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Behavior of Reinforced Concrete Plates under Pure Torsion

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A B S T R A C T

The behavior of reinforced concrete members under torsional loading has interested many researchers during the last decades. These researches focused mainly on the response of reinforced concrete beams at different reinforcement conditions and the size effects. On the other hand, the behavior of concrete plates or slabs has not been investigated clearly under pure and/or combined torsional loading. In the present study, nine reinforced concrete plates were prepared and tested under pure torsion. Effect of steel reinforcement ratio and size change was studied and they have a great effect on the plated strength, capacity, stiffness and ductility. As stated by torsion theories of reinforced concrete beams, the torsional strength of slabs was upgraded also with increasing in cross section and transverse reinforcement ratio.

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سلوكية البلاطات الخرسانية المسلحة تحت تأثير اللي الصافي

اسامة عبدالرزاق مخلف كلية الهندسة/ جامعة تكريت/ قسم الهندسة المدنية

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الخلاصة

تصرف المنشات الخرسانية المسلحة تحت تأثير احمال اللي لقي اهتماما خلال العقود الاخيرة من قبل العديد من الباحثين. ركز الباحثون بصورة اساسية على تصرف العتبات الخرسانية المسلحة تحت مختلف انواع التسليح والابعاد. على صعيد اخر, لم يلق تصرف السقوف الخرسانية او الصفائح الاهتمام نفسه سواء تحت تأثير احمال اللي الصافية او المركبة. في هذه الدراسة, تم تهيئة وفحص تسع صفائح كونكريتية مسلحة تحت تأثير حمل اللي الصافي. وتمت دراسة تاثير نسبة حديد التسليح وابعاد المقطع الكونكريتي وتمت ملاحظة مقدار تاثيرها الكبير على مقاومة المقطع, تحمله الاقصى وكذلك قيم الصلادة والمرونة. كما تم اقراره من خلال نظريات اللي للعتبات الخرسانية المسلحة, فان مقاومة اللي للسقوف ايضا تحسنت بازدياد مساحة المقطع ونسبة حديد التسليح العرضي.

الكلمات الدالة: البلاطات الخرسانية ، اللي الصافي, البلاطات المسلحة، التشققات, الالتواء.

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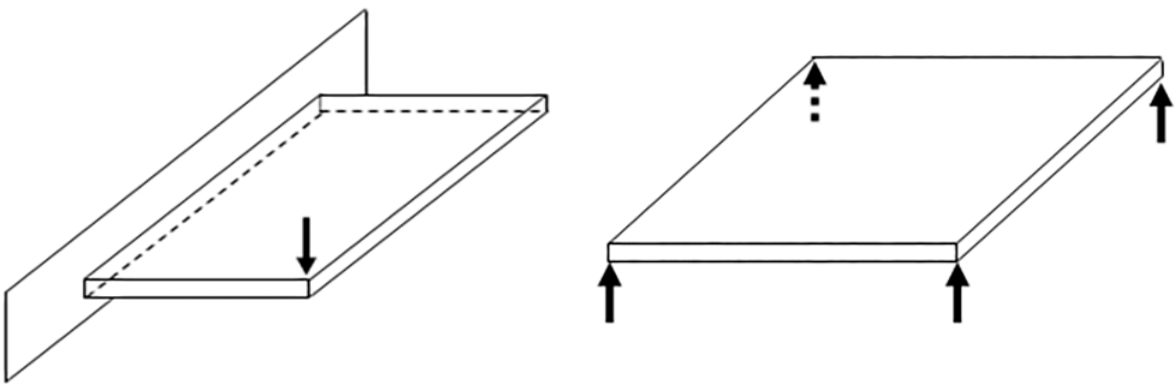
1. INTRODUCTION

The torsional behavior of slabs is usually ignored in structural analysis and design. As a matter of fact, the bending moment is influenced by the torsional forces in the slab. When the torsional stress effect is taken into consideration, the bending moment is relieved approximately 25 percent [1]. Moreover, the widespread cracking due to bending leads to torsional stiffness which becomes 25% of the initial elastic stiffness, as well as the intensity of cracking due to torsion, or shear that leads to relieving the stiffness to about 10% of the initial elastic stiffness. These theories presented theoretically and need investigation. A few number of researchers described methods to predict the trends of the slabs containing load-displacement behavior through an experimental application on reinforced concrete slabs under torsional loading. The stresses and deformations caused by acting the twist in slabs have been studied lesser than they happen in beams [2, 3, 4]. Till the present day, this research is a reference on this topic, and it gives an alert that the ultimate strength moments are sometimes overstated when using the yield lines method and when there is a significant value of torsional moments. Fig. 1 explains some cases where torsion and/or pure torsion may develop within concrete slabs.



(a) Corner-loaded cantilever slab (b) Corner-supported flat slab

Fig. 1 Pure torsion in vicinity of slab corners [5]

Marti and Kong [6] made a study on nine square slab specimens under pure torsion. All specimens have similar square dimensions of 1.7 m ×1.7 m and 0.2 m thickness. Steel reinforcement ratio the only parameter investigated when changed from 1 - 0.25 %. The specimens reinforced by two steel meshes as a closed hoop in the x and y-direction. The ultimate strength and cracks number were increased proportionally to steel ratio while the first cracks show independency. Torsion was applied by couples of opposite and equal forces P applied at the corners of the sample, the specimens were put under torsion and bending. Moreover, ultimate resistance ranged from 5-46% lower than calculated by yield-line theory. Ultimate resistance ranged from 8-117% larger than calculated, based on torsion design provisions of the American (1983) code ACI-83 code. May et al. [7] studied the behavior of RC elements under bending and twisting moments. Three square slabs with the dimensions of 1.9×1.9×0.15 m were investigated. One of these slabs subjected to combined bending and torsion and compared with two specimens under pure torsion. The nonlinear analysis carried out and compared with the results obtained from the experimental test. The prediction was unconservative at the significant twisting moment and the ratio of experimental to calculated moment (Mtest/Mu) in specimens under pure torsion is smaller than that in combined moments. Lopes [8] tested nine RC square slabs under pure torsion. Six specimens of 2.1×2.1×0.15 m, and three specimens of 2.8×2.8×0.15

