Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Comparative analysis of EC2-04 and ACI318-19 strength provisions for reinforced concrete beams under pure torsion

To cite this article: Samoel Mahdi Saleh 2021 *J. Phys.: Conf. Ser.* **1973** 012224

Comparative analysis of EC2-04 and ACI318-19 strength provisions for reinforced concrete beams under pure torsion

Samoel Mahdi Saleh

Department of Civil Engineering, University of Basrah, Basrah, Iraq.
E-mail: samoel.saleh@uobasrah.edu.iq

Abstract. While the EC2-04 and ACI318-19 provisions use almost the same philosophy to evaluate the torsional strength of reinforced concrete beams, some important details and limitations in these two approaches differ greatly. The objective of the present study is to investigate the differences between these codes and their accuracy by how well they estimate the torsional strength of experimentally tested beams. The predicted torsional strengths based on EC2-04 and ACI318-19 approaches were compared with the results of 120 tested reinforced concrete beams under pure torsion. The inclination angle of the concrete compression struts of the idealized space truss model is chosen to be equals to 45°. It was observed that the ACI318-19 approach is more conservative than the EC2-04 approach in predicting the torsional strength of the tested beams. The graphical comparisons of the predicted to tested torsional strength ratios shows that the EC2-04 approach gives approximately normal distribution curve with a peak at a strength ratio of about 0.85.

Keywords: torsional strength, pure torsion, concrete compression struts, angle of inclination,

1. Introduction
Reinforced concrete beams in buildings, bridges and other structures can be subjected to significant levels of torsional stress; therefore, they should have adequate resistance. Based on a thin-tube space truss analogy, design provisions in building codes and specifications have been well established for torsion. According to this analogy, beams with solid cross section subjected to torsion can be idealized as thin walled tubes with neglected concrete core. The torsional strength of reinforced concrete beams is provided primarily by the longitudinal and transverse reinforcement in addition to the contribution of the concrete as compression diagonals. Some of these design provisions are of the Eurocode 2, EC2-04 [1] and the ACI318-19 code [2], which are the main specifications used around the world in general and in most of Arab Gulf countries as special case for the design of reinforced concrete buildings.
The procedures of evaluation the torsional strength of reinforced concrete beams according to the EC2-04 and ACI318-19 design provisions have important differences in some details and limitations. The objective of the present study is to investigate and evaluate the differences between these two codes in the design of reinforced concrete beam for torsion by how well they estimate the torsional strength of experimentally tested beams through a series of statistical and graphical comparisons. The study is made by comparing the predicted strengths using EC2-04 and ACI318-19 approaches with 120 experimental test results of reinforced concrete beams under pure torsion done by previous researchers.

2. Provisions for torsion design

2.1. EC2-04 provisions
As mentioned previously, the design of a reinforced concrete beam for torsion in the EC2-04 is based on the assumption that the beam behaves in a similar way to a thin walled tube with an effective wall

thickness. The tube is reinforced with closed stirrups as transverse reinforcement and longitudinal reinforcement that may distributed uniformly around the stirrups. Accordantly, the nominal torsional strength (T_{EC2}) of a reinforced concrete beam is the lesser of the following;

$$T_{EC2} = \frac{2\, A_k\, A_v\, f_{yt}\, cot\theta}{s} \tag{1}$$

$$T_{EC2} = \frac{2\, A_k\, A_s\, f_y\, tan\theta}{U_k} \tag{2}$$

where:

$A_k = (D - t_{ef}) \times (B - t_{ef})$, area enclosed by the centreline of the section thin wall (mm^2)
$U_k = 2(D + B - 2t_{ef})$, perimeter of the area enclosed by the centerline of the section thin wall (mm)
$t_{ef} = \max\left({}^{A}/_{P_c}, 2c\right)$, effective thickness of section wall (mm)
$A = B \times D$, area of the concrete beam cross section (mm^2)
$P_c = 2(B + D)$, perimeter of the concrete beam cross section (mm)

and

D overall depth of the concrete beam cross section (mm)
B width of the concrete beam cross section (mm)
c distance from the beam cross section edge to the longitudinal reinforcement centreline
A_v area of one leg of the closed stirrup (mm^2)
A_s area of the longitudinal reinforcement (mm^2)
s spacing between closed stirrups (mm)
f_{yt} yield strength of stirrups (MPa)
f_y yield strength of the longitudinal reinforcement (MPa)
θ inclination angle of the compression diagonals (degree)

The equations (1) and (2) relating the torsional strength to the quantity of closed stirrups and longitudinal reinforcement, respectively. For pure torsion, the evaluated (T_{EC2}) must not exceeded the maximum torsional strength (T_{max}) of the beam cross section, which represents the capacity of concrete diagonal struts.

$$T_{max} = 2\nu\alpha_c f_c' A_k t_{ef} sin\theta cos\theta \tag{3}$$

where:

$\upsilon = 0.6\left[1 - ({}^{f_c'}/_{250})\right]$
α_c a coefficient taking equals to 1 for nonprestressed members
fc' specified compressive strength of concrete (MPa)

2.2. ACI318-19 provisions

Although the ACI318-19 is based on the space truss analogy to evaluate the torsional strength of reinforced concrete beams, there are main differences in its provisions comparing with the EC2-04. The nominal torsional strength (T_{ACI}) of a cracking reinforced concrete beam can be estimated by taking the lesser of the following two expressions (4) and (5), which are mainly related to the provided quantity of closed stirrups and longitudinal reinforcement, respectively.

