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SHEAR STRENGTH OF REINFORCED CONCRETE T-BEAMS WITHOUT STIRRUPS

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Abstract

This paper presents the test results of experimental study on shear strength of reinforced concrete beams without stirrups. The test variables in this study were type of beam cross section and ratio of longitudinal reinforcement. Six simple supported beams, consisting of three beams with rectangular cross section and three beams with T section, subjected to two point load were tested until failure. During the test, the values of the diagonal crack load and the maximum load were observed as well as the deformation of the beams. Existing empirical equations for shear strength of concrete presented in the literature and design codes were used and then compared to that value obtained from the test. Comparison between test results and theoretical shear capacity show that all of equations conservatively estimate the occurrence of shear failure with the values of the test results 10 to 90% higher than the theoretical values. It was confirmed from the test that the shear capacity of T-beams were higher than for rectangular beams, with the values ranging from 5 to 25%, depending on the ratio of longitudinal reinforcement. Also, it was observed that ratio of longitudinal reinforcement influences the shear capacity of the beam as well as the angle of diagonal shear crack. In addition, based on the test results, a simple model for predicting the contribution of flange to shear capacity in T-beam was presented.

Keywords: Reinforced concrete, T-beam, shear crack, Longitudinal reinforcements ratio, Angle of diagonal crack.

1. Introduction

Study on shear performance of reinforced concrete structures has been carried out by other researchers over the last 60 years [1-6]. The test variables used to investigate shear behavior of reinforced concrete structures frequently found in literature refer

Nomenclatures

a	shear span length
b_f	width of flange
b_w	width of web
c	neutral axis depth
d	effective depth
f_c'	concrete compressive strength
h_f	height of flange
k	$1.0+\sqrt{(200/d)} \leq 2.0$
V_c	shear capacity of concrete

Greek Symbols

α	parameter taking into account the effect of flange in T section
ρ_w	ratio of longitudinal reinforcement (%)

Abbreviations

ACI	American Concrete Institute
SNI	Standar Nasional Indonesia
LVDT	Linear Variable Differential Transformer
RCCSA	Reinforced Concrete Cross Section Analysis

to the main parameters affecting the occurrence of shear failure e.g. concrete compressive strength, longitudinal reinforcement ratio, shear span to effective depth ratio and effect of member size. Most studies in this area focused only on reinforced concrete beams with rectangular cross section.

Bresler and McGregor [2] reported that shear failure is commonly initiated by the occurrence of diagonal cracks developing in the shear span. It is also stated in their paper that the flexural cracks always come before the occurrence of diagonal cracks in rectangular, I or T sections. Bresler and McGregor noted that the shape of the beam (I and T sections) influences the shear capacity and the behaviour of propagation of diagonal cracking due to the different magnitude of shearing stress developed in the web. However, not much attention has been given to the behavior of reinforced concrete beams with T sections.

In another report, Swamy and Qureshi [5] proposed an analytical procedure to calculate the ultimate shear strength of the compression zone of T-beams with long shear span. The theory of this procedure was derived using the concept of biaxial stress criterion and was based on Mohr's theory of failure. In this method the variables affecting the ultimate shear strength of the compression zone of T-beams are concrete compression strength, longitudinal reinforcement ratio, shear span length and effective depth of the section. Even though Swamy and Qureshi stated that their theory showed good agreement with test results their computation procedure is not simple, it needs several steps of calculation and difficult to apply in practice.

A series of tests designed to study shear failure in reinforced concrete beams without stirrups has been carried out previously [7]. In this earlier study, the type of cross section was rectangular and the test variables were ratio of longitudinal reinforcement and shear span to effective depth ratio. It is reported from this study that most of the beams tested collapsed suddenly after the formation of diagonal shear cracks. On the other hand, diagonal shear cracks were not noticeable if the flexural capacity of the beams was lower than the shear capacity of the concrete and in this case the beams failed in flexural mode. It is also reported that the ratio of longitudinal reinforcement influences not only the shear capacity but also the angle of diagonal shear cracks.

So far, the codes have not covered the behavior of shear capacity of reinforced concrete beams with T sections. In addition, existing equations for shear capacity of concrete available in international design codes do not take into account the influence of the flange in T sections [8, 9]. Due to this fact, the main objective of this experimental work is to add to the data on this topic by focusing on the contribution of the flange to the shear capacity of reinforced concrete T-beams.

In order to achieve the aim of this research, three beams with rectangular sections and three beams with T sections were tested. The effect of longitudinal reinforcement ratio to the shear capacity and the growth of diagonal shear cracks were examined during the test. In addition the angle of diagonal cracks was also measured in order to observe the influence of longitudinal reinforcement ratio on the distribution of stresses in the shear span zone. Empirical equations for shear capacity of concrete available in literature and design code were also used in this study and then compared with shear strength obtained from the test. Finally, available experimental data from literature was added to the data obtained from this study and by using a simple statistical procedure a model for predicting the contribution of flange to the shear capacity of concrete in reinforced concrete beams with T sections was proposed.