m. Reinforcement type, and concrete compressive strength were the main parameters presented. Mechanism of the test put the specimens under torsion and bending forces. There's no clear effect of steel reinforcement ratio on first crack while the ratio of pre-cracking stiffness to post-cracking stiffness was enhanced significantly. Nguyen et al. [9] presented an experimental study by taking seven RC square slabs of 1.9×1.9 m tested under combined loading. Specimens designed to ensure that failure will not occur by bending or shear. The parameters studied were steel ratio, curing time, and slab thickness. Slab with larger thickness has greater torsional stiffness, especially when meshes of reinforcement are placed away from mid plain. Effect of reinforcement to the torsional stiffness is negligible before cracking of the concrete, while after cracking, the torsional stiffness decreased quickly when compared to stiffness before cracking. The influence of reinforcement in this stage is significant and clear. Finally, Nguyen and Tinh [10] presented an experimental and analytical study on three similar reinforced concrete slabs with the dimensions of 1.9×1.9×0.15m subjected to combined torsion and modeled using a finite element method. A comparison between numerical and experimental data showed that both results are closed and agreeing. At the post-cracking stage, the torsional stiffness of slabs is about 1/25 of it in the pre-cracking stage for the steel ratio of 0.32%, and racks on the top and bottom surface are orthogonal. In the present study, the behavior of reinforced concrete slabs under pure torsion will be investigated, and the effect of steel reinforcement and the aspect ratio will be collected.

2. EXPERIMENTAL PROGRAM

The experimental program consists of casting and testing nine RC slabs with three different reinforcement spacing and aspect ratios. These elements have a constant thickness and were tested under pure torsion loading.

2.1. Specimens Details

The length of the slabs was chosen to be 800 mm and thickness was limited to 50 mm with 3 values of width 400, 500, and 600 mm. Fig. 2 shows the details of the dimensions.

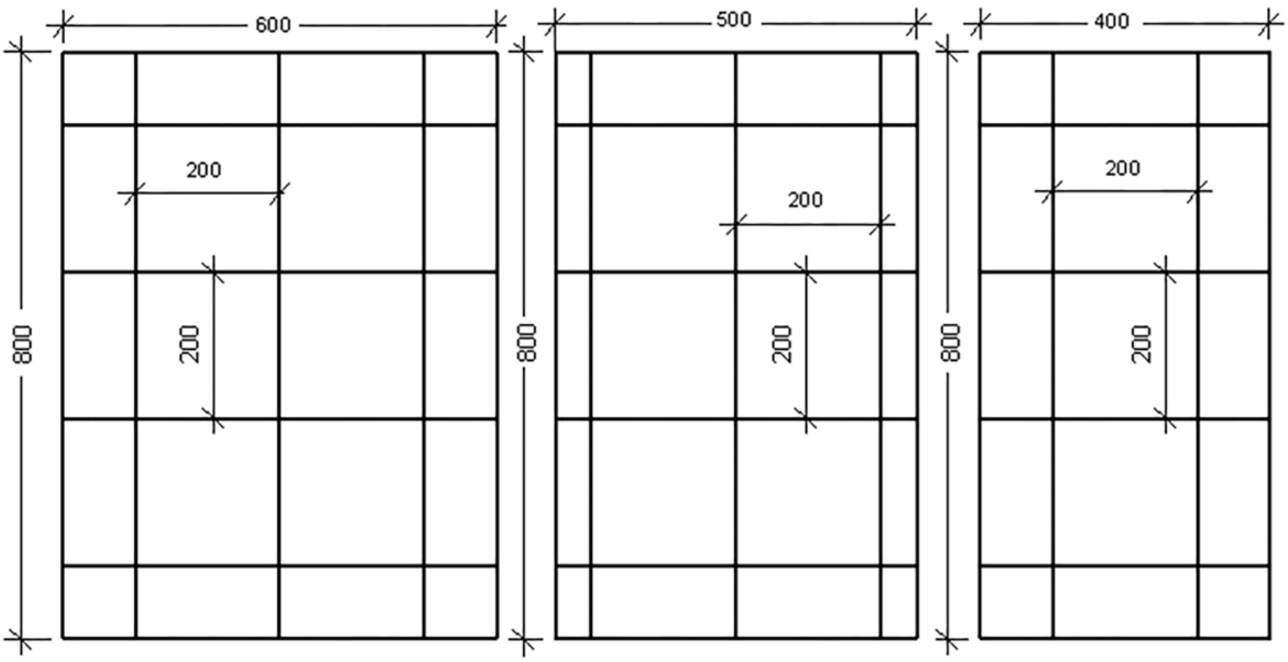


Fig. 2. Details of reinforcements and dimensions of slabs in (mm)

These specimens were reinforced in two directions at a spacing of 200 mm, 160 mm and 120 mm at mid-depth of the plate. All specimens were designed according to ACI 318-14 code [11] requirements [12, 13].

2.2. Materials

All specimens were made of normal concrete. Ordinary Portland cement, fine aggregates, coarse aggregates and tap water were used.

2.2.1 Concrete Mix Design

The mixture was designed according to the American method for mix design (ACI-211.1-91) [14] to get normal concrete with design strength 32 MPa at 28 days for standard cube. Design was based on a maximum aggregate size of 12.5 mm. The quantities of mix used as shown in Table 1 below.

