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Flexural Behavior of Reinforced Concrete Beams with Openings Created by PVC Pipes: An Experimental and Numerical Study

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

It is a very common practice in several countries to find service pipes passing through beams transversely and vertically during construction. This practice has the potential of threatening the full-strength capacity of the structural element. This paper presents an experimental and numerical investigation on the flexural, deflection and crack performance of reinforced concrete (RC) beams with embedded conduit pipes. A total of ten (10) reinforced concrete beams were made and tested. Two of the RC beams served as control beams while the remaining eight RC beams had embedded conduit pipes of different sizes (50mm and 100mm) and at different positions (vertical and transverse). Loads were applied in increments of 2kN to the beams until failure. From the experimental results, the two control beams had an average failure load of 50kN, while the RC beams embedded with conduit pipes had an average failure load capacity of 44.75kN, which represents a 10.5% reduction. Similarly, the control beams had an average experimental first crack load of 17kN, whereas the conduit pipe embedded beams averaged 16.88kN first crack load. The RC beams with conduit pipes inserted transversely recorded an average failure load of 43kN, lower than RC beams with conduit pipes inserted vertically, which had an average failure load of 46.5KN. Reinforced concrete beams embedded with PVC pipes were observed to produce more cracks than the control beams, especially at the openings due to stress concentration. The embedment of PVC pipes in the beams resulted in a significant 20.47% increase in the average mid-span deflection. The numerical simulation of the beams performed with ABAQUS software demonstrated an adequate estimate with the experimental results obtained. The percentage variation between the ultimate load results obtained from the experimental test and finite element analysis ranged from 2% to 9%.

Keywords: RC beams; flexural strength; PVC conduit pipes; cracking behaviour; deflections.

1. INTRODUCTION

Reinforced concrete beams are structural elements which play a crucial role in reinforced concrete structures by transferring loads from slabs to the reinforced concrete columns, which further transfer them to underlying soil through RC foundations. RC beams are designed to resist ultimate bending moments, shear force and torsional moments. At the same time, serviceability requirements of deflection and cracking are considered to ensure satisfactory performance under working loads (Mosley and Bungey, 1990). Reinforced concrete beams can be classified according to their cross-section, position of reinforcement and support conditions. Beams reinforced with tension steel only are referred to as singly reinforced beams and those with both tension and compression steel bars are known as doubly reinforced. The inclusion of compression steel bars increases the moment capacity of the beam, allows more slender sections to be used and provide support for stirrups. Doubly reinforced beams are widely used in RC structures but under certain conditions, T- and L- beams are more economical than rectangular beams since some of the concrete below the neutral axis, is removed resulting in a reduced unit weight of beam. The support conditions of beams may be simply supported at the ends, cantilevered or continuous (Chanakya, 2009). ACI Committee 318 (American Concrete Institute, 2008) classifies beams according to the shear span-to-depth ratio into: deep, moderate, and ordinary. A beam with a ratio smaller than 1.0 is named as deep beam and beams with ratio greater than 2.5 as ordinary beams. A moderate deep beam has ratio in between these two limits. Beams with hollow cross sections, maximize the efficiency of their strength/mass and stiffness/mass ratios, decreasing the beams contribution to seismic response and load on the columns and foundations. Openings or holes in reinforced concrete beams during construction have become very popular and allow the passing of PVC pipe conduits through RC beams of buildings through which utility lines such as a network of pipes and ducts necessary for the provision of essential services like water supply, sewage, air-conditioning, electricity, telephone, and computer network. Openings are classified according to their direction, those in the direction of the width of the beam are known as the horizontal or transverse openings while the opening in the direction of the height of the beam is the vertical opening (Hamzah and Ali, 2020). Many building contractors often prefer this practice as it can be convenient but can compromise on the integrity of RC beams or the building as a whole. The durability of structural concrete and the factors influencing the stability and durability of a structure include the flexural strength (British Standards Institution, 1997, British Standards Institution, 2009, Kpo et al., 2024). The flexural strength formula depicts that the width and depth of a beam contribute to its stiffness. Therefore, the influence of openings on the flexural capacity, deflection and crack performance on RC beams relies on the size and location of the opening. ACI Committee 318 (American Concrete Institute, 2008) states that conduits, pipes and sleeves can be embedded within concrete, but should be done in a way that the structural integrity is not affected**.** Plastics are used for a wide range of commercial and industrial piping applications. The most common are polyvinyl chloride (PVC) pipes embedded in beams, columns and walls to serve as piping systems for drinking water supply, gas distribution and sewage disposal (Plastics Europe, 2017). Furthermore, research has showed that, to enhance the durability and improve performance of concrete under varying conditions, glass fiber and micro silica can be added to concrete (Agarwal and Shekhawat, 2023). For gravity sewer pipes, PVC has been extensively used over decades and has become a dominant construction material. The cost efficiency, ease of installation, availability of a range of diameters (40–630 mm) and its chemical resistance make it widely applicable (Davidovski, 2016).

Al-Gasham, 2015 studied the behavior of six (6) simply supported moderate deep beams with PVC pipes of diameters (25.4, 50.8, 76.2 and 101.6 mm) placed longitudinally either at the center or near the tension reinforcement. Tests indicated that pipes with diameters less than one-third of the beam width had limited effect on the capacity and rigidity of beam. For larger pipes, the ultimate strength of beams decreased between 16.7% and 33.3% and stiffness decreased between 103% and 297%.

Al-Sheikh, 2014 studied 27 RC beams with openings of various shapes and sizes, including one control beam. These beams were subjected to four-point loading to assess how the size and position of the openings influenced its performance. The study found that RC beams with small openings at shear zone recorded a maximum of 2.5% reduction in ultimate load whilst beams with small openings in flexure zones recorded a maximum reduction of 1.5%. Beams with large openings at the shear zone and flexure zone recorded 64% and 10% respective decrease in ultimate load compared with the control beam. Additionally, circular openings outperformed rectangular openings with equivalent area. When beams are subjected to transverse loading, they tend to bend and deflect. The flexural modulus, a physical property that indicates a material's ability to bend, is essentially equivalent to the material's modulus of elasticity (Kumar and Murthy, 2012).

Hasan and Abdul, 2022 studied concrete beams with vertical and horizontal openings in the flexural zone. The results showed a significant 11% reduction in ultimate load and 20% increase in midspan deflection for beams with vertical openings compared to control beams. Shear cracks were more prone to occur around openings due to stress concentrations and finite element modeling effectively predicted these behaviors.

This paper specifically examines the effects of transverse and vertical conduit pipe embedment on the flexural behaviour of reinforced concrete beams. The effect of the embedment of conduit pipes on the failure load, cracking behaviour and the deflections of reinforced concrete beams were investigated. The study was limited to the use of 50mm and 100mm PVC pipes, positioned vertically and transversely within the reinforced concrete beam.

