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Shear performance of concrete beams reinforced with perforated functional steel plates

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Abstract

This study seeks to examine a novel shear reinforcing method employing steel plates as a substitute for conventional reinforcement in concrete beams. Six reinforced concrete specimens, differing in plate characteristics (type, position, and texture), measuring 1200 mm in length, 200 mm in height, and 120 mm in width, underwent a two-point bending test to assess their shear strength, load-bearing capacity, displacement characteristics, and cracking patterns. The concrete had a compressive strength of 25 MPa. The experimental results indicated that reinforcement with rough-textured perforated steel plates (BR-10%) attained superior load-bearing capacity, demonstrating an 182.4% enhancement in shear strength relative to the reference beam (B0). This signifies that these plates can substitute conventional shear joints in beams.

1. Introduction

Reinforced concrete (RC) beams are horizontal structural elements engineered to convey loads from floor slabs to columns. An important aspect to focus on is understanding the generated shear stresses. Shear stresses are generated in concrete beams because of the applied shear force. Shear reinforcement is used to resist these stresses [1]. These stresses cause many problems for structures, including the development of dangerous diagonal cracks, which can lead to sudden and unexpected collapse. Shear reinforcement is typically performed using transverse reinforcing bars. Numerous studies have presented alternatives to traditional steel bar reinforcement, one of which involves the utilization of steel plates [2].

Using steel plates to reinforce shear joints is a common method in structural engineering. This method is employed to increase capacity, reduce deflection, and strengthen connections between beams and columns, both externally and internally. Among the researchers who applied the plates externally, Liu et al.[3] discussed the effectiveness of the bolted side-plating (BSP) method in rehabilitating reinforced concrete (RC) beams in existing buildings. They found that BSP beams increased flexural capacity without reducing ductility and shear strength without noticeable diminishment. Ashraful Alam et al. [4] study explores the use of embedded connectors to optimize steel plates for the shear reinforcement of reinforced concrete beams. They found that the connector reduced debonding failure and increased shear failure load, highlighting premature debonding as a weakness. The study by Jarallah et al. [5] found that externally bonded steel plates improved shear cracking load and ultimate shear capacity in nine RC beams, with larger improvements as the plating ratio increased and compressive strength decreased.

Adhikary and Mutsuyoshi [6] examined the structural effectiveness of steel plates externally bonded to both sides of a concrete beam using epoxy and bolts. They suggested that the shear contribution was optimized when the steel plate was positioned at the highest feasible section

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depth rather than by augmenting the thickness of the steel plate. Sudarsana et al. [7] recommended fastening a U-shaped steel plate and two L-shaped steel plates as shear reinforcement within the shear span. This study revealed that insufficient plate thickness might cause out-of-plane distortion when the beam is subjected to increased stresses. Furthermore, they observed that narrow steel plates were incapable of withstanding concentrated transverse loads at the bolt hole, resulting in localized failure. Osman et al. [8] presents a steel plate repairing technique that strengthens RC members, controls failure modes, and improves the functionality of pre-cracked reinforced concrete beams with apertures. The method involves applying a temporary pre-stressed force to close existing shear cracks. The benefits of this technique stem from sealing existing fissures around apertures through epoxy injection. The findings indicate that both the extent of pre-existing damage and the reinforcement of steel plates significantly influence the efficiency of strengthening and the manner of failure.

Arslan et al. [9]attached external steel plates to the sides and soffits of beams using epoxy resin. Five of the six examples demonstrated premature failure due to shear when the steel plates separated from the beams. The two prevalent techniques for externally affixing steel plates to concrete beams as supplementary shear reinforcement, namely bolting and epoxy resin bonding, exhibited premature failure of the steel plates. Insufficient plate thickness led to premature localized failure at bolt holes, while excessive plate thickness resulted in delamination of the plate. The literature above indicates that, while utilizing steel plates as an external retrofit for beams during the service stage is viable, the concern regarding the premature failure of these external plates requires consideration. Using recommendations derived from these experiments, other researchers have incorporated steel sheets or sections into beams from the inside before casting to address the problems of detachment, warping, and localized failure associated with external steel retrofit technology.

Ibrahim et al. [10]study investigated the shear performance of reinforced concrete beams including internally embedded vertical shear steel plates. The results indicated that the orientation of the steel plate augmented shear capacity, while transverse hollow steel plates improved ductility and shear performance. The study by Ammash [11] studied on reinforced concrete beams using steel strip plates as a shear reinforcement instead of stirrups bars is presented in this paper. Five specimens with same dimensions and properties were used in this study. One of them has regular ties as shear reinforcements and is used as a reference beam. Other specimens used steel plates as shear reinforcements with an equivalent area of the regular ties of the reference beam. Four thicknesses of plates were used, 1mm 2mm, 3mm, and 4mm. The experimental results showed a good agreement in term of the ultimate load within the range of 99.86 – 113.33 % of the ultimate load of the reference beam. The steel strips work as a regular tie to control the cracks (number and width). The analytical result showed that there is a good agreement between the numerical results and the experimental results in the term. The research conducted by Chai et al. [12] investigates an innovative shear reinforcing technique employing slender mild steel plates in deep beams, revealing that 2.0 mm-thick TMS (Thin Mild Steel plates) enhanced load-carrying capacity by 2.9.

