Effect of web openings on effective flange width of reinforced concrete T-section

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Abstract: In this study an evaluation of empirical formula is carried out for effective flange width with and without web openings based on previous experimental results. The results of empirical equation were compared with the codes of practice formulas such as ACI 318M-14, BS8110, AS 3600 and CSA. Also, three researchers’ equations without the effect of web opening are used to compare with the results of the present study. Square and circular web openings with different size and locations are studied. The effect of compressive strength (f’c), flange reinforcement (ρf'), flexural reinforcement (ρb), shear reinforcement (ρv), thickness of flange (hf) and clear span (ln) are investigated and included in the suggested formula. Finally, the previous researcher’s equations are modified to include the effect of web openings on effective flange width.

Keywords
Reinforced concrete T-beam, effect of web opening, effective width, ratio of reinforcement.

1. Introduction
A reinforced concrete system normally consists of slab and beams that is cast monolithically and as a result T-beams are created and the two parts act together to resist the applied loads [1].

In the construction of modern buildings, networks of pipes and ducts is included to accommodate essential services like air-conditioning, water supply, sewage, electricity, computer network and telephone. Ducts and pipes networks are usually placed underneath the beam soffit or penetrate horizontally the web beam or vertically the slabs and for aesthetic reasons, are covered by a suspended ceiling or by special decoration, [1]

The inclusion of openings in simply supported T-beams are subjected to high stress in the opening corners and it can lead to cracking, since the strength of concrete in tension is considerably lower than its strength in compression. So, the design for shear becomes of major importance in all types of concrete structures. The reduced stiffness of the beam may also give rise to excessive deflection under service load and result in a considerable redistribution of moments and internal forces in a continuous beam. The strength and serviceability of such a continuous beam may be seriously affected when special reinforcement is provided in sufficient quantity with proper detailing. [2]

2. Shear lag and effective width of T-beams.
In the conventional engineering theory of bending assumes that “the plane sections before cracks remain plane after bending” which means that shearing strains are neglected.
The term ‘shear lag’ is used to describe the variances between the approximate engineering theory, and the real behavior that results in both an increase in the stresses in the “flange component adjacent to the web component” in a T-beams, and a decrease in the stresses in the flange component away from the web, as shown in the Figure (1).

![Figure 1 Shear Lag and Effective Width of T-beams](image)

3. Calculation of the effective flange width
The effective flange width can be defined in a variety of ways. It is generally a function of the longitudinal strain at the top surface of the flange; so it can be obtained by integration of the accurately computed longitudinal strain at the top surface of flange and divided by the peak strain value, fig.(1).[5]

\[
be = \frac{\int_0^b \varepsilon_z \, dx}{(\varepsilon_z)_{\text{max}}}
\]  

where \((b_e)\) is effective flange width, \((b)\) is a flange width, \((\varepsilon_z)\) is a strain in the longitudinal direction (normal strain), and \((\varepsilon_z)_{\text{max}}\) is the peak strain (maximum normal strain).

Equation (1) is calculated using an approximate method rule (Simpson’s rule). The required calculations are done by using Microsoft EXCEL computer program.

4. Web opening
Height limitations are often imposed on multistory buildings based on economic requirement, zoning regulations, and aesthetic considerations including the need to match the floor heights of existing buildings. Web openings of the beams can help to minimize story height because, its used to pass utilities through beams. A decrease of building height reduces of interior volume and exterior surface of a building, which reduces the maintenance and the operational cost. The disadvantage point, that web openings can significantly reduce the bending capacity and shear for reinforcement concrete T-beams.

5. Experimental program [4]
The experimental program consists of testing twenty four simply supported T-beams. All beams were divided in two groups which have been illustrated in (Group A and Group B). Group A considers the change in geometry and reinforcing parameters (without web opening), Group B considers the change in location, size, shape and number of openings (with web opening) as detailed in tables (1) and (2). The specimens have been achieved with condition of ACI 318M-14 [8] to check the clear span to depth ratio (Ln / h > 4.0), all beams are designed to fail in flexural test. Some of affecting principle parameters on strain distribution at top flange, and the effective width of flange of T-section are investigated. In each subgroup, all the parameters being held constant except one, which has been considered to vary for studying the effect this parameter.

