Effect of Longitudinal Steel Reinforcement on Shear-Flexural Behavior of Hybrid GFRP/Steel Reinforced Concrete Beams

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**Abstract.** This paper presents experimental results on shear-flexural behavior of concrete beams reinforced with a combination of glass fiber-reinforced polymer (GFRP) and steel bars. A total of four reinforced concrete (RC) were cast and tested in four-point bending, with a shear span/equivalent depth ratio *a/d* = 3.65. Different longitudinal steel reinforcement ratios, ranging from 0% to 1.01%, were analyzed to study the effect of the longitudinal steel reinforcement ratio on the shear-flexural behavior of hybrid GFRP/steel RC beams. The results obtained revealed the significant influence of the longitudinal steel reinforcement ratio on shear-flexural strength of hybrid GFRP/steel RC beams.

**Keywords:** GFRP; Concrete beam; Hybrid reinforcement; Shear-flexural; Strength

1. Introduction

Reinforced concrete (RC) structures have gained widespread use in the construction industry due to their strength, versatility, and durability. Nevertheless, just like any other material, reinforced concrete structures are prone to degradation over time. The durability of RC structures depends on a complex of factors affecting both the concrete and steel reinforcement, as noted in previous studies [1-4]. One of the most affecting factors is the corrosion of steel reinforcement, especially in RC structures exposed to corrosive environments.

Fiber Reinforced Polymer (FRP) reinforcement is becoming an increasingly popular alternative to traditional steel reinforcement in the construction industry due to its outstanding properties, including high strength-to-weight ratio; corrosion resistance; durability, ease of installation, non-magnetic properties, design flexibility, and sustainability [5-10]. Despite these advantages, FRP reinforcement also has certain disadvantages, including a low elastic modulus and lack of plasticity, which can significantly affect the performance of FRP RC beams. These disadvantages may result in high deformation, wide crack width, low ductility, brittle failure, etc. of FRP RC structures [5, 6, 8]. To overcome these problems, FRP RC bending elements are typically designed with over-reinforced characteristics and conservative safety coefficients. With the purpose of improving the stiffness, ductility and other characteristics, additional steel bars were suggested to add to FRP reinforced concrete (RC) structures. As a result, the hybrid FRP/steel reinforced concrete is provided. In the last decades, hybrid FRP/steel RC beams were intensively investigated. Most of the research focused on the flexural behavior of these beams [11-14]. Few studies on time-dependent behavior have been conducted [15]. However, research on shear-flexural behavior of hybrid FRP/steel RC beams has not yet been conducted by researchers. To this purpose, current work focuses on the experimental investigation of the shear-flexural behavior of hybrid beams, including the analysis of load-deflection relationships, crack patterns, and material strains.

1. Experimental program
   1. Testing specimens

Three hybrid GFRP/steel and one reference GFRP RC beams with rectangular cross-sections of 100 mm (width) × 200 mm (height) × 2000 mm (length) were manufactured and tested under four-point bending. The testing span was 1700 mm with a pure bending zone of 400 mm. Details of the beam specimens are shown in Fig. 1.



**Fig. 1.** Details of beam specimens.

All reference and hybrid RC beams were designed in accordance with the recommendations of ACI440.1R-15 [16] and other previous studies [17, 18]. In the compression zone, all testing beams were reinforced with one plain round steel bar with a diameter of 6mm and a concrete cover of 20mm. Meanwhile, in the tension zone, a single GFRP bar with a diameter of 14mm was utilized to reinforce all beams, which had a concrete cover of 15mm. For hybrid beams, a ribbed steel bar with a diameter of either 10mm, 12mm, or 14mm and a concrete cover of 40mm was included. All beams were provided with shear reinforcement, which consisted of single-legged plain round steel bars with a diameter of 6mm and a spacing of 100mm in the shear span. Details of the geometry and reinforcement of testing beams were displayed in **Table 1.**

**Table 1.** Details of beam specimens.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Beam’s ID | Dimensions, mm | | | | | Longitudinal reinforcement | | | | | |
| *b × h* | *Cf* | *Cs* | *df* | *ds* | GFRP | | Steel | | Total | |
| *Af*, mm2 | *ρf*,  % | *As*, mm2 | *ρs*,  % | *At*, mm2 | *ρt*,  % |
| C-0% | 100×200 | 15 | - | 178 | - | 127.6 | 0.72 | - | 0 | 127.6 | 0.72 |
| H-0.51% | 15 | 40 | 178 | 155 | 127.6 | 0.72 | 78.50 | 0.51 | 206.1 | 1.23 |
| H-0.73% | 15 | 40 | 178 | 154 | 127.6 | 0.72 | 113.1 | 0.73 | 240.7 | 1.45 |
| H-1.01% | 15 | 40 | 178 | 153 | 127.6 | 0.72 | 153.9 | 1.01 | 281.5 | 1.73 |

Notes: The ID of the beam is comprised of two parts: the first part indicates the beam type, where C denotes a control beam and H refers to a hybrid beam, and the second part indicates the longitudinal steel reinforcement ratio; *Cf* and *Cs* represents the clear concrete covers of GFRP and steel bars, respectively; *df* and *ds* are the distances from the centroid of GFRP and steel bars to the outermost compression face, respectively; *Af* and *ρf* are the area and reinforcement ratio of GFRP; *As* and *ρs* are the area and reinforcement ratio of steel; *As* and *ρs* are the total area and total reinforcement ratio.

* 1. Materials

A concrete mix with an expected compressive cubic strength of 40 MPa was used. The mix comprises Portland cement PCB40, fine and coarse aggregates, water, and had a W/C ratio of 0.5. The actual concrete strength was determined by testing five cubics, which were poured along with the beam specimens. All beams were cast from the same batch of concrete mix.

