hybrid reinforcement. Six concrete beams reinforced with a combination of steel and glass fiber-reinforced polymer (GFRP) bars and three other beams reinforced with only GFRP bars were tested in flexure. Over-reinforced hybrid beams showed higher strength and ductility than their GFRP-reinforced counterparts. The CSA-S806-12 equation accurately predicted the deflections of the hybrid-reinforced beams with high effective reinforcement ratios. Based on the test results, a bond coefficient was proposed to predict the crack width of the hybrid-reinforced beams using the ACI-440.1R-06 equation. A modified deformability factor was also utilized to assess the deformability of the hybrid-reinforced beams. Comparison between the experimental and predicted results showed the adequacy of the models used in predicting the load-carrying capacity, deflection, crack widths, and deformability of hybrid-reinforced concrete beams.

1. Introduction

Fiber-reinforced polymers (FRPs) have been widely used as reinforcing materials in the last decades. Due to their anti-corrosive characteristics, FRP bars are becoming very promising alternatives to conventional steel bars in reinforcing concrete structures. However, one of the main disadvantages of FRP bars is their brittleness. FRP materials exhibit linear elastic behavior up to failure, which adversely affects the ductility of the concrete structure and limits its inelastic response. The failure modes of FRP-reinforced structures vary widely with the amount of the reinforcement used. A low amount of FRP reinforcement leads to the rupture of the bars prior to concrete crushing. When high reinforcement ratios are used, concrete in compression crushes, while tensile stresses in FRP bars remain below their ultimate strength. Most design codes and guides call for over-reinforcing FRP-reinforced structures to ensure plastic deformation of the compressed concrete and to enhance ductility.

In addition to their lack of ductility, FRP bars are known by their low modulus of elasticity as compared with steel bars. As a result, the FRP-reinforced structure suffers excessive deflections and wide cracks that affect its serviceability. In this case, design of FRP-reinforced structures should be governed by their serviceability limit state rather than their ultimate limit state. Therefore, the

* Corresponding author.
E-mail addresses: ahmed.elrefai@gci.ulaval.ca (A. El Refai), fabed@aus.edu (F. Abed).

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Nomenclature

A_f	area of GFRP reinforcement
A_s	area of steel reinforcement
a	distance between the support and the point load (shear span)
b	width of cross section
c	distance from extreme fiber in compression to neutral axis
d	distance from extreme fiber in compression to center of reinforcement
d_c	thickness of concrete cover from the tension face to the center of the closest bar
DF	deformability factor
DF_{mod}	modified deformability factor
f_f	tensile stress in GFRP bars
f_{fu}	ultimate tensile stress in GFRP bars
f_s	tensile stress in steel reinforcement
f_y	yield stress in steel reinforcement
E_c	modulus of elasticity of concrete
E_f	modulus of elasticity of GFRP bars
E_s	modulus of elasticity of steel bars
f'_c	concrete compressive strength
I_{cr}	cracked moment of inertia
I_e	effective moment of inertia
I_g	gross moment of inertia
k	coefficient = c/d
k_b	bond coefficient
L	beam length
L_g	distance from the support to the point where $M = M_{cr}$
M_a	applied moment at the critical section
M_{cr}	cracking moment
M_s	service moment
M_u	ultimate moment
M_y	yielding moment
n_f	ratio of modulus of elasticity of GFRP bars to modulus of elasticity of concrete
n_s	ratio of modulus of elasticity of steel bars to modulus of elasticity of concrete
P_a	applied load
P_u	ultimate load
R	ratio of axial stiffness of steel bars to axial stiffness of GFRP bars
s	spacing of reinforcing bars
w	maximum crack width
β	ratio of the distance between the neutral axis and the tension face to the distance between the neutral axis and the centroid of reinforcement
β_1	ratio of depth of equivalent rectangular stress block to depth of the neutral axis
β_d	reduction coefficient as given in Eq. (9)
Δ_m	maximum deflection at midspan of the beam
ε_{cu}	maximum concrete compressive strain (0.003 for ACI-318-08 provisions)
ε_f	tensile strain in GFRP bars
ε_s	tensile strain in steel bars
ε_{su}	ultimate tensile strain in steel bars
ε_y	yield strain in steel bars
η	coefficient given in Eq. (11)
ρ_{eff}	effective reinforcement ratio in hybrid sections given by Eq. (6)
ρ_f	GFRP reinforcement ratio
ρ_{fb}	balanced reinforcement ratio
ρ_s	steel reinforcement ratio
ψ_s	curvature at service moment
ψ_u	curvature at ultimate moment
ψ_y	curvature at yield moment

concept of combining steel bars with FRP bars (hybrid system) in reinforcing concrete structures seems to be a practical solution to overcome the ductility and serviceability problems of purely FRP-reinforced structures. This approach of using hybrid reinforcement in concrete elements has gained interest in the last decades. In a hybrid system, the addition of steel reinforcing bars ensures the ductility of the structure and enhances its serviceability, whereas the FRP bars maintains its load-carrying capacity. Near-surface-mounted (NSM) technique is one form of hybrid construction in which FRP bars are placed near the tensile surface to strengthen steel-reinforced concrete elements. Research studies conducted on NSM hybrid reinforcement showed its effectiveness in restoring the strength and serviceability of the concrete elements [17]. However, the use of hybrid system in reinforcing new concrete structures is relatively new.

In their experimental work, Aiello and Ombres [1] carried out flexural tests on hybrid concrete beams reinforced with a combination of aramid FRP (AFRP) and steel bars. Steel and AFRP bars were placed either at the same level or at different levels in the tensile zone. It was reported that the addition of steel reinforcing bars to heavily AFRP-reinforced concrete sections significantly enhanced the ductility and reduced the crack widths and spacing. However, the contribution of added steel reinforcement to the flexural capacity did not exceed 15% in over-reinforced hybrid beams. An increase in stiffness was reported for hybrid beams with steel bars placed above the AFRP bars.

Leung and Balendran [14] investigated the flexural response of hybrid concrete beams reinforced with glass FRP (GFRP) and steel bars placed at different levels. The authors reported that the hybrid-reinforced beams had higher flexure strength than the steel- or GFRP-reinforced beams. Over-reinforced hybrid beams failed by concrete crushing. The test results showed that the stiffness of hybrid-reinforced beams increased after the steel bars had yielded, indicating that the GFRP bars became more effective at this stage.

Qu et al. [15] carried out an experimental and analytical investigation on six hybrid-reinforced beams. The amount of reinforcement and the ratio of GFRP to steel bars were the main parameters investigated. The test results showed that the use of steel reinforcement in combination with GFRP bars improved the ductility of the hybrid-reinforced beams. Beams with higher reinforcement ratios showed higher load-carrying capacity than the other beams. Lau and Pam [13] reported similar results after testing twelve steel-, FRP-, and hybrid-reinforced concrete beams. The latter beams behaved in a more ductile manner when compared with the flexure behavior of FRP-reinforced beams. Ductility improvement was more pronounced in over-reinforced FRP beams than in their under-reinforced or balanced-reinforced counterparts.

Recently, Safan [16] investigated both experimentally and analytically the structural behavior of twelve concrete beams reinforced with hybrid (GFRP and steel) bars arranged at different levels, with the GFRP bars placed at the outer layers of the tensile zone. All hybrid-reinforced beams failed due to concrete crushing after yielding of steel reinforcement. The authors reported that GFRP bars were effective in maintaining the flexure capacity of the beams and in enhancing their serviceability aspects. This