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Effect of development reinforcement strut in concrete deep beam

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Abstract. The effect of the development of reinforcement strut on the performance of discontinuity regions in concrete deep beams was tested through an experimental program. Four reinforced concrete deep beams with two different designs reinforcement (conventionally reinforcement and strut reinforcement) and with various amounts of web reinforcement tested to select the optimum design of deep beams. The geometry and main reinforcement were constant for all specimens. Measurements of cracking patterns, recording the strain in the axis and edges of the struts by (DIC) technique, and analyses of load-displacement at mid-span of investigated concrete deep beams. The data results indicated that the capacity of the deep beam with reinforcement strut higher than the control deep beam with traditional reinforcement and with less displacement. A control deep beam was failed by diagonal tension stresses in the struts, not present in the reinforcement strut specimens. Where the compression stresses were found in the axis of the strut.

Keywords: Deep beam, Strut and tie model, Reinforcement strut, strain, DIC

1. Introduction
The deep beam has a comparatively small clear span-to-depth ratio; therefore, the shear strength becomes controlled rather than the flexural strength. A deep beam has got great attention in structural engineering studies. As a result, the high resistance capacity of the deep beam was used as load distribution members such as transfer members in high-rise structures as well as used in the foundation wall, pile caps, tanks, offshore structures, and transfer girders, often receiving many few loads and conveying them to a small number of reaction points. The American Concrete Institute ACI 318-14 code [1] defines deep beams that are “Structural Members loaded on one face and supported on the opposite face such that struts-like compression elements can develop between the loads and the supports and that satisfy (a) or (b): a) Clear-span does not exceed four times the overall member depth b) Concentrated loads exist within a distance of 2h from the face of the support. “Plane sectional theory (Bernoulli theory) is not appropriate for the design of a deep beam, in which the plane section does not remain plane after bending even under the elastic theory; therefore, a deep beam considered distributed (discontinuity) region in the stress distributed is called the (D-region). The region when the “Bernoulli” theory (plane section remaining plan after bending) applied this region is called the (B-region). The (D-region) cannot be designed by using B-region designs, they need to be designed using a strut tie model (STM) which, is a unified method design used for both D- and B-regions. The stress paths result in truss members loaded with uniaxial stresses. Truss members in compression are termed struts, while the force paths in tension are defined ties. The intersections of the struts and ties are at the nodes. The first investigations
development of deep beams started in the early sixties of the last century on elastic behaviour; certain elastic studies can simply be directed nowadays. The main disadvantage of elastic studies is the usual hypothesis of isotropic materials subject to Hook’s law. Subsequently, they do not give sufficient guidance for practical design [2]. Tan [3] studied the effect of web reinforcement and the ultimate shear strength of 18 deep beams with high-strength compressive concrete between 55 to 86 MPa. The tested deep beams were divided into three groups according to the ratio of shear span to total height a/h. Six deep beams in each group with various arranged for horizontal and vertical distributed reinforcement. Instruments and testing procedures included measurement of the middle-span deflection, crack widths, failure modes, and ultimate shear strength. The data proved that the vertical distributed reinforcement is more useful than the horizontal distributed reinforcement for deep flexible elements with a/h greater than 1.00, or a shear span to effective depth ratio a/d ≥ 1.13. It is also revealed that the orthogonal distributed reinforcement, which includes vertical and horizontal reinforcements, is most effective to increase the stiffness of the deep beam, limiting the development of the width of the diagonal cracks and improving the ultimate strength. Three failure modes are known in this investigation, Crushing of strut failure, diagonal-splitting failure, and shear-compression failure. Hwang [4] proposed a new strategy for the prediction of shear strength in deep beams by using a softened strut-and-tie model. The proposed model is based on the concept of the strut-and-tie-model and satisfied the equilibrium, compatibility and stress-strain relationship of cracked reinforced concrete. The variables analyzed consist of the ratios of horizontal and vertical distributed reinforcement, the compression concrete strength, and the shear span-to-depth ratio. 123 test specimen results prepared in the literature are used to support the suggested model and the results are compared with the shear strength predictions of the model and the empirical formulas of ACI code 318-95. The comparison indicated that the performance of the softened strut-and-tie model is better for all compared parameters than the approach of the ACI 318-95 code. The softened strut and tie beam model can be developed to enhance current deep beam design techniques by incorporating real shear strength mechanisms by predicting the supply of shear strength to the deep beams. Michael [5] reported the results of an experimental study to adopt the behaviour and efficiency factor of a bottle-shaped strut. The specimens consisted of a concrete panel (914 x 914 x 142) mm with variables the amount and layout of the steel reinforcement by using different reinforcement cages. The ultimate load of the specimen was divided by the compressive strength and bearing area of that particular specimen to determine the efficiency factor. The common