Engineering and Technology Journal 41 (05) (2023) 619- 628

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Flexural Performance of Concrete Beams Reinforced with Hybrid FRP-Steel Bars: A mini review

Marwah S. Abduljabbar*, Wael S. Abdulsahib
Civil Engineering Dept., University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.
*Corresponding author Email: Marwah.S.Abduljabbar@uotechnology.edu.iq

HIGHLIGHTS

- Using hybrid FRP/ steel bars in reinforcing concrete beams demonstrated better flexural performance.
- Existing design method for reinforced concrete beams with hybrid reinforcements is reviewed.
- Experimental and analytical studies regarding hybrid reinforced concrete beams are presented.
- Further research directions are proposed to better understand the effect of many parameters on the flexural capacity.

ARTICLE INFO

Handling editor: Mahmoud S. Al-Khafaji

Keywords:
Concrete beams
Fiber reinforced polymer
Flexural behavior
FRP bar
Hybrid reinforcement

ABSTRACT

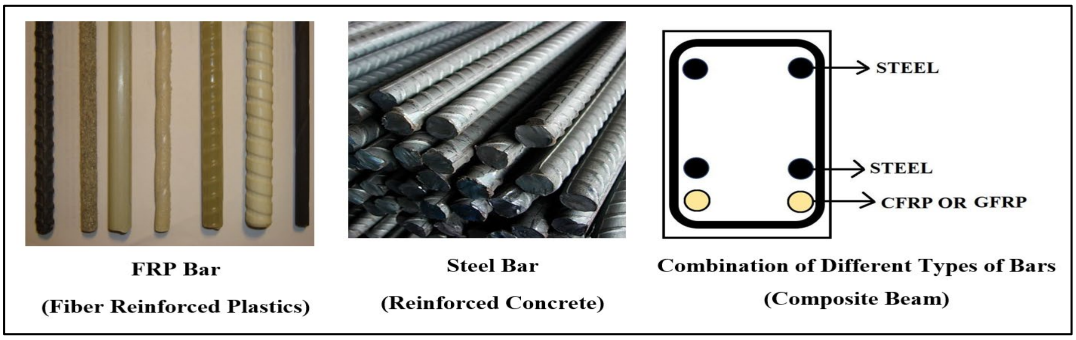
Reinforced concrete beams are the most generally used structural parts in building, bridges, and many other structures. In the past two decades, many investigations have been conducted using various fiber-reinforced polymer (FRP) material types /steel bars to reinforce concrete beams under flexural test. The purpose of this paper is to review the flexural performance of concrete beams reinforced with hybrid FRP and steel bars to better understand their behavior. The main parameters addressed by researchers were dimensions of beams, FRP bar material type, and hybrid reinforcement ratio. The researchers established that the use of the combination between steel and FRP reinforcement bars improves the performance of the concrete beams. Moreover, the studies showed that the ductility of the hybrid reinforced beams increased compared to that of conventional steel reinforced beams, however, it decreased when the ratio of (A_f/A_s) increased. The application of using hybrid FRP/steel bars in reinforcing concrete beams will further increase upon utilizing techniques for reducing the brittleness and higher cost of FRP bars. The general structure of this paper consists of presenting the formulas offered by ACI 440.1R-15 building code relating to the flexural strength calculation of concrete beams reinforced with FRP/steel bars. The paper also details some of the current experimental tests and analytical works published for concrete beams reinforced with hybrid system, and outlines research directions and identifies gaps required for additional research.

1. Introduction

Traditionally, reinforced concrete, which consists of a combination of concrete and steel reinforcement bars, is used in constructing facilities and structures. When exposed to harsh environmental conditions, steel bar corrosion could cause the loss of durability and service life of RC structures [1-5]. In the past two decades, researches have been renewed in material called Fiber Reinforced Polymer (FRP) to replace steel bars in traditional RC members, as a result of its noncorrosive property [6,7]. This material constructed of fibers within a polymeric resin [8]. FRP bars first used in Russia as reinforcement bars [9,10]. Then, in 1990, FRP composite started to be used as reinforcement material in inadequate structures in the USA [11]. Thereafter, various studies have made on strengthening and retrofitting by FRP composite as externally bonded or interior reinforcement [12]. Based on previous studies, there are four types of FRP: Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), Basalt Fiber Reinforced Polymer (BFRP), and Aramid Fiber Reinforced Polymer (AFRP) [13,14]. These products have been proposed to use as an alternative to traditional steel rebars due to their high tensile strength, harsh corrosive resistance, lighter weight compared to steel bars, and nonmagnetic feature [15-18]. FR composite is the most popular choice to retrofit many concrete elements including, columns, shear walls, slabs, and beams [19,20]. In spite of these advantages, the elastic modulus of FRP bars are lower than that of steel rebars, where for GFRP bars is 30-50 GPa, for CFRP is 120-150 GPa, and for AFRP is 70-180 GPa, which results in cracks and large deflection [21,22]. In spite of the higher strength of FRP bars in comparison with steel bars (In case of CFRP and BFRP bars, the tensile strength is at least 600 MPa,

http://doi.org/10.30684/etj.2022.135764.1284
Received 29 October 2022; Accepted 21 December 2022; Available online 22 January 2023
2412-0758/University of Technology-Iraq, Baghdad, Iraq

483 MPa for GFRP bars, and 1720 MPa for AFRP bars) [23], the FRP bars show a brittle behavior without a yield point contrasting to the inelastic performance of the steel rebars. The linear elastic behavior of the FRP bars until failure results in this brittle behavior without any clear indication. Hence, concrete elements should utilize over-reinforcement with FRP bars to comply with the serviceability condition [24]. Moreover, steel bars can be easily bent to various shapes compared to FRP bars [16]. To overcome these problems, hybrid FRP/steel reinforcement bars can be used in concrete beams [25,26], as presented in Figure 1. The ductileness of FRP-reinforced concrete beams can considerably improve by adding the steel reinforcing bars, because suitable ductility can provide warning before failure [27]. Therefore, in a hybrid concrete beam, FRP bars provide strength and steel bars provide ductility. The hybrid section was firstly proposed in 1995 [28]. The proposed section consists of steel bars located at the inner level, while the FRP bars were positioned at the exterior level. The results showed that a sufficient corrosion resistance and the required flexural capacity was achieved.



