Mechanical characteristics of deep beams considering variable a/d ratios: an experimental investigation

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Abstract. In this investigation, the influence of the shear span to the effective depth ratio on the mechanical properties of deep beams was expansively illustrated. For this aim, three specimens representing deep beams with a medium scale were prepared using the same concrete grade. The specimens had similar dimensions of 1250 ×300×150 mm and identical details of reinforcement. The beams were subjected to a four-points load test, which was gradual until the specimens failed. Three different a/d ratios were inspected; 0.75, 1.25, and 1.75. the experimental observations were compared in terms of deformations, ultimate loads, stiffness, ductility, and toughness. The results of tests indicated that the a/d had a considerable influence on the mechanical characteristics of deep beams, except for ductility.

Keywords: deep beams; a/d ratio; shear; strength; ductility; toughness; stiffness.

1. Introduction
Reinforced concrete beams with a shear span to effective depth ratio of less than 2.0 are named as deep beams [1, 2]. Because of this low ratio, significant shear stresses produce making the strain distribution across the depth of beams non-linear. Therefore, the structural behavior of a such beams entirely differs from that of conventional beams [1, 3]. In deep beams, the shear deformation is remarkable and could not be discounted as in case of conventional beams, where the shear deformation is insignificant. Therefore, although all shear stresses types are critical in the different structural members [4-8], the shear strength is the main issue in the design of deep beams to avoid sudden failure owing to shear [9-11].

Up to date, many studies have inspected the structural performance of deep beams as broadly reviewed in reference [2]. These investigations confirmed that the strength of deep beams depends mainly on several characteristics such as shear span to effective depth ratio (a/d), beam span to depth ratio (l/d), concrete grade, flexural reinforcement, skin reinforcement and the web reinforcement.

A total of 12 deep beam specimens were tested by Manuel et al. [12] to examine the influence of (l/d) on deep beams. They observed that the shear strength of deep beams remarkably reduced as the (l/d) ratio increased. Tan and Lu [13] then confirmed this conclusion. The authors attributed this conclusion to the need for a giant arch to transfer the force to the support, which causes an excessive deflection with more flexural cracks. Hence, the shear capacity of beams declines. The second parameter influencing the response of deep beams is the grade of concrete. Sayed et al. [14] studied this parameter and commented that the shear strength of the deep beams enhanced as the concrete grade augmented with the non-linear rate. Also, they noticed that as the concrete grade exceeded 60 MPa, aggregates fractured, resulting in less friction, and therefore, a slight improvement in the shear
capacity of deep beams was registered with respect to the beams fabricated from normal strength concrete. In contrast, Londhe [15] showed contradictory results. He found that based on varying the concrete grade from 24 to 37 MPa, the structural response of deep beams affected by concrete grade marginally. Mau and Hsu [16] inspected the effect of longitudinal reinforcement on deep beams. They declared that the shear capacity of deep beams developed noticeably with increasing the ratio of the longitudinal steel reinforcement. Other studies [15, 17] stated that a linear enhancement in shear strength of the deep beams with the ratio of the longitudinal steel reinforcement until a specific limit, and then the influence became insignificant. This strength enhancement was attributed to the efficiency of the longitudinal bars to limit the crack size, increase the mechanism of shear transfer and magnify the dowel action.

Skin reinforcement (horizontal reinforcement) is provided in the deep beams to enhance the shear capacity. Despite that, a study of Kong et al. [18] showed a slight influence in the shear capacity of deep beams with the change in the skin steel reinforcement ratio. This conclusion was established later by Smith and Vantsiotis [19], mainly when a low ratio of web reinforcement was used. However, Ashour [17] concluded a critical influence for the skin reinforcement on the strength of deep beams with shear span to effective depth ratio a/d less than 0.75. The essential influencing parameter on the strength of deep beams is the web reinforcement. The major function of web reinforcement is to enhance the concrete confinement, which reflects on increasing the strength of deep beams [2]. Also, it is more effective to prevent the sudden failure of deep beams owing to shear compared to the skin reinforcement. Therefore, the ductility of deep beams improves with increasing the web reinforcement. The previous investigations [18, 20-23] observed a linear correlation between the enhancement in the strength of deep beams and the ratio of web reinforcement. Nevertheless, the contribution of web reinforcement was discovered to be reduced for beams with a/d ratio of less than 1.0. Ashour [17] emphasized this finding; he found a significant contribution to the web reinforcement in the strength of deep beams with a/d ratio higher than 0.75. Shahnewaz et al. [2] indicated that the strength of deep beams improves with increasing the web reinforcement ratio to 1.42%. After this limit, the effect of the web reinforcement became negligible.

