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Research paper

New Technique to Enhance the Shear Performance of RC Deep Beams Using Mild Steel Plates

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Abstract

This study suggested a new technique to improve a behavior of RC deep beams using mild steel plates as a vertical web reinforcement rather than the conventional rebars. Nine simply supported RC deep beams were tested under the effect of four-point load with a ratio of shear span to an effective depth (a/d) ranged from 0.75 to 1.75 at intervals of 0.5. The test specimens were divided into three groups, each one included three beams. The first group included specimens with conventional vertical web reinforcement. The second and third groups included specimens with mild steel plates as the vertical web reinforcement. The mild steel plates in the second and third groups were configured as strips and sheets, respectively. All the specimens had a length of 1200 mm, a clear span of 900 mm, and a rectangular cross-section of 150 mm wide and of 300 mm depth. The test results confirmed that both of mild steel plate configurations contributed effectively in improving the ultimate load capacity of tested beams, compared with those of conventional shear re-bars, by about (15.4% to 28.26%) and the ductility factor by about (6.06% to 30.56%). Furthermore, specimens with mild steel plates had a low sectional height under tension by about (10.11% to 32.08%).

Keywords: *Deep Beams, Steel plates, Stirrups, Reinforced concrete, span to depth ratio.*

1. Introduction

RC deep beams are usually used in different structures such as off-shore structures, pile caps, foundations, slabs under the horizontal loads, etc. [1-5]. According to ACI 318-2014[6], deep beams are structural members loaded on a single face and transmitting an applied load to an opposite supported face. Moreover, they should satisfy one of the following conditions:

(1) The ratio of clear span to the total depth for a section does not exceed four.

(2) The ratio of shear span to effective depth does not exceed two [6].

The shear strength is a dominant issue in designing the RC deep beams where a large amount of an applied load is transmitted to supports through a diagonal concrete strut because of a relatively low (a/d) ratio [7-8].

The web reinforcement enhances significantly the shear strength of RC deep beams by confining the concrete, and delaying an appearance and limiting a spread of inclined cracks. Thus, making the failure is more ductile [9].

Several studies confirmed that the shear capacity of RC deep beams increased linearly with increasing the vertical web reinforcement [10-16]. However, an experimental study, conducted on 52 deep beams by Smith [5], confirmed that the vertical web reinforcement had a marginal effect on enhancing the shear capacity at (a / d) ratio less than one. The same conclusion was confirmed by Ashura [17] but when (a / d) was less than 0.75.

Many investigations were presented to explain the influence of beams' size on their shear strength without web reinforcement. Earlier one carried out by Kani[18], in 1967, confirmed that a 40% reduction in the shear strength was observed when the depth of R C deep beams was increased to four times. Similarly, Shioya et al [19] in 1989 reported a 25% drop in the shear capacity of deep beams with enlarging their thickness from 1200mm to 3000mm. There are two common explanations for the reduction in shear strength with increasing the depth of deep beams; the first explanation is due to a decrease in the aggregate interlock because of the growth of wider crack. The second one is attributed to release more an energy when the crack is formed, leading to faster interconnection for the cracks formed with increasing the depth of the deep beams [20-21].

Recently, many studies were presented to enhance the shear strength of RC deep beams using FRP composite. In 2004, Zhang and Moren [22] explored the ability of CFRP in improving the shear strength of deep beams. They reported that the strengthening by this technique had a limited effect, as the shear span to depth ratio declined. Islam et al [23] stated that a 40% enhancement in shear strength of deep beams was realized when the a/d ratio was 1.3, as a result of employing the CFRP sheets in strengthening. Light-weight deep beams were externally CFRP-strengthened by Asghari et al [24]. These beams had a/d ratio of 1.0, and the test results announced a 30% improvement in the shear strength. Same enhancement was reported by Khudair and Atea[25] when they utilized CFRP sheets in strengthening self-compacting concrete deep beams, having a/d ratio of 2.0.

However, the strengthening by CFRP sheets is limited to an external use and it needs more efforts to prepare the surfaces where these sheets to be applied and to install the sheets on these surfaces. This

leads to be CFRP-technique of high cost. Moreover, although the strengthening by CFRP increases the shear strength of the deep beams considerably, it makes these beams more brittle.
This paper aims at improving the shear strength and ductility of deep beams through an experimental program, in which mild steel plates were introduced as a web reinforcement. The test parameters were; the orientation of steel plate and the a/d ratio.

2. Experimental program

2.1. Test specimens

The experimental program consisted of nine simply supported RC deep beams fabricated with a rectangular cross section of (150mm by 300mm) and a length of 1200 mm. The samples were designed to experience a shear failure. All beams were longitudinally reinforced at top and bottom with2 Ø 10, 2Ø20, respectively. Moreover, these specimens were provided with a skin reinforcement, which was Ø6 distributed in both sides of the web at a spacing of 50mm center to center.
The shear reinforcement was varied and the specimens were categorized into three groups, each one containing three samples. Rebar with 6mm-diameter was adopted in group one. In the remaining two groups, mild steel plates with a cross section of 20 by 4 mm were used. In group two, these plates were orientated so that the long side was parallel to the length of the specimens, this configuration was briefed as a shell configuration. Nevertheless, the steel plates were presented in-group three so that their long side placed perpendicularly with the beam axis, this arrangement was known as a strip. In general, the shear reinforcement was supplied in all specimens with a shape of a closed stirrup distributed equally along the beam at a 50 mm-distance, as illustrated in Figure (1a). Table (1) shows the mechanical properties of all re-bars and steel plates used, which were evaluated according A615/A615M − 15a [26] and E8/E8M − 15a[27] , respectively. It is worth to mention that the steel plates had a yield force (i.e, a yield strength by an area of the cross-section) equal to that of the 6mm-diameter bar. The reinforcement cages, as demonstrated in Figure (1b), were positioned inside the molds, leaving 20mm as a concrete cover.
All specimens were built using the same concrete mix, as summarized in Table (2). This mix achieved a cubic compressive strength of 32 MPa. The compressive strength test was performed according to ASTM standardC192/C192M – 15 [28].
It may be noted that the specimens were identified by a code comprising two terms, the first one refers to the adopted shear reinforcement (i.e, DS= steel bar closed stirrups, DPST. = strips mild steel plates and DPSH. =sheets mild steel plates) and the second one indicates the (a/d) ratio (0.75, 1.25 and 1.75.

