Effective length and area of bolted steel plates attached externally to strengthen reinforced concrete beams

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Abstract. In this research an investigation has been done on eight reinforced concrete beams. Each beam was strengthened by bolted steel plates attached to their bottom side, of which length and thickness ratio varied, except one beam which has been tested without steel plate as controlling test. Two limits have been introduced upon the maximum plate area used and its minimum length. The first limit is to insure a ductile tension failure, and the latter is to prevent loss of interaction between the two components. Bolts with head were used to provide suitable connection through the specimens of concrete beams and the steel plates through predrilled holes in the steel plates. All beams have similar dimensions and tested simply supported over an effective length of 1600 mm and loaded with central load. Test results show that the plated beam gain an increase in strength over that of unplated beam of about 145%. Also, beams with relatively thin plates, the plate length has little effect upon the ultimate strength, however, for beams with thicker plates the results show a decrease in strength of about 16%.

Keywords
Strengthened beam, steel plates, FRP, shear connectors, composite

1. Introduction
Concrete structures in service or any of their elements may be found unsatisfactory for different reasons such as functional change, faulty design, and structural damage. In such state of affairs, there are two possible methods; demolish and rebuild or carrying out a program of rehabilitation. Various techniques were used for strengthening and repair of an existing structure, depending on the type of construction and the encountered damage. For structures made of concrete, the most common processes are[1]; substituting non-structural topping with structural one, providing extra props to reduce span length, providing external post-tensioning, adding supplementary any type of reinforcement by pin, and polymer impregnation. One or more of these methods is often used to strengthen the structural members. The plate bonding technique is now being recognized to be an effective and convenient method of improving the serviceability performance and strength of concrete structures due to many advantage that may be gained[2]; minimum site disruption, simply and quickly, cheap and versatile, and minimum additional self-weight. The new structural element (concrete with external plate) can be considered as a composite element and the method of connecting the two components is a key parameter to establish the composite behaviour.

2. Literature review
Since early seventies, several studies are concerned with strengthening plain and reinforced concrete beams by steel plate bonded by using any adhesive materials [2-4]. From these studies, the tested specimens did not sustain their predicted ultimate strength and failed by unexpected separation of the plate ends together with a layer of week concrete. As well as using any end anchorage to the bonded
plates could not prevented this type of failure and have marginal effect in improving the ultimate strength, especially when strengthening process with thicker plates. Also, many tests were carried out on concrete beams strengthened by fibre reinforced polymer (FRP) plates, which are made of small fibres bonded together with a resin matrix [5-9]. In general, the results of these tests showed, the behaviour of such plated beams is similar to those strengthened with steel plates and failed suddenly by plate separation (premature failure) [10].

The steel plates can be attached mechanically to structural concrete elements by using different type of connectors which refer to as bolting technique. The connectors are used as anchors which are distributed along the beam and will transfer load to the core of the concrete section as well as provided vertical and horizontal resistance to forces developed at the plate interface [11]. Using this type of technique can improve the stiffness of the plated beams and prevent the sudden failure for specimens with thick plates.

3. Research significant

From the literature survey, it can be concluded that few survey work has been accomplished on concrete beam enhanced mechanically with bolted steel plate and most previous works are concerned with concrete beams strengthened with epoxy bonded plates. The common mode of failure for these tests is a premature failure with characterized by ripping off the plate together with concrete cover which it may be attached. So, it can be concluded that the bolting technique (bolted plates) is the more efficient one.

4. Experimental program

The current experimental program consisted of a series of tests carried out on eight reinforced concrete beams strengthened by steel plates being attached to their tension face using headed studs, except one beam which has been tested without steel plate as controlling test. Details of these beams are shown in Table (1). Two parameters were varied throughout the test program which are the steel plate thickness (2, 3 and 5) mm and steel plate (l) to beam (L) length ratios ( \( l/L=0.5,0.7 \) and 0.9). The nominal dimensions of the tested beam are (150mm) in width, (200mm) in depth, and (1800mm) overall length as shown in Figure (1). The beams were tested in simply supported manner on an effective span of (1600 mm) and loaded with a central load.
Table 1. Details of Beams.

| Beam No. | Steel Plate Dimensions b×t×l (mm) | Plate Length to Beam Ratio (l/L) % | Steel Plate Area (mm²) | Total number of shear connectors |
|----------|-----------------------------------|-----------------------------------|------------------------|---------------------------------|
| B1       | Control beam                      | -                                 | -                      | -                               |
| B2       | 150×2×1440                        | 0.9                               | 300                    | 8                               |
| B3       | 150×3×1440                        | 0.9                               | 450                    | 12                              |
| B4       | 150×5×1440                        | 0.9                               | 750                    | 24                              |
| B5       | 150×2×1120                        | 0.7                               | 300                    | 8                               |
| B6       | 150×2×800                         | 0.5                               | 300                    | 8                               |
| B7       | 150×3×1120                        | 0.7                               | 450                    | 12                              |
| B8       | 150×3×800                         | 0.5                               | 450                    | 12                              |

