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Review of Affected Parameters on Flexural Behavior of Hollow Concrete Beams Reinforced by Steel/GFRP Rebars

Shahrad Ebrahimzadeh

Abstract**—**Nowadays, the main efforts of the researchers aim to constantly evolve new, optimized, and efficient construction materials and methods related to reinforced concrete beams. Due to the fewer applied materials and higher structural efficiency than solid concrete beams with the same concrete area, hollow reinforced concrete beams (HRCBs) internally reinforced with steel rebars have been employed extensively for bridge structural members and high-rise buildings. Many experimental studies have been conducted to investigate the behavior of hollow beams subjected to bending loading and found that the structural performance of HRCBs is critically affected by many design parameters. While the proper design of the HRCBs demonstrated comparable behavior to solid sections, inappropriate design leads beams to be extremely prone to brittle failure. Another potential issue that needs further investigation is replacing steel bars with suitable materials due to their susceptibility to corrosion. Hence, to develop a reliable construction system, the application of Glass Fiber Reinforced Polymer (GFRP) bars as a non-corroding material has been utilized. Furthermore, this study aims to critically review the different design parameters that affect the flexural performance of the HRCBs and recognize the gaps of knowledge in the better design and more effective use of this construction system.

Keywords**—**Design parameters, experimental investigations, hollow reinforced concrete beams, steel, GFRP, flexural strength.

I. INTRODUCTION

THE detrimental effects of steel corrosion in reinforced concrete structures are significant and impose substantial economic burdens worldwide. Insufficient concrete cover, design or construction flaws, and exposure to aggressive agents like seawater, moisture, and high temperatures can all contribute to concrete cracking and corrosion of steel reinforcement. In Australia alone, the cost of repair or replacement related to steel corrosion amounts to an estimated AU$13 billion per year [1]. Similarly, in North America, approximately 85% of bridge failures between 1980 and 2012 were reported, with around 5% attributed to steel corrosion [2]. The annual cost of steel corrosion in Canada reaches approximately $46.4 billion, while 15% of bridges in the United States are deemed deficient due to steel corrosion, necessitating an annual expenditure of approximately $8.3 billion to address corrosion control [3]. These staggering figures underscore the urgent need for effective solutions to mitigate steel corrosion in reinforced concrete structures and the significant economic impact it has on countries around the world.

As a construction material, reinforced concrete has several benefits, including strength and durability. However, it has a major disadvantage in terms of weight, which can result in increased loads and bearing stresses on the soil. This can necessitate the use of deeper foundations to support the structure, increasing the cost and complexity of the construction process. In addition, the weight of reinforced concrete can also limit its use in certain applications where lighter materials are preferred, such as in the construction of high-rise buildings or bridges. As a result, it is critical to closely consider the potential drawbacks of reinforced concrete and, when suitable, evaluate alternative materials and construction techniques.

Regarding environmentally friendly materials, unfortunately, besides the heavyweight of reinforced concrete, the manufacture of cement, which is the primary material for making the concrete mixture, entails extreme CO_2 emission. It was estimated approximately 900 kg of carbon dioxide will be emitted during the process of 1 ton of cement being produced [4]. One of the main candidate solutions is the application of the optimized structural sections. Hollow sections are a form of structural section that has been optimized to reduce structural members' cross-sectional size, resulting in less weight and less concrete material consumption. Because of their smaller size, hollow sections are lighter and more cost-effective than solid parts [5]. However, a smaller section implies a lower moment of inertia, which may result in lower strength and higher deformations. To address this problem, appropriate reinforcement techniques can be used to improve the flexural strength and behavior of reinforced concrete beams with hollow sections. This method is effective in a variety of applications, enabling engineers to design structures with maximum strength and efficiency while using the least number of resources.

Previous studies [17], [18], [52]-[59] show that hollow beams can be considered as a solution to decrease the weight of the structure and provide a more environment-friendly solution. This type of beam is profoundly affected by several design parameters, including the height (H) of the section, inner (ID) to outer diameter (OD) ratio (i/o), reinforcement ratio (ρ), number of longitudinal bars (NL), shape and location of the hollow part in the section, concrete compressive strength (f'c), the ratio between application of load and support to a depth of section (a/d) and presence of the stirrups.

This study aims to provide a comprehensive review of the

Shahrad Ebrahimzadeh is with Centre for Future Materials (CFM), School of Civil Engineering and Surveying, University of Southern Queensland, Toowoomba, QLD 4350, Australia (e-mail: shahrad.ebrahimzadeh@usq.edu.au).

current state-of-the-art in HRCBs. It focuses on identifying the key design parameters that influence the behavior of hollow beams under bending loads and addressing the structural issues associated with steel-reinforced hollow beams. The study also examines the challenges related to the durability and sustainability of existing steel-reinforced HRCBs. Furthermore, the research investigates the fundamental behavior of concrete beams internally reinforced with GFRP bars. The analysis aims to explore the potential of using GFRP bars as an alternative reinforcement material to overcome the structural and environmental concerns associated with steel-reinforced HRCBs. By analyzing the performance and characteristics of GFRP-reinforced concrete beams, the study aims to contribute to the development of more sustainable and durable structural solutions for HRCBs.

II. Flexural Behavior of HRCBs and Design Parameters

HRCBs have been adopted in numerous construction projects in the last few decades. HRCBs are expected to become more widespread in the construction industry, especially in bridge construction and specifically utilization in long-span structures owing to their benefits (e.g., lower mass compared to solid reinforced concrete structures), development of fabrication techniques for manufacturing, facilitation of transportation, and installation on-site [14]. In the section below the affected parameters on the seismic performance of HRCBs internally reinforced by steel, rebars were discussed.

A. Deflection and Ductility

Ductility is the significant property of any structure that indicates its ability to absorb energy before failure. The fact that GFRP bars do not yield like steel raises a challenge in the ductility index of the concrete structures reinforced with GFRP bars and this crucial factor should be investigated. The ductility of a beam in reinforced concrete construction refers to its ability to endure significant plastic deformations and high loads under flexural loading without experiencing sudden or brittle failure [49]. This means that the beam can retain structural integrity even when subjected to high levels of stress, which is an important factor in ensuring a structure's safety and stability.

The higher the ductility index results the more ductility capacity of the beam. To express the most reasonable representation of ductility, some authors used the peak deflection, which is associated with the highest load resisted by the beam, while others indicated the ultimate deflection, which corresponds to the failure load. The method for evaluating the ductility is the 20% load reduction after reaching the peak load proposed by [27], [50], [51] used to calculate the ductility of high-strength reinforced concrete beams.

Several researchers [48], [49] have proposed an equation to estimate flexural ductility in the context of concrete beams reinforced with FRP bars. This estimation is based on the concept of total energy absorption about the absorbed energy in the elastic stage or by assessing the flexural ductility through beam deformability, specifically by comparing the curvatures at the ultimate stage and the service stage. As a property of any structure, ductility represents its ability to absorb energy before failure. However, the challenge lies in estimating ductility for concrete structures reinforced with FRP bars, as FRP bars do not exhibit yielding behavior like steel. Therefore, it becomes crucial to investigate the ductility of concrete beams reinforced with FRP bars. In conventional concrete structures reinforced with steel bars, flexural ductility is defined by the ratio of the ultimate displacement to the displacement at steel yielding [7].

B. Stiffness and Load-Carrying Capacity

Generally, it can be noticed that the load-deflection diagram consists of two parts, the first is below the yielding limit which has a linear fashion when the deflection levels are close to each other and the difference between them is barely distinguishable till the yielding. The second stage is recognized after the yielding limit of steel reinforcement when the cracks develop abruptly, and an extended deflection response can be observed. Furthermore, in a very general term, the hollow beams' stress strain consists of three stages; the first stage is before the first crack limit when the effect of the hollow part is still inconsiderable. The second is after such a limit till the yielding when the effect of hollow shape, location, and i/o ratio are more evident. The third stage begins beyond the yielding of steel reinforcement and the diversity between hollow parts is also clear till failure. The concrete compression strain consists of two distinct stages, the first is the linear portion before yielding when the difference between the specimens can be recognized while the second stage starts after the yielding of the steel when no significant behavior is obvious between the specimens due to the change in the existing circumstances till failure [55].

C. Experimental Studies on Comparison of Steel-Reinforced Solid and HCBs

This review was limited to the flexural response of the HRCBs subjected to static four-point bending and reinforced by steel, GFRP bars, or both materials as a hybrid system. The summary results of the experimental works conducted to investigate the behavior of the HRCBs subjected to bending were presented in Table I. The detailed design parameters for the experimental samples are then reported in reference number of study, number of specimens (No.), the geometry of the cross section (G) (circular (C), square (S), rectangular (R), triangle (T) and ellipse (E)), height (H), length (L), the outer dimensions of the sections (OD), the inner dimensions of the sections (ID), distance of the hollow from top of the section (DHT), the inner-to-outer diameter, (i/o) ratio and (a/d) ratio of the beam, reinforcement ratio (ρ), number of longitudinal reinforcement bars (N_L), concrete compressive strength (f_c'), failure mechanism (flexural (F), shear (S) and flexural-shear (F-S)), load at the initial crack (F_{Cr}) and ultimate load (F_u), deformation of the beam at the first crack (δ_{Cr}) and the ultimate load carrying capacity (δ_u) and the design parameters investigated by the study.

D. Impact of Critical Parameters on Flexural Behavior

Herein is based on experimental investigations on the behavior of HRCBs affected parameters extracted. According to studies conducted in past few years on literature [17], [18],

[21], [22], [27], [34], [40], [42], [52]-[59], the main variable affected the flexural strength and investigated by the researchers is illustrated in Fig. 1.

