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Parametric Variations in Reinforced Concrete Beam Relative to Utility Ducts

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ABSTRACT

This article investigated the structural behaviour of reinforced concrete (RC) beams incorporating transverse service ducts of varying sizes, shapes, and locations. A total of thirty-six simply supported RC beams were tested under four-point bending, including a control beam (CTB) without ducts and beams with square, circular, and diamond ducts of 25, 40, and 50 mm diameters positioned at different fractions of the span (one half, one third, and one fifth from the support). All beams were designed to fail in flexure, with longitudinal and shear reinforcement provided in accordance with BS EN 1992 (2004). Load versus deflection responses, first crack, yield, and failure loads, as well as ductility indices, were systematically evaluated. Results indicate that the presence of service ducts reduces first crack, yield, and failure loads, with the magnitude of reduction primarily governed by duct size and location. Beams with larger ducts or ducts positioned near supports exhibited the greatest reductions in strength, while duct shape had a minor effect. Despite reductions in stiffness and ultimate load, ductility remained largely preserved, with only minor decreases in specific cases. The study highlights that careful design of service ducts, minimizing size and avoiding critical shear or tensile zones, can mitigate adverse effects on beam performance. Service ducts in RC beams should be kept small relative to beam depth and preferably positioned within the middle third of the span to minimize strength reduction. Where larger openings are unavoidable, additional shear reinforcement or localized strengthening should be provided, and appropriate design modification factors should be considered to account for duct size and location. These findings provide guidance for the design of ducted RC beams in serviceable structures.

Keywords — ***Service ducts, Shape, Size, Ductility, Stiffness, Load, Ductility index***

1. INTRODUCTION

The increasing integration of mechanical, electrical and plumbing (MEP) services within structural systems has become a defining feature of modern building construction (Wael & Weldy, 2020). To accommodate these services, openings and ducts are frequently embedded within reinforced concrete (RC) beams to allow the passage of pipes, cables and conduits without increasing floor depth or compromising architectural space (Abdelhameed & Saputra, 2019). While this practice enhances functional efficiency and aesthetics, it introduces geometric discontinuities within the beam that alter stress flow, stiffness distribution and cracking behaviour (Elnagar *et al.*, 2024; Ahmed *et al.*, 2025).

In conventional RC beam design, structural performance is evaluated assuming a continuous and homogeneous cross-section (Anwar & Najam, 2016; Di Carlo *et al*., 2023). The introduction of service ducts violates this assumption by reducing the effective concrete area and disrupting the load-transfer mechanism between compression and tension zones (Ahmed *et al*., 2012; El Ame *et al*., 2020). These discontinuities act as stress concentrators, which can accelerate crack initiation, reduce load-carrying capacity, and modify failure modes (Boukeloua & Chaib, 2025). Consequently, the size and location of service ducts along the beam span become critical parameters governing the structural behaviour of ducted RC beams (Haji & Abdullah, 2025).

The influence of duct size is particularly significant because larger openings remove greater volumes of concrete, thereby reducing the effective moment of inertia and shear resistance of the beam (Arabzadeh & Karimizadeh, 2019; Khalaf & Al-Ahmed, 2020). Similarly, duct location along the span determines whether the opening is positioned within a region of high bending moment, high shear, or combined action (Elansary *et al*., 2022). Ducts located near mid-span primarily affect flexural performance, while those placed close to supports interfere with shear transfer and anchorage of reinforcement (Thanga, 2012; Yooprasertchai *et al*., 2021). The interaction between duct size and position therefore governs stiffness degradation, deflection response, crack propagation and ultimate failure of RC beams (Amiri *et al*., 2011).

Despite the widespread use of embedded ducts in practice, current design codes provide limited guidance on how to account for their structural implications, particularly when ducts vary in size and location. Many existing studies (Amiri *et al*., 2011; Arabzadeh & Karimizadeh, 2019; Khalaf & Al-Ahmed, 2020) focus on openings in web regions or idealized circular holes, often without systematically examining how different duct geometries interact with critical stress zones along the beam. Moreover, experimental data capturing the combined influence of duct size and longitudinal position on beam behaviour remain scarce, especially under realistic loading conditions.

