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SHEAR MECHANISM AND SHEAR STRENGTH PREDICTION OF REINFORCED CONCRETE T-BEAMS

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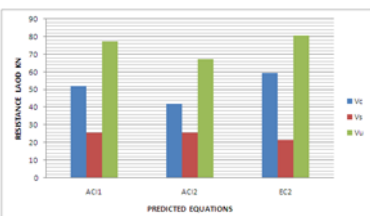
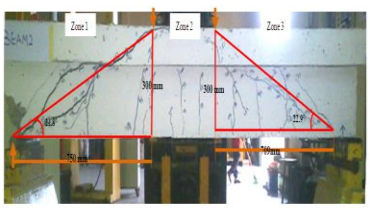
Graphical abstract





Abstract

Shear failure in reinforced concrete beams are sudden failures and should be avoided at all times. However, the shear behaviour of a reinforced concrete beam is a complex mechanism and requires in-depth study. To understand the shear mechanism, two (2) simply supported reinforced concrete T-beams, BEAM1 and BEAM2 were tested until failure subjected to a 4-point bending test. Both beams were designed to the recommendations and specifications of two (2) established design codes by ACI318-08 and Eurocode2 (EC2). The study comprises of two reinforced concrete T-beams having similar variables and parameters with longitudinal reinforcement of ρ = 2.15% and shear span-to-effective depth ratio (a_v/d) of 3.5. Shear reinforcement or stirrups has been added to the specimen and its spacing of stirrups has been provided with the provisions of the codes. The findings from the study indicate that ACI318-08 and EC2 design codes shows significant differences in determining its shear strength capacity V_n and concrete shear resistance V_c of the T-beams. However, both results were less conservative in its prediction when compared to the experimental results.

Keywords: Shear Resistance Mechanism, Reinforced Concrete T-beam, ACI318-08, EC2

Abstrak

Kegagalan ricih dalam rasuk konkrit bertetulang adalah kegagalan secara tiba-tiba dan harus dielakkan pada setiap masa. Walau bagaimanapun, tingkah laku ricih rasuk konkrit bertetulang adalah mekanisme kompleks dan memerlukan kajian mendalam. Untuk memahami mekanisme ricih, dua (2) rasuk-T konkrit bertetulang disokong mudah, BEAM1 dan BEAM2, telah diuji sehingga gagal akibat ujian lenturan 4-mata. Kedua-dua rasuk telah direkabentuk atas cadangan dan spesifikasi dua kod rekabentuk ACI318-08 dan Eurocode2 (EC2). Kajian ini terdiri daripada dua rasuk-T konkrit bertetulang yang mempunyai pembolehubah dan parameter sama dengan tetulang membujur ρ = 2.15% dan nisbah ricih span-ukurdalam berkesan (a_v/d) 3.5. Setiap spesimen telah di lengkapkan dengan tetulang ricih atau stirrup dengan jarak antara stirrup yang tertakluk kepada peruntukan kod. Penemuan daripada kajian ini menunjukkan bahawa kod rekabentuk ACI318-08 dan EC2 telah menunjukkan perbezaan yang signifikan dalam menentukan keupayaan kekuatan ricih V_n dan rintangan ricih konkrit V_c daripada rasuk-T. Walau bagaimanapun, kedua-dua keputusan telah menunjukkan nilai yang kurang konservatif dalam ramalan apabila dibandingkan dengan keputusan eksperimen.

Kata kunci: Mekanisme ricih rintangan, Rasuk-T Konkrit Tetulang, ACI318-08, EC2

1.0 INTRODUCTION

The design for shear comprises of two types of design procedures. When the shear resistance is higher than the shear forces, the beam can design without adding shear reinforcement, but is recommended by most codes of practices to provide minimum shear reinforcement to prevent any possibility of sudden cracks to occur. However, when the shear resistance is lower than the shear forces, the beam must be design with shear reinforcement or stirrups.