TABLE I
REVIEW OF PAST EXPERIMENTAL STUDIES CONDUCTED ON HRCBS

Ref.	Geometry		Height (mm)	Length (mm)	Inner diameter (mm)	Outer diameter (mm)	Hollow distance from the top (mm)	i/o ratio	a/d	Reinforcement ratio (%)	f_c' (MPa)	Failure mode	F_{Cr} (kN)	F_u (kN)	δ_{Cr} (mm)	δ_u (mm)	Design parameters
	Solid	Hollow															
[59]	R	S, R, C	200	1000	62.7-75	150	72.5, 125.5	0.37-0.5	1.5	1.45	100	F, F-S, S	50-99	368-445	-	8.3-11.13	i/o ratio, shape, and location
[58]	R	S	230	1000	50	120	115	0.42	1.41	1.45,1.6	23	F-S, S	12.5-17	44-83	0.07-0.11	1.7-3.4	Spacing of stirrups
[57]	R	C	350	3300	120*60, 180*120	150*350	190, 220	0.8	1.14-1.5	1.14 -1.5	25	F	10.2-12.6	136.08-138.41	0.49-0.63	27.11-30.94	Size and i/o ratio
[18]	R	C	200	1500	35,70	150*200	100	0.23-0.47	2	1.15	55	F-S, S	-	121.9-156.45	-	6.96-9.28	Location
[56]	R	R, S	300	1200	50*40, 80*50	200*300	150	0.25	1.83	0.4	24	F, F-S	39.2-40.6	150-155	0.1	4.9-5.15	Shape
[55]	T-beam	C, E	300	2000	32, 50	35*65, 40*60, 150*300	105-190	0.21-0.33	3.33	0.66	28.6	F, F-S	23-28	152-155.6	-	49-52.6	Location and shape
[54]	R	C	300	2300	45,50	200	150	0.2, 0.25	2.22	1.05	30	F-S	150-162.5	237.5-251	-	5.7-6	i/o
53]	R	R	320	3000	40,50	200	150	0.2, 0.25	8.1	1.05	35	F	-	121.8, 136	-	57.03, 62.5	i/o
17]	R	S, C	200	1500	64,75	150	80	0.43, 0.5	2.5	0.2	27.5	F-S	19, 20.5	53.5-57.5	1.7-1.9	14.2-19.7	Shape
52]	R	T, S, C, R	300	3000	45-65	150	150	0.33-0.43	3.33	0.46	39-52	F	20.6-30.1	85.4-110.4	-	18.5-27.5	Shape, f_c'
34]	R	R	300	1200	20-60	200	150	0.1-0.3	1.83	0.42	24	F	-	154	-	4.8-5.9	i/o
27]	S	S	150	850	60-100	150	75	0.4-0.67	1.66	0.54-1.81	63.27-73.34	F, F-S, S	18.77-32.28	64.8-117.4	0.87-1.316	6.72-20.55	i/o, f_c', ρ, stirrups
42]	R	C	200	1200	63.5	150	130	0.42	2.01	0.84	35.3	F, F-S	-	74-104	-	4.82-7.12	Location
40]	S	S	150	1700	35,65	150	75	0.23, 0.43	3.33	0.9-1.29	48-50	F	8.9	42.6-58.26	0.55	22.5-28.8	ρ
22]	R	C	250	1700	25-64	150	45-180	0.17-0.43	1.89-2.69	0.9	24-28	F, F-S, S	24-48	106-120	0.1-0.225	2.98-6.247	a/d, Size, and location
21]	R	C	250	1700	25-50	150	45-180	0.2-0.33	2.69	0.9	26.4	F	22-28	112-120	-	-	Size and location

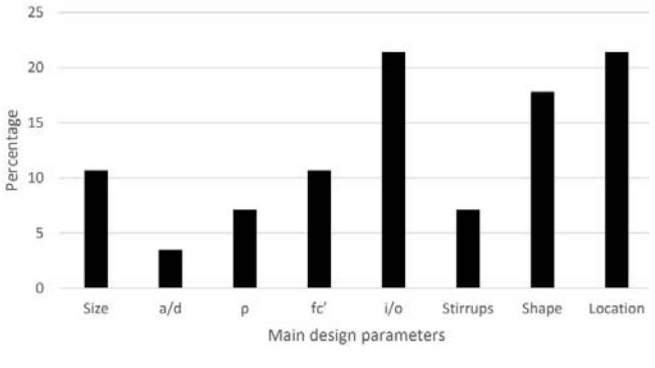


Fig. 1 Critical design paraments for HRCBs

1. Shape of the Hollow Part

Several studies have been conducted to assess flexural strength and observed to show how the shape has influenced the performance of the hollow beams under pure bending [15]-[18]. With the same void area, the square shape offered lower flexural capacity than the circular shape by 4.35% [15]. These results are consistent with Wei et al. [24] who investigated the flexural stiffness of the beam under dynamic four-point bending. They reported a marginal improvement in the flexural behavior of the circular hollow holes in the cross-section compared to rectangular holes. Furthermore, Daud et al. [40] also reported a 5% reduction in ultimate load-carrying capacity between circular and square hollow shapes as well. Other reports also showed complete consistency: The beam with a circular section showed a decrease of 4.2% in load-carrying capacity when compared to a solid beam. In similar ways, the other beams with sections of square, triangular and rectangular shapes openings showed a decrease in ultimate load-carrying capacities by 7.1%, 9.1%, and 12.3% respectively [52]. Also in the mentioned study, while the ductility index of the beam with a circular hole has the highest ratio of 10.33 compared to the solid beam with a ductility ratio of 9, the square, triangle, and rectangular-shaped openings had a ductility ratio of 9.05, 8.8 and 8.66, respectively. The existence of hollow (circular or square sections) has a significant effect on the first cracking load. However, for hollowness size of 10% of the whole section, it seems that the hollow shape does not affect the first cracking load. While for hollowness size of 15%, it is clear that the square section has a greater influence on the first cracking load than that of the circular hollow for any hollow location. This phenomenon is associated with the hollow section's sharp edge, which causes high-stress concentrations at the tip, causing a decrease in the first cracking load. However, the shape of the presence of hollow circular, or square has a negligible effect on the ultimate load [59]. These detrimental effects, however, have been reduced when the corner radius increases and the stress is more uniformly distributed. Sometimes the corners of the rectangular transverse opening are rounded off, to reduce possible stress concentration at sharp corners, thereby improving the cracking behavior of the beam in service. The problem of stress concentration around the transverse opening has been treated by several investigations, such as Savin [19] who dealt specifically with the stresses around small openings in the beam subjected to pure bending. The theory of elasticity, which assumes that the material is homogeneous and isotropic, has been used and follows Hooke's law as well. The effects of opening on the behavior of concrete beams and their results showed that the circular hole had achieved 9% more ultimate load-carrying capacity compared with equivalent square openings [20], [21]. Also, in terms of comparison between circular and ellipse hole shapes, since the ellipse allowed stress to be equally distributed along a longer perimeter length of the beam than the circular shape, the hollow beams with ellipse holes performed slightly better than those with a circular shape [16]. Among horizontal and vertical ellipse hollow parts in the beam, the horizontal hollow beam exhibits better performance rather than the vertical one in strength ductility, with flexural strength nearly 6.59% less than the solid beam and ductility deflection of the hollow increased by 10.87%. Compared to vertical hollow flexural strength which performed 22.06% less than the solid beam, horizontal hollow has significantly better performance [18].

TABLE II
IMPACT OF SHAPE ON HOLLOW CONCRETE BEAMS

Author	Dimensions (mm)	Hollow shape 1	Hollow shape 2	Influence on flexural behavior
Van Loon et al. [33]	800×450	Circular	Rectangular	M_y (yield moment) increased for circular by 15%
Van Loon et al. [33]	800×450	Circular	Square	Ultimate load for circular increased by 7%
Manikandan et al. [33]	200×150	Circular	Square	Ultimate load and deflection for circular increased by 4.5 and 23.2% respectively.
Rokiah et al. [18]	200×150	2 Horizontal circles	2 Vertical circles	Ultimate load increased for horizontal by 16.5%
Anuradha and Madhavi [52]	300×150	Solid	Circular	Load carrying capacity decreased by 4.2%
	300×150	Solid	Square	Load carrying capacity decreased by 7.1%
	300×150	Solid	Triangle	Load carrying capacity decreased by 9.1%
	300×150	Solid	Rectangular	Load carrying capacity decreased by 12.3%

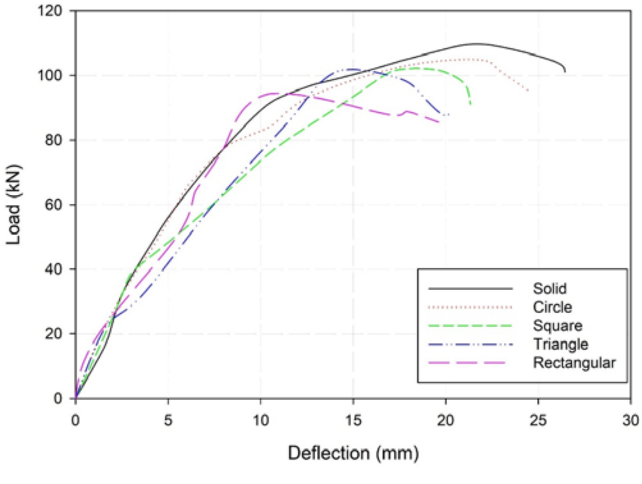


Fig. 2 Load-deflection relationship of HRCBs based on different hollow shapes from results of [52]