failure was noted in each test was the refined STM of the bottle-shaped strut. The failure was caused by damage to the strut while the node remained uncrushed. The effect of the reinforcement panel had minimal based on the results from the specimens a constant value of the strut efficiency factor (Bs=0.6) would provide adequate safety. Brown [6] calculated the amount of transverse reinforcement for bottle-shaped to the tensile stresses developed so that reinforcement must be within the strut to carry the transverse tension. Three test groups of deep beams were used with 476 test specimens to determine the equilibrium-based equations ACI 318-05 determined two methods for calculating the reinforcement in the bottle-shaped strut. The first is that the components of the reinforcement perpendicular to the crack formed in the strut must be greater than 0.0003 times the area of concrete. The second method was the angle of dispersion of compression 2:1. The important recommendations in this study were, the use of angle dispersion 2:1 depends on the dimensions of specimens and strut, so it may or may not be equivalent, not allowed use of a bottle-shaped strut without horizontal reinforcement, and the amount of horizontal reinforcement can be calculated from the applied force to the strut. Zhang [7] presented an experimental program and a modified strut and tie model (STM) on a series of three main groups consisting twelve RC deep beams to test the possible reasons for the size effect. It is well known that the shear strength decreases with the increase in the height of the deep beam. The height of the concrete deep beams varied from 350 to 1000mm, and the width of the loading and support plate from 52.5 to 150mm. All the beams have the same span to depth ratio, and the flexural reinforcement. The authors proposed the modified the strut and tie models was presented as follows:
The specimens were loaded under the same boundary conditions. “Size effect” in flexural has little influence on the shear strength. Which is consistent with the observations that the larger beams show a higher rate of bending crack propagation. In the final state, however, the effect of the arc dominates the behaviour of the deep beam instead of bending. Group 1 has a much smaller size effect than the carriers in groups 2 and 3, which indicates that the reinforcement of the evenly distributed bands also plays an important role in weakening the effect of size in deep beams. The authors suggested a modified strut-and-tie model that takes the purposes of the size effect into account. It contains strut geometry (which determines the size of the loading and support plates and the length of the strut) and the boundary conditions of the strut (which determine the distance and the diameter of the distributed reinforcement across the strut). The modified model provides a better match than the original STM. Sahoo [8] studied the effective influence of the strut angle on strength. It is revealed that there is a direct linear connection between the strut inclination and strut efficiency factor. Pujol [9] reported different vertically oriented specimens with various strut widths to test this hypothesis. The specimens were loaded under the same boundary conditions. They did not notice any relationship between the shape of the specimens and their ultimate strength. As ACI 318-14 (ACI Committee 318 2014) suggested reinforced the strut and the tie, the concrete member was modeled as a truss (or collection of axially loaded elements). Lim [10] revealed a numbers of parametric studies were evaluated to calculate the most appropriate macro model that indicates the performance of a deep beam’s shear strength (structural behaviour) by utilizing result from 118 (RC) deep beam. The study found that the most important structural variables for modelling a deep beam are the definition of a shear member that corresponds to the discontinuity of the force, considering the elastic behaviour when defining the strut’s width, the effect of a steel load plate on the force spread and the appropriate selection of probable types of failure. Abdul-Razzaq et. al. [11-13] suggested alternatives for simply supported RC deep beams and pile caps via reinforcing only struts and ties in addition to removing concrete that the paths of STM do not pass through. Authors proposed lighter, more economical and specimens with service passage openings while maintaining the same load capacity as the reference control specimens. As mentioned before, an investigation was carried out by Jalil [14] tested the behavior of RC continuous deep beams when reinforcing their struts and ties, depending on the (STM) of ACI 318M-14. The parameters taken in this investigation were the strut angle (35°, 50°, 64°), type of loading (one concentrated load and uniform load), and the width of the specimens (150mm, 200mm). Twelve continuous two spans deep beams consisted of three series. Each series contained (conventionally reinforced reference beam, specimens with the strut and tie reinforced, and cast concrete only in the path of the strut and tie, and specimens with a reinforced strut and tie without shoulders of beams). The data showed that the STM specimens with the struts and ties reinforced had higher strength than the reference continuous deep beams due to supply a reduction in cost and weight and provide a front side area for service use. In also experimental research was reviewed by Rezaei [15] carried out a test on five specimens to separate the behavior of a diagonal strut in a full-scale deep beam. The parameters considered were different in shape (rectangular and truss-like), main reinforcement (external unbounded and internal bounded), and two strut angles (30° and 45°). It was shown with the same angle that the ultimate load of the truss-like more than rectangular. The failure of truss-like specimens resulted from the development of diagonal tension in the strut, which started from crushing concrete in the support node under the load point, and the failure of rectangular specimens starting from the breaking off the top corner of the beams, followed by crushing of the support node.