Figure 1. Beam Details (dimensions in mm)

4.1 Material properties
The constituent materials of the concrete used throughout this investigation are ordinary Portland cement, natural sand as fine aggregate and river crushed gravel as coarse aggregate. The grading of fine and coarse aggregate which obtained by sieve analysis lie within the range defined by ASTM C33-86. Concrete mix was designed for 28 days compressive strength of (35 Mpa). Steel bars were used to reinforce the concrete beams, they are (12mm) for flexure and (5 mm) for shear with yield stress of (470 and 520) Mpa, respectively, see Figure (1). The external plates were made of mild steel with three different thicknesses of (2, 3, and 5 ) mm with yield stress of(225, 250, and 326) Mpa, respectively. The steel plates were jointed to the concrete beams by headed studs (shear connectors) of diameter (10 mm). Number of bolts (shear connectors) that used for each beam was dependant on the
area of external steel plates to keep the degree of interaction is full for all plated specimens, see Table (1).

5. Results and discussion

5.1 General behavior

Crack patterns of the tested beams are shown in Figure (2) and test results are shown in Table (2). All beam exhibited ductile flexural failure, as shown in Figure (2), at early stage of loading, several flexural cracks initiated in the tension zone, with further loading, these cracks extended upward and wider, followed by crushing of the concrete in the compression zone. For all plated beams, no separation encountered between the concrete beams and the steel plates. Also, the failure occurred without shearing off the bolts (shear connector).

![Figure 2. Crack Patterns of Tested Beams.](image)

**Table 2. Mode of Failure and Ultimate Strength of Tested Beams.**

| Beam No. | Steel Plate Dimensions b×t×l (mm) | Plate Length to Beam Ratio (L/L) % | Steel Plate Area (mm²) | Ultimate Load (kN) | Mode of Failure |
|----------|----------------------------------|-----------------------------------|------------------------|--------------------|-----------------|
| B1       | Control beam                     | -                                 | -                      | 58                 | Flexure         |
| B2       | 150×2×1440                       | 0.9                               | 300                    | 88                 | Flexure         |
| B3       | 150×3×1440                       | 0.9                               | 450                    | 110                | Flexure         |
| B4       | 150×5×1440                       | 0.9                               | 750                    | 142                | Flexure         |
| B5       | 150×2×1120                       | 0.7                               | 300                    | 89                 | Flexure         |
| B6       | 150×2×800                        | 0.5                               | 300                    | 82                 | Flexure         |
| B7       | 150×3×1120                       | 0.7                               | 450                    | 110                | Flexure         |
| B8       | 150×3×800                        | 0.5                               | 450                    | 92                 | At Plate End    |

5.2 Ultimate strength

The observed final load at failure stage of the tested beams are shown in Table (2). The results from these tests show that the plated beams gain an increase in strength over that of unplated beam of about (52, 90 and 145) % for beams with steel plate of thickness (2, 3 and 5) mm, respectively. Indicating the significance of plate thickness (area of external reinforcement). For tested beams with (2 mm) thick reinforcing plates and have different plate length ratio, the ultimate load had no effect and similar to that of beam with full plate length, indicating the insignificance of this parameter upon ultimate strength for the cases of relatively thin plates. However, the ultimate load for beam with thicker plate...
(3mm) and had length ratio of (50 %) was decreased of about (16%) in comparison with beam of full plate length (90%), due to the shifting of the critical section to the zone of plate end.

6. Predicted ultimate strength

In the design of concrete structures, it is generally demanded to insure that ultimate strengths are dominated by flexure rather than shear, where this type of failure (shear failure) is more dangerous, due to the lack of ductility and small deflection, thereby, lack of warning.

Here, a theoretical model has been proposed to find the ultimate strength of the composite section (reinforced section plus bolted steel plate). The last load at failure stage of this type of beams were assumed a bending failure and that an adequate number of bolts were added at the interface layer, such that the flexural strength is not reduced due to distortion of shear connectors. The approach is based, the tension component couple is shared by steel bars (T_s) and steel plates (T_p) and are known as:

\[ T_s = A_s f_s \quad \text{and} \quad T_p = A_p f_p \]

where: \((A_s, f_s)\) and \((A_p, f_p)\) point out, respectively, the sectional area and yield stress of the familiar steel reinforcement and plate.

The deepness of the concrete rectangular stress block (a) can be calculated when checking the equilibrium of the horizontal level of forces and will arrive at,

\[ a = \frac{A_s f_s y_s + A_p f_p y_p}{0.85 f'c . b_c} \]

where: \(f'c\) and \(b_c\) are, respectively, concrete compressive strength of concrete in term of cylinder and width of concrete section.