Wang et al. [13] discovered specimens with interval holes in the web of concrete-encased steel sections demonstrated improved ultimate shear resistance and shear stiffness, due to the composite interaction between the I-section and the concrete. Consequently, these tests illustrate that adequate bonding between embedded steel sections in concrete beams is crucial, and this bonding can be attained through the placement of shear studs or the incorporation of perforated holes in the webs of steel sections. Previous studies and research have exhibited the capability of using plates to improve shear resistance, either by externally fixing them with bolts or epoxy, or by internally immersing them. These results yielded promising results, with some reservations regarding the weak bond between the outer plates and the concrete. To the authors knowledge, rare studies were conducted to study the effect of perforated internal embedded plates considering surface roughness on the shear strength of concrete beams. In this study, to further investigate the shear strength of concrete beams containing embedded steel plates, six beam specimens were manufactured using three parameters: plate location (mid, edge), plate surface texture (smooth, rough) and type of plate (solid with no holes, with holes). The steel plate holes were circular, 40 mm in diameter, and spaced 15 mm apart. The steel plate was embedded longitudinally and secured with 8 mm diameter steel stirrups.

For a 25 MPa cubic compressive strength target, the concrete mixture was designed with proportions of (1:2.22:3.23) and a water-to-cement ratio (w/c) of (0.37). After completing the curing period, all beams were cleaned and painted white to ensure clear visibility of cracks and their propagation during the test. The beams with a span of 1200 mm were tested under a four-point loading scheme over a clear span of 1000 mm using a testing machine with a capacity of 400 kN. The distance between the points of loading was 300 mm. The load was applied to the simply supported beam by a loading rate of 1 kN/min. to ensure accurate observation of crack initiation and progressive failure mechanisms. This was measured using a load cell with a capacity of 400 kN. The deflection at the center was measured by a digital dial gauge (LVDT) with a capacity of 50 mm and an accuracy of 0.01mm, placed under the mid-span point.

Regarding the effect of perforations on potential plate corrosion during loading, stress concentrations may form around the perimeter of the holes, promoting micro-cracks in the concrete. These cracks can then become pathways for moisture and harmful steel (such as chlorides in marine environments), increasing the risk of corrosion behind and around the steel plate.

2. Materials and Methods

2.1 Mix Design and Procedure

For a 25 MPa cubic compressive strength target, the concrete mixture was designed with proportions of (1:2.22:3.23) and water to cement ratio (w/c) of (0.37), as shown in Table 1. Moreover, the slump value was 59 mm; all specimens were cured for 28 days in the same situation.

Table 1. Proportions of concrete mixture

Materials	Mix proportions
Cement (kg/m^3)	325
Fine aggregate (kg/m^3)	720
Coarse aggregate (kg/m^3)	1050
Water (L/m^3)	120
Superplasticizer	-------

The chemical and physical tests of cement are listed in Table 2 and Table 3, Table 4 Classification of Coarse Aggregate and Table 5 Classification of Fine Aggregate

Table 2. Physical properties of the cement

Physical properties	Test Results	Limits of ASTM C150/C150M
Initial setting time, min	188.5 min.	≥45 min
Final setting time, min	220.5 min.	≤ 375 min.
Compressive strength in MPa @ 3 days	12.8 Mpa	≥8 (minimum)
Compressive strength in MPa @ 7 days	17 Mpa	≥15 (minimum)

Table 3. Chemical composition of the cement

Compound	% By Weight	Limit of Iraqi Specifications No. 472 for the year 1993
CaO	60.05	-----
SiO2	21.3	------
Al2O3	3.99	------
Fe2O3	4.27	------
MgO	4.155	<5

Compound	% By Weight	Limit of Iraqi Specifications No. 472 for the year 1993
SO3	2.1	<3.5
Limestone saturation factor	0.85	0.66-1.02
C3A	3.3	------
Insoluble Residue I.R	1.13	<1.5
Loss on Ignition L.O.I.	3.16	<4.0

Table 4. Classification of coarse aggregate

Sieve size (mm)	% Passing by weight	Limits of Iraqi specification No. 45/1984
20	98.5	95-100
10	48	30-60
5	7.5	0-10

Table 5. Classification of fine aggregate

Sieve size (mm)	% Passing by weight	Limits of Iraqi specifications No.45/1984 Zone 2
4.75	97.5	90-100
2.36	90	75-100
1.18	80	55-90
0.6	57	35-59
0.3	25	8-30
0.15	8.3	0-10
75 microns	1.3	No more than 5%

2.2 Specimen Description

Six reinforced concrete specimens (B0, BT2, BR-10%, BM, BE, and BHC-10%) were prepared. The specimens had a span length of 1200×120 mm in width× 200 mm in depth. Longitudinal reinforcement bars of 2T10 and 4T16 were affixed at the upper and lower extremities of the specimens, respectively. (Fig. 1) shows the reinforcement details of the tested specimens. Minimum shear reinforcement of T8 was added at 400 mm intervals, as illustrated in (Fig. 1a). Tensile tests were conducted on all steel bars, as shown in Table 2 ((Reinforcing steel is manufactured through basic stages that begin with extracting iron ore from mines and converting it into molten steel. This steel is then poured into continuous molds to be cooled and subsequently shaped by rolling to become bars of specific diameters and lengths)).