$$T_{ACI} = \frac{2\, A_o\, A_v\, f_{yt} \cot\theta}{s} \tag{4}$$

$$T_{ACI} = \frac{2\, A_o\, A_s\, f_y \tan\theta}{P_h} \tag{5}$$

where:

$A_o = 0.85 A_{oh}$, area enclosed by the path of shear flow around the tube section perimeter (mm^2)

A_{oh} the area enclosed by the beam outermost closed stirrup centreline (mm^2)

P_h perimeter of the outermost closed stirrup centreline (mm)

Moreover, ACI318-19 showed that in the case of pure torsion, the evaluated torsional strength is limited by the capacity of the concrete beam cross section (T_{max}), which can be expressed for normal weight concrete as follows;

$$T_{\max} = \frac{17\sqrt{f_c'}\, A_{oh}^2}{12\, P_h} \tag{6}$$

2.3. Angle of inclination

The angle of inclination (θ) that appeared in the previous expressions of torsional strength evaluation for a reinforced concrete beam is physically represents the angle between the beam axis and the concrete compression struts of the idealized space truss that used to model the behaviour of the beam under torsion. While the limits ($22^o \leq \theta \leq 45^o$) are recommended by EC2-04, the Eurocode 8, EC8-04 [3] stated that the value of (θ) shall be equal to (45^o) for the design of reinforced concrete beams in primary seismic regions, which is the same value that the ACI318-19 permitted to take for nonprestressed concrete members. The value of (θ = 45°) is considered in the present study.

3. Review of experimentally tested beams

In 2006, Chalioris [4] tested 56 plain and reinforced concrete beams subjected to pure torsion. The effect of beam section aspect ratio, amount of stirrups, and the amount and arrangement of longitudinal reinforcement were examined on the torsional behaviour of the tested beams. Moreover, the study presented an analytical approach to describe the behaviour by using a combination of two different models. A smeared crack analysis is achieved to predict the elastic behaviour until the first crack of tested beams, whereas the softened truss model with a modification to consider the confinement effect in the concrete is employed to describe the post cracking part.

Fang and Shiau [5] studied in 2004 the deformation and torsional strength of 16 reinforced concrete beams under pure torsion. The concrete compressive strength and the quantity of torsional reinforcement were the main parameters that considered in their study. Eight of the tested beams had a concrete with normal compressive strength of about (35MPa), whereas the others with high compressive strength of about (70MPa). They observed that the beams with high strength concrete produced higher cracking stiffness and higher torsional strength compared with those with normal strength concrete. After the beams reached their ultimate strengths, it is found that the increase in torsional reinforcement ratio produced a steeper decay in their strength for high strength concrete beams in comparison to those with normal strength concrete.

Rasmussen and Baker [6] examined in 1995 the behaviour of 12 reinforced concrete beams subjected to pure torsion. The main variable that considered in their study was the concrete compressive strength, which ranged from (35 MPa) to (110 MPa). They observed that the beams with high strength concrete developed higher torsional stiffness, higher ultimate torsional capacity and attained to higher cracking load comparing with those with normal strength concrete. Moreover, the crack width and reinforcement stresses were lower for high strength concrete beams.

In 1978, McMullen and Rangen [7] investigated the effects steel reinforcement amount and the aspect ratio on the behaviour of 10 rectangular reinforced concrete beams under pure torsion. It was noted that the torsional strength of a reinforced concrete beam inversely proportion to its aspect ratio. Moreover, it was found that, for a rectangular concrete beam, the yield stress in the short legs of the transverse torsional reinforcement (closed stirrups) might start before the long legs yielding.

The experimental results of 47 reinforced concrete beams subjected to pure torsion were presented by Hsu in 1968 [8]. The influence of various parameters on the torsional behaviour of the tested specimens were considered. The concrete strength, the amount of steel reinforcement, the ratio of transverse to longitudinal reinforcement, the depth to width ratio of beams section and the scale effect were the main parameters that considered. The experimental results showed that the behaviour of the cracked reinforced concrete beams are different from that predicted by the principle of Saint Venant.
The section dimensions, material properties and the experimental test results of the 120 reinforced concrete beams that collected in this study are listed in tables (1 – 5).