\[
V_n = \frac{1}{2 \sin 2\theta s + \frac{\sin \theta s}{f t A c} + \frac{\sin \theta c}{f c A st r}}
\]

Where: \(\theta s\) = Angle between the longitudinal tension reinforcement and the diagonal strut, \(A c\) = Beam effective cross-sectional area, \(A st r\) = Cross-sectional areas of the concrete diagonal struts, \(f t\) = Combined tensile strength of reinforcement and concrete, and \(f c\) = Concrete compressive strength.

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2nd International Scientific Conference of Engineering Sciences (ISCES 2020)
There has been some current research on the actual behavior of some elements of strut and tie models. This project aimed to shed additional light on the act of the strut, and how this contributes to improving the performance of the concrete deep beam.

2. Research significance

An optimization method based on the proposed model by using the strut and tie method (STM) for specimens. This was done by getting a good layout for reinforcement in RC deep beams. The objective of this research was to determine the behavior of reinforcement-inclined compression strut in simply supported deep beams to select the optimum shear design under monotonic loading.

3. Experiential program

The experimental program conducted at the engineering college of AL-Qadisiay University included the experimental testing of four concrete deep beams. Table 1 showed the naming and detailing of the tested deep beams. The beam had an overall length of 1100mm, width 150mm, height of 400mm, and strut angle 33° (the angle between the axis of strut and tie). The clear span was 900mm between the supports and with a constant shear span to depth ratio (1.25). The clear concrete covers were approximately 25mm for all sides of the beam. The ends of all flexural reinforcement extended with the steel bar had a 90° hook and a length 192mm at each end to provide sufficient anchorage. The main reinforcement for the deep beam (Ø16). The dimensions and flexural reinforcement were kept steady for all deep beams. The first specimen was a conventionally reinforced control deep beam designed according to the design provisions of (ACI Code 318-14). The control beam Reinforced with Ø16mm as flexural reinforcement at bottom and Ø10 for every 100mm deformed bars were provided as horizontal and vertical web reinforcement.

| No. | Specimens | Description |
|-----|-----------|-------------|
| 1   | Sc        | Normal strength concrete deep beam model was used as a Control under Static load |
| 2   | S10       | Normal strength concrete deep beam model was used 100% from the excess weight of web reinforcement under Static load |
| 3   | S5        | Normal strength concrete deep beam model was used 50% from the excess weight of web reinforcement under Static load |
| 4   | S0        | Normal strength concrete deep beam model was used 0% from the excess weight of web reinforcement under Static load |

3.1. The proposed strut and tie model

The other three specimens were the specimens in which the paths of struts were reinforced. The strut and tie model for one-span deep beam under one-point load showed in Figure 1, according to the (strut reinforcement detailing) in section (23-6) of (ACI Code 318-14). In addition to traditional flexural and different amount of the web reinforcement.
The various quantities of the web reinforcement based on the total weight of the web reinforcement in the control beam, and that was done by the weights of two reinforcement struts and two stirrups in the supports of the deep beam were abstracted from the total weight of the web reinforcement in the control beam. The excess weight used in three forms, geometry, and detailed reinforcement arrangement of the tested specimens are shown in Figure 2 for each specimen has a special weight from web reinforcement: **Specimen I (100%)** have used all excess weight from the web reinforcement, hence, the specimens S10 and SC have the same weight and cost. The distributed reinforcement with vertical web reinforcement (Ø10mm@240mm) and horizontal web reinforcement (1Ø10mm). The main reinforcement (4Ø16) and with two reinforcement diagonal struts each strut reinforced with longitudinal reinforcement (4Ø10) and with closed tie (Ø10@100mm). **Specimen II (50%)** have used half the excess weight from the web reinforcement. The distributed reinforcement with vertical web reinforcement (Ø10mm@500mm) and horizontal web reinforcement (1Ø10mm). The main reinforcement (4Ø16) and with two reinforcement diagonal struts each strut reinforced with longitudinal reinforcement (4Ø10) and with closed tie (Ø10@100mm). **Specimen III (0%)** did not use any weight of the excess from web reinforcement weight. The distributed reinforcement with vertical web reinforcement (3Ø8mm) and no horizontal web reinforcement.

