

Research Article

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Experimental investigation of the effect of horizontal construction joints on the behavior of deep beams

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Abstract: Construction joints serve as interruption points in the concrete placement process, which is necessary because it is often not feasible to pour concrete continuously in many structures. The quantity of concrete that can be poured at a single instance depends on the batching and mixing capacity, as well as the strength of the formwork. An effective construction joint must ensure sufficient flexural and shear continuity across the junction. Many studies investigated the construction joints in the reinforced concrete (RC) normal beams, but there are no studies investigating the effect of construction joints on the behavior of the RC deep beams. This study was prepared to show the behavior of deep beams having horizontal construction joints (HCJs) extended through their entire length. The parameter studied in this research was the location of the HCJ within the beam height. Four simply supported RC deep beams were tested under a two-point static load up to failure. One of these beams was without a construction joint and was considered a reference beam. Each one of the other beams has only one horizontal construction. The location of these joints was below, at, or above the beam mid-height. The crack patterns, the strain distributions, the mode of failure, deflection, and failure load are discussed. It was found that the existence of construction joints below, at, or above the beam mid-height results in a decrease in load failure load by 9, 11, and 1% compared with the reference beam. It can be concluded that the best

location of the HCJ in the RC deep beam is in the upper part of the beam.

Keywords: construction joint, deep beam, horizontal construction joints

1 Introduction

1.1 Construction joints

The process of placing concrete in a continuous operation is impractical in many cases of construction. For this reason, the construction joints are needed to accommodate the construction sequence for concrete placement. There are some parameters, which govern the amount of concrete that can be placed at one time like batching and mixing capacity, casting crew size, and the amount of available time. Correctly located and properly performed construction joints provide limits for following concrete placements, without affecting the structure [1].

Ismail [2] cast ten reinforced concrete (RC) beams with rectangular cross-sections and tested them utilizing two-point loads up to failure in 2005. Eight of the beams were planned with varied numbers and placements of horizontal construction joints (HCJs), while the other two were constructed without them. All the tested beams had the same concrete characteristics and were designed to fail in flexure, in addition to having the same amount and kind of longitudinal and transverse reinforcing. The existence of HCJ in RC beams reduces the cracking and ultimate loads of the beam and increases its ultimate deflection, according to the results of this series of experiments; however, no appreciable change in the value of the beam deflection at the first crack is expected.

In 2008, Mehrath [3] experimentally studied the flexural behavior of RC beams that had a transverse construction joint (TCJ). The study was done by testing 23 simply supported RC beams with a rectangular section of

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150 mm $\times$ 250 mm and a span of 2 m under two-point loading. Three of these beams were cast monolithically and designated as reference beams, whereas each of the remaining 20 beams had one TCJ. The location of the TCJ (either mid-span or two-thirds of the span of the beam), the shape of the TCJ (vertical, 45° inclined, 60° inclined, joggle, or L-shaped), and the existence of an extra stirrup inside the TCJ are all addressed in this study. The optimal placement for the TCJ was determined to be in the mid-span, which reflects the location of the least shear and the highest bending moment.

In 2010, Abdul-Majeed [4] used the computer program (ANSYS v.9) to present a nonlinear three-dimensional finite element study to analyze seven beams, one of them without construction joints and the others having different shapes of TCJs at mid-span. For these beams, the construction joint types were vertical, inclined, joggle, and L-shaped construction joints. He also proposed a TCJ interface concept. According to the findings of this study: To model the joint's fragility and determine how stresses will flow through the joint, interface components must be used to connect the concrete brick elements at the construction joint's site. The beams with joggle joints had a higher load-carrying capacity due to improved interlocking between the old and new concrete, whereas the 45° inclined shape connection had the lowest load-carrying capacity due to joint failure. The addition of one more stirrup across the vertical joint improves the jointed beam's performance, reinforces the joint, and prevents crack propagation. The strength, ductility, and mode of failure of jointed- RC beams were all impacted by the shape of the TCJ.

In 2010, Abdul-Majeed *et al.* [5] investigated the behavior of RC beams that have HCJ by using a nonlinear three-dimensional finite element computer program ANSYS (v.11). The analysis included four beams, the first one is without construction joints and the others having one, two, and three HCJ at equal heights of the beam. The results of the finite element analysis are in excellent agreement with the results of the prior experimental test. For all types of tested beams, the highest variances in ultimate loads were around (8.2–10.4%). The inclusion of one, two, and three HCJ in RC beams under flexure resulted in a reduction in the cracking load and the ultimate load, in which the cracking load becomes 97, 85, and 80% of the reference beam and the ultimate load capacity was 96, 89, and 84%, respectively, in comparison to the reference beam.

In 2012, Abass [6] studied the effect of construction joint placement on the behavior of RC structural elements in addition to the effect of construction joint type (vertical, inclined, and key construction joint) and the addition of stirrups at these joints. The lab is put 19 beams to

the test. 19 beam specimens with a total dimension of 200 $\times$ 200 $\times$ 950 mm were examined. Experimental equipment included a 1,000 kN computer-controlled multifunction electronic testing machine. At each load stage, deflection at the center and/or the site of the construction joint could be determined by placing the specimens in the machine. The experimental program determined that the construction connection should be located at the place where there is the least amount of shear force. A study on the beam specimens indicated that using vertical construction joints had little impact on their overall behavior (the reduction percentage of ultimate load capacity is about 5%) when compared to beams without construction joints. Inclined joints showed a significant reduction in beam strength, this reduction in the ultimate load capacity is normally between 8 and 20%. The failure type and load-carrying capacity are strongly influenced by the addition of stirrups at construction joints. The installation of stirrups across the joint increased the capacity by 7–15% and reduced deflection by 7–15%. The percentage range of deflection decrease is between 20 and 48%.

In 2014, Issa *et al.* [7] studied the relationship between concrete compressive strength and modulus of rupture for plain concrete beams having a vertical construction joint at their center. Seven various concrete mix designs were used. Each concrete mix was poured into six plain concrete beams, half of them monolithic and the other half with a vertical construction joint at the center of the beam. The findings show that when compared to a monolithic piece, there was a reduction in overall flexural strength by about 55% in the case of the existence of the construction joint. The modulus of rupture for construction joints can be computed as follows: $f_r = 0.28(f_c')$. The PCA suggestion of adding a 13 mm diameter bar at a spacing of 750 mm has been validated for the specifications of the plain concrete beam tested.