Table 6. Characteristics of steel reinforcing bars

Type of steel	Diameter (mm)	Yield stress (MPa)	Average ultimate stress (MPa)	Average Elongation (%)
Grade 60	8	657	686.1	15
Grade 60	10	618	634	12
Grade 60	16	612	700	15.9
ASTM 615 limits		Not less than 420	Not less than 620	Not less than 9%

Shear plates were installed on either side of the specimen within the shear span, as depicted in (Fig. 1 (b, c, d, e, f)). Tests' specimens involving embedded plates in concrete were classified into three series: plate location (mid-region, near edge), surface texture (smooth, rough), and presence of holes (solid, with holes). This classification helps in comparing structural performance outcomes across different configurations. Thickness and hole percentage parameters were selected according to continuing research. The tensile strength test results for steel bars and steel plates are presented in Tables 6 and 7, respectively. Holes with a 40 mm diameter were implemented to permit the passage of fresh concrete through the plates, hence facilitating adhesion between the concrete matrix and the plates. Additionally, this investigation employed two plate thicknesses: 1.0 mm and 2.0 mm.

Table 7. Yield strength, maximum tensile strength, and elongation of steel plates

Thickness of tested steel plate (mm)	Average of yield tensile strength (MPa)	Average of ultimate tensile strength (MPa)	% Elongation at ultimate stress
2	290	375	20.5
1	300	380	19

Table 8. Designated names of specimens

Designated name	Plate thickness, mm	Plate surface	Location of the plate	Holes, %
B0	---------	---------	---------	-----------
BT2	2.0	Smooth	Mid	0
BE	1.0	Smooth	Edge	0
BHC-10%	2.0	Smooth	Mid	10
BM	2.0	Rough	Mid	0
BR -10%	2.0	Rough	Mid	10

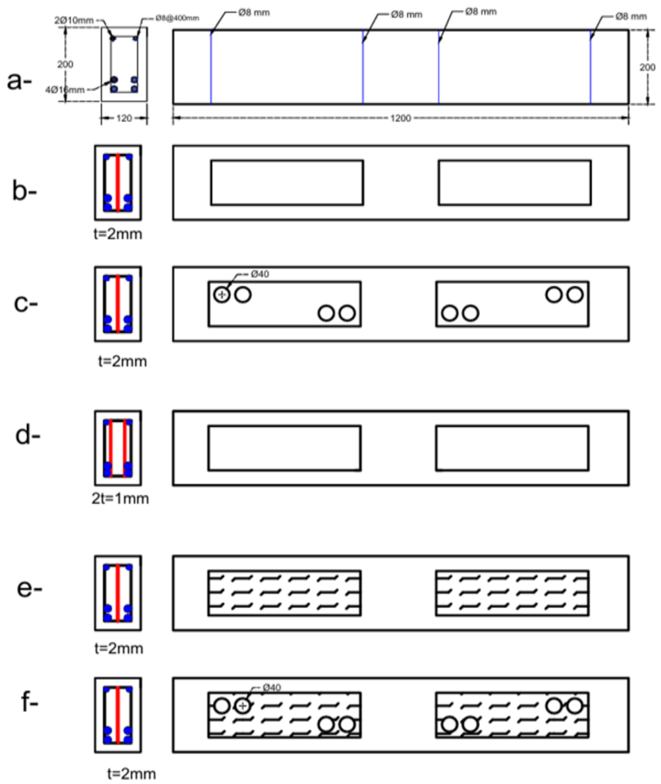

Fig. 1. Reinforcement detailing of samples. (a) sample B0; (b) sample BT); (c) sample BHC-10%; (d) sample BE; (e) sample BM; (f) sample BR-10%

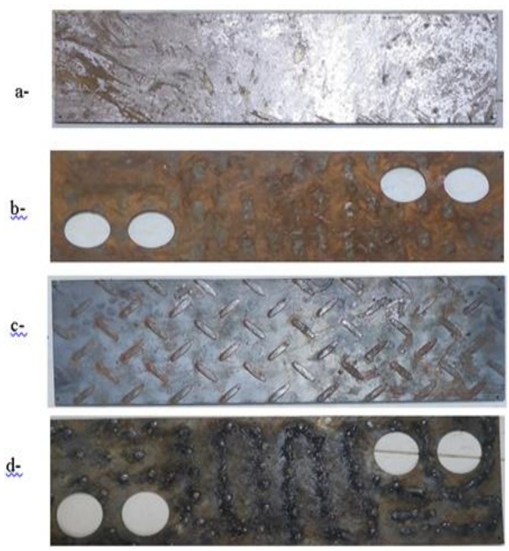

Fig. 2. Configuration of plates. (a) Smooth sold plate, (b) Smooth plate with holes, (c) Rough sold plate, (d) Rough plate with holes

