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A State-of-the-Art Review on the Behavior of RC Beams with Different Types of FRP Reinforcement

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ABSTRACT
Nowadays, several research concerns studying the behavior of FRP reinforcement in different structural members. FRP bars have numerous advantages that make them a good alternative to steel reinforcement, such as superior mechanical properties, non-corrosivity, sustainability, and a relatively higher stiffness-to-weight ratio compared to steel reinforcement. FRP also has good fatigue characteristics, damage tolerance, nonmagnetic properties, simplicity of transportation and handling, and low energy consumption during manufacturing. This paper presents a general review of the behavior of concrete beams reinforced with different types of FRP. The effect of using the different types of FRP reinforcement on the behavior of reinforced concrete beams has been evaluated in terms of the ultimate capacity, deflection, cracking patterns, etc. In addition, this paper aims to evaluate the efficiency of using some techniques for strengthening reinforced concrete beams such as applying externally bonded CFPR or steel plates on the flexural and shear behavior of the tested beams.

Keywords: *Reinforced concrete; beams; CFRP; GFRP; BFRP.*

1. Introduction

Using conventional steel reinforcement in concrete structures is very sensitive to corrosion which significantly affects the serviceability and safety of concrete structures. The effect of corrosion becomes very considerable in the harsh marine environment. FRP (Fiber Reinforced Polymers) bars offer a very promising alternative to conventional steel bars for the aforementioned advantages. FRP bars are commonly used instead of steel in some aggressive environments such as water treatment plants and coastal structures. CFRP (Carbon Fiber Reinforced Polymers), GFRP (Glass Fiber Reinforced Polymers), and BFRP (Basalt Fiber Reinforced Polymers) are some of the available FRP bars on the market. Generally, FRPs present high tensile strength, and high Young's modulus. On the other hand, they have low ductility, thus they exhibit large deflection and wide cracks [1]. Fiber Reinforced Polymer (FRP) is a type of composite material made by mixing small-diameter fibers with a polymeric matrix at the microscopic level to create a synergistic material [2]. In recent years, it has seen a lot of applications in the building business. The material's lightweight, high ultimate tensile, non-conducting behavior, nonmagnetic nature, excellent corrosion resistance, and easy implementation technique all lead to its high demand. These characteristics make the material a good choice for reinforcing new structural members as well as strengthening reinforced concrete structures.

2. Recent Studies

2.1 Glass Fiber-Reinforced Polymer (GFRP)

Glass Fiber-Reinforced Polymer (GFRP) is the most commonly used FRP material in structural components. Extensive research have been carried out to evaluate the structural behavior of beams reinforced with GFRP bars. A lot of research were carried out to investigate both flexural and shear behaviors for beams with GFRP reinforcement. The flexural performance of beams with GFRP reinforcement has been investigated numerically and experimentally. El Refai et al. (2015) [3] studied the structural performance of hybrid reinforced concrete beams. Three beams with only GFRP reinforcement and six other beams reinforced with a combination of GFRP and steel bars were tested to investigate the flexural performance as shown in Figure 1 and Figure 2. Results revealed that using both GFRP and steel bars together has improved the performance of the concrete beams in terms of maximum capacity, cracking stiffness, and deformability as shown in Figure 3. In addition, cracking patterns at failure are shown in Figure 4. Only a few beams reinforced with the combination of steel and GFRP bars failed in a ductile way as a result of concrete crushing following the yielding of the steel reinforcement. The study showed that CAN/CSA S806 standards are conservative in terms of predicting the deflection for concrete beams with hybrid reinforcement.

Sirimontree et al. (2021) [4] compared the flexural behavior of beams reinforced with GFRP bars and compared them with beams reinforced with conventional steel bars. Six full-scale beams with dimensions of (150 × 250 × 2500 mm) were reinforced with steel or GFRP bars and were prepared for the study.

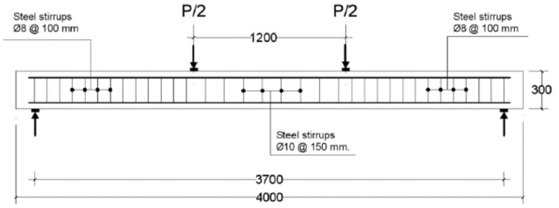


Figure 1. Test configuration (All dimensions in mm) [3]

