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Impact of Void Geometry, Size, and Location on the Structural Behavior of RC Hollow Beams: A Review

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ABSTRACT

Reinforced concrete (RC) hollow beams have been increasingly adopted in structural applications due to their potential for reducing self-weight, material consumption, and environmental impact without significantly compromising structural performance. This review investigates the influence of void geometry, size, and location on the structural behaviour of RC hollow beams. Previous experimental and numerical studies were comprehensively examined to evaluate their effects on load-carrying capacity, cracking behaviour, deflection, ductility, and failure modes. The findings indicated that the presence of voids generally resulted in a reduction in first cracking and ultimate load; however, this reduction was often disproportionately small compared to the achieved concrete volume savings. Circular voids were found to be more effective than square or rectangular voids in preserving strength and enhancing ductility. The location of the void played a crucial role, as placing hollows near the neutral axis or within the tension zone minimized adverse effects on structural performance. Increasing void size led to higher deflections and reduced stiffness, particularly when the void area exceeded approximately 10% of the gross cross-sectional area. The incorporation of additional materials such as steel fibers, steel or aluminium inserts, and fiber-reinforced polymer strengthening systems was shown to significantly improve strength, ductility, and failure behaviour. Numerical simulations using finite element software demonstrated strong agreement with experimental results, confirming their reliability for predicting hollow beam behaviour. Overall, RC hollow beams were demonstrated to be an efficient and sustainable structural solution when void characteristics were properly optimized.

1. Introduction

A beam can be defined as the structural member that transfers the load from roofs and floor to the columns and foundations [1]. The beam resists load acting perpendicularly to its longitudinal axis. It bends in this major axis under loads. When overloaded, a beam typically fails due to excessive deflection or extensive cracking. The loads constitute both the external load and the beam's weight [2].

In the field of buildings and constructions, concrete is a highly influential material owing to its workability, availability in most countries, low cost, low maintenance cost and high fire resistance [3][4]. It is formed from a hardened mixture of cement, fine aggregate, coarse aggregate, water and some admixture. Notwithstanding, concrete materials have a very high weight. Massive exploration of the natural resources for producing concrete affect to the environment condition and global warning;

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Hence, the concrete should be used as efficient as possible and by saving concrete, we can save cement, which reduces the greenhouse gases emissions [5][6].

Reinforced Concrete (RC) structures are known to possess excessive self-weights. The issues related to the self-weights of RC structures become pronounced over long spans [7]. Non-prismatic sections can significantly reduce the self-weights of RC structures. Additionally, non-prismatic sections impart aesthetically attractive architectural designs [8]. A desirable highlight in the construction of tall buildings is to reduce the ceiling heights that could be achieved using non-prismatic sections. These days non-prismatic sections can be found in almost every kind of structure [9][10].

In RC structures, the use of optimized structural sections can also be considered as a solution to reduce the weight of the structure. Hollow sections introduced as the types of optimized structural sections that reduce the cross-sectional size of structural members, leading to a reduced weight and lower consumption of concrete materials [4][11].

Hollow and non-prismatic RC beams have gained popularity in construction for their benefits in reducing weight, enhancing aesthetics, and integrating utilities. Since these design variations directly impact strength, ductility, and failure patterns, their behaviour must be carefully studied.

For decades, concrete has been used widely around the world as a key construction material due to many reasons, including the availability of its raw ingredients, good durability and less required maintenance after construction, the reasonable construction cost, and high mechanical properties in terms of compressive strength in comparing with other materials. However, concrete has a lower resistance against tensile forces and is heavy. Therefore, it can be used in combination with steel bars to resist external forces based on their own high compressive strength and the high tensile strengths of the latter. Whereas the heavy self-weight of concrete can be compensated by adopting various solutions such as using composite materials, lightweight and recycled aggregates. Moreover, a hollow in the structural RC members like beams can be used to largely reduce their self-weights [6][12][13][14][15].

Hollow structural sections are widely used for various practical purposes, including enhancing architectural aesthetics and increasing the overall thickness in the support area above the column, which gives high assurance to services. These sections are commonly used in various types of structures, i.e., tall buildings, marine facilities, ports and towers. One of the popular hollow sections is the RC beam, which can be used for the passages of sewage and water drainage services, water transfer, power transmissions, communications, etc. It is better than extending these services through suspended false ceilings [14][16][17].

2. Previous Studies on RC Hollow Beams

2.1 Experimental Studies

Hollow RC beams have garnered attention for their unique design advantages, primarily in reducing weight and improving material efficiency with reasonable reduction in strength [14]. These beams typically have a hollow core, which can be in the form of a circular, square, or other geometrically optimized void within the cross-section[18]. Hollow RC beams generally show reduced load-carrying capacity and increased deflection compared to solid beams, with reductions in strength ranging from 2% to over 50% depending on void size, shape, and location [19]. Circular voids tend to preserve more strength than square ones, and placing hollows near the neutral axis or in the tension zone minimizes negative effects [20][21].

Alnauimi and Bhatt (2004) Part I [22] proposed a direct design procedure for reinforced concrete hollow beams subjected to combined bending, shear, and torsion. The method, grounded in the theory of plasticity, aims to eliminate the reliance on empirical equations found in existing design codes, providing a more consistent and theoretically sound approach. The procedure involves calculating stresses in different regions of the beam and determining the necessary reinforcement based on these stresses. The design is based on the largest stress where the shear stresses are added and where the bending moment and torsion are also largest as shown in Figure 1.

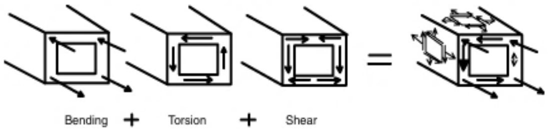


Figure 1. Stresses in Hollow Sections [22]

The study found that the direct design method resulted in steel requirements similar to those of the truss analogy, but with significantly less reinforcement than both the ACI 318 [23] and British Standards [24] codes, particularly in transverse reinforcement under dominant shear and torsion. The researchers affirmed that the direct design procedure is an efficient and reliable method for hollow beam design, offering lower reinforcement demands. However, the study highlighted the need for experimental validation, as presented in Part II [17], and suggested further exploration of geometric configurations and material variations to improve the method's robustness.