2. Location and Size of Hollow Part in the Beam Section

The initial crack load depended on the distance from the center of the hole to the horizontal centroidal axis of the cross-section. It could be concluded that the presence of the longitudinal opening located partly on the compression zone side above the neutral axis led to a decrease in the beam's first crack load compared with that of a hollow opening in the tension zone. This is because the presence of hollow sections above the neutral axis reduced the concrete area in the compression zone and thus reduced the compression force which in turn decreased the internal moment of resistance of the section leading to early failure. The presence of an opening in the tension zone does not influence the compression forces as concrete in the tension zone has an insignificant contribution to tension resistance (Fig. 3) [52]. However, this conclusion is not based on absolute coherency with the experimental investigation conducted on hollow reinforced concrete T-beams. By increasing the depth of the beam from 105 to 170 and 235 mm from the top of the beam section and moving the location of the beam from the compression zone to the neutral axis and tension zone, not only ultimate strength was reduced by 0.39, 1.03% and 2.31%, respectively, but more significantly, the first crack load decreased by 3.57%, 7.14% and 17.86% [55]. This behavior can be interpreted by the loss in flexural rigidity dictated by the decrease in moment of inertia resulting from falling off the internal resistance moment arm. In addition, when the cavity is just below the natural axes, the tension stress is low at the initial levels of load and ingressive failure stress would be late until cracks were when the cavity is located nearby the main reinforcement, the first crack level is low because such zone would undergo the earliest tension cracking. When the diameter of a hole in a beam is larger than the distance between the hole and the outer edge of the beam, the moment of inertia of the cross-section is reduced. This reduction in moment of inertia leads to a decrease in the cracking moment of resistance [22]. In other words, as the size of the hole increases relative to the dimensions of the beam, the beam's ability to resist bending and cracking decreases. Furthermore, when the hole was fully within the stress block, the ultimate load-carrying capacity was found to be less than that of all other hollow beams. As the diameter of the hole increased, the ultimate load-carrying capacity of the beam decreased. This phenomenon is mainly due to the reduction in the lever arm between ultimate compressive and tensile forces as a result of the downward movement of the point of application of compressive force. On the other hand, when the hollow part concentrated fully on the below stress block, the ultimate load-carrying capacity was found to be higher than that of all other hollow beams but less than that of a solid beam. This conclusion was also reported in the experimental and numerical investigation by Daud et al. [40], which presented the influence of different reinforcement ratios of the circular voids positioned at different zones (the compression zone, neutral axis zone, and tension zone) of the reinforced concrete beam cross-section along the beam length. It became clear that the ultimate load decreased with moving the hollow part toward the compression zone by 46% and this was due to the reduction in the compressive stress block for concrete. whilst the ultimate load decreased by moving the hole toward the tension zone by 13% and also this is due to the reduction in tension stiffening [40]. Therefore, it could be understood that the preferable hollow part will be at the neutral axis zone for manufacturing the HRCBs.

Failure mode was not affected by the hole location, while the ultimate capacity was dependent on the hole size and location. Both the yielding and peak loads of the beams decreased as the hole size increased, showing a lower area under the load-deflection curve. This can be attributed to the reduced moment of inertia, which reduces the beams' strength. Furthermore, by increasing the diameter of the hollow part and moving the position of the hollow part of the section toward the top of the beam, deflection also increases [23]. This is mainly due to the reduction in the moment of inertia of the cross-section. It also should be noted in similar work to mentioned experimental programs, Balaji [42] investigated the effect of the location of the hollow part in the HRCBs. Two different diameters of hollow parts were performed at the solid section. The first case was the perforation of a hole with a diameter of 61.5 mm and in the second case with consideration of the same area, two holes with a diameter of 31.75 mm perforated, and the results were compared to a solid beam as well. The results indicate that although the area of the hollow part is almost the same, by performing a double hole instead of one hole in the beam section the ultimate load decreased by 21.5%. On the contrary, the yielding load, deflection, and ductility factor heavily depend on how the hollow part performed in the beam section. by using a PVC along the length of the beam yielding load, the ductility index did not particularly change. In stark contrast, however, by adopting a galvanized iron pipe as a hollow part, the difference in the deflection at the ultimate load and ductility factor between single and double holes became more distinguished. The former reported as 32.3% and the latter differed about 35.3% as well.

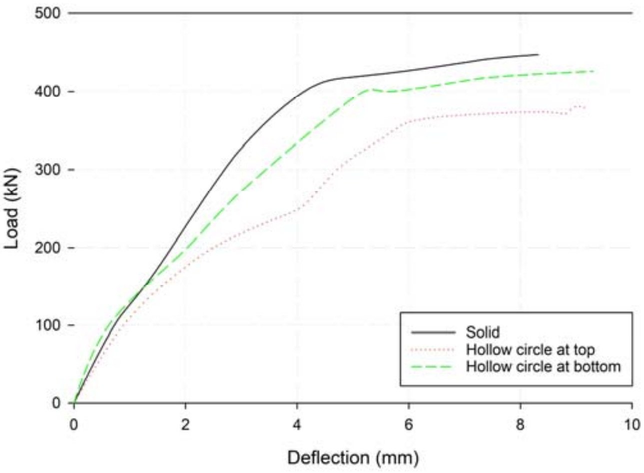


Fig. 3 Load–deflection curve based on different shapes and locations from results of [59]

3. Inner-to-Outer Diameter (i/o) Ratio (Size of the Hollow Part)

The load-carrying capacity of hollow beams reduces as the hole size increases and it is in general lower than that of solid beams. There are different proposed lower bounds for the minimum hollow to the solid part of the section so that the flexural strength reduction becomes negligible. The removal of the solid section from the tension zone of the HRCBs was found to have minimal impact on their flexural response. The removal accounted for approximately 17.5% to 30% of the total section in the tension zone. Despite this removal, the flexural behavior of the HRCBs remained largely unaffected [42]. Increasing the i/o ratio reduces the amount of material used and increases the effect of biaxial stress in the cross-section of beams. The increase in the i/o ratio decreases the thickness of the inner concrete core, which leads to brittle failure, driven mostly by the shear of the concrete after it reaches its ultimate compressive strength capacity [6]. The reduction in deadweight will show up as reduced static moments and reduced earthquake loads on all the structural members, and hence the thin-walled box beams may be subjected to reduced external effects and they can be used instead of the heavier full beams, especially for large-span types of structures, like bridges. Moreover, in terms of comparison between hollow and solid beam rectangular sections, the cross-sectional moment of inertias of the box beams with the ratio of thickness to the height of the section (2t/h = 0.67 and 2t/h = 0.33) are 1.2% and 20% smaller than that of the solid beams, respectively. Despite a considerable loss in moment of inertia as compared to the solid beam of the same outer dimensions, the ratio of (experimental ultimate load)/(theoretical ultimate load) of the thin-walled box beams with 2t/h = 0.33 is measured to be 14% greater than that of the full beams [26].

In a related investigation by Abbass et al. [27], the study findings indicated that the selection of an optimum hollow section can enhance the ductility of high-rise concrete beams (HRCBs) without negatively affecting their flexural strength. Through experimental analysis, it was observed that hollow beams with size reductions of 16% and 28.4% exhibited higher ductility compared to the reference solid beam. Furthermore, the ductility of the hollow beam with a size reduction of 44.4% was found to be comparable to that of the solid beam [27]. A classification and comparison of the limitations of the inner-to-outer ratio and its influence on the ultimate load-carrying capacity are presented in Table III.

TABLE III
IMPACT OF THE INNER–TO–OUTER DIAMETER (I/O) RATIO

Authors	Inner diameter (D: depth of beam)	Impact on flexural behavior
Mansur [28]	< 0.4D	Partial influence on ultimate strength recommended value between 30- 40%
Amiri and AlLibygie [29]	< 0.33D	An increase in hollow part influenced reduction in serviceability
Hua et al. [30]	0.16D	16% Reduction in strength
	0.25D	20% Reduction in strength
	0.33D	36% reduction in stiffness
Amiri and Masoudnia [21]	< 0.48D	No distinctive influence on initial stiffness
Kanna et al. [32]	0.44D	Ultimate load decreased by 34.29% in the circular section

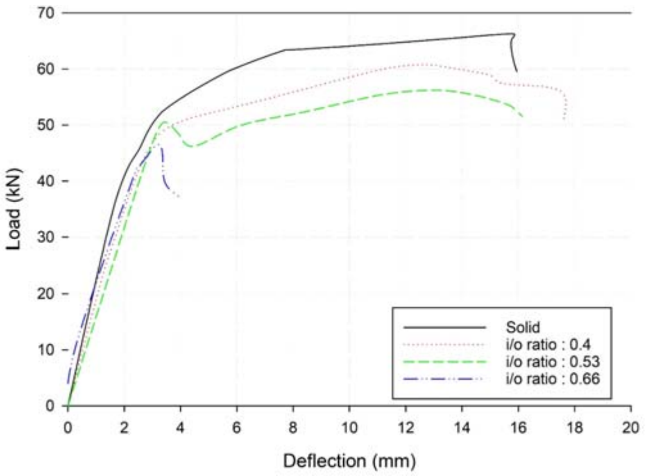


Fig. 4 Effect of i/o ratio on load-deflection relationship from results of [27]

The comparison of the reduction in cross-sectional size of hollow beams, which corresponds to a decrease in weight and cost, and the reduction in load capacity reveals that beam hollowing is advantageous up to an inner-to-outer ratio of 0.53 [27]. Furthermore, after reaching the yield loads, it is evident that the yielding load capacity of hollow beams decreased by approximately 4% to 9% as the section size was reduced by 16% to 28.4%, respectively. Additionally, utilizing less than 10% of the beam cross-section as the hollow portion had a minimal impact on the failure load of the reinforced concrete (RC) beams. In summary, the concrete core did not significantly contribute to the bending capacity of the RC beams [27]; however, it notably influenced the cracking pattern, affecting the length and width of the cracks [34]. These findings are consistent with the results obtained from other experimental programs [35]. The decrease in ultimate load capacity with an increase in the opening size of the beams aligns with the observed behavior of GFRP bars in both investigations. It is also noteworthy that an increase in the shear reinforcement ratio resulted in an enhancement of the ultimate load capacity, which is a common trend in RC structures.

