Improving the Torsional Capacity of Reinforced Concrete Beams with Spiral Reinforcement

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***Abstract*—An experimental program is carried out in this paper to test nine reinforced concrete (RC) beams in order to study the torsional behavior of the beams using transverse reinforcement under different configurations: ordinary, continuous rectangular spiral, continuous circular spiral, and continuous advanced rectangular spiral configuration. The experimental torsional capacity results are compared with the theoretical values determined by the ACI 318-14 code. The results showed that the use of continuous spiral and rectangular reinforcement as transverse reinforcement enhanced the torsional capacity up to 17 % higher than using traditional reinforcements, and the ACI318-14 torsion equations are applicable and conservative for predicting the ultimate torsional capacity for beams with continuous rectangular and spiral reinforcement.**

***Index Terms*—Experimental study, Torsional capacity, Reinforced concrete beams, Spiral stirrups, Continuous rectangular spiral stirrups, advanced rectangular spiral configuration**

I. Introduction

The use of continuous rectangular spiral reinforcement in reinforced concrete (RC) beams as shear reinforcement instead of the traditional or spiral stirrups is a new promising technique [1]-[7]. The main objective of using continuous rectangular spiral stirrups in the beams is to improve the shear and torsion capacities of RC beams in comparison with the traditional closed stirrups. In addition to economic aspects, since the continuous rectangular spiral stirrups reduces the time and labor costs because the steel gage is installed easily and quickly, and the materials cost is reduced since there is no need to form two end hooks for anchorage for each stirrup as the case in the traditional closed stirrups.

Recently the use of continuous spiral reinforcement in RC beams has been studied by limited researchers. Corte and Boel [3] tested 24 beams to investigate the effectiveness of using spiral reinforcement in high strength and self-compacted concrete. The authors concluded that spiral reinforcement performs well as traditional stirrups, and they recommended more tests are required to establish boundaries for the inclination angle. Karayannis and Chalioris [4] investigated the shear behavior of RC beams with rectangular continuous spiral reinforcement and advanced rectangular spiral reinforcement through testing eight beams. The results showed that the shear capacity for the beams with rectangular continuous spiral reinforcement increased 14.9% compared with the beams constructed with traditional stirrups. Furthermore, the shear capacity for the beams with advanced spirals increased 21.7% with respect to the beams with traditional stirrups. Shatarat et al. [5] studied the use of continuous rectangular spiral reinforcement in shear through testing 28 RC beams. Three different spacing were used (125, 150, and 200 mm). The stirrups were inclined at five angles (62°, 70°, 75°, 80° and 85°). The results showed that the shear capacity increased for specimens with continuous rectangular spiral in a range of 11-18 %, 1.5-17 %, and 1.5-30 % for spacing of 125, 150, and 200 mm, respectively. Also, Shatarat et al. [6] studied the shear capacity of self-compacting concrete beams with rectangular inclined spiral reinforcement by testing 20 beams. Two spirals spacing of 150 and 200 mm and five different angles of inclination (72.5°, 75°, 77.2°, 80°, 85°) were used. The authors concluded that the shear capacity of self-compacting concrete beams increased up to 16.67%. Chalioris and Karayannis [7] experimentally studied the pure torsion behavior of RC beams using continuous rectangular spiral reinforcement for 11 beams. The experimental torsional capacity enhanced from 14% to 18% by using such transverse reinforcement.

By examining the previous literature, it can be revealed that the published work on the use of rectangular spiral reinforcement as transverse reinforcement in RC beams with rectangular cross-section is very limited, mainly achieved by a few authors and therefore this area is still an open field of study. This study aims to investigate the torsional behavior of RC beams with continuous spiral and rectangular reinforcement in different arrangements, in addition to find the most efficient inclination angle for rectangular, continuous rectangular spiral reinforcement by comparing the capacity of beams with traditional

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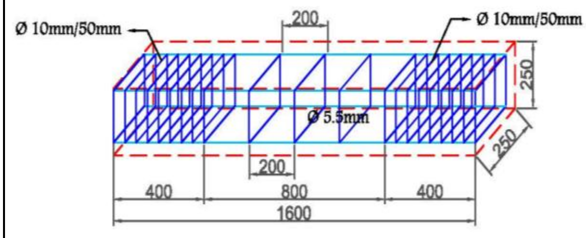
closed stirrups to the capacity of beams with continuous spiral and rectangular reinforcement. The study also aims to check the applicability of the ACI318M-14 [8] torsion equations for reinforced concrete beams with continuous spiral and rectangular reinforcement