2. MATERIALS AND METHODS

2.1 Materials

The materials used for the study as shown in (Fig. 1) included fine aggregates, coarse aggregates, 42.5R ordinary Portland cement, water, 12mm mild steel reinforcement bars as longitudinal rebars, 8mm mild steel reinforcement bars as stirrups, and PVC conduit pipes of diameters 50mm and 100mm. A mix ratio of 1:2:4 and a water-cement (w/c) ratio of 0.55 was used for the specimens. The mixing was done manually on a clean surface.

2.2 Test specimens

2.2.1 Control concrete specimens

Six (6) concrete cube specimens of dimensions 150mm x 150mm x 150mm were cast to determine the compressive strength of the concrete. After 24hours, the cubes were demoulded and cured for 7 and 28 days. Fig. 2

(a) shows the concrete cubes cast in moulds. Three (3) cubes each were tested to determine the average compressive strengths after 7 days and 28 days**.** Six (6) concrete prism specimens of dimension 100mm x 100mm x 500mm were also cast to determine the flexural strength of the concrete. Fig. 2 (b) shows the cast concrete prisms.

Fig. 1. Materials: (a) sand and gravel, (b) cement, (c) 12mm steel rebars with 8mm stirrups and PVC pipes

Fig. 2. Specimens: (a) concrete cubes, (b) concrete prisms

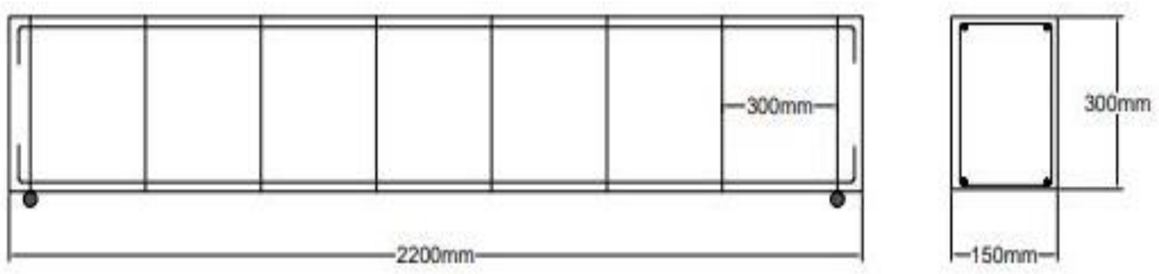


Fig. 3(a). Illustration of control solid beams (B1 and B7) without any opening and PVC pipe

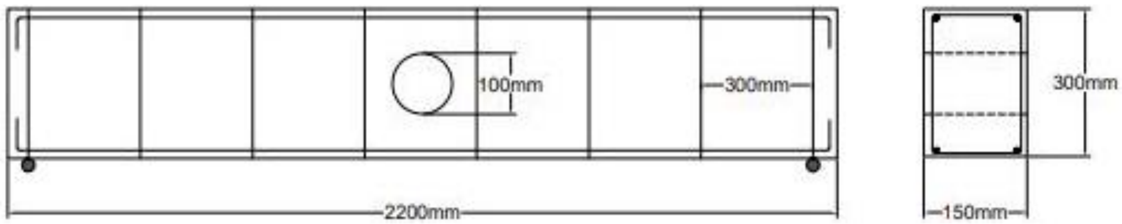


Fig. 3(b). Illustration of test beams (B3 and B5) with opening and 100mm diameter PVC pipe placed transversely at midspan

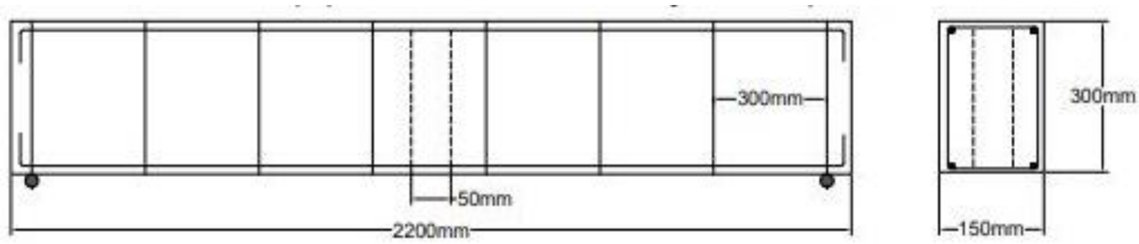


Fig. 3(c). Illustration of test beams (B6 and B8) with opening and 50mm diameter PVC pipe placed vertically at midspan

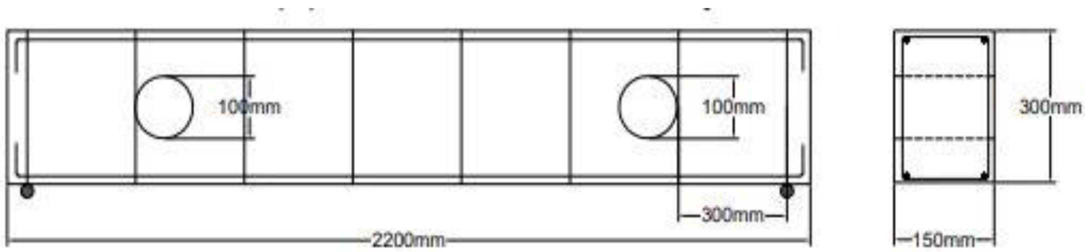


Fig. 3(d). Illustration of test beams (B2 and B10) with two openings and 100mm diameter PVC pipes placed transversely at both shear zones

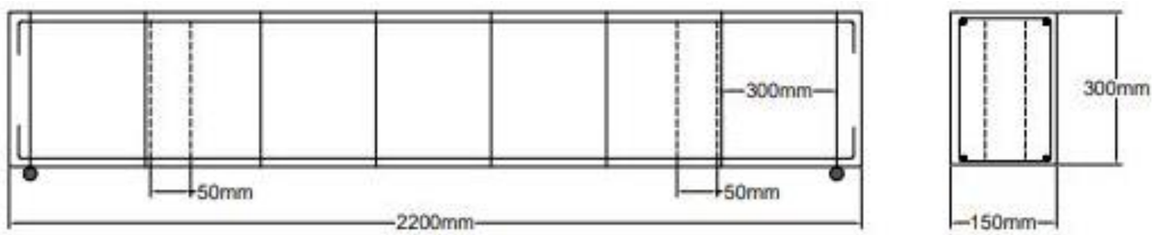
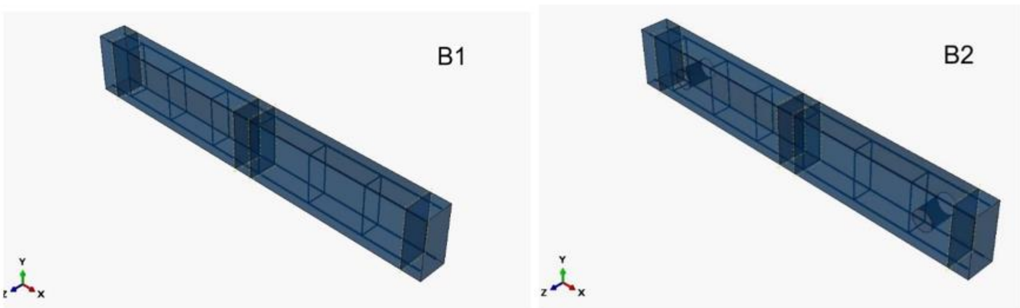