Gerges *et al.* [8] made a comparison between a single reinforced beam with a construction joint at the beam mid-span and a single reinforced monolithic beam by calculating the difference in bending capacity. Various concrete compressive strengths were used. Seven different groups with a total of 42 beams were cast. Half of the beams have a vertical construction joint in the middle, while the other half of the beams were monolithic. Each group has a modified concrete compressive strength (f_c') and nominal bending capacity (M_n). It has been shown that by increasing the concrete's compressive strength, the influence of construction worsens, resulting in less bending strength for the elements of the structure. A graphical method to determine the loss in the bending moment in the case of the existence of the construction joint induced is shown in Figure 1.

Jabir and Salman [9] investigated experimentally in 2017 the effect of the location and design of joints on the performance of seven $200 \times 100 \times 1,000$ mm beam specimens. They found a reduction in strength between 5.0 and 7.5% in beams having a HCJ in the tension zone. They concluded that the compression zone is the best location for HCJ, and they found no effective difference in the strength for beams with inclined construction joints.

Abbas et al. [10] studied the behavior of RC beams containing longitudinal construction joints by testing four beams. The dimensions of these beams were 280 mm in height and 18 mm in width with a total span of 1,000 mm. These joints were located at different heights within the beam, specifically at 7, 14, and 21 cm measured from the bottom of the beam. The construction joint was created by pouring the concrete at the bottom layer, allowing it to cure for 30 days, and then pouring at the top layer. The researchers carried out a test program, which involved casting four beam specimens with a compressive strength of 27.5 MPa. One specimen was cast as a single, continuous unit, while the other three specimens were cast with an HCJ along the beam. The findings of the study revealed a reduction in the ultimate load, first crack load, and stiffness of the beams with construction joints compared to the monolithic beam. The extent of this reduction depended primarily on the level of the construction joint. Specifically, at the 7 cm level, the ultimate load, first crack load, and stiffness decreased by approximately 15.4, 14.7, and 28.7%, respectively compared to the monolithic beam. On the other hand, at the 21 cm level, the decrease in the ultimate load, first crack load, and stiffness amounted to around

26.2, 22.9, and 66.5%, respectively, when compared to the monolithic beam.

Al-Mamoori and Al-Mamoori [11] presented a study to investigate the effect of the hot weather in the summer in Iraq on the behavior of high strength concrete beams having cold joints. To increase the setting time, sugar waste (called sugar molasses; SM) was used as a delayed agent. A total of 24 plain concrete beams, each measuring $110 \times 110 \times 650$ mm, were tested under a two-point load. Half of these beams were cast without any roughening (smooth surface) on the existing layer, while the other half were cast after the existing layer was roughened. The study found that the optimal SM dosage was 0.2% of the weight of the cement, resulting in an approximately 11.2% increase in compressive strength at 28 days. Additionally, it delayed the initial setting time by about 4.617 h (277 min). There were no observed adverse effects on the concrete at this SM concentration for the various concrete cylinder ages studied. The failure load for beams with smooth and rough vertical joints, with SM, ranged between 1.95–2.12 times and 1.46–1.37 times that of beams without SM, respectively.

Ismael et al. [12] investigated experimentally the performance of reinforced self-compacting concrete slender beams that have construction joints. Four beams with dimensions of $125 \times 150 \times 1,000$ mm were tested. One without a construction joint was cast as a reference specimen, the second beam was of HCJ at mid-depth of the beam, and the other two beams had a vertical construction joint, the first at mid-span (maximum bending moment point) and the other at fourth-span (maximum shear region).

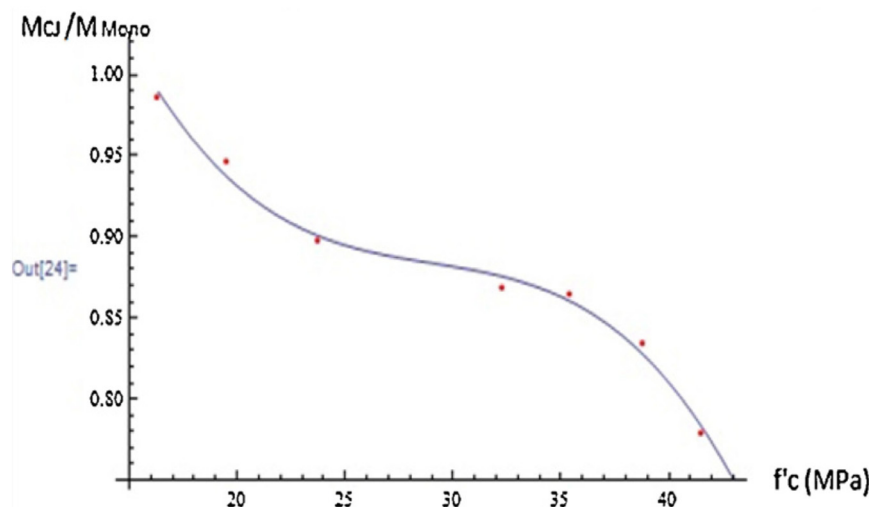


Figure 1: M_{CJ}/M_{Mono} vs f'_c chart [8].

The test results showed that the effect of the construction joint was more significant on the ultimate load than on the first crack load. The better structural performance in that study was for the beam of the HCJ compared with the other cases of the construction joint, in which the decrease in the first crack load and the ultimate load was 6.7 and 26.7%, respectively, as compared with the reference beam. The presence of construction joint made the load deflection less stiff, especially beyond the first crack load.

Mathew and Nazeer [13] studied the effect of construction joints (CJs) on the flexural behavior of reinforced cement concrete (RCC) beams. Two variables investigated in the flexural study were the position and grade of concrete. Concrete grades M20, M40, and M60 were designed and prepared for casting beams. Three RCC beams were cast from each mix with a joint at different locations. The first one is without a CJ, and the second one is with a joint up to one-third of the beam span and leaves the concrete to take the natural slope. The third one was with a joint up to the middle of the beam span and also the concrete left to take a natural slope. From this study, it can be seen that the effect of CJ is very small about 3% decreasing in ultimate load at concrete grade 20. The decrease became between 8 and 11% at concrete grades M40 and M60, respectively. The study concluded that load carrying capacity of beams with joints starting from one-third beam span (type B2) was slightly higher for M20 and M40 grades compared to beams with joints extending from mid-point to outer third span (type B3).

Al-Rifaie *et al.* [14], in 2021, investigated ten rectangular cross-sectioned simply supported RC beams that were tested under a two-point load. Eight of the beams had variations in the number and locations of HCJs, while the remaining beams had no CJs and were considered reference beams for comparison. All tested beams have the same shape, longitudinal and transverse reinforcement, and concrete characteristics, as well as they have been designed to fail in flexure. The existence of HCJs in RC beams produce a decrease in ultimate loads between 2 and 17% and an increase in measured deflection between 2 and 33% compared to the reference beam.