Table 1. Summary of tested beams under pure torsion carried out by Chalioris

No.	Specimen	D×B (mm)	f_c' (MPa)	A_s (mm^2)	f_y (MPa)	A_v (mm^2)	f_{yt} (MPa)	s (mm)	T_{Test} (kN.m)
1	R-r4-5	200 × 100	20.96	201	518.00	79	365.00	50	3.974
2	R-r4-3	200 × 100	20.96	201	518.00	133	365.00	50	4.172
3	R-r6-30	200 × 100	24.59	302	518.00	133	365.00	50	2.640
4	R-r6-5	200 × 100	24.59	302	518.00	133	365.00	50	4.251
5	R-r6-3	200 × 100	24.59	302	518.00	133	365.00	50	4.443
6	R-rb-20	200 × 100	20.07	302	518.00	133	365.00	50	2.452
7	R-rb-15	200 × 100	20.07	302	518.00	133	365.00	50	3.116
8	R-rb-10	200 × 100	20.07	302	518.00	133	365.00	50	3.702
9	R-rb-5	200 × 100	20.07	302	518.00	79	365.00	50	4.163
10	R-rb-3	200 × 100	20.07	302	518.00	79	365.00	50	4.347
11	Rh-r4-5	300 × 100	26.56	201	518.00	79	365.00	50	7.144
12	Rh-r4-3	300 × 100	26.56	201	518.00	79	365.00	50	7.331
13	Rh-r6-30	300 × 100	24.90	302	518.00	133	365.00	50	4.241
14	Rh-r6-5	300 × 100	24.90	302	518.00	133	365.00	50	8.474
15	Rh-r6-3	300 × 100	24.90	302	518.00	133	365.00	50	8.559
16	Rh-r8-30	300 × 100	27.39	402	518.00	133	365.00	50	4.464
17	Rh-r8-5	300 × 100	27.39	402	518.00	79	365.00	50	8.553
18	Rh-r8-3	300 × 100	27.39	402	518.00	133	365.00	50	8.594
19	Rh-rb-20	300 × 100	24.49	302	518.00	133	365.00	50	4.308
20	Rh-rb-15	300 × 100	24.49	302	518.00	133	365.00	50	5.327
21	Rh-rb-10	300 × 100	24.49	302	518.00	133	365.00	50	6.543
22	Rh-rb-5	300 × 100	24.49	302	518.00	79	365.00	50	8.300
23	Rh-rb-3	300 × 100	24.49	302	518.00	133	365.00	50	8.581
24	R4-20	200 × 100	20.96	201	518.00	50	365.00	200	2.385
25	R4-15	200 × 100	20.96	201	518.00	50	365.00	150	2.649
26	R4-10	200 × 100	20.96	201	518.00	50	365.00	100	3.254
27	R6-20	200 × 100	24.59	302	518.00	50	365.00	200	2.873
28	R6-15	200 × 100	24.59	302	518.00	50	365.00	150	3.184
29	R6-10	200 × 100	24.59	302	518.00	50	365.00	100	3.742
30	RH4-20	300 × 100	26.56	201	518.00	50	365.00	200	3.948
31	RH4-15	300 × 100	26.56	201	518.00	50	365.00	150	5.013
32	RH4-10	300 × 100	26.56	201	518.00	50	365.00	100	5.834
33	RH6-20	300 × 100	24.90	302	518.00	50	365.00	200	4.811
34	RH6-15	300 × 100	24.90	302	518.00	50	365.00	150	5.869
35	RH6-10	300 × 100	24.90	302	518.00	50	365.00	100	6.616
36	RH8-20	300 × 100	27.39	402	518.00	50	365.00	200	5.037
37	RH8-15	300 × 100	27.39	402	518.00	50	365.00	150	6.120
38	RH8-10	300 × 100	27.39	402	518.00	50	365.00	100	6.950

Table 2. Summary of tested beams under pure torsion carried out by Fang and Shiau

No.	Specimen	D×B (mm)	f_c' (MPa)	A_s (mm^2)	f_y (MPa)	A_v (mm^2)	f_{yt} (MPa)	s (mm)	T_{Test} (kN.m)
1	H-06-06	500 × 350	78.50	1188	440.00	71	440.00	100	92.000
2	H-06-12	500 × 350	78.50	2027	410.00	71	440.00	100	115.100
3	H-12-12	500 × 350	78.50	2027	410.00	71	440.00	50	155.300
4	H-12-16	500 × 350	78.50	2850	520.00	71	440.00	50	196.000
5	H-20-20	500 × 350	78.50	3420	560.00	127	440.00	55	239.000
6	H-07-10	500 × 350	68.40	1710	500.00	71	420.00	90	126.700
7	H-14-10	500 × 350	68.40	1710	500.00	127	360.00	80	135.200
8	H-07-16	500 × 350	68.40	2850	500.00	71	420.00	90	144.500
9	N-06-06	500 × 350	35.50	1188	440.00	71	440.00	100	79.700
10	N-06-12	500 × 350	35.50	2027	410.00	71	440.00	100	95.200
11	N-12-12	500 × 350	35.50	2027	410.00	71	440.00	50	116.800
12	N-12-16	500 × 350	35.50	2850	520.00	71	440.00	50	138.000
13	N-20-20	500 × 350	35.50	3420	560.00	127	440.00	55	158.000
14	N-07-10	500 × 350	33.50	1710	500.00	71	420.00	90	111.700
15	N-14-10	500 × 350	33.50	1710	500.00	127	360.00	80	125.000
16	N-07-16	500 × 350	33.50	2850	500.00	71	420.00	90	117.300

Table 3. Summary of tested beams under pure torsion carried out by Rasmussen and Baker

No.	Specimen	D×B (mm)	f_c' (MPa)	A_s (mm^2)	f_y (MPa)	A_v (mm^2)	f_{yt} (MPa)	s (mm)	T_{Test} (kN.m)
1	B 30.1	275 × 160	41.70	1544	620.00	79	665.00	90	16.62
5	B 30.2	275 × 160	38.20	1544	638.00	79	669.00	90	15.29
3	B 30.3	275 × 160	36.30	1544	605.00	79	672.00	90	15.25
4	B 50.1	275 × 160	61.80	1544	612.00	79	665.00	90	19.95
5	B 50.2	275 × 160	57.10	1544	614.00	79	665.00	90	18.46
6	B50.3	275 × 160	61.70	1544	612.00	79	665.00	90	19.13
7	B 70.1	275 × 160	77.30	1544	617.00	79	658.00	90	20.06
8	B 70.2	275 × 160	76.90	1544	614.00	79	656.00	90	20.74
9	B 70.3	275 × 160	76.20	1544	617.00	79	663.00	90	20.960