In Part II of their study, **Alnauimi and Bhatt (2004)** [17] experimentally validated the direct design method for reinforced concrete hollow beams under combined bending, shear, and torsion, which was proposed in Part I of their study. They tested eight beams (specimens having overall dimensions of 300 mm × 300 mm for the cross-section, 50 mm wall thickness and length of 3800 mm) designed using the direct design method, subjecting them to various load combinations as shown in Figure 2. The specimens were monitored using strain gauges and displacement sensors to track the crack development, strains, and deflections at the stages of loading. The results showed that the ultimate loads were within 10% of the design predictions, confirming the accuracy of the theoretical method. The beams exhibited ductile failure behavior, consistent with the plasticity theory used in the design procedure. Vertical and inclined cracks developed as expected. The strain ratios in both longitudinal and transverse reinforcement reached near yield values, indicating efficient utilization of reinforcement. The study also found that the direct design method resulted in lower reinforcement requirements compared to traditional code-based designs, particularly in transverse reinforcement for shear and torsion. The results underscore the efficiency, reliability, and practicality of the suggested direct design method.

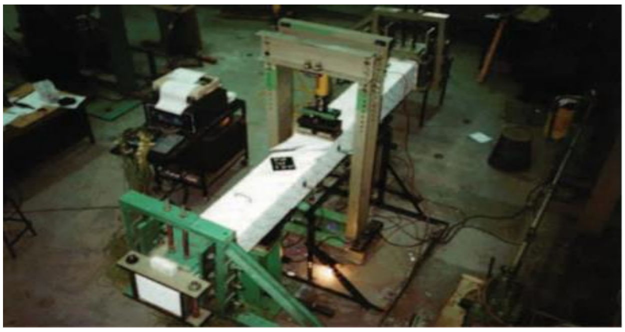


Figure 2. Test Installation [17]

Varghese and Joseph (2007) [25] conducted a study to explore the potential of replacing concrete in the tension zone of RC beams with lightweight materials like Expanded Polystyrene (EPS) and polyurethane foam as hollow core beams. The researcher aimed to assess the impact of such replacements on flexural behavior, load-bearing capacity, and overall performance of the beams, with an emphasis on reducing weight and improving seismic resistance. The methodology included experimental and numerical approaches. Experimentally, they cast and tested nine specimens with and without lightweight material replacements, subjecting them to three-point flexural tests. Numerically, they used ANSYS software to simulate beam behavior under varying core thicknesses, analyzing deformation and natural frequency. The findings showed that while the hollow core beams exhibited slightly higher deflections under the same load, their load-carrying capacity remained similar to solid beams. Additionally, the study highlighted that increasing the core thickness did not significantly affect deformation, suggesting that concrete in the tension zone could be effectively replaced without compromising beam performance. Polyurethane foam provided better damping properties compared to EPS. The study concluded that this replacement method is viable and offers environmental and economic benefits. The study highlighted gaps in material diversity, durability, and seismic performance, suggesting these areas for future research.

Al Nuaimi et al. (2008) [14] conducted a comparative study on the performance of solid and hollow reinforced concrete beams subjected to combined bending, torsion, and shear as shown in Figure 3. Fourteen beams were tested, consisting of seven hollow and seven solid specimens. All beams had a cross-section of 300 mm ×300 mm and a length of 3,800 mm. The hollow beams had a 200 mm ×200 mm internal void, leaving a peripheral wall thickness of 50 mm. Concrete used ranged from 35 MPa to 55 MPa. The findings revealed that solid beams cracked at higher loads compared to hollow beams, especially when bending moments dominated (torque/bending moment (Td/Md) < 1). Hollow beams were more flexible, exhibiting higher displacement for the same load. Failure loads were higher for solid beams, with differences ranging from 21.2% to 50% compared to hollow beams. The solid beams also showed better resistance to bending and shear. The study concluded that hollow beams could offer material savings in torsion-dominated applications, while solid beams are preferable when bending predominates due to their superior cracking resistance and load-carrying capacity.

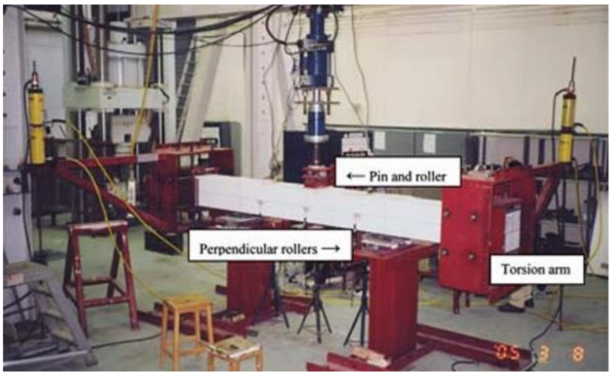


Figure 3. Specimen Testing [14]

In their 2014 study, **Joy and Rajeev** [26] explored the effect of conducting a hollow neutral axis in RC beams. The primary objective was to reduce weight and cost by replacing concrete in the low-stress neutral axis with Polyvinyl Chloride (PVC) pipes, a lightweight material. The researchers used nine specimens, consisting of solid and hollow RC beams, where the hollow beams incorporated PVC pipes of 40 mm and 50 mm diameters in the neutral axis. The dimensions of the beams were (150 mm × 230 mm × 980 mm). The specimens were tested under a four-point flexural test, with concrete compressive strength of 25 MPa and reinforcement details were 10 mm bars and 6 mm stirrups for all beams. The findings revealed that the hollow beams exhibited slightly reduced load capacity and higher deflection compared to the solid beams, though the difference was minimal. The deflection and cracking patterns confirmed that the concrete in the neutral axis does not significantly contribute to structural behavior.

Moreover, the reduction in concrete volume led to a 2.3% saving in material, thus lowering the self-weight of the beams. These results were validated through finite element analysis using ANSYS software, providing further insight into the beams' behavior. The study highlighted that hollow RC beams can be a cost-effective and sustainable alternative for reducing concrete usage, especially in larger structures.