II. Experimental Program

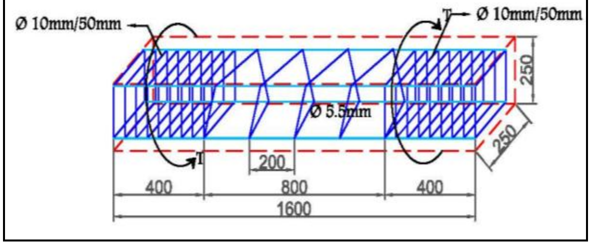
A. Characteristics of The Tested Beams

The experimental program in this study is comprised of nine RC beams with rectangular cross-section. The beams had four types of transverse reinforcement arrangement; traditional (closed stirrup), continuous rectangular spirals, spiral, and advanced continuous rectangular spiral. One beam had no longitudinal and transverse reinforcement and named (A); one beam had longitudinal bars only and named (B); two beams with traditional stirrups and named (NOR); two beams with continues rectangular spiral stirrups and named (CONT); two beams with continues spiral stirrups and named (SP); and two beams with advance continues rectangular spiral stirrups and named (ADV).

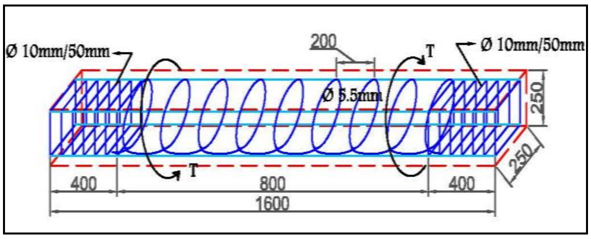
All of the beams had the same geometry properties: a total length of 1600 mm, examined length under the effect of torsion is 800 mm and cross-section dimensions of 250×250 mm. Moreover, the specimens ends were reinforced to ensure no cracking would occur due to the imposed torsional loading. Therefore, the ends were heavily reinforced with 10 mm stirrups spaced at 50 mm. The longitudinal reinforcement was kept the same, where four deformed bars of 14 mm diameter were provided at the corner of the rectangular cross-section. The yield strength (f_y) of the longitudinal reinforcement bars was experimentally obtained equal to 521 MPa, and the ultimate tensile strength (f_u) was equal to 612 MPa. The mild steel reinforcement used as transverse stirrups with diameter equal to 5.5 mm had yield strength (f_y) equal to 394 MPa and an ultimate tensile strength (f_u) equal to 459 MPa. The spacing between transverse reinforcement for all the specimens is 200 mm. The designation C in the end of the name refer to the specimen under the effect of the torsional moment that causes stirrups to be locked (close) and the designation O refer to the specimen under the effect of the torsional moment that causes continues stirrups to be un-locked (open). The concrete used in casting the beams of the presented experimental program was ready-mix concrete provided by local concrete factory with compressive strength equal to 25 MPa. The angle between the transverse reinforcement and the longitudinal axis of the beam (Ø and Ø') in degrees that resulting from the inclination of the vertical legs of the stirrups are: (90^o-90^o), (76^o-104^o), (81^o-99^o), and (63.4^o-116.6^o) for NOR, CONT, SP, and ADV, respectively. Fig. 1 shows the geometry and steel reinforcement of the tested beams and Fig. 2 shows the details of transverse reinforcement for all types.