4. Longitudinal Reinforcement Ratio and Configuration

Both the ACI committee 318-19 [36] code and Eurocode 2 (2011) [37] specify a maximum reinforcement ratio to prevent sudden collapse. However, increasing the longitudinal steel bars in the tensile zone can significantly boost the ultimate flexural strength [38]. For example, when comparing beams with the same dimensions and hollow core size, increasing the reinforcing steel ratio by up to 4.3 times can result in an ultimate flexural load increase of 260%. Additionally, a solid square section measuring 250 mm was compared to a hollow section with a 90 mm square hole. By increasing the steel bars in the section zone from 226 mm^2 to 981.75 mm^2, the ultimate load-carrying capacity increased by 230%.

While increasing longitudinal reinforcement can enhance load-carrying capacity, it often results in reduced ductility. Research shows that compared to a reference beam with two 8 mm bars, adding three or four bars increased yielding load by 57% and 92%, and peak load capacity by 53% and 70%, respectively. However, the ductility index dropped by 17% for three bars and a steep 70% for four bars [27].

Othman et al. [39] added a single bar to the tension and compression zones, upper and lower, respectively, of a rectangular beam with an 8.3% a square hollow section. Beams with additional reinforcement around the hollow section had a 7.5% higher flexural strength than those without bars, but their deflection decreased. Ductility was measured as midspan deflection at the ultimate load, which decreased from 5.1 to 4.0 mm compared to the reference beam (Table IV).

Different configurations of longitudinal rebars also provided different outcomes and impacts on the flexural response of the RC beams. Daud et al. [40] found that replacing 2Φ12 reinforcement with 2Φ10 (as main reinforcement) and 2Φ6 (as additional reinforcement in the constant moment zone) works for both hollow and solid beams. Adding reinforcement bars to hollow beams requires that the hole size not exceed the beam depth divided by 4.

TABLE IV
DIFFERENT CONFIGURATIONS OF LONGITUDINAL REINFORCEMENT

Author	Dimensions	Hollow/Solid	ρ_1 (%)	ρ_2 (%)	Influence
Othman et al. [38]	200×150	Hollow	0.75	1.13	Ultimate load increased by 11.1%
Daud et al. [39]	150×150	Solid	0.9	1.22 (2Φ12)	Ultimate load increased by 43.9%
	150×150	Solid	0.9	1.29 (2Φ10+2Φ6)	Ultimate load increased by 126%
Birgisson [41]	200×236	Solid	0.53	1.19	P_u and M_u increased by 149.42%
	200×189	Solid	0.83	1.19	P_u and M_u increased by 38.17%
	200×335	Solid	0.53	1.55	P_u and M_u increased by 550.96%

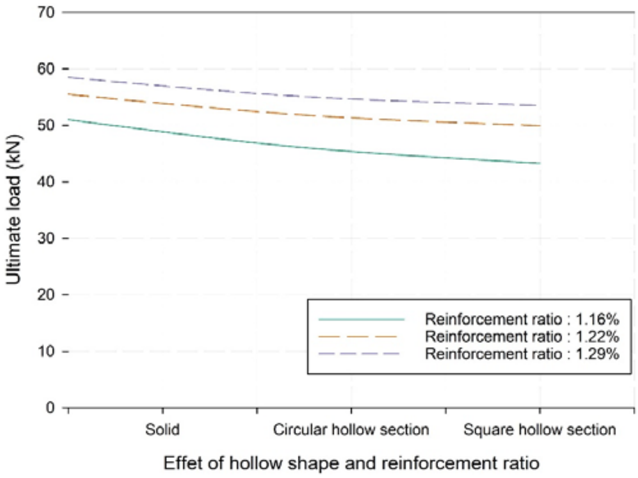


Fig. 5 (a) Effect of reinforcement ratio and shape of hollow in HRCBs on ultimate load capacity

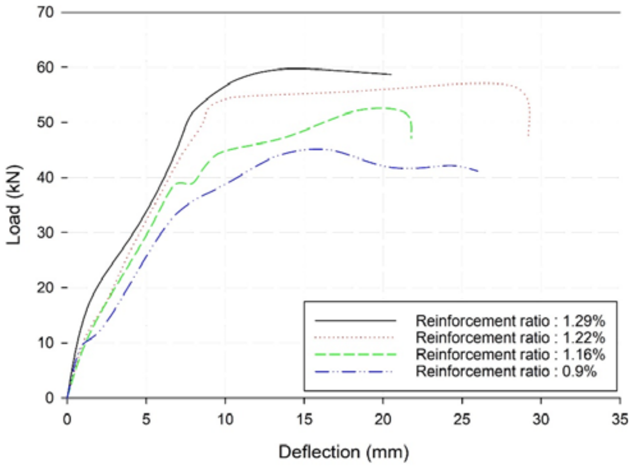


Fig. 5 (b) Load-deflection curve from results of [39]

5. Specification of the Concrete

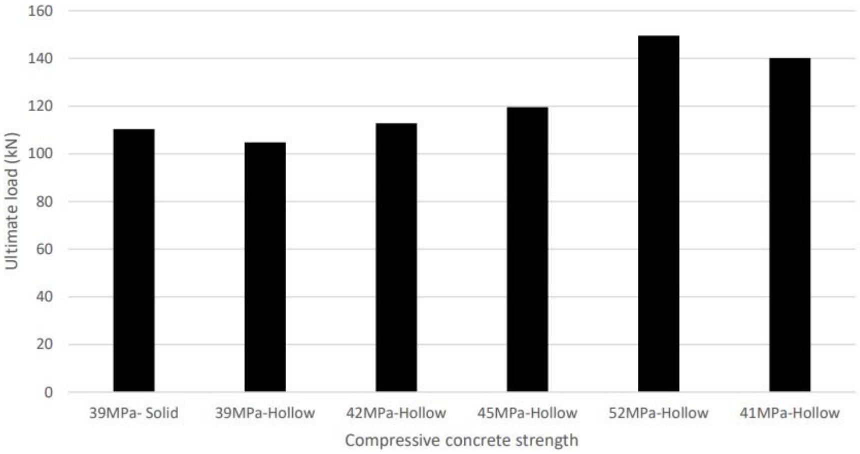
Higher concrete strength and reinforcement ratio can decrease crack widths by distributing cracks along beams [3]. Prior research has explored the flexural behavior of reinforced beams with longitudinal holes and focused on concrete compressive strength [7], [21], [22]. Increasing concrete strength has been shown to boost beam resistance moment. Experimental work on concrete specifications can be broadly categorized into two areas.

a. Concrete Compressive Strength

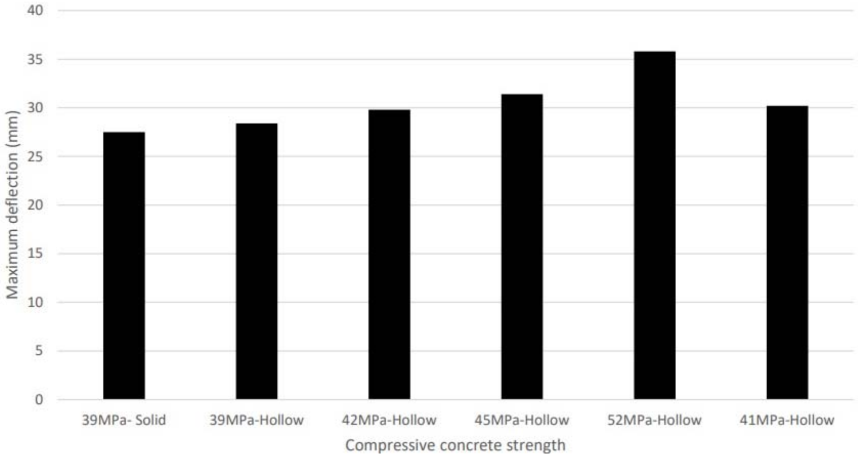
While Manikandan et al. [17] examined the impact of concrete compressive strength, hole shape, and location along the beam length, Murugesan and Narayanan [21], [22] tested the flexural performance of normal strength concrete (23 to 28 MPa) with longitudinal holes in different places. In both investigations, hollow beams with circular or square holes were employed, and it was discovered that increasing compressive strength from 30 MPa to 50 MPa greatly increased carrying load capacity, however increasing compressive strength from 50 MPa to 70 MPa just slightly increased carrying load capacity. This is brought about by the inverse relationship between compressive strength and tension stiffening [40].

b. Improvement in Concrete Tensile Strength

In RC beams, the contribution of concrete on tension zones to flexural response is negligible, and the part can be replaced with weaker or eliminated material. Analytical equations for predicting the flexural strength of concrete beams do not consider the strength of the concrete tension zone. However, the inclusion of polymeric fibers in concrete with a volumetric ratio of 1.0% to 1.5% increased stiffness by 24% to 40% in hollow beams [5]. Comparing the yielding load capacity and ductility of hollow and solid RC beams with 1.0% volumetric steel content, the hollow beam had a 6.2% smaller yielding load but only 3.5% smaller peak load. Lower steel fiber content made strain hardening and softening regions similar in ductility. However, using more fiber in hollow beams improved ductility, providing greater resilience and flexibility under stress. Using hollow sections in RC construction can reduce weight and material consumption while maintaining sufficient strength and ductility for safe and effective performance. As a result, adding an optimal amount of fibers to concrete can improve the post-peak and post-crack behavior of HRCBs. Microfibers prevent crack initiation, formation, and propagation, leading to an improvement in performance [31].