Fig. 3(e). Illustration of test beams (B4 and B9) with two openings and 50mm diameter PVC pipes placed vertically at both shear zones



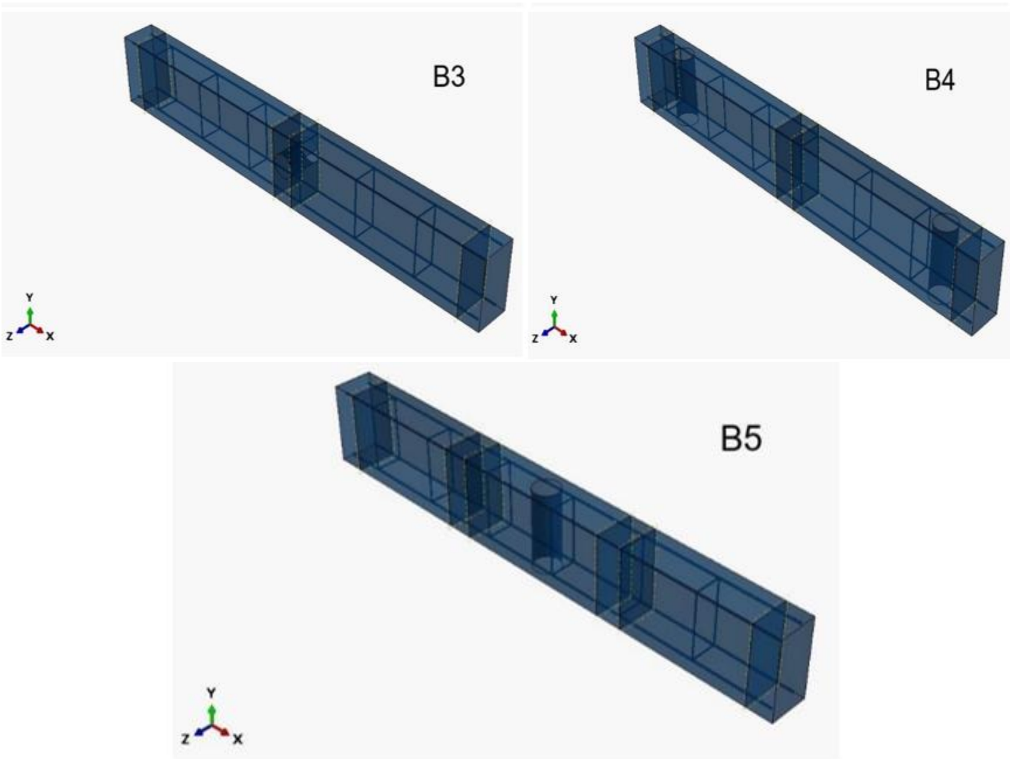


Fig. 3(f). Illustration of test beams modelled using ABAQUS software

2.2.2 Reinforced concrete beams

Ten (10) RC beams of dimensions 2200mm x 300mm x 150mm were cast to investigate the flexural behaviour of reinforced concrete beams with embedded conduit pipes for services. 12mm diameter bars were used for the longitudinal bars and 8mm diameter bars as the shear links with spacing of 300mm center-to-center. 50mm and 100mm PVC pipes were positioned vertically and transversely within the reinforcement bars and held in position with binding wires in the moulds before concrete was poured. The beam sections illustrated in Figs 3(a), 3(b), 3(c), 3(d) and 3(e) respectively represent control solid beams (B1 and B7) without any opening and PVC pipe, test beams (B3 and B5) with opening and 100mm diameter PVC pipe placed transversely at midspan, test beams (B6 and B8) with opening and 50mm diameter PVC pipe placed vertically at midspan, test beams (B2 and B10) with two openings and 100mm diameter PVC pipes placed transversely at both shear zones and lastly, test beams (B4 and B9) with two openings and 50mm diameter PVC pipes placed vertically at both shear zones. Fig. 3(f) illustrates the test beams B1 to B5 after being modelled by finite element (FEM) method using ABAQUS software The beam models depict all reinforcing bars in the concrete.

2.3 Test Procedures

2.3.1 Tensile test of reinforcing steel bar

The tensile strength of the steel reinforcement bars was determined by using the Universal Testing Machine (UTM) and in accordance with BS 4449, 2005 (British Standards Institution, 2005) Three (3) pieces of the reinforcing bar were cut in lengths of 400mm and their actual diameters measured with Vernier calipers. The grip length at each end was marked and the gauge length determined. The specimens were then placed in the upper and lower jaws of the UTM and an extensometer attached at the middle of the gauge length and tensile force was applied gradually till necking and rapture occurred at the maximum load and the corresponding strains were recorded by the extensometer just before necking and rapture. The maximum tensile strength of the steel reinforcing bar specimens were then recorded and the average tensile strength values determined. Fig. 4 shows the tensile strength test of the steel reinforcing bar specimens.

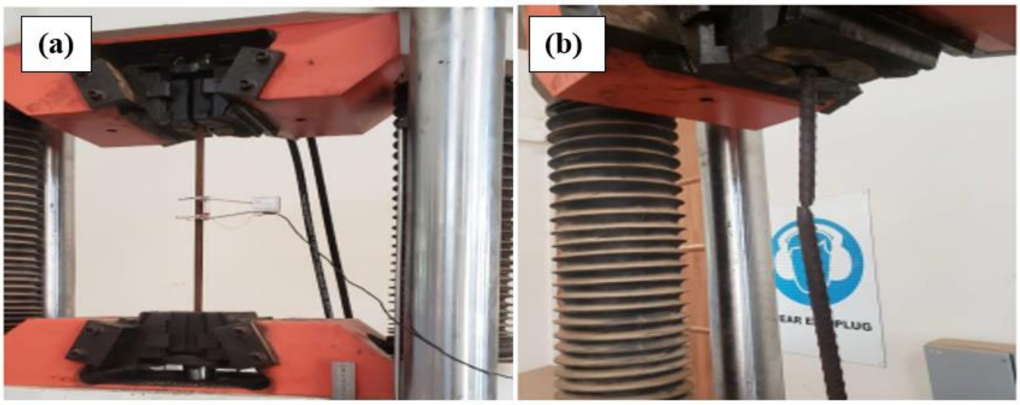


Fig. 4. Steel rebar tensile strength test using UTM: (a) testing of specimen, (b) rupture

2.3.2 Concrete compressive strength

The compressive strength of the hardened and cured concrete cubes was determined at 7 days and 28 days in accordance with BS EN 12390-3, 2009 (British Standards Institution, 2009) using the UTM as shown in Fig. 5(a).