FRP Bar
(Fiber Reinforced Plastics)

Steel Bar
(Reinforced Concrete)

Combination of Different Types of Bars
(Composite Beam)

Figure 1: Concrete reinforced beams with hybrid FRP/steel rebars [21]

The bond characteristics between FRP bars and the surrounding concrete mainly affect the crack distribution of the concrete beam, hence adequate bonding improves the ability of the concrete members to sustain flexural load [15]. El Refai et al. [29] proposed a bond coefficient, which depends on the hybrid reinforcement ratio (Af/As), and the size effect of FRP bars. However, the effect of the surface texture of the FRP reinforcement bars does not take into account on the bond coefficient because of the limited available data.

Until now, an inadequate number of existing studies that have been accomplished to investigate the effectiveness of using hybrid steel/FRP bars as flexural reinforcement in concrete beams. Therefore, several issues associated with their flexural performance remain unsolved. This paper attempts to address the current knowledge of the behavior of hybrid reinforced beams under flexural test. To take a complete advantage of data collected from the literature, this paper reviews their failure modes and common parameters that effect their performance under flexure test. The equations provided by the international code (ACI 440.1R-15) to estimate the flexural capacity of concrete beams reinforced by hybrid bars are also included in this paper. Moreover, this paper identifies the main knowledge gaps in hybrid reinforcements and future research suggestions in this area. The outcome of this paper will help researchers in deep understanding the performance of concrete beams when hybrid FRP/steel bars are used as flexural reinforcements.

2. Estimation of Flexural Strength of Concrete Beams According to ACI Design Provisions

Before investigating the influence of reinforcing concrete beams with combined FRP and steel bars, it is useful to explore the estimation of flexural capacity in American Concrete Institute code ACI 440.1R-15 [30]. This guide contains design guidelines for internal and externally bonded FRP reinforcements.

The nominal flexural strength of a concrete beam can be expressed as shown in Equations (1) -(5) [31].

$$\mathrm{Mn} = (\rho\mathrm{f}\ \mathrm{ff} + \rho\mathrm{s}\ \mathrm{fy})\ (1\text{-}0.59\,\frac{\rho_f f_f + \rho_s f_s}{f_c'})\ \mathrm{bd2} \tag{1}$$

$$\mathrm{ff} = (\sqrt{\frac{1}{4}(\frac{A_s f_y}{A_f} + E_f \varepsilon_{cu})^2 + (0.85\,\frac{\beta_1 f_c'}{\rho_f} - \frac{A_s f_y}{A_f})E_f \varepsilon_{cu}} - \frac{1}{2}\,(\frac{A_s f_y}{A_f} + E_f \varepsilon_{cu}) \leq \mathrm{f\ fu} \tag{2}$$

$$\rho\mathrm{f} = \frac{A_f}{bd} \tag{3}$$

$$\rho\mathrm{s} = \frac{A_s}{bd} \tag{4}$$

$$\beta 1 = \begin{cases} 17 \leq f_c' \leq 28 & \beta_1 = 0.85 \\ 28 \leq f_c' \leq 55 & \beta_1 = 0.85 - \frac{0.05(f_c' - 28)}{7} \\ f_c' \geq 55 & \beta_1 = 0.65 \end{cases} \tag{5}$$

Where ρf is the FRP reinforcement ratio, Ef is the elastic modulus of the FRP bars, ρs is the steel reinforcement ratio, εcu is the ultimate concrete strain, which is equal to 0.003, fy is the yield stress of steel bars, Af is the area of the FRP bars, ff is tensile stress of FRP bars, f fu is the tensile strength of FRP, εfu is the design rupture strain of FRP reinforcement, fc' is the concrete compressive strength, b is the breadth of the concrete beam, d is the depth of the beam, β1 is compressive stress block parameter, a is the depth of corresponding rectangular stress block.

For a hybrid FRP/steel reinforced concrete beam, it important to specify the effective reinforcement ratio, ρeff, and the balanced ratio, ρeff,b , as presented in Equations (6) and (7). The effective ratio, ρeff, is compared to the balanced ratio, ρeff,b, to indicate the flexural failure mode of the concrete beam. If ρeff > ρeff,b, then the concrete beam is over reinforced and the expected failure is concrete crushing. On the other hand, if ρeff ≤ ρeff,b, then the concrete beam is under reinforced and yielding of the steel bars are anticipated prior to concrete crushing [29,32].

$$\rho\mathrm{eff} = \rho\mathrm{s} + \frac{E_f}{E_s}\,\rho_f \tag{6}$$

$$\rho\mathrm{eff,b} = 0.85\beta 1 \frac{f_c'}{f_{fu}}\,\frac{E_f\varepsilon_{cu}}{E_f\varepsilon_{cu}+f_{fu}} \tag{7}$$

The balanced reinforcement ratio for concrete beam reinforced with steel bars only is a condition of concrete crushing and yielding of steel are the failure modes. While, for a concrete beam reinforced with FRP bars only, the mode of failure is concrete crushing and rupture of FRP bars [33]. The balanced ratio for a hybrid concrete beams with FRP/steel bars combined the two cases, where the failure mode is the crushing of concrete, steel bars yielding, and rupture of FRP bars take place at the same time [34]. However, steel bars will have yielded long before the rupture FRP bars, which make this condition is impossible to happen. Therefore, the balanced ratio is proposed to give a state of concrete crushing and failure of FRP bars take place simultaneously, with steel bars yielding.

3. Flexural Behavior of Hybrid Reinforced Beam

The flexural behavior of hybrid reinforcement beam depends on the type of FRP material, number of reinforcement bars, and hybrid reinforcement ratio. Many previous studies investigated the effect of these parameters on the bending capacity, crack width, and ductility of the hybrid beams under flexure test. In general, the strength capacity of hybrid concrete beams has proven to be better in comparing to that of beams reinforced with FRP or steel bars only [29,35,36].