2.2. Test setup and instrumentation

The specimens were tested using four-point loading system with a various shear span to depth ratio (0.75, 1.25, and 1.75), as listed in Table (3). The load control technique was adopted. Firstly, the load was increased at an interval of 5kN until initiating the first crack. Thereafter, the load was increased with an interval of 10 kN up to specimens' failure. The load was applied using a hydraulic jack of 1000 kN capacity, as shown in Figure (2). A load cell, inserted between the jack and the specimens, was employed to measure the load accurately. The strains were evaluated, using an electrical straingauges, located at mid-span for longitudinal bars and at mid of shear span for shear reinforcement, as shown in Figure (1). Additionally, the location of neutral axis was inspected using strain gauges distributed equally across the specimens' depth and fixed on the exterior side face at the mid-length of the specimens where the maximum flexural moment was expected to occur. The vertical displacements were also indicated, employing three linear variable differential transducers (LVDT) located in contact with the lower specimens' face at center and thirds.

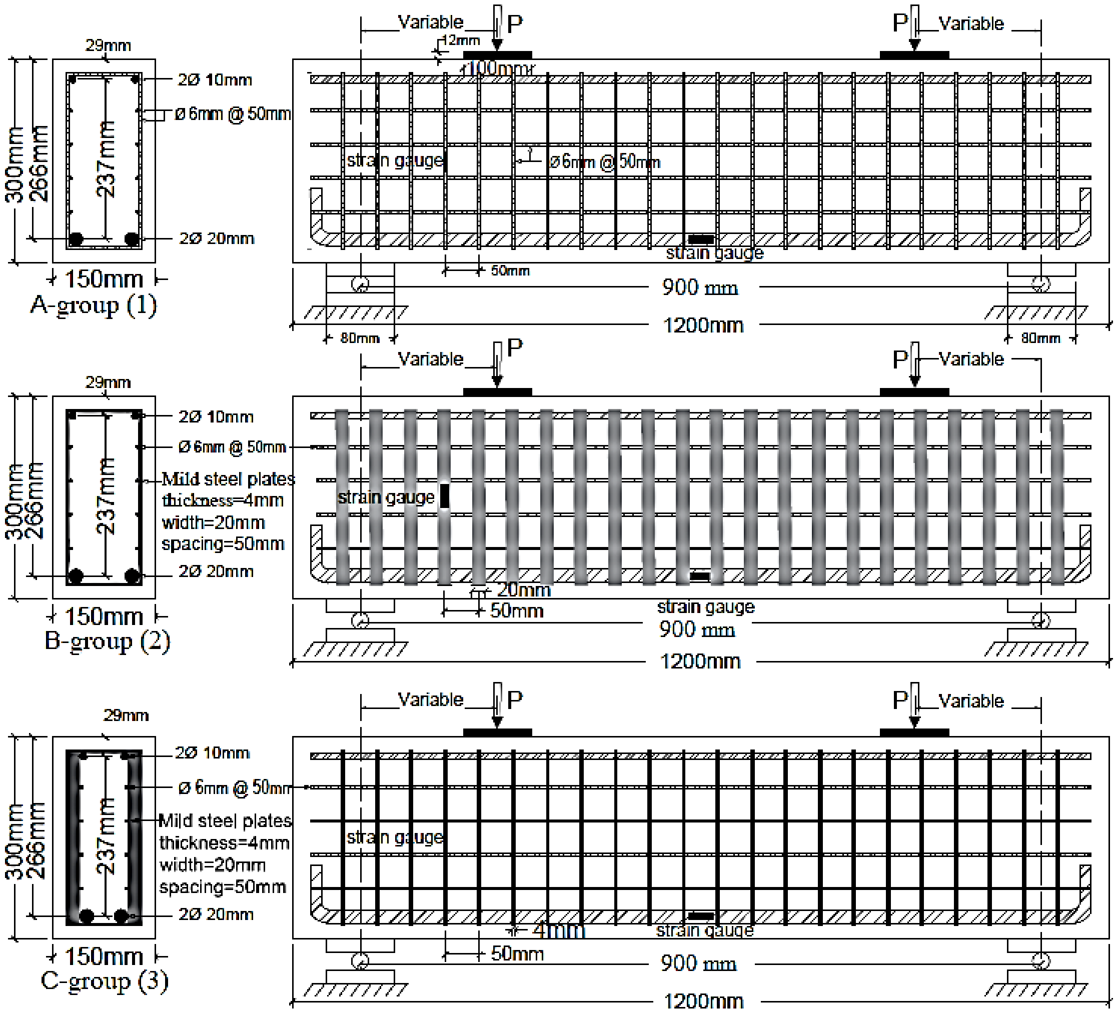
All these test data acquisitions were connected to a data logger that was programed to record readings for each one second of the experiment time. The load, causing a first crack, was registered, the crack propagation was traced carefully with each a load increment. At the test end, the collapse load as well as the failure mode were specified accurately.