All these studies and others have been focused on the effect of CJs on RC normal beams. Many cases studied include concrete properties (normal strength, high strength, and self-compacted), different members (beams, slabs in addition to prisms, cubes, and cylinders), different shapes of CJs, and more. However, there is no study on the effect of CJs on RC deep beams. The current study investigated the behavior of RC deep beams with the existence of HCJs. The investigation included the crack patterns, the strain distribution in concrete and steel, the failure load, and the failure mode.

2 Deep beam

A deep beam is defined as a beam in which either the clear span is equal to or less than four times the overall depth, or the concentrated loads are within a distance equal to or less than two times the depth from the face of support [15]. These members are used in many structural applications such as diaphragms, water tanks, foundations, bunkers, offshore structures, shear walls, and girders used in multi-story buildings to provide offsets of columns, and floor slabs subjected to horizontal loads [16,17]. Many researchers investigated experimentally and theoretically the behavior of deep beams under the effect of variable factors like horizontal and vertical reinforcement, the existence of openings, and strengthening with prestressing. The current study deals with deep beams that have an HCJ. The deep beams were designed according to ACI 318M-2019 code [15] using the strut-and-tie model (STM).

2.1 STM

An STM is a statically determinate truss that represents the internal forces within discontinuity regions to simplify the complex design problem producing a safe solution that satisfies statics. Stress flow in a structural member is idealized as an axial element in a truss member in an STM. Concrete struts resist compressive stress fields while reinforcing steel ties resist tensile stress fields. Struts and ties meet at regions called nodes. An STM is composed of three primary elements: struts, ties, and nodes. To withstand the applied forces, all components must be proportioned. Based on the lower bound theory of plasticity, the capacity of an STM is always lower than the structure's actual capacity provided the truss is in equilibrium and safe. A safe STM needs to be able to redistribute forces evenly into the assumed truss elements and not exceed the strength of those elements or their plastic flow capacity. STM failure can result from crushing of the struts, crushing of concrete at a node, yielding of the ties, or anchorage failure.

Figure 2 shows an example of a beam being supported by a determinate truss shown in Figure 3. Figure 4 illustrates the same truss model with concrete struts, nodes, and reinforcement drawn to scale. Figure 4 shows the idea of a lower-bound solution by removing portions of the beam not included in the beam model. In this example, the applied force is assessed from a fraction of the original beam. The estimated strength of the STM will be less or equal to the beam's actual strength when the laws of statics are obeyed and the materials do not exceed their yield capacities.

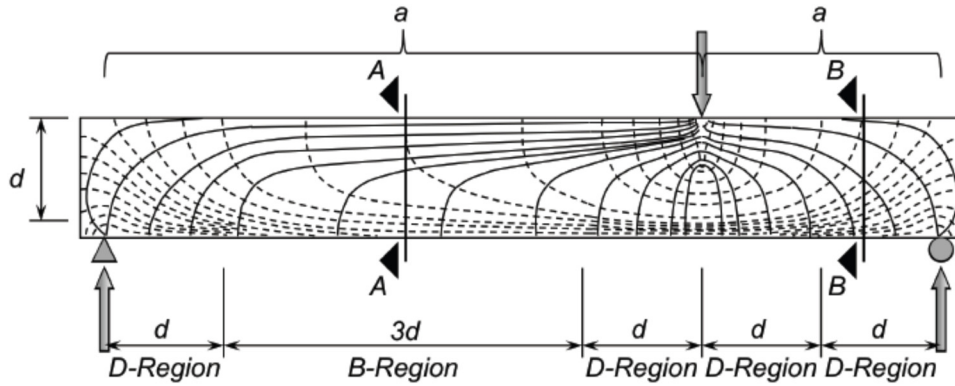


Figure 2: Stress trajectories in B-regions and near discontinuities (D-regions) [18].

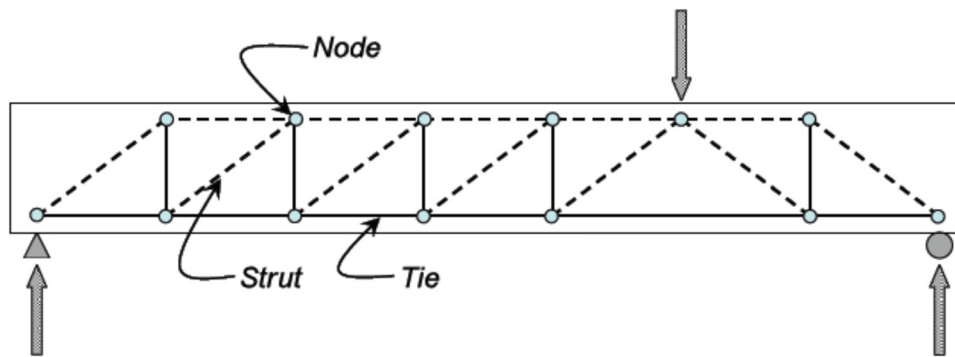


Figure 3: STM: Simply supported beam supporting concentrated load [18].

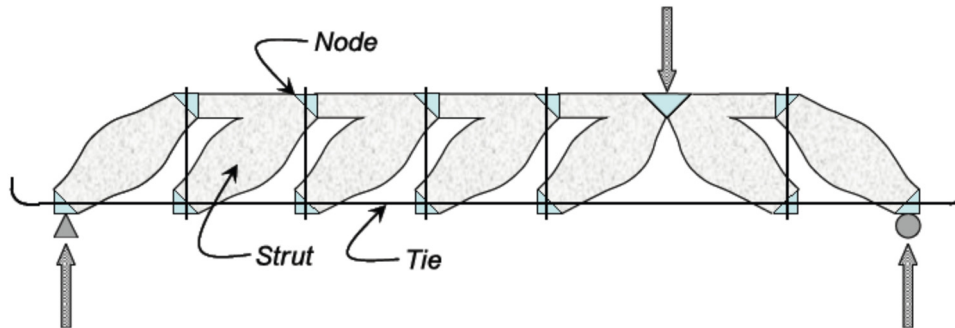


Figure 4: STM with truss elements drawn to scale [18].

2.2 Experimental work

One of the parameters investigated in the previous studies was the type of the CJ. Many types were studied like horizontal, vertical, inclined at certain angles, and key beside the inclined with natural slope. In the present experimental work, the HCJ type was studied. To investigate its effect on the behavior of deep beams, four simply supported deep beams were cast and tested under two-point loading. The overall dimensions of them were 1,500 mm

span $\times$ 400 mm deep $\times$ 150 mm width. The dimensions were chosen according to the definition of the deep beam in the ACI 318M-19 code [15]. They all were reinforced with 3 ϕ 12 mm rebars as main reinforcement, 2 ϕ 8 mm rebars as horizontal reinforcement at 65 mm spacing, and ϕ 8 mm stirrups spaced at 70 mm. The details of the beam dimension and reinforcement are shown in Figure 5. The mechanical properties of bar reinforcement (the yield tensile strength, and ultimate tensile strength of steel bars and elongation) were evaluated according to ASTM A370-2020 [19] and listed in Table 1.