Table 4. Summary of tested beams under pure torsion carried out by McMullen and Rangen

No.	Specimen	D×B (mm)	f_c' (MPa)	A_s (mm^2)	f_y (MPa)	A_v (mm^2)	f_{yt} (MPa)	s (mm)	T_{Test} (kN.m)
1	A1	254 × 254	39.60	284	360.00	32	285.00	79	13.10
5	A1R	254 × 254	36.90	284	360.00	32	285.00	79	12.50
3	A2	254 × 254	38.20	507	380.00	32	285.00	41	22.60
4	A3	254 × 254	39.40	804	352.00	71	360.00	79	27.80
5	A4	254 × 254	39.20	1134	351.00	71	360.00	57	34.50
6	B1	356 × 178	39.90	284	360.00	32	285.00	83	12.80
7	B1R	356 × 178	36.30	284	360.00	32	285.00	83	12.30
8	B2	356 × 178	39.60	507	380.00	32	285.00	44	20.80
9	B3	356 × 178	38.60	804	352.00	71	360.00	83	25.30
10	B4	356 × 178	38.50	1134	351.00	71	360.00	60	31.80

Table 5. Summary of tested beams under pure torsion carried out by Hsu

No.	Specimen	D×B (mm)	f_c' (MPa)	A_s (mm^2)	f_y (MPa)	A_v (mm^2)	f_{yt} (MPa)	s (mm)	T_{Test} (kN.m)
1	B1	381 × 254	27.58	531	313.71	79	341.29	152	22.258
2	B2	381 × 254	28.61	804	316.47	133	319.92	181	29.263
3	B3	381 × 254	28.06	1134	327.50	133	319.92	127	37.511
4	B4	381 × 254	30.54	1521	319.92	133	323.36	92	47.341
5	B5	381 × 254	29.03	1963	332.33	133	321.30	70	56.153
6	B6	381 × 254	28.82	2642	331.64	133	322.67	57	61.690
7	B7	381 × 254	25.99	531	319.92	133	318.54	127	26.890
8	B8	381 × 254	26.75	531	321.99	133	319.92	57	32.540
9	B9	381 × 254	28.82	1134	319.23	79	342.67	152	29.828
10	B10	381 × 254	26.48	2642	334.40	79	341.98	152	34.347
11	M1	381 × 254	29.85	804	326.12	79	353.01	149	30.393
12	M2	381 × 254	30.54	1134	328.88	79	357.15	105	40.562
13	M3	381 × 254	26.75	1521	321.99	133	326.12	140	43.838
14	M4	381 × 254	26.54	1963	318.54	133	326.81	105	49.600
15	M5	381 × 254	27.99	2642	335.09	133	330.95	83	55.702
16	M6	381 × 254	29.37	2945	317.85	133	340.60	70	60.108
17	I2	381 × 254	45.23	804	325.43	79	348.87	98	36.042
18	I3	381 × 254	44.75	1134	343.36	133	333.71	127	45.646
19	I4	381 × 254	44.95	1521	315.09	133	326.12	92	58.074
20	I5	381 × 254	45.02	1963	310.26	133	325.43	70	70.728
21	I6	381 × 254	45.78	2642	325.43	133	328.88	57	76.717
22	J1	381 × 254	14.34	531	327.50	79	346.12	152	21.467
23	J2	381 × 254	14.55	804	333.71	79	340.60	98	29.150
24	J3	381 × 254	16.89	1134	338.53	133	337.15	127	35.251
25	J4	381 × 254	16.75	1521	324.05	133	331.64	92	40.675
26	G1	508 × 254	29.79	531	321.99	79	339.22	187	26.777
27	G2	508 × 254	30.89	804	322.67	79	333.71	121	40.336
28	G3	508 × 254	26.82	1134	338.53	133	327.50	156	49.600
29	G4	508 × 254	28.27	1521	325.43	133	321.30	114	64.853
30	G5	508 × 254	26.89	1963	330.95	133	327.50	86	71.971
31	G6	508 × 254	29.92	796	334.40	79	349.56	127	39.093
32	G7	508 × 254	30.96	1206	333.02	133	322.67	146	52.651
33	G8	508 × 254	28.34	1701	335.77	133	328.88	105	73.440
34	N1	305 × 152	29.51	314	352.32	28	341.29	92	9.095
35	N2	305 × 152	30.41	531	330.95	28	337.84	51	14.462
36	N3	305 × 152	27.30	471	351.63	28	351.63	64	12.202
37	N4	305 × 152	27.30	587	343.01	79	355.77	89	15.705
38	K1	495 × 152	29.85	471	345.43	79	354.39	191	15.366
39	K2	495 × 152	30.61	796	335.77	79	337.84	105	23.727
40	K3	495 × 152	29.03	1206	315.78	133	320.61	124	28.472
41	K4	495 × 152	28.61	1701	344.05	133	339.91	86	35.025
42	C1	254 × 254	27.03	314	341.29	79	341.29	216	11.298
43	C2	254 × 254	26.54	531	334.40	79	344.74	117	15.253
44	C3	254 × 254	26.89	804	330.95	133	329.57	140	19.998
45	C4	254 × 254	27.17	1134	336.46	133	327.50	98	25.309
46	C5	254 × 254	27.23	1521	328.19	133	328.88	73	29.715
47	C6	254 × 254	27.58	1963	315.78	133	327.50	54	34.234