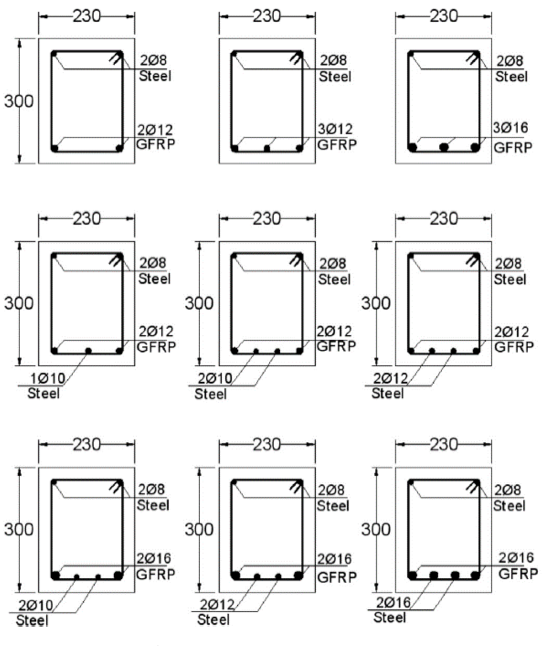


Figure 2. Reinforcement details (All dimensions in mm) [3]

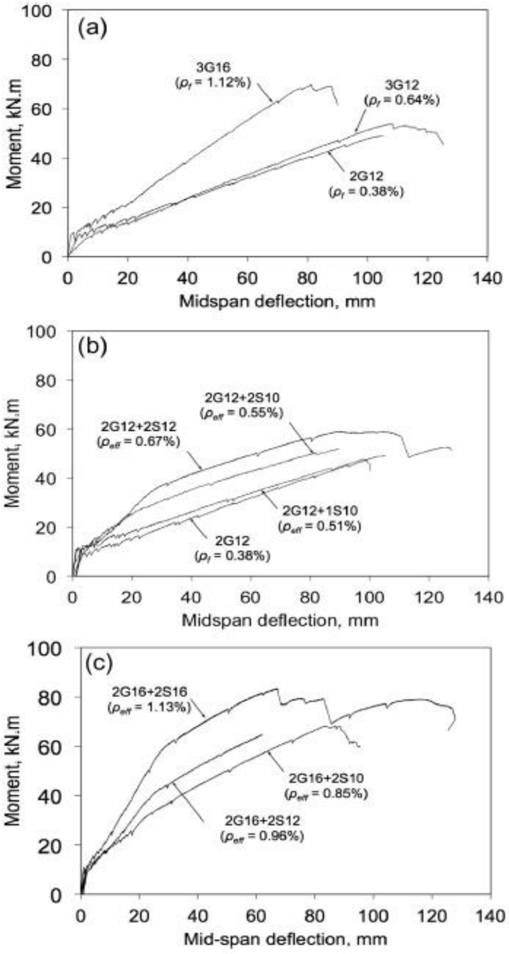


Figure 3. Moment vs. deflection [3]

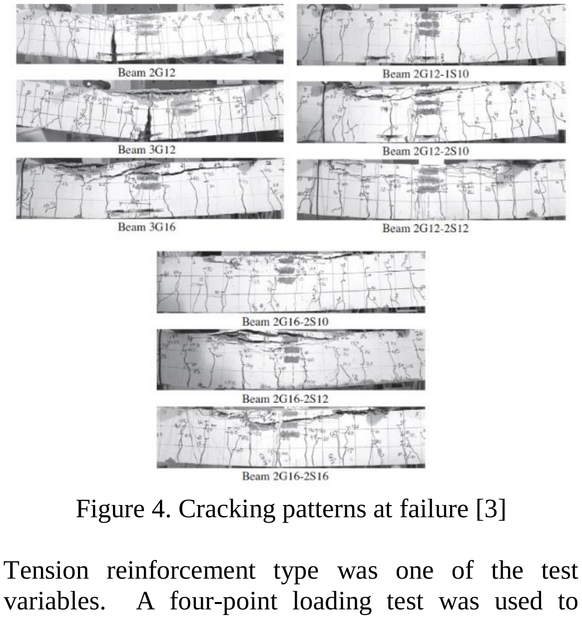


Figure 4. Cracking patterns at failure [3]

Tension reinforcement type was one of the test variables. A four-point loading test was used to evaluate flexural behavior, load-deflection relation, maximum flexural capacity, stiffness, and mode of failure. The experimental findings revealed that as steel strength increased, the load capacity of concrete reinforced with conventional steel bars increased. The load capacity of concrete beams reinforced with GFRP bars was approximately 98 % more than that of beams reinforced with conventional steel bars. On the other hand, beams with the GFRP reinforcement showed relatively lower stiffness values compared to beams reinforced with conventional steel bars as depicted in Figure 5.

