EXPERIMENTAL STUDY ON SHEAR BEHAVIOR OF HPFRC BEAMS REINFORCED BY HYBRID PRE-STRESSED GFRP AND STEEL BARS

Fatemeh SOLTANZADEH
PhD Student, ISISE, University of Minho, Portugal
f.soltanzadeh@civil.uminho.pt

Hadi MAZAHERIPOUR
PhD Student, ISISE, University of Minho, Portugal
hmp@civil.uminho.pt

Joaquim BARROS
Full Professor, ISISE, University of Minho, Portugal
barros@civil.uminho.pt

Mahsa TAHERI
PhD Student, ISISE, University of Minho, Portugal
taheri@civil.uminho.pt

Jose SENA CRUZ
Associated Professor, ISISE, University of Minho, Portugal
jsena@civil.uminho.pt

ABSTRACT: The present study deals with the development of a new generation of high durable reinforced concrete (RC) beams, by combining the benefits of glass fiber reinforced polymer (GFRP), steel bar and high performance fiber reinforced concrete (HPFRC). To achieve low probability of corrosion occurrence for steel, the hybrid system of longitudinal reinforcements, composed by GFRP and steel bars, is properly disposed in order to assure a relatively thick concrete cover for the steel reinforcement. GFRP bars are placed with the minimum cover thickness in order to provide a higher internal arm and, consequently, mobilizing its capabilities efficiently. The HPFRC is designed in an attempt of being capable of replacing steel stirrups in this new structural system, since they are the most susceptible elements to corrosion. Application of prestress overcomes the detrimental effect of the relatively low modulus of elasticity of GFRP bars in terms of deflection for serviceability limit states, and introduces extra shear resistance for the beams. This paper describes an experimental program composed of four point-bending test of I-shaped cross sectional simply supported beams under monotonic load condition, and analyzes the relevant results.

1. Introduction and Motivation

Nowadays there is a big demand for enhancing the sustainability and durability of concrete constructions. The requirement for improving the durability this type of structures becomes outstanding due to the relatively high costs of rehabilitation. The corrosion of steel stirrup is one of the common causes that reduce the lifetime of concrete structures. Finding a method capable of substituting the conventional shear reinforcement is a relatively recent challenge for the scientific community (Cucchiara et al. 2004, Voo et al. 2010). Overcoming this drawback also reduces the needs for manufacturing, detailing and placing the shear reinforcement, leading to better production efficiency. Since the requirement of considering the minimum concrete cover for the stirrups is dropped if they can be suppressed, the element thickness and, consequently, the structural self-weight can be reduced (Ferrara et al. 2007). Several experimental evidences confirmed the efficiency of fibers as shear reinforcement to enhance the ultimate shear capacity and ductility of the structural elements. They increase the bearing capacity of the concrete elements and, therefore, bring the member up to yielding of rebars (Rao and Rao 2009, Lingemann et al. 2010 and Ding et al. 2011).

Further enhancements on the durability and sustainability of concrete elements are obtained by taking the benefits of non-corrodible fiber reinforced polymer (FRP) bars. Recently GFRP (glass fibers) bars are being employed as a promising alternative for replacing steel flexural reinforcement. To improve the ductility and accomplish the serviceability limit state requirements of the GFRP reinforced concrete beams, steel bars as an additional reinforcement is suggested, resulting a hybrid reinforcing system.

Prestressing GFRP bars can also contribute to obviate the deficiencies created by the lower modulus of elasticity. It also helps to control the crack width and increase the shear capacity of RC beams (Soltanzadeh et al. 2013).

Despite the extensive research on shear capacity of beams without shear reinforcement (Bazant and Yu 2005, Lingemann et al. 2010), the accurate evaluation of the shear capacity of steel fiber reinforced concrete beams is still a challenge, due to the specificities introduced by using steel fibers. Additionally, most guidelines do not support the total replacement of stirrups by steel fibers (ACI 544.1R-96, Eurocode 2), unless strain hardening cement composites are used (CEB-FIP MC2010). Even some guidelines do not have a design framework to simulate the contribution of steel fibers for the shear capacity of FRC structures (ACI 544.1R-96).