In reinforced concrete members, the concrete is responsible to resist the cracking and fracture. Accordingly, the flexural toughness of members related closely on concrete, which reflects the drop in the toughness of the cracked concrete members. The last significant factor influencing the shear capacity of the deep beams is the ratio of shear span to effective depth (a/d). As illustrated by previous studies [12, 13, 15, 19, 24], the capacity of deep beams was found to enhance as the a/d reduces. These findings were attributable to the direct transmission of the applied load to the supports through the concrete struts as the a/d decrease. However, the authors of the current study believe that the effect of the a/d ratio on the mechanical properties of deep beams needs more experiments and description. Therefore, they cast three deep beam specimens with different ratios of a/d. These specimens were collapsed gradually under the effect of the four-point loads. The results were demonstrated in expressions of strength, deformation, ductility, and service stiffness.
2. Experimental Program

As introduced, the objective of this experimental study is to estimate the shear capacity and flexural response of deep beams with different a/d ratios. For this purpose, three medium-scale deep reinforced concrete beams were casted and examined in the construction materials laboratory in Wasit University. Normal concrete was used with target cylinder strength of 25 MPa. The used cement was local ordinary Portland cement, while the fine and course aggregates were river sand and crushed siliceous gravel with a peak size of 19 mm. The quantities of cement, sand and gravel in the mixture were 410, 650 and 1150 kg/m$^3$, respectively, while 0.45 water/cement ratio was adopted. The compressive strength of the concrete was evaluated using the average of three standard 150 mm cubes and was found to be 32 MPa.

The beam specimens were identical in configuration, dimensions and reinforcement details. The length of the cast beams was 1250 mm, while the cross-sectional dimensions were 150×300 mm (width × depth). The beams were reinforced with high tension reinforcement ratio to assure shear failure, where two bars of 20 mm diameter were employed as tension reinforcement with the distance from their center to the tension face being 35 mm. This distance was attained by considering a 20 mm concrete cover and using hoop stirrups of 6 mm diameter, which were equally spaced at 50 mm for the entire length of the beam. Two top bars of 10 mm diameter were used to facilitate the use of a large tension steel area. With which, the adopted tension reinforcement ratio could be used without exceeding the maximum steel ratio recommended by ACI 318-14 [25] for ductile beams. In addition to the top and bottom bars, 6 mm diameter longitudinal sidebars were used along the vertical legs of the stirrups. Four sidebars were used along each side of the deep beam section.
Figure 2. Testing arrangement of the three deep beams

The section of the cast beams is shown in Figure 1(a), while Figure 1(b) illustrates the longitudinal configuration of the beams. As is evident in Figures 1 and 2, the specimens were examined under a four-point bending test with a clear simply supported span of 1000 mm. The distance between the two point loads was variable to accommodate a variable shear span-to-effective depth ratio (a/d). The distance between the two point loads was 600, 340 and 70 mm for the beams B1, B2 and B3, respectively, which resulted in a/d ratios of approximately 0.75, 1.25 and 1.75, respectively. Figure 2 illustrates the shear span distances of the three beams. Under the midspan center of the beam, an LVDT was installed to obtain the deflection at each load step. The load cell and the LVDT were linked to a universal data taker so that all measurements are obtained simultaneously. The load was increased gradually with constant slow steps until failure.

3. Test results

3.1. Modes of failure and cracks patterns

The behaviors of all deep beams were comparable before cracking. After that, with further loads, the first cracks appeared when the applied loads reached (16.7% - 19.67%) of the ultimate load in the region bounded by two loading points. Then, more flexural cracks were initiated, which propagated upward and enlarged as the applied loads increased. Shortly before failure, inclined cracks were observed next to supports. According to the development of these inclined cracks, two sudden failure modes were noticed, which were diagonal splitting and strut compression, as shown in Table 1 and Figure 3. Diagonal splitting failure was experienced by beams B2 and B3 with the a/d ratio of higher than 0.75. In this mode, the inclined cracks, which caused the collapse, elongated from support-point to loading-point. The beams B2 and B3 failed at loads of 352.87 kN and 318.72 kN, respectively.
For beam B1, with the lowest a/d ratio, the loads were moved out directly to the supports through concrete struts. As a result, high stresses were produced in these regions that led to failing this beam due to compression strut mode at a load of 396.5 kN.

| Specimen | Initial bending crack load (CL.) (kN) | Ultimate load capacity (UL.) (kN) | % CL. / UL | Failure types |
|----------|--------------------------------------|----------------------------------|------------|---------------|
| B1       | 72.68                                | 396.5                            | 19.67      | Strut compression |
| B2       | 62.45                                | 349.7                            | 17.86      | Diagonal splitting |
| B3       | 54.28                                | 324.9                            | 16.70      | Diagonal splitting |

3.2. Load-deflection response
Figure 4 plots the central- displacement versus the applied load for the three beams. All specimens showed approximately linear responses until the occurrence of the first cracks. Then, the responses advanced in non-linear trends with reduced slope due to developing more flexural cracks. As seen in Figure 4, at the same force, the B3 having the largest a/d ratio exhibited more deflection than others. In order to, clarification the responses of the tested specimens, the behavior of the deep beams were compared together at two stages, service and ultimate load stages. Service load was considered as 70% of the failure load as recommended by previous researches [33, 34]. At service load of beam B3 it is demonstrated that the central deflection of beam B3 is larger than that of B1 and B2 by about 170% and 40.7% respectively. While at a load of 324.9 kN, the failure load of B3, the beam experienced deflection higher than that of B1 and B2 by about 300% and 97%, respectively. This finding was due to generating a significant moment as the a/d ratio augment, and therefore, additional flexural cracks appeared that weakened the beam stiffness.