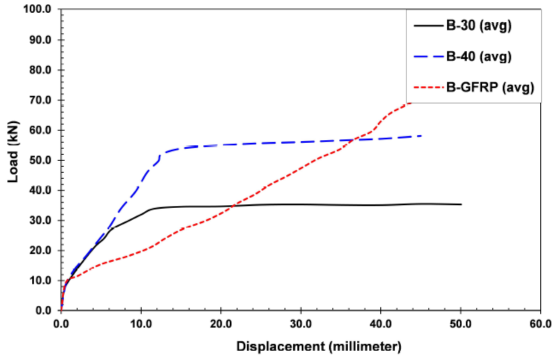


Figure 5. Load and midspan deflection relationships of specimens [4]

Ridwan et al. (2021) [5] proposed an analytical approach to predict the flexural capacity of a beam reinforced with GFRP bars. This approach was based on strain compatibility and internal forces equilibrium. To achieve this condition, the variation of the stress and the strain for concrete and FRP bar throughout the depth of the RC beam was taken into account. The real stress-strain behavior of concrete under compression was also considered in this investigation. The contribution of concrete under uniaxial compression was investigated using a nonlinear stress-strain relationship. The analytical study's obtained flexural capacity was compared to the findings of previously published experimental work [6] as well as the results derived using the ACI 440.1R-15 code [7]. The results showed that the predicted rupture modes by the analytical analysis matched the rupture modes seen in the experiment as recorded in Table 1. Furthermore, flexural capacity obtained using Todeschini's nonlinear curve [5] for specimens with reinforcement ratios greater than the balanced reinforcement ratio performed better than that obtained using ACI code [8] as shown in Figures 6 and 7.

Table 1. Comparison of rupture mode between the experiment [6] and the analytical study [5]

Code of Specimens	A_f (mm^2)	ρ_f	$\rho_{balance}$
FB-2	265.46	0.0025	0.0051
FB-3	398.20	0.0037	0.0051
FB-4	530.93	0.0050	0.0051
FB-6	796.39	0.0075	0.0051
FB-8	1061.86	0.0100	0.0051
HFB-3	398.20	0.0037	0.0061
HFB-4	530.93	0.0050	0.0061
HFB-6	796.39	0.0075	0.0061
HFB-8	1061.86	0.0100	0.0061
HFB-10	1327.32	0.0125	0.0061

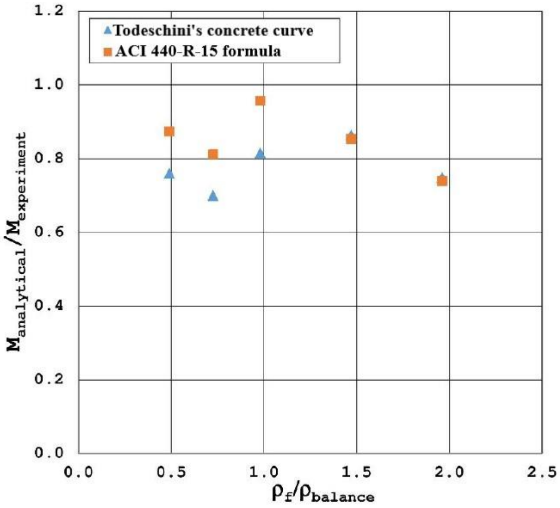


Figure 6. Comparison of flexural capacity ratios of Todeschini's curve to the experiment and the ACI code to the experiment for the FB specimen series (30 MPa concrete beam series) [5]

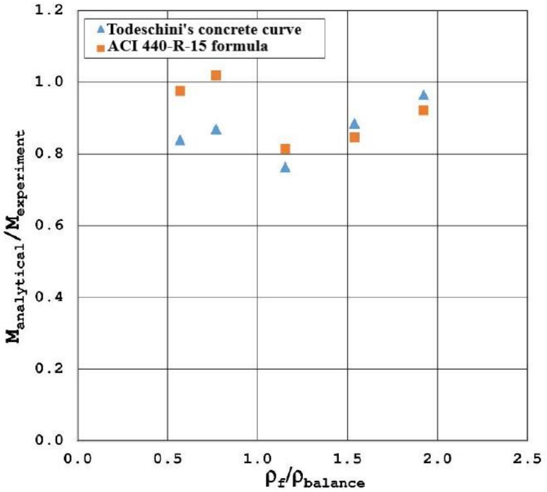
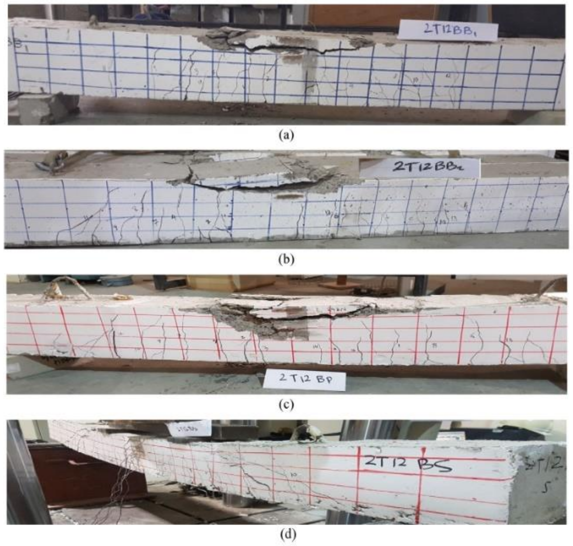


