Proceedings of the 10th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2025)
July, 2025 Imperial College London Conference Center, London, United Kingdom
Paper No. 365
DOI: 10.11159/iccste25.365

Experimental Study and Theoretical Analysis on the Flexural Performance of High Modulus HFRP Reinforced Concrete Beams during Normal Usestage

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Abstract **-** Low-modulus FRP bars used to reinforce concrete structures tend to result in wide cracks and large deflections during the service stage, significantly impacting the structure's usability and safety. This limitation has hindered the widespread application of such materials in engineering. To address this issue, this study investigates the factors affecting the flexural performance of concrete beams reinforced with high-modulus HFRP bars during the service stage. Through four-point bending tests on 3 beams reinforced with single-type FRP bars and 10 beams reinforced with high-modulus HFRP bars, the study analyzes the effects of bar material type, hybrid ratio, reinforcement ratio, and concrete strength grade on the failure mode, crack width, and deflection of high-modulus HFRP-reinforced concrete beams during the service stage. The test results indicate that, compared to beams reinforced with single low-modulus FRP bars, the increased modulus of elasticity brought by fiber hybridization effectively suppresses deflection and crack development in high-modulus HFRP-reinforced concrete beams during the service stage. The findings of this study provide guidance for the design and development of high-modulus HFRP-reinforced concrete beams.

Keywords**:** High-Modulus HFRP Bars; Normal use stage; Flexural Performance

1. Introduction

Current research indicates that using FRP bars as a replacement for steel reinforcement in concrete structures is an effective method for addressing the issue of steel corrosion within reinforced concrete structures1.However, the commonly used GFRP (Glass Fiber Reinforced Polymer) and BFRP (Basalt Fiber Reinforced Polymer) bars in engineering applications today exhibit relatively low elastic modulus, ranging from 38 to 60 GPa. This results in low-modulus single FRP reinforced concrete structures exhibiting drawbacks such as wide cracks and excessive deflections during normal service 2-4. This not only fails to fully leverage the high tensile strength characteristics of low-modulus GFRP and BFRP bars but also compromises structural safety, significantly impacting their performance during regular use.

In this study, high-modulus HFRP bars were developed by blending high-modulus glass fibers with carbon fibers. These HFRP bars offer a cost advantage over CFRP bars while providing a higher elastic modulus than GFRP and BFRP bars, with values ranging from 90 GPa to 142 GPa, placing them at the forefront of international advancements. The application of these high-modulus HFRP bars in concrete beams can effectively reduce the crack widths and increase the stiffness of beams compared to those reinforced with low-modulus single FRP bars. This experiment involved testing 13 beams to analyze the impact of high-modulus HFRP bars on the characteristic loads, deflections, and crack widths of the beams.

2. EXPERIMENTAL PROGRAM

2.1. Design of specimens

This experiment involved the design and fabrication of 13 beams. The detailed design parameters of the test beams are shown in Table 2. The experimental variables included the type of tensile reinforcement material, the concrete strength grade, the reinforcement ratio, and the hybridization ratio.

Table 1: Design plan for test beams.

Test piece number	Type of tensile reinforcement	Concrete strength grade	Reinforcement ratio	Mixed ratio
G40-0.73	GFRP	C40	0.73%	/
B40-0.73	BFRP	C40	0.73%	/
C40-0.73	CFRP	C40	0.73%	/
CG40-0.73-1/2	CG-HFRP	C40	0.73%	1/2
CG40-0.73-1/4	CG-HFRP	C40	0.73%	1/4
CG40-0.73-1/6	CG-HFRP	C40	0.73%	1/6
CG40-0.49-1/4	CG-HFRP	C40	0.49%	1/4
CG40-1.05-1/4	CG-HFRP	C40	1.05%	1/4
CG30-0.73-1/4	CG-HFRP	C30	0.73%	1/4
CG50-0.73-1/4	CG-HFRP	C50	0.73%	1/4
CB40-0.73-1/2	CB-HFRP	C40	0.73%	1/2
CB40-0.73-1/4	CB-HFRP	C40	0.73%	1/4
CB40-0.73-1/6	CB-HFRP	C40	0.73%	1/6

Note: In the specimen numbering, "G," "C," "B," "CG," and "CB" represent GFRP bars, CFRP bars, BFRP bars, CG hybrid bars, and CB hybrid bars, respectively. The numbers "30," "40," and "50" indicate the concrete strength grades of C30, C40, and C50. The values "0.49," "0.73," and "1.05" denote reinforcement ratios of 0.49%, 0.73%, and 1.05%, respectively. The ratios "1/2," "1/4," and "1/6" represent the hybridization ratios of CG hybrid bars as 1/2, 1/4, and 1/6.

