Tests on reinforced concrete deep beams with different web reinforcement types

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Abstract. Due to the high depth to span ratio, shear stresses in deeps impose the need for careful design of shear strength. The shear strength of any reinforced concrete beam is the sum of its sectional strength and web reinforcement strength. Steel bar stirrups are the typical reinforcing material up to date for such a purpose; however, many studies were conducted to evaluate the use of other materials or different configurations to increase the shear strength of deep beams. In this research, closed-form steel plates (gagger plates) were used as alternative shear reinforcement in experimental deep beams. Three beams were cast and tested in four-point bending to investigate this possibility. The first was kept as a reference beam as it was reinforced with conventional closed stirrups, while the rest two beams were reinforced with 4 mm thick and 20 mm wide gagger plates. One with in-plane configuration, where the 20 mm side was aligned in the plane of the beam section, while the third beam was reinforced with out-of-plane gagger plates. Based on the test results, the mechanical behavior of beams with steel plates was noticeably improved compared to the reference beam with conventional stirrups. The in-plane configuration was superior to the out-of-plane and reference beams in strength, service stiffness, ductility, and toughness.

Keywords: Deep concrete beam; web reinforcement, steel plate, shear failure; flexural test.

1. Introduction
Reinforced concrete deep beams are distinguished by their low shear span to effective depth ratio (a/d), which is smaller than 2.0 [1-6]. This low ratio leads to develop significant shear stresses that distribute non-linearly across the depth of beams [7-11]. Consequently, the shear strength is considered the governing issue in the design of deep beams [1, 12, 13]. Although it is known that all types of shear stresses are of major concern for designers due to their brittle failure manner [14-17], shear in deep beams is the major focus of research works in this field.
In the literature, extensive studies have been conducted to improve the shear capacity and to minimize the brittleness of deep beams. Fiber Reinforced Polymers (FRP) has been extensively employed to improve the structural behavior of reinforced concrete elements in the last decade [18-22]. Lee et al. [13] showed that the ultimate load, initial stiffness, and ductility of deep beams improved as the length of CFRP increased. These results were later confirmed by Li and Leung [23]. Albidah et al. [24] compared experimentally the structural behavior of deep beams strengthened by CFRP with those retrofitted by a mesh of weld wires placed around the longitudinal bars. The outcomes confirmed that both methods upgraded the shear capacity of deep beams, and the enhancement was more apparent when CFRP was used. Hybrid carbon/glass fiber reinforced polymer strips were also adopted in
improving the strength of deep beams by Ibrahim et al. [25]. This technique realized a 55.8% increase in the shear capacity of deep beams with augmenting their deformations. Fabric-materials such as glass, carbon, and poly-paraphenylene benzobisoxazole were employed to develop the strength of deep beams by Wakjira and Ebead [26]. The use of these materials resulted in upgrading in the shear capacity of RCDBs up to 56.2%. However, a remarkable increase in the ductility of deep beams was not observed. Azam et al. [27] used cement-based composites and CFRP in upgrading the strength of RCDBs. The findings improved that the strength enhancement using CFRP was more considerable than the method of using cement-based composites. Steel fiber was also found as one of the efficient solutions to enhance the strength and durability of concrete. Steel fibers with lengths from 6 to 60 mm can significantly improve the flexural behaviour of beams [28, 29]. Previous studies showed that steel fibers can also increase the impact resistance and energy absorption capacity several times compared to nonfibrous concretes [30-35].

The previous methods seem to be expensive and time-consuming, and therefore, the search for other simple ways to strengthen the resistance of deep beams is still necessary. In this study, an innovative method to upgrade the structural behavior of deep beams was presented in which gagger steel plates were utilized as shear reinforced instead of conventional bars. The current investigation included preparing and testing three deep beams, which were similar in all properties, except for the web reinforcement. In the control beam, the web reinforcement was conventional stirrups made of 6 mm bars, whereas in the remaining two beams, steel plates with dimensions of 4×20 mm were utilized as shear reinforcement. These plates were positioned in two different directions with respect to the cross-sectional plane of beams.

2. Experimental Program

2.1. Mixture and materials

The experimental program of this study includes the casting and testing of three beams with deep sections. Normal strength concrete was used to cast the three deep beams with a mixed design cylinder compressive strength of 25 MPa. All the materials used to prepare the concrete mix were provided from local material plants. The cement was ordinary Portland cement, while the fillers were sand and gravel. The used sand was well graded, while the maximum size of course aggregate was 19 mm, which is a well-graded crushed stone aggregate. The mix quantities of sand and gravel were 650 and 1150 kg/m³, respectively. Considering the cement quantity of 410 kg/m³, the filler-to-cement ratio is approximately 4.4, which makes it an economical mix with reasonable strength, where the average compressive strength was 32 MPa based on standard 150 mm cubes. The water-to-cement ratio was approximately 0.45, with a total water quantity of 185 kg/m³. Three steel reinforcing bars were used in this study with three diameters of 6, 10, and 20 mm. The recorded yield strength values of the three bars were 693, 517, and 522 MPa for the 6, 10, and 20 mm bars, respectively, while their ultimate tensile strengths were 713, 608, and 617 MPa, respectively. On the other hand, the yield strength and ultimate strength of the 4×20 mm steel plates were 245 and 353 MPa, respectively.