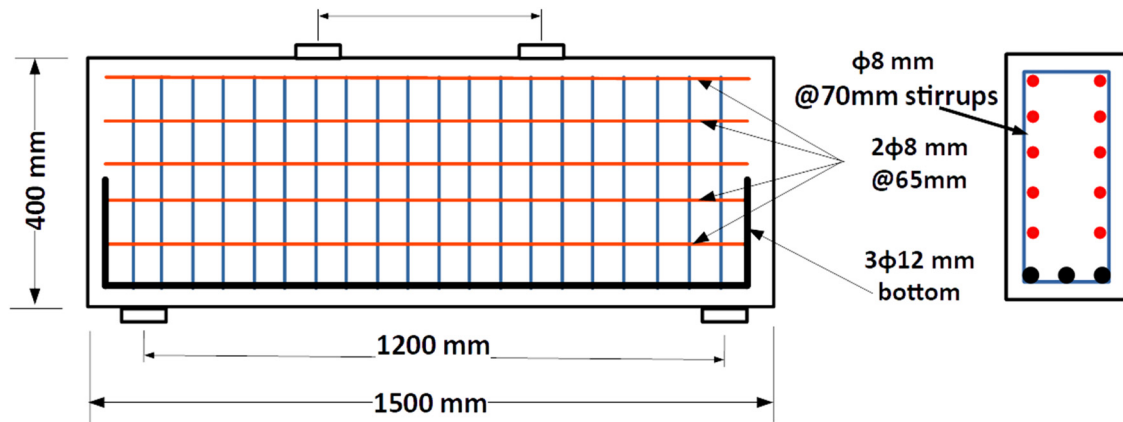


Figure 5: Schematic diagram of beam dimension and reinforcement details.

Table 1: Mechanical properties of steel bars

Nominal diameter, (mm)	f_y (MPa)	f_u (MPa)	Elongation, (%)
φ12	571	701	18.2
φ8	452	550	22.8

2.3 Preparing the samples

The concrete mixture (cement, sand, gravel, and water) was prepared and mixed. The used cement was Al-Jesr High Sulphate Resistant Portland cement produced by Lafarge Iraq. This cement was manufactured according to European standard EN 197-1:2011 [20], and it complies with Iraqi standard IQ.s 5/1984 type V [21]. The used coarse aggregate was crushed gravel as shown in Figure 6. Its grading and physical properties are shown in Table 2. The sieve analysis and other properties



Figure 6: Coarse aggregates.

Table 2: Physical and grading test results of coarse aggregates

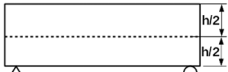
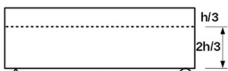
Type of test	Sieve size (mm)	Percentage of passing materials	IQS 45:1984 specification limits for size (5–20)
Grading	37.5	100	100
	20	100	95–100
	10	51	30–60
	5	9	0–10
Deleterious and fine substances	Finer than 0.075 mm (%)	1%	3%
	SO ₃ content (%)	0.095	0.1%

Table 3: Sieve analysis and properties of fine aggregates

Type of test	Sieve size (mm)	Percentage of passing materials	IQS 45:1984 specification limits for Zone II grading
Grading	10	100	100
	4.75	97	90–100
	2.36	85	75–100
	1.18	71	55–90
	0.6	54	35–59
	0.3	21	8–30
	0.15	6	0–10
	Finer than 0.075 mm (%)	3.1%	5%
Deleterious and fine substances	SO ₃ content (%)	0.310	0.5%

of the fine aggregate (sand) were carried out by the specification of IQS No. 45/84 [22] and the results are shown in Table 3. The concrete ingredients (cement:sand:gravel) were mixed in

Table 4: Deep beam details

Beam name	Location of CJ from the bottom of the beam	Beam shape
R	—	
B1	$1/3 h$	
B2	$1/2 h$	
B3	$2/3 h$	

proportions 1:1.92:2.4 by weight with a water/cement ratio of 0.48. The design mix gave a compressive strength of about 23 MPa at the age of 28 days. Plastic spacers were placed before the reinforcement cages in the molds to provide the concrete cover. The first portion of concrete was poured to the required depth of the joint and then vibrated. After 24 h, fresh concrete from a new mixture with the same properties and proportions was placed on top of the old hardened concrete and vibrated. No attempt was made to improve the CJ. Twelve standard test cubes of dimension 150 mm were cast at the same time with the beam samples to determine the compressive strength of the concrete. Six of them were cast with the first layer of beam and the rest with the second layer. The details of the tested beam are shown in Table 4. The cast cubes and beams are shown in Figure 7.

A wet hessian was used to cover the concrete for 28 days for curing. Then, the concrete surfaces were cleaned and prepared to install the strain gauges. The face of the concrete that was poured in the second stage was coated with white emulsion. A 100×100 mm grid of light black lines was drawn to facilitate the observation of the appearance and spread of the cracks.

2.4 Measurement devices

To monitor the concrete strain, six 60 mm base length strain gauges of type PL-60-11-3LJC-F were placed on the surface of the deep beam specimens. Four of these gauges (named G1–G4) were installed at mid-span so that their axes coincide with the beam axis. The other two gauges (D1 and D2) were placed at a height of $H/2$ in the left and