This study introduces a new design framework for constructing a highly durable and structurally effective prefabricated prestressed HPFRC beams. A high performance fiber reinforced concrete (HPFRC) is developed aiming to suppress the steel stirrups without occurring shear failure. The longitudinal GFRP bars are placed with a minimum concrete cover, whose value was previously determined in an extensive pullout bending test program (Mazaheripour et al. 2013). The pre-stressed steel bars are placed with a HPFRC cover thickness that minimizes corrosion attacks, and its reinforcement ratio assures stability in case of a fire, where GFRP bars can lose their tensile capacity.

2. Experimental Program

The test program consists of five I cross section HPFRC beams reinforced with hybrid system of prestressed GFRP and steel longitudinal bars. A relatively high flexural reinforcement ratio was used to explore the potentialities of the HPFRC in terms of shear resistance ($\rho_{sl,eq} = \left(A_s / \left(b_w \times d_s \right) + E_{GFP} / E_s \times A_{GFP} / \left(b_w \times d_{GFRP} \right) \right) \times 100$=0.7, where A_s and A_{GFRP} are the cross section areas of the steel and GFRP bars, E_s and E_{GFRP} are the elasticity modulus of these materials, d_s and d_{GFRP} are the corresponding internal arms, and b_w is the width of the beam's cross section. Table 1 presents the relevant characteristics of the beams of the experimental program, where $d_{s,eq}$ is the equivalent internal arm. The prestress level applied to the flexural reinforcing system was the main variable investigated in this experimental program. All the beams were developed using HPFRC. The following designation was used for the HPFRC beams: SX-YGZ, where X is the prestress level applied to the steel strand (percentage of the nominal tensile strength), Y is the number of GFRP bars applied, and Z is the prestress level applied to the GFRP bar (percentage of the nominal tensile strength).

Table 1 – Specimens dimension and arrangements

Beam ID	**$d_{s,eq}$ mm**	**$a/d_{s,eq}$**	**No. of GFRP bars**	**Prestressing (% of ultimate strength)**	
				Strand	**GFRP**
S00-2G0	419	3.5	2	0	0
S25-2G0	419	3.5	2	25	0
S50-2G0	419	3.5	2	50	0
S50-3G0	421	3.5	3	50	0
S70-2G30	419	3.9	2	70	30

1.1. HPFRC Mix-Designs and Properties

A HPFRC with 90 kg/m^3 (V_f = 1.1%) of steel fibers, a nominal slump flow of 600 mm and an average compressive strength of about 67 MPa at 28 days was developed in the study. This performance was chosen to obtain self-compacting requisites with mechanical properties suitable for the industry of prefabrication. The materials used were: cement CEM I 52.5R limestone filler, sand and crushed granite coarse aggregate of maximum dimension of 4.75 mm and 12.5, respectively. Glenium SKY 617 super plasticizer was used to provide a good flowability for the mix (2.5% of binder). HPFRC has included hooked ends steel fibers of 33 mm length, aspect ratio of 65 and tensile strength of around 1100 MPa. Table 2 includes the adopted composition.

Table 2 – Concrete compositions (Kg/m^3)

Cement	Fly ash	Limestone filler	Water	Super Plasticizer	Fine sand	River Sand	Coarse Agg.	Steel Fiber
462	138	139	208	16	99	697	503	90