This knowledge gap creates uncertainty for engineers when assessing safety margins, serviceability limits and retrofit requirements of ducted RC beams. Inadequate consideration of duct parameters may lead to over-conservative designs that increase construction costs or, conversely, unsafe designs that compromise structural integrity (Ahmed *et al*., 2012; Elansary *et al*., 2022). Therefore, a systematic investigation of the parametric variations in RC beam behaviour relative to service duct size and location is essential to establish reliable performance trends and support rational design guidelines.

Against this background, this article examines the structural response of reinforced concrete beams containing service ducts of different sizes positioned at various locations along the beam span. By evaluating changes in load-carrying capacity, stiffness, cracking behaviour, ductility and failure modes, the research aims to provide a clearer understanding of how embedded ducts modify beam behaviour and to contribute to the development of safer and more efficient structural design practices.

This study is significant because it provides a clear understanding of how service duct size and location affect the structural performance of reinforced concrete beams, including their strength, stiffness, cracking behaviour, ductility, and failure modes. By quantifying these effects, the research helps engineers make informed decisions on duct placement and sizing that minimize structural weakening while still accommodating building services. The findings also support more efficient and economical beam design, reduce the risk of premature damage or excessive deflection, and offer valuable data for improving design guidelines and future research on ducted reinforced concrete members.

2. MATERIALS AND METHODS

2.1. Materials

The laboratory investigation employed a range of materials, including various formwork materials, cement, water, and both fine and coarse aggregates. The binder selected was Portland limestone cement, class 32.5R, conforming to the specifications of BS EN 197-1 (2011). Potable water was utilized throughout all mixing and curing procedures to ensure consistency. The physical characteristics of the fine and coarse aggregates were meticulously assessed in accordance with the standardized methodologies prescribed by ASTM C128 (2021).

2.2. Method

A total of thirty-six (36) simply supported reinforced concrete beams were tested, with three specimens prepared for each test configuration as presented in Table 1. CTB = control beam (no duct); T = transverse duct; S, C, D = square, circular and diamond ducts; 25, 40, 50 = duct size (mm); 1/2, 1/3, 1/5 = duct location as a fraction of beam span from the support. The four-point bending test setup is illustrated in Fig. 1a, while the beam dimensions are shown in Fig. 1b. All beams were designed in accordance with BS EN 1992 (2004) to fail in flexure; therefore, vertical shear links were provided to prevent premature shear failure. Each beam had a rectangular cross-section measuring 100 mm in width and 150 mm in overall depth. A constant longitudinal reinforcement ratio of 0.76% was used for all specimens, comprising two 8 mm diameter ribbed bars at the tension face and two 8 mm diameter bars at the compression face. Shear reinforcement was provided using 4 mm diameter mild steel links.