4. Comparisons and discussions

The predicted torsional strengths obtained from using EC2-04 and ACI318-19 provisions for the beams tested by Chalioris are compared with the experimental results in table 6. It can be seen that both codes gave conservative torsional strengths. However, the predicted results from using the EC2-04 are less conservative comparing with those predicted by ACI318-19. The EC2-4 provisions predicted torsional strengths ranged between 22% and 90% of the test results, while the larger ratio of the predicted torsional strength by using the ACI318-19 approach to the tested ones was about 48%. This is clearly happened because most of the predicted strengths by using the ACI381-19 approach were dominated by the maximum torsional capacity of the concrete beam cross section (T_{max}).

Table 6. Comparison of EC2 and ACI predicted to tested torsional strength, Chalioris

No.	Specimen	T_{Test} (kN.m)	T_{EC2} (kN.m)	T_{EC2} / T_{Test}	T_{ACI} (kN.m)	T_{ACI} / T_{Test}
1	R-r4-5	3.974	2.824	0.711	0.912	0.230
2	R-r4-3	4.172	2.824	0.677	0.912	0.219
3	R-r6-30	2.640	0.557	0.211	0.780	0.295
4	R-r6-5	4.251	3.344	0.787	0.988	0.232
5	R-r6-3	4.443	4.000	0.900	0.988	0.222
6	R-rb-20	2.452	0.836	0.341	0.892	0.364
7	R-rb-15	3.116	1.115	0.358	0.892	0.286
8	R-rb-10	3.702	1.672	0.452	0.892	0.241
9	R-rb-5	4.163	3.330	0.800	0.892	0.214
10	R-rb-3	4.347	3.330	0.766	0.892	0.205
11	Rh-r4-5	7.144	3.092	0.433	1.901	0.266
12	Rh-r4-3	7.331	3.092	0.422	1.901	0.259
13	Rh-r6-30	4.241	0.973	0.229	1.300	0.306
14	Rh-r6-5	8.474	4.638	0.547	1.841	0.217
15	Rh-r6-3	8.559	4.638	0.542	1.841	0.215
16	Rh-r8-30	4.464	0.973	0.218	1.300	0.291
17	Rh-r8-5	8.553	5.839	0.683	1.931	0.226
18	Rh-r8-3	8.594	6.184	0.720	1.931	0.225
19	Rh-rb-20	4.308	1.460	0.339	1.826	0.424
20	Rh-rb-15	5.327	1.946	0.365	1.826	0.343
21	Rh-rb-10	6.543	2.919	0.446	1.826	0.279
22	Rh-rb-5	8.300	4.638	0.559	1.826	0.220
23	Rh-rb-3	8.581	4.638	0.540	1.826	0.213
24	R4-20	2.385	0.836	0.350	0.912	0.382
25	R4-15	2.649	1.115	0.421	0.912	0.344
26	R4-10	3.254	1.672	0.514	0.912	0.280
27	R6-20	2.873	0.836	0.291	0.988	0.344
28	R6-15	3.184	1.115	0.350	0.988	0.310
29	R6-10	3.742	1.672	0.447	0.988	0.264
30	RH4-20	3.948	1.460	0.370	1.901	0.482
31	RH4-15	5.013	1.946	0.388	1.901	0.379
32	RH4-10	5.834	2.919	0.500	1.901	0.326
33	RH6-20	4.811	1.460	0.303	1.841	0.383
34	RH6-15	5.869	1.946	0.332	1.841	0.314
35	RH6-10	6.616	2.919	0.441	1.841	0.278
36	RH8-20	5.037	1.460	0.290	1.931	0.383
37	RH8-15	6.120	1.946	0.318	1.931	0.315
38	RH8-10	6.950	2.919	0.420	1.931	0.278
Mean value				0.468		0.291
Standard deviation				0.177		0.068
Coefficient of variation (%)				37.8		23.4

The torsional strengths of the tested beams done by Fang and Shiau are compared with those predicted based on EC2-04 and ACI318-19 provisions in table 7. It can be seen that the strengths predicted by using the EC2-04 provisions are underestimate (up to 55%) to the tested values except the specimens numbered (11) and (13), which their predicted to tested strength ratios were 1.053 and 1.168, respectively. However, the strengths that predicting by using the ACI318-19 provisions for all beams are underestimate (up to 47%) to the tested values.

Table 8 lists the comparative results of the predicted torsional strengths using the EC2-04 and the ACI318-19 approaches to the test results performed by Rasmussen and Baker. The table shows that the estimated strengths based on the EC2-04 approach are varied from overestimate reaches to 24% to underestimate up to 11% comparing with the test results. All the predicted torsional strength by using ACI318-19 are conservative (up to 50%) compared with the test results, because that most the predicted strengths were dominated by the maximum torsional capacity of the concrete beam cross section (T_{max}).