Figure 7. Comparison of flexural capacity ratios of Todeschini's curve to the experiment and the ACI code to the experiment for the HFB specimen series (50 MPa concrete beam series) [5]

2.1 Basalt Fiber-Reinforced Polymer (BFRP)

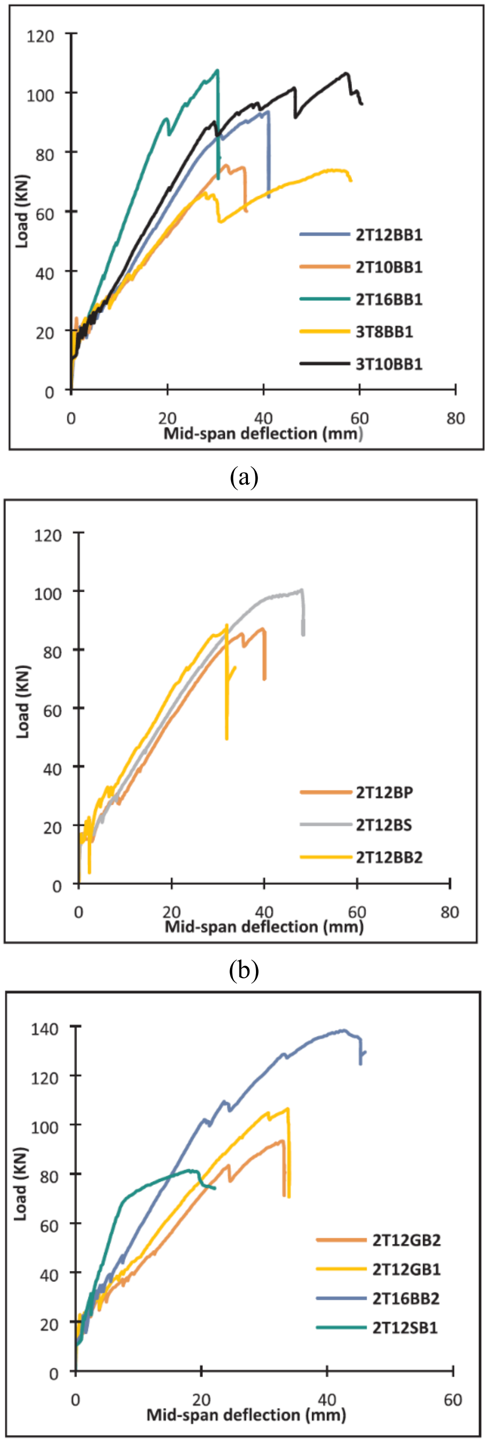
Basalt Fiber-Reinforced Polymer (BFRP) is a relatively new addition to the fiber-reinforced polymer industry. Basalt fiber is produced from mined basalt rocks placed near volcanic areas. To produce basalt fiber, those rocks are heated at a high temperature of 1400°C and thus the molten product of basalt is extruded via specific nozzles [9]. The chemical composition of BFRP is essentially similar to that of GFRP, with the exception that basalt has a high iron ratio, which gives it its peculiar black color [9].

A limited number of studies were carried out to explore the behavior of structures reinforced with BFRP. Abed et al. (2019) [10] investigated the influence of adding various types of fibers to concrete mixtures on the flexural performance of concrete beams reinforced with BFRP bars. Twelve beams with dimensions of (180 × 230 × 2000 mm) were prepared using plain, basalt, and synthetic fiber-reinforced concrete (FRC). All mixes were designed to achieve a compressive strength of 40 MPa. The utilized reinforcement were BFRP sand-coated bars of 8,10, and 12 mm diameter. All beams were tested under a four-point loading test. Some of the failure modes of different fiber-reinforced concrete beams are shown in Figure 8. According to the findings, increasing the BFRP flexural reinforcement ratio improved the flexural capacity of the BFRP reinforced beams irrespective of the concrete type as shown in Figure 9.



