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Numerical Investigation on the Flexural Behaviour of Hybrid BFRP- and GFRP-steel Reinforced Concrete Beams

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Abstract

Steel bars are the typical choice for reinforcing concrete members due to their relatively low cost, high tensile strength and ductile behaviour. However, in some applications where there might be exposure to aggressive agents such as coastal chlorides and de-icing salts, steel bars become susceptible to erosion. In circumstances where high ultimate moment capacity is needed steel bars may not provide the adequate capacity required. The use of Fibre-Reinforced Polymer (FRP) bars as sole and hybrid reinforcement bars was introduced to meet these deficiencies of steel bars. This paper focuses on concrete beams reinforced with hybrid FRP-steel bars. The FRP materials considered in this study are Glass Fibre-Reinforced Polymer (GFRP) and Basalt Fibre-Reinforced Polymer (BFRP). To the author's best knowledge very few studies exist that compare the flexural performance of hybrid GFRP- and BFRP-steel reinforced beams. The performance of these two hybrid reinforcements is compared in terms of deflection and ultimate moment capacity, and a better understanding of the effect of the hybrid reinforcement ratio is gained. This was achieved by conducting a numerical investigation in ABAQUS, where thirteen reinforced concrete beams were modelled and tested under a four-point bending test. Results indicated that the large deflections, experienced by concrete beams reinforced solely with FRP bars can be reduced by opting for the use of hybrid FRP-steel bars as the internal reinforcement. Furthermore, results showed that concrete beams reinforced with hybrid FRP-steel bar exhibited higher ultimate capacity compared to FRP only or steel only reinforced beams. In addition, concrete beams reinforced with BFRP bars outperformed GFRP bars in terms of deflection and ultimate capacity, albeit slightly, both as sole FRP reinforcement and in hybrid FRP-steel scenarios. Lastly, the study found that the hybrid reinforcement ratio can be used to control the deflection and ultimate capacity of hybrid FRP-steel bar reinforced concrete beams. The results of this study provide a better understanding of the two types of FRP materials considered in this study. Knowing how the hybrid reinforcement ratio affects the behaviour of hybrid FRP-steel reinforced concrete beams can help design beams that meet required performance early in the design stage.

Keywords: fibre-reinforced polymer bars, hybrid frp-steel bars, hybrid reinforcement ratio, finite element modelling, basalt fibre-reinforced polymers, glass fibre-reinforced polymers, deflection

1 Introduction

The use of fibre-reinforced polymer (FRP) bars as internal reinforcement in reinforced concrete (RC) beams began in the 1950s as an attempt to mitigate problems associated with steel bars. Two major problems associated with steel bars are inadequate strength (in some circumstances) and corrosion due to the use of de-icing salts, especially on bridges [1-3]. FRP bars are an attractive alternative due to its properties such as a high strength to weight ratio, corrosion and alkali resistance. Other added advantages of FRP bars are their transparency to magnetic and electric fields [3,4]. However, the use of FRP bars in RC beams poses a new set of challenges such as larger deflections and larger crack widths. The larger deflections are due to the low elastic modulus of FRP rebars [4-7]. A study by Ge and Zhang et al. [5] revealed that RC beams reinforced with FRP bars experienced larger deflections compared to RC beams reinforced only with steel bars. RC beams reinforced with hybrid FRP-steel bars were found to have deflected less in comparison to RC beams reinforced with FRP bars, but more than beams reinforced with steel bars. Results from other studies [3,8,9] also showed that the deflection of FRP bars could be reduced by the addition of steel bars. RC beams reinforced solely with FRP bars generally have very high ultimate moment capacities owing to the superior mechanical properties of FRP bars. While adding steel bars to a RC beam reinforced with FRP bars may not contribute much in terms of ultimate capacity, it still has its advantages. Various researchers [3,5,10] suggested that reinforcing RC beams with two layers of bars, with steel bars on the inner layer and FRP bars on the outer layer can promote durability. The increased durability is a result of increased concrete cover and the extra protection of the steel bars provided by the FRP bars. Araba and Ashour [8] suggested that the ultimate moment capacity of an RC beam was dependent on the hybrid reinforcement ratio. They found that an increase in the area of Glass Fibre-Reinforced Polymer (GFRP) bars led to an increase in ultimate moment capacity. Based on the FRP materials studied in existing literature, this study seeks to compare the performance of RC beams reinforced with hybrid Basalt Fibre Reinforced Polymer (BFRP)- and GFRP-steel bars.