A variable which has been investigated in Group A, included sixteen beams were longitudinal reinforcement $\rho_l$, flange reinforcement $\rho_f$, shear reinforcement $\rho_v$, concrete compressive strength $f'_c$, thickness of flange $h_f$, width of flange $b_f$, clear span $l_n$.

Group B included eight beams and the location, size, shape and number of openings were the main variables in this group and location of opening at web were selected at mid span and quarter span, the dimension of openings are 100x100 mm and 150x150 mm for rectangular openings, 100 mm and 150 mm diameter for circular openings, All the openings have been located under neutral axis of the concrete T-beams as shown in figure (2).

![Figure 2 Cross section T-beam with web opening location](image)

The experimental results of twenty four reinforced concrete T-beams with and without web openings are shown in table 2. The test results of beams include cracking load, ultimate load, and failure mode. Also, effecting of adopted parameters on the behaviour of reinforced concrete T-beams such on cracking load, ultimate load and flexure capacities are presented.

6. Analysis of results

In this section, the effective flange width is predicted by process of explaining the experimental results. The statistical methods here showed good agreement results. The first steps in this process include predicting the analytical relationships between the effective flange width and the parameters adopted in the parametric study of previous experimental work [4]. The regression analysis method is used in the analysis process of the results using Microsoft EXCEL program.

The overall objective is to develop a predictive equation to evaluate the effective flange width; the main variables which include in this equation is flange width to clear span length ratio, clear span length to depth ratio, width of web to overall depth ratio, thickness of flange to overall depth ratio and area of opening to area of section ratio.
Table 1  Previous Experimental Work [4]

| Group No | Subgroup | b | Ln | b1 | b2 | \( \theta_s \) | \( \theta_g \) | \( f_t \) MPa | Opening | Effect of parameter |
|----------|----------|---|----|----|----|-----------|-----------|----------|--------|-------------------|
| A1       | E11      | 150| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 21.7    |        | CONT. 1           |
| A1       | E12      | 150| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 21.7    |        | CONT. 2           |
| A2       | E21      | 150| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 25.3    |        | \( f_{\infty} \) |
| A2       | E22      | 150| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 31.2    |        | \( f_{\infty} \) |
| A3       | E31      | 150| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 22.8    |        | \( f_{\infty} \) |
| A3       | E32      | 150| 350| 50 | 0.022498   | 0.001795 | 0.001745 | 22.8    |        | \( f_{\infty} \) |
| GROUP A WITHOUT WEB OPENINGS | A4 | E41 | 150| 350| 50 | 0.0143989 | 0.002693 | 0.001745 | 23.2    |        | \( \theta_s \) |
| A5       | E51      | 150| 350| 50 | 0.0143989 | 0.003590 | 0.001745 | 23.2    |        | \( \theta_s \) |
| A5       | E52      | 150| 350| 50 | 0.0143989 | 0.003590 | 0.001745 | 22.6    |        | \( \theta_s \) |
| A6       | E61      | 150| 350| 75 (25%) | 0.0143989 | 0.001795 | 0.001745 | 22.9    |        | \( \theta_s \) |
| A6       | E62      | 150| 350| 100 (30%)| 0.0143989 | 0.001795 | 0.001745 | 22.4    |        | \( \theta_s \) |
| A7       | E71      | 150| 450 (25%)| 50 | 0.0143989 | 0.001795 | 0.001745 | 23.2    |        | \( \theta_s \) |
| A7       | E72      | 150| 550 (30%)| 50 | 0.0143989 | 0.001795 | 0.001745 | 23.2    |        | \( \theta_s \) |
| A8       | E81      | 150| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 22.9    |        | 1 Rect. * |
| A8       | E82      | 200| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 22.9    |        | 1 Rect. ** |