2. Experimental Study

Six simply supported reinforced concrete beams without stirrups, consisting of three beams with rectangular cross sections and three beams with T cross sections, were tested in this study. The beams were monotonically loaded until failure with two point load using a 500 kN capacity hydraulic jack. Loading position and dimension of the beam are shown in Fig. 1. For all of the beams, the clear span was 2000 mm, the shear span length (*Ls*) was 800 mm and the end anchorage length beyond the support (*La*) was 150 mm. For all of the beams the shear span - effective depth ratio was about 3.7 ($a/d > 2.5$).

Two types of cross section as shown in Fig. 1 were used. The rectangular section had dimensions of 125 mm width and 250 mm height, while T section had 250 mm flange width, 70 mm flange thickness, 125 web width and 250 height. Deformed steel bars with 13 mm diameter, 550 MPa yield strength, and 204 GPa modulus of elasticity were used as longitudinal reinforcement. Three ratios of longitudinal reinforcement (1, 1.5 and 2.5%) were used for both type of cross section as shown in Fig. 1. The bottom and side concrete covers were 30 mm and 20 mm, respectively. Two wooden plates placed at each end side of the beam's formwork and drilled at the position of longitudinal reinforcements were used to keep the bars in position during concrete casting. The longitudinal reinforcements were suspended using steel wire at the middle position of the beam.

Fresh concrete was produced in the laboratory with a concrete mixer using maximum aggregate size of 20 mm and target compressive strength of 30 MPa. Afterwards, the average concrete cylinder strength obtained from compression tests was 32 MPa at age 28 days. For all beams the deflections at midspan and at one of the loading points were measured using two displacement transducers connected to a data acquisition system as illustrated in Fig. 1.

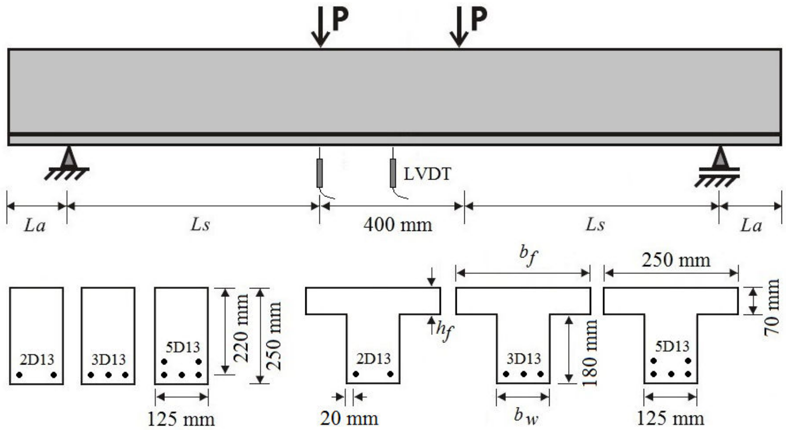


Fig. 1. Test setup and beam dimensions.

3. Theoretical Concrete Shear Strength

Although many empirical equations for concrete shear strength have been suggested in the literature and design codes, only some of them are applied in this study. Four empirical equations listed in Table 1 were used to estimate shear capacity of the concrete. Equation (1) was selected from the literature because of its simplicity, ease of application, and because it takes into account the size effect and ratio of longitudinal reinforcement. This empirical equation is also well-known and frequently used by researchers. Zsutty's equation predicts the shear strength of reinforced concrete beams without stirrups with a high degree of accuracy.

Table 1. Empirical equations for shear capacity of concrete from literature.

Literature	Empirical equations for shear capacity of concrete	
Zsutty [3]	$V_c = 2.17\left(\rho_w f_c' \frac{d}{a}\right)^{1/3} b_w d$	(1)
Niwa [10]	$V_c = 0.2\left(\rho_w f_c'\right)^{1/3}\left(d^{-1/4}\right)\left(0.75 + 1.4\frac{d}{a}\right) b_w d$	(2)
Eurocode 2 [11]	$V_c = \left(0.12k(100\rho_w f_c)^{1/3}\right) b_w d$	(3)
SNI [12]	$V_c = \frac{1}{7}\left(\sqrt{f_c'} + 120\rho_w \frac{d}{a}\right) b_w d$	(4)

Equation (2) was selected as representative of empirical equations developed in response to the needs of a high seismic intensity environment. It also has good agreement with the experimental results [13]. Although apparently complex, parameters used in Niwa's equation are not so different to those used in Eq. (1).