3.1 Common Failure Modes of Hybrid Reinforced Beam

The generally detected failure modes in beams reinforced with hybrid FRP/steel bars are either be controlled by concrete crushing or reinforcement bars rupture [37]. Qu et al. [31] used GFRP bars to reinforced six beams with dimensions of (180mmx250mm) and length of 1800 mm. Steel stirrups with 10 mm diameter were used as shear reinforcement. Two steel bars with 10 mm diameter were used to reinforce the compression part of the shear span of the beam. A four-point bending test was used in this paper. The load-deflection relationships presented that the flexural performance of hybrid beams can be partitioned into four segments: first phase-elastic stage; second phase-after concrete crushing and afore steel bar yielding; third phase- post-yielding of steel bars stage prior to ultimate load and fourth phase- failure stage, as presented in Figure 2. It can be noted that the flexural stiffness improves as effective ratio increasing. The same conclusion was proposed by Nguyen et al. [38] for high GFRP/steel reinforcement ratio, as shown in Figure 3 (a-d). On the other hand, the beams with lack of GFRP/steel reinforcements failed suddenly after GFRP rupture at the end of the third phase. Therefore, it can be concluded that the beams with low FRP/steel ratio undergo merely the first three phases, while the beams with high FRP/steel ratio showed the fourth phase, which is described by the descendant branch of load-displacement responses as a result of the increasing deflection with gradually decreasing in load after the third phase.

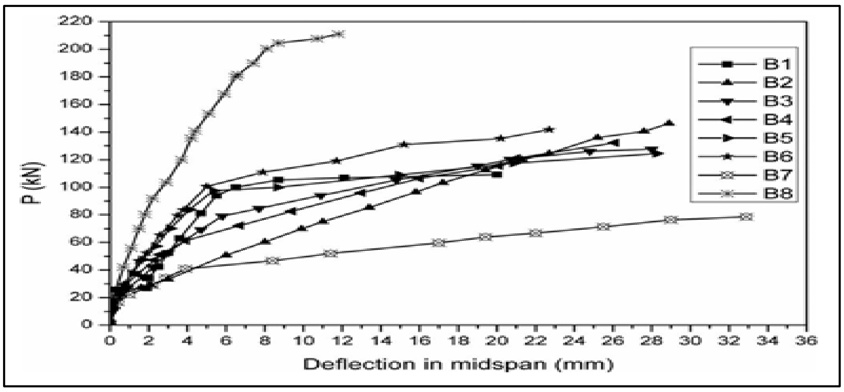


Figure 2: Experimental displacement plots of the tested beams [31]

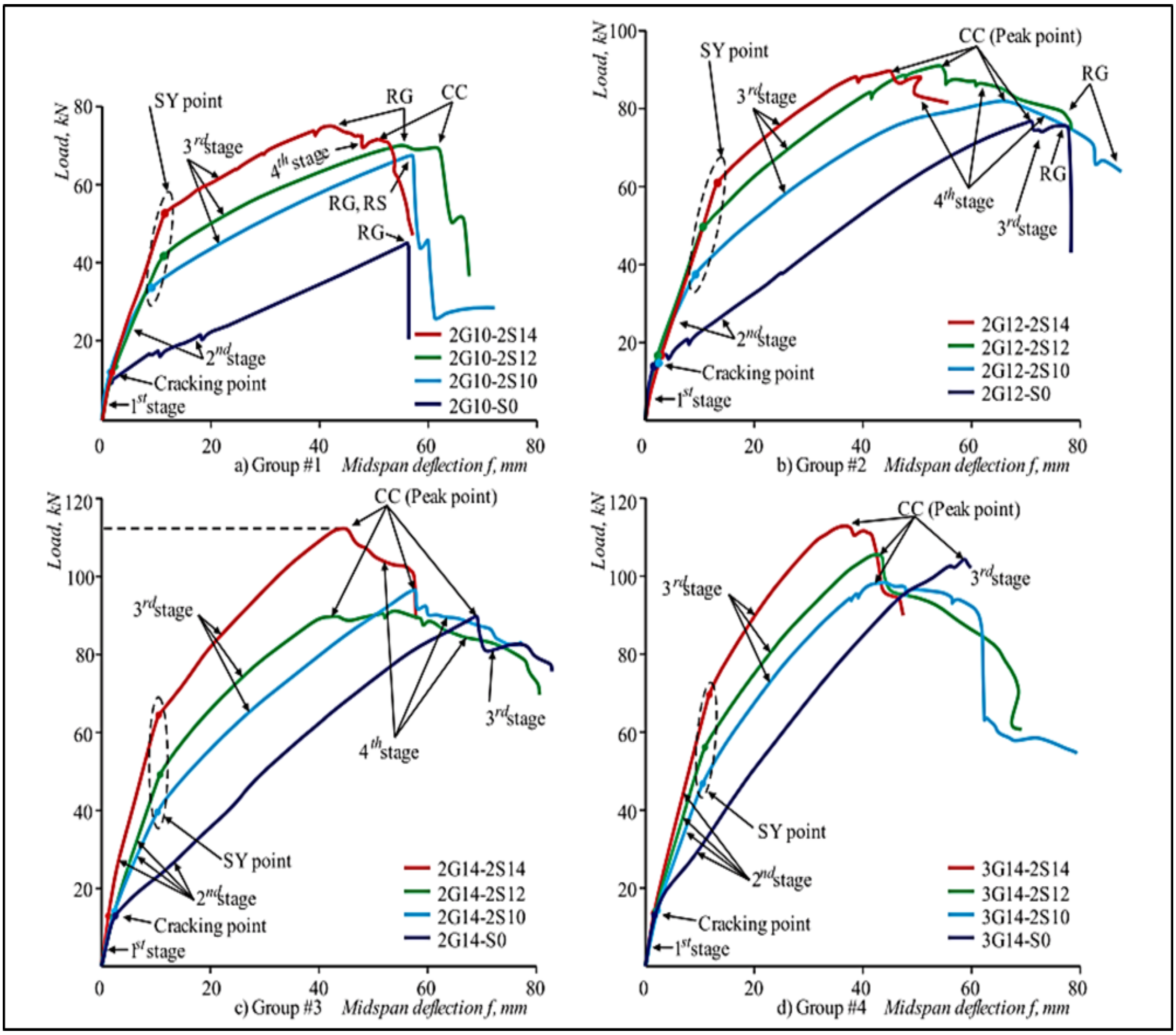


Figure 3: Load-displacement plots of hybrid GFRP/ steel reinforcement beams [38]

Moolaei et al. [39] inspected flexural test on hybrid reinforced concrete beams constructed of GFRP and steel rebars. Three different reinforcement ratios, ρeff, were considered in this work, which were 1, 1.2, and 1.4 times the balanced reinforcement ratio, ρeff,b. The results showed that the beams with hybrid reinforcement ratio 1.2 ρeff,b and 1.4 ρeff,b demonstrated higher loading capacities and cracking loads than the beams with ρeff= ρeff,b.