(a)



(b)

Fig. 6 Effect of concrete compressive strength in HRCBs on (a) ultimate load capacity and (b) deflection from results of [31]

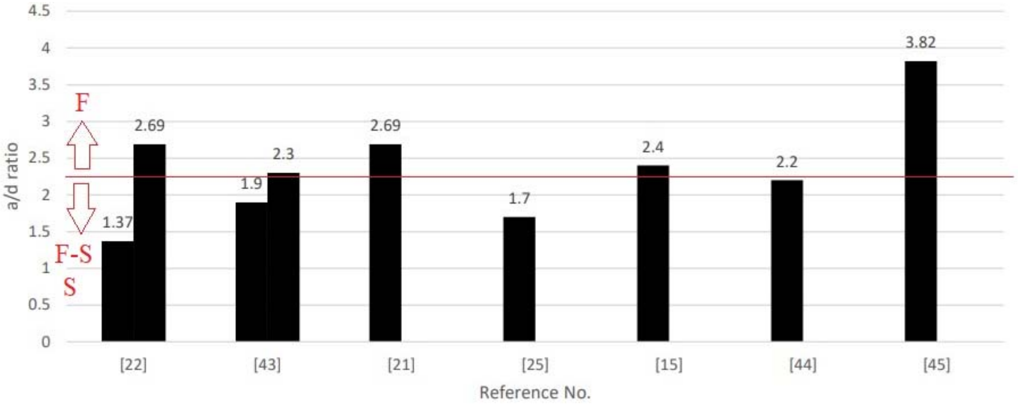


Fig. 7 Distribution of a/d ratio with respect to failure mode

TABLE V
INFLUENCE OF a/d RATIO ON FAILURE MODE

Author	a (mm)	d (mm)	a/d	Failure mode
Al-Gasham [25]	450	266	1.7	Shear
Lim and Ling [43]	500	261	1.9	Shear
Murugesan and Narayanan [22]	414	219	1.93	Flexural - Shear
Murugesan and Narayanan [22]	460	219	2.1	Flexural - Shear
Lim and Ling [43]	600	261	2.3	Flexural
Lim et al. [15]	624	260	2.4	Flexural
Mathew and Varghese [44]	567	261	2.2	Flexural
Murugesan and Narayanan [21]	589	219	2.69	Flexural
Sariman et al. [45]	1200	314	3.82	Flexural

6. a/d Ratio

Both solid and hollow beams exhibit similar failure mechanisms, with flexural cracks forming and widening until failure. However, when the ratio of the distance between load application and support to effective depth of the beam (a/d) was between 1.9 to 2.3, hollow beams exhibited a flexural failure mode, similar to solid beams. At lower values of a/d, shear cracks were the primary failure mode, and at higher values of a/d (above 2.3), the behavior of the beam shifted back to flexural failure mode. Therefore, 1.9 and 2.2 may be considered as transition values for the major failure mode of the HRCBs.

7. Presence of Lateral Stirrups

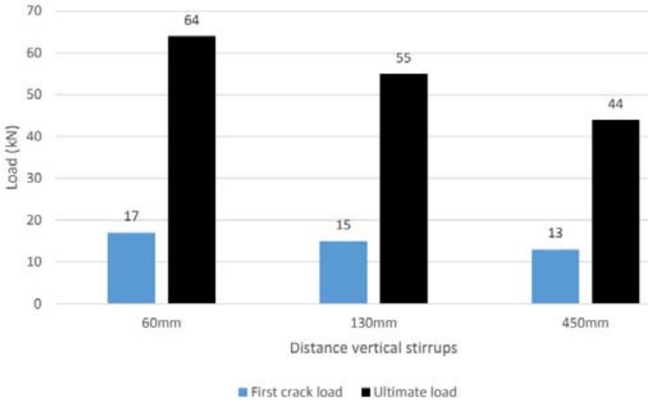


Fig. 8 Effect of stirrups spacing in HRCBs on first crack and ultimate load capacity from results of [58]

Stirrups improve the response of RC beams by providing confinement and increasing their ability to absorb stresses. Beams with stirrups demonstrated better post-peak behavior and increased deflection after the peak load stage [46]-[48]. Lack of appropriate transverse reinforcement causes slanting cracks in beams [39]. Results show that the initial cracking loads of beams without stirrups were comparable to those with stirrups, but yielding loads were slightly lower [27]. Increasing stirrup spacing did not affect the first crack load but decreased the ultimate load. Perforation of the hollow part in the solid beam did not change the first crack load by increasing the stirrups. Deflection at the ultimate load is improved by decreasing the spacing, especially in HRCBs [58].

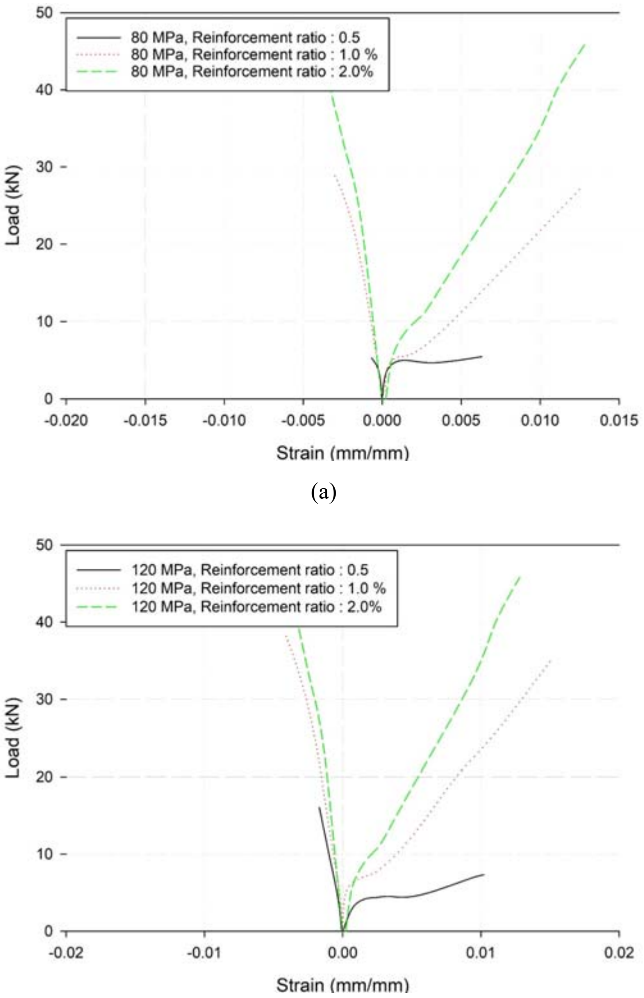
III. SOLID CONCRETE BEAMS REINFORCED BY GFRP

A. Overall Behavior of GFRP-Reinforced in Solid Concrete Beams

FRP bars are replacing steel bars in concrete beams as a result of their advantages in terms of longevity, such as resistance to corrosion, lack of magnetism, and high strength-to-weight ratio. Steel has stronger stiffness and elastic-plastic behaviors before to yielding, whereas GFRP has higher strength and linear elastic behaviors up to failure. Nevertheless, steel and GFRP bars have different material properties. To prevent sudden failure, beams reinforced with FRP bars are often over-reinforced [6]. Most design codes recommend over-reinforced section design for concrete beams reinforced with FRP bars, where concrete crushing is the dominant mode of failure, yielding higher deformability before failure. GFRP-RC beams behaved bilinearly or almost linearly up to failure, with wider cracks than steel-RC beams [3], [7]. Because GFRP bars have a lower modulus of elasticity than steel, the deflections and crack widths of GFRP-RC are greater. Therefore, rather than the ultimate state, the serviceability limit state might be the best criterion for designing hollow beams reinforced with GFRP. The ductility of GFRP-reinforced parts is still an issue, though. ACI 440.1R-06 [70] suggests that flexural members should have a higher reserve strength to compensate for the lack of ductility in GFRP bars. However, ductility should not be neglected because it is closely related to safety, especially in the case of catastrophic loads such as earthquakes. Ductility provides ample warning before failure, which can greatly reduce the risk of loss of human life in GFRP-RC members.

The load-strain behaviors of GFRP reinforcing bars in concrete beams are depicted in Fig. 9. The strain suddenly dropped at the point of cracking, and the post-cracking strain rapidly increased, depending on the quantity of reinforcement. In under-reinforced beams, the strain in the #2S GFRP reinforcement bars increased faster than in over-reinforced beams with #3 and #4 GFRP reinforcement bars. The influence of concrete strength on GFRP reinforcement bar strain was not substantial, and ultra-high-strength concrete GFRP-RC beams had slightly lower strain at the same load level as high-strength concrete GFRP-RC beams.

Limited research has been conducted on evaluating the flexural behavior of hollow beams reinforced with either steel or GFRP longitudinal rebars. The use of GFRP as an internal reinforcement system has advantages, including good post-crack behavior with lower strains in the GFRP bars compared to steel bars, likely due to the good bond behavior of GFRP bars yielding more cracks and smaller strains at the same load level [3].



(a)

(b)

Fig. 9 Load-strain behavior of GFRP-RC beams under static loading from the results of [65]; (a) f_c': 80 MPa, (b) f_c': 120 MPa

The impact of various design parameters has been well investigated and studied for HCBs reinforced by steel bars and solid beams reinforced by GFRP rebars. Different methods have also been proposed to enhance the performance and improve the ductility of beams as well. These techniques include the application of multilayer reinforcement, changes in axial stiffness, and the arrangement of longitudinal reinforcement. Although suggested techniques have significantly improved the behavior of HRCBs, the corrosion of steel bars remains an important issue.