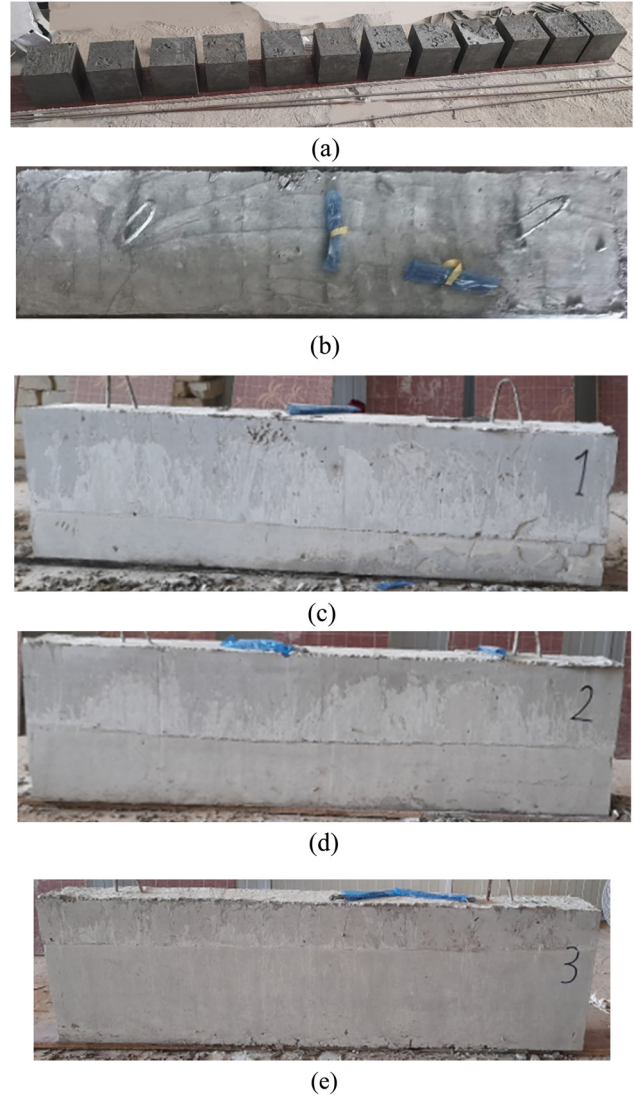


Figure 7: The cast cubes and deep beam samples. (a) Cubes. (b) Reference beam. (c) Beam B1. (d) Beam B2. (e) Beam B3.

right mid-shear spans as shown in Figure 8. In addition, two 5 mm base length strain gauges of type FLAB-5-11-3LJC-F were used to measure the strain in steel reinforcement. One of these gauges (S1) was installed on the main reinforcement at the midspan section, and the other one (S2) was installed at the mid-height of the transverse reinforcement (stirrups) positioned in the middle shear span to measure the shear strain. The locations of the strain gauges in the reinforcement are shown in Figure 9. The vertical displacement (i.e., deflection) was measured at the midspan of the deep beam using Linear variable differential transformer (LVDT) transducers.



Figure 8: Location and names of strain gauges on concrete surface.

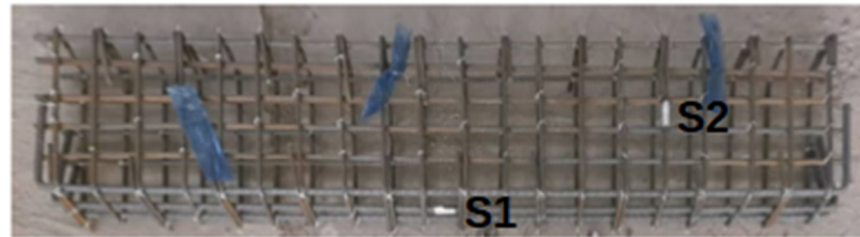


Figure 9: Location and names of strain gauges on steel reinforcement.

2.5 Test setup

To test the deep beam specimens, a load control testing system of 1,000 kN capacity was designed and constructed. The deep beams were tested by subjection to monotonic static loading up to failure. The testing system and test setup for the beams are shown in Figure 10. Tests were conducted on these beams as simply supported beams, where one support allowed horizontal movement as well as rotation, and the second support allowed only rotation.

A rigid steel frame system was employed to carry out the test. The specimens were tested under two-point loading. The load was applied by using a mechanical hydraulic jack. The applied load was divided into two loads by using a spreading steel beam to create a pure bending moment region of 400 mm. The applied load was measured using a load cell connected to the data acquisition system consisting of two 8-channel GEODATA8 connected with the strain gauges, LVDTs, load cell, and PC as shown in Figure 11.

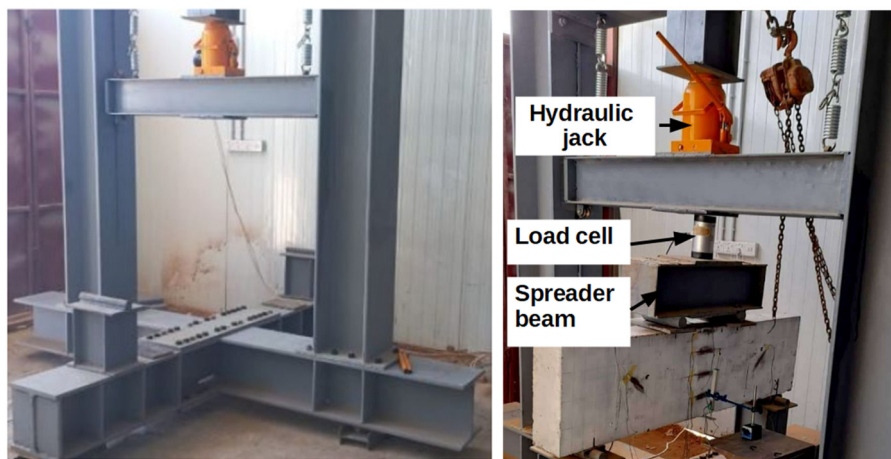


Figure 10: Testing frame with load application device and test setup.

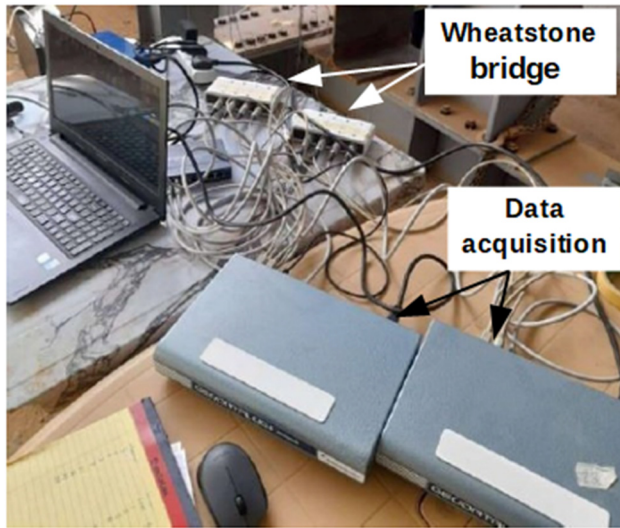


Figure 11: Data acquisition system.

3 Results and discussion

The results discussed in this study are the loads corresponding to the first flexural crack, the formation of the first diagonal crack, modes of failure of each specimen, the differences of ultimate load, and deflection compared with the reference beam, and the strains in the main bottom reinforcement, in addition to the surface strains in concrete along the beam height at mid-span.