The effect of the concrete compressive strength and variable types of reinforcements on the behavior of hybrid reinforced beams were studied by Kim and Kim [21]. After yielding of the steel bars, the hybrid beams displayed less decreased rigidity than steel reinforced beams. This is because, in the hybrid beams, FRP bars resist the increasing load after yielding of the steel bars. It was also reported that the concrete strength increasing improve the capacity of the specimens. However, the deflection at the peak capacity of the hybrid beams was developed about 86-116% than the beams with steel reinforced beams. For the same concrete strength, the use of the hybrid reinforcement led to higher first cracking load as compared to the specimens with steel reinforcement only. Vu and Phan [40] conducted an experimental test on six beams reinforced with hybrid GFRP/steel bars with cross section of 150 mmx250 mm and span of 2700 mm loaded under four-point bending scheme. The work aimed to investigate the effect of various GFRP/steel ratios on the cracking load. The results showed that, in the groups of beams reinforced with various GFRP area (Af) and fixed steel bars area (As), the cracking moment improves with the increase of GFRP bars ratio. Nevertheless, the influence of GFRP bars area on the cracking moment is less than that of steel area due to the greater elastic modulus of steel in comparison with GFRP bars.

Table 1 summarizes the performances of RC beams reinforced with hybrid FRP/steel bars under flexural. It can be seen that GFRP is the most common strengthening type. Most of the studies reveal that the compressive strength of the concrete and the strengthening material effect the performance of RC beams in terms of failure mode under flexure. Moreover, it can be noted that using high strength concrete along with increasing the area of FRP bars, in comparing to the steel area, cause rupture of FRP bars before collapse.

Table 1: Summary of the performances of RC beams reinforced with hybrid FRP/steel bars under flexural

Failure mode	**FRP type**	**fc'(MPa)**	**A_f/A_s**
Steel yielding, concrete crushing	GFRP [36,41-46]	20-68	0.3-3
	CFRP [47]	75.9	0.3-0.8
	BFRP [25,48]	32-36	0.4-2
	AFRP [49]	38	0.6-4.5
Steel yielding, FRP rupture	GFRP [38,50-53]	30-197	0.2-5.2
	BFRP [53]	30	0.1-2.1
	AFRP [54]	30	0.1-0.3
FRP bar slipping, concrete crushing	BFRP [25]	41	2
Concrete crushing	CFRP [21]	40	1
	GFRP [21,39]	34-40	0.5-1.8
	[55]	28	0.4-1

3.2 Ductility

Another key aspect that affects the flexural behavior of the RC beams is the ductility, which can be computed as the ratio of the peak to the yielding deflection. For the only-FRP reinforced beams, no yielding behavior was recorded because of the linear elastic performance of the FRP bars [39]. Maranan et al. [56] concluded that using hybrid system in supporting concrete beams improved the ductility of the concrete beams, and it decreases with reinforcement ratio decreasing. Three hybrid beams reinforced by BFRP/steel bars were tested by Ge et al. [55] with dimensions of 200mmx300mmx2500 mm. The results revealed that the ductility of the hybrid beam is somewhat between the ductility of the conventional beam reinforced with steel bars and the ductility of RC beam reinforced with BFRP bars only. Another similar study on the ductility of hybrid beams was performed by Yoo et al. [52]. The examiners observed that the ductility of hybrid reinforced beams ranged 4.02-6.46 as compared to the ductility of steel RC beams, which was below 2. Therefore, it can be concluded that the use of the hybrid reinforcement has advantages in terms of ductility and deformability than the beams reinforced with FRP bars only. Moolaei et al. [39] implemented experimental tests to investigate the flexural performance of three hybrid GFRP/steel reinforced beams. The results showed that the higher ductility was recorded for the hybrid samples having reinforcement ratio of 1.4 ρeff,b comparing with their companions with steel-only reinforced beams.

Thamrin et al. [57] tested eight hybrid reinforced beams until failure with two-point load. The clear span of all the tested beams was 2000 mm with overall depth of 250 mm. The test parameters include examine the effect of various hybrid bars ratio and the bars' position. Two types of FRP bars (CFRP and GFRP) were used along with steel bars. The concrete compressive strength at 28 days was 20 MPa. The authors detected that the ductility of the hybrid beams was greatly related to the ratio (Af/As). The lower hybrid reinforcement ratio led to the highest ductility, but at the cost of the capacity.

3.3 Crack Width

The anti-corrosive feature of FRP reinforced beams results in disregarding the limitation of the crack width. Nevertheless, the presence of steel bars in hybrid FRP/steel reinforcement beams require controls on the width of flexural cracks that can be developed throughout the beam life time [29]. To calculate the maximum crack width of hybrid beams, Gergely–Lutz formula can be utilized as presented in Equation 8 [58]:

$$\mathrm{Wmax}= \mathrm{kg}\varepsilon\mathrm{s}\beta 1\sqrt[3]{d_cA} \tag{8}$$

Where Kg is the function presents the influence of the bond actions of steel bars on the crack width of hybrid reinforced concrete beams, which is equal to 0.4 [59]. εs is the strain of the steel bars, and β1 is the ratio between the distance from the steel bars to the neutral axis and the space from the tensile area edge to the neutral axis. Maranan et al. [56] suggested that the reinforcement ratio controls the length and width of the cracks through allocating efficiently the cracks along the length of the hybrid beams.

Kim and Kim [21] found that the number of cracks increased more quickly in concrete beams with FRP bars in comparing with steel-only reinforced beams. The reason for this is the lower modulus of elasticity of FRP bars resulted in higher deflection, which caused more cracks. However, at failure, the concrete beams with FRP-only reinforced beams and hybrid CFRP/steel beams showed smaller crack width, as presented in Figure 4 (a-f).

Conversely, the comparisons of crack width made by El Refai et al [29] showed that the crack width of hybrid reinforced beams was 0.54 mm at the onset of steel yielding as compared to 1 mm for the beam reinforced with GFRP bars only. Hence, they proposed that the use of steel reinforcement in the hybrid reinforced beams was the key of reducing crack width of beams beyond their service load. Also, the researchers recognized that increasing the reinforcement ratio resulted in decreasing crack width for all beams whether they reinforced by FRP-only or hybrid reinforced. Sun et al. [48] tested several concrete beams under flexural reinforced with BFRP-only bars, CFRP-only bars, and hybrid BFRP/steel bars. Generally, the researchers found that the crack development was controlled by FRP bars. However, the hybrid beam showed the smallest crack width as compared with other beams as a result of the bonding of steel bars to the surrounding concrete [60]. Ruan et al. [61] reported that the average crack width of the hybrid reinforced beams is greater than that of the reinforced beams with steel-only, and it is effected by the effective ratio ρeff. The larger effective ratio, the smaller the average cracking width. Furthermore, it was established that the ultimate crack width develops faster in the single-layer hybrid reinforced beam compared to the double-layer hybrid beam.