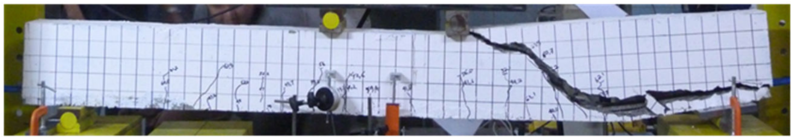
Furthermore, Eq. (3) is an equation adopted from Eurocode2 [11] as representative of the international codes and Eq. (4) is an equation adopted from SNI 03-2847-2002 as representative of the local code [12]. SNI 03-2847-2002 has adopted a similar expression with the equation for concrete shear strength suggested in ACI 318M-08 code [14]. It is shown in Table 1 that all listed equations take into account the concrete compressive strength, longitudinal reinforcements ratio, shear span to effective depth ratio, and size effect. The constant values in each of equation are different due to the choice of mathematical function used to model the observed data and statistical approaches used to analyse it.

4. Results and Discussion

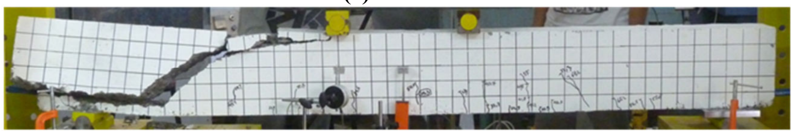
It was observed from the test that the earliest flexural cracks, for both types of beam cross section, developed in the pure moment zone when concrete reached its tensile strength at an average load value of 26 kN. Then, as the load increased, the flexural cracks extended to the shear span zone which then turned to become diagonal shear cracks at an average load value of 36 kN. Soon after that, all of the tested beams failed in shear (shear-tension failure) as expected. This type of shear failure is indicated by rapid propagation of diagonal shear cracks in the shear span zone shortly followed by sudden collapse of the beams. In addition, at failure stage the diagonal cracks continued to develop rapidly towards the support and compression surface of the shear span zone near the point load. The maximum shear load for each tested beam is listed in Table 2. It is shown that the maximum load for beams with T sections is higher than that for rectangular section with the values ranging from 5 to 25%, depending on the ratio of longitudinal reinforcement. This fact confirms that the flange in T beams affects the shear stress distribution and propagation of the diagonal cracks in the web.

Failure modes and cracking patterns of the beams are shown in Fig. 2. The diagonal shear cracks developed in the shear span zone for all beams tested. As shown in Fig. 2, in case of beams with rectangular sections, the height of flexural cracks along the beam length are relatively small especially for beams R-02E and R-03E. On the other hand, in case of beam T-01E, the flexural cracks were developed up to the flange. While for the other two beams with higher reinforcement ratio (T-02E and T-03E) the height of flexural cracks are relatively small. This indicates that the flange and ratio of longitudinal reinforcement not only affects the shear capacity of the beams but also influences the crack formation of the beams significantly.

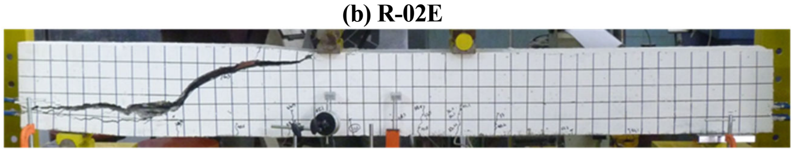
This can be explained using calculated strain distributions of rectangular (R-01A, R-02A and R-03A) and T sections (T-01A, T-02A and T-03A) as shown in Fig. 3. These strain distributions were obtained numerically based on layered element method described in literature [15]. In this method, the reinforced concrete cross section is divided into finite layer elements. A nonlinear stress-strain relationships of concrete and steel should be used in the calculation process. The strains and the corresponding stresses in both steel and concrete elements are then predicted through an iterative procedure by estimating neutral axis depth for a given curvature which satisfies the equilibrium conditions. A numerical procedure was applied to determine the full response of a reinforced concrete cross section until the failure load. This procedure was implemented using a computer program named Reinforced Concrete Cross Section Analysis (RCCSA) developed by Thamrin [16].



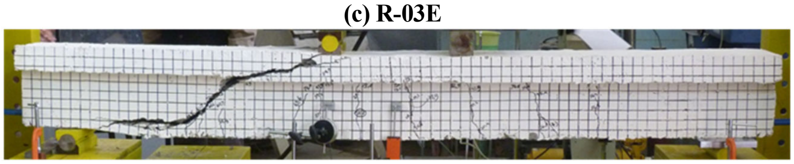
(a) R-01E



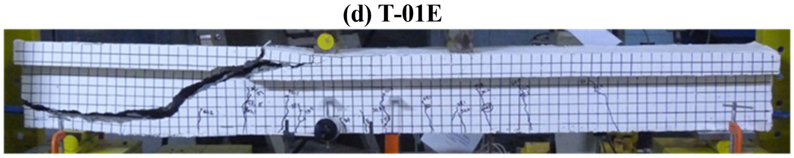
(b) R-02E



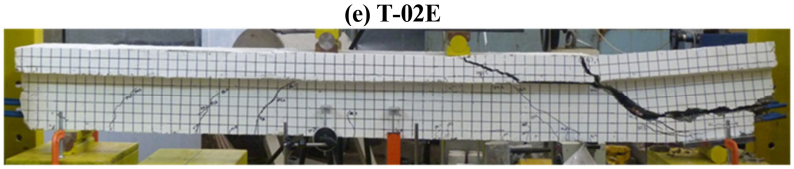
(c) R-03E



(d) T-01E



(e) T-02E



(f) T-03E

Fig. 2. Failure modes and cracking patterns of the beams.