(Fig. 2) illustrates the specific arrangement of the plates for each series. Table 8 presents the assigned nomenclature for all specimens. Three concrete cubes were cast, and from the mean value of the three specimens, the 28-day concrete compressive strength was 26.4 MPa. A concrete cylinder was cast, and the splitting tensile strength was 4.13 MPa.

2.3 Testing configuration

This study employed a four-point loading test. A testing apparatus with a capacity of 400 kN was employed to evaluate the performance of the six specimens. The specimens were subjected to monotonous loading under load control. The inter-plate spacing was established at 300 mm All specimens were supported by two bearing plates at the reaction base, with a clear span of 1000 mm. A single linear variable differential transducer (LVDT) was positioned at the specimen's base to quantify vertical displacement during testing, as illustrated in (Fig. 3).

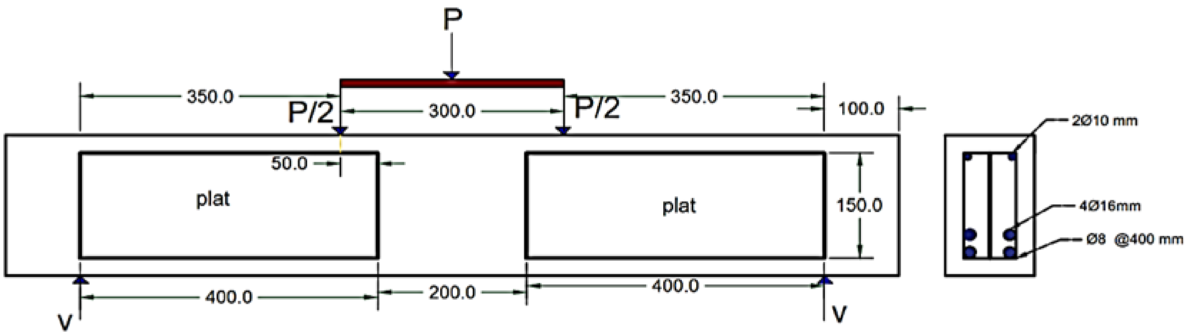

Fig. 3. Details of the test setup

3. Experimental Results and Discussion

The experimental results of the analyzed specimens are evaluated for their load-bearing capacity, load-displacement behavior, cracking patterns, and failure modes. Comparisons are made between reference specimen B0 and specimens incorporating steel plates.

3.1 Load-Bearing Capacity

Table 9 and Fig. 4 show the failure loads of the tested samples. The maximum load capacity of the reference specimen B0 is 57 kN. It is emphasized in a red bar. In (Fig. 4). Additionally, the Percentage of difference between the reference beam and the beams containing steel plates is presented in Table 10.

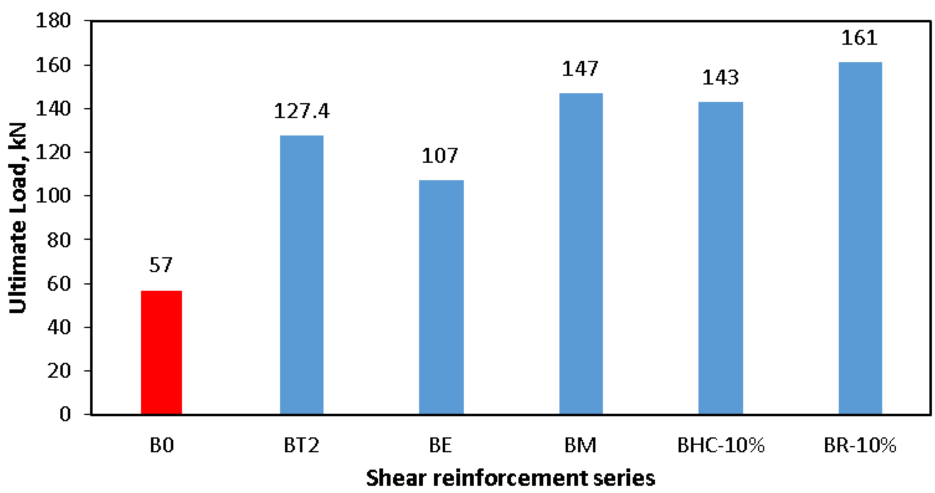

Fig. 4. Ultimate load for each specimen

Table 9. Experimental findings on ultimate load and deflection

Samples	Max. load (kN)	Comparison with sample B0 (%)	Deflection at Mid-Span under Max. Load (mm)
B0	57	-------	5.6
BT2	127.4	123.5	6.8
BE	107	87.7	6
BM	147	157.9	8
BHC-10%	143	150.8	5.28
BR-10%	161	182.4	8