The difference in crack pattern between two reinforcing material (CFRP and GFRP) was noted by Thamrin et al. [57] after failure. The low elastic modulus of GFRP bars caused higher deflection, hence wider and higher cracks in the beams reinforced with GFRP/steel in comparison to the other concrete beams reinforced with CFRP/steel.

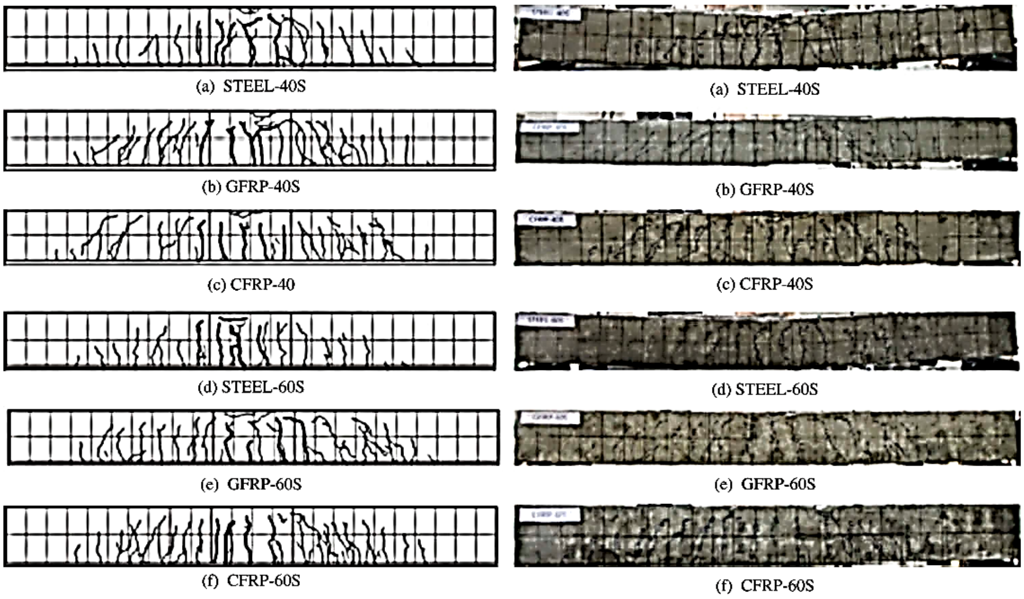


Figure 4: Crack pattern of concrete beams tested by Kim and Kim [21]

4. Aspect Behavior of Flexural Capacity

In general, it can be identified from the studies with concrete compressive strength more than 35 MPa that the beams had collapsed in concrete crushing mode of failure followed by FRP bars rupture. Also, it was observed that the concrete compressive strength has more important effect on the flexural capacity for continuous hybrid beams, as shown in Figure 5.

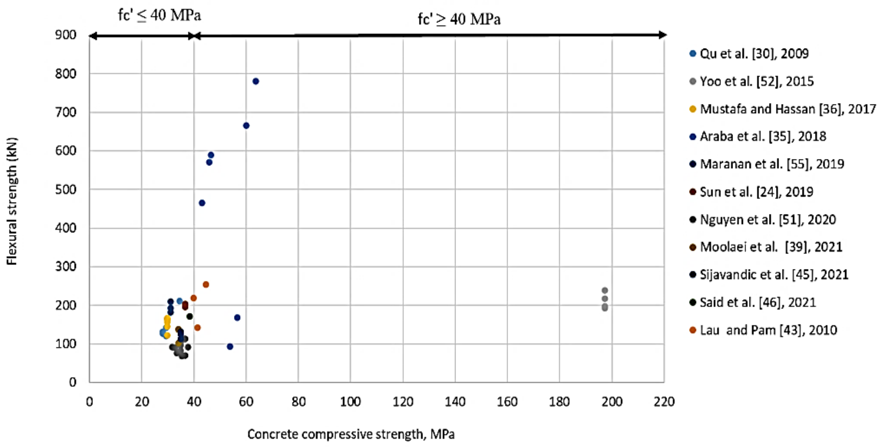


Figure 5: Effects of Concrete compressive on the ultimate flexural strength

Figure 6, presents the effect of different hybrid reinforcement ratios on the bending capacity of concrete beams. It is found from the data gathered from some literatures that the influence of the higher hybrid reinforcement ratio have had greater moment capacities than under-reinforced beams (ρeff.% < ρeff,b%). Interestingly, the test results of this graph tend to propose the benefit of the combination of concrete compressive strength fc' > 38 MPa and ρeff.% > 1 in developing the flexural capacity of the hybrid concrete beam. However, further studies are recommended to validate this assumption.

As mentioned before, FRP reinforcement bars are responsible for resisting the flexural strength, while the steel bars are employed to improve the ductility of the concrete beams. From the perspective of ductility, investigation and analysis of the flexural results of hybrid beams shows that decreasing the hybrid ratio (Af/As) led to increase the values of absorption energy.

In other words, with the contribution of the concrete compressive strength, the ductility of most concrete beams can be improved with high concrete compressive strength and low hybrid ratio.

Also, the type of FRP material has an effect on the ductility and deformation of the concrete beams. The aforementioned literatures showed that failure recognized from the concrete beams with hybrid CFRP/steel reinforcement bars is the sudden failure by concrete crushing immediately after reaching the peak load at low deflection, compared to other FRP types such as GFRP and AFRP. The higher modulus of elasticity of the CFRP bars generates the brittleness failure. Conversely, the position of the hybrid reinforcement has a little effect on the capacity and ductility of the reinforced concrete beams [57].