B. Comparison of Experimental Results

The parameters of the studies are indicated in Table VI for each specimen: tension zone of the beam section at the bottom (B), compression zone of the beam section at the top (T), height (H), length (L) and width (W) of the beam, sand coated GFRP bars (SCG), helically grooved GFRP bars (HGG), concrete compressive strength (fc'), number of the GFRP bars used in the beam (NL), reinforcement ratio (ρ), a/d ratio, results of the experiment based on flexural strength (applied load (kN) at the peak (Pu), bending moment (failure resistance bending moment as Mu (kN.m)), ductility (maximum deflection as δm (mm), ductility index (μ: Δu/Δy)), curvature (ψ), maximum concrete strain (εcm), maximum GFRP strain (εfm), details and also failure mechanism observed in the experiment (include: concrete compression (CC), GFRP bar rupture due to tension (T), steel yield (SY), steel bar buckling (SB), brittle (B), flexural failure (FF), shear failure (SF)).

TABLE VI
REVIEW OF PAST EXPERIMENTAL STUDIES ON BEAMS INTERNALLY REINFORCED BY GFRP BARS

Ref.	Beam properties	H*L*W (mm)	f_c' (Mpa)	ρ (%)	a/d	Stirrups	Flexural strength, P_u	Cracking load, P_{cr}	Flexural strength, M_u (kN.m)	First crack moment, M_{cr}	Ductility Index / Curvature	Ultimate Deflection (mm)	Failure mechanism	Design Parameters
[69]	Steel GFRP	250*2000*150	80.1	1.2	2.8	$Ø_S$8@100	200-230	17.5-30	69.9-82	5.9-8.75	μ_{min}: 1.0 μmax: 4.2	17.26-49.36	CC, SY CC	Arrangement
[68]	Steel GFRP	250*1800*180	30.95-40.65	0.29-3.49	2.4	$Ø_S$10@100	78.5-146.3	-	-	-	μ_{min}: 1.0 μmax: 2.29	12.08-33.29	SY, CC	P by increase in diameter
[67]	Steel GFRP	300*2600*200	48-75	0.6-3.5	4.3	$Ø_S$10@100	94.44-772.2	-	-	-	μ_{min}: 1.0 μmax: 2.35	31.9-70.6	T, CC, SF	Increase in diameter
[66]	Steel GFRP	200*2500*150	30,50	0.59	3.5	$Ø_S$6@25	34.2-77.3	-	-	-	μ_{min}: 1.0 μmax: 2.19	53.8-93.5	SY, T, CC	f_c' ρ
[65]	GFRP	200*2500*150	30,50	0.59, 0.81	3.5	$Ø_S$6@25	34.2-77.3	-	-	-	μ_{min}: 1.0 μmax: 1.31	58.3-81.8	T, CC	ρ
[63]	GFRP GFRP+ mild/high yield steel	380*4600*280	35.3-45.9	0.35-2.09	5.52	$Ø_S$8 @50	-	-	19.6-252.7	-	μ_{min}: 1.0 μmax: 6.01	0.88-193.6	CC, T	ρ Configuration of angle of hook of stirrups
[62]	GFRP	300*4000*230	40	0.38-1.13	4.16	$Ø_S$8 @100	-	-	49.03-85.53	-	Ψ_{min}:1.37E−05 Ψmax:3.53E−05	62.05-127.1	T, CC, SY CC	ρ
[50]	GFRP#5 SteelΦ16	300*3100*200	31	0.5-2.09	4.33	$Ø_{GFRP}$9.5 @100	125-210	17-20	-	-	μ_{min}: 1.3 μmax: 2.4	27.5-84.6	CC, SY, SB, FF	Type of GFRP Arrangement
[3]	No.13 SCG No.25 HGG Steel 10M	400*4250*200	30,65	0.36-1.78	3.43	Φ10@100	-	-	45.88-189.06	11.98-24.06	Ψ_{min}:0.004 Ψmax:0.019	41.3-71.4	CC, T, SY	Type of GFRP ρ, diameter
[7]	GFRP	300*3100*200	35,65	0.38-1.63	3.66	Φ10@100	-	-	50.9-124.1	7.9-56	Ψ_{min}:3.76E−05 Ψmax:7.83E−05	32-56	CC, T	f_c' ρ

C. Effect of GFRP Rebars on Flexural Behavior of Solid Beams

1. Longitudinal Reinforcement Ratio

As the reinforcement ratio increased, the severity of failure decreased, and the stiffness after cracking of the hybrid beam increased, reducing crack widths and spacing [60]. However, increasing the reinforcement ratio resulted in higher ultimate load carrying capacity and ultimate bending moment. In normal and high strength concrete, increasing the GFRP reinforcement ratio significantly increased load carrying capacity, energy absorption capacity, and bending stiffness [7], [64], [65]. Increasing the amount of tensile reinforcement was found to enhance the performance of GFRP-RC beams under static loading [65]. Experimental results showed that increasing the reinforcement ratio resulted in a higher load-carrying capacity and a reduction in mid-span deflection [65], [69]. The number of cracks increased with increasing reinforcement ratio, but the width and depth of cracks decreased [3], [7]. However, the effect of bar diameter and surface texture on the ultimate load-carrying capacity of the GFRP-RC beams could not be quantified [3]. Increasing the GFRP reinforcement ratio had a greater impact at the service stage than at the ultimate stage due to the over-reinforced design of the beams [3]. The effect of increasing the GFRP reinforcement ratio was almost independent of concrete strength at the ultimate stage, and the deflection–moment relationship had some non-linearity before beam failure due to concrete nonlinearity, which decreased with increasing GFRP reinforcement ratio [3], [7], [64], [65].

Fig. 11 shows that all beams had similar relationships between concrete compressive strain and applied moment. The concrete compressive strain increased as the moment increased. Initially, all beams had a steep slope and linearly increased with the moment until a strain of about 100-200 με. The initial slope was almost the same for normal and high-strength concrete beams, but it was higher for high-strength concrete. This suggests that the initial slope was dependent only on concrete properties. Afterward, the concrete compressive strain increased with a second, very shallow slope or almost plateaued until it reached a strain of 300-400 με. Finally, a third slope occurred and increased to approximately 43% and 32% of the initial slope for normal and high-strength beams, respectively. This third slope increased as the GFRP reinforcement ratio increased.

Fig. 12 shows that GFRP bars had a more substantial effect on high-strength concrete (HSC) beams than on conventional strength concrete beams. Regardless of the concrete strength, it is critical to prevent exceeding the tensile strain capacity of the GFRP bars. The usage of 16 mm diameter GFRP bars resulted in satisfactory designs with a safety margin of 20% to 25% before the GFRP bars reached their rupture strain limit, according to the data.

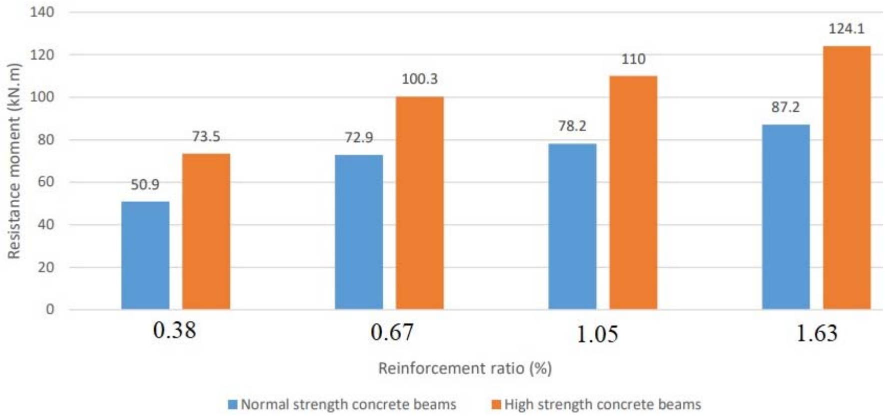


Fig. 10 Moment – reinforcement ratio in SCBs reinforced by GFRP from the results of [7]

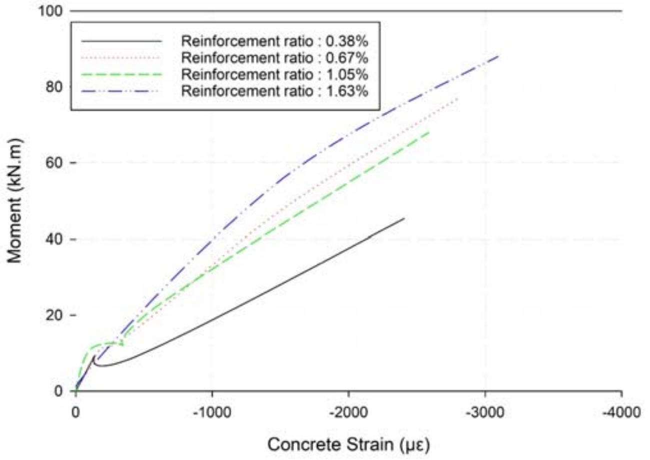


Fig. 11 Concrete moment – strain relationship with f_c': 35MPa from the results of the [7]

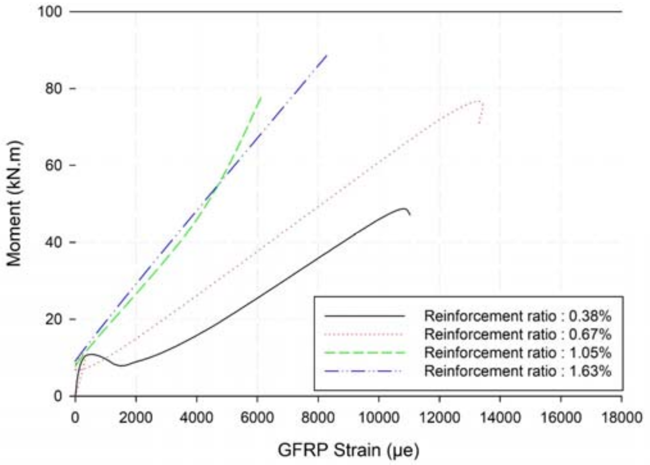


Fig. 12 GFRP moment–strain relationship with f_c': 35MPa from the results of the [7]

Fig. 11 shows the P-Δ response of control beams (reinforced by GFRP) in three stages. Hybrid beams have a four-segment P-Δ curve, with higher cracked stiffness due to the presence of steel bars. Nonlinear behavior occurs with further loading, signifying steel yielding and crushing failure of concrete. Adding steel reinforcement improves the stiffness of hybrid beams, and stiffness increases with an effective reinforcement ratio. After yielding, stiffness decreases due to the low modulus of elasticity of GFRP bars, resulting in excessive deflections before the failure of hybrid beams [60], [62].