All FRP-reinforced concrete beams have a total length of 2200 mm, with a calculated span of 1800 mm. The cross-sectional dimensions of the beams are 150 mm × 250 mm, and the thickness of the concrete cover is 20 mm. In the compression zone of the test beams, two CG1/4-HFRP bars with a diameter of 10 mm are arranged. The reinforcement ratios in the tension zone are 0.49%, 0.73%, and 1.05%, with the arrangements consisting of two HFRP bars with a diameter of 10 mm, three HFRP bars with a diameter of 10 mm, and three HFRP bars with a diameter of 12 mm, respectively.

The stirrups are made of 10 mm high-modulus GFRP stirrups, with a spacing of 70 mm in the bending-shear region and a spacing of 200 mm in the pure bending region. The stirrups are closely spaced at the supports, with a spacing of 40 mm. The dimensions and reinforcement layout of the test beams are illustrated in Figure 1.

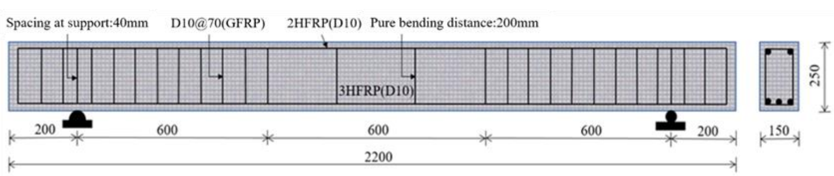

Fig. 1. Schematics of the tested specimens (Unit in mm).

2.2. Test setup

The flexural tests on the FRP-reinforced concrete beams were conducted using a four-point bending load configuration with static incremental loading. Prior to cracking, each load increment was set at 5 kN, while after cracking, each increment was increased to 10 kN, with each loading stage maintained for 2 minutes to record the crack widths in the pure bending region. The test was stopped when the applied load decreased to 80% of the ultimate load. The arrangement of measurement points is shown in Figure 2. Data was collected using a data acquisition board and corresponding software, with a sampling frequency of 1 Hz.

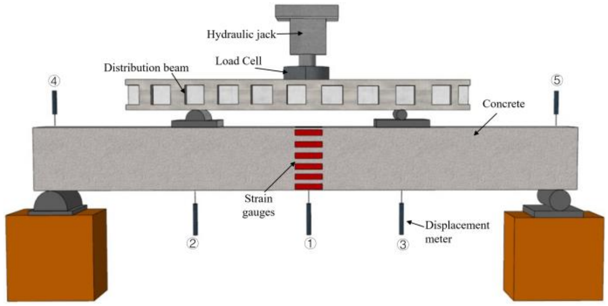

Fig. 2. Test setup and measurement layout. (Unit: mm)

3. Test Results

3.1. Failure modes

During the loading process of the test beams, each beam exhibited its first vertical crack in the pure bending region, with the crack height approximately ranging from 2/5 to 4/5 of the beam height. The beams with higher hybridization ratios and reinforcement ratios exhibited relatively lower initial crack heights, around 2/5 to 1/2 of the beam height. As the load continued to increase, both the number and width of cracks in the pure bending region increased steadily, and the cracks gradually extended upward along the height of the beam. Upon reaching the ultimate load, all test beams experienced crushing failure of the concrete in the compression zone of the pure bending region.

Table 2. Test results.

Test piece number	Cracking load (kN)	Crack width under 0.3Pu load (mm)	Mid span deflection under 0.3Pu load (mm)	Ultimate load (kN)	Destruction mode
G40-0.73	15.1	0.58	6.94	120.2	CC
C40-0.73	19.7	0.53	5.83	165.7	CC
B40-0.73	14.5	0.61	7.25	132.4	CC
CG40-0.73-1/2	19.6	0.38	5.07	176.1	CC
CG40-0.73-1/4	19.1	0.45	5.21	168.2	CC
CG40-0.73-1/6	18.5	0.45	5.01	149.8	CC
CG40-0.49-1/4	18.2	0.57	4.60	132.4	CC
CG40-1.05-1/4	19.8	0.37	5.20	180.8	CC
CG30-0.73-1/4	17.8	0.43	4.67	150.0	CC
CG50-0.73-1/4	20.8	0.45	5.43	174.6	CC
CB40-0.73-1/2	19.4	0.38	5.31	174.2	CC
CB40-0.73-1/4	18.9	0.50	5.57	166.4	CC
CB40-0.73-1/6	18.2	0.48	5.17	145.7	CC

Note: 0.3Pu represents the service limit state load, while Pu denotes the ultimate load capacity of the test beams. The failure mode "CC" stands for "Concrete Crushed"failure.