2.2. HPFRC Properties

To assess the flexural behavior of the HPFRC, three prismatic specimens were cast and subjected to the three point bending test configuration according to the recommendations of CEB-FIP MC2010. The Force-CMOD (crack mouth opening displacement) and the Force-Deflection obtained from bending tests of the notched beams are plotted in Fig. 1a and 1b. Based on the force values for the CMOD$_j$ (j=1 to 4), the corresponding force values, F_j, were obtained, and the residual flexural tensile strength parameters ($f_{R,j}$) were determined from $f_{R,j} = 1.5 F_j L \big/ \left(b h_{sp}^2 \right)$ where F_j [N] is the force corresponding to CMOD=CMOD$_j$ [mm], and L, b h_{sp} are the specimen's span length, and the width and distance from the notch tip to the top surface of the cross section. The obtained $f_{R,j}$, as well as the limit of proportionality, $f_{ct,L}^{f}$ are presented as $f_{R,j}$ Table 3.

Table 3 – Residual flexural tensile strength parameters of HPFRC

Specimen ID	Residual tensile strength parameters					
	CMOD$_1$=0.5 mm	CMOD2=1.5 mm	CMOD3=2.5 mm	CMOD4=3.5 mm		
	$f_{R,1}$ MPa	$f_{R,2}$ MPa	$f_{R,3}$ MPa	$f_{R,4}$ MPa	$f_{R,3} / f_{R,1}$	$f_{ct,L}^{f}$ MPa
PS1	14.24	15.84	15.02	12.83	1.05	8.17
PS2	16.23	18.42	14.91	11.07	0.92	7.97
PS3	14.98	17.28	15.44	14.45	1.03	6.24
Average:	15.15	17.18	15.12	12.78	0.99	7.46
(CoV):	(6.66)	(7.53)	(1.85)	(13.24)	(7.29)	(14.22)

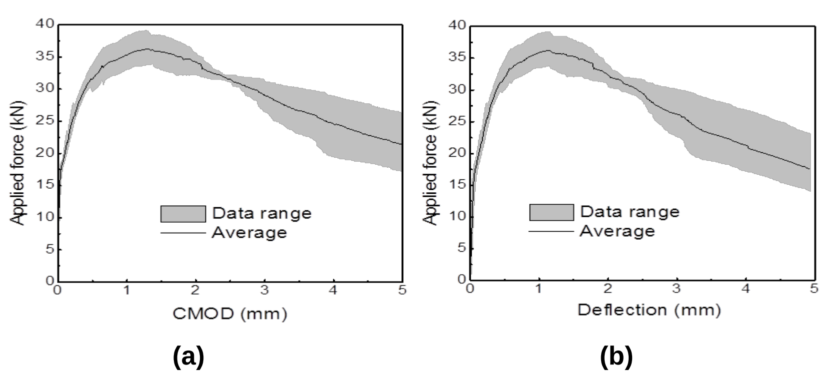

Fig. 1 – Results of the notched beam tests in terms of (a) Force-CMOD and (b) Force-Deflection

1.3. Reinforcing system of the beams

Each beam was longitudinally reinforced with one prestressed steel strand (15.2 mm diameter with a nominal cross-section of 140 mm^2) of seven wires (of 5 mm diameter), and 2 or 3 passive or prestressed GFRP bars of 12 mm diameter and with ribbed-surface (Mazaheripour et al. 2013). The ribs of the GFRP bar have a constant height of 6% of the bar diameter and a spacing of about 8.5 mm. From tensile tests executed according to the standard ASTM D7205/D7205M-06, an average value of 56 GPa was obtained for a measured diameter of the bar's cross section of 13.0 mm. In contrast with the behavior of the steel strand, the GFRP bar behaves elastically and linearly up to failure. The yielding and ultimate tensile stress of steel tendon are 1785 and 1917 MPa, while the ultimate tensile strength of GFRP bar is 1350 MPa.

1.4. Specimens Preparation and Test Setup

The configuration and test setup of the hybrid steel/GFRP HPFRC beams are shown in Fig. 2. The shear span to effective depth ratio, $a/d_{s,eq}$, was 3.5 for the first 4 beams. After investigating the effect of prestressing on shear behavior of the beam, the final beam was developed and tested with $a/d_{s,eq}$ =3.9. Table 1 indicates the prestressing percentage and reinforcing arrangements of each beam. In all the beams, the prestressed force was released 3 days after casting. The beams were cured at the average temperature of 23 °C and 60% moisture for 7 days. They were tested at the age of 28 days.

