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Deflection and cracking behavior of SFRSCC beams reinforced with hybrid prestressed GFRP and steel reinforcements

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ABSTRACT

In the present work, the deflection and cracking behavior of I-shaped cross-sectional beams of Steel Fiber Reinforced Self-Compacting Concrete (SFRSCC) reinforced in flexure with hybrid prestressed steel strand and glass fiber reinforced polymer (GFRP) bars was investigated. Combining prestressed GFRP bars of relatively low elasticity modulus, but immune to corrosion (located with a small concrete cover), with prestressed steel strand (with higher concrete cover to avoid corrosion), a good balance in terms of reinforcement effectiveness, ductility, durability and cost competitiveness can be obtained. The steel strand aims also to assure the necessary flexural strengthening of the beams if GFRP bars become ineffective in case of fire occurrence. This work presents and discusses the results obtained from the experimental study of the beams tested in flexure under monotonic loading conditions. Additionally, the predictive performance of the available formulation in the design codes for the case of Fiber Reinforced Concrete (FRC) and FRP Reinforced Concrete (FRP-RC) was assessed to be used for the proposed hybrid system.

1. Introduction

The interest in Fiber Reinforced Polymer (FRP) bars as internal reinforcements for concrete has been significantly increased during the last three decades due to the non-corrosive properties of FRP materials. Concrete elements internally reinforced with FRP bars, herein designated as FRP-RC, can, therefore, present higher durability than conventional steel RC elements. So far, many studies have been developed to evaluate the structural performance of FRP-RC structures [1–6]. Also, there are several codes and guidelines dedicated to the design of concrete member reinforced with FRP bars, which is an indicator of the interest of the construction industry in this technology [7–9]. USA, Canada, Switzerland and Germany are the countries that widely use FRP bars in bridge decks, in an attempt of overcoming the damages caused by corroded reinforcement due to the use of salts in de-icing process. FRP bars are, however, brittle materials, a property that decreases the ductility of FRP concrete members comparing to conventional steel RCs. This property may limit the use of FRP bars in many other applications of the construction industry. Additionally, the relatively low axial stiffness of FRP bars (e.g. Glass FRP), as well as the lower FRP-concrete bond strength [10,11] when compared to steel-concrete bond, usually cause higher deformability and crack width under service loads. For these reasons, some attempts have been already done in order to improve the ductility of FRP-RCs, as well as to enhance their structural performance, mainly at Serviceability Limit State (SLS) conditions. These attempts can be mainly categorized as follow:

(1) *Using hybrid FRP reinforcing bars*: the first idea of improving the ductility of FRP concrete members was to use hybrid FRP bars. These bars were fabricated by combining a set of yarns of two or more different types of fibers in an attempt to increase their ductile behavior in tension. By using this technique, a certain pseudo plasticity was given to the tensile behavior of these bars. Harris et al. in 1998 [12] carried out a group of concrete beam specimens reinforced by this type of hybrid FRP bars (CFRP material as core yarn and Aramid yarn surrounding the core part). The ductility was