**Figure 1.** Strut and tie model for the deep beam with one-point load

**Figure 2.** Details of reinforcement deep beams
4. Materials
Normal strength concrete (NSC) was used to pour different areas of the samples. It was designed according to (ACI211-05). All materials used in this test are conform to the Iraqi standard. The specimens of the deep beams and cylinders were cast on the same day using the concrete mixture design shown in Table 2. Reinforcement was shown in Figure 3. Put inside the molds and molds filled with concrete in two-layer with three-minute vibration. Then, the concrete surface was finished and leveled using a steel tower. After 48 hours, molds were removed from the beam, and then they covered with burlap sacks as, which remained moist for 28 days.

| Description | Cement | Sand | Gravel | Water | compressive strength f’c (Mpa) (cylinder) 7days | compressive strength f’c (Mpa) (cylinder) 28days |
|-------------|--------|------|--------|-------|-----------------------------------------------|-----------------------------------------------|
| The mixing proportion | 1 | 1.06 | 2.35 | 0.35 | 21.45 | 30 |
| Quantities (kg/m³) | 423 | 451 | 996 | 148 | |

Figure 3. Preparation of reinforcing steel for deep beams
5. Experimental Tests

Deep beam specimens were subjected to static applied pre-axial compression loads on the upper side of the beam. A one-point load was used in this investigation and to concentrate the load using a steel plate with dimensions (150 x 150 x 10) mm and a steel plate (100 x 150 x 10) mm for the local failure at the support points of the beam. The clear span length in each tested beam was 900mm. The supporting system was a simply supported deep beam (roller and pin). The hydraulic universal testing machine as shown in Figure 4. It was used to test the deep beams. The machine contains a hydraulic actuator, load cell, support in span, plate for applied load, and the program (lab view) on the computer. The full capacity to machine about 2000 KN.

![Figure 4. Hydraulic testing machine of deep beam specimens](image)

The measurement was made by the compression of an image series that is captured over a time scale from microseconds to years. (GOM) correlation software package 2019 program used to measure the 2D plane by camera Nikon is located on one side of the beam. This technique was used to measure displacement, strain, monitor to crack development, and distance between any points in the specimens at any stage during loading. The side front of the camera was painted white, and after that, black pattern spots using magic pen were made to capture the simple change that occurred in the deep beam by the (GOM) program. The (LVDT) installed at the mid-span bottom of the deep beam, the load was applied gradually in increments10 KN. The white-painted side of the deep beam to follow the development of the crack by magic pen and the dotted side to record the videos in the camera for the (DIC) technique. As the load proceeded, new cracks appeared and the cracks became wider and be longer, and the deflection value corresponding to the load was recorded by the program every second. The test was stopped when concrete crushing.

6. Experimental results and discussion

The outcomes from the deep beam experimental testing program will be explained in this section, including the crack patterns, marked failure modes, strains parallel and perpendicular to the strut axis, and ultimate capacity.

6.1. Crack pattern

The crack patterns for the control deep beam represented as a perpendicular flexure crack began to form at mid-span and grow up toward the bearing loading plate. It appeared at about 41% of the test ultimate strength. Then, the first shear cracks showed up at about 49% of the test ultimate strength, as shown in Table 3. As the load is more increased, further flexural and diagonal shear cracks formed, and major diagonal cracks extended to meet the applied loads with the supports. The deep beam with reinforcement strut (S10), a single vertical flexure crack appeared at about 24% of the test ultimate strength in the mid-
span, as the control specimen grew toward the load point and extended under further load. First, inclined diagonal shear cracks showed up at about 37% of the test ultimate strength located near the support nodal zone. Other deep beams with reinforcement strut (S5, S0). Which that with different amounts of the web reinforcement, the behavior of these deep beams was almost the same that of (S10). More cracks formed in (S5, S0) along the bottom of the beam and some of the flexure cracks, then cracks run from the support nodal zone.