For beams without shear reinforcement, the strength of concrete (concrete resistance) will resist the shear forces, where the internal forces will distribute along the beam using the strength of the aggregate until it reaches its maximum. As concrete is weak in tension, cracks will start to appear at the bottom or tension zone of the beam.

However, for beams with shear reinforcement, the presence of concrete (concrete resistance) and shear reinforcement will combine to resist the shear force, where the internal forces will be redistributed upon the shear reinforcement and aggregate. As a result, the shear forces will be resisted by the contribution of the concrete and shear reinforcement strength [1]-[4].

In addition, there are also other factors affecting the shear strength of the beam with or without shear reinforcement such as span to depth (a_v/d) ratio, size effect and stirrups ratio [5], [6]. Shear can be designed and checked to ensure that the shear failure will not occur. The codes of practices comprises of various steps, expressions and equations, which have been driven out through experimental works. These expressions contained limitations for design of shear under ultimate limit state. The codes of practice provide expressions and equations to design for shear with or without shear reinforcement [7], [8].

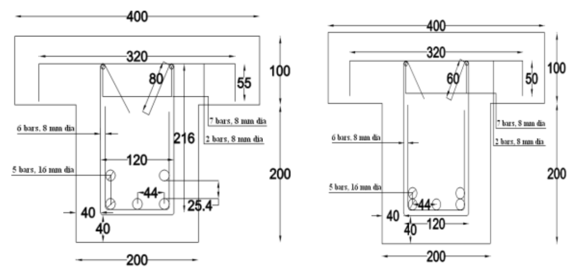
Hence, a study focusing on the shear behavior of simply supported reinforced concrete T-beams designed from two established codes of practice namely ACI 318-08 [9] and EuroCode2 (EC2) [10] were conducted. The specifications and limitations of each standard will be identified, output from experimental results will be used to generate the differences in the design techniques.

2.0 EXPERIMENTAL WORK

To understand the characteristic shear behaviour of a reinforced concrete structure, test on two reinforced concrete T-beams, BEAM1 and BEAM2, subjected to 4-point bending test were conducted up to failure. BEAM1 and BEAM2 were design under the recommendations and specifications of ACI318-08 [9] and EC2 [10] design codes of practice respectively.

Figure 1 shows the cross sectional beam and reinforcement details for BEAM1 and BEAM2. T-beam size of 1500 mm long x 150 mm wide x 300 mm deep and a flange size of 300 mm x 120 mm were selected for the experimental work.

The characteristic compressive strength of concrete was targeted at f_c = 35-40 N/mm^2 and tensile tests on the reinforcing bars was conducted to achieve its yield and ultimate strength of the bars. The T-beams were tested until failure using the 2000 KN Magnus Frame and subjected to the 4-point bending test with shear span to depth ratio (a_v/d) of 3.5. The beams were loaded gradually until failure in shear occurs. The load-deflection at various points along the length of the beam were measured. The modes of failure, its pattern and crack width were measured and recorded.



(a) (b)

Figure 1 Beam size and detail reinforcements for (a) BEAM1 (b) BEAM2

Table 1 Details of experimental beam specimens

Bar	Yield strength f_y (MPa)	Diameter (mm)	Elastic modulus E_s (GPa)	Tensile strength f_t (MPa)
R8	270	7.68	200	270 to 327
Y16	540	15.85	200	540 to 626

3.0 EXPERIMENTAL RESULTS

The behavior of beams subjected to a combination of shear force and bending moment was observed during the test of the un-crack beam specimens. Crack patterns and failure modes of the test specimens were observed at every load stage of the test. BEAM1 represents the specimen made in accordance to ACI318-08 [9] design code whilst BEAM2 were made in accordance to EC2 [10]. Table 2 shows the detail specification of each specimen, its load and deflection at failure.