Table 1
Quantities of materials used in concrete mix design

Water kg/m3	**Cement kg/m3**	**Sand kg/m3**	**Gravel kg/m3**	**Compressive strength MPa**	**Slump mm**
176.6	378.2	805.8	910	32.65	71

All specimens were casted in laboratory in steel molds and cured to testing day. The plates were reinforced by 6 mm steel bars that have 390 MPa yield strength and 570 MPa ultimate strength. Fig. 3 shows steel reinforcement within mold and casted specimens.

Fig. 3. (a) Steel reinforcement, (b) Casted specimens

2.3. Test Mechanism

The testing mechanism used by (Ameli et al [15], Calioris [16]) to apply pure torsion on RC beams was adopted here. This arm transfer load from the load cell to ends of the slab was used to achieve pure torsion as shown in Fig 4.

The load applied gradually by load cell installed on the transverse arm. Dial gauge was installed to read deflection under each arm and the average reading was taken. Fig 4 shows the insulation of load cell and dial gauge.

3. RESULTS AND DISCUSSION

All essential results of tested slabs were recorded in Table 2. Cracking torsional moment T_{cr}, cracking twist angle θ_{cr}, maximum torsional moment T_{max}, and twist angle at maximum torque θ_{max} are recorded under pure torsion.

Fig. 4. Test mechanism

Table 2
Test results of the specimens

Specimen	Cracking torsional moment T_{cr} (kNm)	Max. torsional moment T_{max} (kNm)	θcr (rad)	θmax (rad)
S20-400	0.705	2.436	0.0154	0.190
S20-500	0.764	3.000	0.0100	0.168
S20-600	0.831	3.500	0.0075	0.130
S16-400	0.766	3.074	0.0125	0.230
S16-500	0.867	3.596	0.0080	0.200
S16-600	0.898	4.060	0.0052	0.144
S12-400	0.832	3.800	0.0100	0.210
S12-500	0.905	4.650	0.0051	0.193
S12-600	0.986	5.100	0.0035	0.150

3.1. Effect of Slab Width

Width of specimens is one of the main parameters investigated in the present study. 400, 500, and 600 mm is the width varied with a constant length of 800 mm. Fig. 5 , Fig. 6, and Fig. 7 shows the torque-twist curve for different percent of steel reinforcement.

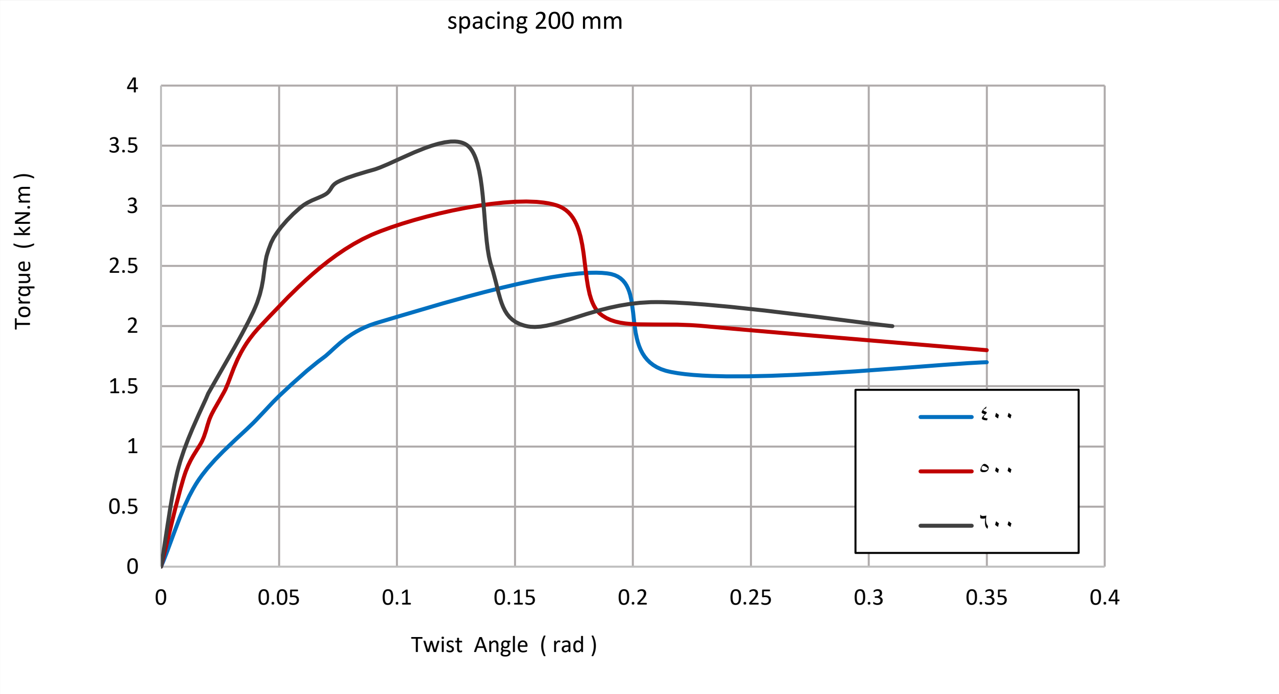


Fig. 5. Torque- twist curves of 200 mm reinforcement spacing.