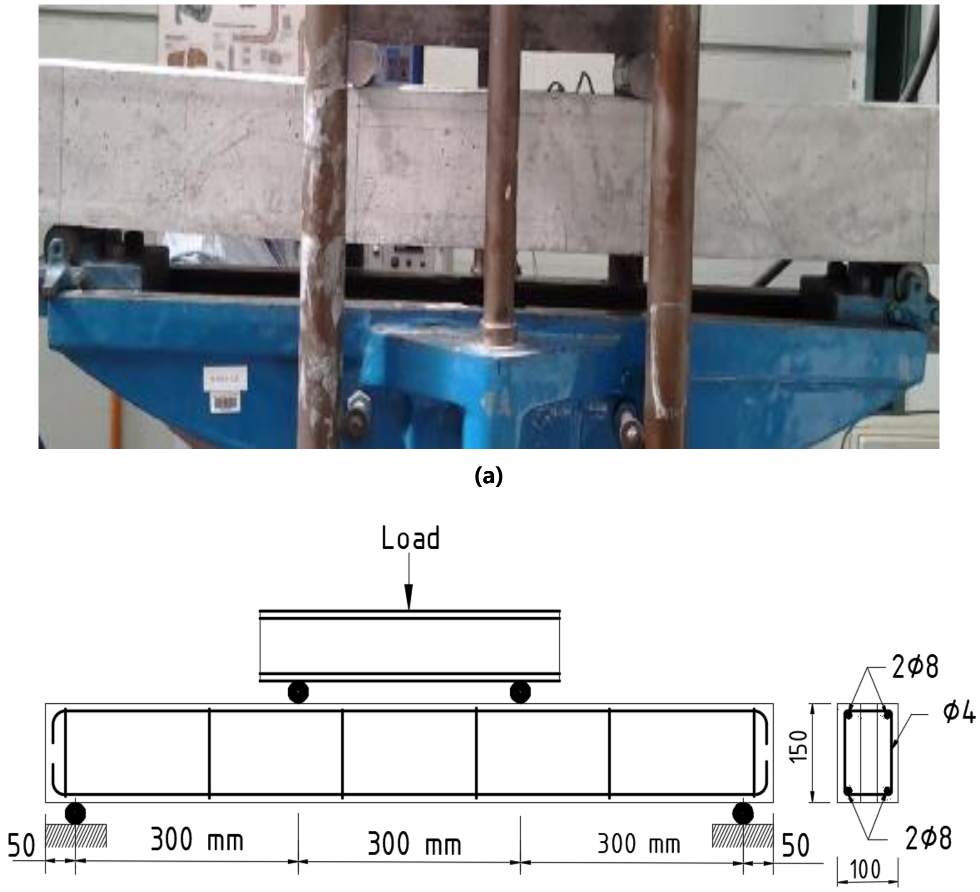
Service ducts were introduced transversely to the beam's longitudinal axis and positioned at different locations along the span. The concrete mix was proportioned to achieve a target compressive cylinder strength of 15 MPa.

Table 1: Ducted (RC) beam Configuration

Sample type	Duct Shape	Size of the duct, (mm)	Beam Section, (mm)
CTB	-	-	100 x 150 x 1000
TSB-50-1/2	Square	50	100 x 150 x 1000
TSB-50-1/3	Square	50	100 x 150 x 1000
TSB-50-1/5	Square	50	100 x 150 x 1000
TDB-50-1/2	Diamond	50	100 x 150 x 1000
TDB-50-1/3	Diamond	50	100 x 150 x 1000
TDB-50-1/5	Diamond	50	100 x 150 x 1000
TCB-50-1/2	Circular	50	100 x 150 x 1000
TCB-50-1/3	Circular	50	100 x 150 x 1000
TCB-50-1/5	Circular	50	100 x 150 x 1000
TDB-25	Diamond	25	100 x 150 x 1000
TDB-40	Diamond	40	100 x 150 x 1000
TDB-50	Diamond	50	100 x 150 x 1000

2.2.1. Test set up: As illustrated in Fig. 1b, all beams were simply supported over a clear span of 0.9 m. The ratio of shear span (300 mm) to effective depth (130 mm) was 2.3 for all bending tests. An overhang of 100 mm was provided beyond each support, and the supports consisted of 25 mm diameter cylindrical steel rollers.

Loading was applied through two actuators to produce a four-point bending condition. Midspan deflection was measured at the soffit of the beam using a dial gauge. The tests were carried out under displacement control at a loading rate of 0.02 mm/s and continued until failure occurred.



(a)

(b)

Fig. 1: (a) Dimensions of ducted beam text; (b) Experimental arrangement

3. RESULTS AND DISCUSSION

3.1. Load Carrying Capacity

Table 2 clearly revealed that the CTB exhibited the highest first crack load of 7.62 kN, indicating the best resistance to tensile cracking. This is expected because the control beam had no service duct, and therefore possessed an uninterrupted concrete cross-section with maximum effective depth and stiffness. In contrast, all beams containing service ducts showed a significant reduction in first crack load, confirming that the presence of ducts creates stress concentration zones and reduces the tensile capacity of the concrete. Among the ducted beams, specimens with larger duct sizes (50 mm) and those located closer to the support (1/5 span) recorded the lowest cracking loads. For example, TSB-50-1/5 (4.5 kN), TDB-50-1/5 (3.7 kN), and TCB-50-1/5 (3.7 kN) cracked much earlier than CTB. This behavior is attributed to the fact that ducts near the supports lie within regions of high shear and flexural–shear interaction, which accelerates crack initiation. Furthermore, diamond and circular ducts produced lower cracking loads than square ducts due to their greater disturbance of stress flow and weaker concrete cover around curved edges.