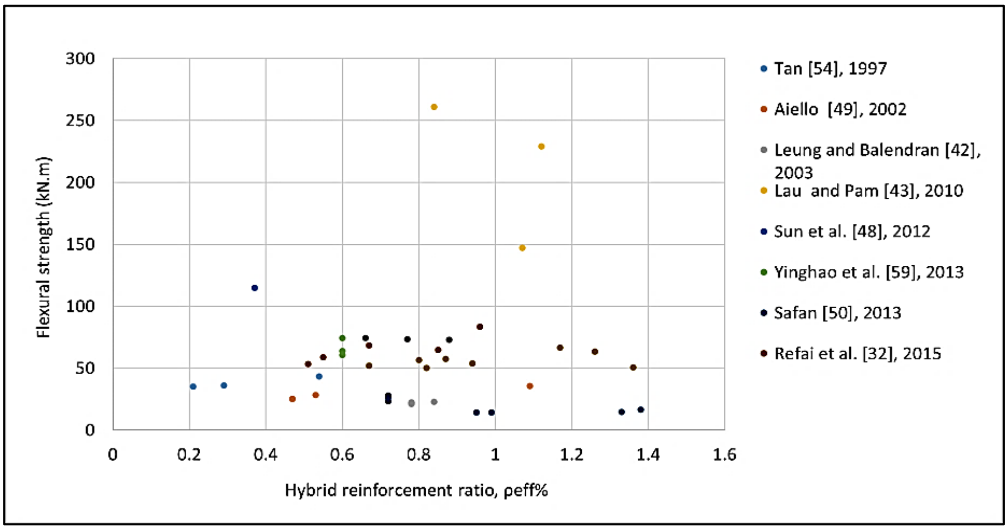


Figure 6: Effects of hybrid ratio on the ultimate moment

5. Future Research Directions

This review shows that the employment of hybrid FRP/steel bars currently seems to be the most effective way to reinforce concrete beams than using either steel or FRP bars only. However, there still some obstacles require further investigations, which can be presented as follows:

1) It can be noticed from the previously available studies, the most of specimens (nearly 92%) had a normal compressive strength between (20-48.5) MPa. However, the studies on flexural strength of hybrid reinforced concrete regarding high strength concrete (HSC) are very limited and needs to be extended.
2) The studies cover an area where are a very limit scope of the structural performance of hybrid deep beams under flexural test.
3) To date, studies regarding continuous hybrid beams reinforced with FRP/steel bars are still limited. However, studies on simply supported hybrid beams have been widely published.
4) A limited standards for hybrid FRP/steel design. Developments of design guidelines and recommendations are required.
5) Inadequate knowledge concerning FRP/ high strength steel bars in reinforcing concrete beams.
6) Further research is needed to assess the influence of the surface texture of the FRP bars on the flexural performance of the concrete members.

6. Conclusion

This paper reviewed the current knowledge in researches related to the influence of RC beams with hybrid FRP/steel rebars. The article emphasized the influence of the ratio as being the indicator of the mode of failure of hybrid RC beams. There are two types of reinforcement, steel and FRP bars, if the hybrid ratio is not well designed, the brittle failure of FRP bars decreases the flexural strength of the hybrid reinforced concrete beam. Also, the adequate hybrid ratio can limit the maximum crack width in concrete. Based on the available information in this review, it is noted that the hybrid reinforcement of CFRP or GFRP with steel bars is widely used among FRP composites because of their high resistance under flexure test, and low cost. However, there is progressively need to use hybrid FRP/ steel bars in reinforcing different structures. At the end, this paper brings lights to new research needs for who interested in hybrid reinforcement for concrete structures.

Author contributions

All authors contributed equally to this work.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

All papers used in this review are available online.

Conflicts of interest

No conflicts of interest are disclosed by the authors.

References

[1] H. M. Mohamed and B. Benmokrane, Design and performance of reinforced concrete water chlorination tank totally reinforced with GFRP bars: Case study, J. Compos. Constr., 18 (2014) 05013001. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000429

[2] Z. Wang, X. Zhao, G. Xian, G. Wu, R. Singh Raman, S. Al-Saadi, and A. Haque, Long-term durability of basalt-and glass-fibre reinforced polymer (BFRP/GFRP) bars in seawater and sea sand concrete environment, Constr. Build. Mater., 139 (2017)4 67–489. https://doi.org/10.1016/j.conbuildmat.2017.02.038

[3] H. Shaowei, C. Qiyong, G. Nina, Effect of acid corrosion on crack propagation of concrete beams, Sādhanā, 43, (2018)1–13. https://doi.org/10.1007/s12046-018-0790-5

[4] G. Xu, L. Liu, H. Bao, Q. Wang, J. Zhao, Mechanical properties of steel corrosion products in reinforced concrete, Mater. Struct., 50 (2017) 1–10. https://doi.org/10.1617/s11527-016-0985-3

[5] A. I. A.-D. Abd El Fattah, K. Riding, M. Thomas, Field evaluation of corrosion mitigation on reinforced concrete in marine exposure conditions, Constr. Build. Mater., 165 (2018) 663–674. https://doi.org/10.1016/j.conbuildmat.2018.01.077

[6] Y. Tang and Z. Wu, Distributed long-gauge optical fiber sensors based self-sensing FRP bar for concrete structure, Sensors (Switzerland), 16 (2016). https://doi.org/10.3390/s16030286

[7] C. Jiang, Y.-F. Wu, and M.-J. Dai, Degradation of steel-to-concrete bond due to corrosion, Constr. Build. Mater., 158 (2018)1073–1080.

[8] P. E. Team, FRP Rebar (AFRP, CFRP, GFRP). Purdue University, 1–6, 2007. https://doi.org/10.5703/1288284315719

[9] H. N. Garden and L. C. Hollaway, An experimental study of the influence of plate end anchorage of carbon fibre composite plates used to strengthen reinforced concrete beams, Compos. Struct., 42 (1998) 175–188. https://doi.org/10.1016/S0263-8223(98)00070-1

[10] L. C. Hollaway, A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties, Constr. Build. Mater., 24 (2010) 2419–2445. https://doi.org/10.1016/j.conbuildmat.2010.04.062

[11] ACI440.2R-08, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. Technical Documents. 2008.

