Evaluating planner hoop steel plates as web reinforcement for deep reinforced concrete beams

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Abstract. An experimental attempt was conducted in this paper, aiming at enhancing the shear and flexural behaviors of deep beams, where steel plates were applied as web reinforcement. Three beams having the same details were prepared using normal concrete strength. Their dimensions were 1250 mm long, 300 mm deep, and 150 mm wide. The specimens were designed to fail in shear, and therefore, they were supplied with two bars with a 20 mm diameter in addition to the top and skin reinforcement. For web reinforcement, the steel plates were cut in dimensions of 4×20 mm and then were applied as closed rectangular stirrups with the longer side (20 mm) aligned in the plane of the beam section. The beams were inspected by applying four-point bending with three shear span to the effective depth ratios (a/d) of 0.75, 1.25 and 1.75. The experimental outcomes revealed that the shear strength, stiffness, and toughness of deep beams enhanced as the a/d ratio dropped.

Keywords: Shear reinforcement; hoop steel plates; deep beam; reinforced concrete; cracking; sectional strain.

1. Introduction

All beams, slabs, footings, and other concrete structures are designed to not fail in shear. This is because of the brittle manner of shear failure, which is unfavorable compared to the flexural ductile failure. Therefore, all types of shear stresses that arise due to gravity loads, direct shear or other load configurations must be well withstood by sufficient sections and adequate reinforcement quantities and configurations for any possible loading conditions [1-6]. Beams are a type of member that usually are subjected to shear stresses due to their function of bearing gravity loads from floors. When reinforced concrete beams are built with a low ratio of the shear span to effective depth (a/d) of smaller than 2.0, they are classified as deep beams [7-12]. In such beams, high shear stresses develop, resulting in significant shear deformations that make the strain distribution through the beams’ depth non-linear. Therefore, the dominant failure in deep beams is the shear mode. As known, this mode is brittle and occurs suddenly without giving an appropriate warning. Accordingly, the deep beams should be built with sufficient shear strength to prevent such catastrophic collapse [7, 13-15].

The shear strength of deep beams is impacted by several factors like the concrete compressive strength, the flexural and web reinforcement, the ratio of total or shear span to the effective depth, and the existence of the skin reinforcement [7]. Up to recent times, many studies were conducted to improve the shear strength of deep beams through using materials other than the conventional steel stirrups [16-20]. Among these studies, Fiber Reinforced Polymers (FRP) were used to upgrade the strength of reinforced elements such as beams [21-25]. Lee et al. [14] disclosed that the mechanical...
properties of deep beams, including load-capacity, stiffness, and ductility, improved with lengthening the applied CFRP sheets. Islam et al. [26] conducted an experimental program in order to enhance the structural response of deficient deep beams by means of an externally attached FRP scheme. The results of the study illustrated that using a bonded FRP scheme resulted in much slower growth of diagonal shear cracks, accompanying with significant enhancement in the beams’ shear strength. Two methods of strengthening of deep beams were presented by Albidah et al. [27], which were CFRP and weld wires meshes placed around the longitudinal bars. Despite that two methods managed to increase the structural behavior of deep beams, the CFRP method was more effective than the form of wire meshes. Another procedure was introduced by Azam et al. [28], where cement-based composites and CFRP were applied to develop the strength of deep beams. The findings revealed that the CFRP strengthening gave more significant upgrading for the beams’ strength than the use of cement-based composites. Steel fibers were also used vastly as an internal short discrete strengthening material that can increase the load capacity, ductility, toughness and impact energy of concrete under static and impact loads [29-34].

Based on the previous discussion, additional studies to develop the structural performance of deep beams are required. Hence, this paper presented a method aiming at enhancing the shear strength of deep beams through using inexpensive and available materials, which were steel plates. These plates were used as an alternative web reinforcement; the effectiveness of these plates was investigated with variable a/d ratio.