3.1 Cracking pattern and failure modes

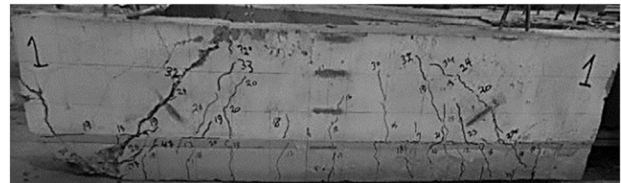
From the experimental work, it has been noticed that the first crack in the tested beams appeared under load ranges from 80 to 120 kN. The first flexural and shear cracks appeared at the same stage of loading for each beam. All tested beams failed in shear. The least failure load was measured in the case of the existence of a CJ at the beam mid-height. It speeds the propagation of cracks towards the upper part of the beam, becoming a source for branching them, making them more intensive, and decreasing the ultimate load. The best location according to the current study is above the beam mid-height, which is far from the area of the start of cracks and has no effect on the first and ultimate cracks. The first flexural and shear cracks and the ultimate load for each one of the tested beams are listed in Table 5.

Table 5: First crack and ultimate loads

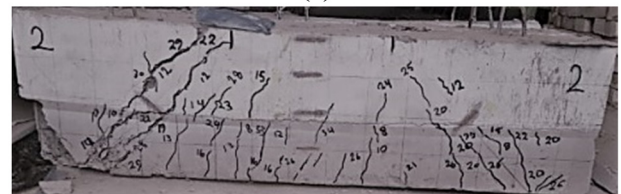
Specimen no.	First flexural crack load (kN)	First shear crack load (kN)	Ultimate load (kN)
R	100	100	395
B1	120	120	360
B2	80	80	350
B3	110	120	390



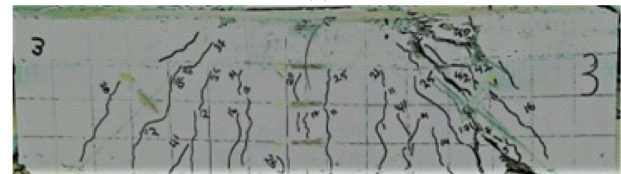
(a)



(b)



(c)



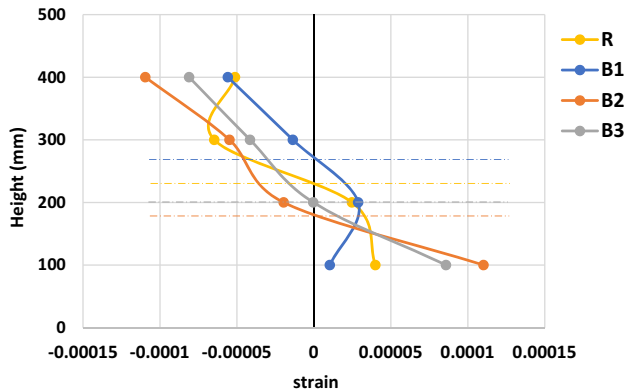
(d)

Figure 12: Crack patterns. (a) Beam R. (b) Beam B1. (c) Beam B2. (d) Beam B3.

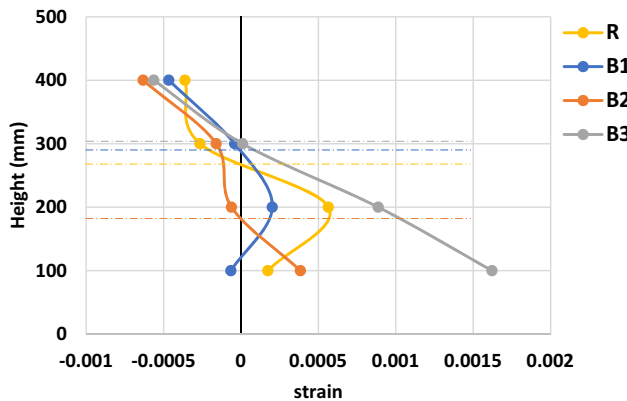
The final crack patterns and development of all cracks are given in Figure 12.

3.2 Strains along beam height

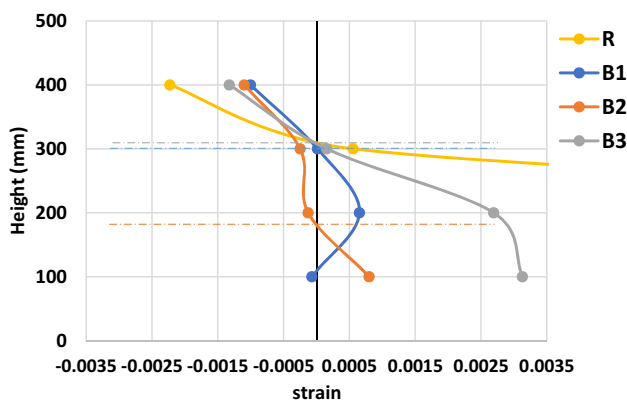
Figure 13 shows typical strain distribution profiles for the deep beam specimens. These profiles are drawn at loads



(a)



(b)



(c)

Figure 13: Strains along beam height at mid-span. (a) At load = 40 kN. (b) At load = 150 kN. (c) At load = 350 kN.

equal to 40, 150, and 350 kN for critical sections at mid-span. The strain distribution is nonlinear. The strains of the mid-span section increase as the load increases, but for beams B#1 and B#2, the strains in the tension zone did not give real indication due to cracks and the flexibility of this area. Figure 14 shows the strains computed at the main reinforcement by strain gauge S1 and at the lower strain gauge G4 on the mid-span face of concrete, (locations of strain gauges S1, and G4 are shown previously in Figure 8). It can be seen that there is a similar behavior between them. Thus, the steel strain at the tension zone is governed and can be used to estimate the concrete strain at the bottom. The neutral axis has a changeable depth till the failure. The upward movement of the neutral axis is associated with the cracking progress under increasing load.

3.3 Failure load

In the current study, the existence of an HCJ leads to a decrease in the failure load when compared with the reference beam. Depending on the location of the CJ, the decrease in failure load was 9, 11, and 1% when it was below, at, or above the mid-depth of the beam, respectively. It can be noticed that the existence of an HCJ above the beam mid-height could be considered to not affect the ultimate load, which coincides with the previous conclusion for normal beams [23]. Because there are no studies on the CJ in the deep beam, the current results are compared with the available data on the normal beams. Previous studies [2,9,10,14] showed that the existence of CJs below a mid-depth of the beam led to a decrease in the failure load ranges between 5 and 11%. This percentage was 2–5% when the location of the CJ was at mid-height. While the percentage ranges between 0 and 26% when it is located above mid-height. The percentages of the decrease in the failure load for the current study and the previous studies are listed in Table 6 and Figure 15.