With respect to yield load as presented in Table 2, the control beam again showed the highest value (24.1 kN), indicating superior flexural capacity. Beams with ducts generally exhibited slightly lower yield loads, especially those with 50 mm ducts. However, the reduction in yield load was less pronounced than the reduction in first crack load, implying that once cracking occurred, the steel reinforcement continued to dominate load resistance. Beams with ducts located at mid-span (1/2) or one-third span (1/3) showed higher yield loads than those at 1/5 span, because bending moments are higher in the mid-span region and the reinforcement is more effectively mobilized there. For instance, TDB-50-1/2 and TDB-50-1/3 both achieved 23.3 kN, close to the control value, whereas TDB-50-1/5 dropped to 20.0 kN. This shows that duct location is more critical than duct shape in influencing yield behavior.

The failure load followed a similar trend. The control beam failed at 36.0 kN, the highest among all specimens. Beams with service ducts showed a reduction in ultimate capacity, particularly those with larger duct sizes and those closer to the support. For example, TSB-50-1/2 (35.0 kN) and TDB-50-1/2 (35.0 kN) were close to the control, while TSB-50-1/5 (29.4 kN) and TCB-50-1/5 (30.0 kN) experienced much lower failure loads. This reduction is mainly due to the loss of effective compression and tension zones caused by the duct, which reduces the lever arm between compressive and tensile forces. Larger ducts remove more concrete, leading to greater reductions in stiffness and ultimate strength.

The results demonstrate that duct size and location have a stronger influence on beam strength than duct shape and it was also confirmed by El-Ame *et al*. (2020). Beams with 50 mm ducts placed at 1/5 span consistently showed the poorest performance, while those with ducts at mid-span performed comparatively better. This confirms Boukeloua and Chaib (2025) that service ducts should be kept small and placed away from critical shear zones to minimize strength reduction.

3.2. Assessment of Structural Stiffness

Fig. 2 shows the load-vs-deflection curves illustrate the flexural response of the control beam (CTB) and beams incorporating transverse service ducts of different sizes and locations. All specimens exhibit the typical three-stage behaviour of reinforced concrete beams: an initial near-linear elastic region, a post-cracking nonlinear region with reduced stiffness, and a final stage approaching ultimate failure. This was in agreement ACI Committee 318 (2019).

The CTB curve consistently lies above the ducted beams, indicating higher stiffness, higher ultimate load, and lower deflection at comparable load levels. This is expected because the control beam has an intact concrete cross-section, allowing more efficient stress transfer between concrete and reinforcement. The absence of ducts eliminates stress concentration zones and premature cracking, hence the superior load-carrying capacity.

Beams incorporating transverse ducts exhibited increased deflections at relatively low load levels, particularly beyond the onset of first cracking. This response is consistent with the observations of Elnaga *et al.* (2024), who reported that enlarging opening sizes leads to greater structural deflections accompanied by a reduction in ductility, primarily due to the limited capacity of the member to redistribute internal stresses. The effect is further amplified with increasing duct size or when ducts are located closer to the critical tension zone. The associated reduction in flexural stiffness is attributed to the loss of effective concrete area and the disruption of stress trajectories within the beam, which promotes earlier crack initiation and accelerates crack propagation.

Comparing specimens with similar duct ratios but different configurations (TSB, TDB, TCB), it is observed that beams with ducts placed nearer the neutral axis show better performance than those closer to the tension face. This is because the tensile zone governs flexural cracking; placing voids in this region amplifies tensile stress concentration, leading to earlier cracking and larger deflections.

A salient observation from the experimental results is that certain ducted beams attained comparable, and in some cases higher, deflection capacities at failure despite exhibiting reduced ultimate load resistance. This response reflects an improvement in ductility, which is primarily attributed to the reduction in post-cracking stiffness that facilitates enhanced redistribution of internal forces and the development of higher reinforcement strains prior to failure, thereby mitigating the likelihood of sudden brittle collapse. Similar behaviour has been reported by Hammood *et al*. (2023).