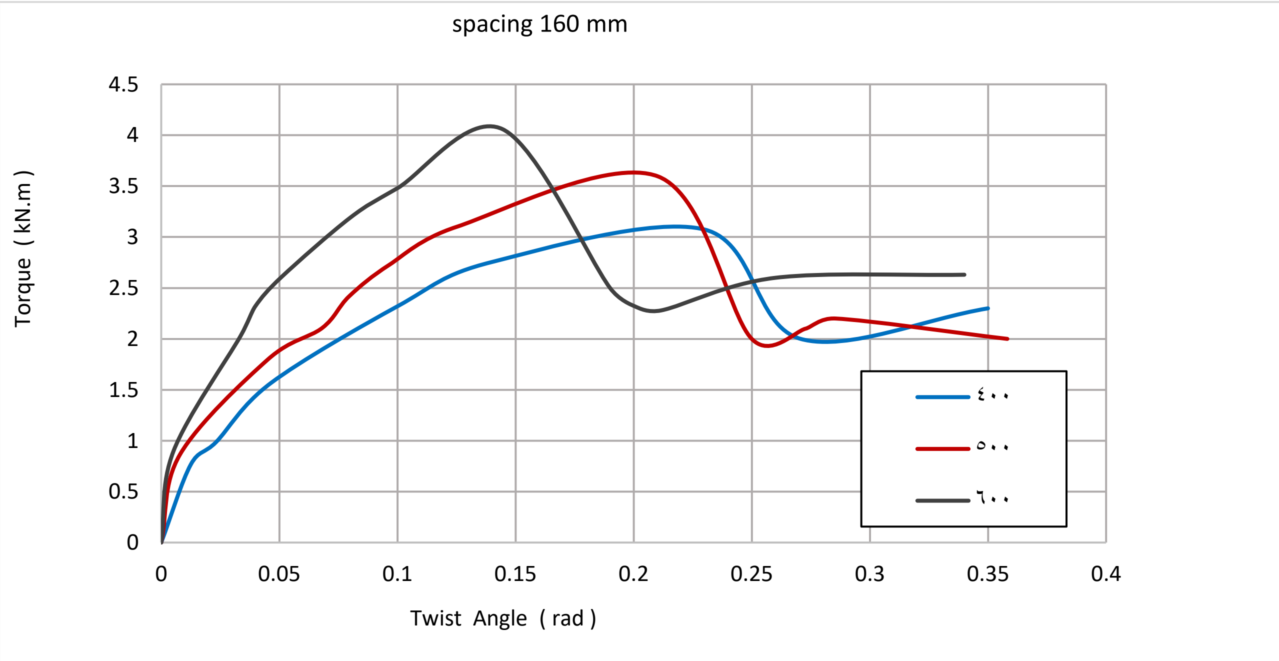


Fig. 6. Torque- twist curves of 160 mm reinforcement spacing.

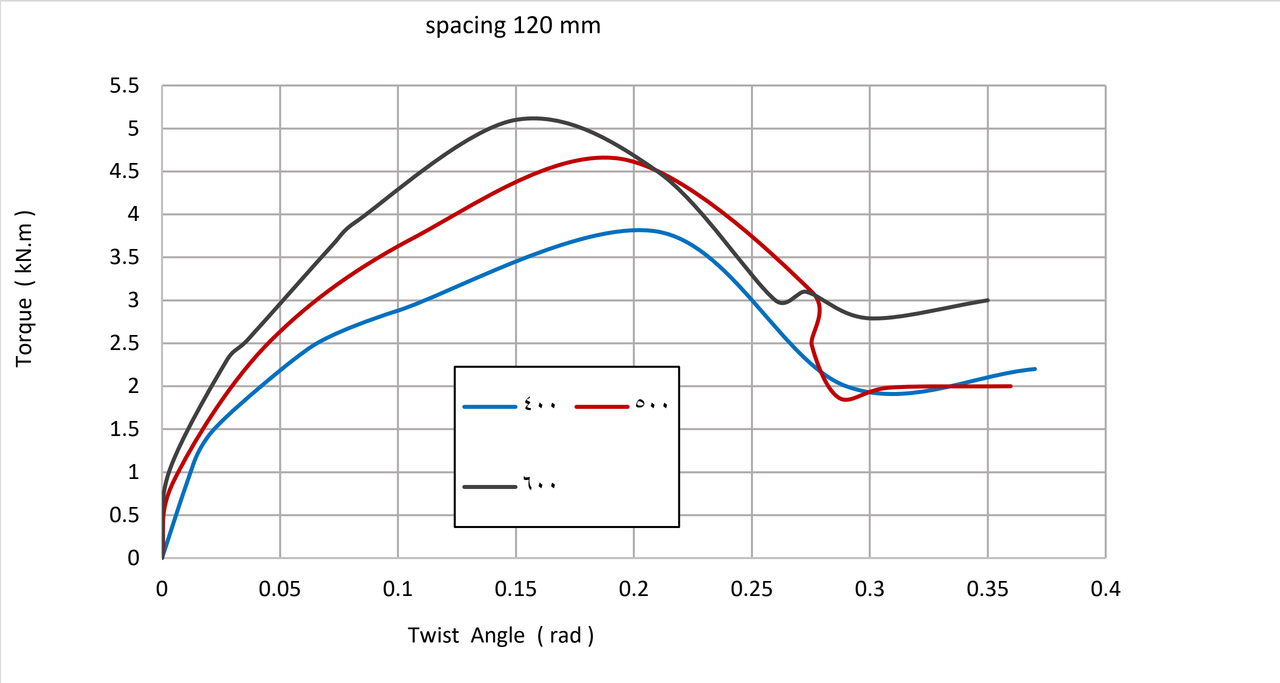


Fig. 7. Torque- twist curves of 120 mm reinforcement spacing.

It is observed from the above figures that the torque-twist curve moves linearly up to the first crack, in which the torque is recorded as a cracking torque. These cracks occurred due to reaching the torsional tensile stress value to the tensile strength of concrete. This crack is considered as the end of the linear (elastic) stage then the steel reinforcement starts to carry the significant part of torsional loads. Cracking torque increased with slab width value from 400 to 600 mm for all reinforcement ratios. This trend was stated also by Peng and Wong [17], Bernardo and lopes [18]. Beyond this stage, the curves move with lesser slop and the torque strength increases up to maximum value.