Table 7. Comparison of EC2 and ACI predicted to tested torsional strength, Fang and Shiau

No.	Specimen	T_{Test} (kN.m)	T_{EC2} (kN.m)	T_{EC2} / T_{Test}	T_{ACI} (kN.m)	T_{ACI} / T_{Test}
1	H-06-06	92.000	61.512	0.669	71.954	0.782
2	H-06-12	115.100	61.512	0.534	71.954	0.625
3	H-12-12	155.300	123.023	0.792	127.143	0.819
4	H-12-16	196.000	123.023	0.628	143.908	0.734
5	H-20-20	239.000	198.826	0.832	152.503	0.638
6	H-07-10	126.700	65.240	0.515	76.315	0.602
7	H-14-10	135.200	111.839	0.827	130.826	0.968
8	H-07-16	144.500	65.240	0.451	76.315	0.528
9	N-06-06	79.700	61.512	0.772	71.954	0.903
10	N-06-12	95.200	61.512	0.646	71.954	0.756
11	N-12-12	116.800	123.023	1.053	102.555	0.878
12	N-12-16	138.000	123.023	0.891	102.555	0.743
13	N-20-20	158.000	184.549	1.168	102.555	0.649
14	N-07-10	111.700	65.240	0.584	76.315	0.683
15	N-14-10	125.000	111.839	0.895	99.625	0.797
16	N-07-16	117.300	65.240	0.556	76.315	0.651
Mean value				0.738		0.735
Standard deviation				0.201		0.210
Coefficient of variation (%)				27.2		16.3

Table 8. Comparison of EC2 and ACI predicted to tested torsional strength, Rasmussen and Baker

No.	Specimen	T_{Test} (kN.m)	T_{EC2} (kN.m)	T_{EC2} / T_{Test}	T_{ACI} (kN.m)	T_{ACI} / T_{Test}
1	B 30.1	16.62	19.060	1.147	8.364	0.503
2	B 30.2	15.29	18.829	1.231	8.005	0.524
3	B 30.3	15.25	18.914	1.240	7.804	0.512
4	B 50.1	19.95	18.717	0.938	10.182	0.510
5	B 50.2	18.46	18.717	1.014	9.787	0.530
6	B50.3	19.13	18.717	0.978	10.174	0.532
7	B 70.1	20.06	18.520	0.923	11.388	0.568
8	B 70.2	20.74	18.463	0.890	11.358	0.548
9	B 70.3	20.960	18.660	0.890	11.306	0.539
Mean value				1.028		0.530
Standard deviation				0.142		0.020
Coefficient of variation (%)				13.8		3.8

Comparisons between the experimental results done by McMullen and Rangen and the predicted torsional strengths by using the EC2-04 and the ACI318-19 approaches are shown in table 9. It can be seen that both the EC2-04 and ACI318-19 approaches predicted conservative torsional strength (up to 45% and 51%, respectively). Moreover, the torsional strengths that predicted by using ACI318-19 provisions for the specimens numbered. (4, 5, 9, and 10) are dominated by the maximum torsional capacity of the concrete beam cross section.

Table 9. Comparison of EC2 and ACI predicted to tested torsional strength, McMullen and Rangen

No.	Specimen	T_{Test} (kN.m)	T_{EC2} (kN.m)	T_{EC2} / T_{Test}	T_{ACI} (kN.m)	T_{ACI} / T_{Test}
1	A1	13.10	8.089	0.617	8.083	0.617
2	A1R	12.50	8.089	0.647	8.083	0.647
3	A2	22.60	15.060	0.666	15.574	0.689
4	A3	27.80	20.583	0.740	18.873	0.679
5	A4	34.50	27.577	0.799	18.825	0.546
6	B1	12.80	7.077	0.553	7.241	0.566
7	B1R	12.30	7.077	0.575	7.241	0.589
8	B2	20.80	12.826	0.617	13.659	0.657
9	B3	25.30	17.679	0.699	15.556	0.615
10	B4	31.80	23.486	0.739	15.536	0.489
Mean value				0.665		0.609
Standard deviation				0.079		0.063
Coefficient of variation (%)				11.9		10.3

Table 10 displays the comparisons between the experimental results done by Hsu and the predicted torsional strengths using the EC2-04 and the ACI318-19 approaches. It can be observed that the predicted torsional strengths for some specimens based on the EC2-04 approach are unconservative (up to 15%) comparing to the test results, but the strengths of the other specimens are conservative (up to 52%). On the contrary, the torsional strength values that predicted based on the ACI318-19 approach are conservative (up to 59%), where 55% of those strengths are dominated by the maximum torsional capacity of the concrete beam cross section (T_{max}).

It was observed from the present comparisons that the predicted torsional strengths with the use of ACI318-19 approach for about 66% of the examined 120 experimentally tested beams are governing by the limitation of the maximum torsional capacity of the concrete beam cross section (T_{max}). This may related to that the (T_{max}) in the ACI318-19 provisions did not affect by the angle of inclination (θ), as in the EC2-04 approach, which plays a significant role in the analysis of concrete beams under torsion.

An examination of the mean values of the predicted to tested torsional strength ratios listed in table 11 indicate that the predicted torsional strengths based on the EC2-04 approach are closer to the test results than those based on the ACI318-19 approach, However, there are some predicted strengths based on EC2-04 approach somewhat overestimate the test strengths.