Figure 3 shows that at the level of failure load, the maximum compression strain of T sections is smaller than rectangular sections except for T-01A. This confirms that the flange of T sections significantly decreases the strain quantity in the compression zone. Consequently, the tensile strain of reinforcement in T sections are higher than tensile strain in rectangular sections. In addition, the strain in the compression surface of the section for both types of cross sections do not reach the maximum value of concrete compression strain (0.003). These results indicate that no concrete crushing occurs in the compression surface of the pure bending zone (between two load points) as also shown in Fig. 2. While sections R-01A and T-01A reach the yield strain value (0.0027) of the bar due to a smaller ratio of longitudinal reinforcement. This means that, for these two beams, the shear failure occurs after the tensile reinforcement yield.

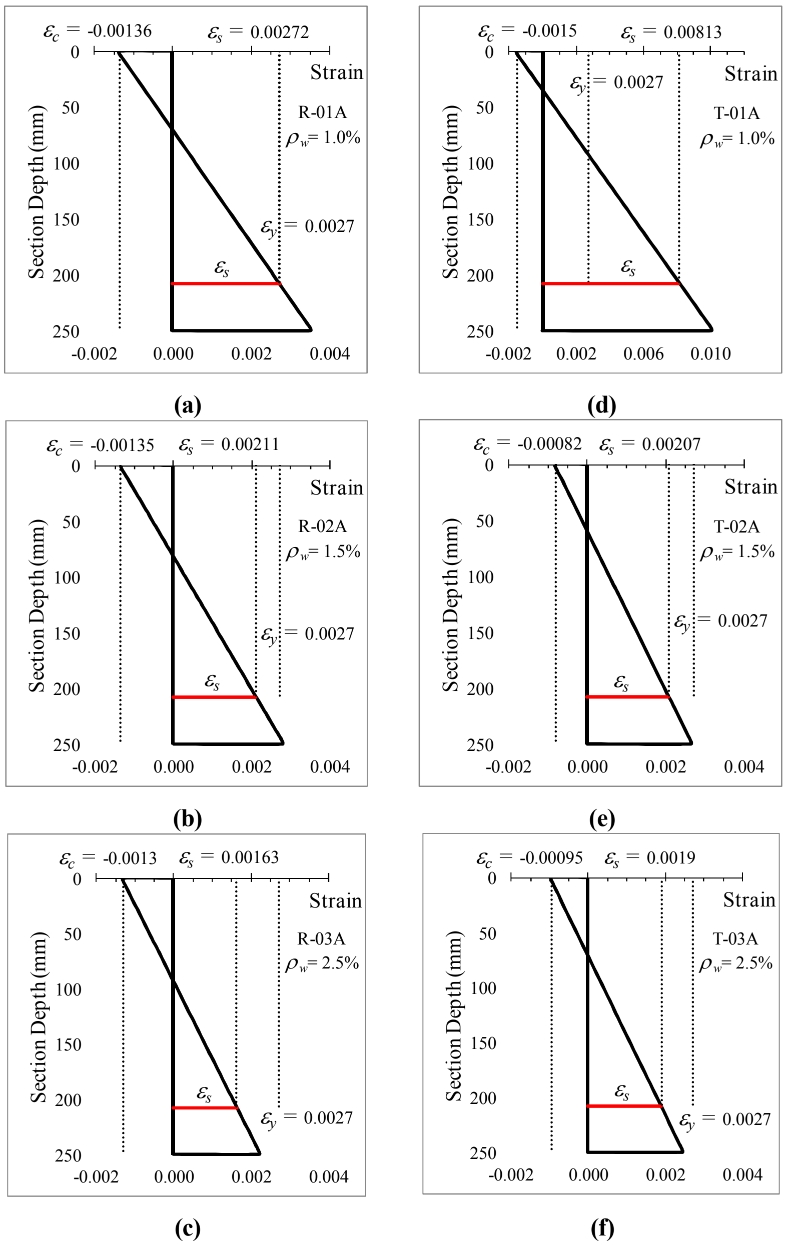
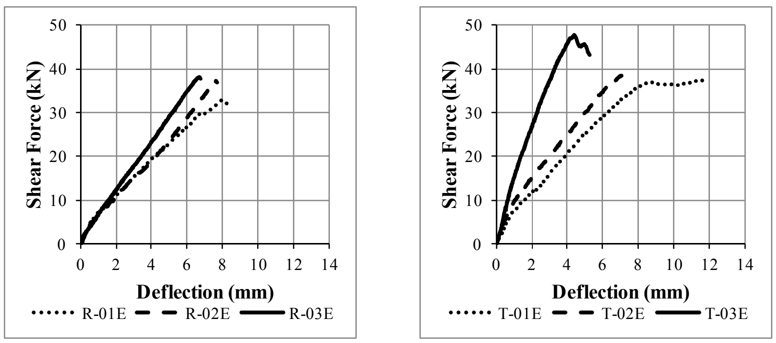