Table 2 Detail specification for BEAM1 and BEAM2, experimental ultimate load and deflection

Specifications		BEAM1 (ACI318-08)	BEAM2 (EC2)
a_v/d		3.5	3.5
Reinforcement		High Yield	High Yield
f_c MPa		43.5	40.4
b_w (mm)		200	200
h_w (mm)		200	200
h_f (mm)		100	100
b_f (mm)		400	400
d (mm)		231	230
a_v (mm)		825	825
L (mm)		2000	2000
Longitudinal Reinforcement	Quantity of bars	1st layer 3	1st layer 3
		2nd layer 2	2nd layer 2
	d_b (mm)	16	16
	A_s (mm^2)	989	989
	ρ (%)	2.14	2.15
Ultimate Load (KN)		228	204
Deflection at ultimate (mm)		8.19	7.98

3.1 BEAM1 (ACI318-08)

BEAM1 has been designed to its limitation and instructions in accordance to ACI318-08 [9] design code. The cross-sectional details of BEAM1 are as illustrated in Figure 1(a), showing the longitudinal reinforcement ratio at ρ = 2.15%. Five bars of 16 mm in diameter placed in two layers as tension longitudinal reinforcement were provided; two of the bars were placed within the mid-span of the beam. In accordance to ACI318-08 [9], the two layers of reinforcement are required to be spaced apart by at least 25mm. Links are provided by three bars of 8 mm diameter within Zone 1 and Zone 3 of the beam. These links were spaced at intervals of 245 mm. In addition, two more links of 8 mm diameter were provided to hold the top and bottom reinforcement within Zone 2 of the beam. In the flange, seven bars of 8 mm diameter were used as transverse reinforcement. Shear span to depth ratio (a_v/d) for BEAM1 was selected at 3.5. Figure 2 shows the cracks pattern of BEAM1. The behavior of this beam can be summarized as follows:

1. The critical shear crack for BEAM1 was observed as a diagonal tension failure mode.
2. First flexural cracks were developed at a point load of 71 KN (V_c = 35.5KN) in Zone 2.
3. At load of 118 KN (V_c = 59KN), the first shear cracks started to develop in Zone 1 and Zone 3.
4. By observation, a maximum crack width of 2mm had developed at a point load of 204KN (V_c = 102KN).
5. The beam failed in shear upon reaching a point load of 228 KN.
6. The critical shear crack angle in Zone 1 was measured at 22.9° and 23.4° for Zone 3.

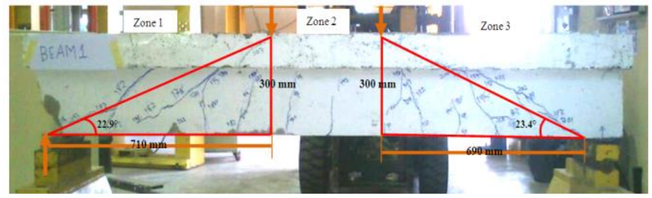


Figure 2 Crack patterns and failure modes for BEAM1

3.2 BEAM2 (EC2)

BEAM2 has been designed to its limitation and instructions in accordance to EC2 [10] design code. The cross-sectional details of BEAM2 are as illustrated in Figure 1(b), showing the longitudinal reinforcement ratio at ρ = 2.15%. Five bars of 16 mm in diameter placed in two layers as tension longitudinal reinforcement were provided; two of the bars were placed within the mid-span of the beam. In accordance to EC2 [10], the two layers of reinforcement are not required to be spaced apart but are placed adjacent as shown in Figure 1(b). Links are provided by three bars of 8 mm diameter within Zone 1 and Zone 3 of the beam. These links were spaced at intervals of 290 mm. In addition, two more links of 8 mm diameter were provided to hold the top and bottom reinforcement within Zone 2 of the beam. Similarly to BEAM1, BEAM2 were also reinforced with seven bars of 8 mm diameter in the flange area with shear span to depth ratio (a_v/d) of 3.5. Figure 3 shows the crack pattern of BEAM2. The behavior of this beam can be summarized as follows:

1. The critical shear crack for BEAM2 was similarly observed as a diagonal tension failure mode.
2. First flexural cracks were developed at point load of 43 KN (V_c = 21.5KN), in Zone 2.
3. At point load of 123 KN (V_c = 61.5KN), the first shear cracks started to develop in Zone 1 and Zone 3.
4. By observation, the maximum crack width developed at failure load of 202KN (V_c = 101KN), was measured at 7 mm.
5. The beam failed upon reaching a point load of 204 KN.
6. The main crack angle of inclination for Zone 1 was measured at 21.8° and for Zone 3 at 22.9°.