(a)
(b)
(c)
(d)

Figure 8. The failure mode of different fibers reinforced concrete beams, (a) Basalt fibers (24 mm), (b) basalt fibers (12 mm), (c) plain concrete, and (d) synthetic fibers. [10]



(a)
(b)
(c)

Figure 9. Load vs mid-span deflection for beams with different (a) reinforcement ratios, (b) fibers types; (c) reinforcement types [10].

The bond-dependent coefficient (kb) and the structural behavior of BFRB bars in concrete beams were investigated by Elgabbas et al. (2016) [10, 11].

Six samples with dimensions of (200 × 300 × 3100 mm) were cast and longitudinally reinforced with 10,12, and 16 mm BFRP bars then all beams were tested under the four-point loading test. The results revealed a kb of 0.76, which is consistent with the CSA S6 standards [13]. The research also revealed that the axial stiffness of the used reinforcement had a significant impact on the flexural performance of the beams. Beams with higher axial stiffness exhibited less deflection, strains, and crack count. At the pre-cracking stage, all beams showed the same behavior as the performance of the concrete beam is governed by the concrete at this stage. Beams with larger reinforcement ratios demonstrated greater stiffness after the initiation of the first crack as shown in Figure 10. In addition, crack patterns and failure modes of the tested beams are shown in Figure 11.

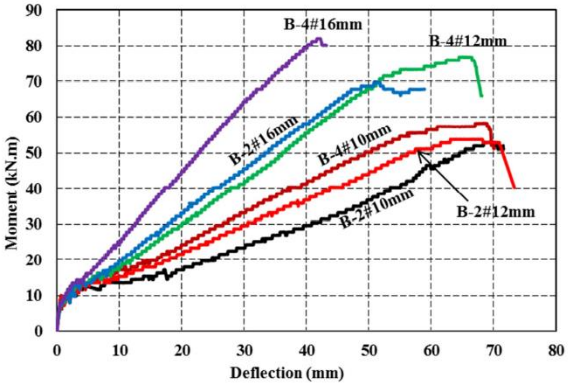


Figure 10. Moment-mid-span vs. deflection [11]

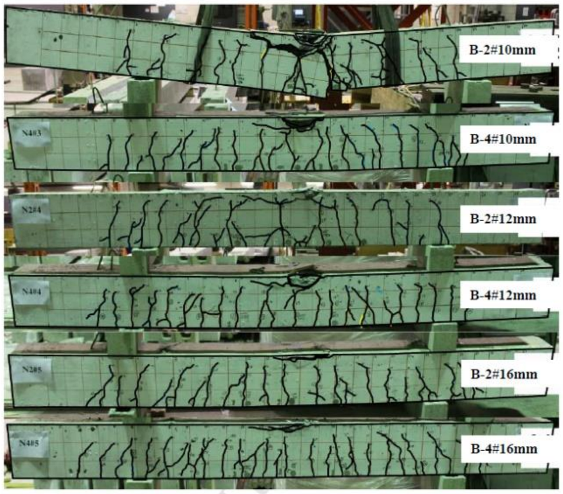


Figure 1. Crack patterns and failure modes of the tested beams [11]

2.1 Carbon Fiber-Reinforced Polymer (CFRP)

Carbon fiber reinforced polymer (CFRP) has become a promising choice as flexural reinforcement in concrete structures during the past twenty years [6, 13]. CFRP bars have gained popularity for their superior material properties. Some of these exceptional properties are the high tensile strength (e.g., up to 3690 MPa), and their relevant high strength-to-weight ratio compared to conventional steel bras (e.g., up to 15 times higher than steel bars). In addition, they are nonmagnetic and non-corrosive materials [6], [14–19]. Furthermore, CFRP bars have a very good performance in aggressive environments as they have high resistance to acids, alkaline solutions, etc. [20–22]. Most studies and design codes advocate for the over-reinforcement of CFRP RC beams because it results in a less catastrophic failure than the rupture of CFRP bars [6], [14], [23–27]. Furthermore, due to a lower elastic modulus than steel bars, it produces wider cracks and larger deflections at the serviceability limit states [26, 28, 29]. As a result, the performance of CFRP reinforced concrete beams is commonly governed by the serviceability limit states [31]. In this perspective, the effect of concrete compressive strength is essential on over-reinforced CFRP beams. The bond properties between CFRP reinforcing bars and concrete are another important aspect influencing the flexural strength of CFRP-reinforced beams. The bond strength between the CFRP bars and the concrete plays an important role in obtaining the maximum capacity of the CFRP-reinforced beam [16]. Henceforward, Flexural strength is determined by neglecting the bond behavior between CFRP bars and concrete assuming a perfect bond [14, 23, 25], and [32]. Moreover, no single model exists that can be used to calculate the minimum required bond strength of CFRP bars used as flexural reinforcement. As a result, it is important to study the effect of surface treatment on the flexural behavior of CFRP-reinforced beams [32-36].