The statistical distribution of predicted to tested torsional strength ratios based on the EC2-04 and ACI318-19 approaches are compared in figures 1. It is observed that the EC2-04 approach gives approximately normal distribution for the examined experimental torsional strengths with a peak located at the strength ratio of about 0.85. On the other hand, the use of the ACI318-19 approach gives wider spread distribution for the predicted to tested torsional strength ratios.

Table 10. Comparison of EC2 and ACI predicted to tested torsional strength, Hsu

No.	Specimen	T_{Test} (kN.m)	T_{EC2} (kN.m)	T_{EC2} / T_{Test}	T_{ACI} (kN.m)	T_{ACI} / T_{Test}
1	B1	22.258	18.704	0.840	17.869	0.803
2	B2	29.263	24.801	0.848	26.934	0.920
3	B3	37.511	34.391	0.917	31.978	0.853
4	B4	47.341	46.637	0.985	33.363	0.705
5	B5	56.153	59.391	1.058	32.524	0.579
6	B6	61.690	65.895	1.068	32.408	0.525
7	B7	26.890	19.074	0.709	18.222	0.678
8	B8	32.540	19.197	0.590	18.340	0.564
9	B9	29.828	18.666	0.626	20.272	0.680
10	B10	34.347	16.983	0.494	20.231	0.589
11	M1	30.393	20.138	0.663	21.328	0.702
12	M2	40.562	28.298	0.698	30.732	0.758
13	M3	43.838	31.001	0.707	31.223	0.712
14	M4	49.600	40.274	0.812	31.102	0.627
15	M5	55.702	49.827	0.895	31.939	0.573
16	M6	60.108	62.960	1.047	32.716	0.544
17	I2	36.042	29.391	0.815	28.079	0.779
18	I3	45.646	35.873	0.786	40.035	0.877
19	I4	58.074	47.035	0.810	40.475	0.697
20	I5	70.728	60.156	0.851	40.506	0.573
21	I6	76.717	71.522	0.932	40.845	0.532
22	J1	21.467	19.333	0.901	18.654	0.869
23	J2	29.150	29.458	1.011	23.025	0.790
24	J3	35.251	36.244	1.028	24.811	0.704
25	J4	40.675	39.879	0.980	24.709	0.607
26	G1	26.777	20.391	0.761	20.508	0.766
27	G2	40.336	31.145	0.772	31.132	0.772
28	G3	49.600	40.059	0.808	44.381	0.895
29	G4	64.853	53.345	0.823	49.662	0.766
30	G5	71.971	70.708	0.982	48.435	0.673
31	G6	39.093	30.993	0.793	31.948	0.817
32	G7	52.651	42.043	0.799	46.578	0.885
33	G8	73.440	59.733	0.813	49.722	0.677
34	N1	9.095	4.325	0.475	4.649	0.511
35	N2	14.462	7.396	0.511	7.444	0.515
36	N3	12.202	6.461	0.529	6.945	0.569
37	N4	15.705	11.570	0.737	7.054	0.449
38	K1	15.366	10.241	0.666	11.326	0.737
39	K2	23.727	16.983	0.716	14.878	0.627
40	K3	28.472	21.003	0.738	14.488	0.509
41	K4	35.025	30.627	0.874	14.384	0.411
42	C1	11.298	8.407	0.744	8.784	0.777
43	C2	15.253	15.102	0.990	15.393	1.009
44	C3	19.998	19.179	0.959	15.592	0.780
45	C4	25.309	26.132	1.033	15.671	0.619
46	C5	29.715	34.146	1.149	15.691	0.528
47	C6	34.234	35.700	1.043	15.790	0.461
Mean value				0.825		0.681
Standard deviation				0.164		0.140
Coefficient of variation (%)				19.9		20.6

Table 11. Statistical results of the 120 tested beam listed in tables (11-15)

References	Number of Tested Beams	Mean Torsional Strength Ratio	
		T_{EC2} / T_{Test}	T_{ACI} / T_{Test}
Chalioris [3]	38	0.468	0.291
Fang and Shiau [4]	16	0.738	0.735
Rasmussen and Baker [5]	9	1.028	0.530
McMullen and Rangen [6]	10	0.665	0.609
Hsu [7]	47	0.825	0.681
Mean value *		0.702	0.547
Standard deviation		0.211	0.175
Coefficient of variation (%)		30.1	32.0

* Mean value = ∑{(number of tested beams) × (mean torsional strength ratio)} / ∑(number of tested beams)

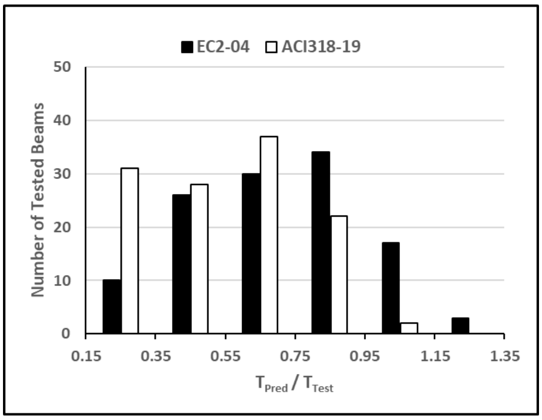

Figure 1. Statistical distribution of predicted to tested torsional strength ratios

In order to expand the statistical comparison between the EC2-04 and ACI318-19 provisions to predict the torsional strength of concrete beams, a regression analysis was made for the experimental torsional strengths of the collected 120 tested beams and that predicted by using the two codes. Linear models were considered in this analysis. Figure 2 shows the suggested relations of the experimental with the predicted torsional strengths by using the EC2-04 and ACI318-19 procedures. It is clearly shown that the coefficient of determination for the two suggested linear regression models relating the EC2-04 or ACI318-19 predicted torsional strengths with the experimental ones have an acceptable coefficient of determination (R-squared), which equals to 0.9086 and 0.9581, respectively.