The purpose of this paper will be to investigate the flexural behaviour of the hybrid reinforced beams such as deflection and ultimate moment capacity.

2 Methods

The study was conducted through a numerical investigation using ABAQUS, a finite element modelling software. The numerical models were validated by experimental data obtained from testing thirteen RC beams.

Beam Design

Thirteen RC beams each measuring 2500mm long, 300mm high and 250mm wide were considered in this study. The section views showing the internal reinforcement details of the RC beams are shown in Figure 1. The beams had a concrete cover of 30mm all-round and 8mm diameter stirrups spaced at 100mm were provided for shear resistance along the shear spans. No stirrups were used in the middle section of the beam as this section experienced a constant bending moment under the four-point bending test used in this study. Figure 2 shows the longitudinal profile of a typical RC beam used in this study as well as the four-point bending test setup.

Control beams

2Φ8 2Φ8 2Φ8

3Φ10 3Φ10 3Φ10

Beam 3S10 Beam 3G10 Beam 3B10

GFRP-steel reinforced concrete beams

2Φ8 2Φ8 2Φ8 2Φ8 2Φ8

3Φ10 3Φ10 | 3Φ16 3Φ10 | 5Φ16 3Φ10 | 3Φ10 3Φ16 | 3Φ10 5Φ16

B am 3G10 - 3S10 Beam 3G10 - 3S16 Beam 3G10 - 5S16 Beam 3G16 - 3S10 Beam 5G16 - 3S10

BFRP-steel reinforced concrete beams

2Φ8 2Φ8 2Φ8 2Φ8 2Φ8

3Φ10 3Φ10 | 3Φ16 3Φ10 | 5Φ16 3Φ10 | 3Φ10 3Φ16 | 3Φ10 5Φ16

B am 3B10 - 3S10 Beam 3B10 - 3S16 Beam 3B10 - 5S16 Beam 3B16 - 3S10 Beam 5B16 - 3S10

Figure 1: Section diagrams showing the internal reinforcements of the three groups of RC beams.

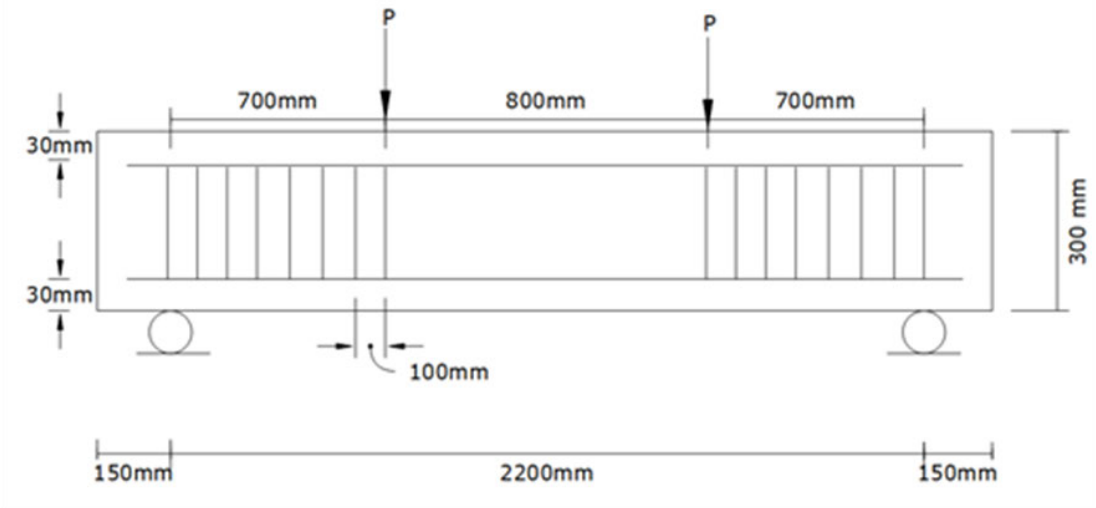


Figure 2: Longitudinal profile of a typical control beam and the four-point bending setup.