2.2. Details of the Deep Beams

Excluding the type of shear reinforcement, all of the other geometrical and reinforcement details of the three beams are identical. The depth of the beams’ section was 300 mm with an effective depth of 264 mm, which resulted from a 20 mm concrete cover and 6 mm stirrups. On the other hand, the width of the section was 150 mm, while the beam length was 1250 mm. All of the three beams were reinforced with the same quantities of tension (bottom), compression (top), and side reinforcements of 2Ø20 mm, 2Ø10 mm, and 8Ø6 mm, respectively, as shown in Figure 1. The only difference is the adopted type of web reinforcement, as shown in Figure 2, while the spacing of web reinforcement along the span is the same for all beams, which was 50 mm. The web reinforcement sectional details of the three beams are shown in Figure 1 and listed in Table 1. The first beam was reinforced with the typically closed bar stirrups with a diameter of 6 mm. This beam was denoted as STR, referring to the stirrups shear reinforcement. On the other hand, 4×20 mm steel plates fabricated in a closed rectangular form were used as web reinforcement in the second and third beams. However, in the second beam, the plates
were aligned out of the section plan so that its longer sectional direction (20 mm) was parallel to the beam span. Therefore, this beam was denoted as OPSP, referring to the type of web reinforcement, which is an out-of-plane steel plate. The web plates in the third beam were aligned in the sectional plan, with the 20 mm side being perpendicular to the span. Hence, the beam identification was derived from the term in-plane steel plates (IPSP). The dimensions of plates were selected to produce a similar yielding force as the 6 mm-bars.

2.3. Flexural Test
The beams were tested monotonically under the flexural four-point test with the span divided into approximately equal two shear spans and one intermediate zero-shear span, as shown in Figure 2. The deflection at the center of the beam’s span was measured using one linear variable differential transducer (LVDT), while the load was captured using a 1000 kN capacity load cell. In addition to load and deflection, strain measurements were also obtained for the tested beams. Steel strain gages were attached to the tension bars and the web reinforcement (in the shear span) and embedded in the concrete (Figure 2). Similarly, five concrete strain gages were aligned along the vertical centerline of the beam side surface, as shown in Figure 2. The readings from the load cell, LVDT, and strain gages were simultaneously recorded using a universal data logger. As the beam was gradually loaded by steps of 5 kN, the surface cracks were visually inspected, which allowed monitoring the cracking response of the beams step-by-step.

![Figure 1. Sectional characteristics of the tested deep beams](image1.png)

![Figure 2. Span details of the tested deep beams](image2.png)

| Beam ID | Tension Reinforcement | Compression Reinforcement | Shear Reinforcement |
|---------|-----------------------|---------------------------|---------------------|
| STR     | 2Ø20 mm               | 2Ø10 mm                   | Ø6 mm stirrups @50 mm |
3. Discussion of experimental results

3.1. Failure modes and cracks patterns

Table 2 summarises the loading test results of the three beams from cracking to failure. The behavior of all deep beams was similar at the initial stages of loading. As the applied load was augmented, the first cracks appeared when the applied load reached (17.03% - 23.9%) of the ultimate load in the region between two points load. Afterward, new flexural cracks appeared, expanded, and extended toward the top surface of beams. Before reaching the peak loads, diagonal cracks in the shear zone were seen. These inclined cracks then developed and were the reason for the failure of the beam. Two modes of failure were distinguished based on the development of diagonal cracks, as illustrated in Figure 3. Diagonal splitting failure was the first pattern recognized. In this mode, the oblique cracks advanced as a straight line passing through loading and supporting points. Specimen STR failed due to this mode at a force of 352.87 kN. The second mode, shear-compression failure, was experienced by beams having steel plates, OPSP and IPSP. In this failure, in addition to the diagonal cracks, concrete crushing also happened at supporting and loading points.

| Beam ID | Cracking load (kN) (CL) | Ultimate load (kN) (UL) | % CL/UL | Percentage increase in CL | Percentage increase in UL | Failure types          |
|---------|------------------------|------------------------|---------|--------------------------|--------------------------|------------------------|
| STR     | 62.45                  | 352.87                 | 17.7    | Reference                | Reference                | diagonal splitting     |
| OPSP    | 72.41                  | 406.78                 | 17.8    | 15.95                    | 15.28                    | shear compression      |
| IPSP    | 100.12                 | 420.32                 | 23.82   | 60.32                    | 19.11                    | shear compression      |

Figure 3. Failure modes of the tested specimens
Generally, the specimens with steel plates experienced fewer cracks when compared with the control beam reinforced by bars, as plotted in Figure 4. This observation reflects the capacity of steel plates to delay the initiation and expansion of cracks. Accordingly, the beams with plates cracked at loads higher than the control beams, by around 16% and 60.3% for beams OPSP and IPSP, respectively.