Al-Maliki (2013) [27] tested five non-prismatic RC beams (1170 mm × 260 mm × 150 mm) under two-point loading to assess the impact of hollow cores and Carbon Fiber Reinforced Polymer (CFRP) retrofitting on shear strength. The specimens included a solid beam, beams with 50 mm circular Polyvinyl Chloride (PVC) or square steel hollows, and four beams strengthened with CFRP strips as shown in Figure 4. Results showed that all the specimens failed in shear, hollow cores reduced stiffness and capacity; a circular PVC hollow caused a 53% load drop, while a square steel hollow reduced it by only 17%. CFRP retrofitting increased capacity by an average of 27%, and closer shear stirrup spacing provided a 30% gain.

Figure 4. Specimens Details [27]

Varghese and Joy (2015) [6] conducted an experimental study on the flexural behavior of RC beams with hollow cores at various depths, focusing on the optimization of material usage. Their study, as shown in Figure 5, involved the casting of ten beams with a size of 2000 mm × 200 mm × 300 mm, the included hollow cores made using PVC pipes at varying depths from the top surface. The beams were subjected to four-point bending tests to assess their performance in terms of load carrying capacity, deflection, and crack propagation. The findings revealed that the hollow core beams exhibited comparable flexural strength to traditional solid beams but showed superior performance in terms of deflection under the same load conditions. Beams with hollow cores at depths around 160mm (B2 which had 54% of total depth) demonstrated the best performance in terms of load carrying capacity and minimal deflection. As the depth of the hollow core located below this point, both load carrying capacity and deflection decreased.

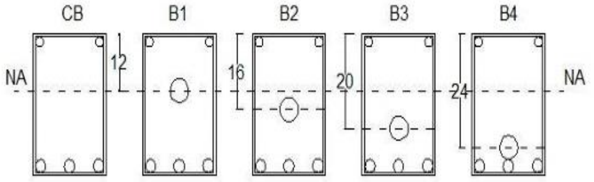


Figure 5. The Cross-sectional View of Specimens [6]

The study also highlighted the environmental and economic advantages of using hollow core beams. The reduction in concrete volume, achieved by replacing part of the low-stress zone with PVC pipes as zigzag pattern as depicted in Figure 6, resulted in concrete savings of about 3.7%, as detailed in the calculations for weight and concrete savings. This reduction not only lowers material costs but also contributes to the sustainability of the construction process by decreasing the carbon footprint associated with cement production. Furthermore, the reduced material volume leads to lighter structures, which can be particularly advantageous in high-rise buildings, where reducing dead load can mitigate seismic effects. The study shows that hollow core RC beams can be an effective solution for reducing material costs without compromising structural integrity, especially in applications like plinth beams, raft foundations, and piers, where concrete wastage is significant. According to **Soman and Anima (2016)** [8], locating a circular hole directly beneath the neutral axis results in no significant loss of load-bearing capacity base on experimental and analytical investigation. Their study on 150 mm × 200 mm sections and length 1200 mm with hole diameters of 25 mm, 50 mm, and 75 mm. They found that beams incorporating PVC pipes exhibited higher ultimate load capacity than solid reference beams. This increase is attributed to the mechanical properties of the PVC.

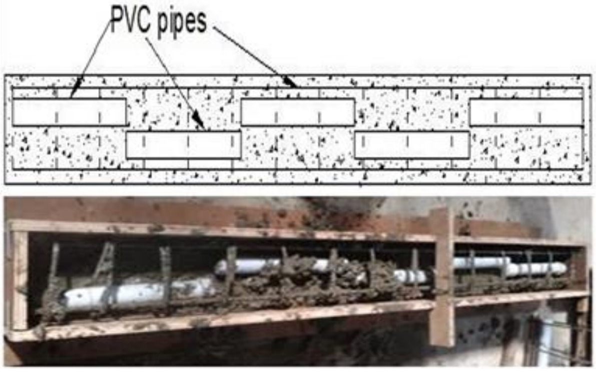


Figure 6. The Specimen With Replaced Concrete-PVC [6]

Dhinesh and Satheesh (2017) [28] investigated the flexural behavior of hollow core RC beams with varying core depths. The study aimed to examine the effect of hollow core placement on the load-carrying capacity, deflection, and strain behavior of the beams. The experimental setup involved casting eight beams of 150 mm×150 mm ×1000 mm, with hollow core depths of 34 mm, 75 mm, and 116 mm as shown in Figure 7. The beams were tested under three-point loading conditions, and the concrete mix had a compressive strength of 23 MPa. The findings revealed that the presence of hollow cores did not significantly reduce the strength of the beams. In fact, the load carrying capacity of beams with hollow cores at the tension zone was higher than other hollow core positions. As the depth of the hollow core increased, both the ultimate load and deflection decreased. The optimum hollow core depth was found to be 116 mm from the top of beam (about 77% of the total depth). The crack pattern was similar across all specimens, showing flexural-shear failure. Additionally, the experimental results closely matched the theoretical calculations, confirming the reliability of the test methods. In general, the study emphasized that the hollow cores, particularly in the tension zone, offer a viable method for reducing the weight and material usage of reinforced concrete beams, contributing to more sustainable construction practices. The research suggests further investigation using different PVC pipe diameters and the exploration of other parameters such as impact resistance and fatigue.

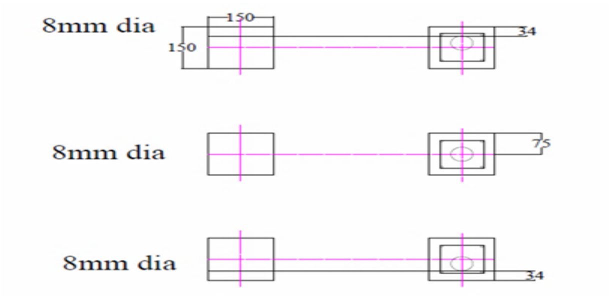


Figure 7. Schematic View of Specimens [28]

Parthiban and Neelamegam (2017) [29] conducted an experimental study to investigate the flexural behavior of reinforced concrete beams with a hollow core in the shear section. The study focused on optimizing the concrete material by replacing the low-stressed region below the neutral axis with PVC pipes, thereby reducing the weight and volume of concrete. The beams were designed with steel reinforcement, and PVC pipes of various diameters (50 mm, 25 mm, and 16mm) were used to create the hollow core. The experimental program involved casting eight beams of 1200 mm×150 mm ×200 mm size, with a mix design of 30 MPa concrete. These beams were tested using a two-point loading test as shown in Figure 8. The study also highlighted that the use of PVC pipes in the neutral axis region did not significantly affect the load-carrying capacity of the beams but did result in higher deflections when compared to solid beam. The optimum hollow core depth was identified as 71 mm, just below the neutral axis. The experimental results showed that the beams with hollow cores exhibited similar flexural behavior to conventional beams, with an increased deflection due to the reduced concrete volume. The use of PVC pipes resulted in a concrete saving of about 4.9%, with the hollow beams showing a reduction in self-weight, contributing to material and cost savings. The study concluded that replacing concrete in the neutral axis with PVC pipes leads to significant material savings without compromising the structural integrity of the beams.