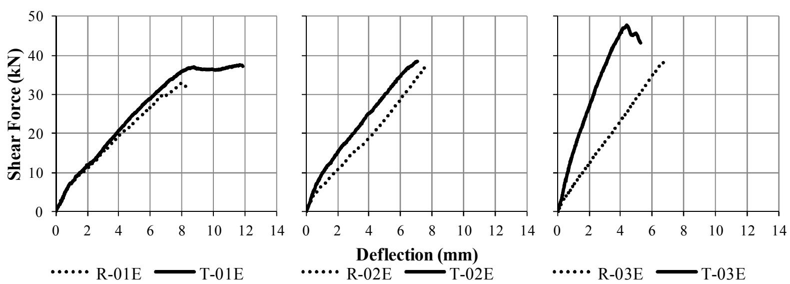
Fig. 3. Analytical strain distributions of rectangular and T sections.

Figures 4(a) and (b) show load-deflection curves of the tested beams. It is shown from these figures that beam capacity increases as the ratio of longitudinal reinforcement increases. In addition, it is confirmed from Fig. 4 that beam R-01E and T-01E failed in shear after longitudinal reinforcement yielded. This is indicated by the flat region in the end part of load-deflection curve. However, the reinforcement in beams R-02E, R-03E, T-02E and T-03E did not reach the yield strength up to the occurrence of shear failure. Comparison between load-deflection curves for individual beams with rectangular and T sections are shown in Fig. 5. Due to the contribution of flange in the compression zone of the section, it is revealed that the capacity and stiffness of beams with T sections are higher than that of beams with rectangular sections.



(a) (b)

Fig. 4. Load-deflection curves obtained from test.

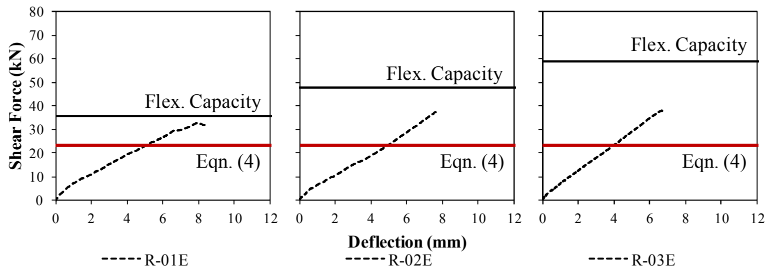


(a) (b) (c)

Fig. 5. Comparison between load-deflection curves for beams with rectangular and T sections.

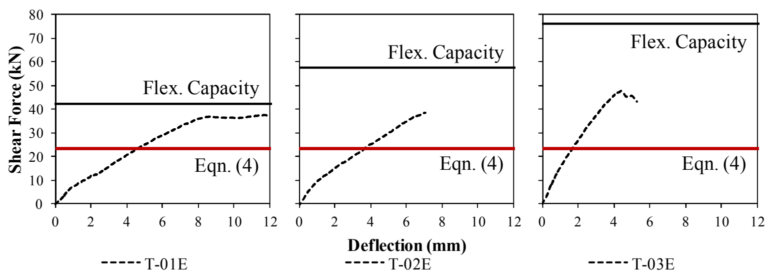
Figures 6 and 7 are plotted in order to compare the shear capacity of the beams from both theoretical (red line) and experimental results (dash line) with flexural capacity (black thick line) of the cross sections. Equation (4) is used as a representative value of theoretical shear capacity. Flexural capacities of the beams plotted in this figures were obtained numerically using the RCCSA program and in this calculation the maximum strain of concrete in compression is 0.003.

It is shown from Figs. 6 and 7 that none of the beams tested reached the flexural capacity of the cross section due to premature shear-tension failure. Additionally, the level of load at failure for of all of the beams exceeds the theoretical shear capacity of concrete calculated using Eq. (4). As well, flexural capacity of cross section increases as the ratio of longitudinal reinforcement increases. These figures also illustrate clearly the quantity of shear force needed to achieve the flexural capacity for each increment of longitudinal reinforcement ratio. The higher the ratio of longitudinal reinforcement, the higher the shear strength required for failure.



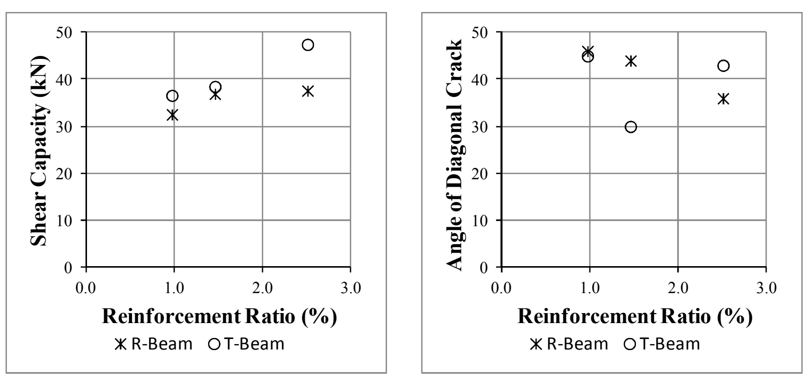
(a) (b) (c)

Fig. 6. Experimental shear and flexural capacities of rectangular beams.