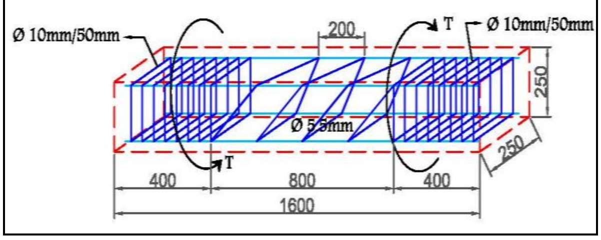
(a) NOR



(b) CONT



(c) SP

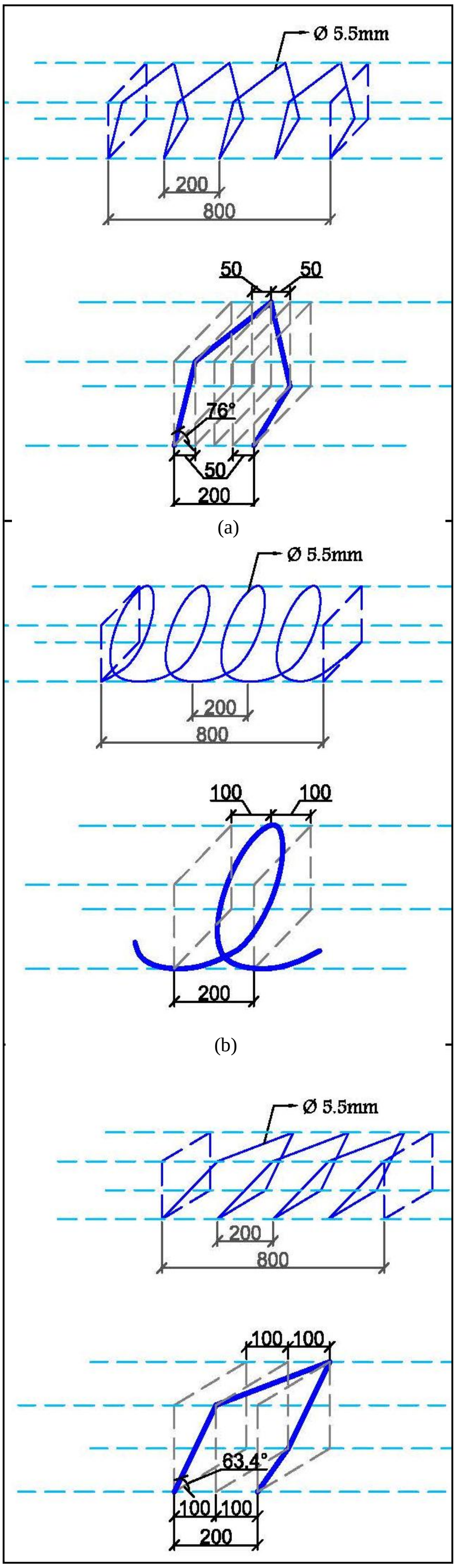


(d) ADV

Figure 1. Geometry and steel reinforcement of the tested beams.

B. Test Setup

The specimens will be subjected to pure torsion using commonly torsional test rig, as shown in Fig. 3. The total length of all beams is 1600 mm, where it is supported on two roller supports that are 1400 mm apart to ensure that the specimen is free to rotate during the test. The load is applied on diagonally placed I-section steel beam, where the I-section beam is supported by two steel arms fixed at the ends of each specimen. The examined torsional region of the specimen is 800 mm long between the two steel arms. The load was applied consistently at a low rate, and it was measured by a load cell with accuracy equal to 0.025 kN.



(a)

(b)

(c)

Figure 2. Details of transverse reinforcement for: (a) CONT; (b) SP; (c) ADV.