Geometrical Modelling

The RC beam models were built by modelling all the individual components of the RC beams individually and then assembling them together. For a reduced computational cost, symmetry was used and only half of the beam was modelled as shown in Figure 3. The reinforcing bars and stirrups were modelled as being embedded into the concrete and as such, the bond between the internal reinforcement components and the concrete was assumed as perfect. Due to computational limitations of the computer system, a mesh size of 20mm x 20mm was used.

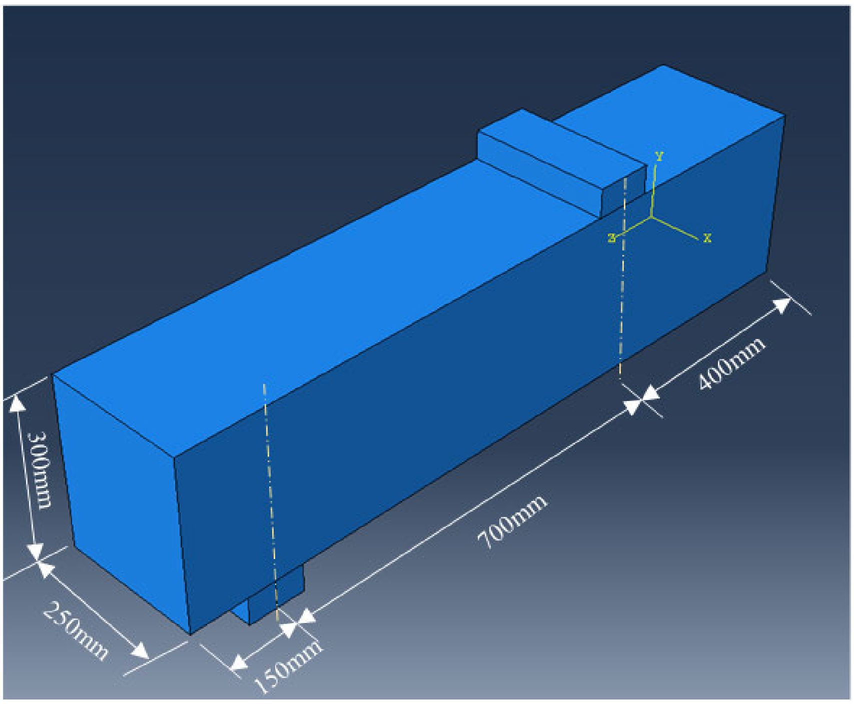


Figure 3: A half model of a typical RC beam modelled in ABAQUS.

Material Properties

The material properties of the reinforcing bars used in this study are presented below in Table 1. The material properties of the FRP bars were obtained from manufacturers Owencorning [11] and Pulwell Composites [12]. The concrete used in this study was modelled to have a density of 2500 kg/m3, a compressive strength of 35MPa and a poisons ratio of 0.2. The concrete was modelled using the Concrete Damage Plasticity (CDP) model. The CDP was chosen because of its ability to represent the inelastic behaviour of concrete in tension and compression, as well as its damage characteristics.

Material	Elastic Modulus [GPa]	Density [kg/mm^3]	Poisson's ratio	Tensile strength [MPa]
Steel	200	7900	0.3	470
BFRP	55	2.0×10^{-6}	0.2	1300 (*1100)
GFRP	46	1.975×10^{-6}	0.2	827 (*724)
*Tensile strength values not in brackets are for 10mm rebar, and those in brackets are for 16mm rebar.				