- Effect of The Location of The Plate:

Table 9 clearly highlighted that specimen (BT2), which involves a steel plate of 2 mm in thickness, demonstrated an increase of 123.5% compared to the reference specimen (B0). It is important to note that when two plates replaced the middle plate (BT2) with equivalent thickness (BE), the shear strength decreased by 36%. This behavior resulted from the isolation effect that was caused by the placement of the plate, which separated the concrete core from the outer margins [14]. As a result, each component started to behave independently from the other component, which led to a reduction in overall strength. However, in comparison to specimen (B0), specimen (BE), which has two plates at the edge of the specimen's cross-section, exhibited an increase of 87.7% in shear strength.

- Effect of The Surface Texture of The Plate

A rough surface plate with a thickness of two millimeters was located at the middle of the specimen BM. The load carrying capacity was found to be 157.9% higher than that of the reference specimen B0. Similarly, specimen BT2, which involves a plate of entirely smooth surface with a comparable thickness of two millimeters, shows a 123.5% enhancement in shear strength compared with reference specimen B0. While both specimens exhibited significant improvement in the load carrying capacity, a 15.9% increase was observed for the specimen reinforced with a rough steel plate. This result proves the hypothesis that bond strength notably improves the load capacity. Because of the rough surface of the plate [15]. The connection between the concrete and the plate was improved, and the sliding between them was minimized [16].

- Effect of The Holes in The Plate

Specimen BHC-10% contains a two mm-thick vertical plate at the middle of the section with holes that comprise 10% of the total plate area. The findings demonstrated that the load-bearing capacity exceeds that of specimen B0 by 150.8%, which reflects the contribution of the adhesion between the concrete and the plate to the shear strength. Likewise, specimen BR-10%, which is similar in reinforcement but contains a plate with a rough surface, demonstrated a significant increase in shear strength by 182.4% compared with specimen B0. This means that the specimen with the rough plate exceeds that of the specimen with the smooth plate by 12.5%. This is due to the presence of protrusions on the surface of the rough plate, which enhances the adhesion between the concrete and the plate, reduces slippage, and thus increases the structural load capacity [17]. Moreover, the perforations in the plate enhance the adhesion between the concrete and the plate, allowing the concrete to flow and form bonding pins. Furthermore, the holes in the plate reduce its weight, thus reducing the dead load on the specimens [18]

3.2 Load-Displacement Behavior

The load-displacement behavior of tested specimens is shown in (Fig. 5) and summarized in the following sections.

- Effect of The Location of The Plate

By observing the load-displacement curves in (Fig. 6) for samples BT2 and BE, it is noted that they exhibited a higher stiffness curve than the reference sample (B0), indicating the significant effect of the embedded steel plates on the load-displacement behavior. Comparing the curve shapes of the two samples (BT2 and BE), it is observed that sample BT2 showed higher stiffness than sample

BE. This is attributed to the plate's position in the middle of the section, which enhanced stiffness, unlike the end sample, where the plate was located at the edges, isolating the concrete core from the cover and reducing stiffness [19].

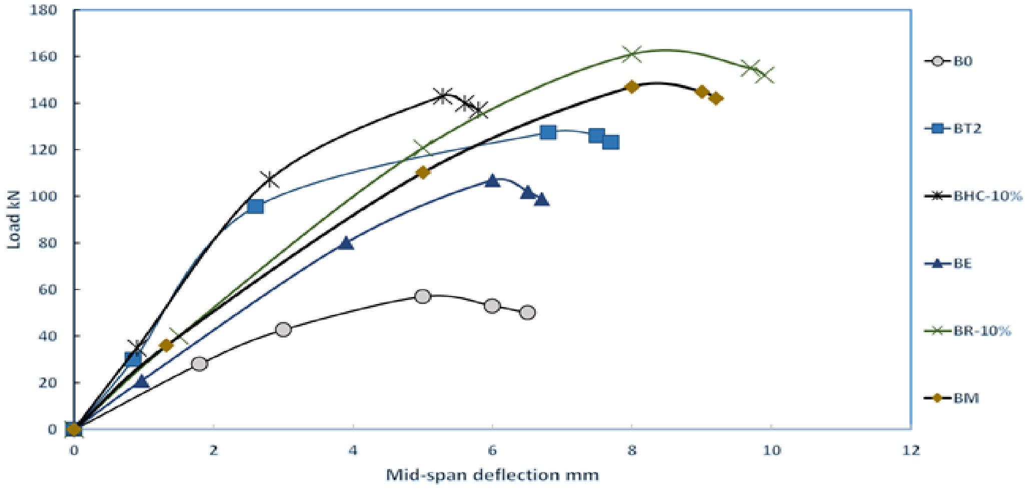

Fig. 5. Load against mid-span deflection graph for B0, BE, BT2,BHC-10%,BR-10%and BM

- Effect of The Surface Texture of The Plate

The displacement curve diagram for sample (BM) shows that it is more flexible than sample (BT2), which has a smooth plate. This increased flexibility can be attributed to the presence of grooves on the outer surface of the plate, which reduce the overall stiffness of the specimen and allow for larger deformations under the same applied load. These differences in behavior are clearly illustrated in the load-deflection diagram presented in (Fig.7), highlighting the influence of plate modifications on the overall structural flexibility of the beams [20].