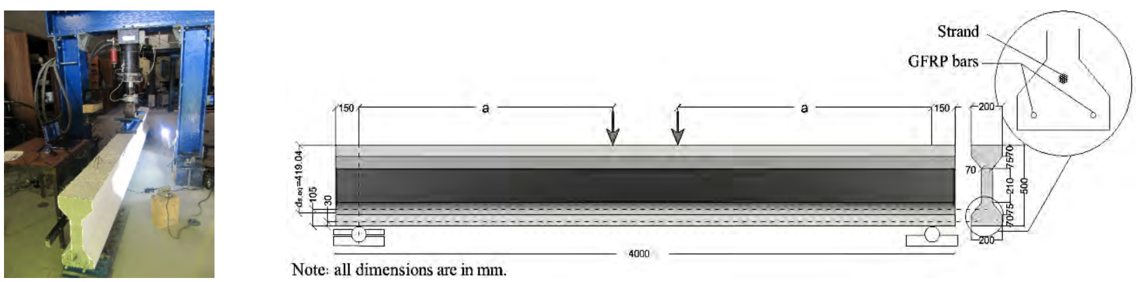

Fig. 2 – Beam configuration and test setup (dimensions in mm)

Deflection of the beams was measured using five Linear Voltage Differential Transducers (LVDTs) (No. 1 to 5, marked in blue color in Fig. 3) disposed according to the arrangement indicated in Fig. 3. Two LVDTs (No. 7 and 8 in red color) were used for measuring the deformation on the compressive strut on the front sides of the beam, and 2 others (No. 6 and 9 in green color) were used for measuring crack widths on the shear span. Another LVDT was also used to control the loading procedure at a displacement rate of 10 µm/s up to the failure of the beams. Seven strain gauges (SGs), SG1 to SG7, were installed on GFRP surface to measure the strains. One more strain gauge was used at the top of the beam, in the center, to measure the concrete strain during loading the beam. The applied load was measured using a load cell of ±700 kN and ±0.05% accuracy.

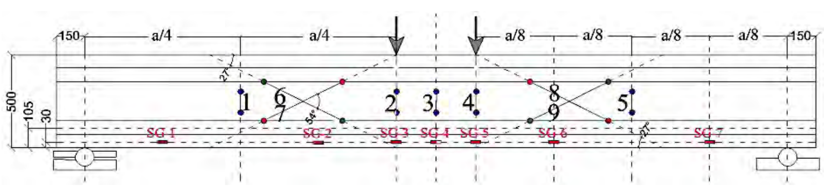

Fig. 3 – Instrumentation details (dimensions in mm)

2. Experimental Results and Discussion

Fig. 4 represents the load versus mid-span deflection (*F-u*) of the tested beams. Due to the relatively high flexural capacity, all the beams failed in shear, but for a considerable deflection level, much higher than the deflection for serviceability limit states, SLS (L/250=16mm), δ_{SLS}. Comparing to the reference HPFRC beam, S00-2G0 beam, (without any prestress level for the hybrid reinforcement), it can be concluded that