Table 1: Mechanical properties of steel bars and mild steel plates.

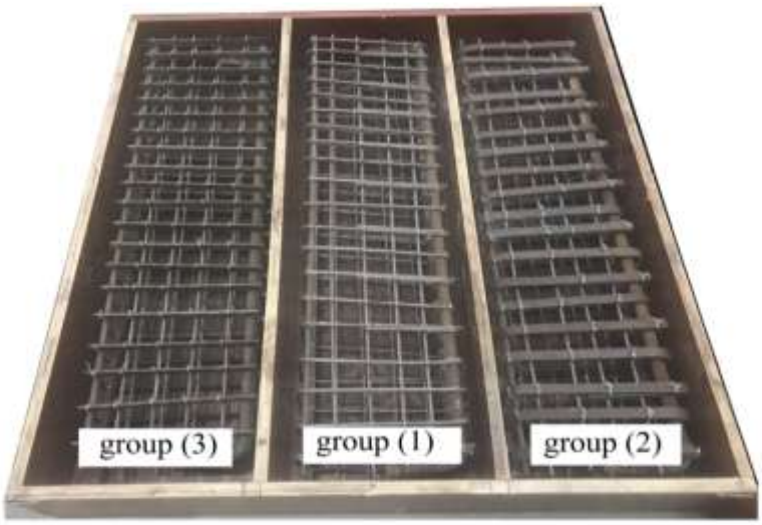
Steel type	Yield strength (MPa)	Ultimate strength (MPa)	Yield strain (Micro- (Micro-strain)	Ultimate strain (Micro-strain)
Steel bar (Diameter 6mm)	693.2	712.5	3500	3712
Steel bar (Diameter 10mm)	517	607.5	3000	3125
Steel bar (Diameter 20mm)	522	617.2	2500	2625
Steel plate Thickness 4mm	245	353.4	2880	3000

Table 2: Mix proportions of concrete

(W/C) Ratio	Water (Kg/m3)	Cement (Kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)
0.45	185	410	650	1150



(a) Sketch of tested specimens.



(b) Beam specimens before concreting

Fig.1: Details of specimens.

Table 3: Description of tested specimens.

Beam		a/d	Bottom Rein-forcement	Top reinforcement	Horizontal shear reinforcement	Vertical shear reinforcement
Group	Designation					
1	DS -0.75	0.75	2 Ø 20mm	2 Ø 10mm	Ø6mm@50mm	closed stirrups Ø6mm@50mm
	DS – 1.25	1.25	2 Ø 20mm	2 Ø 10mm	Ø6mm@50mm	closed stirrups Ø6mm@50mm
	DS - 1.75	1.75	2 Ø 20mm	2 Ø 10mm	Ø6mm@50mm	closed stirrups Ø6mm@50mm

2	DPST.- 0.75	0.75	2 Ø 20mm	2 Ø 10mm	Ø6mm@50mm	steel plates thickness = 4 mm width (Wm) = 20mm spacing = 50 mm strips distribution
	DPST.- 1.25	1.25	2 Ø 20mm	2 Ø 10mm	Ø6mm@50mm	steel plates thickness = 4 mm width (Wm) = 20mm spacing = 50 mm strips distribution
	DPST.- 1.75	1.75	2 Ø 20mm	2 Ø 10mm	Ø6mm@50mm	steel plates thickness = 4 mm width (Wm) = 20mm spacing = 50 mm strips distribution
3	DPSH.- 0.75	0.75	2 Ø 20mm	2 Ø 10mm	Ø6mm@50mm	steel plates thickness = 4 mm width (Wm) =20mm spacing = 50 mm sheets distribution
	DPSH.-1.25	1.25	2 Ø 20mm	2 Ø 10mm	Ø4mm@50mm	steel plates thickness = 4 mm width (Wm) = 20mm spacing = 50 mm sheets distribution
	DPSH.-1.75	1.75	2 Ø 20mm	2 Ø 10mm	Ø6mm@50mm	steel plates thickness = 4 mm width (Wm) = 20mm spacing = 50 mm sheets distribution

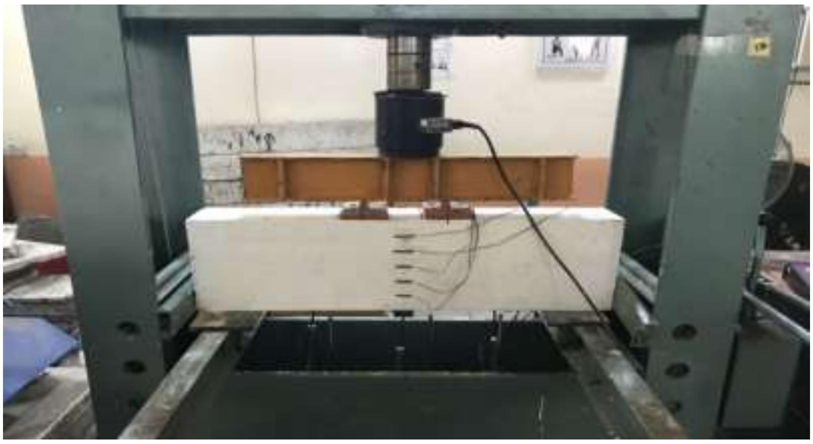


Fig.2: Beam specimen setup.

3. Test results

3.1. Cracking patterns and failure modes

At early stages of loading, all specimens showed a compatible behavior. They were cracked firstly in the zone between loading points at loads ranging 17.13% to 23.51% of the corresponding collapse loads. Subsequently, new flexural cracks began to develop with increasing the applied loading; they also propagated towards the upper face of beams. Then, an initiating of diagonal cracks was observed in the shear span, especially next to supports. At failure, three-collapse mode were noticed depending on the developing the diagonal cracks, as illustrated in Figure (3). The first pattern was a diagonal splitting failure, where the diagonal crack extended between the loading and supporting points. This mode was shown in samples DS –1.75 and DS - 1.25 at a failure load of 316.5 and 350.22 kN, respectively.