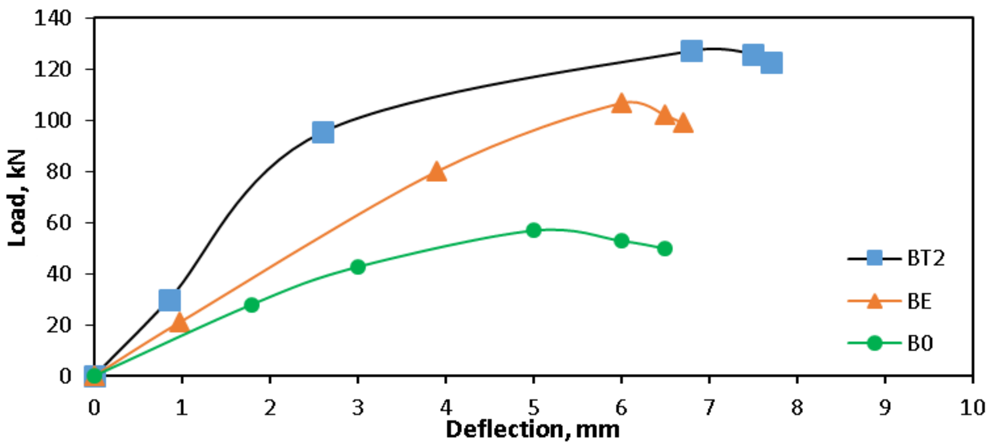

Fig. 6. Load against mid-span deflection graph for B0, BE, and BT2

- Effect of The Holes in The Plate

When comparing the load-deflection curve results for samples containing an embedded perforated plate with the reference specimen (B0), it has been observed that the former recorded a higher curve. This indicates a higher stiffness of the sample's structure, which results from the presence of the plate in the cross-section that postpones the onset of shear cracking's[21] .The results also show that the specimen containing a rough-surfaced plate (BR-10%) had a higher curve than the sample containing a smooth-surfaced plate (BHC-10%). This demonstrates that the surface grooves of the plate played a significant role in giving the sample high hardness [22] as shown in (Fig.8).