GROUP B WITH WEB OPENINGS

| Group No | Subgroup | b | Ln | b1 | b2 | \( \theta_s \) | \( \theta_g \) | \( f_t \) MPa | Opening | Effect of parameter |
|----------|----------|---|----|----|----|-----------|-----------|----------|--------|-------------------|
| B1       | E11      | 130| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 22      | 3 Rect. | 1 Rect. - * |
| B1       | E12      | 130| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 22      | 3 Rect. | 1 Rect. - ** |
| B2       | E21      | 130| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 21.5    | 1 Circ. | 1 Circ. - * |
| B2       | E22      | 130| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 21.5    | 1 Circ. | 1 Circ. - ** |
| B3       | E31      | 130| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 21.6    | 1 Circ. | 1 Circ. - *** |
| B3       | E32      | 130| 350| 50 | 0.0143989 | 0.001795 | 0.001745 | 23.4    | 1 Rect. | 1 Rect. - ** |

All dimension in (mm)
Table (2) Experimental Results of Previous Work [4]

| GROUP NO | Sub Group | Beams | Mode of Failure | \( P_a \) | \( P_r \) | \( P_{ef} \) | \( b_e \) | \( b_0 \) | Effect of parameter |
|----------|-----------|-------|----------------|--------|--------|--------|--------|--------|-------------------|
| A1       | A11       | Flexure | 155             | 420    | 0.370  | 212    | 0.61   |       | CONT.1            |
| A1       | A12       | Flexure | 150             | 400    | 0.375  | 183    | 0.53   |       | CONT.2            |
| A1       | A21       | Flexure | 160             | 450    | 0.355  | 224    | 0.64   |       |                   |
| A2       | A22       | Flexure | 180             | 460    | 0.390  | 242    | 0.69   |       |                   |
| A3       | A31       | Flexure | 160             | 450    | 0.355  | 230    | 0.66   |       |                   |
| A3       | A32       | Flexure | 165             | 450    | 0.366  | 241    | 0.69   |       |                   |
| A4       | A41       | Flexure | 160             | 410    | 0.390  | 225    | 0.65   |       |                   |
| A4       | A42       | Flexure | 160             | 415    | 0.385  | 248    | 0.71   |       |                   |
| A5       | A51       | Flexure | 165             | 420    | 0.393  | 217    | 0.62   |       |                   |
| A5       | A52       | Flexure | 165             | 425    | 0.388  | 222    | 0.64   |       |                   |
| A5       | A61       | Flexure | 155             | 425    | 0.365  | 224    | 0.64   |       |                   |
| A5       | A62       | Flexure | 155             | 425    | 0.365  | 237    | 0.64   |       |                   |
| A6       | A71       | Flexure | 155             | 420    | 0.369  | 293    | 0.65   |       |                   |
| A6       | A72       | Flexure | 155             | 425    | 0.365  | 266    | 0.67   |       |                   |
| A7       | A81       | Flexure | 150             | 410    | 0.365  | 232    | 0.65   |       |                   |
| A7       | A82       | Flexure | 145             | 400    | 0.365  | 240    | 0.65   |       |                   |
| A7       | B11       | Shear   | 120             | 300    | 0.400  | 204    | 0.59   |       | 1 Rect.          |
| A7       | B12       | Flexure | 115             | 250    | 0.411  | 182    | 0.52   |       | 1 Rect.          |
| A7       | B13       | Shear   | 100             | 240    | 0.417  | 182    | 0.52   |       | 3 Rect.          |
| A7       | B14       | Shear   | 130             | 350    | 0.371  | 208    | 0.60   |       | 1 Circ.          |
| A7       | B21       | Shear   | 130             | 350    | 0.371  | 208    | 0.60   |       | 1 Circ.          |
| A7       | B22       | Shear   | 130             | 310    | 0.419  | 185    | 0.53   |       | 1 Circ.          |
| A7       | B23       | Shear   | 125             | 280    | 0.446  | 184    | 0.53   |       | 3 Circ.          |
| A7       | B31       | Shear   | 80              | 150    | 0.533  | -      | -      | -      | 1 Rect.          |
| A7       | B32       | Shear   | 60              | 180    | 0.333  | -      | -      | -      | 1 Rect.          |