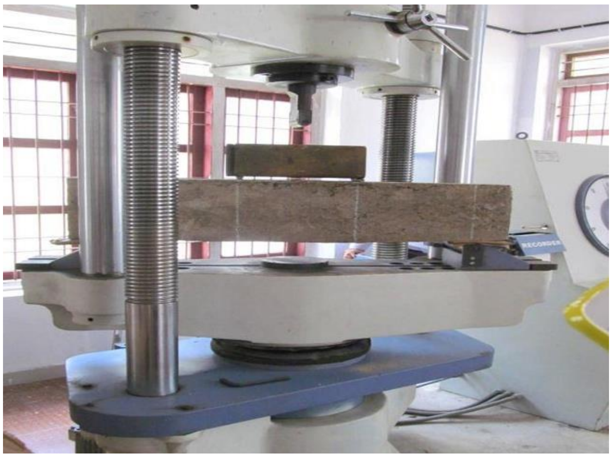


Figure 8. Test Setup [29]

In 2019, **Abbass et al.** [11] conducted a study to investigate the effect of steel fibers on the flexural behavior and ductility of high-strength concrete hollow beams. The purpose was to explore how adding steel fibers to concrete beams, both solid and hollow, influences their cracking, peak load capacity, and overall ductility. The study involved eight beams with square cross-sections (150 mm side length and 850 mm length), including four solid and four hollow beams with a central square hole (80 mm). The concrete used had a compressive strength of 60 MPa, and steel fibers were added at volumes of 0%, 0.5%, 1.0%, and 1.5%. A four-point bending test was applied to all beams, and displacement was measured. The findings revealed that steel fibers significantly enhanced the flexural behavior as seen in load-deflection behavior in Figure 9, hollow beams performed better than solid beams at the highest fiber content (1.5%) while the other specimens the solid beams failed at higher peak load. Steel fiber addition improved the beams' ductility, hollow beams exhibited higher ductility compared to solid beams. However, hollow beams with lower fiber contents showed reduced strength at cracking, yielding, and peak load stages.

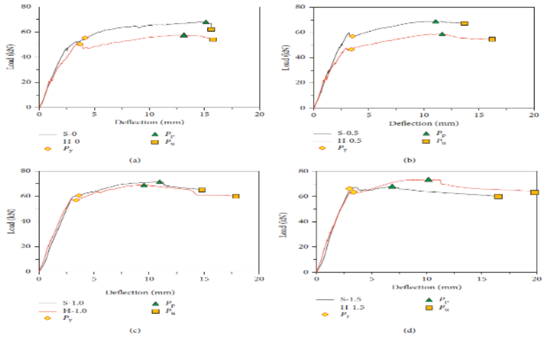


Figure 9. Load – Deflection curves (Solid beams vs Hollow beams) [11]

Noh et al. (2020) [30] studied the flexural behaviour of hollow reinforced concrete beams with PVC pipes placed at the neutral axis to reduce concrete usage and self-weight. Four beams (1200 mm × 160 mm × 160 mm) were tested under three-point bending, including one solid control beam and three hollow beams with void diameters of 40 mm, 50 mm, and 100 mm. The hollow beams showed higher ultimate loads (32.5 to 38.25 kN) compared to the control beam (15.35 kN). The 50 mm void beam exhibited the best performance with about 49% strength increase as depicted in load deflection curve in Figure 10. Concrete usage and self-weight were reduced by up to 35% and 33%, respectively. The study concluded that neutral-axis voids can reduce material consumption while maintaining or improving flexural performance.

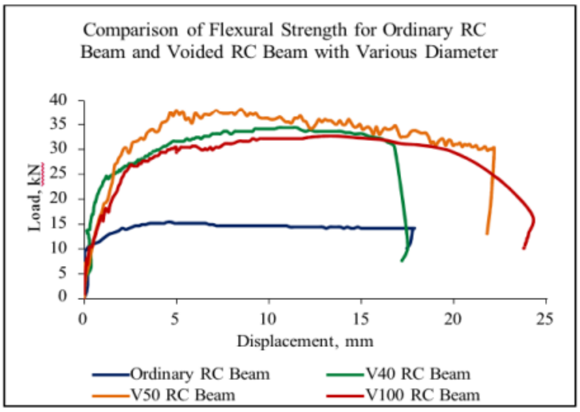


Figure 10. load deflection curves for specimens [30]

Rokiah et al., (2021) [31] conducted a study to investigate the effect of different positions of hollow sections on High-Strength Concrete (HSC) beams, incorporating eggshell powder as a partial cement replacement and tire crumb as a partial sand replacement. The study involved four types of beams: solid beams, one hollow beam, Two Vertical Hollow Beams (TVHB), and Two Horizontal Hollow Beams (THHB). The beams were cast with 150 mm × 200 mm × 1500 mm dimensions, using high-strength concrete was 60 MPa and incorporating 10% eggshell and 10% tire crumb and the configuration for holes shown in Figure 11. The beams were subjected to a four-point bending test, measuring deflections, crack patterns, and ultimate load capacity. The findings showed that the solid beam exhibited the highest strength, while the THHB configuration provided the best performance in terms of load resistance and deflection. However, the hollow beams were more efficient in reducing material usage. The study concluded that the position of the hollow section affects beam performance, with the THHB configuration being the most effective. It also identified a research gap in optimizing hollow section size and placement under varying load conditions and exploring the long-term durability of such beams.