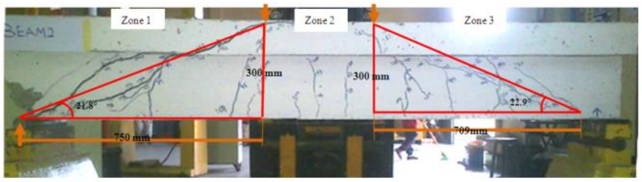


Figure 3 Crack patterns and failure modes for BEAM2

3.3 Shear Resistance Mechanism

Table 3 shows results for concrete shear resistance (V_c) and shear reinforcement resistance (V_s) from equations obtained from ACI313-08 [9] cl.11.2.2.1 and EC2 [10] cl.6.2.2(1) for BEAM1 and BEAM2 respectively. Equation from ACI318-08 [9] cl.11.2.2.1 calculates the concrete shear strength taking into consideration the steel reinforcement ratio (ρ) and shear span to depth ratio (a_v/d). Shear force at failure (V_u) and first shear crack (V_{cr}) were obtained from the experimental results and are as recorded in Table 3 below. In addition, the failure mode of both beams was observed to be in diagonal tension failure. Note that the design loads are not multiplied by partial factors in this table. From observation of Table 3, results indicate that for BEAM1 (ACI318-08), the experimental shear resistance at failure (V_u) achieved higher shear value compared to the theoretical shear force value (V_c + V_s) by 56%. This observation slightly differs for BEAM2 (EC2) where the experimental value also overestimated it strength to the theoretical shear resistance but by only 38%, a difference of 28%.

3.4 Effect of Stirrup Spacing to Shear

BEAM1 and BEAM2 have been designed to different specifications from two established design codes, i.e. ACI318-08 [9] and EC2 [10] respectively. From the design requirements of each code, spacing of stirrups required were 115mm for BEAM1 and 172mm for BEAM2. However, to ensure that the beam failed in shear, a larger stirrup spacing was selected at 245mm for BEAM1 and 290mm for BEAM2. From the beam test, the shear crack width from the two specimens was recorded and it was observed that at failure, BEAM1 had a shear crack width of 2 mm in the web area and 2.5 mm at the flange. In comparison to BEAM2, larger crack width of 7 mm at the web and 5 mm at flange was measured. The results indicate that larger spacing of stirrups, provided by EC2 [10], lead to larger openings of the shear cracks. This behaviour demonstrates the influenced of stirrup spacing and its importance towards the size of the crack width. It is widely known that the design of the spacing of stirrups is related to the equation for shear reinforcement resistance. However, the equation for the design for concrete shear resistance (V_c) in EC2 [10] cl.6.2.2 (1) consists of steel reinforcement ratio ρ which leads to an increase in the concrete shear resistance but with decreasing shear reinforcement resistance. This eventually leads to an increase in the spacing of stirrups. In this section the equation from ACI318-08 [9] cl.11.2.1.1 for the design for concrete shear resistance (V_c) was applied. This equation ignores the influence of steel reinforcement and shear span to depth ratio (a_v/d). Hence, as shown in Table 3, this leads to a decrease in the concrete shear resistance and increasing shear reinforcement resistance, hence the reduction in the spacing of stirrups. Table 4 shows the design spacing of stirrups for specimen BEAM1 and BEAM2 and the effect of shear resistance to concrete and reinforcement.