by increasing the prestress level on the steel strand the load carrying capacity for SLS (F_{SLS}) has increased significantly (6.81%, 15% and 14.86% for S25-2G0, S50-2G0, S50-3G0 beams, respectively). However, the ultimate load carrying capacity was almost the same, since it is limited by the shear resistance of the beams. Comparing the behavior of the beam S50-3G0 reinforced using 3 GFRP bars with that of its similar prestressed case, beam S50-2G0 with 2 GRFP bars, it is observed that the higher flexural reinforcement ratio has assured a larger post-cracking stiffness, with higher load carrying capacity for the deflection at serviceability limit state conditions. However, the deflection at ultimate load has decreased because the beam's load carrying capacity is limited by its shear resistance that is common for both beams. Shear resistance can be increased by enhancing the post-cracking behavior of HPFRCC. However, this requires extra costs that are not justifiable, since by adopting suitable pre-stress level for steel and GFRP bars a quite high load carrying capacity can be obtained for serviceability limit state conditions, with a crack width lower than the required limit. In fact, adopting a pre stress percentage of 70% for the steel strand and 30% for the GFRP bars in S70-2G30 beam, a F_{SLS} of about 220 kN was obtained. This load level guarantees that this type of beams can be used in pre-fabrication structural systems of buildings of industrial or commercial activities, where they give support to pre-stressed slabs of a span length 12 to 20 m for a live load 4 to 6 kN/m^2, which is one of the objectives of the present research project. According to previous studies (Soltanzadeh, et al. 2013), this pre-stress is the maximum one that should be applied to the adopted GFRP bars. In spite of having higher $a/d_{s,eq}$ ratio, and therefore the comparison cannot be a straightforward process between S70-2G30 beam and previous beams (3.9 instead 3.5 in the previous beams), the *F-u* clearly supports the benefits of increasing, as much as possible, the prestress level in both flexural reinforcements. Table 4 resumes the relevant results.
Fig.4 shows the crack patterns registered at the failure of the beams. It is quite evident the formation of a much diffuse crack pattern in S70-2G30 beam, with several potential shear failure cracks, which was responsible for the pseudo-plastic plateau in the F-u response above a deflection of about 30 mm.

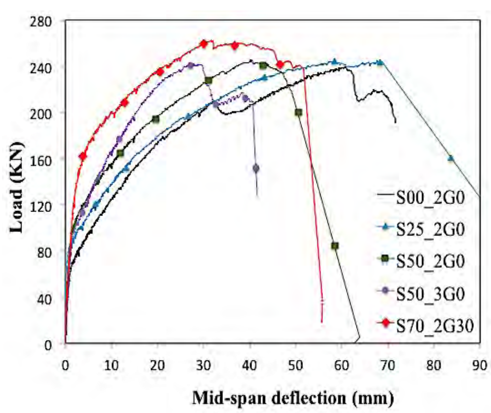

Fig. 4 – load *vs.* deflection relationship

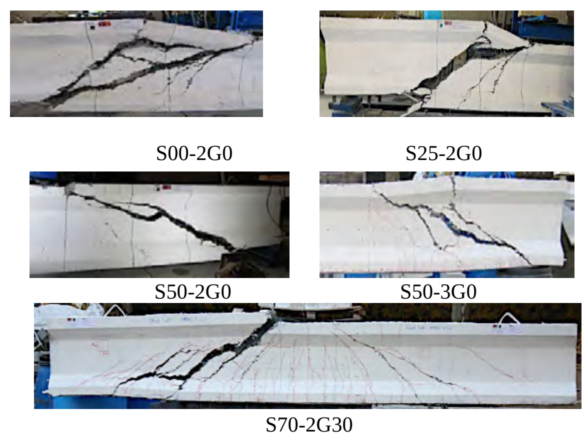

Fig. 5 – Final crack pattern of the beams

Table 4 – Main results

Specimen ID	F_{SLS} (KN)	P_u (KN)	V (KN)	δ_u (mm)
S00-2G0	151.42	240.12	120.06	60.71
S25-2G0	161.98	244.80	122.40	67.68
S50-2G0	178.14	245.60	122.80	40.21
S50-3G0	198.84	242.48	121.24	27.91
S70-2G30	218.55	263.00	131.10	32,70

P_u : Peak load; V: Shear load; δ_u: Deflection at maximum load; F_{SLS}: Load at serviceability limit state

3. Conclusion

An experimental program composed of 5 quasi-real scale I-shape HPFRC beams flexurally reinforced with a hybrid system of a steel strand and GFRP bars applied with different level of prestress was executed for assessing the potentialities of these new types of materials for the development of an innovative structural system almost immune to corrosion concerns. The obtained results have evidenced that using the HPFRC and adopting a prestress level of 70% for the steel strand and 30% for the GFRP bars, a quite high load carrying capacity can be achieved (this even exceeded the load at yield initiation of the strand with the ratio of 1.17) with a very ductile response, since deflection at failure was about 3 times higher the deflection at serviceability limit states.