The second one, shear compression failure, was observed in specimens DPST.- 1.25, DPST.- 1.75, DPSH.– 1.25 and DPSH.- 1.75 at a failure load of 418.11,405.93,404.14 and 382.28 kN, respectively. In this mode, the diagonal cracks created within the shear span, extending from a point adjacent to support, to a loading point. Additionally, this failure was companied with crushing of concrete at points located in the flexural zone close to a loading point.

The strut compression failure was the third mode, which specimens with a/d ratio of 0.75 experienced at failure loads ranged from 396.01 to 467.97 kN. Since the shear span in these specimens was relatively small, the loading was transferred directly through a path, strut, extending between the points of loading and support. Therefore, the compression stress in this path was significantly large leading to crush the concrete.

In general, the specimens with steel plates, comparing with those with bars, experienced less cracks. In addition, these cracks distributed at a large spacing and did not much widen. Figure (4) compares the failure modes of specimens with a/d of 1.25.

It is worth to illustrate that the existing of mild steel plates as the shear reinforcement led to delay the initiation of the first cracks and enhance noticeably the failure loads, compared with similar specimens supplied with bars. The cracking load in groups two and three were 50.94% -66.67 % and 16.67- 35.71% respectively, larger than those of group one. Similarly, an increase in collapse load of about 18.17% - 28.26% and15.40%-20.78% was indicated in groups two and three, respectively. Table (4) briefs the test results.

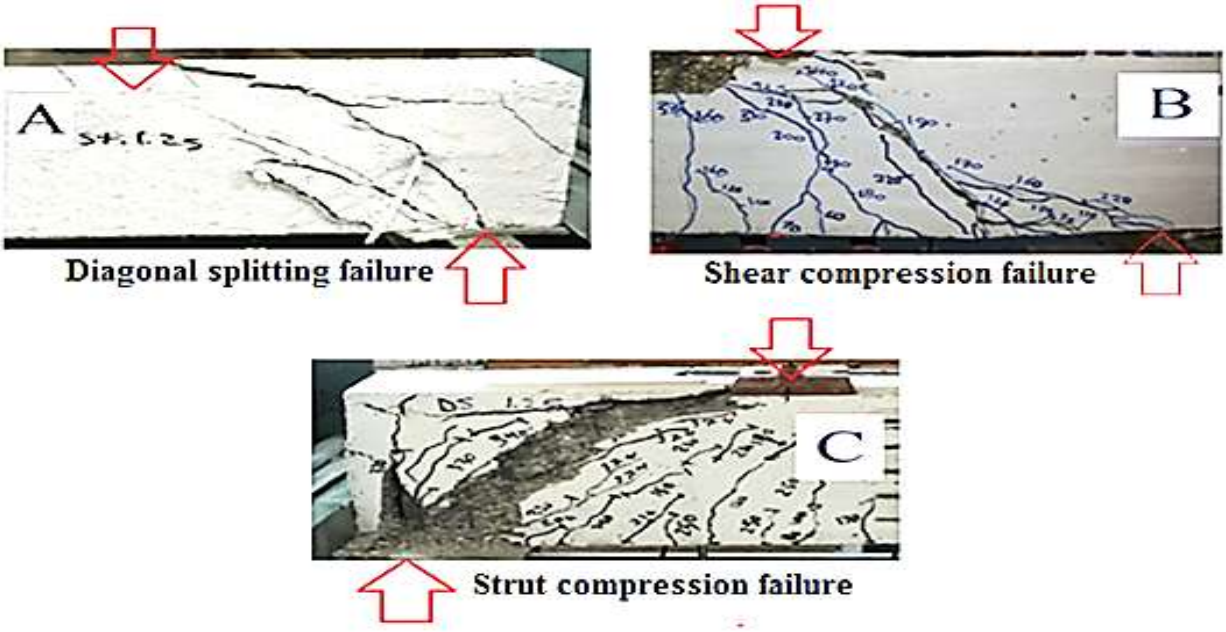


Fig.3: Failure modes of tested specimens.

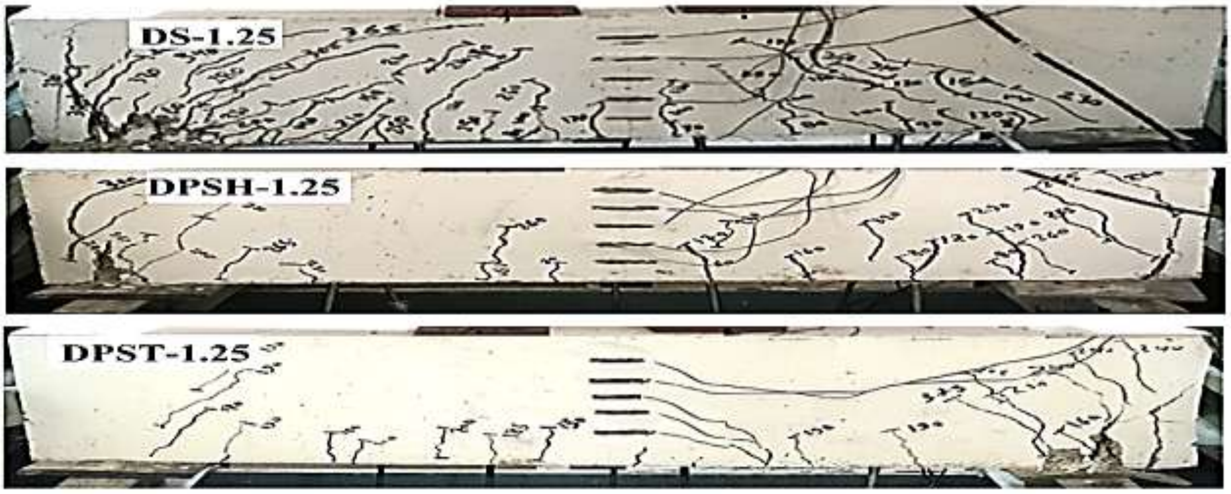


Fig.4: Cracks pattern for the specimens with (a/d =1.25).