2. Experimental program
In the presented work, three deep reinforced concrete beams were cast from normal concrete and tested in flexure. This study aims to investigate the flexure-shear behavior of deep beams reinforced with steel plates as shear reinforcement. Therefore, steel plates with 4 mm thickness and 20 mm width were configured, as shown in Figure 1(a) as continuous stirrup-like web reinforcement hoops. It is worth stating that steel plates were employed since they have sufficient strength and available as waste from the blacksmithing operations. Therefore, this usage is eco-friendly and relatively inexpensive.

The beams were fabricated with a total length of 1250 mm and cross-sectional width and depth of 150 and 300 mm, respectively. As the research goal is to investigate the shear behavior, the beams were provided with a sufficient quantity of tension reinforcement to prevent steel yielding and hence to assure shear failure. Two 20 mm diameter bars were utilized as bottom tension reinforcement for all three samples, while top bars of 10 mm were also adopted for the three beams. In addition to the top and bottom bars, four sidebars with 6 mm diameter were distributed along with the depth of each of the vertical sides of the section. The steel-plate hoops were distributed along the full span length at an equal spacing of 50 mm. The cross-sectional and longitudinal reinforcement details are shown in Figure 1.

The three types of steel bars (20, 10, and 6 mm) and the steel plate used as hoop stirrups were tested in tension in the laboratory to determine their mechanical properties, which are shown in Table 1. Ordinary Portland cement conforming to the Iraqi cement standards from a local Iraqi plant was used as the only binder material of the mixture, which was used at 410 kg/m³. The fine aggregate was river sand with a grading conforming to the requirements of the Iraqi standard, while 19 mm maximum aggregate size crushed gravel was used as the main filler of the mixture. The used quantities of the sand, gravel, and water in the mixture were 650, 1150, and 185 kg/m³, respectively. Three concrete cubes with 150 mm side length were taken from each mix batch (beam) and left in the curing tank with the cast beams for 28 curing days. The average compressive strength of cubes was 32 MPa.

The three beams were tested under a monotonic four-point flexural testing setup, as shown in Figure 2. The flexural span was 1000 mm, while the distance between the point loads was variable. As the main investigated parameter is the shear span-effective depth ratio (a/d), the beams were identical in all details, while the shear span was different. The beams DB1, DB2, and DB3 were tested with shear spans of 200, 330, and 465 mm, respectively, which gives approximately a/d ratios of 0.75, 1.25, and 1.75, respectively, as detailed in Table 2.
The central deflection of the beam was tested using an LVDT, while strain gauges were installed on the side surface of concrete and the tension steel bars. Five electrical-resistance strain gages were distributed along with the depth of the beam section, as shown in Figure 2, to capture the concrete sectional strain distribution. Similarly, two strain gauges were attached to the steel tension bars to monitor their stresses during the loading sessions, which allow checking the visualized failure pattern. The cracking of the concrete on the bottom and side surfaces of all beams were carefully inspected, and the crack width was recorded at each load step. Finally, the failure pattern of each of the three beams was carefully assessed based on visual inspection and strain records.

![Diagram of beam dimensions and reinforcement](image)

**Figure 1.** Details of beam dimensions and reinforcement of the deep beams

| Strength               | Ø 20 mm bars | Ø 10 mm bars | Ø 6 mm bars | 4 mm-thick Steel plates |
|------------------------|--------------|--------------|-------------|-------------------------|
| Yield Strength (MPa)   | 522          | 517          | 693         | 245                     |
| Ultimate Strength (MPa)| 617          | 608          | 713         | 353                     |

**Table 1.** Yield and ultimate strengths of the used steel bars and plate
Figure 2. The test setup of deep beams

Table 2. Shear span-effective depth ratios of the deep beams

| Beam ID | Shear Span (a) | Distance between Point Loads | a/d  |
|---------|------------|-----------------------------|------|
| DB1     | 200        | 600                         | 0.75 |
| DB2     | 330        | 340                         | 1.25 |
| DB3     | 465        | 70                          | 1.75 |