(a)Beam CG40-0.73-1/2 failure mode diagram

(b)Beam CG40-0.73-1/4 failure mode diagram

(c)Beam CG40-0.73-1/6 failure mode diagram

(d)Beam CB40-0.73-1/2 failure mode diagram

(e)Beam CB40-0.73-1/4 failure mode diagram

(f)Beam CB40-0.73-1/6 failure mode diagram

Fig. 3. Failure mode diagram of High modulus HFRP concrete beam

3.2. Load-mid-pan deflection curve

The load-displacement curves for all beams in this experiment are shown in Figure 4. The load-mid-span deflection curve of the high-modulus HFRP-reinforced concrete beams exhibits a bilinear mode.

In the first stage, prior to cracking, the high-modulus HFRP-reinforced concrete beams remain in the elastic deformation phase, with mid-span deflection showing a linear increase as the load increases. In the second stage, after the concrete has cracked, the stiffness of the test beams deteriorates. Due to the linear elastic stress-strain relationship of the FRP bars, the load-mid-span deflection curve continues to exhibit linear growth even after cracking occurs.

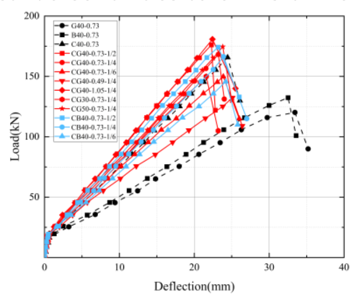

Fig. 4. Load-mid-pan deflection curve

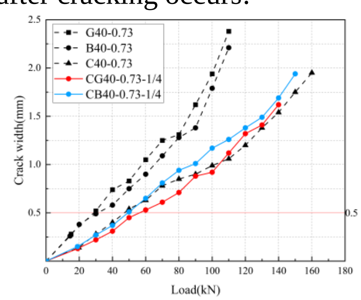

Fig. 5. The influence of different types of tensile reinforcement on crack width

As the elastic modulus of the reinforcement material increases, both the cracking load and the ultimate load capacity rise significantly, with the reinforcement ratio having a considerable impact on the cracking load and ultimate load of high-modulus HFRP-reinforced concrete beams. Compared to the test beam G40-0.73, the cracking load of the high-modulus HFRP-reinforced concrete beams increased by as much as 29.8%, while the ultimate load capacity saw a maximum increase of 46.5%.

In contrast to beams reinforced solely with low-modulus FRP bars, the enhancement of modulus due to hybridization effectively reduces the deflection of the test beams. Under the same reinforcement ratio at the service limit state load, the deflection of high-modulus HFRP-reinforced beams was reduced by 24.9% compared to GFRP-reinforced beams.

The increase in the elastic modulus of the tensile FRP bars augmented the axial stiffness of the test beams' cross-section, leading to reduced deformation. Consequently, the initial crack widths of the test beams gradually decreased, and at the same load level, the crack widths of the test beams also diminished. Under the same reinforcement ratio at the service limit state load, the crack widths of CG hybrid fiber FRP-reinforced beams were reduced by up to 34.5% compared to GFRP-reinforced beams.

Conclusion

(1) The elastic modulus of the high-modulus HFRP bars produced through hybridization can reach up to 142 GPa, and they possess secondary fracture capability. Compared to conventional GFRP bars, the elastic modulus of CG1/2-HFRP bars has been enhanced by 186.5%.

(2) The increase in modulus resulting from fiber hybridization leads to greater ultimate load capacity and cracking load for the beams, enhancing the axial stiffness of the beams. This significantly addresses the issue of excessive deflection in FRP-reinforced concrete beams during the service stage and effectively suppresses the development of cracks in the reinforced concrete beams during normal use. Under the same reinforcement ratio during the service stage, the maximum deflection was reduced by 24.9%, while the crack width could be minimized by up to 34.5%.

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