Table 3 Shear resistance mechanism for BEAM1 and BEAM2

Specifications	BEAM1 (ACI318-08) KN	BEAM2 (EC2) KN
Compressive strength of concrete (N/mm^2)	43.50	40.40
Concrete shear resistance, V_c (Theory)	51.80	59.80
Shear reinforcement resistance, V_s (Theory)	25.50	21.40
Shear crack resistance, V_{cr} (Experimental)	59.00	61.50
Shear force at failure, V_u (Experimental)	114.00	102.00
V_{cr} / V_c	1.14	1.03
$V_{cr} + V_s$	84.50	81.20
$V_c + V_s$	77.30	74.09
$V_u / (V_{cr} + V_s)$	1.35	1.26
$V_u / (V_c + V_s)$	1.47	1.38
Failure mode	Diagonal tension cracks	Diagonal tension cracks

Table 4 Effect of stirrup spacing to shear

Specifications	BEAM1 (ACI318-08)	BEAM2 (EC2)
Concrete shear strength, V_c	41.80 KN	59.40 KN
Shear reinforcement strength, V_s	25.50 KN	21.40 KN
Minimum spacing of stirrups (mm)	115.5	172.5
Maximum spacing of stirrups (mm)	360	277
Selected stirrup spacing (mm)	245	290

3.5 Predicted and Experimental Shear Strength

Generally, the nominal shear strength V_n for a reinforced concrete beam will be the contribution from the nominal concrete shear strength V_c and the nominal shear reinforcement strength V_s.

$$\phi V_n = \phi (V_c + V_s)$$

As highlighted in Section 3.3 and 3.4, predicting the nominal concrete shear strength V_c, from ACI318-08 [9] consists of two equations as given by cl.11.2.1.1 and cl. 11.2.2.1. The equations are clearly shown below.

ACI318-08, cl.11.2.1.1

$$V_c = 0.17\,\lambda\sqrt{f_c}\,b_w\,d$$

ACI318-08, cl.11.2.2.1

$$V_c = \left[0.16\,\lambda\sqrt{f_c} + \left(17.2\,\rho_w\,\frac{V_u d}{M_u}\right)\right] b_w d$$

$$\leq 0.29\,\lambda\sqrt{f_c}\,b_w\,d$$

$$\frac{V_u d}{M_u} = \frac{a_v}{d}$$

The equation to calculate concrete shear strength from EC2, cl.6.2.2(1) is as shown below.

$$V_{Rdc} = \left[C_{Rdc}\,k\,(100\,\rho_1\,f_{ck})^{\frac{1}{3}}\right] b_w\,d$$

$$k = 1 + \sqrt{\frac{200}{d}} \quad and \quad C_{Rdc} = 0.18$$

Figure 4 and Table 5 highlights the shear resistance of V_c and V_s predicted from established design codes of ACI318-08 [9] and EC2 [10], and the shear strength capacity V_n (ACI1, ACI2 and EC2 – see Figure 4, Table 5). As observed, ACI318-08 [9] gave a predicted shear strength capacity of 77.3kN and 67.3kN whilst EC2 [10] gave a higher shear strength capacity at 80.8kN. By observing Figure 4 and Table 5, ACI318-08 [9] design code provides two equations for the prediction of the concrete shear resistance i.e. cl.11.2.1.1 and cl.11.2.2.1. From ACI318-08 [9], higher concrete shear strength V_c of 51.8kN was recorded from cl.11.2.1.1 but a lower V_c was observed from cl.11.2.2.1 at 41.8KN. This shows a difference of 10KN or 19%. However, both predicted values of V_c underestimated the experimental value of V_c at 59KN for BEAM1 from 41.8kN from cl.11.2.1.1 and 51.8kN from cl.11.2.2.1 respectively. This large difference in value occurs because ACI318-08 [9] equation cl.11.2.1.1 did not take into account the contribution factor of steel percentage (ρ) and (a_v/d), as compared to cl.11.2.2.1, because of that the predicted concrete shear resistance was lower for cl.11.2.1.1. Unlike ACI318-08 [9], EC2 [10] design code, cl.6.2.2(1), provided with only one equation to predict the concrete shear resistance V_c which contains factors of steel reinforcement ratio (ρ) and shear span to depth ratio (a_v/d) in the equation. Table 5 shows that the concrete shear resistance V_c from EC2 [10] predicted a value of 59.4KN, which was slightly lower than the experimental value of V_c at 61.5KN or 3.4% in difference for BEAM2. Furthermore, by comparing results between ACI318-08 [9] equation cl.11.2.1.1 and EC2 [10] cl.6.2.2(1), shows the prediction by EC2 [10] was higher by 7.6KN or 12%.