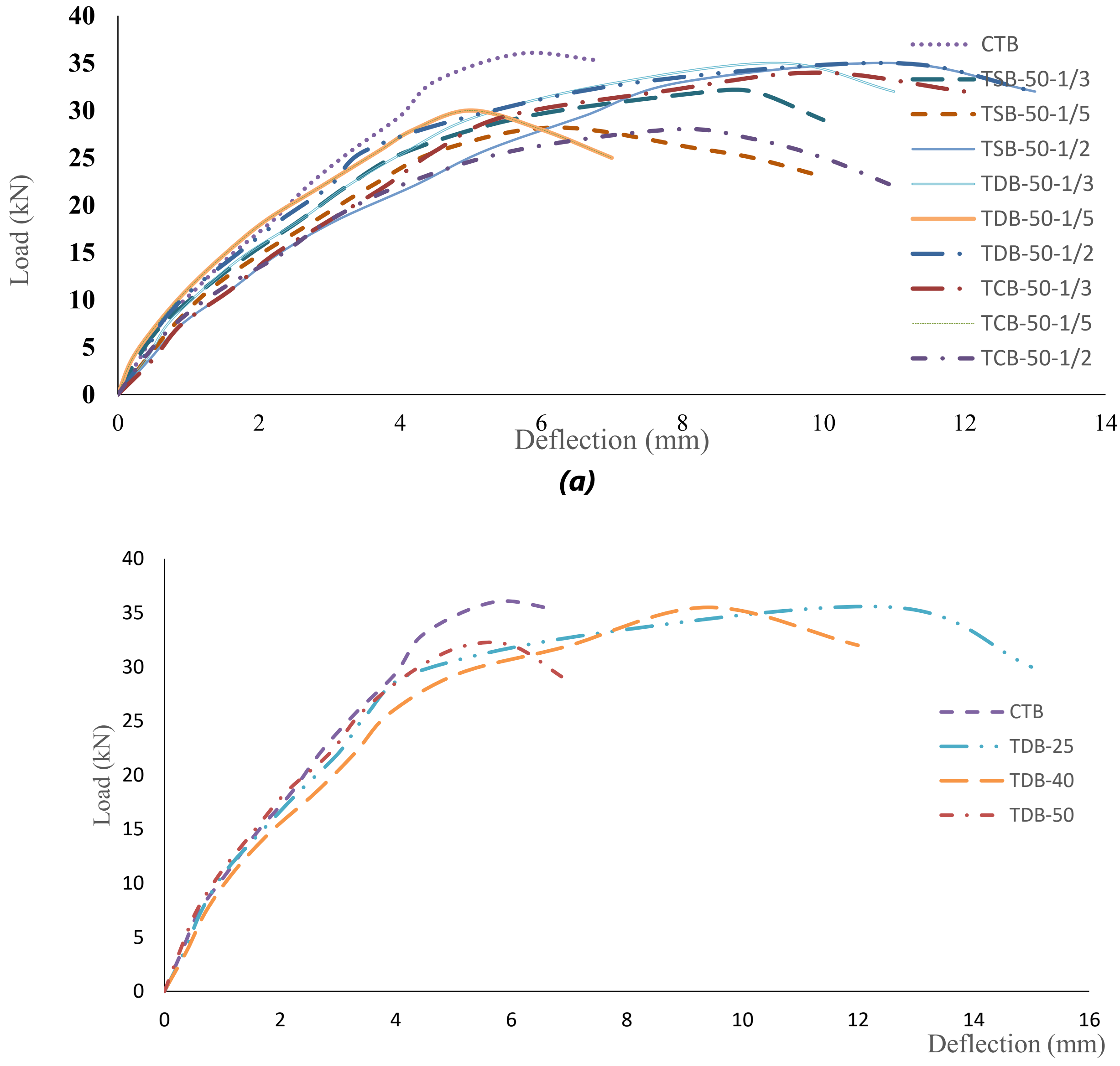
Table 2: Test Results

Sample type	First Crack Load (kN)	Deflection at First Crack (mm)	Yield Load (kN)	Deflection at Yield Load (mm)	Failure Load (kN)	Deflection at Failure Load (mm)
CTB	7.62	0.60	24.1	3.8	36.0	5.7
TSB-50-1/2	5.2	0.4	23.3	7.3	35.0	11
TSB-50-1/3	4.7	0.3	21.3	6	32.0	9.0
TSB-50-1/5	4.5	0.4	19.6	4.4	29.4	6.6
TDB-50-1/2	3.7	0.4	23.3	7.3	35	11
TDB-50-1/3	3.8	0.43	23.3	6.2	35	9.4
TDB-50-1/5	3.7	0.2	20.0	3.3	30	5.0
TCB-50-1/2	3.9	0.4	18.7	5.3	28	7.9
TCB-50-1/3	2.7	0.5	22.7	6.6	34	9.9
TCB-50-1/5	3.7	0.2	20	3.3	30	5.0
TDB-25	4.5	0.4	23.2	8.4	35.5	12.6
TDB-40	4.0	0.35	23.0	6.3	34.8	9.40
TDB-50	3.7	0.4	21.3	4.0	32.0	6.0

Table 3: Ductility index

Sample type	Deflection at Yield Load (mm)	Deflection at Failure Load (mm)	Ductility index
CTB	3.8	5.7	1.5
TSB-50-1/2	7.3	11	1.5
TSB-50-1/3	6	9.0	1.5
TSB-50-1/5	4.4	6.6	1.5
TDB-50-1/2	7.3	11	1.5
TDB-50-1/3	6.2	9.4	1.5
TDB-50-1/5	3.3	5.0	1.5
TCB-50-1/2	5.3	7.9	1.48
TCB-50-1/3	6.6	9.9	1.5
TCB-50-1/5	3.3	5.0	1.5

TDB-25	8.4	12.6	1.5
TDB-40	6.3	9.40	1.4
TDB-50	4.0	6.0	1.5



(a)

(b)

Fig. 2. Load -Deflection for the study beams

3.3 Structural ductility

The ductility index presented in Table 3 provides a measure of the deformation capacity of the beams relative to their yield point, indicating the ability of the structure to undergo inelastic deformations before failure. Across most of the tested beams, the ductility index remains relatively consistent at 1.5, suggesting that the introduction of transverse service ducts, regardless of size or location, has a limited impact on the overall ductility of these reinforced concrete beams.