Amran et al. (2020) [23] studied the properties of the hardened concrete and the water permeability of concrete wrapped with layers of carbon fiber polymers (CFRP). A total number of 42 cubes of 150 mm size having various concrete grades were wrapped with layers of CFRP after being cured. Compressive strength, depth of water penetration, and water permeability were studied according to BS EN 12390-3, BS EN 12390-8 [38], and ASTM C 1585 [39], respectively. Table 2 shows the obtained compressive strength results. It can be seen that the compressive strength was significantly improved with increasing the amount of the CFRP layers as shown in Figure 12. In addition, concrete with CFRP wrapping exhibited a much lower permeability coefficient than its counterparts without wrapping as depicted in Figure 13. Thus, this means better performance in resisting relevant deterioration effects such as corrosion. Moreover, the water penetration depth in the wrapped concrete was significantly much lower than those without wrapping as shown in Figure 14. The findings of this research demonstrate that CFRP layers have an important influence as moisture barriers, potentially reducing steel corrosion and concrete deterioration. As a result, retrofitting efforts can boost the sustainability, economic efficiency, and durability of building structures.

Table 1. Percentage compressive strength [23].

pecimen	Control	1 Layer of CFRP	2 Layer of CFRP	3 Layer of CFRP
$f_c^{`}$ (N/mm2)	27.19	40.50	52.31	59.09

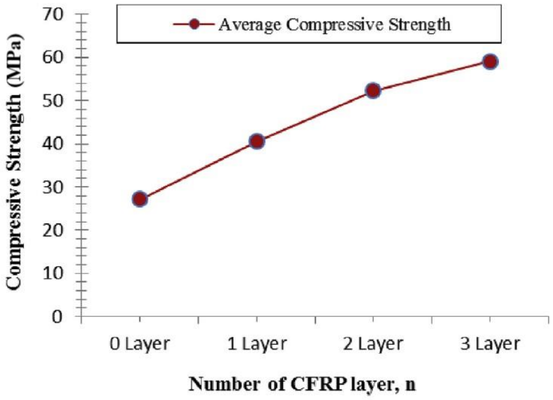


Figure 2: Average compressive strength versus layers of CFRP [23]

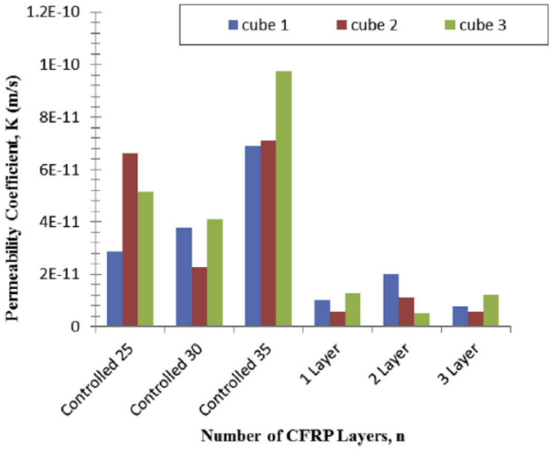


Figure 13: Permeability coefficient versus layers of CFRP [23]

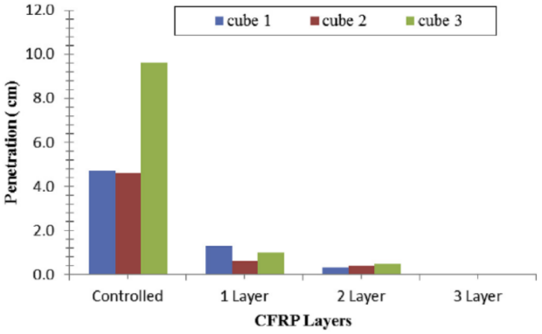


Figure 3: Water penetration versus layers of CFRP [23]