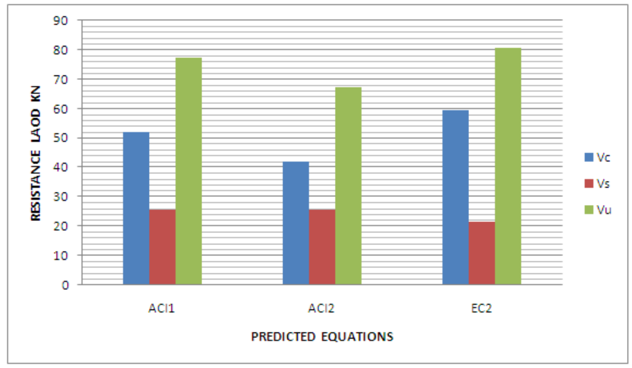


Figure 4 The predicted shear strength capacity from ACI318-08 [9] and EC2 [10]

Table 5 Comparison between predicted and experimental shear strength

	Shear Resistance	BEAM1 (ACI318-08)	BEAM2 (EC2)
	Failure Load (P) kN	228	204
ACI 318-08	V_{c1} (cl 11.2.1.1) kN	41.8	x
	V_{c2} (cl 11.2.2.1) kN	51.8	x
	V_{s1} kN	25.5	x
	V_{s2} kN	25.5	x
	$V_{n1} = V_{c1} + V_s$ kN (ACI1)	67.3	x
	$V_{n2} = V_{c2} + V_s$ kN (ACI2)	77.3	x
EC2	V_{Rdc} kN	x	59.4
	V_s kN	x	21.4
	$V_{n1} = V_{c1} + V_s$ kN (EC2)	x	80.8
	Experimental Results V_c kN	59	61.5
	Experimental Results V_{exp} kN	114	104
	V_{n1} / V_{exp}	0.59	0.57
	V_{n2} / V_{exp}	0.68	x

4.0 CONCLUSION

Some of the important findings from this research are summarized as follows:

1. The design for BEAM1 and BEAM2 have implemented the recommendations and specifications of ACI318-08 [9] and EC2 [10].
2. BEAM1 and BEAM2 were designed to fail in shear and the critical shear crack was observed to behave in the diagonal tension crack failure mode.
3. The presence of flexural cracks at mid-span were developing first before the shear cracks started to develop and propagate to the flange area at both ends of the beam.
4. BEAM1 (ACI318-08) produces smaller crack width of 2mm compared to 7mm for BEAM2 (EC2).

5. Design equations from cl.11.2.1.1 and cl.11.2.2.1 from ACI318-08 [9] and cl.6.2.2(1) from EC2 [10] were applied to predict the concrete shear strength V_c for the T-beam.
6. The equations for predicting the shear strength capacity from ACI318-08 [9] cl.11.2.2.1 and EC2 [10] cl.6.2.2(1) shows significant differences. However, both equations takes into account its steel reinforcement ratio ρ and shear span to depth ratio (a_v/d).
7. ACI318-08 [9] provides a more simplified approach in predicting the shear strength capacity.
8. The specifications and recommendations of ACI318-08 [9] and EC2 [10] provided significant differences but it is acknowledge that both design codes gave good and sensible approaches in predicting the shear strength of concrete.

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