(a) (b) (c)

Fig. 7. Experimental shear and flexural capacities of T-beams.



(a) (b)

Fig. 8. Effect of reinforcement ratio on shear capacity and angle of diagonal crack.

The effect of longitudinal reinforcement ratio on shear capacity and angle of diagonal cracks are plotted in Fig. 8. It is shown that most of the beams failed with the angle of diagonal crack around 45^0. However, as concrete is a non-homogeneous material, a wide variation of angle of diagonal crack is shown in beams R-03E and T-02E. Generally speaking the angle of diagonal crack decreases as the ratio of longitudinal reinforcement increases. It is also demonstrated that the ratio of longitudinal reinforcement significantly affects the shear capacity and angle of diagonal crack.

The test results from this study and selected additional data from literature [7, 17, 18] are summarized in Table 2. All cited data listed in Table 2 are from beams without stirrups and collapsed in diagonal tension failure mode as also attained in this study. For all T-beams listed in Table 2, the concrete compressive strength varies between 13 and 40 MPa. The wide variation of concrete compression strength is an advantage in this study in order to examine the effect of concrete strength on the shear capacity of concrete. The ratio of longitudinal reinforcement ranges between 0.49 to 5.2. The maximum flange width and flange height are 610 mm and 102 mm respectively. While the effective depth ranges between 200 and 399 mm.

Table 2. Test results and theoretical values of V_c.

Specimens	fc' (MPa)	b_w (mm)	h_f (mm)	b_f (mm)	d (mm)	a/d	ρ_w (%)	Zsutty[3] (kN)	Niwa[10] (kN)	*EC2* [11] (kN)	*SNI* [12] (kN)	Exp. *Vmax* (kN)	Proposed Model (kN)
							Data from this study						
R-01E	32	125			219	3.7	1.0	26.05	28.45	20.17	23.31	32.6	23.31
R-02E	32	125			219	3.7	1.5	29.82	32.57	23.09	23.94	37.0	23.94
R-03E	32	125			212	3.8	2.5	34.31	37.75	27.03	24.43	37.6	24.43
T-01E	32	125	70	250	219	3.7	1.0	26.05	28.45	20.17	23.31	36.6	25.34
T-02E	32	125	70	250	219	3.7	1.5	29.82	32.57	23.09	23.94	38.5	25.96
T-03E	32	125	70	250	212	3.8	2.5	34.31	37.75	27.03	24.43	47.5	26.51
							Thamrin et al. [7]						
BSL-02	13.0	130			200	2.3	0.6	19.85	20.95	12.38	14.55	42.5	14.55
BSL-03	13.0	130			200	2.3	0.9	22.81	24.07	14.22	15.16	44.9	15.16
BSN-05	33.5	130			200	2.3	0.6	27.21	28.73	16.97	22.66	48.9	22.66
BSN-06	33.5	130			200	2.3	0.9	31.27	33.00	19.49	23.26	53.9	23.26
BSL-08	13.0	130			200	3.0	0.6	16.71	18.76	12.38	14.28	27.4	14.28
BSL-09	13.0	130			200	3.0	0.9	19.20	21.56	14.22	14.74	29.2	14.74
BSN-11	33.5	130			200	3.0	0.6	22.92	25.72	16.97	22.39	35.7	22.39
BSN-12	33.5	130			200	3.0	0.9	26.33	29.55	19.49	22.85	43.9	22.85
							Kotsovos et al. [17]						
I	40	50	65	200	240	10.4	5.2	15.26	18.01	16.35	11.88	19.0	12.49
II	40	50	65	200	240	10.4	5.2	15.26	18.01	16.35	11.88	22.0	12.49
III	40	50	65	200	240	3.3	5.2	22.30	23.82	16.35	14.07	37.0	14.68
							Palaskas et al. [18]						
N0.2	32.8	190	102	610	374	4.14	0.69	58.52	55.94	41.76	60.17	72.0	66.6
A00	32.7	190	102	610	394	3.92	0.66	61.80	58.25	42.83	63.31	64.7	69.4
B00	32.0	190	102	610	399	3.88	0.49	56.45	53.04	38.89	62.90	70.5	68.9

The equations listed in Table 1 were used to calculate the shear strength of the beams and the results are shown in Table 2. It is noted that all of empirical equations listed in Table 1 ignore the contribution of flanges in T-beams. The comparisons between theoretical values of shear capacity and experimental are presented in Fig. 9. It is shown from Fig. 9 that Eq. (1) and (2) conservatively predict the test results while Eqs. (3) and (4) extremely conservatively predict the shear capacity for both beams with rectangular and T sections. In addition, theoretical predictions for beams with T sections show lower values compared to that obtained from the test especially from the experimental study carried out by Kotsovos et al. [17] and Palaskas et al. [18].