When considering 400 mm width as a reference width, it was noted that; for specimens with 200 mm spacing, the increase in slab width from 400 to 600 mm gives an increase to maximum torque by about 22.4 and 42.8%, respectively. For specimens reinforced by 160 mm spacing, the increment in maximum torque value ranged from 17.3% to 32.2 % for slabs with 400 and 600 mm width, respectively. Reinforcement of specimens with 120 mm spacing gives also an increment in torque to about 22.4% and 34.2 %, respectively. Generally, the effect of slab width or aspect ratio, minimize clearly with increasing steel reinforcement ratio. This increment was found to be compatible with analytical equations stated by ACI code for torsional resistance of concrete section (ACI-318, 22.7.6.1) [11], which are based on space truss analogy, stating that the normal torsional resistance of the section is the proportion with an enclosed area of cross-section. Moreover, a clear agreement between data obtained and this was concluded and stated by Peng and Wong [17].

3.2. Effect of steel reinforcement

Steel reinforcement ratio which is represented here by the spacing between reinforcement bars plays an important role in the behavior of RC slabs. Torque-twist curves are shown in Fig. 8, Fig. 9, and Fig.10 which show the effect of reinforcement spacing on the behavior of slabs under pure torsion.

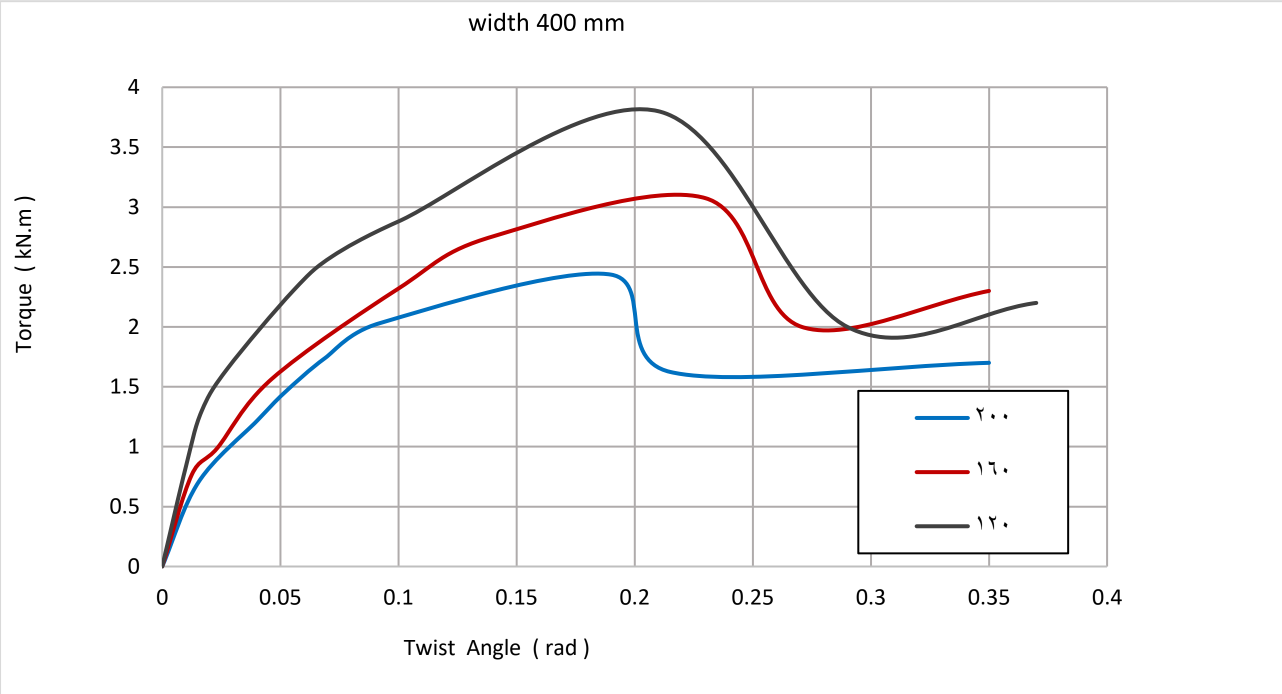


Fig. 8. Torque- twist curves for 400 mm slab width.