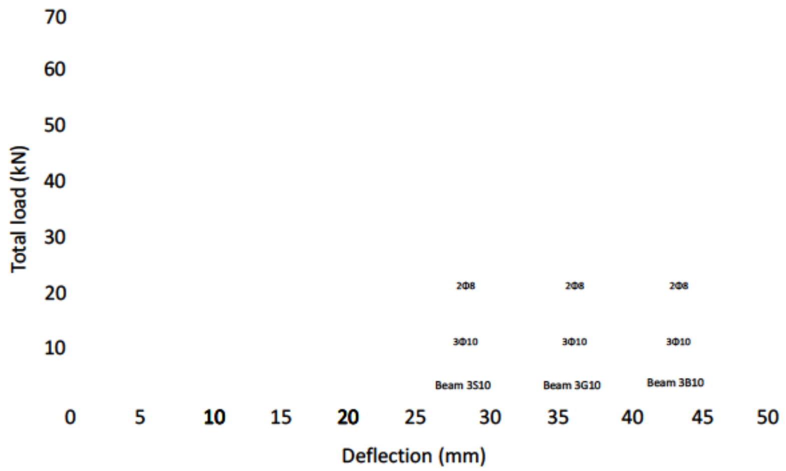
Table 1: Material properties of the reinforcing bars used in modelling of the beams.

3 Results

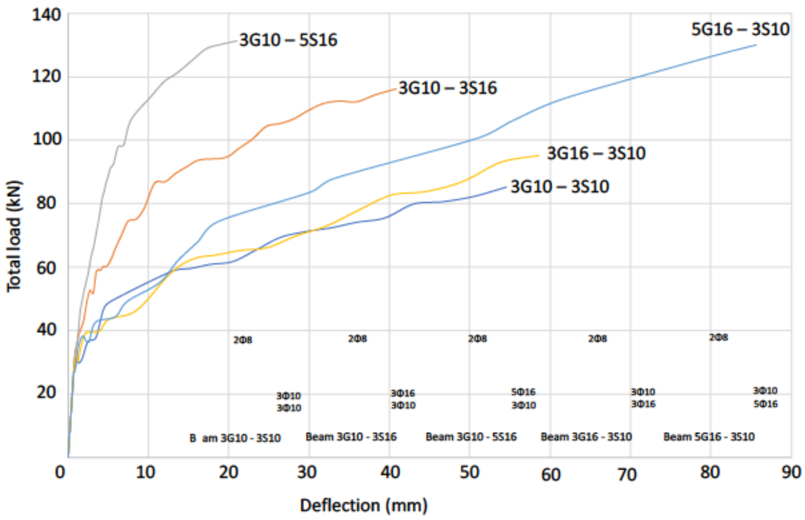
Deflection

The results of the simulated four-point bending test, depicting the load-deflection curves, are presented in Figure 4. Figure 4(a) shows a comparison of the load-deflection curves of the control beams, thus comparing the effect of reinforcement bar type on the deflection of the beam. Beam 3S10 had the lowest maximum midspan deflection of 27.93mm, followed by beam 3B10 with a maximum midspan deflection of 40.55mm. Beam 3G10 experienced the largest maximum midspan deflection of 46.56mm. Two findings can be deduced from Figure 4(a), firstly, FRP bar reinforced beams experience larger deflections compared to steel bars, and secondly, beams reinforced with BFRP bars experience less deflection in comparison to those reinforced with GFRP bars. The steel, BFRP and GFRP bars used in this study had elastic moduli values of 200GPa, 55GPa and 46GPa, respectively. This justifies the observed behaviour because a lower elastic modulus leads to a larger deflection. Figures 4(b) and 4(c) show the load-deflection curves for the beams reinforced with hybrid GFRP- and BFRP-steel bars. It can be observed that hybrid beams with increased area of steel bars experienced reduced deflections It can also be observed that an increase in the area of GFRP and BFRP bars led to an increase in deflection. Figure 4(d) summarises the deflection behaviour of beams reinforced with hybrid FRP-steel bars. A clear trend can be observed, keeping the hybrid reinforcement ratio low keeps the maximum midspan deflections low and it can also be seen that hybrid BFRP-steel reinforced concrete beams experience less deflection compared to GFRP-steel bars.