Taking moments about the centre of the stress block, the extreme level of resistance moment \((M_u)\) is specified by:

\[ M_u = A_s f_s (d_a - \frac{a}{2}) + A_p f_p (d_p - \frac{a}{2}) \]

where: \(d_a\) and \(d_p\) are efficient depths of the common steel reinforcement and steel platelet, respectively.

Since steel plates are connected externally to enhance an existing deteriorated reinforced concrete section with a predesign steel proportion \((A_v/ b_c, d_c)\). There should be a restrict inserted on the sectional area of the steel plate to be added, so as to enclose a ductile tension failure (under-reinforced section) for this type of combined section.

Substituting eq. (2) in eq. (3), hence, this equation can be written in terms of the steel plate area as,

\[ K_1 . A_p^2 + K_2 . A_p + K_3 = 0 \]

where:

\[ K_1 = \frac{(f_{yp})^2}{1.7 f'c . b_c} , \quad K_2 = \frac{T_s . f_{yp}}{0.85 f'c . b_c} - f_{yp} \cdot d_p , \quad \text{and} \quad K_3 = \frac{(T_s)^2}{1.7 f'c . b_c} - d_a . T_s + M_u \]

and all symbols are as defined earlier.

Eq. (4) can be solved for the value as plate area provided at the section to give,

\[ A_p = \frac{-K_2 + \sqrt{(K_2)^2 - 4K_1 K_3}}{2K_1} \]

The value of \(A_p\) obtained from the above equation should be restricted to the balanced steel platelet area \((A_{pb})\) which can be known as the plate area at balanced load states and also the maximum plate area to ensure a ductile tension failure. For any given section, \((A_{pb})\) can be found,

\[ y_p = \frac{\frac{0.003}{0.003 + \epsilon_{ys}} \cdot d_s}{0.003 + \epsilon_{ys}} \]

considering forces equilibrium of the balanced section gives:

\[ A_s . f_s + A_p . f_p = 0.85 f'c . b_c . a_b \]
where: \( a_b = B_1 \cdot y_b \)

\[
A_{pb} = \frac{0.85 B_1 y_b f'c_{bc} - As\cdot f_y}{f_y} \quad \ldots(8)
\]

A concrete beam may be plated for a part of its length and not necessary extensive to the supports. The length difference should content with a confirmed limit, so as to restrain premature failure and loss of interaction. This limit is found by considering the reinforced concrete section only to resist the applied moment. This case will exist at the plate ends which is distance from the support by the \( a_p \). For the situation of simple span with a single point load of \( (P_u) \) at the centre of span, the maximum cut-off length must satisfy the following restrict:

\[
a_p \max. \leq \frac{2M_{ul}}{P_u} \quad \text{where: } M_{ul} \text{ is the ultimate moment of resistance of concrete section with bar reinforcement alone.}
\]

A comparison between predicted and experimental values of ultimate load shown in table (3). It can be noticed from this table a close agreement between these values with mean ratio of the measured to calculated ultimate strength of (1.1) and a standard deviation of (5.6).

**Table 3. Comparison between Experimental and Predicted Ultimate Load.**

| Beam No. | Plate Length to Beam Ratio \( (L/L) \% \) | Steel Plate Area (mm\(^2\)) | Ultimate Load (kN) | Experimental/Predicted |
|----------|------------------------------------------|----------------------------|--------------------|------------------------|
|          |                                          |                            | Experimental       | Predicted              |
| B1       | -                                        | -                          | 58                 | 52                     | 1.11                   |
| B2       | 0.9                                      | 300                        | 88                 | 79                     | 1.11                   |
| B3       | 0.9                                      | 450                        | 110                | 95                     | 1.15                   |
| B4       | 0.9                                      | 750                        | 142                | 135                    | 1.05                   |
| B5       | 0.7                                      | 300                        | 89                 | 79                     | 1.12                   |
| B6       | 0.5                                      | 300                        | 82                 | 79                     | 1.03                   |
| B7       | 0.7                                      | 450                        | 110                | 95                     | 1.15                   |
| B8       | 0.5                                      | 450                        | 92                 | 95                     | 0.96                   |

| Mean Ratio | 1.1                          |
| Standard Deviation | 5.6                          |

7. Conclusions
1. Using shear connectors to attach the steel plate is very successful and they are efficient in developing the composite action up to failure.
2. All beams exhibited a ductile tension failure, without separation at the plate ends or shearing of the bolts (connector).
3. The use of external steel plates connected to the tension face of the beam could be enhanced the flexural capacity up to a maximum increase of 145%.
4. Two limits have been introduced on the sectional area and length of steel plate, which are based on a derived balanced plate area and the efficiency of the reinforced concrete section alone in sustaining the applied moment at the plate ends.
5. A good agreement established between the measured and predicted approach results of ultimate load.

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