7. Comparison of test results with codes and researchers equations.

The experimental results of effective flange width are compared with the codes practice formula such as ACI318-14, [8] BS8110 [9], AS3600 [10] and CSA [11]. Table 3 illustrates the close value with limitation, which has been explained above. Also, three researchers’ equations are used to compare with the results of the present study, the first equation is adopted by Sutandi [5]:

\[
\frac{b_e}{b_f} = 0.3507 \left( \frac{b_f}{L_n} \right)^{-0.4451} \cdot \left( \frac{L_n}{h} \right)^{0.1451} \cdot \left( \frac{b_w}{h} \right)^{0.1204} \cdot \left( \frac{b_f}{h} \right)^{0.2128} \quad \cdots (2)
\]

Second equation is adopted by Utku [6]
\[ \frac{b_e}{b_f} = 0.6310 - 0.9560 \left( \frac{b_f}{L_n} \right) + 0.0090 \left( \frac{L_n}{h} \right) + 0.0852 \left( \frac{b_w}{h} \right) + 0.3440 \left( \frac{h_f}{h} \right) \ldots (3) \]

Third equation is adopted by Kucukarslan [7]:

\[ \frac{b_e}{b_f} = 0.322 \left[ \left( \frac{b_f}{L_n} \right)^{0.2947} \right] * \left( \frac{L_n}{h} \right)^{0.2463} * \left( \frac{b_w}{h} \right)^{0.0913} * \left( \frac{h_f}{h} \right)^{0.1698} \ldots \ldots (4) \]

### Table 3

| GROUP NO. | BEAMS NO. | EFFECTIVE WIDTH (mm) Test Results | ACI [8] mm | BS [9] mm | AS 10 [10] mm | CSA [11] mm |
|-----------|-----------|-----------------------------------|-------------|------------|----------------|-------------|
| A1        | 61        | 212                               | 350         | 350        | 350            | 350         |
| A2        | 62        | 183                               | 350         | 350        | 350            | 350         |
| A3        | 63        | 224                               | 350         | 350        | 350            | 350         |
| A4        | 64        | 242                               | 350         | 350        | 350            | 350         |
| A5        | 65        | 230                               | 350         | 350        | 350            | 350         |
| A6        | 66        | 241                               | 350         | 350        | 350            | 350         |
| A7        | 67        | 235                               | 350         | 350        | 350            | 350         |
| A8        | 68        | 257                               | 350         | 350        | 350            | 350         |
| A9        | 69        | 256                               | 350         | 350        | 350            | 350         |
| A10       | 70        | 232                               | 350         | 350        | 350            | 350         |
| GROUP B WITHOUT OPENING | B1 | 240 | 350 | 350 | 350 | 350 |
| B2 | 254 | 350 | 350 | 350 | 350 |
| B3 | 255 | 350 | 350 | 350 | 350 |
| B4 | 256 | 350 | 350 | 350 | 350 |
| B5 | 257 | 350 | 350 | 350 | 350 |
| B6 | 258 | 350 | 350 | 350 | 350 |
| B7 | 259 | 350 | 350 | 350 | 350 |
| B8 | 260 | 350 | 350 | 350 | 350 |
| B9 | 261 | 350 | 350 | 350 | 350 |
| B10 | 262 | 350 | 350 | 350 | 350 |

Table 4. shows the comparison of researchers’ equations with experimental results that are obtained in the present study.