These results demonstrate that shear capacity of concrete is significantly influenced by concrete compressive strength, longitudinal reinforcements ratio, shear span to effective depth ratio and effect of member size. Additionally, the presence of flange in case of T-beams also affects the shear capacity of the beams significantly.

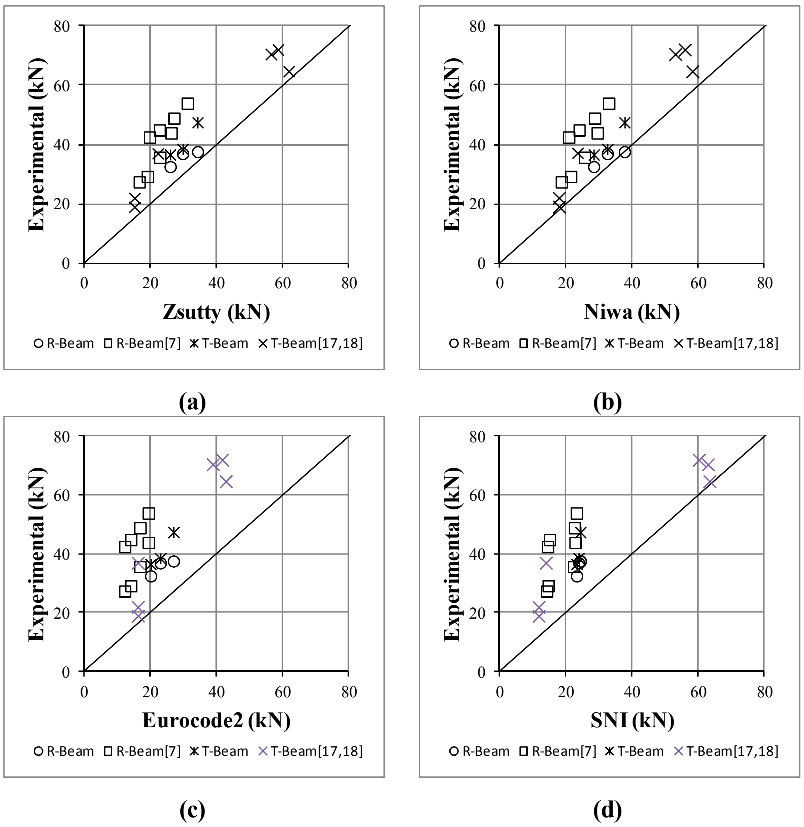
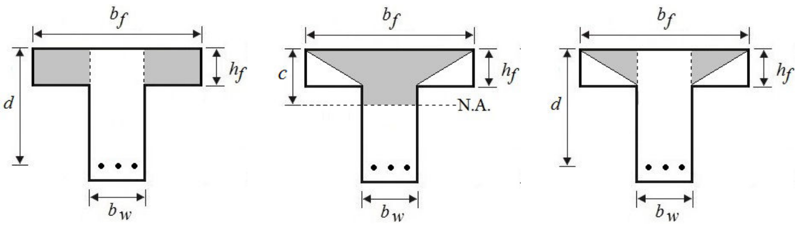


Fig. 9. Comparison of theoretical values of shear capacity with experimental data.

5. Modified Shear Strength Equation for T-Beam

Figure 10 illustrates three models of T section with ignored and effective shear areas. As already described in the previous section, existing empirical equations listed in Table 1 ignore the effect of flange in T-beams as illustrated by the shaded area in Fig. 10(a) and only include the white area ($b_w d$). While Fig. 10(b) shows the effective shear area (shaded area) of concrete in the flange zone according to Zararis et al. [8] and Tureyen et al. [9]. In their report, Zararis et al. [8] suggested a design procedure to calculate the effect of flange, however the procedure proposed is difficult to use in practice. Hence, it is necessary to estimate the effect of flange on the shear capacity using a more simple procedure.



(a) (b) (c)

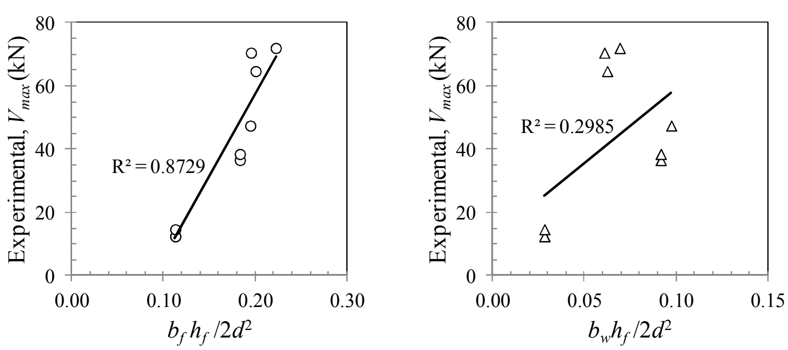
Fig. 10. Ignored and effective shear area of T section.