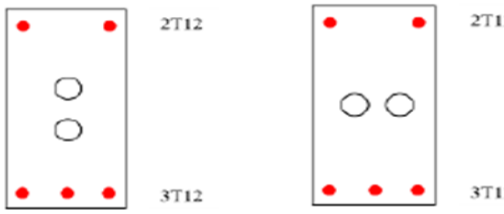


Figure 11. Voids configuration [31]

Al-Smadi et al. (2022) [13] studied the effect of longitudinal hole shape, size, and location on the flexural behavior of RC beams. Nine RC beams with dimensions 150 mm × 250 mm × 1300 mm were tested, including one solid control beam and eight with various hole shapes: circular PVC pipes (50 mm and 75 mm), square (50 mm ×50 mm), and rectangular wooden tubes (50 mm ×100 mm), located at 90 mm and 160 mm from the top of the beam as shown in Figure 12. The beams were tested under four-point bending, and load-deflection curves, crack patterns, and failure modes were recorded. The study found that while all beams failed in flexural, hollow beams with circular holes showed a 11 to 20% reduction in ultimate strength, while square and rectangular holes showed about 19% reduction. Beams with circular holes exhibited higher ductility, whereas square and rectangular holes showed varied behavior. The location of the hole had minimal effect on strength. Analytical models validated experimental results, accurately predicting cracking, yielding, and ultimate loads. The study highlighted the need for further research into larger hole sizes, reinforcement configurations, and dynamic loading to develop comprehensive design guidelines for hollow RC beams.

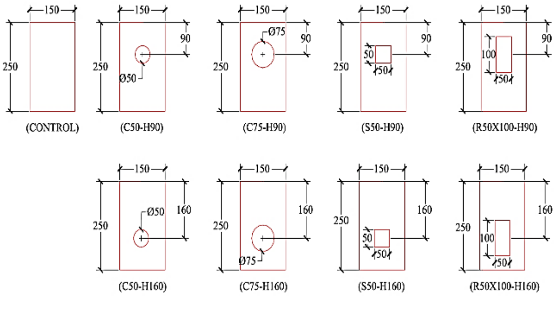


Figure 12. Specimen Details [32]

in 2022, **Ismaeel and Hameed** [33] investigated the structural performance of Self-Compacting Concrete (SCC) RC beams with longitudinal circular hollow cores formed using recycled plastic pipes. Five hollow specimens, each measuring 1000 mm in length, 150 mm in height, and 100 mm in width, were tested under two-point bending alongside a solid as reference beam. The hollow cores, created with pipes of outer diameters 32 mm, 36 mm, 40 mm, 46 mm, and 52 mm as shown in Figure 13, removed 5.4% to 14.2% of the concrete volume. All beams were reinforced with two 10 mm diameter steel bars in tension and 6 mm stirrups at 50 mm spacing. Results showed that increasing the void diameter reduced the first crack load by 9.1% to 22.7% and the ultimate load by 2.3% to 10.5% compared to the solid beam. Crucially, the reduction in ultimate strength was significantly lower than the reduction in concrete volume, demonstrating structural efficiency. The load-deflection behavior revealed that stiffness decreased, and ductility increased with larger voids, with ultimate deflections rising by up to 9.02%. A comprehensive sustainability analysis using the Alcorn method quantified that the embodied energy and CO_2 emissions decreased proportionally with the concrete removed, by 5.4% to 14.2%. The finding showed that the hole with 46 mm diameter as the optimum configuration corresponding to 30.7 % from the total height of the beam. This beam achieved an 11.1% reduction in concrete volume while limiting the reduction in cracking and ultimate load to only 13.6% and 9.3%, respectively. This optimum ratio offers the best balance between material savings, structural performance, and environmental benefit for sustainable construction.

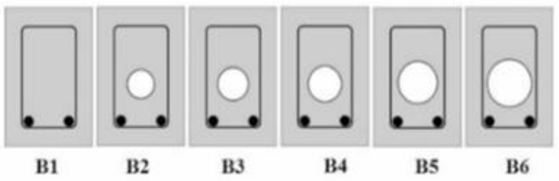


Figure 13. Holes Configuration [33]

In the 2022, **Ling et al.,** [34] investigated the structural behavior of RC hollow beams with embedded PVC pipes. Eleven beam specimens were tested, including two solid beams and nine hollow beams, all with dimensions of 150 mm × 300 mm × 1650 mm. The concrete used had compressive strength of 25 MPa, the PVC pipes, with diameters 25 mm, 50 mm and 75 mm at depths between 39 mm and 139 mm from beam bottom as shown in Figure 14, were embedded in the tension zone at varying depths. A four-point loading test was applied, and displacement measurements were recorded. The findings revealed that hollow beams generally exhibited lower strength than solid beams. Larger PVC pipe sizes (≥50 mm) significantly reduced ductility, and the first crack occurred at 26 to 40% of the ultimate load. Hollow beams with smaller pipes (≤25 mm) failed in flexure, while those with larger pipes failed in shear compression.

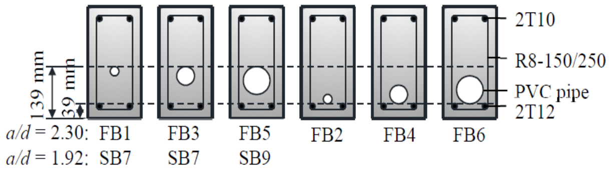


Figure 14. Specimen Details [34]

Sirisonthi et al., (2022) [19] investigated the flexural performance of large-scale hollow section RC beams and possible enhancement of bending using strengthening of CFRP sheets. The study utilized nine specimen beams in three groups, each group had three specimens measuring 250 mm × 300 mm in cross section and 3000 mm in length, featuring either solid section, 50 mm × 50 mm hollow cores, and 100 mm × 100 mm hollow cores. The difference of groups was strengthening existence where first group was without strengthening while the other groups had strengthening of CFRP (bottom bonded and U wrap) sheets as shown in Figure 15. These specimens were reinforced with two bars of 16 mm in tension and two bars of 12 mm as compression bars, then tested under a four-point loading. The findings showed that the hollow openings did not degrade ultimate load capacity as shown in Figure 15, although they reduced the initial cracking load from 22 kN in solid beams to 15 kN in the largest hollow sections. Two CFRP configurations were evaluated: a single bottom-bonded sheet and a U-wrap configuration. Results showed that the U-wrap was superior, increasing the ultimate load of the 50 mm hollow beam from 72.01 kN to 115.47 kN with 60% improvement. While the bottom-bonded sheets often failed due to sudden debonding, the U-wrap specimens achieved higher capacity before undergoing CFRP rupture. In general, this research suggests a good technique for strengthening of using continues U-wrap of CFRP sheet which maintained best results in strength enhancement and deformation reduction.