2. Axial Reinforcement Stiffness (A_fE_f)

The use of GFRP bars for reinforcement reduces axial stiffness, resulting in increased beam ductility and larger deflections. However, increasing the axial stiffness (AfEf) of the GFRP bars results in more cracks with smaller width and depth [7]. The bond characteristics of sand-coated GFRP bars appear to be better than those of helically grooved GFRP bars, as sand-coated bars led to fewer cracks. Beams with the same AfEf for GFRP and steel bars exhibited similar load-deflection relationships up to the yield point of the steel bars [3].

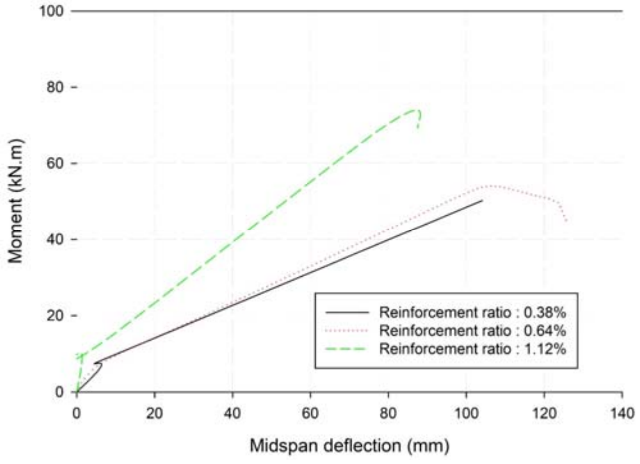


Fig. 13 Moment – midspan deflection relationship with different rebars diameter from the results of [62]

The moment-deflection curves of the test beams in Fig. 13 showed initially linear relationships until cracking. The slope of the uncracked portion slightly varied depending on the cracking condition before testing. After cracking, all beams had reduced stiffness and increased deflections as shown by the reduced slope of the moment-deflection curves. The GFRP-reinforced beams had bilinear moment-deflection relationships in both uncracked and cracked stages, and the reduction in stiffness after cracking was mainly influenced by the amount of GFRP reinforcement [62].

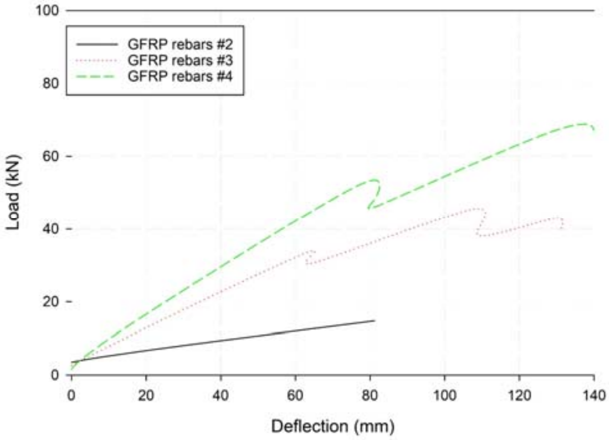
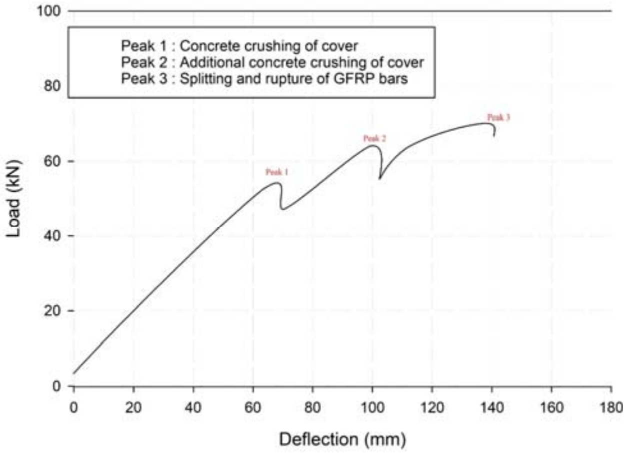
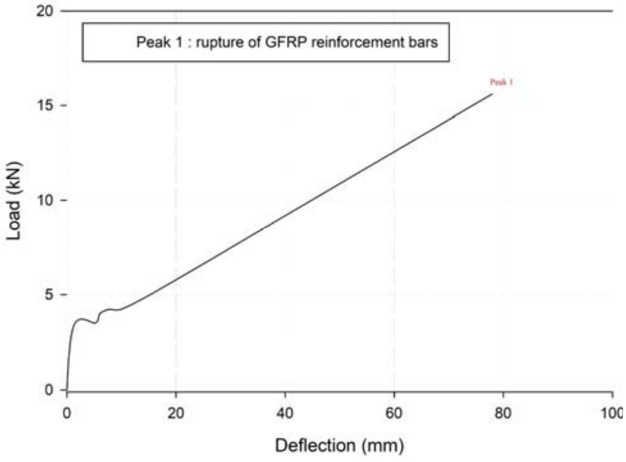


Fig. 14 Load – midspan deflection behavior of different bar size GFRP-RC beams subjected to static loading from the results of [65]



(a)



(b)

Fig. 15 Definition of peak loads in the behaviour of GFRP-RC beams under static loading from the reference of [65]: (a) Over-reinforced GFRP–RC beam; (b) Under-reinforced GFRP-RC beam

GFRP-RC beams exhibited bi-linear behavior until failure, as shown in Fig. 14, similar to FRP-RC beams reported in [50], [62]-[67]. Under-reinforced high strength and ultra-high-strength concrete GFRP-RC beams failed due to GFRP reinforcement rupture, while over-reinforced ones showed some pseudo-ductility. See Figs. 15 (a) and (b) for the behavior of GFRP-RC beams at various loading levels [65].

3. Steel/GFRP as a Hybrid System of Reinforcement

Hybrid systems that mix steel and GFRP bars are a viable solution to the low modulus of elasticity and lack of ductility of FRP bars in concrete beams [60], [61], [66]. Steel reinforcing bars ensure ductility and serviceability, whereas FRP reinforcing bars preserve load-carrying capability. In some cases, it may be beneficial to place FRP bars at the exterior surface of the tensile zone [62]. FRP bars have high tensile strength, and corrosion resistance, and are lightweight compared to steel bars. Placing FRP bars at the exterior surface can provide effective reinforcement against tensile forces and help prevent corrosion issues, especially in aggressive environments or marine structures. Because of the yielding of the steel reinforcement, hybrid beams display more ductile compression failure with ample warning than GFRP-only reinforced beams [61]. The use of a GFRP-steel hybrid system enhances serviceability and ductility, improves beam performance in fire conditions, and reduces crack width and spacing through the presence of steel reinforcement [60]. Hybrid beams are designed by allowing steel bars to yield first before concrete crushing or GFRP rupture to ensure adequate deformation [62].

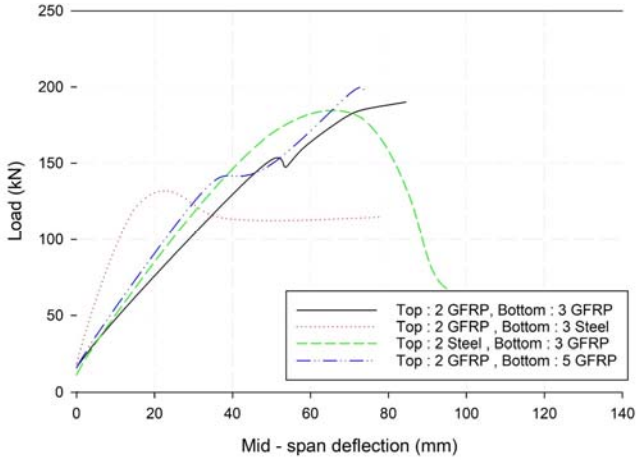
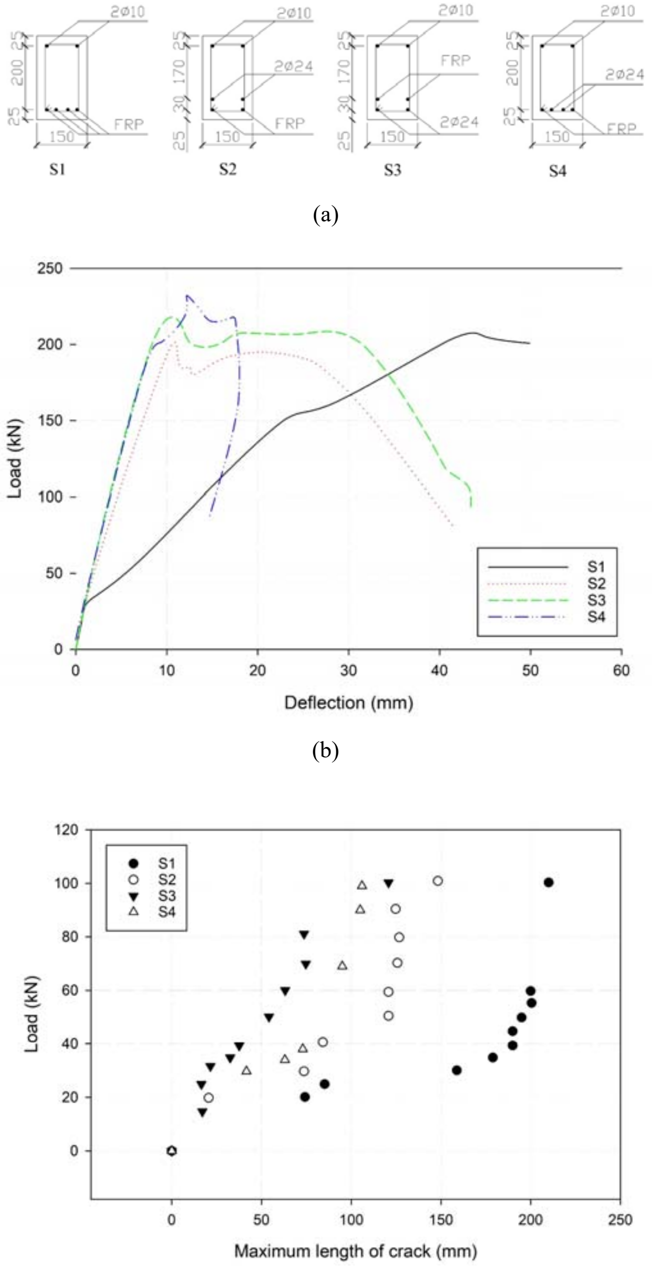