2.3.3 Concrete modulus of rupture

The concrete flexural tensile strength test also known as modulus of rupture was conducted to determine the tensile strength of the concrete. This was determined by testing the concrete prisms in accordance with BS 12390-1: 2000. (British Standards Institution, 2000) and BS EN 12390-5: 2019 (British Standards Institution, 2000) as shown in Fig. 5(b). The specimens were simply supported at the ends and subjected to single-point loading using the Universal Flexural Testing Machine with a 220kN load capacity. The flexural tensile strength (modulus of rupture) of the beam is expressed as:

Modulus of Rupture (f_t) = $\frac{3PL}{2bd^2}$ … (Eqn 1)

where, f_t = flexural tensile strength of test specimen (N/mm²),

P = maximum load applied (N),

L = span of the test beam (mm),

b is the breadth and d is the depth of the cross section (mm).

2.3.4 Test of the RC beams

The beams were placed on two steel supports which were 100mm from the ends of the beams, spaced 2000mm apart in a rigid steel frame. A hydraulic jack was connected to a loader and subjected the beams to a 3-point loading as shown in Fig. 6. Nine (9) beams were subjected to a 3-point loading and one (1) beam (B6) was subjected to a 4-point loading with a central constant moment section at intervals of 2kN. For a 3-point loading, the maximum bending stress occurred at the midpoint of the beam whereas with the 4-point loading, the maximum bending stress is spread over the section of the beam between loading points. The load was then applied at midspan till failure and the failure load recorded. A dial gauge was also placed under the beam, at the midspan to record the central deflections.

2.4 Finite Element Simulation

The beams were modeled in ABAQUS using various theoretical approaches to simulate both three-point and four-point bending analysis of the behavior of reinforcing steel bars, ensuring reliable outcomes. The material models were developed based on their properties and the adopted theories, divided into two key components. First, concrete was modeled using the concrete damaged plasticity model (CDP), which offers greater accuracy compared to the smeared cracking model. Second, steel was represented using the classical metal plasticity (CMP) theory, based on the von Mises yield criterion (Genikomsou and Polak, 2015, Pasiou and Kourkoulis, 2018).

C3D8R (an 8-node linear brick element with reduced integration) finite elements were used for the beam concrete components and the steel reinforcements were modeled using the 2-node truss element (T3D2). Concrete's modulus of elasticity and Poisson's ratio were also defined, and the bearing plates were assumed to be

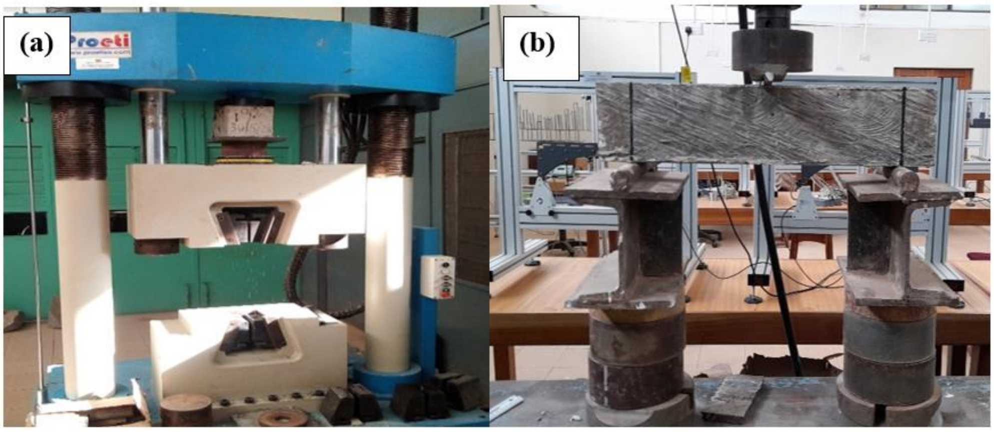


Fig. 5. (a) Compressive strength test, (b) Flexural tensile test on concrete

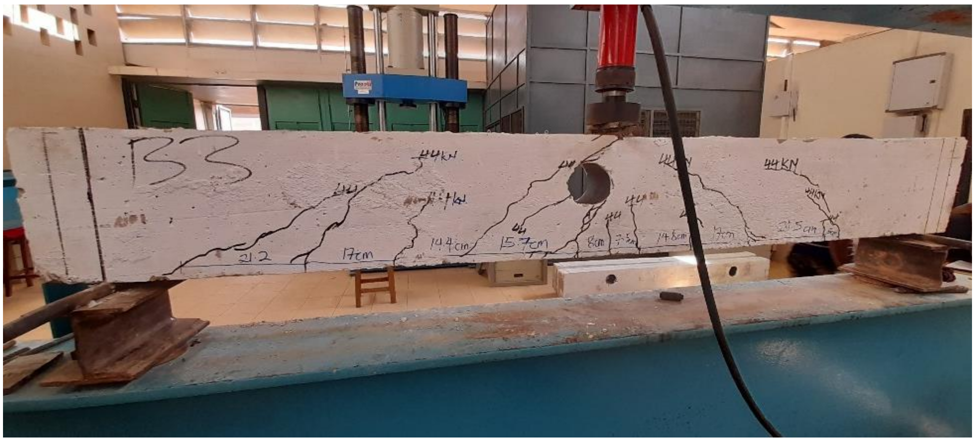


Fig. 6. 3-point loading test of RC beams with openings embedded with PVC pipes

Table 1. Concrete damage plasticity

Parameters	Poisson ratio	Dilation angle (ψ)	Eccentricity (ϵ)	f_{b0}/f_{c0}	Tensile meridian (k)	Viscocity parameter (μ)
Values	0.2	30	0.1	1.16	0.67	0.0005

made of elastic steel. In the next modeling phase, the beam components were assembled, and static loads were applied. The bond between reinforcing steel bars and concrete was assumed to be ideal, and the interactions among all beam sections were detailed. Boundary conditions for roller and hinge supports were also established. During meshing, efforts were made to identify the optimal mesh size of 15mm, resulting in satisfactory outcomes. The finite element theories utilized relied on parameters representing the typical properties of concrete in its standard state (See Table 1). These parameters were determined through extensive research on concrete behavior (Somes and Corley, 1974, Mansur et al., 2001).

3. RESULTS AND DISCUSSION

3.1 Slump Test Results

The slump test result recorded for the 1:2:4 concrete mix used for the study was 25mm which is stipulated by BS EN 12350-2 (European Committee for Standardization, 2009) and comparable to the slump values (10mm to 210mm) reported by previous researchers (Diab et al., 2014) which indicates a good workability for structural reinforced concrete beam.

3.2 Tensile Strength of Steel Rebar

Three (3) steel rebar samples of nominal diameter 12mm labelled A, B and C respectively and of length 400mm, were used for the steel tensile strength test and an average yield strength of 586.88N/mm^2 was recorded as shown in Table 2. This result indicates the reinforcing steel bars used for the RC beam specimens in the study can be classified as high yield steel and exceeds the minimum value of 460N/mm^2 specified building codes (British Standards Institution, 1997, British Standards Institution, 2005).