Concerning the ultimate loads, a significant improvement in the shear strength of deep beams was registered because of using steel plates as an alternative web reinforcement. Compared to the reference beam, the enhancement in the shear strength of deep beams approached 15.3% and 19% for beams OPSP and IPSP, respectively.

The above discussion revealed that placing the steel plates in the plane of the beam cross-section area was more effective than positioning them out of the plane. This was due to existing plates in the broader area when they were directed in the plane of cross-section. Therefore, more resistance to cracking was obtained.

3.2 Load-deflection response

Figure 5 depicts the deflection recorded at the center of beams against the applied loads. It can be noted that the curves of beams were almost identical, with marginal differences up to 300 kN. After that, the divergence in these curves got apparent. At this level, the reference beams exhibited a deterioration in its stiffness, and the stirrup bars could not be able to provide more confinement. Therefore, more cracks grew and expanded, and thus, an excessive deflection with a slight increase in the applied load was disclosed for the reference beam. On the other hand, the presence of steel plates retarded the cracking; and the decay in the stiffness was postponed up to a load level of 400 kN. Then, the plastic plateau appeared until occurring the failure.

The stiffness is an important measurement to define the load-deflection behavior of flexural members [28, 36]. However, another exciting conclusion was that the area under these curves demonstrates the ability of beams to absorb energy before the collapse. These areas, as seen in Figure 5, increased remarkably due to the steel plates. This means that the toughness of deep beams improved when steel plates were employed as an alternative form of web reinforcement. The toughness value defines the ability of reinforced concrete members to resist the dynamic loads [29, 37-41], and hence, installing the steel plates makes the deep beams more suitable for constructions at seismic zone.

3.3 Load-strain relationships

Figure 6 shows the variation in the strain of tensile bars at mid-span with the applied loads for the three considered beams. The recorded strains ranged from 52% to 68.8% of yielding strain. At the start of tests, the strain readings were marginal, and then, a noticeable increase in these readings was observed due to cracking the concrete and transferring the stresses into tensile reinforcement. It is evident from this figure that the beams reinforced by steel plates displayed lesser strain than that
recorded in the reference beams at the same force. This was due to restricting the plates the growth of cracking, and therefore, smaller stresses transmitted to the tensile bars of beams with plates compared to the control beam. However, the tensile bars did not attain the yield limit since all beams failed because of shear.

Figure 7 shows the strain of vertical web reinforcement recorded at each increment of applied loads for all beams. These curves can be divided into three parts. In the first part, negligible values of strains were measured for all beams up to nearly 100 kN because no inclined cracks were generated at this range. After the appearance of shear cracking, excessive strain values for web reinforcement were read since the web reinforcement resisted significant shear stresses. At the peak loads, the third part was shown in which an enormous rise in the strain of web reinforcement was noticed without an essential change in the applied loads. Despite the fact that steel plates produced remarkable confinement against crack growth, the plates gave less strain than bars at the same force during the test events.

Figure 8 illustrates the concrete strain variation across the depth of the beams at their mid-spans measured at the failure loads. As seen, the strain distribution of concrete for all beams was non-linear through the depth of the beam. This non-linearity in strains is attributed to the considerable deformation due to high shear stresses developed in the deep beams. Also, the deep beams showed more than one neutral axis. However, these axes diminished as the applied load increased. Due to the ability of plate to limit the growth of cracks, the compression area above the neutral axis for beams with plates was larger than that of the control beam.
4. Conclusions

In this paper, an experimental attempt was introduced to improve the strength of deep beams by using steel plates as web reinforcement instead of the traditional bars. Three specimens were fabricated in similar details except for the shear reinforcement. One of them was a reference, where 4mm-bars were used as stirrups. In the remaining two beams, steel plates with dimensions of 20×4 mm were utilized as shear reinforcement in two designations; in or out the plane of beams cross-sections. The beams were tested by applying four-point loading until collapse, and the followings are the main outcomes of the study:

- All beams failed due to shear, but two distinguished modes were observed. The first mode was the diagonal splitting, which was experienced by the reference beams. The shear-compression was the second mode that was exhibited by beams with steel plates.
- The existence of steel plates helped restrict the growth and expansion of cracks, and due to this characteristic, beams with plated cracked at loads higher than that of the reference beam by about 16% - 60.3%. Also, they failed at loads 15.3% - 19% greater than that of the reference beam.
- The beams with plates displayed a stiffer response in comparison with the control beam. Moreover, they had a higher toughness.
- Since all beams exhibited brittle failure, the strain of the tensile bars did not arrive at the yielding limit. Besides, the strain distribution across the beams depth was non-linear, and the compression zone of the beams with plates was broader than in the control beams.

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