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Nomenclature

a	shear span of beam
A_f	area of FRP bar's cross section
A_g	gross area of SFRSCC beam's cross section
A_s	area of steel strand's cross section
b	width of bottom flange in SFRSCC beam's cross section
b_n	width of beam in the notched beam bending tests
b_w	width of web in SFRSCC beam's cross section
c	the depth of neutral axis
c_b	the depth of neutral axis at the balanced section condition
C_d	the strength effect in calculation of ductility index
C_s	the deformation effect in calculation of ductility index
d_f	the arm of tensile force of FRP bars at SFRSCC beam's cross section
d'_f	SFRSCC concrete cover of FRP bars (measured from bottom surface of section)
d_{fr}	the arm of the resultant of the residual tensile force by fibers at beam's cross section
d_s	the arm of tensile force of steel strand at SFRSCC beam's cross section
D_{mid}	mid span deflection of tested beams
D_y	mid span deflection corresponding to yielding of steel strand
E_c	Young's modulus of SFRSCC material
E_f	Young's modulus of FRP bar
E_s	Young's modulus of steel strand
f'_c	the concrete compressive strength
f_{ct}	SFRSCC tensile strength
$f_{ct,L}$	limit of proportionality calculated for CMOD = 0.05 mm in standard notched beam test
I^h_{cr}	the moment of inertia of cracked hybrid FRP/steel SFRSCC beam's cross section
I_{eff}	the effective moment of inertia of FRP-RC beam
$I^h_{eff,\exp}$	the experimental effective moment of inertia of hybrid FRP/steel SFRSCC beam
I^h_{eff}	the effective moment of inertia of hybrid FRP/steel SFRSCC beam
I_g	the moment of inertia of uncracked hybrid FRP/steel SFRSCC beam
k_1	the factors that take into account the bond quality (Eq. (39))
k_2	the factors that take into account the form of strain distribution (Eq. (39))
k_3	factors taking into account the bond quality (Eq. (42))
k_4	factor taking into account the bond degree of the reinforcements (Eq. (43))
k_5	factors taking into account the duration of the loading or of repeated loading (Eq. (43))
k_b	the factors that take into account the bond quality (Eq. (41))
l	span of the standard notched beam test
l_{cs}	characteristic length defined by Model Code 2010
L	span of the I shaped hybrid SFRSCC prestressed beam
m_{fr}	factor to calculate balanced reinforcement ratio by Eq. (11)
m_1	modification factor to calculate the depth of neutral axis by Eq. (17)
m_2	modification factor to calculate the depth of neutral axis by Eq. (17)
m_s	factor to calculate balanced reinforcement ratio by Eq. (4)
M_a	the maximum applied moment carried by I shaped SFRSCC beam at each level of loading
M_{cr}	the cracking moment of I shaped SFRSCC beam
M_{cd}	the moment corresponding to V_{cd}
M^L_{cr}	the cracking moment of I shaped SFRSCC beam calculated, replacing f_{ct} by $f_{ct,L}$
M_n	the nominal flexural strength of beam
M_p	moment due to the eccentrically applied prestress force
β_d	factor that takes into account the relatively smaller tension stiffening effect of FRP bars
β_{sh}	factor that takes into account the crack shear propagation in the proposed direct method
γ	factor to calculate the depth of neutral axis by Eq. (16)
ε_c	SFRSCC compressive strain
ε_{cu}	concrete ultimate compressive strain
ε_{cp}	SFRSCC compressive strain at onset of its plastic behavior
ε_{ct}	SFRSCC tensile strain
ε_f	tensile strain of FRP bars
$\bar{\varepsilon}_f$	mean tensile strain of FRP bars at distance between two consecutive cracks
ε^{pre}_f	pre-strain of FRP bars
ε_{fu}	the ultimate tensile strain of FRP bars
ε_s	tensile strain of steel strand
ε^{pre}_s	pre-strain of steel strand
ε_{su}	ultimate tensile strain of steel strand
μ	ductility index of beam
ρ_c	defined by Eq. (9)
f^{pre}_f	prestress of FRP bar
f_{fu}	the ultimate tensile stress of FRP bars
f_{Fts}	the residual flexural stress of SFRSCC defined by Model Code 2010
$f_{R,j}$	the residual flexural stresses of SFRSCC defined by Model Code 2010 ($j = 1, 2, 3, 4$)
f^{pre}_s	prestress of steel strand
f_{su}	the ultimate tensile stress of steel strand
f_{sy}	yielding stress of steel strand
F^{SFRSCC}_c	the resultant of compressive force at cracked SFRSCC beam's cross section
$F^{SFRSCC}_{c,b}$	the resultant of compressive force at balanced cracked SFRSCC beam's cross section
$F_{f,b}$	the tensile force of FRP bars at balanced cracked SFRSCC beam's cross section
F_j	the applied force in notched beam test corresponding to $f_{R,j}$
F_f	the tensile force of FRP bars at cracked SFRSCC beam's cross section
F_{fr}	the resultant of tensile force at cracked SFRSCC beam's cross section (due to fibers)
$F_{fr,b}$	the resultant of tensile force at balanced cracked FRC beam's cross section by fibers
F_s	the tensile force of steel strand bars at cracked SFRSCC beam's cross section
F_{sy}	yielding force of steel strand
$G_{f,u}$	spent mode I fracture energy of SFRSCC at balanced section
h	height of I shaped SFRSCC beam's cross section
h_1	height of the flanges in I shaped SFRSCC beam's cross section
h_2	height of the flanges in I shaped SFRSCC beam's cross section
h_3	height of the web in I shaped SFRSCC beam's cross section
h_{sp}	height of the notched section in the standard notched beam benign test
I_{cr}	the moment of inertia of cracked FRP-RC beam's cross section
M_{SLS}	the applied moment corresponding to $L/250$