3. Test results

3.1. Cracking behavior and modes of failure
For all tested specimens, shear cracks appeared when the applied loads reached about 20.3 to 23.9% of the failure load. As the loading incremented, these shear cracks increased, expanded and advanced towards the loading points. At the peak loads, some of these cracks banded together to initiate one huge inclined crack that suddenly failed beams. Broadly, two distinctive modes of failure were registered; shear-compression failure and strut compression failure. For beams with a/d less than 1.25, DB2, and DB3, shear-compression failure was seen, where in addition to diagonal cracks developed between the supporting and loading surfaces, local concrete crushing in these surfaces was also detected. The second failure type was noticed in the beam DB1, strut compression failure, in which concrete crushing extended along the concrete strut bonded between points of loading and support. The cracking and failure loads were decreased with augmenting a/d ratio. Cracking loads of samples DB1, DB2, and DB3, with a/d ratios of 0.75, 1.25, and 1.75, were approximately 470, 420, and 408 kN. On the other hand, their failure loads were 112, 100, and 83 kN, respectively.

3.2. Load–deflection relationship
Figure 3 shows the load-central deflection of three considered beams. The responses were nearly identical, where two discrete regions for each curve was noted. Up to the ultimate loads, all responses were almost linear since a few flexural cracks appeared during the test events. Then, due to creating huge shear cracks with concrete crushing, the beams suffered enormous deformations without essential increments in the applied loads. Therefore, plastic plateau or softening in their responses was seen in Figure 3. Also, it can be discovered that the slope of linear parts of these curves, which represent the service stiffness [35-38], decreased while the a/d ratio increased. This result could be assigned to the significant produced moment that resulted in more cracking and hence less stiffness. Moreover, the area under these curves up to the ultimate strength, which defines the toughness of beams [37-42], was found to be reduced with enlarging the a/d ratio. This means, in other words, the deep beams absorbed more energy to experience a remarkable decline in the load-capacity as the a/d ratio dropped. Concerning the cracking and ultimate loads, these loads augmented when the a/d ratio decreased due to the fact that the loads were transmitted to the supports by means of concrete struts directly. The concrete struts became much apparent with a low a/d ratio. Compared with the DB1 beam, the cracking loads of beams DB2 and DB3 decreased, about 10.9% and 26.3%, whereas the collapse forces rose by nearly 10.6% and 13.3%, respectively.
3.3. Load-strain relationships

Figure 4 plots the variation in the strain of the tensile bars with the applied loads for the three beams. No beam arrived at the yielding strain since they failed due to brittle shear failure; the recorded strains were in the range of 43.8% to 57.82% of the yielding strain value. At the same force, the beam had the lowest a/d ratio, DB1, experienced the smallest strain of tensile bars of all beams.

Figure 5 states the strain in vertical reinforcement for all tested RC deep beams. All strain gages were installed at the mid of the shear span. In the early stages of loading, no noticeable strain readings were recorded since no cracking in concrete was initiated. After cracking, the readings start to increase up to the peak loads. Then, an excessive augment in the strain of steel plates was recorded due to creating huge inclined shear cracks. All plates reached the yielding strain, and also, the beams with the smallest a/d ratio exhibited the lowest values of strain for steel plates compared with the other two beams.

The strain profile across the depth of beams at their mid-span is plotted in Figure 6. As seen, the strain distribution for all beams was non-linear since, in deep beams, high shear deformations were produced due to a low a/d ratio. These deformations caused the non-linearity in the strain distribution through the beam depth. Also, it can be observed that there were multiple neutral axes; this is considered as a distinct characteristic for deep beams.

4. Conclusion

In this investigation, an experimental set was conducted to improve the structural performance of deep beams through using steel plates as an alternative web reinforcement. Three similar detailed beams were prepared and then tested by applying the four-point loads up to failure. In these tests, three
different ratios of the a/d were considered; 0.75, 1.25, and 1.75. according to the findings of the current study, the below points are the most crucial conclusions,

- All beams failed by brittle shear failure, and two types of this failure were noticed that are shear-compression and strut compression failures. These types were found to relate strongly to the a/d ratio.
- All beams showed similar load-deflection responses throughout the tests. However, the stiffness and toughness of beams increased as the a/d ratio was reduced.
- The shear strength of deep beams significantly enhanced as the a/d decreased.
- The tensile bars for all beams did not yield, and the strain profile across the beam depth was non-linear.

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