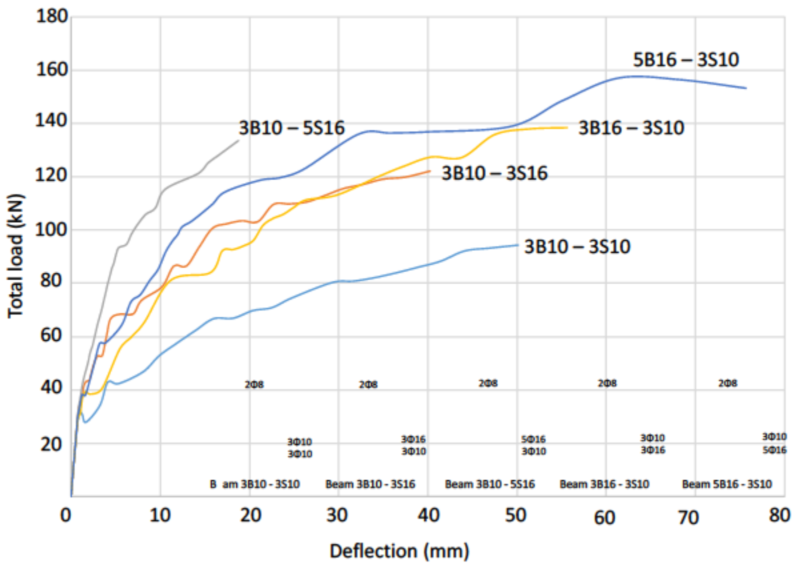
(a)


Total load (kN)
Deflection (mm)
2Φ8
3Φ10
Beam 3S10
Beam 3G10
Beam 3B10

(b)


3G10 – 5S16
3G10 – 3S16
5G16 – 3S10
3G16 – 3S10
3G10 – 3S10
Total load (kN)
Deflection (mm)
B am 3G10 - 3S10
Beam 3G10 - 3S16
Beam 3G10 - 5S16
Beam 3G16 - 3S10
Beam 5G16 - 3S10

(c)


5B16 – 3S10
3B10 – 5S16
3B16 – 3S10
3B10 – 3S16
3B10 – 3S10
Total load (kN)
Deflection (mm)
B am 3B10 - 3S10
Beam 3B10 - 3S16
Beam 3B10 - 5S16
Beam 3B16 - 3S10
Beam 5B16 - 3S10

(d)