[12] A. A. K. Sharba, H. D. Hussain, M. Abdulhussain, Retrofitting of RC beams using FRP techniques: a review, in IOP Conf. Ser.: Mater. Sci. Eng., 1090 (2021) 012054. https://doi.org/10.1088/1757-899X/1090/1/012054

[13] H. Zhu, C. Li, S. Cheng, and J. Yuan, Flexural Performance of Concrete Beams Reinforced with Continuous FRP Bars and Discrete Steel Fibers under Cyclic Loads, Polymers, 14 (2022) 1399. https://doi.org/10.3390/polym14071399

[14] X. Fan and M. Zhang, Experimental study on flexural behaviour of inorganic polymer concrete beams reinforced with basalt rebar, Compos. Part B Eng., 93 (2016) 174–183. https://doi.org/10.1016/j.compositesb.2016.03.021

[15] O. A. Mohamed, W. Al Hawat, and M. Keshawarz, Durability and mechanical properties of concrete reinforced with basalt fiber-reinforced polymer (Bfrp) bars: Towards sustainable infrastructure, Polymers, 13 (2021). https://doi.org/10.3390/polym13091402

[16] A. Richardson and P. Drew, Fibre reinforced polymer and steel rebar comparative performance, Struct. Surv., 29(011) 63–74. https://doi.10.1108/02630801111118412

[17] A. Cripps, B. Harris, and T. Ibell, Fibre-reinforced polymer composites in construction, Ciria, 2002.

[18] H. Ashrafi, M. Bazli, N. A. V. O. Esmaeil Pournamazian, The effect of mechanical and thermal properties of FRP bars on their tensile performance under elevated temperatures, Constr. Build. Mater., 157 (2017) 1001–1010. https://doi.org/10.1016/j.conbuildmat.2017.09.160

[19] D. G. Goodwin, S. Sattar, J. D. Dukes, J. H. Kim, L. P. Sung, C. C. Ferraris, Research Needs Concerning the Performance of Fiber Reinforced (FR) Composites Retrofit Systems for Buildings and Infrastructure, Special Publication (NIST SP) - 1244. 2019. https://doi.org/10.6028/NIST.SP.1244

[20] C. Bakis, E. Lawrence, C. Bank, V. Brown, E. Cosenza, J. F. Davalos, J. J. Lesko, A. Machida, S. H. Rizkalla, T. C. Triantafillou, Fiber-reinforced polymer composites for construction—State-of-the-art review, J. Compos. Constr., 6, (2002) 73–87.https://doi.org/10.1061/(ASCE)1090-0268(2002)6:2(73)

[21] S. Kim and S. Kim, Flexural behavior of concrete beams with steel bar and FRP reinforcement, J. Asian Archit. Build. Eng., 18 (2019) 94–102. https://doi.org/10.1080/13467581.2019.1596814

[22] A. F. Ashour, Flexural and shear capacities of concrete beams reinforced with GFRP bars, Constr. Build. Mater., 20 (2006) 1005–1015. https://doi.org/10.1016/j.conbuildmat.2005.06.023

[23] I. S. Abbood, S. A. Odaa, K. F. Hasan, M. A. Jasim, Properties evaluation of fiber reinforced polymers and their constituent materials used in structures - A review, Mater. Today Proc., 43 (2021) 1003–1008. https://doi.org/10.1016/j.matpr.2020.07.636

[24] H. Zhu, Z. Li, C. Wen, S. Cheng, Y. Wei, Prediction model for the flexural strength of steel fiber reinforced concrete beams with fiber-reinforced polymer bars under repeated loading, Compos. Struct., 250 (2020) 112609. https://doi.org/10.1016/j.compstruct.2020.112609

[25] Z. Sun, L. Fu, D. C. Feng, A. R. Vatuloka, Y. Wei, G. Wu, Experimental study on the flexural behavior of concrete beams reinforced with bundled hybrid steel/FRP bars, Eng. Struct., (2019) 197. https://doi.org/10.1016/j.engstruct.2019.109443

[26] H. G. Harris, W. Somboonsong, and F. K. Ko, New ductile hybrid FRP reinforcing bar for concrete structures, J. Compos. Constr., 2(1998) 28–37. https://doi.org/10.1061/(ASCE)1090-0268(1998)2:1(28)

[27] R. Qin, A. Zhou, D. Lau, Effect of reinforcement ratio on the flexural performance of hybrid FRP reinforced concrete beams, Compos. B. Eng., 108 (2017) 200–209. https://doi.org/10.1016/j.compositesb.2016.09.054

[28] C. Arya, F. Ofori-Darko, and G. Pirathapan, 27 FRP Rebars and The Elimination of Reinforcement Corrosion in Concrete Structures. in Non-Metallic (FRP) Reinforcement for Concrete Structures, in Proceedings of the Second International RILEM Symposium, 1995.

[29] A. El Refai, F. Abed, A. Al-Rahmani, Structural performance and serviceability of concrete beams reinforced with hybrid (GFRP and steel) bars, Constr. Build. Mater., 96 (2015) 18–529. https://doi.org/10.1016/j.conbuildmat.2015.08.063

[30] ACI Committee 440, ACI440.1R-15 Guide for the Design and Construction of Structural Concrete Reinforced with Firber-Reinforced Polymer (FRP) Bars, 22, 2015.

[31] W. Qu, X. Zhang, and H. Huang, Flexural Behavior of Concrete Beams Reinforced with Hybrid (GFRP and Steel) Bars, J. Compos. Constr., 13 (2009) 350–359. https://doi.org/10.1109/MACE.2010.5536776

[32] L. Pang, W. J. Qu, P. Zhu, J. J. Xu, Design propositions for hybrid FRP-steel reinforced concrete beams, J. Compos. Constr., 20 (2016) 04015086. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000654

[33] P. Preinstorfer, T. Huber, S. Reichenbach, J. M. Lees, B. Kromoser, Parametric Design Studies of Mass-Related Global Warming Potential and Construction Costs of FRP-Reinforced Concrete Infrastructure, Polymers, 14 (2022) 2383. https://doi.org/10.3390/polym14122383

[34] F. Bencardino, A. Condello, and L. Ombres, Numerical and analytical modeling of concrete beams with steel, FRP and hybrid FRP-steel reinforcements, Compos. Struct.,140 (2016) 53–65. https://doi.org/10.1016/j.compstruct.2015.12.045

[35] A. M. Araba and A. F. Ashour, Flexural performance of hybrid GFRP-Steel reinforced concrete continuous beams, Compos. Part B Eng., 154 (2018) 321–336. https://doi.org/10.1016/j.compositesb.2018.08.077

[36] S. A. A. Mustafa , H. A. Hassan, Behavior of concrete beams reinforced with hybrid steel and FRP composites, HBRC J., 14 (2018) 300–308. https://doi.org/10.1016/j.hbrcj.2017.01.001

[37] T. Renić, I. Hafner, and T. Kišiček, 'Ductility of hybrid FRP – steel reinforced concrete sections', Proceedings of the 2nd International Conference CoMS 2020/21, no. May, 118–126, 2021.