3.3 Concrete Compressive Strength

Concrete cube specimens of dimensions 150mm x 150mm x 150mm tested had average compressive strengths of 14.65N/mm^2 and 17.09 N/mm^2 after 7 days and 28 days respectively as shown in Table 3.

3.4 Modulus of Rupture

Concrete prism specimens of dimension 100mm x100mm x 500mm were tested to determine the average flexural tensile strength also known as the modulus of rupture was 4.4N/mm^2 as shown in Table 4.

3.5 Theoretical Analysis of RC Beam

3.5.1 Cracking moment of RC beam

The modulus of rupture of the concrete determined using equation 1 was used to determine the cracking moment in the RC beam as expressed in equation 2

Cracking moment (M_{cr}) = $f_t \frac{bd^2}{6}$……… (Eqn 2)

where f_t is the modulus of rupture (N/mm^2).

b and d are the breadth and depth of the prism in millimeters respectively.

3.5.2 Cracking Load of RC Beam

(a) For a 3-point symmetrical loading of beam: Cracking load (P_{cr}) = $\frac{4Mcr}{L}$……… (Eqn 3)

(b) For a 4-point symmetrical loading of beam: Cracking load (P_{cr}) = $\frac{6Mcr}{L}$……….. (Eqn 4)

3.5.3 Theoretical failure load of RC beams

3.5.3.1 Assuming steel yields first

(a). For a 3-point symmetrical loading of beam:

Failure Load (P_{ult}) = $\frac{4Mrs}{L}$…………………. (Eqn 5)

where M_{rs} is the moment of resistance of steel in tension.

M_{rs} = 0.87fyAs x 0.775d………… . (Eqn 6)

where fy is the yield stress of steel (N/mm^2), A_s is the area of steel for the tension bars (mm^2), d is the beam effective depth (mm) and L, the effective span of the beam (mm).

(b). For a 4-point symmetrical loading of beam:

Failure Load (P_{ult}) = $\frac{6Mrs}{L}$………… (Eqn 7)

3.5.3.2 Assuming concrete crushes first

(a). For a 3-point symmetrical loading of beam:

Failure Load (P_{ult}) = $\frac{4Mrc}{L}$……… (Eqn 8)

where M_{rc} is the moment resistance of concrete in compression taking the steel in compression into consideration that is:

M_{rc} = 0.156f_{cu}bd^2 + 0.87fyAs (d – d$'$)…. (Eqn 9)

where f_{cu} is the compressive strength of concrete (N/mm^2), d is the effective depth of beam (mm), d$'$ is the inset of compression steel (mm), b is the width of beam (mm), A_s is the area of steel for the steel compression bars (mm^2).

(b). For a 4-point symmetrical loading of beam:

Failure Load (P_{ult}) = $\frac{6Mrc}{L}$…………….. (Eqn 10)

Table 2. Tensile strength test of reinforcing steel bars

Specimen ID	Nominal Diameter (mm)	Actual Diameter (mm)	Lower Yield Stress (LYS) (N/mm^2)	Upper Yield Stress (UYS) (N/mm^2)	Tensile Stress, fu (N/mm^2)	Yield stress, fy (N/mm^2)
A	12	10.50	228.30	244.10	774.50	626.52
B	12	10.50	251.50	270.20	698.20	579.74
C	12	10.50	240.50	258.38	667.66	554.38
Average	**12**	**10.50**	**240.10**	**257.56**	**713.45**	**586.88**

Table 3. Compressive strength of concrete

Days	Average Compressive Strength (N/mm^2)
7 days	14.65
28 days	17.09

Table 4. Flexural tensile strength of concrete

Specimen ID`	Tensile strength (N/mm^2)
1	4.10
2	4.30
3	4.80
Average	**4.40**

3.5.3.3 Assuming shear failure occurs first

Critical shear in a beam occurs at a distance equal to the effective depth of the beam and at an angle of 45 degrees from the support, therefore the steel stirrups are supposed to prevent cracks developed at the shear zones and also ensure that the ultimate strengths are governed by flexure rather than shear.

The shear failure load, $V_f = 0.87 \frac{Asv}{Sv} (f_y d) + v_c bd$… (Eqn 11)

where f_y = yield strength of steel stirrups (N/mm^2), v_c is the concrete shear strength (N/mm^2), A_{sv} is the area of shear reinforcement (mm^2), s_v is the spacing of stirrups (mm), b is the width of the beam (mm) and d is the effective depth (mm). The maximum shear force is twice the shear failure load v_f.

3.6 Failure Loads

The results from the flexural strength test of the RC beam specimens embedded with PVC pipes and control RC beams were compared. Table 5 summarizes the results of the experimental and theoretical failure loads of the ten (10) RC beams investigated. The control beams (B1 and B7) had the highest average failure load of 50kN. The embedment of PVC pipes in the test beams caused a reduction in the flexural strength capacity of the beams. Beams embedded with conduit pipes recorded an average failure load of 44.75kN, representing a 10.5% reduction in strength capacity. The average failure load of RC beams embedded with smaller PVC pipes (50mm) was 46.5kN, which is higher than the average failure load of 43kN recorded by beams with bigger PVC pipe diameters. (100mm). The RC beams with 100mm PVC pipes embedded transversely at the shear zones (B2 and B10) recorded the lowest average experimental failure load of 41kN while RC beams with 100mm PVC pipes embedded within the flexure zone (B3 and B5) recorded an average failure load of 45kN. The beams (B4, B6, B8, B9) with PVC pipes embedded vertically recorded a higher average failure load capacity of 46.5kN, compared to RC beams (B2, B3, B5, B10) with PVC pipes inserted transversely which recorded 43kN average failure load.

3.7 Crack Pattern and Modes of Failure

The control beams (B1 and B7) displayed typical flexural cracks that originated at the tension zone near midspan and propagated towards the neutral axis (Fig. 7). These beams had fewer cracks compared to those with conduit pipes, indicating higher structural rigidity The beams with PVC pipes embedded transversely in the shear zones (B2 and B10) showed significant shear cracks near the supports, with additional cracks forming around the pipe openings. On the other hand, RC beams with PVC pipes inserted vertically in the shear zones (B4 and B9) displayed relatively less shear cracks. Cracks were still present around the openings, but with less disruption in the shear zones. For beams with PVC pipes inserted at the midspan (B3 and B5; B6 and B8), they exhibited more flexural cracks near the midspan where bending moments were highest, and fewer shear cracks.

The mode of failure in beams with PVC pipes was significantly influenced by both the location and orientation of the pipes. Beams with pipes inserted in shear zones primarily exhibited shear failure, while those with pipes at the midspan were more prone to flexural failure. Studies have highlighted the bond between concrete and reinforcing steel bar as important in crack propagation and structural performance (Huang and Cheng, 2022).