- Table (3) shows that the British standard and Australian codes are more conservative than others whereas the Canadian code gives the close values to experimental data and the reason is the difference in strain distribution above the flange at location of point load which is higher than other positions along the beam. So, to be more precise one has to consider the real width ($b_l$), as total effective width ($b_e$).
- In Table (4), the comparison of the ratio ($b_e/b_l$) obtained by other equations with experimental results, indicates that the present study gives higher results than that obtained by finite element analysis (Researcher’s equations).
Codes of practice and researchers’ equations ignore the effects of openings on flange effective width. In the present study, the effects of these parameters are investigated and taken into consideration. Figures (3) and (4) show these effects.

**Table 4.** Comparison of experimental results (be/bf) with researchers’ equations.

| Main GROUP NO. | BEAMS NO. | EFFECTIVE WIDTH (mm) | b_r | Present Study | Sotadani Eq. | Udou Eq. | Sattar Eq. |
|----------------|-----------|----------------------|-----|---------------|--------------|----------|-----------|
| A11            | 212       | 350                  | 0.61| 0.51          | 0.54         | 0.48     |
| A12            | 183       | 350                  | 0.53| 0.51          | 0.54         | 0.48     |
| A21            | 224       | 350                  | 0.64| 0.51          | 0.54         | 0.48     |
| A22            | 242       | 350                  | 0.69| 0.51          | 0.54         | 0.48     |
| A31            | 230       | 350                  | 0.66| 0.51          | 0.54         | 0.48     |
| A32            | 241       | 350                  | 0.69| 0.51          | 0.54         | 0.48     |
| A41            | 225       | 350                  | 0.65| 0.51          | 0.54         | 0.48     |
| A42            | 248       | 350                  | 0.71| 0.51          | 0.54         | 0.48     |
| A51            | 217       | 350                  | 0.62| 0.51          | 0.54         | 0.48     |
| A52            | 222       | 350                  | 0.64| 0.51          | 0.54         | 0.48     |
| A61            | 224       | 350                  | 0.64| 0.55          | 0.56         | 0.50     |
| A62            | 237       | 350                  | 0.68| 0.57          | 0.58         | 0.52     |
| A71            | 293       | 450                  | 0.65| 0.45          | 0.48         | 0.44     |
| A72            | 366       | 550                  | 0.67| 0.41          | 0.41         | 0.42     |
| A81            | 232       | 350                  | 0.65| 0.55          | 0.58         | 0.52     |
| A82            | 240       | 350                  | 0.68| 0.60          | 0.61         | 0.56     |

| GROUP A WITHOUT OPENING |
|-------------------------|
| B11                     | 204         | 350                  | 0.59| 0.51          | 0.54         | 0.48     |
| B12                     | 182         | 350                  | 0.52| 0.51          | 0.54         | 0.48     |
| B13                     | 182         | 350                  | 0.52| 0.51          | 0.54         | 0.48     |
| B21                     | 208         | 350                  | 0.6  | 0.51         | 0.54         | 0.48     |
| B22                     | 185         | 350                  | 0.53| 0.51          | 0.54         | 0.48     |
| B23                     | 184         | 350                  | 0.53| 0.51          | 0.54         | 0.48     |
| B31                     | -           | 350                  |     | -            | -            | -        |
| B32                     | -           | 350                  |     | -            | -            | -        |

**8. Statistical analysis**

Evaluation of empirical formula is carried out using some statistical properties which express the conformity between predicted values by using these equations with the experimental results of tested T-beams, six statistical properties are adopted in this study: (Mean, SDV, COV%, max. value, min. value, and range)
9. Results of analysis and proposed equations.

The main object of the regression method is meant that a line through points (experimental data) is to fit, so that the squared deviations are minimized for the observed points from that line. Regression method can be allowing the researcher to obtain a set of coefficients for an equation.