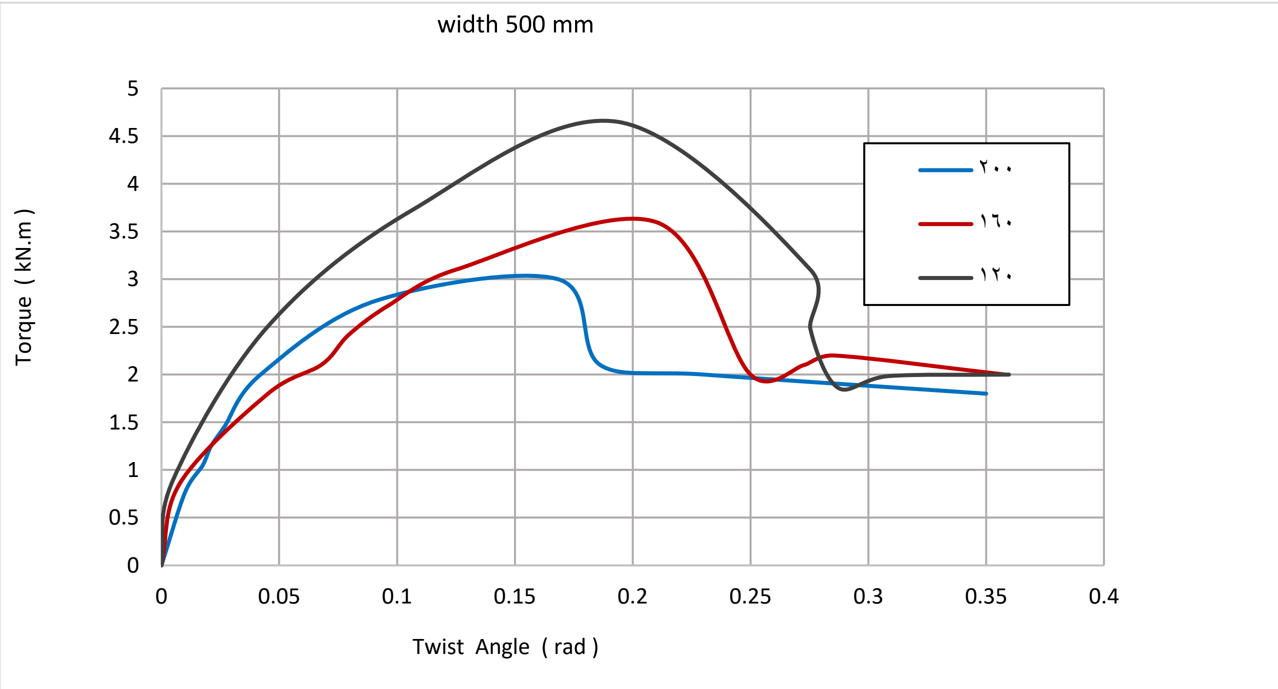


Fig. 9. Torque- twist curves for 500 mm slab width.

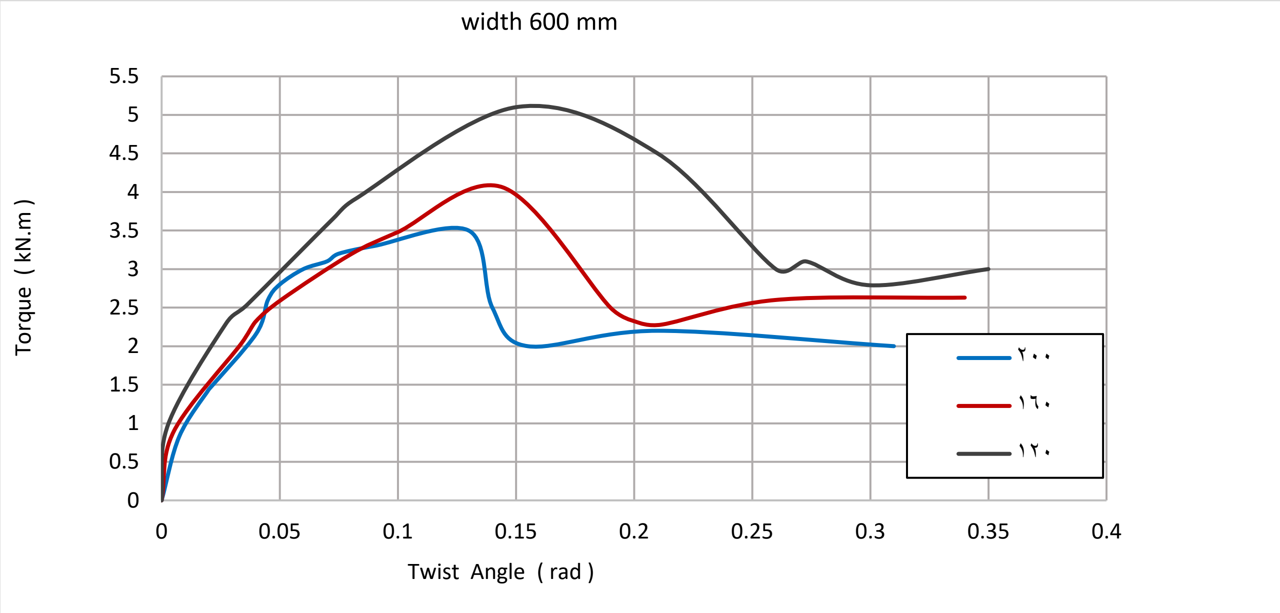


Fig. 10. Torque- twist curves for 600 mm slab width.

It was noted that the cracking torque increases with the increase of steel spacing as explained in Table 2. It is also observed that the maximum torque increases with decreasing the spacing of steel bars for all aspect ratios. Specimens with 400 mm width, Fig. 8, the increment in maximum torque was noted when steel bars spacing decreased to 160 mm and 120 mm to be 25.3% and 55.1%, respectively. For specimens with 500 mm width, the increment in torsional strength ranged between 20% and 55% due to decreasing in reinforcement spacing to 160 mm and 120 mm, respectively. Finally, specimens of 600 mm width, showed a 16% and 45.7% increase in maximum torque. Effect of steel reinforcement ratio on maximum torque was noted clearly at slabs with small depths (i.e. lesser aspect ratio). These results have a good agreement with equation presented by ACI code for torsional resistance in RC elements (ACI-318-22.7.6.1) [11]. Moreover, it was observed from the torque-twist curve that the behavior after maximum torque (softening behavior) for minimum reinforcement 200 mm spacing, the curve dropped vertically, and start to decrease gradually with lesser slop when increasing the reinforcement ratio as in Lopes and Bernardo [3].

When noting twist angle for different spacing values, it was found that for 200 mm spacing, the twist is lesser than the other spacing due to decreasing reinforcement, but for other spacing observed that twist angle for 160 mm is greater than in 120 mm. According to Peng and wong [17], “It was experimentally observed that their lower reinforcement amounts resulted in a larger increment of steel strains and hence a larger increment of twist angles when cracks first occurred”.

3.3. Stiffness

Torsional stiffness is the amount of resistance provided by the member for each degree of change when twisted. Torsional stiffness before cracking is defined as pre-cracking stiffness (K_{pre}). It can be computed from torque-twist curve as the tangent slope of this curve before cracking, while stiffness after cracking is defined as a post-cracking stiffness (K_{post}), that is reduced significantly when compared with pre-cracking stiffness, it represents the tangent slope of the torque-twist curve after cracking Peng and Wong [17], McMullen and El-Degwy [19]. This method is used to compute stiffness in the present study. It is observed for orthogonal reinforcement that (K_{pre}) reduced to about 20, 15, and 13% from

(K_{post}) for 200, 160, and 120 mm spacing, respectively. Moreover, it's noted that the pre-cracking and post cracking stiffness increases with decreasing spacing, but it increases more when increasing aspect ratio. These values of stiffness were listed as in Table 3.