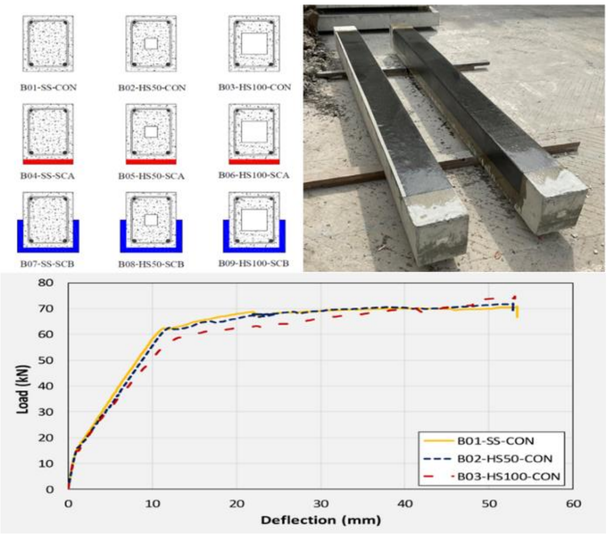
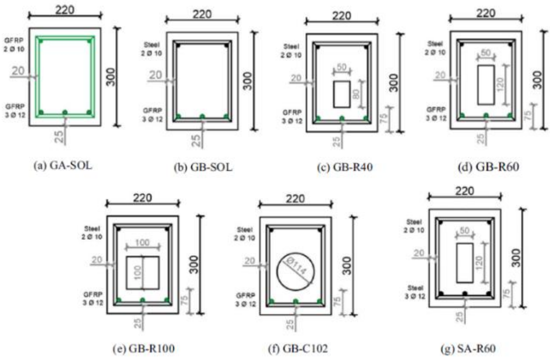


Figure 15. Beams Details and Load- Deflection Curves Relationships for the First Group [19]

Alharthi et al., (2024) [35] explored the impact of longitudinal holes in concrete beams reinforced with GFRP bars and understanding how varying hole sizes (6% to 15% of the beam cross-section) and shapes (circular and rectangular) affect the flexural strength. Figure 16 shows the different holes shapes used in investigation. The overall behavior of these beams is compared to solid GFRP and steel RC beams. The study involved seven beams with a cross-section of 220 mm by 300 mm and a span of 2000 mm, reinforced with either GFRP or steel bars. Concrete used had a compressive strength of 46.7 MPa. The beams were tested under four-point bending to assess cracking and ultimate loads. Results showed that while the presence of holes led to some reduction in ultimate load (ranging from 0.4% to 10.5%), circular holes performed better than rectangular ones. The study also found that hole location was crucial, with holes in the tension zone yielding better performance. GFRP-reinforced beams exhibited high flexural strength but lacked the ductility seen in steel-reinforced beams. The steel specimen exhibited less crack and deflection indicating that it is stiffer than GFRP beam. Also, the finding showed the circular holes better in cracking and ultimate capacity experimentally.



(a) GA-SOL (b) GB-SOL (c) GB-R40 (d) GB-R60

(e) GB-R100 (f) GB-C102 (g) SA-R60

Figure 16. Specimens Holes Configuration [35]

2.2 Numerical Studies

In 2018, **Hassan et al.,** [36] conducted a study on the flexural behavior of hollow reinforced concrete beams by inserting PVC pipes in the tension zone. The purpose was to explore how hollow sections could reduce beam weight without compromising strength. Ten beams with dimensions 2500 mm × 200 mm × 300 mm were tested, including two solid control beams and eight with PVC pipes of 50 mm and 75 mm diameter at depths of 160 mm and 180 mm from the top. Concrete with compressive strength 30 MPa was used, and the beams were reinforced with 3 Ø16 tension bars and 6 Ø8 stirrups, the beams were subjected to a four-point bending test. The results showed that smaller PVC pipes had little effect on the load capacity, while larger pipes (75 mm) reduced the capacity when placed at 180 mm depth. Beams with PVC pipes exhibited wider cracks and brittle shear failures. Additionally, the study utilized further analysis using finite element modelling (ANSYS) can provide more insights into the behavior of hollow core beams, although the finite element results showed a slight underestimation of the failure load compared to the experimental data.

Mansour et al. (2023) [20] investigated a novel approach to enhance the flexural performance of hollow reinforced SCC beams by embedding aluminum sections within the longitudinal voids. The research combined experimental testing of three 200 mm ×200 mm square beams, each 1500 mm long, with an extensive numerical parametric study using ABAQUS as shown in Figure 17. The specimens included a solid reference beam (B00), a hollow beam with an 80 mm × 80 mm square void (BH80), and a hollow beam with the same void reinforced by a 1.38 mm thick aluminum box section (BHA80). All beams were reinforced with two 12 mm steel bars in tension and 8 mm stirrups at varying spacings. The finite element model, validated against experimental results, was used to study the effects of void area (16 to 49% of beam cross-section), void shape (square vs. circular), longitudinal reinforcement ratio (0.41 to 1.19%), and shear reinforcement ratio (0 to 0.56%).

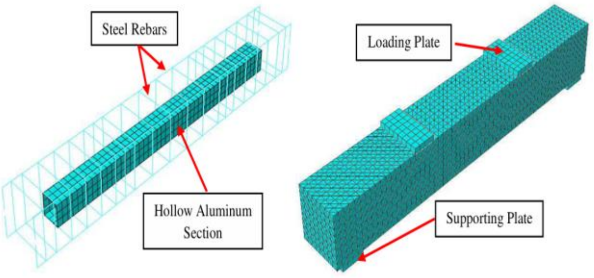


Figure 17. Modelling of Experimental Tested Specimen Via ABAQUS [33]

Findings showed that the unreinforced void (16% area) reduced ultimate capacity by only 4%, while the aluminum-reinforced void increased by 29%. The embedded aluminum promoted uniform flexural cracking and delayed shear failure, enhancing ductility and toughness by 31% compared to the solid beam. Parametric results revealed that aluminum sections could fully restore the capacity of hollow beams with void areas up to 36% of the cross-section. Beyond this threshold (49% void), capacity decreased even with aluminum. A crucial geometric finding was that circular voids outperformed square voids of equal area, with circular-aluminum reinforced beams achieving up to 44.2% higher capacity than the solid reference.