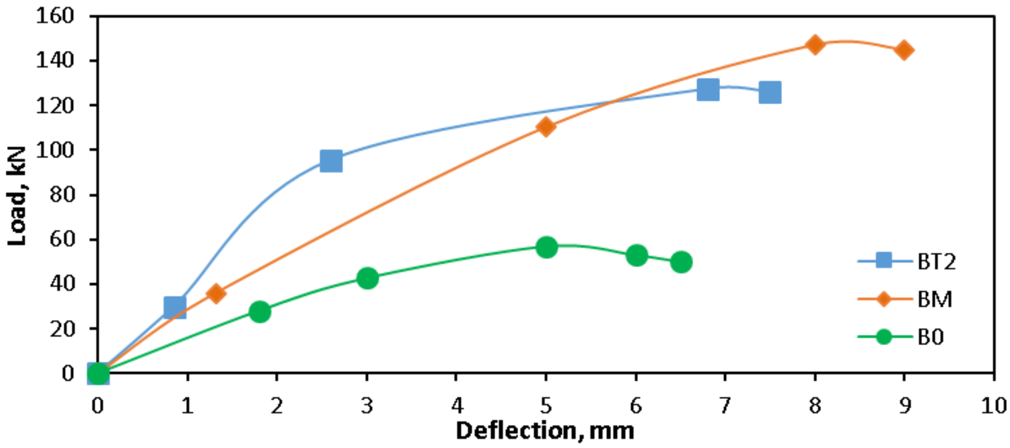

Fig. 7. Load against mid-span deflection graph for B0, BT2, and BM

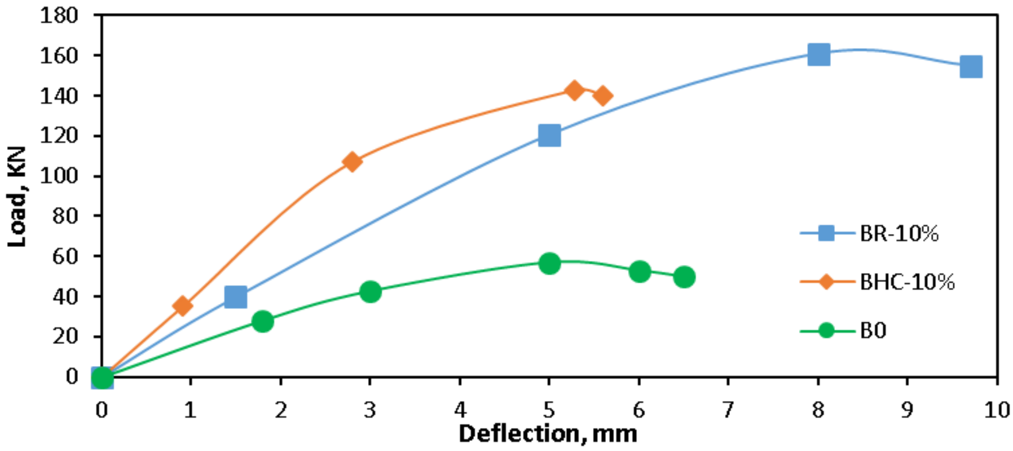

Fig. 8. Load versus mid-span displacement curve for B0, BHC-10%, and BR-10%

3.3 Fracture Pattern and Failure Mechanism

The fracture pattern and failure mechanism can be divided into three main categories.

- Impact of The Plate's Location

Fig. 9 depicts the crack pattern and mode of failure of specimens B0, BT2, and BE, respectively. It shows that all specimens exhibited the same failure mode, where the diagonal shear crack begins from the support and progresses to the applied load. Specimens B0, BE, and BT2 recorded initial crack loads shown in Table 10 below. The cracks of specimen BT2 were smaller, fewer in number, and had smaller crack widths compared to specimen BE, which had more numerous cracks and larger crack widths. This was due to the plate being located at the edge of the cross-section rather than in the middle [23], as in specimen BT2. This isolated the concrete core from the cover, negatively impacting the failure mode in terms of the number of cracks and their width.

Table 10. First crack load for B0, BE and BT2

Specimens	First crack load(kN)
B0	28.12
BE	21
BT2	30

- Effect of The Surface Texture of The Plate

Specimens BT2 and BM containing non-perforated plates exhibited the same shear failure behavior and crack pattern. Compared to the reference specimen B0, cracks in specimen BM, which contained a rough-surfaced plate, were more pronounced and numerous than in specimen BT2, which had a smooth surface. The three specimen's recorded initial failure loads listed in Table 11 and the shapes and paths of the cracks are illustrated in the figure. (Fig.10).

Table 11. First crack load for B0, BT2 and BM

Specimens	First crack load(kN)
B0	28.12
BT2	30
BM	36

- Effect of The Holes in The Plate

As shown in Fig.11, all specimens (B0, BHC-10%, and BR-10%) exhibited the same cracking and failure pattern, namely diagonal shear failure. However, specimen (BR-10%), which contained an embedded plate with a rough surface and containing holes, had large and clear cracks and recorded an initial crack load of 40 kN. As for the sample (BHC-10%), which included an embedded plate with a smooth surface and containing holes, the cracks were smaller, the number of cracks was lower, and an initial crack load of 35 kN was recorded.