3.3. Shear capacity of beams
The failure loads of the three specimens were compared in Figure 5. It is evident that the shear strength of deep beams enhanced noticeably as the a/d reduced, and this outcome agreed with the previous investigations [12, 13, 15, 19, 24]. This result is attributed to the initiating the strut and tie action mechanism as the a/d ratio drops. In this mechanism, the shear forces transferred to the supports straightway by concrete struts with a few flexural cracks, thus, the shear strength of beams increased compared to other specimens with higher a/d ratio. In general, the shear strength of B1 was 13.4% and 22% above that of B2 and B3, respectively.

Table 1. Experimental test results

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3.4. **Ductility of the test beams**

Ductility reflects adequacy of the reinforced concrete members to realize and disperse energy before failure [26-29], and it is an indication of the amount of inelastic deformation. There are various ways to determine the ductility in flexure [30, 31], while ductility can also be used to compare energy absorption under impact and other types of loads [32-37]. Among these approaches, the method proposed by Spadea et al. [38] is more fit for deep beams since the others rely mainly on the strain yield of tensile reinforcing bars that is absent in the deep beams because of brittle shear failure. In this approach, the ductility factor (DF) is calculated as a ratio of absorbed energy (i.e., the entire area beneath the load-deflection curve) to the energy absorbed up to the service load. As mentioned before in reinforced concrete elements, a force equating 70-75% of the failure load could be taken as a service load [39, 40]. The determined ductility factors for all beams are recorded in Table 2. This table states that all beams give close values of ductility with a little difference since the three beams experienced brittle shear failure. Hence, the ductility factors of deep beams with the a/d ratio ranged from 0.75 to 1.75, did not relate to the a/d ratio.
3.5. Secant stiffness of the test beams

The secant stiffness is the slope of line running between the start of the experiment and the point of failure load [31, 41, 42]. This criterion was adopted herein to assess the a/d impact on the deep beams. Table (2) shows the secant stiffness for all test samples, and it is evident that the beam stiffness enhanced when the a/d decreased. Compared to the B3, with the largest a/d ratio, the service stiffness increased by around 122% when the a/d ratio reduced by 57.1%. Also, the results displayed that the stiffness of specimen with moderate a/d ratio enhanced by about 52% above the stiffness of the beam with largest a/d ratio. This enhancement was significant and could be signed to the transmission of applied force to the supports directly without creating a remarkable moment, and hence, a few flexural cracks were initiated.

3.6. Flexural toughness of the test beams

The toughness is a standard that indicates the energy absorbed by reinforced concrete beams up to the collapse [29]. This measure can be evaluated through summing the area restricted by the load-deflection curve of beams up to the peak load and corresponding displacement. Since the beams displayed different ultimate deflection, their toughness values were normalized by dividing them on the ultimate displacement to obtain a reliable index, as done in [31]. The normalized toughness values of specimens are summarized in Table 2. It is apparent that as the a/d ratio decreased, the ability of beams to absorb energy increased. This could be attributed to reducing the number of cracks as the a/d dropped. The previous investigations confirmed that the relationship between toughness and cracking is inverse [26-29]. In this study, a reduction in the a/d ratio of deep beams by about 57.1% resulted in a 18.1% enhancement in the toughness of deep beams, in additional, a slight increasing in the flexural toughness of beam B1 with respect to the beam B2 were observed.

| Specimens | Ductility factor (D.F) | Service stiffness (kN/mm) | Normalized toughness kN, mm/mm |
|-----------|------------------------|---------------------------|-------------------------------|
| B1        | 3.3                    | 94.4                      | 237.3                         |
| B2        | 3.4                    | 64.8                      | 230                           |
| B3        | 3.6                    | 42.6                      | 201                           |

4. Conclusions

The essential conclusions of this study as follows;

- The parameter of a/d influenced the structural responses of deep beams remarkably. Two modes of brittle shear failures were observed with the variation in a/d ratio, which were splitting diagonal and strut compression modes.
- At the same load level, the beam having a 1.75 a/d ratio showed higher deflection when compared with the other two specimens with lesser a/d ratios.
- The shear strength of deep beams was found to be affected significantly by the a/d ratio. The beam with a/d ratio of 0.75 experienced an ultimate load, about 22% above that of the beam with 1.75 a/d ratio.
- Since all beams collapsed owing to shear failure, the a/d ratio had a slight impact on the ductility index of the examined specimens.
- A remarkable enhancement in the stiffness of deep beams, nearly 122%, was recorded as the a/d ratio dropped from 1.75 to 0.75. Such enhancement was also observed for the flexural toughness of deep beams but in a smaller percentage, reaching 18.1%.
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