Table 5. Experimental and theoretical properties of beams

Beam ID	Theoretical cracking load, Pcr (kN)	Experimental cracking load, P'cr (kN)	Theoretical failure load based on			Experimental failure load P'ult (kN)	P'cr/Pcr	P'ult/Pult	Observed cracks
			Steel Yielding (kN)	Concrete Crushing (kN)	Shear Failure (kN)				
B1	19.8	16	*36.86	89.54	83.8	50	0.808	1.356	Flexural
B2	19.8	8	*36.86	89.54	83.8	36	0.404	0.977	Flexural, Shear
B3	19.8	15	*36.86	89.54	83.8	44	0.404	1.194	Flexural, Shear
B4	19.8	16	*36.86	89.54	83.8	42	0.505	1.139	Flexural, Shear
B5	19.8	22	*36.86	89.54	83.8	46	0.404	1.248	Flexural, Shear
B6	28.29	20	*52.66	127.91	83.8	50	0.707	0.949	Flexural, Shear
B7	19.8	18	*36.86	89.54	83.8	50	0.909	1.356	Flexural, Shear
B8	19.8	16	*36.86	89.54	83.8	46	0.808	1.248	Flexural
B9	19.8	22	*36.86	89.54	83.8	48	1.111	1.302	Flexural
B10	19.8	16	*36.86	89.54	83.8	46	0.808	1.248	Flexural, Shear

** Governing failure load of Beam*

Table 6. Experimental failure load and maximum deflections of the beams

Beam ID	Experimental failure load (kN)	Average crack spacing (mm)	Maximum deflection (mm)
B1	50	177.30	6.96
B2	36	176.15	5.86
B3	44	147.60	6.96
B4	42	129.95	8.32
B5	46	131.74	9.30
B6	50	168.30	12.0
B7	50	129.95	7.40
B8	46	167.10	8.65
B9	48	180.80	8.50
B10	46	158.20	9.60

Table 7. Experimental vs FEM results

Experimental Beam ID	FEM Beam. ID	Experimental cracking load(kN)	FEM cracking load	Experimental Ultimate Load (kN)	FEM Ultimate Load(kN)	Experimental Deflection (mm)	FEM Deflection (mm)
B1&B7	B1	17	24.2	50	48.3	7.18	6.12
B2&B10	B2	12	18.8	41	42.7	7.73	3.52
B3&B5	B3	18.5	16.5	45	40.7	8.13	5.29
B4&B9	B4	19	18.8	45	42.9	8.41	3.6
B6&B8	B5	18	25.1	48	48.8	10.33	5.87