The process to determine the basic parameters affecting the shear capacity of T-beams can be described using Fig. 10(b) and the following assumptions. As shown in Fig. 10(b), the total shaded area, A_{ct}, can be calculated as:

$$A_{ct} = cb_w + \left(\frac{b_f - b_w}{2} h_f \right) \tag{5}$$

If only the shaded area in flange zone, A_{cf}, as shown in Fig. 10(c) is considered, the total shaded area in Eq. (5) can be reduced to:

$$A_{cf} = \left(\frac{b_f - b_w}{2} h_f \right) \tag{6}$$



(a) (b)

Fig. 11. Effect of b_f and b_w on the shear capacities.

Figure 11 is plotted in order to examine the effect of b_f and b_w on the shear capacities of the beams with T section. In addition, the square of the effective depth, *d*, of the cross section is used as a normalized variable. It is shown in Fig. 11(a) that R-square value of the trend line obtained from this simple statistical analysis is higher than that value in Fig. 11(b). These results demonstrate that b_f

affects the shear capacity of the beams considerably more than b_w. Moreover, since the effect of b_w on the shear capacity is not significant it can be ignored. For that reason the shear area of T section in the flange can be proposed as illustrated in Fig. 10(c) and the basic equation to estimate the effect of flange on the shear capacity can be simplified as:

$$\alpha = \left(\frac{b_f h_f}{2d^2} \right) \quad (7)$$

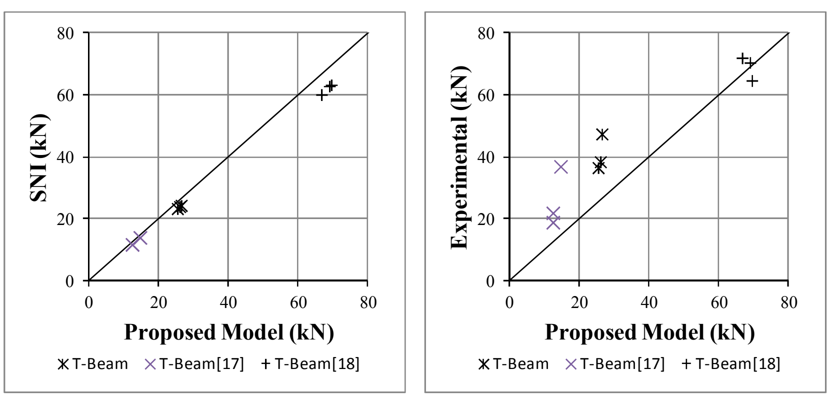
Therefore the width and thickness of the flange become the main variables predicting the additional shear strength contributed by the flange. Eq. (7) was then modified to fit the test results and data from the literature using simple statistical procedure to produce Eq. (8).

$$\alpha = 1.0 + \left(\frac{b_f h_f}{4d^2} \right) \quad (8)$$

Eq. (8) gives a value of 1 in the case of beams with rectangular cross section (h_f = 0). Furthermore, Eq. (4) which is adopted from SNI 03-2847-2002 was modified in order to add the effect of the flange in beams with T section. This is done by substituting Eq. (8) in to Eq. (4) as a multiplication factor for the square root of concrete compressive strength and the modified equation can then be proposed as follows:

$$V_c = \frac{1}{7}\left(\alpha \sqrt{f_c'} + 120 \rho_W \frac{d}{a} \right) b_W d \quad (9)$$

Figure 12 compares shear capacity predicted by the proposed model with experimental results obtained from this study and literature. It can be shown from Fig. 12(a) that the shear capacity of the proposed model is slightly higher than that obtained using Eq. (4). While Fig. 12(b) shows that the shear capacity of the proposed model still conservatively compares to values obtained from the test.



(a) (b)

Fig. 12. Comparison of shear capacities between proposed model and experimental data.

6. Conclusions

Six reinforced concrete beams, consisting of three beams with rectangular cross sections and three beams with T sections, were tested to study the effect of flange and longitudinal reinforcement on the shear capacity. The following conclusions are noted from this study:

- Shear capacity of the tested T-beams is significantly influenced by the flange and the amount of longitudinal reinforcement ratio. The shear capacity of T-beams is 5 to 20% higher than that of beams with rectangular cross section.
- The angle of diagonal crack in the shear span zone was also significantly influenced by the ratio of longitudinal reinforcement. Commonly, for both rectangular and T sections, the angle of diagonal crack decreases as the longitudinal reinforcement ratio increases.
- All of empirical equations used to calculate shear strength of concrete conservatively predict the shear capacity of the beams especially for equations suggested by the codes. Values of the test results are 10 to 90% higher than the theoretical values.
- A new model is proposed to predict the shear strength of reinforced concrete beams with T sections. Shear strength calculated using the proposed model still compares conservatively to experimental values.

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