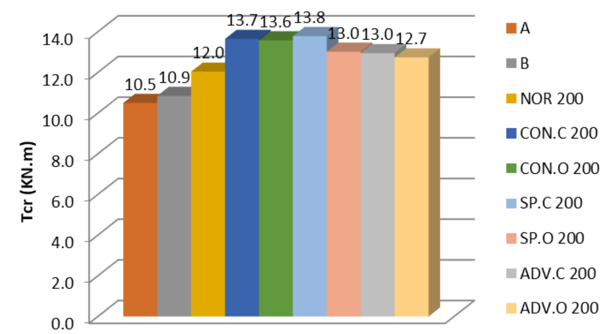
Figure 3. Test setup

III. Test Results And Discussions

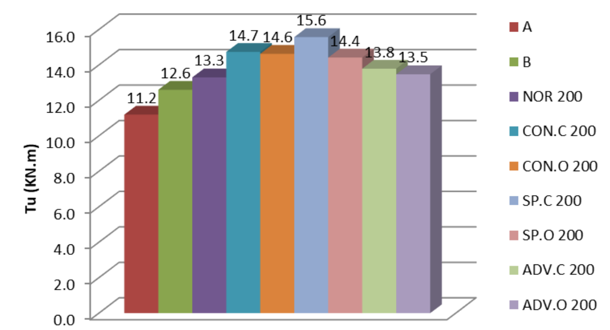
The experimental cracking torsional moment (T_{cr}), and the experimental ultimate torsional moment (T_u) for all nine beams are shown in Fig. 4. It was noticed that the cracks propagate from the casting surface and start to widen to form helical and diagonal cracks at all faces. The failure angle values of 44^o, 37^o, 52^o, 35^o, 32^o, 44^o, and 42^o were measured for NOR, CON.C, CON.O, SP.C, SP.O, ADV.C, and ADV.O, respectively, and shown in Fig. 5,6,7,8,9,10, and11, respectively.

Based on cracking torsional moment (T_{cr}) results, it is clearly shown that where twisting direction closes the stirrups, significant enhancement of capacity was achieved. The enhancement percentages reached 13.8%, 14.9%, and 7.9% for CON.C, SP.C, and ADV.C, respectively, compared with NOR. However, where twisting moment direction opens the stirrups, the enhancement percentages of 13.2%, 8.5%, and 6.2% were achieved for CON.O, SP.O, and ADV.O, respectively, in comparison with NOR. While based on ultimate torsional moment (T_u), it is clearly shown that where twisting direction closes the stirrups, enhancement of ultimate capacity is achieved. The enhancement percentages reach 10.8%, 17.1%, and 3.7% for CON.C, SP.C, and ADV.C, respectively, compared with NOR. On the other hand, where twisting moment direction opens the stirrups, the enhancement percentages of 10.0%, 8.4%, and 1.3% were achieved for CON.O, SP.O, and ADV.O, respectively, compared to NOR.

Considering results of specimens and taking in account cracking behavior and failure angle, it is noticed that the beams with transverse reinforcement showed more ductile behavior than specimens A and B due to the presence of transverse reinforcement. After the observation of the first crack, the additional torsional loading has been carried by the transverse and longitudinal reinforcement until the failure of the specimens. The imposed additional twist increased the formation of helical and diagonal cracks that became excessively wide. Beam with spiral and rectangular transverse reinforcements that are locked during the imposed twisting exhibited decrease in the inclination of the helical and diagonal cracks. On the contrary, cracking of beams that are unlocked (spiral and rectangular) during the imposed twist exhibited increase in the inclination of the helical and diagonal cracks. Thus, the crucial effect of locking and unlocking of the spirals on the torsional response of the tested specimens is clearly observed. This result could be explained by the fact that when the member is under locking effect the cracks will be crossing approximately vertically the spiral and rectangular links, on the other hand in the unlocking effect the cracks will be almost parallel to the spiral and rectangular links.



(a)



(b)

Figure 4. (a) Experimental cracking torsional moment (Tcr), and (b) experimental ultimate torsional moment (Tu) for all the beams.