Table 3. Measured and estimate failure load

| Specimen name | First flexural cracking load $P_{cr}$ (KN) | First shear cracking load $P_{cr, diag}$ (KN) | Ultimate load $P_u$ (KN) | Theoretical design load $P_{STM}$ (KN) |
|---------------|------------------------------------------|---------------------------------------------|--------------------------|----------------------------------------|
| SC            | 238                                      | 281                                         | 570                      | 438                                    |
| S10           | 163                                      | 250                                         | 670.9                    |                                        |
| S5            | 139                                      | 210                                         | 536                      |                                        |
| S0            | 161                                      | 208                                         | 492                      |                                        |

6.2. Load Mid-span Deflection Curves

The load-versus-displacement curves that taken from testing all deep beams were shown in Figure 5. Every specimen, the load-versus-displacement curve is approximately linear in the major portion of the loading process, after that, the curve began the nonlinear behavior. This reveals the control shear deformation in all specimens, which led to a brittle manner. The brittle failure manner decreased the ductility of the deep beams, which led to a decrease in their strength of them below the flexural strength.

![Figure 5. Load mid-span deflection curves for all specimens](image-url)
6.3. Failure modes

The captured images in the (DIC) were processed at various load stages compared to the reference image taken before the applied load. Figure 6 showed a photo of the control deep beams and strut reinforcement deep beam before, during, and immediately the following failure. They were photographed by utilizing a video shooting in-camera to convert videos to photos to use them in the (DIC) technique. The control deep beam with conventional reinforcement, as shown in Figure 6 (a). The failure in it occurred when the diagonal shear crack developed and extended from the support plate to join the zone where the applied load in the loading plate. At the load stage near failure, the diagonal shear cracks became wider. Finally, the corner of the deep beam fracture close to the line between the edge of the load plate and the edge of the support plate. So the failure of the control deep beam was caused by a diagonal splitting failure in the strut. The deep beams with strut reinforcement (S10, S5, and S0) had similar failure mechanisms but with a difference in ultimate load, as appeared in Figure 6 (b). The failure of these deep beams was caused by the two inclined cracks forming a concrete compression strut in the edges of the strut in each shear span of the deep beam. Their failure in them occurred when the two diagonal edges surrounding each reinforcement strut developed and extended from the edges of the support plate to bearing plate of the node under the load. At the load stage near failure, the diagonal shear cracks became wider. So the failure of these deep beams was caused by the crushing of the strut which caused crush the concrete under compression.

![Failure modes](image)

Figure 6. COM correlate images before, during and after failure by using DIC testing technique (a)SC (b)S10

7. Analysis of test results and discussion

The experimental variables were provided in this study were:

**Effect of specimen design type:** The study was carried out to select the optimum design for the deep beam by reinforcing the strut in the deep beam, and followed by the behaviour of the beam in comparison with traditional reinforcement in a control deep beam. The experimental results revealed that all specimens resist loads greater than the theoretical design load of STM in the ACI-318-14, as showed in Figure. 7.
Many researchers also achieve this. The design loading of the ACI is less than the ultimate loading by approximately 30.14%, 53.2%, 22.4%, and 12.4% for the specimens of SC, S10, S5, and S0, respectively. In Table 4, it was also found that the capacity of the specimen S10 greater than the control specimen SC by about 17.7%, with a decrease in deflection in the S10 about 24.47% compression with SC. Therefore, specimen S10 saved the cost and the weight with higher strength, where the specimens S10 and SC had the same as the term of the weight and the cost. And also the ultimate load and the displacement for S5 decreased by about 5.9% and 51.1%, respectively and the ultimate load and displacement for S0 decreased by about 13.6% and 61.1%, respectively related to the reference SC.