Table.4:.Experimental test results.

Beam		First flexural cracking load, kN (Pcr.f)	failure load, kN	% Pcr.f/Pu	%Increase in first flexural cracking load with respect to control	%Increase in ultimate load with respect to control	failure modes
Group	Designation						
1	DS– 1.75	53	316.5	16.75	Control	Control	diagonal splitting
	DS – 1.25	60	350.22	17.13	Control	Control	diagonal splitting
	DS – 0.75	70	396.01	17.68	Control	Control	strut compression
2	DPST.–1.75	80	405.93	19.71	50.94	28.26	shear compression
	DPST.- 1.25	100	418.11	23.92	66.67	19.38	shear compression
	DPST. –0.75	110	467.97	23.51	57.14	18.17	strut compression
3	DPSH.- 1.75	65	382.28	17.00	22.64	20.78	shear compression
	DPSH.– 1.25	70	404.14	17.32	16.67	15.40	shear compression
	DPSH.– 0.75	95	458.2	20.73	35.71	15.70	strut compression

3.2. Load-deflection relationship

The relationships between the applied loads and the vertical mid-span deflections are shown in Figures (5) to (7) for specimens with a/d ratio (0.75-1.75), respectively. These figures clarify that all specimens exhibited a linear response before creating the first cracks. Subsequently, their response becomes non-linear because of a decline of stiffness due to the emergence and increase cracks.

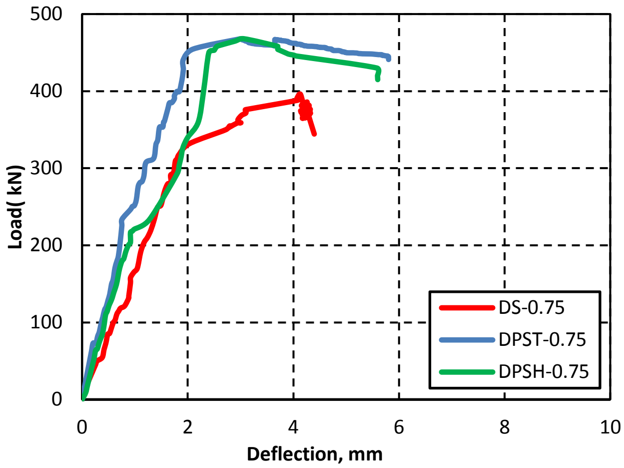


Fig. 5: Load-midspan deflection relationship of tested specimens with (a/d=0.75).

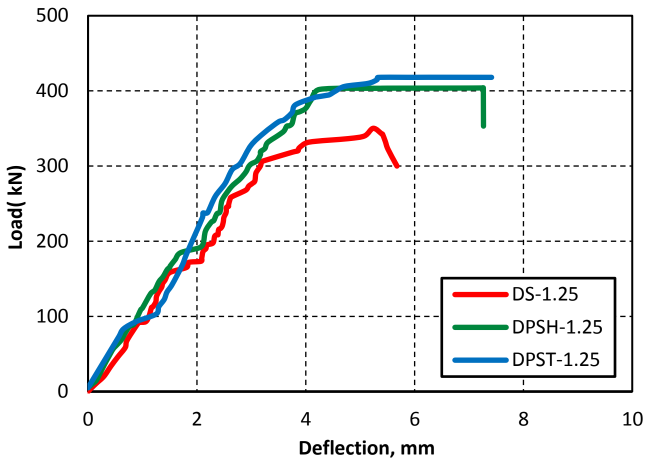


Fig.6: Load-midspan deflection relationship of tested specimens with (a/d=1.25)

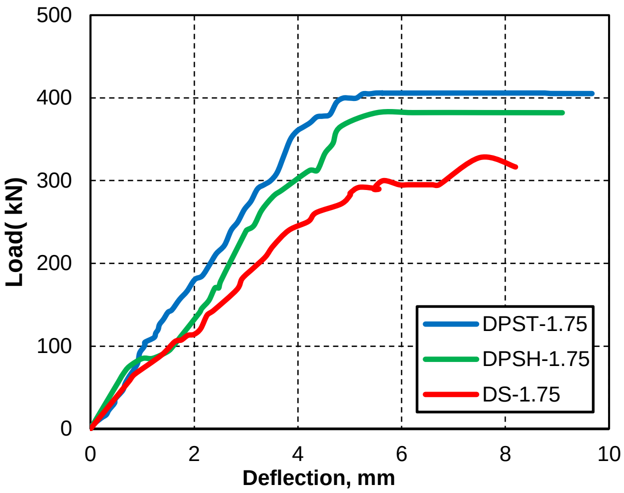


Fig. 7: Load-midspan deflection relationship of tested specimens with (a/d=1.75).