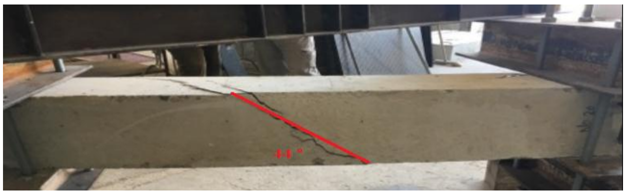


Figure 5. Photos of the failure angles of Beam NOR

Figure 6. Photos of the failure angles of Beam CON.C

Figure 7. Photos of the failure angles of Beam CON.O

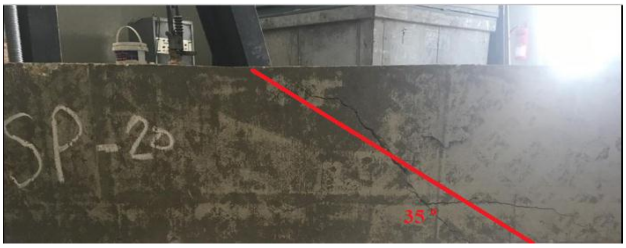


Figure 8. Photos of the failure angles of Beam SP.C

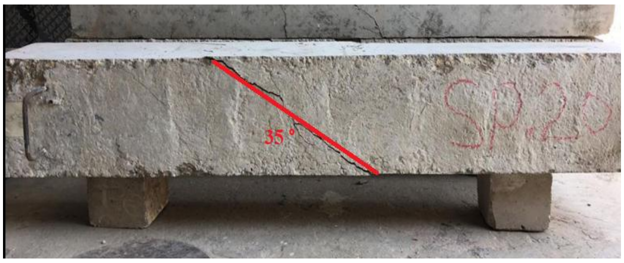


Figure 9. Photos of the failure angles of Beam SP.O

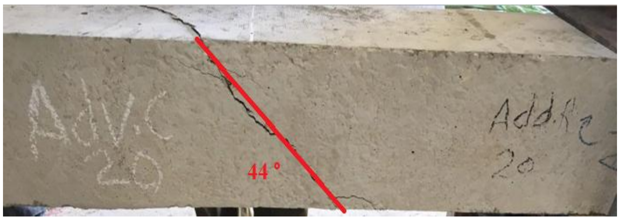


Figure 10. Photos of the failure angles of Beam ADV.C

Figure 11. Photos of the failure angles of Beam ADV.O

IV. Comparison with Theoretical Values

In this section, the experimental cracking torsional moment (T_{cr}), and the experimental ultimate torsional moment (T_u) are compared with the theoretical values obtained from ACI 318 M-14 [8]. The theoretical torsional moment capacity before cracking is calculated per the following equation [8]:

$$T_{cr} = 0.33 * \sqrt{fc'}\left(\frac{A_{cp}^2}{p_{cp}}\right). \quad (1)$$

where A_{cp} is the area enclosed by outside perimeter of concrete cross section in mm^2, p_{cp} is the outside perimeter of concrete cross-section in mm, and fc' is the compressive strength for concrete in MPa.

The calculated T_{cr} per (1) is equal to 6.5 kN.m for all specimens. Comparison between this value and the test results showed that the actual cracking torsional moment capacity is higher than the calculated value per the ACI. This means that the concrete section has a considerable capacity before cracking, and the ACI code is more conservative in calculating T_{cr} values. Fig. 12 shows the comparison between T_{cr} obtained by the ACI 318-14 and the experimental. Based on the results, it is shown that the experimental values are higher than ACI theoretical results. Experimental results ranged from 184% to 212% for T_{cr} values. The maximum value is recorded for SP.C specimen and the minimum value is recorded for NOR specimen.

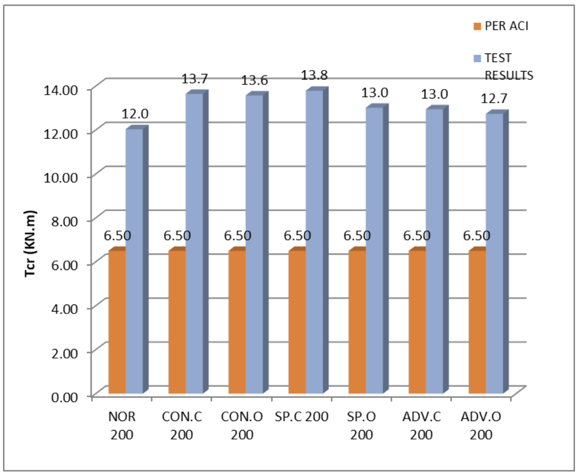


Figure 12. Cracking torsional moment (Tcr) comparison

The theoretical value of the ultimate torsional strength per the ACI 318-14 [8] can be determined as the minimum of the following equations:

$$T_{n1} = \frac{2\,A_\circ\,A_t\,f_{yt}}{S}\cot(\theta). \quad (2)$$

$$T_{n2} = \frac{2\,A_\circ\,A_l\,f_y}{P_h}\cot(\theta). \quad (3)$$

Where $A_\circ$ is the gross area enclosed by shear flow path in mm^2, A_t is the area of one legged steel stirrups in mm^2, f_{yt} is the yield strength of the transverse reinforcement in MPa, S is the spacing of steel transverse reinforcement in mm, A_l is the area of the total steel longitudinal reinforcement in mm^2, f_y is the yield strength of the longitudinal reinforcement in MPa, P_h is the perimeter of the centerline of the shear flow in space truss analysis in mm, and θ is the angle of cracks in degree. The above equations are based on the torsional resisting capacity of the transverse and the longitudinal, respectively, neglecting any contribution from the concrete, and they are based on space truss analogy, where the transverse reinforcements are perpendicular to the longitudinal reinforcement.