Abd (2024) [37] conducted a numerical investigation using Abaqus software to evaluate the impact of single and multi-longitudinal hollow openings on the flexural behavior of RC beams. The beams with dimensions of 1000 mm × 150 mm × 100 mm across three groups: varying circular hole sizes (32 to 52 mm), different shapes (circular, square, and rectangular), and the number of openings (one, two, and three) as shown in Figure 18. Results indicated that while all hollow beams experienced reduced ultimate strength, circular openings were most efficient, showing only a 10.46% reduction compared to 18.60% for rectangular and 19.76% for square shapes. Increasing the number of longitudinal voids further decreased load-bearing capacity and led to higher threshold deformations and stress concentrations. The study concluded that circular openings are the most effective for maintaining structural integrity while achieving a concrete volume reduction of up to 14.2%. These findings suggest that hollow RC beams offer a sustainable and cost-effective alternative for construction if the opening size and shape are carefully optimized to minimize strength loss during design.

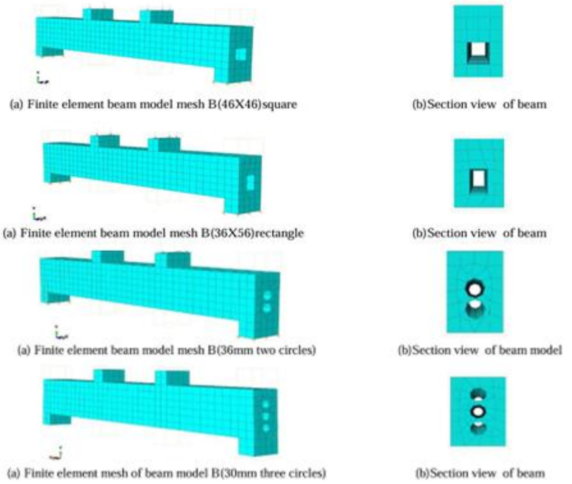

(a) Finite element beam model mesh B(46X46)square
(b)Section view of beam
(a) Finite element beam model mesh B(36X56)rectangle
(b)Section view of beam
(a) Finite element beam model mesh B(36mm two circles)
(b)Section view of beam model
(a) Finite element mesh of beam model B(30mm three circles)
(b)Section view of beam

Figure 18. Configuration of Specimens [37]

2.3 Experimental and Numerical Studies

Abu Altemen et al. (2021) [38] conducted a numerical study using ANSYS software to investigate the flexural behaviour of HSC beams containing both longitudinal and transverse openings. The models, validated against experimental data with 99% accuracy in ultimate load, featured beam dimensions of 1910 mm × 250 mm × 150 mm with 50 mm × 50 mm square openings located at the mid-section as shown in Figure 19. The study found that the presence of these openings significantly reduced structural stiffness and increased beam deflection. While the beams exhibited shear cracks, the ultimate failure mode was controlled by flexural cracking occurring at the mid-span near the opening locations. Stress concentrations were most prominent at the corners of the openings, which served as the primary sites for crack development. The research concluded that while such openings are beneficial for reducing weight and accommodating service pipes, they necessitate careful design considerations to mitigate the resulting loss in load-bearing capacity and stiffness.

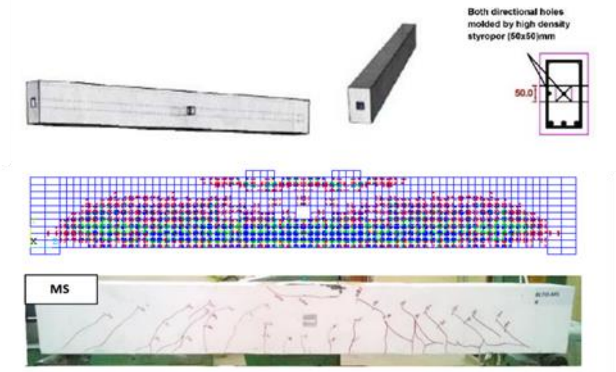


Figure 19. Beam configuration and the crack pattern [38]

In the 2021, **Elamary et al.,** [32] investigated the flexural behavior of hollow concrete beams experimentally and numerically. Elamary et al. examined the size and position of internal longitudinal hollow cores effect on the flexural strength of RC beams. The study tested four specimens (200 mm × 300 mm and a length of 1200 mm), with three beams containing hollow cores (3%, 7%, and 10% of gross cross-sectional area) and one solid control beam. The concrete had a compressive strength of 24 MPa, and the beams were reinforced with 12 mm diameter bars for tension and 10 mm bars for compression, with 8 mm stirrups designed to hold the hollow core as shown in Figure 10, the specimens were subjected to a three-point bending test. The results showed that the hollow beams initially performed similarly to solid beams, but as the load increased, their capacity decreased. The maximum load capacity of hollow beams decreased by 5% when the hollow core size reached 10% of the beam's cross-sectional area. The study also found that increasing the hollow size further reduced the beam's strength, particularly when the hollow width exceeded 50%. The study concluded that while hollow cores offer some reduction in weight, they also lower the load-carrying capacity, emphasizing the need for further optimization of hollow beam designs for better performance under various loading conditions. Finite element software ABAQUS utilized to validate the experimental results, also a parametric study was performed by making a transverse aperture having same dimension as the longitudinal hollow near the support and in the middle as shown in Figure 20. The results of parametric study showed that the transverse outlet near the support did not significantly affect the ultimate load. While changing the location of transverse opening in the mid span resulted in decreasing the ultimate load capacity to half.