Slight variations are observed in specific cases. For instance, TCB 50 1/2 exhibits a marginally lower ductility index of 1.48, while TDB 40 shows a slightly reduced value of 1.4. These minor reductions indicate a subtle decrease in the beam's ability to sustain large deformations without failure, which may be attributed to localized stress concentrations around the ducts or less effective stress redistribution due to the size and placement of the openings.

The results suggest that while service ducts can influence strength and stiffness, their effect on ductility is generally minimal, except in cases where duct size or configuration significantly disrupts the tensile zone. This finding aligns with previous observations (Hammood *et al*., 2023; Elnagar *et al*., 2024), which reported that although openings can increase deflections, the reduction in ductility is typically modest unless the openings are positioned in highly stressed regions.

4. CONCLUSION

The presence of transverse service ducts in reinforced concrete beams reduces first crack, yield, and failure loads, with the extent of reduction primarily influenced by duct size and location. Beams with larger ducts (50 mm) or ducts positioned near the support (1/5 span) exhibited the poorest structural performance, whereas ducts located at mid-span or closer to the neutral axis had less pronounced effects. Duct shape had a smaller influence on flexural behavior, although curved ducts (diamond or circular) caused slightly greater reductions in stiffness and cracking resistance compared to square ducts. Overall, structural stiffness decreased in beams with ducts, as reflected by higher deflections at comparable load levels, while ductility was largely preserved, with only minor reductions in some cases. These findings underscore the importance of careful design, suggesting that service ducts should be kept small and positioned away from critical shear or tensile zones to minimize adverse effects on structural performance.

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