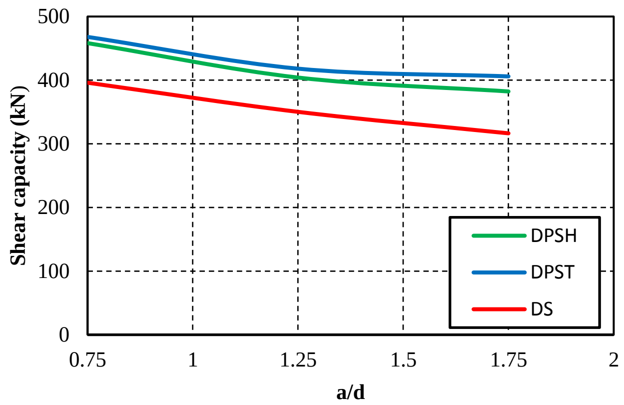


Fig.8: Relation between shear force and shear span to depth ratio.

Moreover, the steel plate specimens offered stiffer behaviors than those of bar specimens; especially those had steel plates with the strip configuration. This could be attributed to the ability of the steel plates to confine the propagation, widening, and growth of the cracks as illustrated in Figure. (4).

3.3. Effect of shear span to depth ratio

The shear span to depth ratio (a/d) had a consistent effect in all tested RC deep beams as plotted in Figure (8). The experimental results confirmed clearly a significant increase in shear capacity with decreasing in the value of (a/d); this is consistent with many previous studies [29-35]. The enhancement in the shear strength reached 25.12%, 19.86% and 15.28% for groups (1), (2) and (3), respectively, as (a/d) ratio reduced from 1.75 to 0.75. This enhancement was a result of the arch action that became more effective with a low a/d ratio, due to an increase in an angle bounded between the longitudinal axis of the RC deep beams and the diagonal strut, which led to the transfer of the shear force to the nearest support, be more effective. Furthermore, the increasing of (a /d) ratio led to increasing tensile strain which in turn led to decrease the compression capacity of the inclined strut.

3.4. Load-strain relations

Figures (9) to (11) present the relationships between the applied loads and strains which evaluated in the bottom bars at mid-span of test specimens. In these curves, a marginal strain was indicated at the pre-cracking stage. After this, the bottom bars strained more and more up to failure. However, the bottom bars did not reach the yield strength, since the specimens experienced no flexural failure as stated previously. At failure loads, the strain of bottom bars realized 50%-72.8% of the yielding strain.

On the other hand, the ability of mild steel plates in restricting the crack growth was obviously reflected on the strain indicated in bottom bars, where these specimens showed smaller strain in the respect with bar specimens. In group two and three, these strains were 19.34% -21.42% and 7.14% - 10.16% below the corresponding in group one, respectively.

Figures (12) to (14) graph the strain induced in shear reinforcement versus the applied load. Since a large amount of diagonal tensile stress was resisted by the concrete in the shear span before appearing the diagonal cracks, the strain values recorded in the shear reinforcement were relatively trivial. Beyond reaching the applied load (53 - 70) kN, (80- 110) kN and (65 - 95) kN for the groups (1), (2) and (3), respectively, the shear cracks began to develop. As a result of that, the shear reinforcement strained rapidly, furthermore, the steel plates strained lesser than the bars at same loading level. In general, the strain in shear reinforcement of similar specimens augmented with a rising in a/d ratio. This was attributed to develop the concrete strut, transferring the load to supports, as a/d ratio dropped. The web reinforcement did not yield in specimens of 0.75 a/d. For other specimens, the steel plates yielded only. Comparing with bar specimens, (6.26% - 16.85%) and (3.12% -12.42%) increment in ultimate strain were noted in groups 2, and 3, respectively.

The profiles, representing concrete strain distribution across the specimens' depth in the failure load of the R C deep beams, are shown in Figures (15) to (17). It can be noticed that the concrete strain distributed nonlinearly due to a considerable shear deformation in RC deep beams. This is in contrast with shallow beams, where the sectional plane did not remain linear after a deformation, this result was comparable to one introduced by [31]. Generally, the deep beams developed more than one neutral axis and these axes declined with augmenting the applied load. However, the specimens of steel plates showed a smaller tension sectional height, under the neutral axis, compared with those reinforced by bars. The reduction in tension area achieved (20.07%, 10.11%, and 17.45%) for the specimens DPSH.- 0.75, DPSH.-1.25 and DPSH.-1.75, respectively, and (26.58%, 20.89% and 32.08%) for the specimens DPST.- 0.75, DPST.- 1.25 and DPST.- 1.75 , respectively , compared with a similar one with shear bars.

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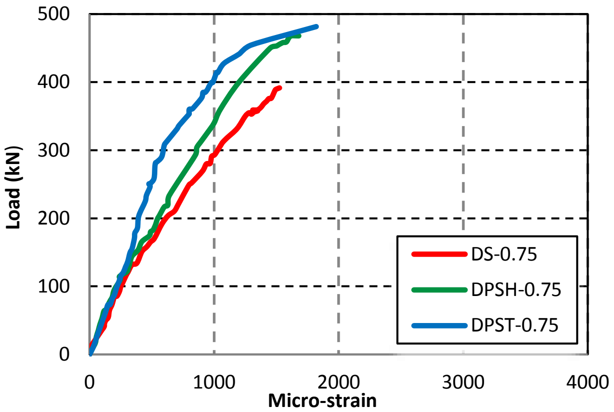

Fig.9: Load–midspan strain relationship for bottom reinforcement of tested specimens with(a/d=0.75).