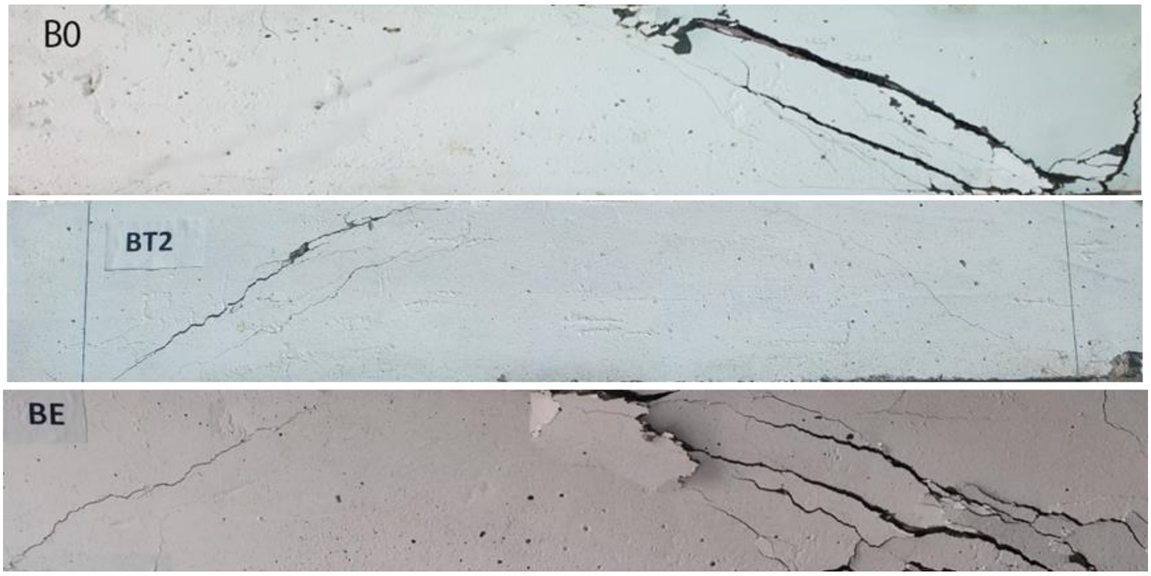

Fig. 9. Crack development of specimens B0, BT2, and BE

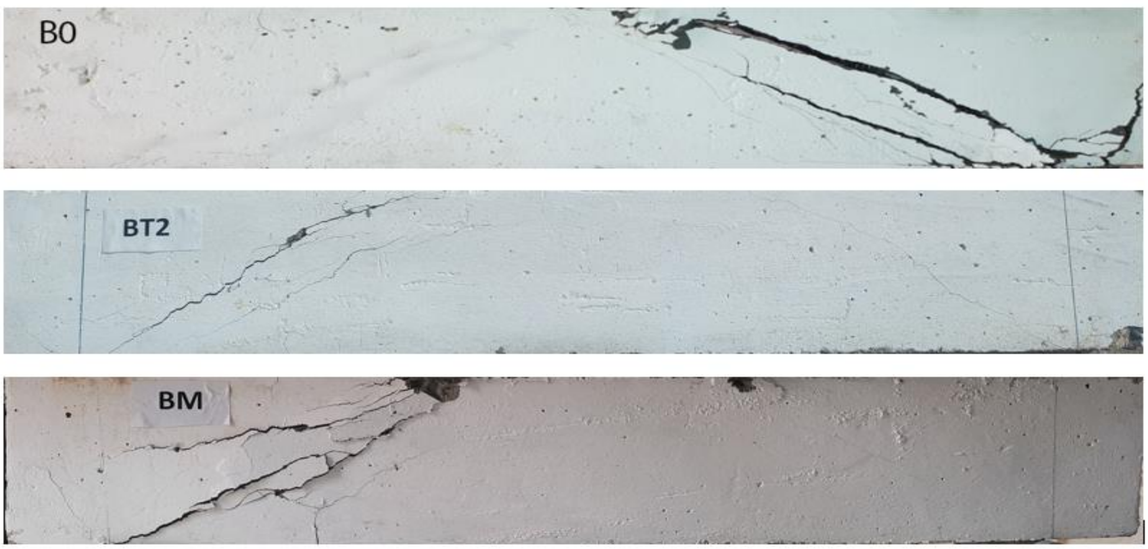

Fig. 10. Crack development of specimens B0, BT2, and BM

Fig. 11. Crack development of specimens B0, BHC-10%, and BR-10%

4. Conclusions

This study experimentally examined the strength of beams utilizing plates as shear reinforcement in place of traditional shear stirrups. The impacts of three distinct detail designs on the plates were investigated: (a) the location of the plates, (b) the surface roughness of the unperforated plate, and (c) the surface roughness of the perforated plate. Six beam samples were manufactured, including one reference specimen (specimen B0) with slight shear reinforcement. A four-point load test was conducted on each specimen experimentally. Based on the results, the following were determined:

- Adding steel plates to concrete beams as an alternative to conventional shear steel achieves excellent results in resisting shear forces. Specimen BT2 showed a 123.5% augmentation of maximum load capacity in relation to the reference specimen B0. Furthermore, the specimens exhibited high stiffness in the load-displacement curve.
- Using a centrally embedded plate is significantly better than placing it at the edges in terms of sample load-bearing capacity and stiffness. Specimen BT2, which has a central plate, demonstrated a 19% enhancement in load-bearing capability relative to Specimen BE, which has two edge plates,
- Adding perforations to the plates improves their load-bearing capacity compared to the reference and solid samples. The perforations in the plates facilitate the flow of concrete, promoting the development of concrete cavities and increasing the adherence of the perforated plates with concrete. Specimen BHC-10% showed a 150.8% increase in strength compared to Specimen B0. Compared to Specimen BT2, which did not contain perforations, Specimen BHC-10% recorded a 12.2% increase. The addition of perforations also enhances the strength of the sample.
- It is preferable to use a steel plate with a rough surface over a smooth plate, as the rough surface enhances adhesion between the concrete and the plate, leading to increased load-carrying capacity and efficiency pertaining to the structural components. This is evident in the increased load-bearing capability of Specimen BM compared to Specimen BT2, which increased by 15.3%.
- The combination of the surface roughness factor of the plate with the presence of openings and the position of the plate in the middle gave excellent results in the efficacy of the structural element regarding load-bearing capability, stiffness, failure mode, and first crack load. This is observed in the sample BR-10%, as it gave the highest load-bearing strength compared to all samples by 161 kN and was the best among the samples in stiffness, strength, and first crack load.

- Embedded steel plates provide an effective method to enhance the shear capacity and seismic resilience of reinforced concrete structures. Their incorporation might mitigate prevalent problems linked to external reinforcement techniques, including debonding and exposure.
- It is recommended to conduct a full-scale test to investigate the shear behavior of concrete beams. Moreover, fatigue behavior is another important aspect to consider as the next step of research.

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