Based on the average results of a tensile test conducted on a 12mm-diameter ribbed steel bar, the yield strength and ultimate strength were found to be 396 MPa and 589 MPa, respectively. The elastic modulus of the steel bar was determined to be 200 GPa

GFRP bars used for the beam specimens were manufactured by FRP Vietnam, JSC. According to the manufacturer’s data, the tensile strength and elastic modulus of the GFRP bar were 970 MPa and 44.3 GPa, respectively.

* 1. Test setup

Four-point static bending tests were carried out in this study. The schematic and actual diagrams of the test were shown in **Fig. 1** and **Fig. 2**, respectively. The load from a hydraulic jack was applied on the beams as concentrated loads 400m mm apart through a distribution beam, the load rate was controlled by mid-span displacement with a rate of 2 mm/min. The loading span is 1700 mm and the shear span (a) is 650 mm. The shear span ratio (*a/d)* of the tested beams was 3.65, which ranged from 3 to 5, and was expected to occur inclined tension and shear–compression as for RC beams.

All beam specimens were instrumented with three strain gauges to measure the strain in compression zone (S1), in GFRP bar (S2) and steel bar (S3) as shown in **Fig. 1**. One LVDT was attached to the beam at midspan to measure the deflection, also two dual indicators were fixed at both supports to eliminate the holder’s displacement. The load value from the hydraulic jack was controlled by a loadcell with a capacity of 300 kN. All instruments were connected to data acquisition system STS-WIFI (BDI, America), which was connected to a computer through a program. Data from these instruments were automatically recorded on the computer. Data from dual indicators were collected by naked eyes.

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Description automatically generated

**Fig. 2.** Actual test setup.

1. Test results and discussions
   1. Crack patterns

**Fig. 3** shows the crack patterns observed in tested beams at failure. Initially, normal cracks formed in the pure bending zone, followed by inclined cracks. As the load increased, both normal and inclined cracks developed and continued to widen until the longitudinal steel bar yielded. After yielding, the number of new cracks decreased, but existing cracks continued to widen until the beam ultimately failed on an inclined section with an inclination angle ranging from 33.5 to 45.9 degrees relative to the beam axis. At the failure, the critical inclined crack had developed extensively, leading to the crushing of concrete at its peak due to a sudden reduction in the compression zone height.

In the classical theory of RC, shear failure can be classified into 3 subtypes such as shear-tension failure, shear-compression failure, and flexural-shear failure [19]. In the test, all 4 beams showed shear failure modes consistent with the corresponding shear span/depth ratios. It can be seen that the presence of longitudinal steel reinforcement does not change the failure pattern of these beams.

The number of main cracks in the tested beams varied from 9 to 11, with an average spacing ranging from 97 mm to 138 mm. The crack spacing tended to decrease as the amount of longitudinal steel reinforcement in hybrid beams increased.

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a) Beam C-0%

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b) Beam H-0.51%



c) Beam H-0.73%



d) Beam H-1.01%

**Fig. 3.** Crack patterns at failure of tested beams.

* 1. Load-midspan deflection relations

**Fig. 4** illustrates the load-midspan deflection curves of all tested beams. Unlike the failure mode, the load-deflection curves of hybrid RC beams differ from that of the control GFRP RC beam. From the begging of loading to complete failure, the hybrid RC beams undergo three obvious stages: from beginning to yielding of steel; after yielding of steel to peak load; and after peak load. Meanwhile, the control beam undergoes only one stage.

Due to the contribution of steel rebar, the stiffness of hybrid RC beams is higher than that of the control beam. Therefore, before yielding of the steel bar, the slopes of load-deflection curves of hybrid beams are higher compared with that of the control beam. After yielding, the stiffness of hybrid and control beams are similar, i.e. the slopes of load-deflection curves of all hybrid and control beams are nearly the same. This shows that the contribution of the steel bar to the stiffness of the hybrid beam is neglectable after steel yielding (SY). Furthermore, the contribution of the steel bar reduces the deflections of the hybrid beams at the yield point and peak point.



**Fig. 4.** Load-midspan deflection curves.

* 1. Strain in materials

The strain in materials versus applied load curves of all tested beams are illustrated in **Fig. 5**. As mentioned earlier, the compression zone of all beams was crushed, and therefore the maximum compressive concrete strain reached its ultimate value (approximately 3‰) for all beams. In the case of hybrid beams, the obtained strain results exhibited that the longitudinal steel bar has reached its yield strength (strain of 0.2%). Moreover, at the same load value, the strains in compressive concrete of hybrid beams are significantly smaller than that of the GFRP RC beam. Meanwhile, for the control beam, due to the absence of a steel bar, the strain of GFRP is much larger than that in hybrid beams.

|  |  |
| --- | --- |
| a) Beam C-0% | b) Beam H-0.53% |
| c) Beam H-0.71% | d) Beam H-1.01% |
| Note: S1 – strain gaugue on the outermost compression concrete layer; S 2 – strain gauge on the GFRP bar; S3 – strain gauge on the steel bar | |

**Fig. 5.** Development of strains in materials.

Conclusions

This work focuses on the effect of the steel rebar ratios on the behavior of hybrid GFRP/steel RC beams. The following conclusions can be drawn:

- The contribution of steel bars in beams significantly affects the load-deflection curve of the hybrid beams. Increasing the amount of steel bar increases the yield load and the bending stiffness of the beam.

- At the span ratio a/d=3.65, the experimental results indicates that there is no change in the failure mode of the hybrid beams. Shear-flexural failure was observed in all beams.

Further experiment on different shear span/depth ratios should be carried out to better understand the importance of the amount of steel bar on failure modes as well as the shear resistance mechanism of hybrid beams.

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