### Table 4. Comparisons between all static specimens in terms of ultimate load and deflection

| Specimen symbol | Ultimate load (Pu) (KN) | Increase Ultimate Load* (%) | Maximum deflection (Δu) (mm) | Decrease deflection** % |
|-----------------|------------------------|-----------------------------|-------------------------------|------------------------|
| SC              | 570                    | -------                     | 12.34                        | -------                |
| S10             | 670.9                  | 17.7                        | 9.32                         | 24.47                 |
| S5              | 536.25                 | -5.9                        | 6.03                         | 51.1                  |
| S0              | 492.32                 | -13.62                      | 4.8                          | 61.1                  |

**Effect of various amounts of web reinforcement:** The ratio of distributed reinforcement was directly affected of the shear strength, which was controlled in the deep beam. Therefore, the decreased values lead to reduce the strength of the specimens. The difference between the three deep beams (S10, S5, and S0) was the ratio of web reinforcement, which was reduced from one to another. The data showed that the reduction in reinforcement weight about 3%, 9.7% and 18.6% for the specimens S10, S5, and S0, led to increase in the capacity of (S10) about 17.7% and decreases in the capacity of S5 and S0 about 5.9% and 13.6% , respectively, related to (SC). Table 5 illustrated the comparisons between the reinforcement strut deep beams under monotonic in terms of reinforcement weight, which result from summation the weights of (flexural reinforcement, strut reinforcement, and web reinforcement). The flexural and strut reinforcement were constant for all reinforcement strut deep beams,
Table 5. Comparison between deep beams in terms of reinforcement weight

| Specimen | Ultimate load \( P_u \) (kN) | Increase in ultimate load † | Strut reinforcement weight (Kg) | Web reinforcement weight (Kg) | Reinforcement total weight (Kg) ‡ | Decrease in the reinforcement weight ‡‡‡ |
|----------|-------------------------------|-----------------------------|---------------------------------|------------------------------|----------------------------------|-----------------------------------------|
| SC       | 570                           | ------                      | 0                               | 9.44                         | 18.5                             | ------                                  |
| S10      | 671                           | 17.7                        | 5.4688                          | 3.428                        | 17.959                           | 3                                       |
| S5       | 536                           | -5.9                        | 5.4688                          | 2.31915                      | 16.85                            | 9.7                                     |
| S0       | 492                           | -13.62                      | 5.4688                          | 1.0665                       | 15.598                           | 18.6                                    |

*The percentage increase in ultimate load for static deep beams was measured with respect to (SC) and
** Reinforcement total weight = web reinforcement weight + strut reinforcement weight + main reinforcement weight
Main Reinforcement weight= 9.063 for all tested deep beams.
*** The percentage decrease in the reinforcement weight for static deep beams was measured with respect to (SC)

8. Strain of concrete beams using (DIC)

8.1. The strain of the axis and edges of strut behavior

GOM is a software program used for material study and component testing and evaluation in DIC technology. It was presented a 2D digital image correlation that approved the assessment of the series of digital images. DIC technology provided a cost-effective answer for any specimens tested by using a digital camera and grid distribution by black after painting the specimen white. The strain can be measured for any level of the load through the investigation. Calculating the strain values supplied an idea about the maximum strain and revealed how the first cracks were developed. Besides, measuring strain rates supported in better conclusion the real stress flow during the strut from the loading zone to the supporting plate. Average strain values are measured for examining deep beams at critical locations 0.9 from the ultimate load. Measured strain by the DIC technology appeared that the strain in the right side of the deep beam different from the strain in the left side due to the concrete is a heterogeneous material. In addition, the micro-crack in the concrete formed by drying shrinkage. Three points (start, middle, and end) along the axis of the strut to record the longitudinal strain showed in Figure 8 (a) for the surface of the control deep beam. Strain values grew rapidly when the applied load increased, and the concrete cracking became clear. The tension strain values in the axis of the strut for the control deep beam gave recordings in the middle of the strut axis higher than the strain at the other two ends. Also, in the control deep beam, the strain at the middle axis of the strut greater than the strain in the edge of the strut showed in Figure 9 (a). This would reveal the strain concentrated in the axis of the strut, which would justify the reason for the increased strain at the diagonal tension. The strain in the edge of the strut in the control beam less than the strain at the edge of the strut reinforcement, so this explained no crack appeared in the two edges of the strut. Similar results relatively were observed in all strut reinforcement deep beams. The compression strain at three points on the strut-axis was lower than the strain in the strut-axis of the control deep beam, showed in Figure 8 (b) and Figure 9 (b). So, no shear crack in this diagonal strut due to the decreased stresses of the strut-axis for the reinforcement strut deep
beams. Also, in the reinforcement strut, the strain in the edges of the strut where longitudinal reinforcement for the strut was found, greater than the strain in the middle of the axis strut. This appeared due to the spread of stresses caused by diagonal tension at the two edges of the strut with tension recordings shown in Figure 9 (b). The two diagonal tension at the edge of the strut caused strain compression in the strut axis. Therefore, the data of strain showed that a control deep beam failed due to diagonal tension stresses in the struts, not present in the strut reinforcement specimens. Where the compression stresses appeared along the axis of the strut, and tension stresses appeared in the edges of the stresses.