For the analysis purposed and in order to obtain a rational comparison with the experimental results, the factors below (k1, k2, k3, k4 and k5) are used in regression of values until being converged with researcher equations, this is discussed later.

\[
\frac{be}{bf} = k_1 - k_2 \left( \frac{bf}{Ln} \right) + k_3 \left( \frac{Ln}{h} \right) + k_4 \left( \frac{bw}{h} \right) + k_5 \left( \frac{hf}{h} \right)
\]  

(5)

Most of proposed studies, when the level of independent variable X is specified, the value of dependent variable Y is not uniquely determined, this relations are called statistical relations. Statistical relations can be defined either linear or nonlinear. To make a comparison with the previous studies, the model that defines the relation between dependent and independent variables as a nonlinear is used in this study.
Equations by researchers which were presented previously, have been modified to get rapprochement between the experimental results for present study and the theoretical results of these equations then the regression of results for beam with opening calculated based on these equations with added terms of effect of the openings by calculating the percentage of area of openings to area of gross longitudinal section.

As a result, it is meant to provide four empirical equations, three equations have been modified to consider the effect of openings and one is proposed equation with effect of web openings based on experimental results, this criteria of equation to illustrate the difference and convergence between the experimental works and analytical study.

This proposed equations take into account the effect of openings if in addition to beams or without it, by neglected the terms of area and to be equal to zero.

* Proposed equation which neglected the effecting of openings is:

\[
\frac{be}{bf} = 0.65 - 0.956 \left( \frac{bf}{Ln} \right) + 0.01 \left( \frac{Ln}{h} \right) + 0.0952 \left( \frac{bw}{h} \right) + 0.354 \tag{6}
\]

* Proposed equation with effective web openings is:

\[
\frac{be}{bf} = 0.65 - 0.956 \left( \frac{bf}{Ln} \right) + 0.01 \left( \frac{Ln}{h} \right) + 0.0952 \left( \frac{bw}{h} \right) + 0.354 \left( \frac{hf}{h} \right)
- 0.2 \left( \frac{A \text{ opening}}{A \text{ gross section}} \right) \quad \ldots \ldots \tag{7}
\]

The modified researchers’ equations have the effect of openings, include the five major terms that affect effective flange width as shown below:

\[
\frac{be}{bf} = 0.3507 \left( \frac{bf}{Ln} \right)^{-0.4451} \left( \frac{Ln}{h} \right)^{0.1451} \left( \frac{bw}{h} \right)^{0.1204} \left( \frac{hf}{h} \right)^{0.2128} \left( \frac{A \text{ opening}}{A \text{ gross}} \right)^{0.03} \tag{8}
\]

\[
\frac{be}{bf} = 0.6310 - 0.9560 \left( \frac{bf}{Ln} \right) + 0.0090 \left( \frac{Ln}{h} \right) + 0.0852 \left( \frac{bw}{h} \right) + 0.3440 \left( \frac{hf}{h} \right)
- 0.1 \left( \frac{A \text{ opening}}{A \text{ gross}} \right) \tag{9}
\]

\[
\frac{be}{bf} = 0.322 \left( \frac{bf}{Ln} \right)^{-0.2947} \left( \frac{Ln}{h} \right)^{0.2463} \left( \frac{bw}{h} \right)^{0.0913} \left( \frac{hf}{h} \right)^{0.1698} \left( \frac{A \text{ opening}}{A \text{ gross}} \right)^{0.03} \tag{10}
\]

Where:
- \(b_e\) = Effective flange width.
- \(b_f\) = Real flange width.
- \(L_n\) = Clear span length.
- \(h\) = Beam depth.
- \(bw\) = Web width.
- \(h_f\) = Thickness of flange.
- all dimensions in (mm)

10. Comparison between proposed equation results and modified researchers equations and ACI318-14.

Figure 5 shows the parameters were used in this study and compared with ACI 318-14 [8], Sutandi with [5], Utku [6] and Kucukarslan [7] all these equations with effect the term of web openings. Bar
chart illustrates the beams without openings have values that is nearest to ACI code, while the other
equations (Eq2[5], Eq3 [6], Eq4[7]) with effect openings have close values.

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