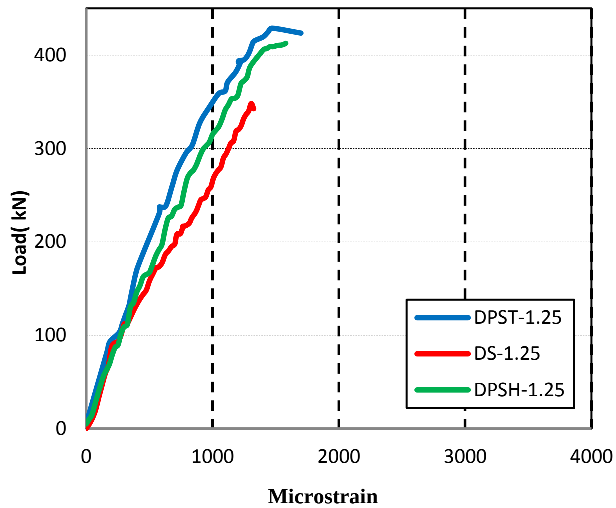

Fig.10: Load–midspan strain relationship for bottom reinforcement of tested specimens with (a/d=1.25).

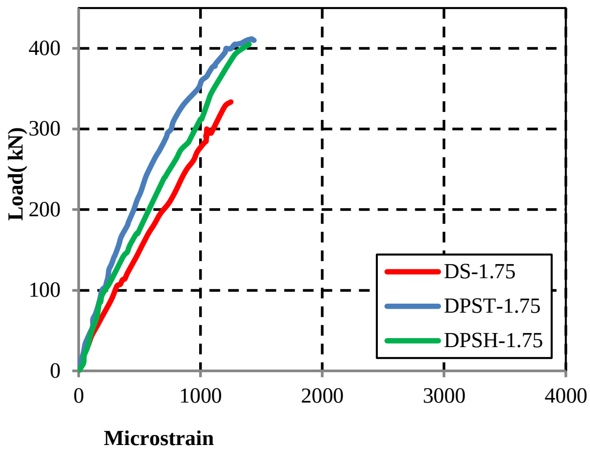

Fig.11: Load–midspan strain relationship for bottom reinforcement of tested specimens with (a/d=1.75).

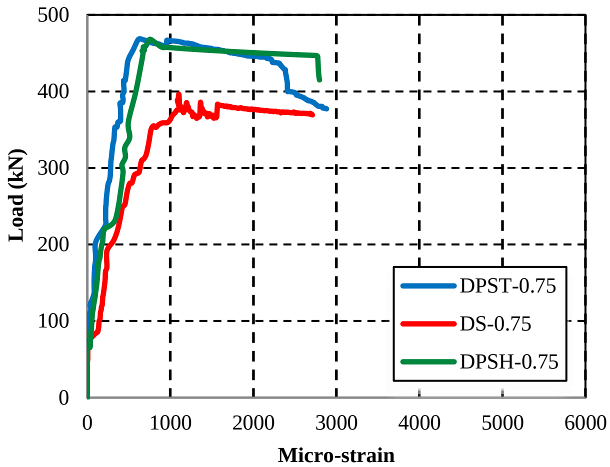

Fig.12: Load–strain relationship of transverse reinforcement at mid of shear span for tested specimens with (a/d=0.75).

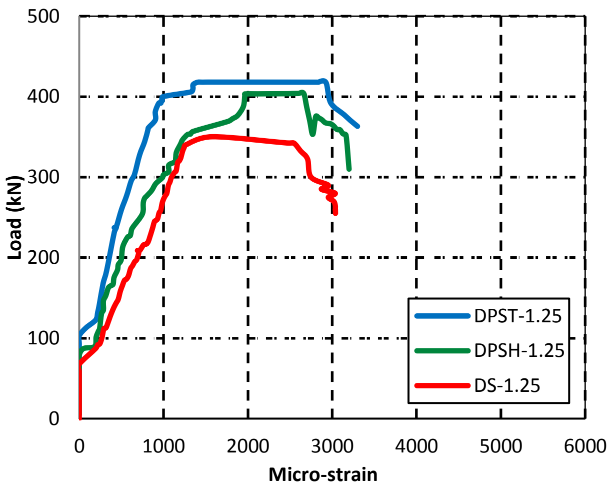

Fig.13:Load–strain relationship of transverse reinforcement at mid of shear span for tested specimens with (a/d=1.25).

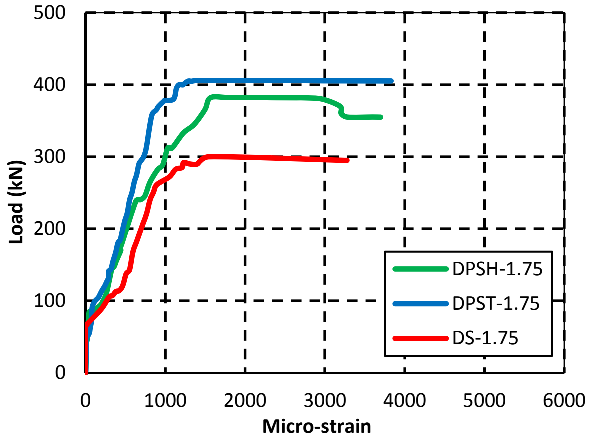

Fig.14:Load–strain relationship of transverse reinforcement at mid of shear span for tested specimens with (a/d=1.75).