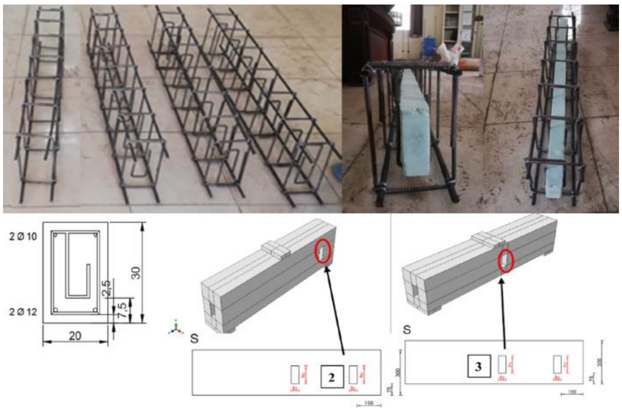


Figure 20. Investigation Parameters [32]

Suparp et al. (2023) [39] experimentally and numerically investigated the structural behavior of RC tapered beams and hollow sections, using both conventional steel and GFRP bars. Six specimens utilized, each with dimensions of 1700 mm length, 250 mm height, and 150 mm width, were tested under four-point bending as shown in Figure 21 and concrete compressive strength of 30 MPa. The findings revealed that prismatic solid beams exhibited the highest shear demand, failed at 62.82 kN, while introducing a tapered section increased capacity to 70.47 kN and significantly improved ductility, with deflections reaching 16.26 mm. Hollow sections reduced the peak load of prismatic beams to 42.21 kN, but this reduction diminished to only 2.17% in non-prismatic hollow beams, demonstrating their efficiency.

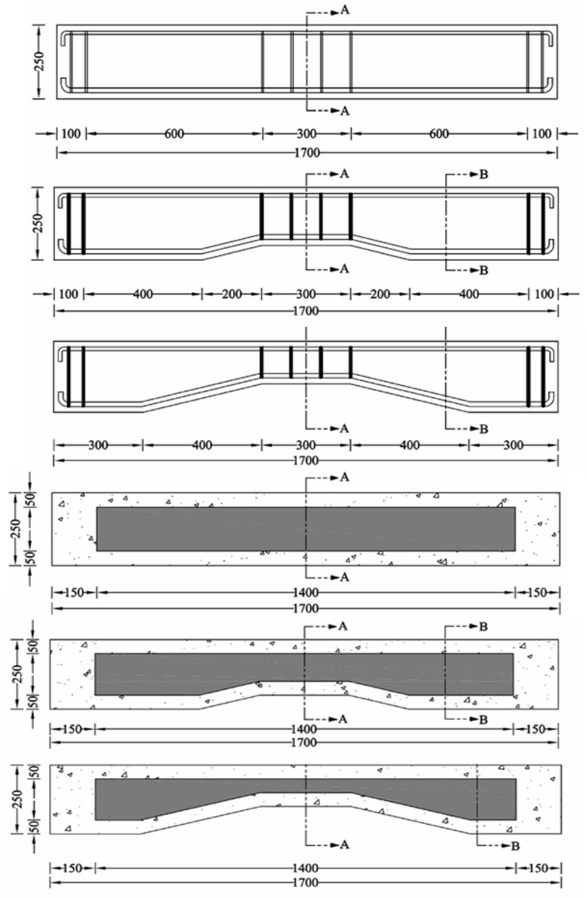


Figure 21. Specimens Details [39]

FE Analysis in ATENA validated experimental results also. A parametric study was evaluated, showing that increasing concrete strength from 15 MPa to 30 MPa or using larger 25 mm diameter reinforcement enhanced load capacity without altering failure modes. Crucially, beams reinforced with GFRP bars demonstrated comparable ultimate load capacities to steel-reinforced beams, with a maximum difference of only 23%, confirming their viability as a corrosion-resistant alternative.

In 2025, **Ridha and Numan** [40] conducted an experimental and numerical study on flexural behavior of solid prismatic and non-prismatic reinforced concrete beams, focusing on non-prismatic geometry and CFRP strengthening. The study involved nine beam specimens with varying arch lengths as shown in Figure 21, cast with concrete of 40 MPa compressive strength. Results showed non-prismatic beams had lower ultimate loads and stiffness but CFRP strengthening improved load capacity by 25.31%, reduced deflection by 31.51%.

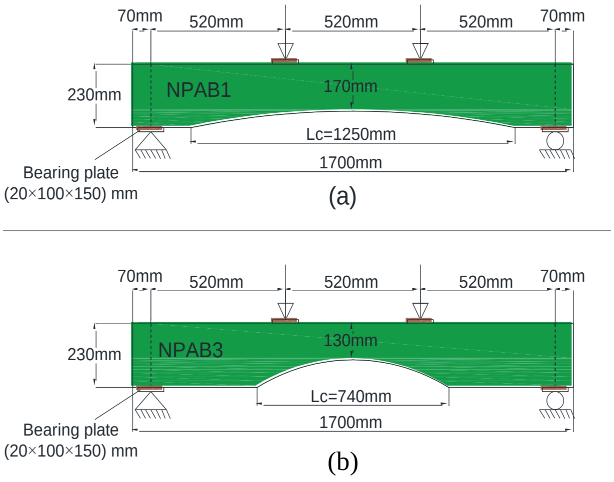


Figure 21. Non-Prismatic RC Beams Configuration [40]

3. Conclusions

Based on reviewed literature, several findings can be concluded:

- Hollow RC beams can achieve significant weight reduction (up to 14%
- concrete volume saving) with a disproportionately small decrease in ultimate load capacity.

- Circular voids generally preserve more structural integrity and provide higher ductility than square or rectangular voids.

- Increasing the void diameter or area typically leads to a reduction in the first crack load and ultimate strength. Structural performance remains stable as long as the void area stays below 10% of the gross cross-sectional area.

- Locating the hollow section near the neutral axis or in the tension zone minimizes the negative impact on load-bearing capacity.

- Hollow beams are generally more flexible and exhibit higher deflection compared to solid beams.

- The inclusion of materials like steel pipes or steel fibers can enhance ductility and, in some cases, slightly increase the ultimate load capacity due to the mechanical properties of the insert.

- The application of FRP Strengthening, particularly in a U-wrap configuration, is highly effective in restoring and even exceeding the strength of hollow beams, preventing premature failure and reducing deformation.

- Finite Element Analysis using software like ANSYS and ABAQUS has proven to be a reliable tool for predicting the behavior of hollow beams, showing strong correlation with experimental results regarding cracking patterns and ultimate loads.

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