**Figure 8.** Strain along strut-axis at 0.9 \( p_{\text{max}} \) by using DIC testing technique (a)SC (b)S10

**Figure 9.** Strain along the edges of the strut at 0.9 \( p_{\text{max}} \) by using DIC testing technique (a)SC (b)S10

### 8.2. Load-strain behavior

Generally, recording the concrete strain values gave an idea concerning the maximum concrete strains and revealed the measuring concrete strain recordings helped in better thought the actual stress flow from the loading to the supporting plats. Average concrete strain values are measured for testing specimens at critical locations as demonstrated in the Table 6.

| Recording designation | Location          |
|-----------------------|-------------------|
| AS                    | axis of strut     |
| ES1                   | Edge of strut 1   |
| ES2                   | edge of strut 2   |

Using the DIC technique, three points located in the axis and the two edges of the strut were selected to observe the concrete strain value for every increase (100) kN in the applied load for each beam.
specimen. Figure 10 to Figure 13 showed the compression and tension strain values for the axis-strut and the two edges of the strut of SC, S10, S5, and S0 deep beams at their corresponding applied load. In this basis, it is important to note these points:

1. Load strain values of the axis-strut of the control beam (SC) were tension strain recordings compared with reinforcement strut deep beams (S10, S5, and S0) with compression strain recordings less than the (SC) tension strain recordings.

2. The compression and tension strain values of (S10) deep beam were less than (SC). This is thought to be mainly due to the enhancement in the designed reinforcement of (S10) deep beam.

3. With the decreasing in the amount of web reinforcement in the reinforcement strut deep beams (S10, S5, and S0), the load-strain recordings for these beams increased in compression and tension as showed in Figure 11 to Figure 13.

![Figure 10. Strain measurement for the specimen SC (a) Strain point’s locations (concrete) in DIC testing technique (b) Applied load versus average concrete strains](image-url)
Figure 11. Strain measurement for the specimen S10 (a) Strain point’s locations (concrete) in DIC testing technique (b) Applied load versus average concrete strains
Figure 12. Strain measurement for the specimen S5 (a) Strain point’s locations (concrete) in DIC testing technique (b) Applied load versus average concrete strains
Figure 13. Strain measurement for the specimen S0 (a) Strain point’s locations (concrete) in DIC testing technique (b) Applied load versus average concrete strains

9. Summary and conclusion
The work of this research was to reveal the variation in behavior between deep beams with compression strut reinforced according to the strut reinforcement in ACI 318-14 and concrete deep beam with traditional design reinforcement by STM in ACI 318-14. The experimental work contained casting and testing four deep beams with geometry and flexural reinforcement constants for all deep beams. The parameters that were taken into consideration were the design type and amount of web reinforcement. The deep beams were tested to failure and loads, crack patterns, and strains along the strut axis, and edges were calculated. The ultimate strength was compared to the theoretical strength of STM using ACI 318-14. Several conclusions can be done according to the data results of this project:
1. The capacity of the reinforcement strut deep beam S10 greater than the control deep beam SC by about 17.7%, with a decrease in deflection in the S10 compression with SC. Therefore, specimen S10 saved cost and weight with higher strength, where specimens S10 and SC had the same of the term of the weight and the cost as mentioned before. In addition, the experimental results showed that all deep beams failed at higher loads than the theoretical design load of STM in the ACI-318-14.

2. The deep beams with reinforcement strut (S10, S5, and S0) had similar failure mechanisms but with variations in ultimate strength. The crushing of the strut caused the failure of these deep beams. While the failure of the control deep beam was caused by a diagonal splitting failure in the strut.

3. The effect in the reduction amounts of web reinforcement caused a decrease in the capacity of the specimen. This appeared when the reduction in reinforcement weight about 3%, 9.7% and 18.6% for the beams S10, S5, and S0, led to increase in the ultimate capacity of (S10) about 17.7% and decreases in the capacity of S5 and S0 about 5.9% and 13.6%, respectively, related to (SC).