Kara et al. (2015) [25] afforded a numerical method to evaluate the moment-curvature relation, and the ultimate capacity for hybrid concrete beams. Hybrid beams in this research were concrete beams reinforced with FRP and steel bars, and concrete beams reinforced with steel and strengthened by NSM FRP bars or stirrups. Various modes of failure were set based on the count of the FRP bars such as rupture of the FRP bars, and concrete crushing. The findings of the research revealed that the ductility and stiffness have significantly improved while reinforcing concrete beams with both steel and FRP reinforcement. In addition, the existence of the FRP reinforcement in the over-reinforced concrete beams had a substantial role in resisting loadings after the yielding of the steel reinforcement. Furthermore, it was concluded that hybrid GFRP and steel-reinforced concrete beams show a relevant reduction in the stiffness after cracking and yielding of the steel reinforcement compared to the hybrid CFRP and steel-reinforced ones. Kandil et al. (2020) [40] presented different techniques for strengthening reinforced concrete beams with large openings at two different locations. Fourteen beams of dimensions (300 x 100 x 2000 mm) were prepared and longitudinally reinforced with (2 Φ 12) steel bars as flexural reinforcement, and (2 Φ 10) steel bars as compression reinforcement. Moreover, all beams were provided with two legs stirrups of 8 mm diameter every 200 mm. The proposed techniques were applying externally bonded CFPR or steel plates as shown in Figure 15 and Figure 16. They aimed to evaluate the efficiency of using each technique on the flexural and shear behavior of the tested beams. All specimens were tested under the four-point loading test, and the behavior of all beams with the different used strengthening techniques was compared to the reference samples without any strengthening. Results showed that all applied strengthening techniques have improved the behavior of the tested beams in terms of load capacity, deflection, and toughness. It is worth mentioning that, using the CFRP plates as a strengthening technique had the most significant improvement in the behavior of beams with mid-span openings. The ultimate load and load-deflection relationship for all the tested samples are shown in Figure 17.

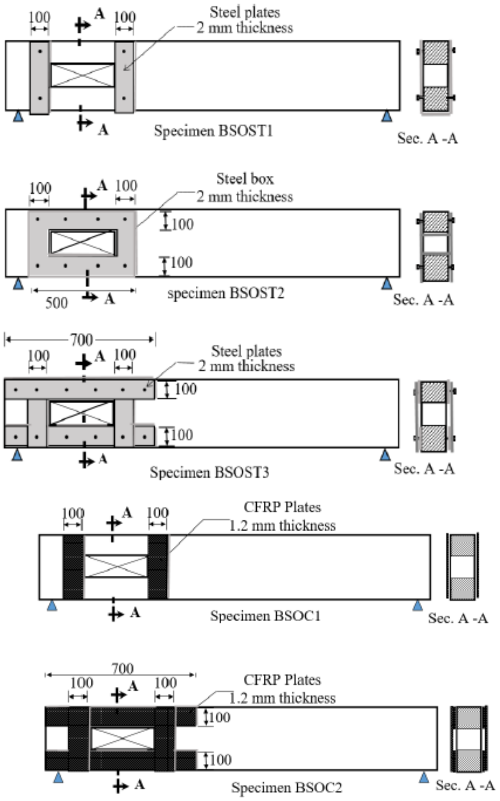
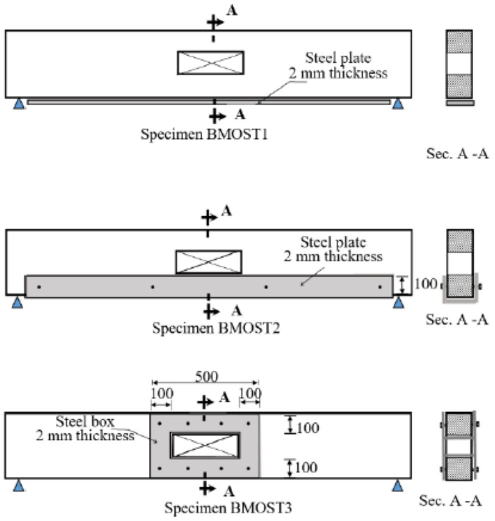


Figure 4: Strengthening details of specimens in Group 2 [40]



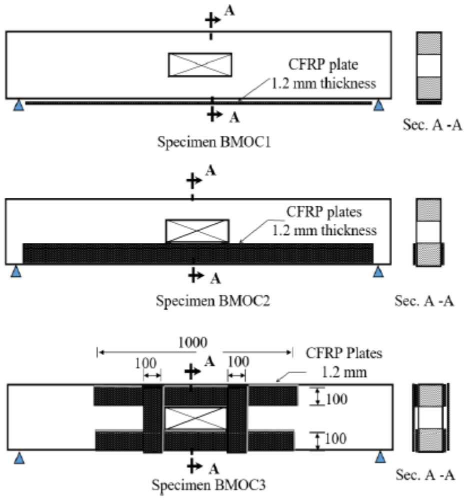
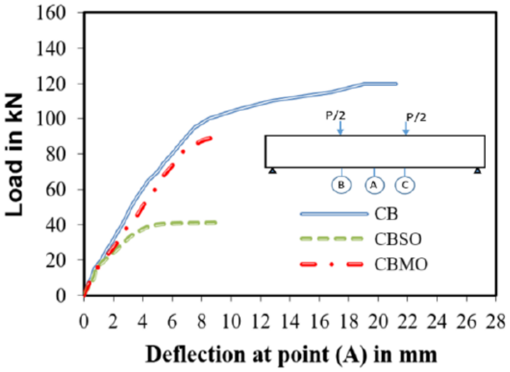
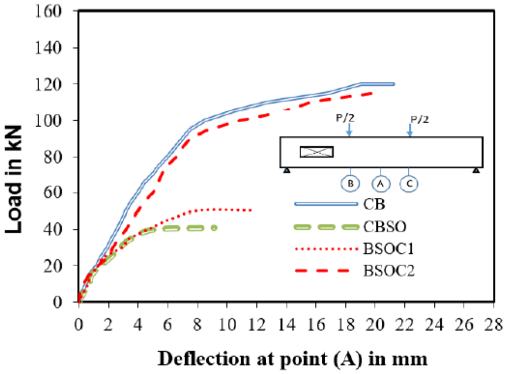