Fig. 13 shows the comparison between T_u obtained by the ACI 318-14 [8] and the experimental values. Based on the results, it is shown that the experimental values are higher than ACI theoretical results. Experimental results ranged from 418% to 490% of theoretical results. The maximum value is recorded for SP.C specimen and the minimum value is recorded for NOR specimen.

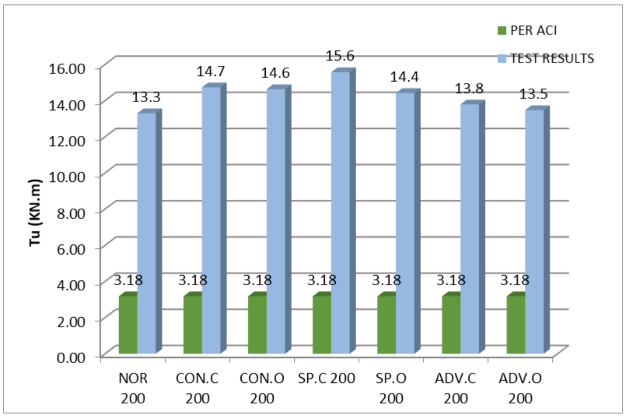


Figure 13. Ultimate torsional moment (Tu) comparison

V. Summary

The RC beams are always designed and reinforced for shear and torsion forces using single closed stirrups as a transverse reinforcement. In this paper, a new promising approach was proposed to improve the shear and torsion capacity of RC beams compared to the traditional ones by adopting continuous rectangular spiral, continuous circular spiral, and continuous advanced rectangular spiral configuration. Those configurations had a very positive impact on the strength of RC beams and on the economic aspects of the construction. The continuous spiral stirrups reduces significantly the time and labor costs because the steel gage is installed easily and quickly, and the materials cost is reduced since there is no need to form two end hooks for anchorage for each stirrup as the case in the traditional closed stirrups.

The literature showed that the published work on the use of spiral reinforcement as transverse reinforcement in RC beams is very limited and mainly was adopted to improve the shear strength of RC beams. There was only one study carried by Chalioris and Karayannis [7] that used continuous spiral reinforcement to improve the torsion capacity in RC beams. The results of this study were promising and showed that this area is still an open field of study. The results of the program study of this paper showed that the torsion capacity was enhanced using continuous rectangular spiral, continuous circular spiral, and continuous advanced rectangular spiral configuration in comparison with the RC beams with traditional closed stirrups.

Hence, the objectives of this study have been achieved since the torsional strength of RC beams has improved and the positive impact of the economic aspects of the construction has been achieved.

VI. CONCLUSIONS

An experimental program is conducted in this research to investigate the torsional behavior of RC beams made with transverse reinforcement under different configurations: ordinary, continuous rectangular spiral, continuous circular spiral, and continuous advanced rectangular spiral configuration. Furthermore, guidance on the application of the ACI-318-14 torsion equation for RC beams with transverse reinforcement is presented. The following points summarize the research outcomes:

1) In all specimens with transverse reinforcement, beams gain higher torsional moment capacity than the control beam with no reinforcement.
2) Test results of this research show that the use of continuous spiral and rectangular reinforcement as transverse reinforcement provides enhanced torsional capacity of up to 17 % higher than using traditional reinforcements.
3) The use of continuous spiral and rectangular reinforcement as transverse reinforcement with locking effect (stirrups closing) provides enhanced torsional capacity and improved post-peak performance much more than that with the unlocking effect (stirrups opening).
4) The ACI318M-14 torsion equations are applicable and give conservative values for beams with continuous rectangular and spiral reinforcement.

Accordingly, using the continuous spiral and rectangular reinforcement as transverse reinforcement in RC beams is a very promising techniques.

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