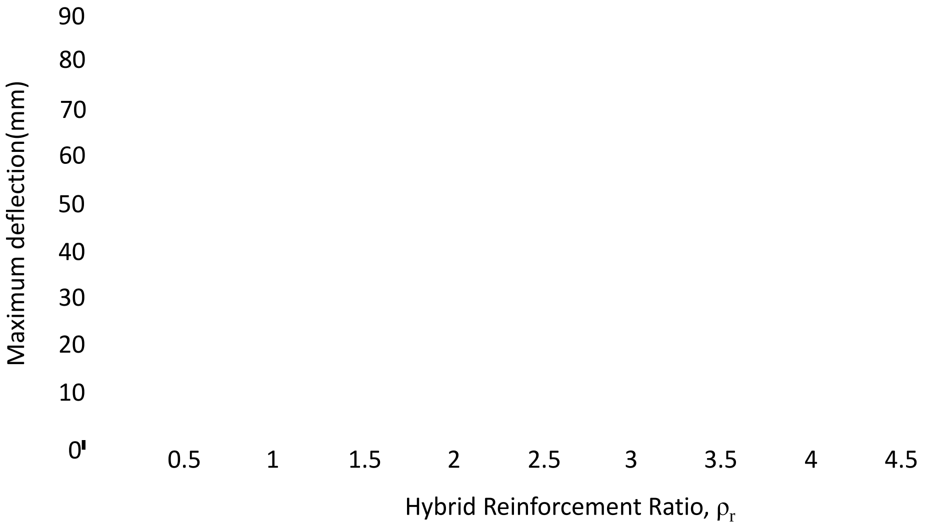


Figure 4: (a) Load-deflection curves of control beams (b) load-deflection curves of GFRP-steel beams (c) load-deflection curves of BFRP-steel beams (d) relationship between hybrid reinforcement ratio and deflection of hybrid FRP-steel beams.

Ultimate Moment Capacity

The ultimate moment capacities of the beams are presented in Figure 5. Beam 3G10 and 3B10 can be seen to have higher ultimate moments of 35.32kN.m and 45.18kN.m compared to beam 3S10 which had an ultimate moment capacity of 20.72kN.m. Beam 3B10 had a larger ultimate moment than beam 3G10 due to BFRP bars having a higher tensile strength compared to GFRP bars. As such, all hybrid BFRP-steel reinforced beams were found to have higher ultimate moments compared to hybrid GFRP-steel reinforced beams. Adding the FRP bars to form hybrid reinforced beams leads to an increase in ultimate capacity as can be observed in Figure 5. The percentage increase in the ultimate moment capacity of beam 3G10-3S10 compared to beams 3S10, 3G10 and 3B10 was 188%, 68.97% and 32.10% respectively. While the percentage increase in ultimate moment capacity of beam 3B10-3S10 in comparison to beams 3S10, 3G10 and 3B10 was 218.6%, 86.92% and 46.13%.

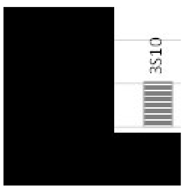


Figure 5: Ultimate moments of the control beams and the hybrid FRP-steel reinforced beams.

In figure 6 we observe the relationship between the hybrid reinforcement ratio and the ultimate moment capacity of the beams. It can be seen that the difference in the ultimate moments of beams with a low and high hybrid reinforcement ratio is not that much. Therefore, considering the lower cost of steel bars compared to FRP bars and that the hybrid FRP-steel reinforced beams with more steel bar area (lower hybrid reinforcement ratio) experience smaller deflections, it is more advantageous to opt for beams with a lower hybrid reinforcement ratio.

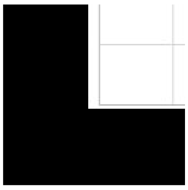


Figure 6: Effect of hybrid reinforcement ratio on the ultimate moment capacity of the hybrid FRP-steel beams.

4 Conclusions and Contributions

This numerical study investigated the flexural performance of thirteen beams reinforced with steel, FRP and hybrid FRP-steel bars. The following conclusions can be drawn from the study:

- Increasing the area of tensile steel reinforcement leads to a decrease in hybrid reinforcement ratio which subsequently leads to a decrease in midspan deflection.
- The type of FRP bar used has an influence on the deflection. Hybrid GFRP-steel bar reinforced beams exhibited larger midspan deflections compared to hybrid BFRP-steel bar reinforced beams, due to their lower elastic modulus.
- BFRP only and BFRP-steel bar reinforced concrete beams exhibited higher ultimate moment capacities compared to GFRP only and GFRP-steel bar reinforced beams, due to BFRP bars having a higher tensile strength than GFRP bars.
- For hybrid reinforcement ratios greater than one, ultimate moment capacity increases as the hybrid reinforcement ratio increases. However, for hybrid FRP-steel bar reinforced beams with hybrid reinforcement ratios less than or equal to one, the ultimate moment capacity increases as the hybrid reinforcement ratio decreases/approaches zero. A lower hybrid reinforcement ratio closer to zero is more appealing than a bigger one, due to the lower cost of adding steel bars.

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