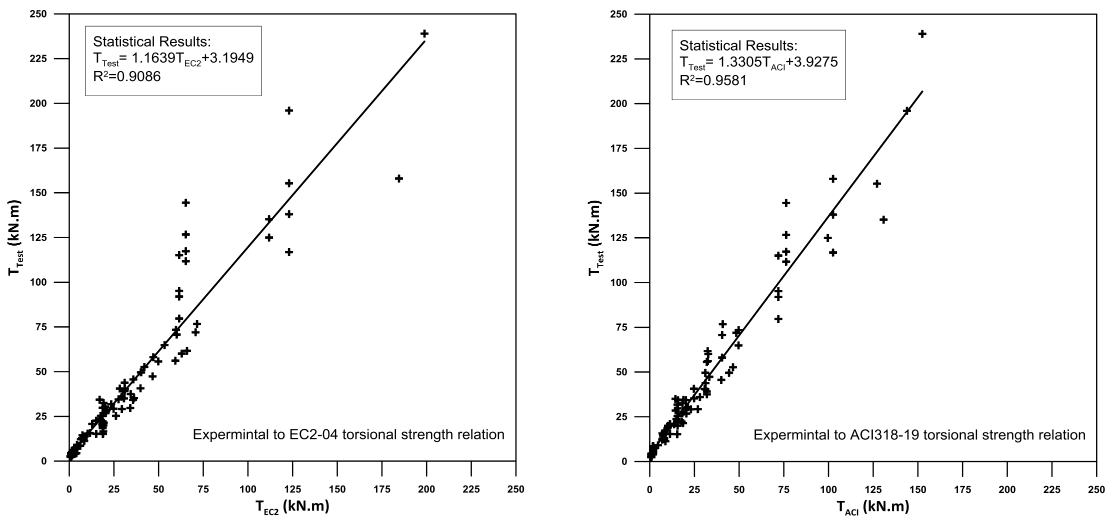

Figure 2. Relations of concrete beams experimental to EC2-04 and ACI318-19 predicted torsional strength.

5. Conclusions

The experimental results of 120 reinforced concrete beams under pure torsion performed by previous researchers were examined to predict the differences and the accuracy of the torsional strength provisions of EC2-04 and ACI318-19 codes. As compared with the experimental results, the ACI318-19 approach is observed to be more conservative than the EC2-04 approach in predicting the torsional strength of reinforced concrete beams. This may related to the domination of the maximum torsional capacity limitation of the concrete beams cross section that stated by the ACI318-19 approach. This limitation represents a major difference between the EC2-04 and ACI318-19 approaches in the evaluation of concrete beams torsional strength. Where, the EC2-04 depends on an analytical formula to evaluate the maximum torsional capacity of concrete beams taking into account the effect of the capacity of concrete diagonal struts and their inclination angle (θ), whereas the formula stated by the ACI318-19 was originally derived on the basis of crack control. The adopted value for the angle of inclination (θ) equals to 45°, leads to predicted accurate torsional strengths for the examined beams by using the EC2-04 approach than the use of the ACI318-19 approach. The statistical analysis for the predicted to tested torsional strength ratios for the collected 120 specimens indicates that the EC2-04 approach gives approximately normal distribution curve with a peak located at strength ratio of about 0.85.

References

[1] Européen commette for standardisation (CEN), 2004. *Eurocode 2: Design of concrete structures, Part 1-1: General rules and rules for buildings (EN 1992-1-1)*. Lausanne, Switzerland.

[2] ACI Committee 318, 2019. *Building code requirements for structural concrete and commentary (ACI 318M-19)*. American Concrete Institute, Farmington Hills, MI.

[3] Européen commette for standardisation (CEN), 2004. *Eurocode 8: Design of structures for earthquake resistance, Part 1: General rules, seismic actions and rules for buildings (EN 1998-1)*. Lausanne, Switzerland.

[4] Chalioris, C. E., 2006. Experimental study of the torsion of reinforced concrete members. *Structural Engineering and Mechanics*. 23. 713-737.

[5] Fang, I.-K., Shiau, J.-K., 2004. Torsional behaviour of normal and high strength concrete beams. *ACI Structural Journal*. 101. 304-313.

[6] Rasmussen, L. J., Baker, G., 1995. Torsion in reinforced normal and high strength concrete beams - Part 1: Experimental test series. *ACI Structural Journal*. 92. 56-62.

[7] McMullen, A. E., Rangan, V., 1978. Pure torsion in rectangular sections – A re-examination. *ACI Journal Proceedings*. 75. 511-519.

[8] Hsu, T. T. C., 1968. Torsion of structural concrete - Behaviour of reinforced concrete rectangular members. Torsion of structural concrete, *SP-18. American Concrete Institute*, Farmington Hills, MI., pp. 261-306.