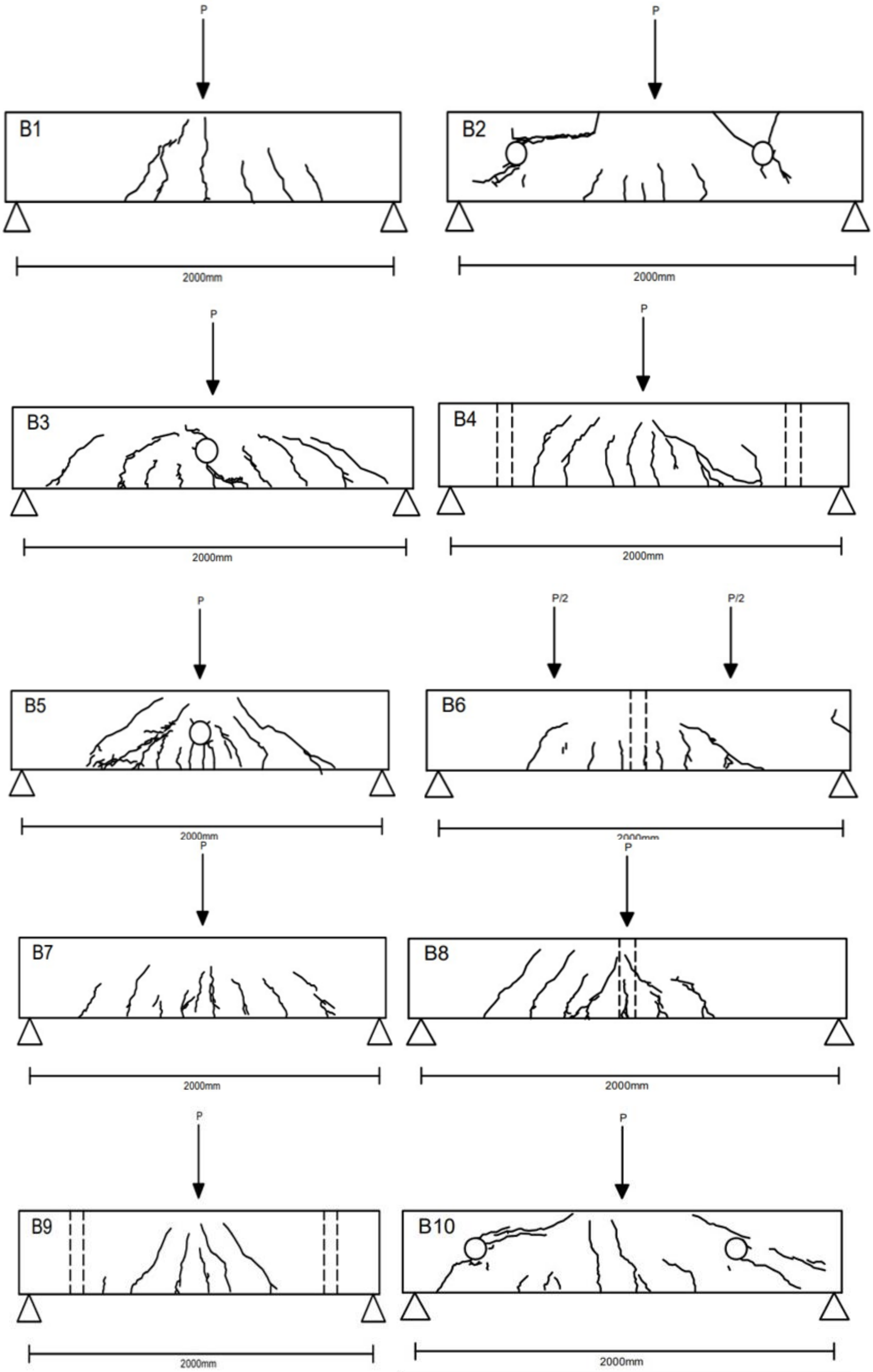


Fig. 7. Illustration of crack patterns on test and control beams

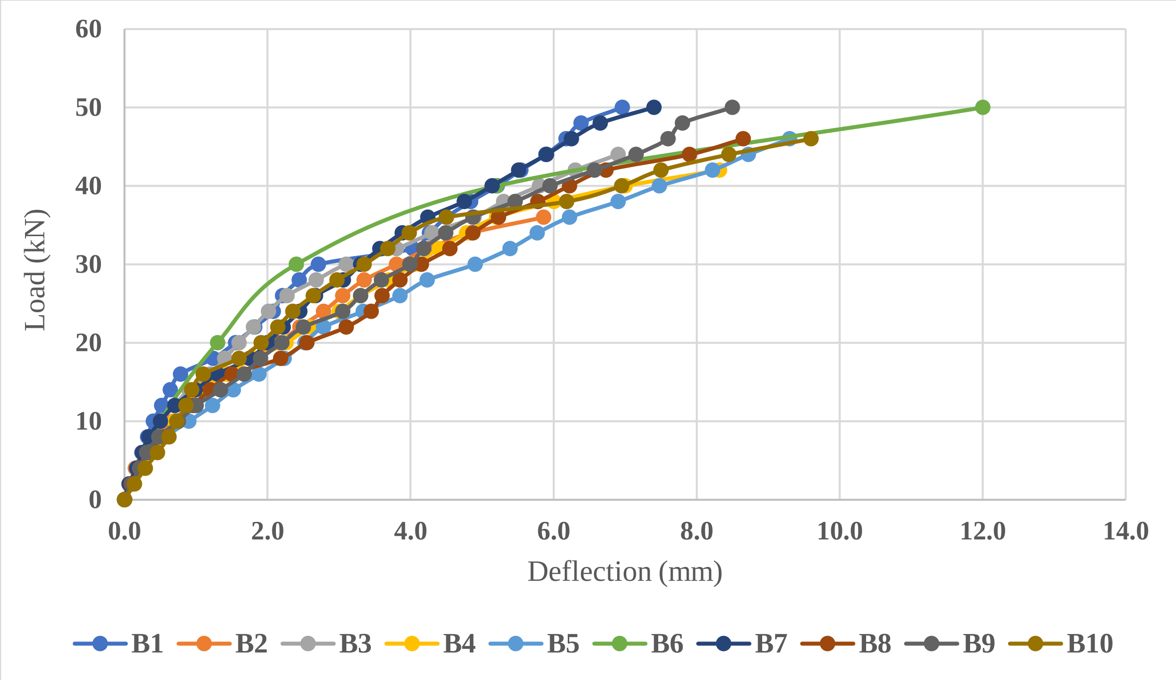


Fig. 8. Load-deflection curves for tested RC beams

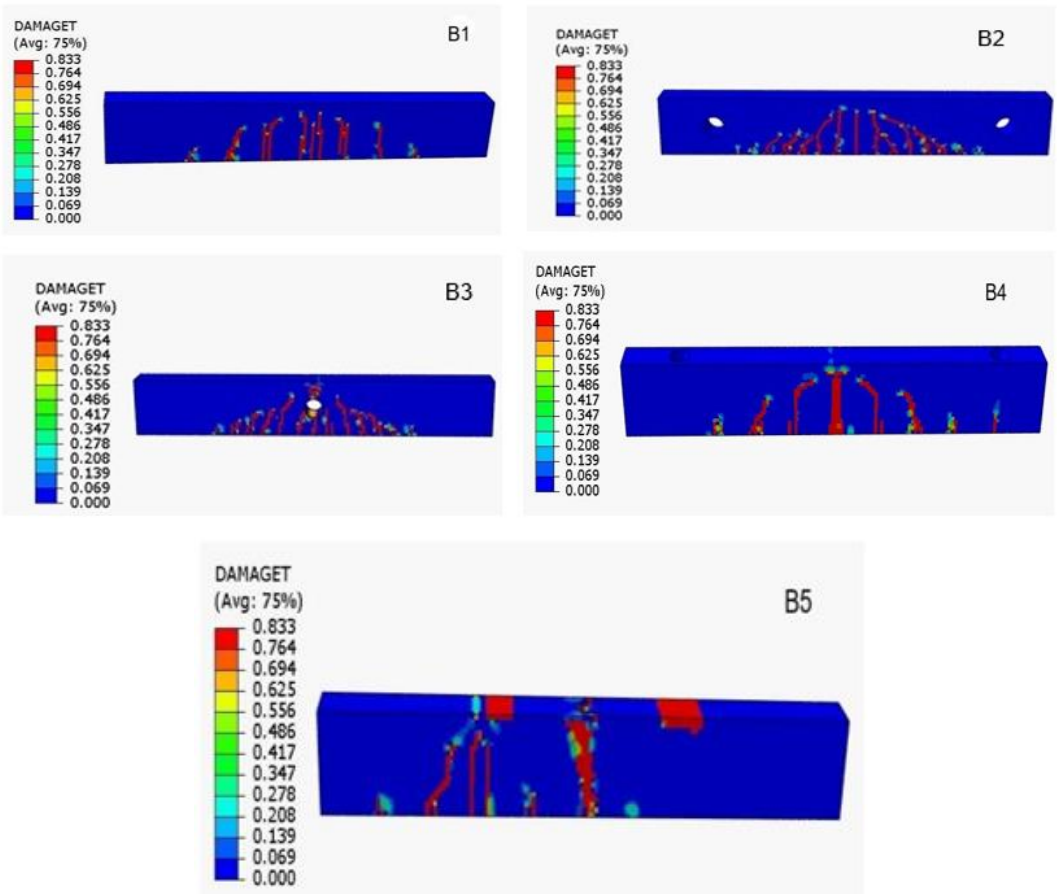


Fig. 9. Crack patterns

The larger 100 mm pipes had a more detrimental effect on the overall strength, particularly when inserted transversely, leading to lower failure loads and more severe crack patterns. Conversely, the smaller 50 mm pipes, especially when inserted vertically, resulted in higher failure load capacities and less pronounced cracking, indicating a better retention of the beam's structural rigidity.

3.8 Load-Deflection Characteristics

The load-deflection responses of the specimens are shown in Fig. 8 and Table 6. The specimens initially showed high stiffness in the uncracked elastic stage, with effective stress transfer between concrete and reinforcements. After cracking, stiffness decreased slightly, and reinforcements took over load resistance. The elastic response continued until reinforcement yield, followed by significant deflection in the post-yield stage, ultimately leading to failure at the peak load capacity. From Fig. 8 and Table 6, the control solid beams (B1 and B7) without PVC embedment recorded lower deflections of 6.96mm and 7.40 mm (average deflection of 7.18mm), corresponding to the highest average failure load (50kN). This indicates a higher performance compared to the beams with conduit pipes. Beams (B6 and B8) with opening and 50mm diameter PVC pipe placed vertically at midspan recorded higher deflections of 12mm and 8.65mm. The beams (B4, B6, B8, B9) with vertically embedded PVC pipes exhibited maximum deflections of 8.32mm, 12.0mm, 8.65mm, and 8.50mm (average deflection of 9.37mm). Furthermore, the maximum deflections observed in the RC beams (B2, B3, B5, B10) with transversely inserted PVC pipes were recorded at 5.86mm, 6.96mm, 9.30mm, and 9.60mm (average deflection of 7.93mm).

Table 6 further demonstrates that, embedding PVC pipes significantly increased the average mid-span deflection of 8.65mm in contrast to the lower average mid-span deflection of 7.18mm recorded for the control beams (B1 and B7). This signifies a 20.47% increase in deflection. This phenomenon can be attributed to the substantial reduction of concrete in the critical region caused by the vertical opening as confirmed by previous research (Hasan and Abdul, 2022). Moreover, for a specific load (the maximum load of a beam containing a vertical opening), switching the orientation of the opening from horizontal to vertical leads to an increase in mid-span deflection. Increasing the opening from 50mm to 100mm leads to higher deflections and further reduction in ultimate strength of the beam.