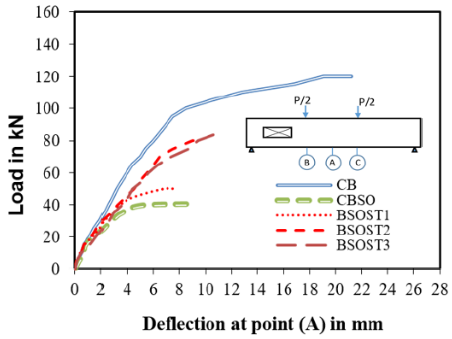
Figure 16: Strengthening details of specimens in Group 3 [40]



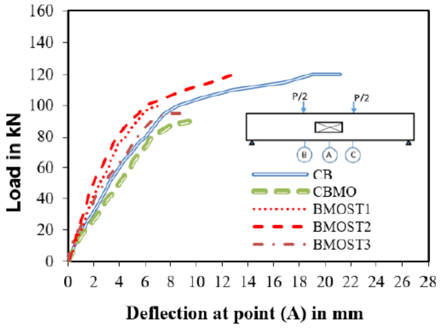
Load vs. deflection for reference beams in Group (1)



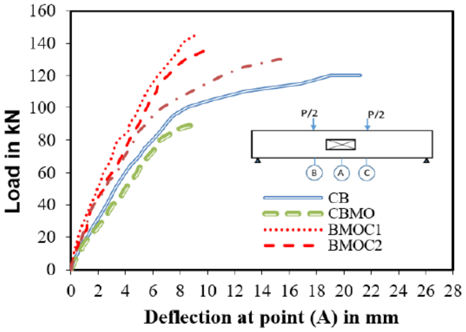
Load vs. deflection for beams strengthened by CFRP plates in Group (2)



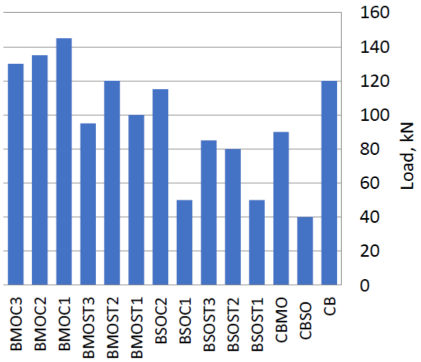
Load vs. deflection for beams strengthened by steel plates in Group (2)



Load vs. deflection for beams strengthened by steel plates in Group (3)



Load vs. deflection for beams strengthened by CFRP plates in Group (3)



Ultimate loads of all tested beams

Figure 17: Load vs. deflection and ultimate loads for all beams [40]

3. Conclusions

Based on performing the analysis of the systematic literature, several conclusions can be manifested concerning the behavior of RC beams reinforced with various types of FRP:

Using both GFRP and steel bars together has improved the performance of the concrete beams in terms of maximum capacity, cracking stiffness, and deformability.

CAN/CSA S806 standards are conservative in terms of predicting the deflection for concrete beams with hybrid- reinforcement.

Increasing the BFRP flexural reinforcement ratio improved the flexural capacity of the BFRP reinforced beams irrespective of the concrete.

The axial stiffness of the BFRP reinforcement had a significant impact on the flexural performance of the beams. Beams with higher axial stiffness exhibited less deflection, strains, and crack count.

CFRP layers have an important influence as moisture barriers, potentially reducing steel corrosion and concrete deterioration. As a result, retrofitting efforts can boost the sustainability, economic efficiency, and durability of building structures.

The existence of the FRP reinforcement in the over-reinforced concrete beams had a substantial role in resisting loadings after the yielding of the steel reinforcement.

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