Table 3
Stiffness and ductility of the specimens

Specimen	Pre-crack Stiffness (kNm)	post-crack Stiffness (kNm)	ductility
SXY20-400	45.77	9.91	12.33
SXY20-500	76.40	14.15	16.80
SXY20-600	110.8	21.78	17.33
SXY16-400	61.28	10.61	18.40
SXY16-500	108.37	14.21	25.00
SXY16-600	172.69	22.78	27.69
SXY12-400	83.20	14.84	21.00
SXY12-500	177.45	19.93	37.84
SXY12-600	281.71	28.08	42.85

Fig. 11 and Fig. 12 shows the effect of parameters on pre and post stiffness value respectively.

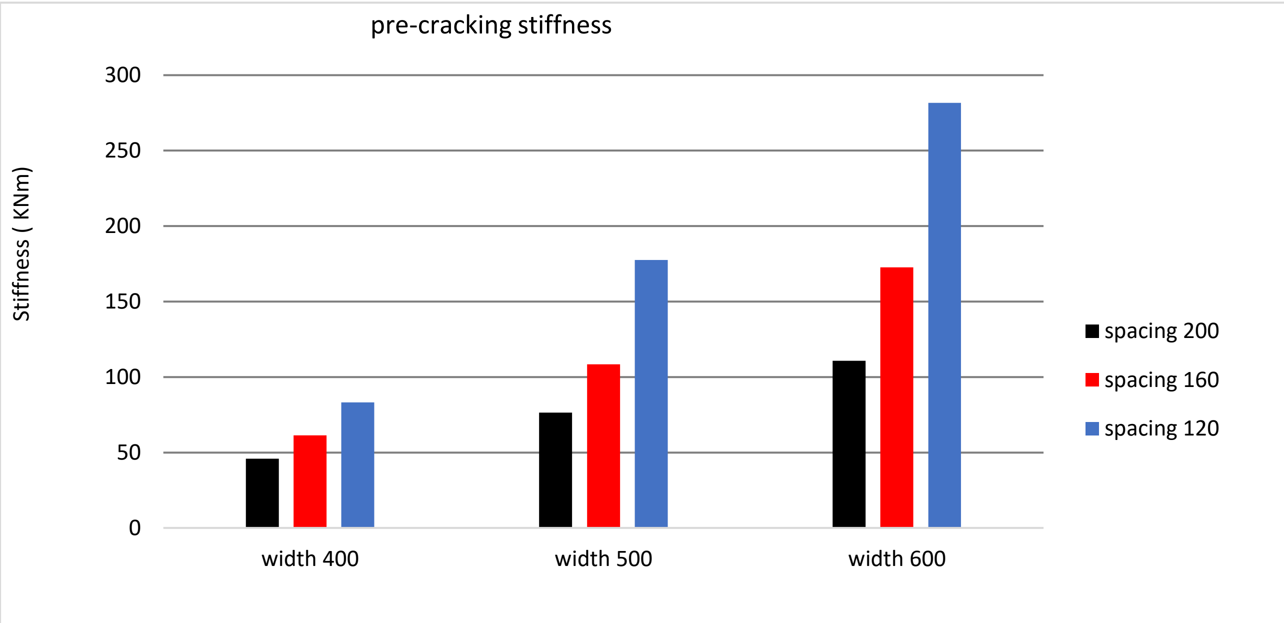


Fig. 11. Effect parameters on pre-cracking stiffness value

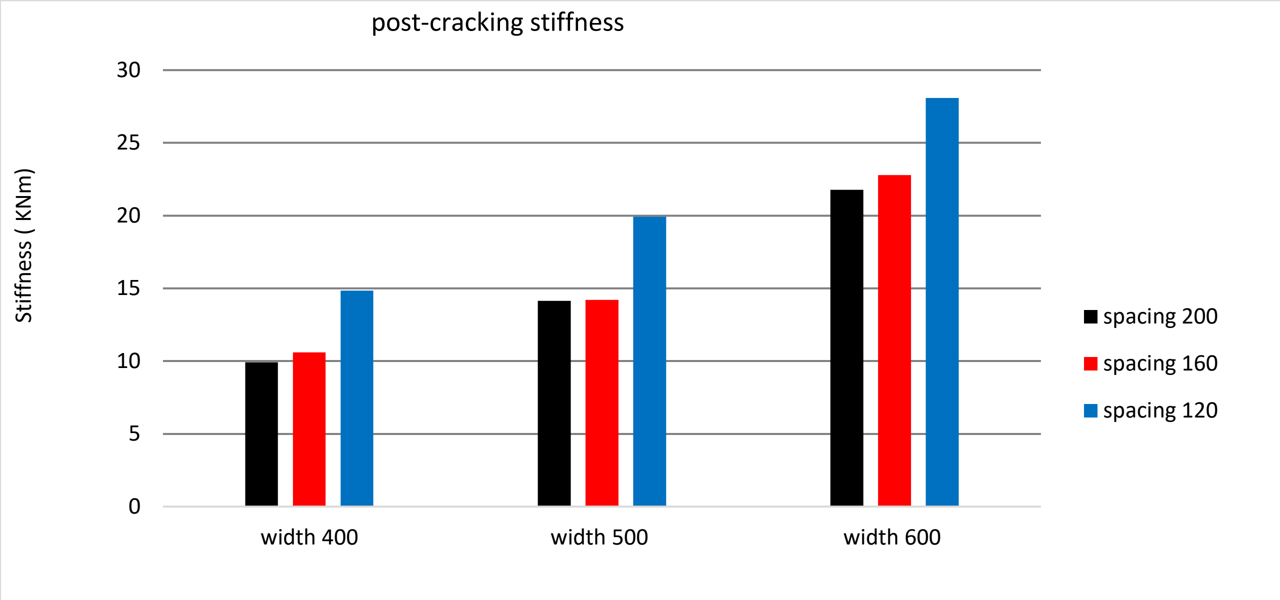


Fig. 12. Effect parameters on post-cracking stiffness value

3.4. Ductility

Ductility is defined as the proportion of deformation at the failure to the deformation at yield. It can be calculated from the torque-twist curve when this curve transfers from the elastic to the plastic stage Naji et al [20], Jomaa'h et al [21]. Table 3 shows the values obtained from the specimen used. It is observed that the increment of ductility that resulted in an increased aspect ratio larger than it when increasing steel reinforcement. Also, the ductility of oblique is less than it in orthogonal reinforcement. Fig. 13 shows the values obtained.