[38] P. D. Nguyen, V. H. Dang, N. A. Vu, Performance of concrete beams reinforced with various ratios of hybrid GFRP/steel bars, Civ. Eng. J., 6 (2020) 1652–1669. https://doi.org/10.28991/cej-2020-03091572

[39] S. Moolaei, M. K. Sharbatdar, A. Kheyroddin, Experimental evaluation of flexural behavior of HPFRCC beams reinforced with hybrid steel and GFRP bars, Compos. Struct., (2021) 275. https://doi.org/10.1016/j.compstruct.2021.114503

[40] H. D. Vu and D. N. Phan, Experimental and Theoretical Analysis of Cracking Moment of Concrete Beams Reinforced with Hybrid Fiber Reinforced Polymer and Steel Rebars, Adv. Technol. Innov., 6 (2021) 222–234. https://doi.org/10.46604/aiti.2021.7330

[41] W. Abdullah, Z. Z. Zhuang, R. X. Jie, Flexural Behavior of Concrete Beams Reinforced With Hybrid FRP Bars and HRB Bars, IOSR J. Eng., 9 (2019) 25–33. https://doi.org/10.1061/(asce)cc.1943-5614.0000035

[42] H. Y. Leung, and R. V. Balendran, Flexural behaviour of concrete beams internally reinforced with GFRP rods and steel rebars, Struct. Surv.,21 (2003) 146–157. https://doi.org/10.1108/02630800310507159

[43] D. Lau , H. Pam, Experimental study of reinforced concrete beams, Eng. Struct., 32 (2010) 3857–3865. https://doi.org/10.1016/j.engstruct.2010.08.028

[44] G. Xingyu, D. Yiqing, J. Jiwang, Flexural behavior investigation of steel-GFRP hybrid-reinforced concrete beams based on experimental and numerical methods, Eng. Struct., (2020) 206. https://doi.org/10.1016/j.engstruct.2019.110117

[45] K. Sijavandi, M. K. Sharbatdar, A. Kheyroddin, Experimental evaluation of flexural behavior of High-Performance Fiber Reinforced Concrete Beams using GFRP and High Strength Steel Bars, Structures, 33 (2021) 4256–4268. https://doi.org/10.1016/j.istruc.2021.07.020

[46] M. Said, A. S. Shanour, T. S. Mustafa, A. H. Abdel-kareem, M. Khalil, Experimental flexural performance of concrete beams reinforced with an innovative hybrid bars, Eng. Struct., 226 (2021) 111348. https://doi.org/10.1016/j.engstruct.2020.111348

[47] Y. S. Yoon, J. M. Yang, K. H. Min, H. O. Shin, Flexural strength and deflection characteristics of high-strength concrete beams with hybrid FRP and steel bar reinforcement, in Special Publication, 2011, 57-77.

[48] Z. Y. Sun, Y. Yang, W. H. Qin, S. T. Ren, and G. Wu, Experimental study on flexural behavior of concrete beams reinforced by steel-fiber reinforced polymer composite bars, J. Reinf. Plast. Compos., 31 (2021) 1737–1745. https://doi.org/10.1177/0731684412456446

[49] M. A. L. O. Aiello, Structural performances of concrete beams with hybrid (fiber-reinforced polymer-steel) reinforcements, J. Compos. Constr., 6 (2002) 133–140. https://doi.org/10.1061/(asce)1090-0268(2002)6:2(133)

[50] M. A. Safan, Flexural behavior and design of steel-GFRP reinforced concrete beams, ACI Mater. J., 110 (2013) 677-685.

[51] D. P. Nguyen ,V. Q. Dang, Limiting Reinforcement Ratios for Hybrid GFRP/Steel Reinforced Concrete Beams, Int. J. Eng. Technol. Innov., 11 (2021) 01–11. https://doi.org/10.46604/IJETI.2021.6660

[52] D. Y. Yoo, N. Banthia, Y. S. Yoon, Flexural behavior of ultra-high-performance fiber-reinforced concrete beams reinforced with GFRP and steel rebars, Eng. Struct., 111 (2016) 246–262. https://doi.org/10.1016/j.engstruct.2015.12.003

[53] S. Kartal, I. Kalkan, A. Beycioglu, M. Dobiszewska, Load-deflection behavior of over-and under-reinforced concrete beams with hybrid frp-steel reinforcements, Materials, 14 (2021) 5341 . https://doi.org/10.3390/ma14185341

[54] K. H. Tan, Behaviour of hybrid FRP-steel reinforced concrete beams, in In Proc., 3rd Int. Symposium, FRPRCS, 487–494,1997.

[55] W. Ge, J. Zhang, D. Cao, and Y. Tu, Flexural behaviors of hybrid concrete beams reinforced with BFRP bars and steel bars, Constr. Build. Mater., 87 (2015) 28–37. https://doi.org/10.1016/j.conbuildmat.2015.03.113

[56] G. B. Maranan, A. C. Manalo, B. Benmokrane, W. Karunasena, P. Mendis, and T. Q. Nguyen, Flexural behavior of geopolymer-concrete beams longitudinally reinforced with GFRP and steel hybrid reinforcements, Eng. Struct., 182 (2019) 141–152. https://doi.org/10.1016/j.engstruct.2018.12.073

[57] R. Thamrin, Z. Zaidir, and D. Iwanda, Ductility Estimation for Flexural Concrete Beams Longitudinally Reinforced with Hybrid FRP–Steel Bars, Polymers, 14 (2022) 1017. https://doi.org/10.3390/polym14051017

[58] P. Gergely , L. A. Lutz, Maximum crack width in reinforced concrete flexural members, Spec. Publ., 20 (1968) 87–117.

[59] H. Huang, Experimental study of steel-GFRP reinforced concrete beam, Shanghai: Tongji University, 2004.

[60] L. Yinghao and Y. Yong, Arrangement of hybrid rebars on flexural behavior of HSC beams, Compos. Part B Eng., 45 (2013) 22–31. https://doi.org/10.1016/j.compositesb.2012.08.023

[61] X. Ruan, C. Lu, K. Xu, G. Xuan, and M. Ni, Flexural behavior and serviceability of concrete beams hybrid-reinforced with GFRP bars and steel bars, Compos. Struct., 235 (2020) 111772. https://doi.org/10.1016/j.compstruct.2019.111772