4. Acknowledgements

This work is supported by FCT (PTDC/ECM/105700/2008) and QREN (Project UrbanCrete n. 30367). The authors also thank the collaboration of the following companies: Tensacciaci in the name of Eng. F. Pimenta for the assistance on the application of prestress reinforcements; Sireg and Schoeck (GFRP bars); Casais (moulds); Maccaferri and Exporplas (fibers); Secil (Cement), SIKA (superplasticizers); CiviTest (production of HPFRC specimens).

5. References

ACI 544.1R-96. “State-of-the-Art Report on Fiber Reinforced Concrete.” ACI committee report, 1996.

ASTM D7205/D7205M-06. “Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars”, ASTM International, US, 2006.

Bazant, Z.P., and Yu, Q. “Designing against size effect on shear strength of reinforced concrete beams without stirrups”, Journal of Structural Engineering, Vol. 131, No. 12, 2005, pp. 1877-1885.

CEB-FIP. “Model Code 2010: Final Draft”, Model Code prepared by Special Activity Group 5, Lausanne, September 2011.

Cucchiara, C., Mendola, L. L., Papia, M. “Effectiveness of stirrups and steel fibers as shear reinforcement”, Journal of Cement and Concrete Composites, Vol. 26, 2004, pp. 777–786.

Ding, Y., Youb, Z., Jalali, S. “The composite effect of steel fibers and stirrups on the shear behaviour of beams using self-consolidating concrete”, Journal of Engineering Structures, Vol. 33, 2011, pp. 107–117.

Eurocode 2: ENV 1992- 1-1:1991 and EN 1992- 1-1:2004: Design of concrete structures – Part 1-1: General results and rules for buildings.

Felekoğlu, B., Türkel, S., Baradan, B. “Effect of water/cement ratio on the fresh and hardened properties of self-compacting concrete”, Journal of Building and Environment, Vol. 42, 2007, pp. 1795–1802.

Ferrara, L., Park, Y., Shah, S. P. “A method for mix-design of fiber-reinforced self-compacting concrete”, Journal of Cement and Concrete Research, Vol. 37, 2007, pp. 957–97.

Lingemann, J., Sauer, J., and Zilch, K. “Shear capacity of steel fiber reinforced concrete beams with stirrups”, 3rd fib International Congress, Washington, D.C. United States, 2010.

Mazaheripour, H.; Barros, J.A.O.; Sena-Cruz, J.M.; Pepe, M; Martinelli, E., “Experimental study on bond performance of GFRP bars in self-compacting steel fiber reinforced concrete”, Composite Structures Journal, Vol. 95, 2013, pp. 202-212.

Rao, G., A., and Rao, A., S. “Toughness indices of steel fiber reinforced concrete under mode II loading.” Journal of Material and Structure, Vol. 42, 2009, pp. 1173-1184.

Soltanzadeh, F., Mazaheripour H., Barros J., Sena-Cruz J. “Shear capacity of HPFRC beams flexurally reinforced with steel and prestressed GFRP bars”, FRPRCS-11, 11th international symposium on fiber reinforced polymers for reinforced concrete structures, Proceeding, 2013.

Voo, Y., Poon, W., and Foster, S. “Shear Strength of Steel Fiber-Reinforced Ultrahigh- Performance Concrete Beams without Stirrups”, Journal of Structural Engineering, Vol.136, No.11, 2010, pp.1393–140.