3.9 Effect of Opening Orientation

This section highlights the effect of opening orientation (horizontal and vertical openings) on the performance of the reinforced concrete beams. Beams with horizontal openings averaged an ultimate failure load of 43kN while beams with vertical openings recorded an average ultimate failure load of 46.5kN. Horizontal openings in RC beams produced a greater reduction in the load-carrying capacity of the beam than the vertical openings. Inserting PVC pipes horizontally potentially decreases the effective depth of the beam, which significantly reduces the beam’s moment of inertia, thereby reducing the flexural stiffness of the beam.

3.10 Numerical Results

The numerical results demonstrated a high degree of consistency with the experimental data, particularly in terms of the beams' load-bearing capacity and ultimate deflection. Validation of the numerical models confirmed that the load-displacement curves followed a similar trend to the experimental findings. For the finite element method (FEM), B1 represents the solid beams, B2 represents the beams with transverse openings at shear zones, B3 represents beams with transverse opening at midspan, B4 represents beams with vertical openings at the shear zones and B5 represents beams with vertical opening at the midspan. The ultimate load recorded in the experimental tests for the solid beam B1 and B7 was 50kN compared to 48.3kN predicted by its corresponding FEM test counterpart(B1). The theoretical analysis based on limit state design also predicted failure load of 36.86 kN that was governed by the yielding of steel rebars. The experimental test also recorded a slightly larger deflection of 7.18mm in contrast with 6.12mm predicted by the FEM. As shown in Fig. 10, the load-deflection curve by the FEM predicted cracking loads of 24.2kN, 18.8kN, 16.5kN, 18.8kN and 25.1kN for beams B1, B2, B3, B4 and B5 respectively. In contrast, experimental cracking loads of 17kN, 12kN, 18.5kN, 19kN, 18kN were obtained for beams (B1and B7), (B2 and B10), (B3 and B5), (B4 and B9) and (B6 and B8) respectively. The trend noticed is that the FEM predicted slightly higher loads values. Pertaining the ultimate loads shown in Table 7,

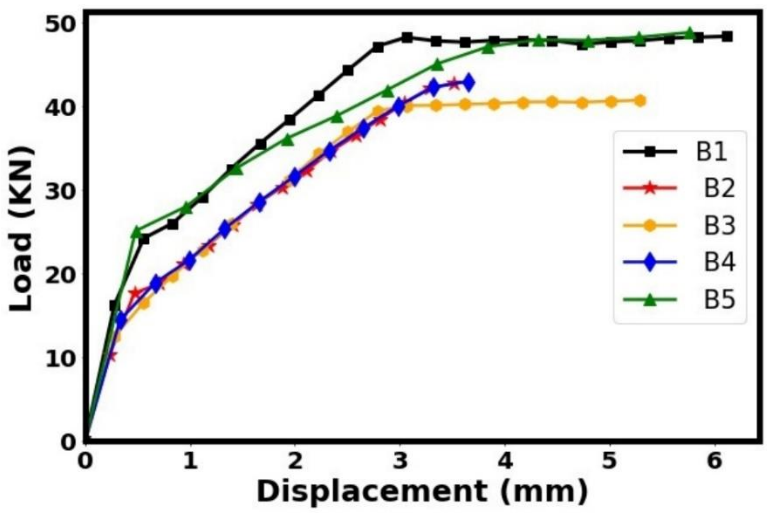


Fig. 10. Load-displacement curve

the FEM predicted 48.3kN,42.7kN, 40.7kN, 42.9kN and 48.8kN compared to 50kN, 41kN, 45kN, 45kN and 48kN recorded by the experimental tests. However, deflection values predicted by FEM were lower than the values yielded by the experimental tests. Despite these differences, they fell within an acceptable range, supporting the reliability of the FEM for further studies involving parameter adjustments. The agreement between experimental and numerical load-displacement results was satisfactory, as evidenced by the corresponding curves. The results achieved in ABAQUS were based on numerous theoretical considerations and iterative refinements aimed at ensuring accuracy and consistency between the experimental and numerical outcomes. Fig. 9 further illustrates the crack patterns of all the beams tested using ABAQUS.

4. CONCLUSIONS

This research investigated the flexural strength, cracking behaviour, and deflection of reinforced concrete beams embedded with PVC pipes. The effect of different opening sizes (50mm and 100mm), different placement positions (transverse and vertical) and different embedment zones on the structural behavior of reinforced concrete beams were investigated. Based on the experimental results obtained and numerical analysis made, the following conclusions are drawn:

1. Generally, embedding conduit pipes in RC beams causes a reduction in the load-carrying capacity of the beam. Reinforced concrete beams with embedded PVC pipes recorded 10.5% lower average ultimate failure load compared to the control beams.
2. The size of the embedded pipe or the size of opening affects the performance of the reinforced concrete beam. RC beams embedded with 50mm diameter pipes recorded 7.53% higher average ultimate failure load than reinforced concrete beams embedded with 100mm diameter pipes.
3. Inserting pipes transversely in beams produces a higher reduction in ultimate failure load. RC beams with transversely conduit pipes recorded average ultimate failure load of 43kN while the RC beams with pipes embedded vertically averaged 46.5kN ultimate failure load. This shows that reducing the depth of the beam significantly affects the flexural strength of the beam compared to reducing the beam's width.
4. Reinforced concrete beams embedded with PVC pipes were observed to have a lot of cracks than the control beams, especially at the openings due to stress concentration.
5. The mode of failure in RC beams with PVC pipes was significantly influenced by both the location and orientation of the pipes. RC beams with pipes inserted in shear zones primarily exhibited shear failure, while those with pipes at the midspan were more prone to flexural failure.
6. The embedment of PVC pipes within the beams negatively impacted deflections,

leading to a significant increase in the average mid-span deflection by 20.47%. This effect is primarily due to the considerable reduction of concrete in the critical regions of the beam section where the pipes were embedded.

7. The numerical values derived from Finite Element Method (FEM) demonstrated a satisfactory consistency with the experimental data concerning the load-bearing capacity and deflection of concrete beams embedded with service PVC pipes. The load-displacement curves, along with the modes of failure, exhibited notable similarities between the experimental and numerical components.

5. LIMITATIONS OF THE STUDY

The findings of this study indicate the conduit sizes and orientations have a significant effect on the structural behavior of RC beams. The two PVC pipe diameters that were used in this study were 50mm and 100mm. These two sizes represent a small range of pipe sizes that are frequently used in the construction industry. This study also focuses on transverse and vertical orientations. While these diameters and orientations may provide useful information, the results may not fully capture the behavior of beams with smaller or bigger PVC pipe diameters. Beams with pipe diameters and orientations other than the ones talked about in this study could behave differently in terms of flexural strength, deflection and crack patterns. However, the findings might help design codes by emphasizing how conduit orientation and location can affect the flexural strength, deflection and cracking behavior of RC beams.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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