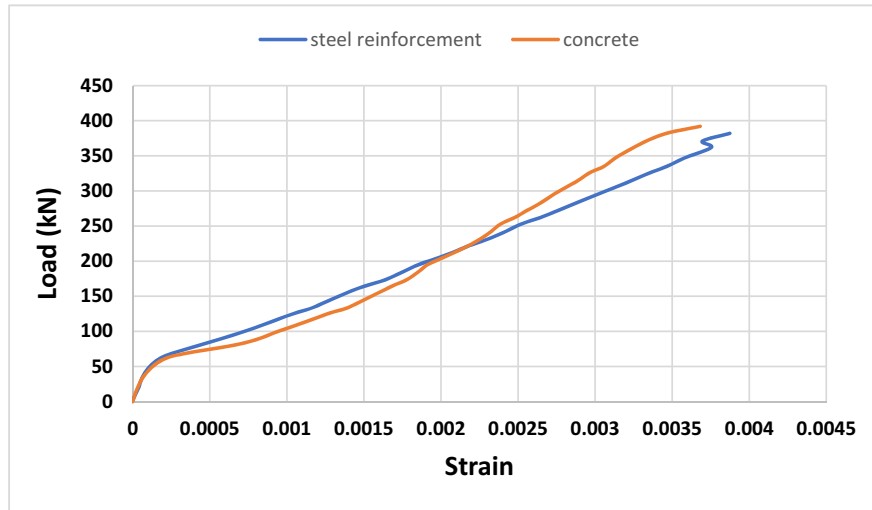


Figure 14: Strains in steel and concrete for beam B3.

Table 6: Decreasing in failure load

Researcher	Beam type		
	CJ below mid-depth	CJ at mid-depth	CJ above mid-depth
Current study	9%	11%	1%
Al-Rifaie [14]	11%	3%	4%
Abbas et al. [10]	15%	2%	26%
Ismail [2]	—	5%	—
Jabir et al. [9]	5%	—	0%

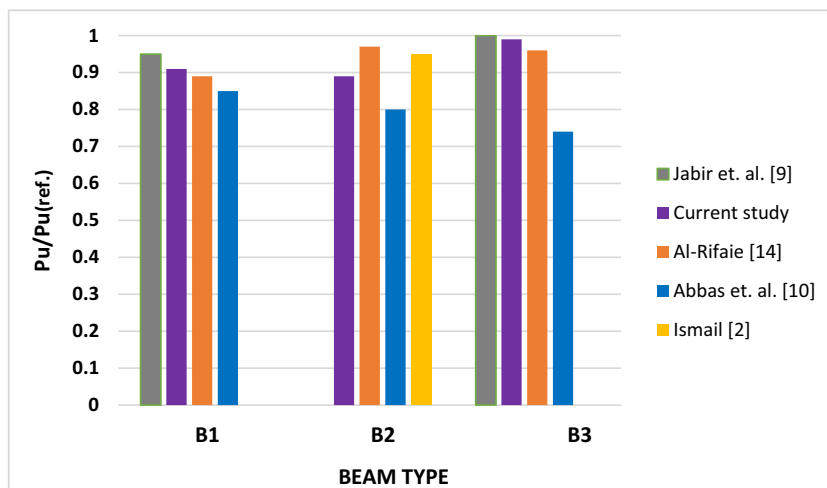


Figure 15: Effect of CJ on failure load.

3.4 Deflection

The existence of an HCJ in the deep beam led to a change in the measured deflection. These changes range from a decrease in the deep beam having a CJ at or below the mid-depth of the beam, to an increase in the deep beam having a CJ above the beam mid-depth. The percentage of the change is shown in Table 7. A comparison with the available data on normal beams is done and shown in Figure 16. The current percentages were close to most of these results.

Table 7: Change in deflection at mid-span

Researcher	Beam type		
	CJ below mid-depth	CJ at mid-depth	CJ above mid-depth
Current study	14%	15%	−15%
Al-Rifaie [14]	14%	8%	2%
Abbas et al. [10]	18%	77%	120%
Ismail [2]		7%	
Jabir et al. [9]	−29%	—	−6%

beam, the strains developed in steel bars faster in the early stages than the beams that had a CJ. With the increase in the applied load, the strains in the steel bars in all beams showed similar behavior. At the end, the reference beam and beam B2 reached the yielding stage before the other beams.

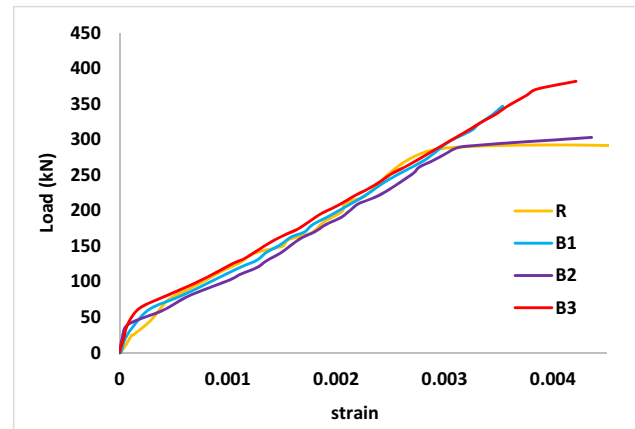


Figure 17: Strains in main reinforcement.

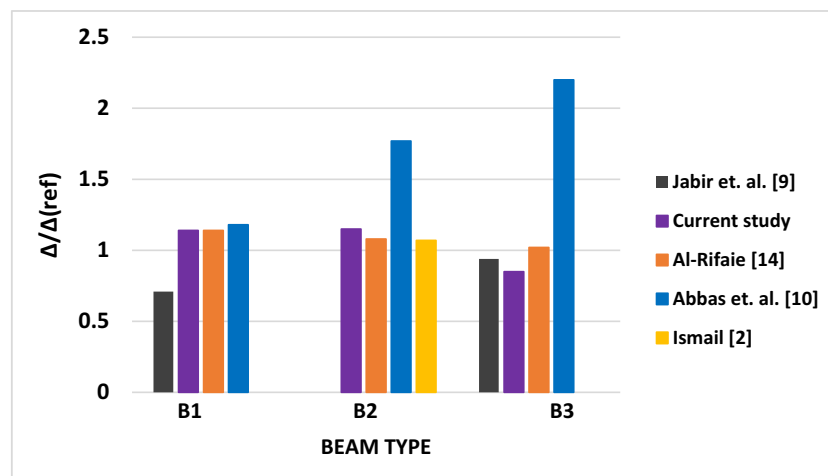


Figure 16: Effect of CJ on the measured deflection.