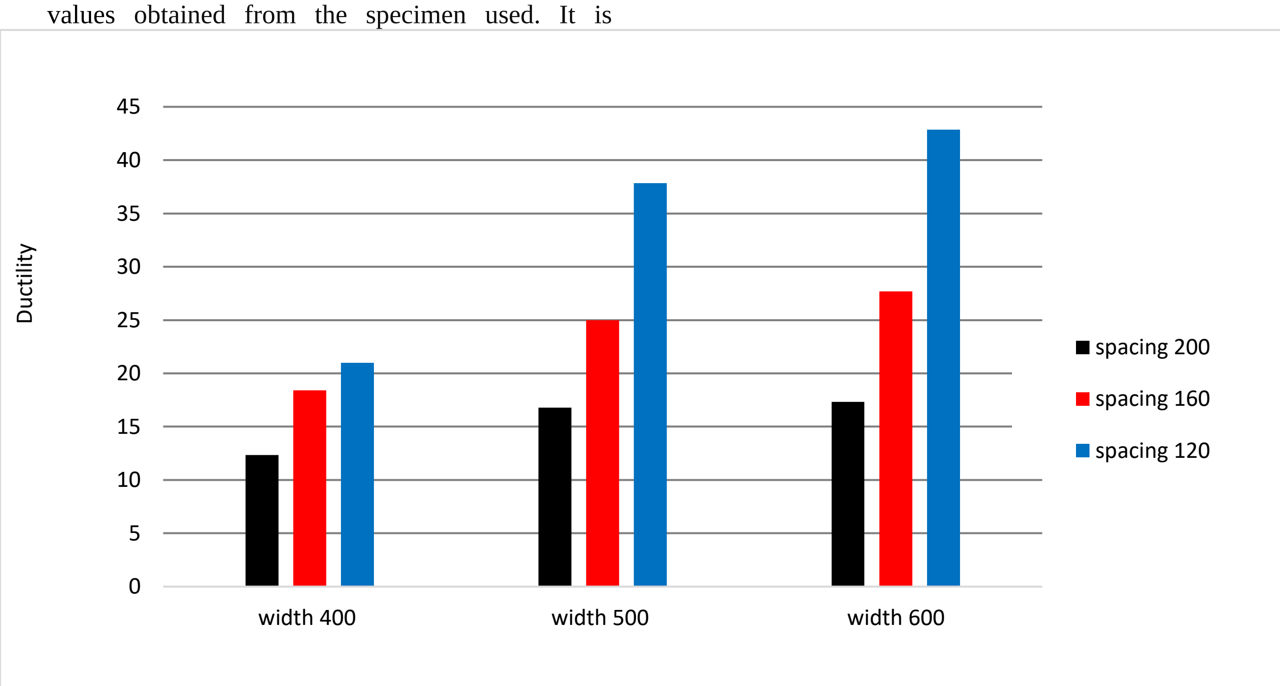


Fig. 13. Effect parameters on ductility value

3.5. General Behavior and Failure Mode

Torque-twist curve is considered the main relation for studying the behavior of reinforced concrete slabs under pure torsion. It's noted that there are three stages of development of the curve: The first stage, when the curve grows linearly elastic up to the first crack. In this stage, the torsional behavior usually depends on plane concrete because the reinforcement contribution is neglected. Some theories described the torque failure at pre-cracking stages, such as elastic theory, plastic theory, thin tube theory, and skew bending theory. In the second stage, small cracks developed with the increase of the applied torque. Torque-twist curve evolves with slop lesser than that in the first stage; also it is developed in a semi nonlinear path. In these stages the torsional stiffness decreases with the increase of the torsional moment due to crack in plane concrete and transfer of the load from concrete to steel reinforcement up to the maximum torque.

The third stage is the stage of softening behavior; it gives an impression about the ratio of steel in member. There is some mode in this stage; first, the vertical drop due to less reinforcement. Second; less severe decline. Third; the gradual decline that happens in case of normal reinforcement Lopes and Bernardo [3]. In the case of over reinforcement, the torque increased significantly up to the maximum torque and then dropped suddenly.

The cracks in torsional loading occur at the spiral path, it appears clearly at an approximate angle of 45° with the longitudinal axis. It's noted that a single crack appears in spiral form on the top and bottom face of the slab. It's widened with the increase in applied torque to failure, and it is noted that its shape and pattern are not affected greatly by the increase in reinforcement ratio and specimens width. See Fig. 14

Fig. 14. Cracks and failure mode

4. CONCLUSIONS

Pure torsion test was done on nine rectangular concrete plates and the following conclusions can be drawn:

- The torsional capacity of RC plates increased significantly with increasing specimen width by about 42.8% and 32.2 % for low and high reinforcement ratio, respectively.
- Steel reinforcement ratio increased the torsional strength of specimens to about 55%.

- Limited effect of steel reinforcement and concrete size on cracking load value.
- Ductility and stiffness improved also after increasing plate size and steel bars.
- All RC plates were failed after the appearance and widening of the single spiral crack of the top and bottom face of the plate.

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