4. Three points along the axis of the strut to measure the longitudinal strain on the surface of the control deep beam. The tension strain values in the middle of the strut axis higher than the strain on the other two ends. Also, the strain in the middle axis of the strut greater than the strain at the edge of the strut. This explains the reason for increased strain in the diagonal tension. Similar results were observed for all strut reinforcement deep beams. The compression strain values at three points on the strut-axis were lower than the strain in the strut-axis of the control deep beam recordings. Also in the reinforcement strut, the strain at the edges of the strut where longitudinal reinforcement for the strut, greater than the strain in the middle of the axis strut due to the spread of stresses caused by diagonal tension in the two edges of the strut.

5. The compression and tension strain recordings of (S10) deep beam were less than (SC) due to the enhancement in the reinforcement designing of (S10) deep beam. In addition, with the decreasing in the amount of web reinforcement in the reinforcement strut deep beams, the load-strain recordings for (S10, S5, and S0) deep beams increased in compression and tension.

References
[1] A. C. I. C. 318, Building Code Requirements for Structural Concrete (ACI 318-14)[and] Commentary on Building Code Requirements for Structural Concrete (ACI 318R-14). 2014.
[2] F. K. Kong, Reinforced concrete deep beams. CRC Press, 1991.
[3] K.-H. Tan, F.-K. Kong, S. Teng, and L. Guan, “High-strength concrete deep beams with effective span and shear span variations,” Struct. J., vol. 92, no. 4, pp. 395–405, 1995.
[4] S.-J. Hwang and H.-J. Lee, “Strength prediction for discontinuity regions by softened strut-and-tie model,” J. Struct. Eng., vol. 128, no. 12, pp. 1519–1526, 2002.
[5] M. D. Brown, C. L. Sankovich, O. Bayrak, and J. O. Jirsa, “Behavior and efficiency of bottle-shaped struts,” ACI Mater. J., vol. 103, no. 3, p. 348, 2006.
[6] M. D. Brown and O. Bayrak, “Minimum transverse reinforcement for bottle-shaped struts,” ACI Struct. J., vol. 103, no. 6, p. 813, 2006.
[7] N. Zhang and K. Tan, “Size effect in RC deep beams : Experimental investigation and STM verification,” vol. 29, pp. 3241–3254, 2007, doi: 10.1016/j.engstruct.2007.10.005.
[8] D. K. Sahoo, “Effect of inclination on the strength of struts,” vol. 63, no. 2, pp. 111–117, 2011, doi: 10.1680/macerc.9.00178.
[9] S. Pujol, J. M. Rautenberg, and M. A. Sozen, “Compressive strength of concrete in nonprismatic elements,” Concr. Int., vol. 33, no. 9, pp. 42–49, 2011.
[10] E. Lim and S. Hwang, “Modeling of the strut-and-tie parameters of deep beams for shear strength prediction,” Eng. Struct., vol. 108, pp. 104–112, 2016, doi: 10.1016/j.engstruct.2015.11.024.
[11] K. S. Abdul-Razzaq and S. F. Jebur, “Suggesting alternatives for reinforced concrete deep beams by reinforcing struts and ties,” in MATEC web of conferences, 2017, vol. 120, p. 1004.
[12] K. S. Abdul-Razzaq, S. F. Jebur, and A. H. Mohammed, “Concrete and steel strengths effect on
deep beams with reinforced struts,” *Int. J. Appl. Eng. Res.*, vol. 13, no. 1, pp. 66–73, 2018.

[13] K. S. Abdul-Razzaq and M. A. Farhood, “Design-Oriented Testing and Modeling of Reinforced Concrete Pile Caps,” *KSCE J. Civ. Eng.*, vol. 23, no. 8, pp. 3509–3524, 2019.

[14] Jalil, A. M., 2019. Behavior of Reinforced Concrete Continuous Deep Beams with Reinforced Struts and Ties, M.Sc. Thesis, Dept. of Civil Eng., University of Diyala.

[15] N. Rezaei, G. Klein, and D. B. Garber, “Strut Strength and Failure in Full-Scale Concrete Deep Beams,” *ACI Struct. J.*, vol. 116, no. 3, pp. 65–74, 2019.