3.5 Strains in main steel

Figure 17 represents the load–strain relationship for the longitudinal steel bar for the four beams. A very slight difference in the behavior is observed. In the reference

4 Conclusion

The current work studied the effect of HCJs on the behavior of deep beams. The effect on the ultimate load, deflection, first crack load, and strain distribution were studied. Based

on the current experimental results, the following conclusion can be derived:

- The existence of HCJ below, at, or above the beam mid-height decreases the ultimate load by 9, 11, and 1%, respectively.
- The existence of HCJ below or at the beam mid-height increases the maximum measured deflection by 14 and 15%, respectively.
- The existence of HCJ above the beam mid-height decreases the maximum measured deflection by 15%.
- The existence of the HCJ in the mid-height of the deep beam led to a decrease in the first cracks by 0.25 compared with the appearance of the first crack in the reference beam. The existence of HCJ above or below the beam mid-height does not affect the appearance of the first crack.

For future work, more factors may be studied like the effect of increasing concrete strength, adding bonding agents, strengthening using different methods [24–26], the performance of the numerical model to represent the CJ in deep beams using different methods like EFE, ANSYS, ABAQUS, etc. [27,28], and studying the effect of other types of CJs.

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References

- [1] Halvorsen GT, Poston RW, Barlow P, Fowler DW, Palmbaum HM, Barth FG, et al. Joints in concrete Econstruction. vol. 224, USA: American Concrete Institute, ACI; 1995.
- [2] Ismail AK. Flexural behavior of reinforced concrete beams having horizontal construction joints. M.Sc. thesis. University of Technology, Baghdad, Iraq; 2005.
- [3] Mehrath HJ. Flexural behavior of reinforced concrete beams having transverse construction joints. M.Sc. thesis. University of Technology, Baghdad, Iraq; 2008.
- [4] Abdul-Majeed Q. Evaluation of transverse construction joints of reinforced concrete beams. *Eng Technol J*. 2010 Jul;28(14):4750–73.
- [5] Abdul-Majeed Q, Ghaleb LA, Ghaddar MG. Effect of the number of horizontal construction joints in reinforced concrete beams. *Eng Technol J*. 2010;28(19):5803–21.
- [6] Abass ZW. Effect of construction joints on performance of reinforced concrete beams. *Al-Khwarizmi Eng J*. 2012 Feb;8(1): 48–64.
- [7] Issa CA, Gerges NN, Fawaz S. The effect of concrete vertical construction joints on the modulus of rupture. *Case Stud Constr Mater*. 2014 Jan;1:25–32.
- [8] Gerges NN, Issa CA, Fawaz S. The effect of construction joints on the flexural bending capacity of singly reinforced beams. *Case Stud Constr Mater*. 2016 Dec;5:112–23.
- [9] Jabir HA, Salman TS. Effect of construction joints on the behavior of reinforced concrete beams. *J Eng*. 2017 Ap;23(5):47–60.
- [10] Abbas AN, Al-Naely HK, Abdulzahra HH, Al-Khafaji ZS. Structural behavior of reinforced concrete beams having construction joint at different elevation. *Int J Civ Eng Technol*. 2018;9:712–20.
- [11] Al-Mamoori FH, Al-Mamoori AH. Reduce the influence of horizontal and vertical cold joints on the behavior of high strength concrete beam casting in hot weather by using sugar molasses. *Int J Eng Technol*. 2018;7:794.
- [12] Ismael MA, Hameed YM, Abd HJ. Effect of construction joint on structural performance of reinforced self-compacting concrete beams. *Int J Civ Eng*. 2019;10(1):297–306.
- [13] Mathew AA, Nazeer M. Flexural behavior of reinforced concrete beams with construction joints. *IRJET*. 2020 June;7(6):3789–96.
- [14] Al-Rifaie A, Al-Hassani H, Shubbar AA. Flexural behaviour of reinforced concrete beams with horizontal construction joints. In *IOP Conference Series: Materials Science and Engineering*. Vol. 1090. Issue. 1. IOP Publishing; 2021 Mar. p. 012003.
- [15] ACI Committee. Building code requirements for structural concrete: (ACI 318-19) and commentary (ACI 318R-19). American Concrete Institute. 2019.
- [16] Darwin D, Dolan CW, Nilson AH. Design of concrete structures. New York, NY, USA: McGraw-Hill Education; 2016.
- [17] Russo G, Venir R, Pauletta M. Reinforced concrete deep beams-shear strength model and design formula. *ACI Struct J*. 2005 May;102(3):429.
- [18] Tuchscherer RG. Strut-and-tie modeling of reinforced concrete deep beams: Experiments and design provisions. Dissertation. The University of Texas at Austin; 2008.
- [19] ASTM A370-20. Standard test methods and definitions for mechanical testing of steel products. 2020.
- [20] EN BS. 197-1. Cement-Part 1: Composition, specifications and conformity criteria for common cements. London: European Committee for Standardisation; 2011.
- [21] Iraqi Specifications No. (5), 1984 for Portland Cement, Baghdad. 1984.
- [22] IQS NO. 45, 1984. Aggregate from natural sources for concrete and construction. Central Agency for Standardization and Quality Control, Baghdad, IQS, 45; 1984.
- [23] Kadhum SB, Al-Zaidee SR. A review of previous studies on the construction joints in reinforced concrete beams. *Des Eng*. 2021 Nov(8);16472.
- [24] Abbas HQ, Al-Zuhairi AH. Flexural Strengthening of prestressed girders with partially damaged strands using enhancement of carbon fiber laminates by end sheet anchorages. *Eng Technol Appl Sci Res*. 2022 Aug12(4):8884–90.
- [25] Daraj AJ, Al-Zuhairi AH. The combined strengthening effect of CFRP wrapping and NSM CFRP laminates on the flexural

- behavior of post-tensioning concrete girders subjected to partially strand damage. *Eng Technol Appl Sci Res.* 2022 Aug;12(4):8856–63.
- [26] Azeez AA, Jaafar AA, Yussof MM, Blash AA. Study of the behavior of reactive powder concrete RC deep beams by strengthening shear using near-surface mounted CFRP bars. *Open Eng.* 2023 Jun;13(1):20220433.
- [27] Abbas E, Al-Zuhairi AH. Non-smooth behavior of reinforced concrete beam using extended finite element method. *Civ Eng J.* 2019 Oct;5(10):2247–59.
- [28] Jaafar AA, Yussof MM, Azeez AA, Mezher TM, Ali Blash AA. The nonlinear analysis of reactive powder concrete effectiveness in shear for reinforced concrete deep beams. *Open Eng.* 2023 Jun;13(1):20220412.