Fig. 16 Impact of the hybrid system in load–midspan deflection relationship (from the results of [60])

Moreover, hybrid beams that combine GFRP and steel reinforcing offer greater strength and flexibility while consuming less weight and material. Steel reinforcement adds support and stiffness to the structure, ensuring structural integrity under extreme stress. However, after the initial crack and yielding of steel reinforcement, the lower stiffness of GFRP reinforcement can induce greater deflection. Despite this constraint, hybrid reinforcement is a viable solution for increasing strength and durability in RC construction [13].

4. Arrangement of the GFRP Reinforced Rebars



(a)

(b)

(c)

Fig. 17 Impact of effectiveness Arrangement from the results of the study [64]; (a) Different types of arrangement, (b) Load-deflection curve, (c) Crack length

Hybrid beams with different configurations have varying deflections after cracking, and the position of steel rebars significantly affects the beam's stiffness. The ductility index is higher when GFRP bars are arranged at the outer layer of the concrete beam compared to the inner layer [64]. The ultimate bending moment of beams with different arrangements of GFRP and steel rebars varies with the highest moment occurring when the steel bars are on the outer layer and GFRP bars on the inner layer. Steel rebars also control the maximum crack width, which decreases as the depth of the steel layers increases.

As illustrated in Fig. 17, beams with GFRP bars at their inner layer perform better ductility and flexural strength compared to the beam reinforced by GFRP at their outer layer. Furthermore, the maximum width and depth of the cracks in hybrid beams are mainly controlled by steel rebars. With the depth of steel layers increasing, the maximum crack width decreases.

5. Transverse GFRP Reinforcement

Increasing the transverse GFRP reinforcement in continuous concrete beams can decrease deflection while enhancing ductility and stiffness by increasing the vertical shear reinforcement ratio [11]. The initial crack load value depends on transverse reinforcement, which can compensate for the presence of a hollow in the beam section [12]. The effectiveness of hook angle in stirrups in GFRP internally lateral reinforced systems is illustrated in Fig. 18.

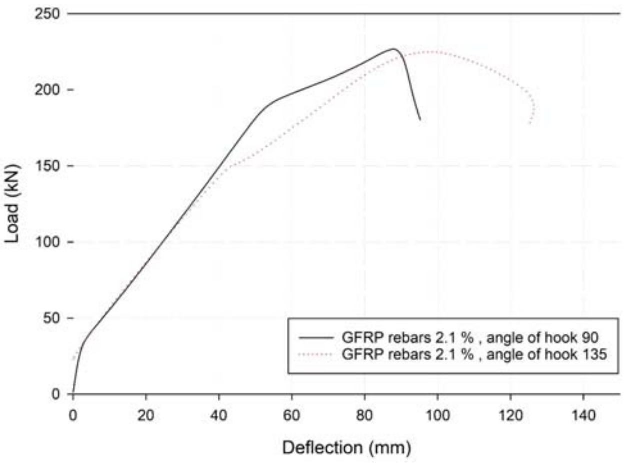


Fig. 18 Effectiveness of 135° hooks in lateral reinforcement of GFRP reinforced beams from the results of [63]

6. Impact of Concrete Compression Strength on GFRP Reinforced Beams

GFRP-RC beams display a bilinear moment-strain relationship, with HSC beams exhibiting higher cracking moments than normal strength concrete beams [3]. Increasing the concrete strength from normal to high strength reduced the strains in the GFRP bars slightly for beams with the same reinforcement type and amount at the same load level (Fig. 12).

IV. DISCUSSION

A. GFRP Bars as an Internal Reinforcement System for HRCBs

The majority of research and development on concrete structures reinforced with GFRP bars has been concentrated on solid concrete members. However, the authors have recently completed pioneering experimental and analytical work on the use of GFRP on hollow sections. The concentric compressive behavior of GFRP-reinforced hollow columns was investigated using different design parameters such as the inner-to-outer diameter ratio (i/o) ratio [8], longitudinal reinforcement ratio [9], and transverse reinforcement ratio (v) [10].

Test results show that creating a hollow part in GFRP-RC columns increases axial strength, deformation capacity, ductility, and confined strength compared to solid columns. It also prevents catastrophic final failure and leads to a more progressive failure. Introducing GFRP bars and spirals as reinforcement for hollow concrete columns increases confined strength and ductility factor by 22% and 74%, respectively. Increasing longitudinal reinforcement ratio (ρ) significantly contributes to lateral confinement and strength. GFRP bars as internal reinforcement in hollow concrete beams maintain strength and prevent sudden failure caused by crushing of the inner section. Increasing ρ leads to a significant increase in flexural strength and ultimate bending moment sustained by the beam. This innovative system is a promising solution to develop non-corroding structures [8]. The GFRP reinforcement system, as an effective solution, exhibits an effective method to increase the flexural response of the beam subjected to static and cyclic loads and provides a novel construction approach for developing non-corroding structures. The usage of GFRP/steel bars as a hybrid reinforcing system is expected to introduce the most cost-effective and practical means of increasing the ductility and strength of HRCBs.

B. Opportunities and Future Research

The use of steel reinforcement in concrete structures in Australia is at risk of corrosion damage due to severe coastal environments and aggressive soil conditions, exacerbated by climate change [71]. Fiber-reinforced polymer (FRP) composite bars have become an effective alternative to steel reinforcement because of their noncorrodible, nonmagnetic properties, high tensile strength, and long durability. GFRP bars are particularly useful as they have a lower economic and environmental footprint compared to steel bars [72]. Research has been carried out globally, including in several Australian universities, to develop corrosion-resistant, durable, environmentally friendly, and highly sustainable infrastructures using FRP bars. GFRP bars are being utilized in various applications, including rail signal loops, hospital magnetic resonance imaging (MRI), and nuclear science buildings, and are also being considered as a solution for RC bridges and other critical infrastructures to achieve a 100-year service life by transport authorities and asset owners in Australia, such as the Queensland Department of Transport and Main Roads (TMR) [73].

The behavior of solid concrete beams reinforced with GFRP is different from those reinforced with steel, and the flexural response of hollow beams is heavily dependent on various factors. Therefore, there is a need for new design codes to incorporate GFRP materials in hollow sections. However, extensive research is required before incorporating GFRP bars as internal reinforcement into design codes.

Previous studies have not thoroughly investigated the static and dynamic behavior of hollow flexural members with GFRP reinforcement. Future studies should focus on examining the structural performance of these members under static and cyclic loadings by optimizing various design parameters including the geometry of the hollow, reinforcement ratio, and concrete compressive strength. GFRP bars are an effective solution to the corrosion issue of steel-RC beams due to their high strength, modulus of elasticity, and resistance to chemical effects.

C. Suggestions

Future studies will investigate the behavior of hollow concrete beams reinforced with GFRP bars to understand their performance. Objectives include examining the influence of hollow size, reinforcement arrangement, and hollowness on the quasi-static and seismic behavior of the beams. Additionally, the study will conduct an empirical evaluation, numerical analysis, and develop a design model for the hollow GFRP- RC beams under quasi-static and seismic loading.

V. CONCLUSION

This state-of-the-art review identified the design parameters, affecting variable and potential future research on the structural performance of hollow and solid beams reinforced by GFRP and steel rebars. The opportunities provided by the application of the GFRP reinforcement in this type of construction system were also analyzed. According to this literature review and analysis, the following conclusion may be derived:

1. Considering factors such as purpose, availability, cost, skilled labor, and structural performance, it is suggested to utilize GFRP bars as a strengthening material, replacement, or hybrid reinforcement technique with conventional steel in HCBs.
2. Beams reinforced with GFRP exhibited high initial stiffness, and nonlinear behavior decreased with increasing GFRP reinforcement ratio, with nearly complete disappearance at high reinforcement ratios.
3. Combining steel bars with GFRP bars (hybrid system) in concrete beam reinforcement appears to be a practical solution for overcoming ductility and serviceability issues in purely GFRP-reinforced beams.
4. The outcomes of this review indicate potential research areas for further investigation into how critical design parameters and different loading conditions affect the structural performance of GFRP-reinforced hollow concrete beams.
5. The future study will experimentally and numerically evaluate the use of GFRP bars as a new reinforcing system for hollow flexural and shear members under cyclic loadings.

DATA AVAILABILITY

Some or all data gathered from the literature that support the findings of this study are available from the corresponding author.

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