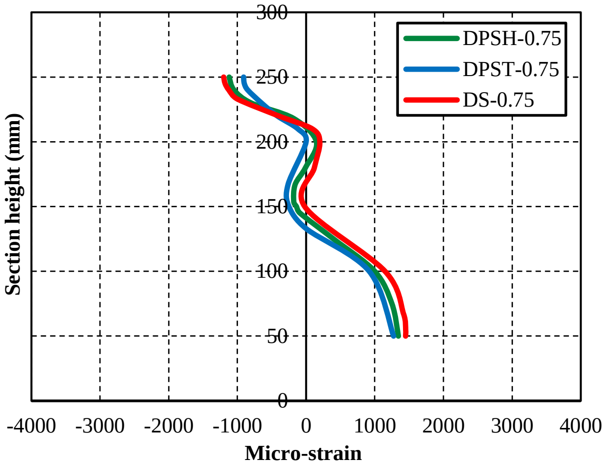

Fig.15: Strain distribution of tested specimens with (a/d=0.75) at ultimate Load

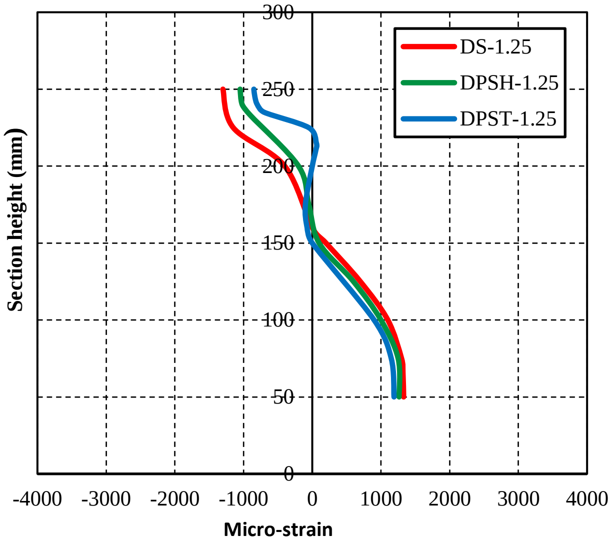

Fig.16 .Strain distribution of tested specimens with (a/d=1.25) at ultimate Load.

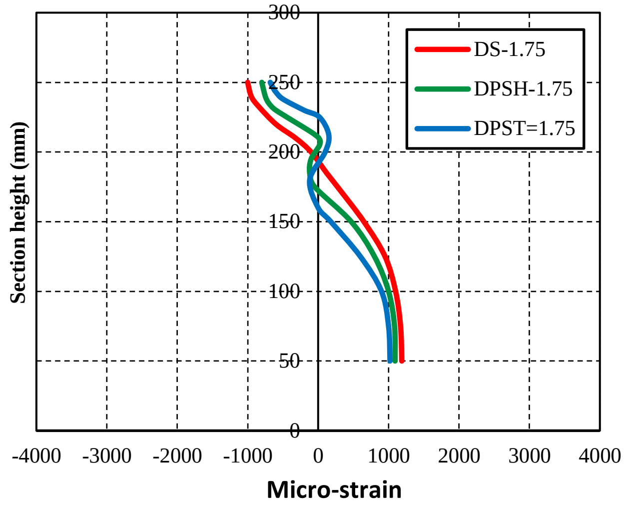

Fig.17. Strain distribution of tested specimens with (a/d=1.75) at ultimate Load.

3.4. Ductility

Ductility expresses the amount of energy absorbed by a structure or a material without it's a critical failure, and it also gives a reference to the magnitude of plastic deformation that can be exposed to the material during the loading stages before the ultimate load, this deformation may be in several patterns such as strain, deflection, or curvature. Ductility is expressed mathematically by the ratio of the deformation in the ultimate load to that realized at the yield load, but the flexural reinforcement in the deep beams do not yield. Spadea et al. [36] proposed an expression to evaluate the ductility, named as ductility factor. In which, the ductility is defined as the ratio of the total dispersed energy, representing the total area under the load-deflection curve, to the energy dispersed at the service load, representing the area under the load-deflection curve at the service load. The service load can be taken as 70-75% of the ultimate load [29].
Table (6) shows the ductility factor for nine R C deep beams. All tested specimens with mild steel plates showed an increase in ductility factor compared with specimens without mild steel plates; the highest increase was 30.56% for the specimen (DPST. - 1.75).

Table 6: Ductility factor of test specimens.

Specimens		Ductility factor (D.F)	Increase in DF%
Group (1)	DS– 1.75	3.6	Control
	DS – 1.25	3.4	Control
	DS – 0.75	3.3	Control
Group (2)	DPST.–1.75	4.7	30.56
	DPST.- 1.25	4.3	26.47
	DPST. –0.75	3.8	15.15
Group (3)	DPSH.- 1.75	4.3	19.44
	DPSH.– 1.25	3.7	8.82
	DPSH.– 0.75	3.5	6.06

4. Conclusion

This paper explores the ability to improve the shear behavior of deep beams by using steel plates as the shear reinforcement. Nine specimens were manufactured and tested under the effect of four-point loading up to failure. The study focused on the influence of a/d ratio and the configuration of steel plates. The main conclusions are listed as follows;
Using the mild steel plates contributed effectively to increase both the cracking and ultimate loading, compared with similar specimens reinforced with bars. The enhancement in the cracking load ranged 16.67% - 66.67%, and in the ultimate loading achieved 15.4 % - 28.26%.

The shear strength of the deep beams proportioned inversely with a/d ratio. As a/d ratio increased from 0.75 to 1.75, the failure load in mild steel plate specimens decreased to 17.61%. In the beams with bars, this drop reached 20.1%.
At same loading level, the specimens having steel plates exhibited stiffer behavior than those of beams having steel bars.
The specimen with steel plates displayed a more ductile behavior, compared with a similar one constructed with steel bars. The increase in the ductility realized 30.56%.

The profiles of concrete strain distribution in the failure load of all R C deep beams were nonlinear. The specimens with mild steel plates had a low sectional height of tension by about (10.11%-20.07%) and (20.89%-32.08%) for the specimens with sheets and strip configurations of the mild steel plate, respectively.

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