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THE INFLUENCE OF REINFORCEMENT ON THE TORSION CAPACITY OF THE HYBRID BEAMS

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Abstract

This paper discusses experimentally the torsion behaviour of hybrid reinforced concrete beams composed of reactive powder concrete (RPC) at the peripheral and conventional concrete (CC) at the core. Hybrid reinforced concrete members are used extensively to deal with strength related to flexural, shear and torsion in the structural system. The torsion failure is undesirable because of its brittle nature. It is preferable to avoid this kind of failure in earthquake areas. The experimental work includes casting seven reinforced concrete beams that are tested to failure using two opposite cantilevers steel arms that contribute to transferring the torque to the centre of the beam. The overall dimensions of the beams were 100 mm, 200 mm and 1500 mm as width, height and length, respectively. In all hybrid beams, (five of) the thickness of the surrounding RPC was 40 mm. The first beam was poured from RPC mix. The second one was poured from normal concrete CC, and the remaining four beams were poured as hybrid ones. The experimental data for all beams focused on the ultimate capacity, the cracking torsional loads, the failure pattern and the twisting angle gained for each beam. Experimental results showed higher ultimate torsional strength for hybrid beams compared to the CC ones by about 50% and lower than RPC specimen in about 16.7%.

Keywords: Conventional concrete, Hybrid concrete, Reactive powder concrete.

1. Introduction

Recently hybrid reinforced concrete structures gained great interest by engineers due to their lower cost and good performance under loading. To explain the concept of the hybrid concrete section, a specific type of concrete in a specific zone of the section was used [1]. For shear, bending and torsion hybrid beams proved to be quite successful, as well as less costly compared to RPC ones.

In the past few decades, considerable efforts of research were dedicated to the studies of the torsional behaviour of reinforced concrete structural members. Several studies by Hilman [2] have been devoted to developing the analytical models to predict the distribution of elastic stress and strength limits of the concrete beams under torsion. There are many different structures where the torsional loading can be considered as significant. The most noticeable structures are bridges and spandrel beams. Pure torsion is a twisting loading, with no axial or lateral force. It is also possible to have a pure torque loading on a beam. The latter is composed of two parallel but opposite separated forces of equal magnitude. Al-Zuabidi [3] mentioned that it can be applied or reacted anywhere on a rigid body and have the same effect.

Two mixes were used in this work: CC and RPC. Seven beams were as follows: (a) one of CC, (b) one of RPC, and (c) five hybrid beams: of CC in the core surrounded by (40 mm) thickness of RPC on the peripheral.

The latter five had different reinforcement: (a) longitudinal reinforcement includes: 314 mm^2, 452.16 mm^2 and 615.44 mm^2. (b) Stirrups reinforcement includes: 12.57 mm^2, 28.27 mm^2 and 50.27 mm^2. Beam *H*1 is a reference one of the hybrid group.

2. Beams Details

The beams studied in this research work included two control beams (CC and RPC) and five hybrid ones. The CC had the ratio of 1:1.5:1.75:0.5 (cement: sand: gravel: w/c) respectively. The RPC had the ratio of 1:1:0.25:6%:0.2 (cement: fine sand: silica fume: superplasticizer: w/c) with steel fibre Vf = 1% respectively. All beams were designed and cast with the same mixes, following the ACI 318M code procedure [4]. The overall dimensions of the seven beams and reinforcement ratio and hybrid concrete position are presented in Table 1 and Figs. 1 to 3. The loads applied on the steel plate above two steel arms are opposite at the beam ends to obtain torsional loading.

Table 1. Properties of beams.

Name of beams	Classification	Al $(mm)^2$	At $(mm)^2$	Spacing (mm)
NC	CC	452.16	28.27	50
RP	RPC	452.16	28.27	50
***H*1**	Hybrid	452.16	28.27	50
***H*2**	Hybrid	314	28.27	50
***H*3**	Hybrid	615.44	28.27	50
***H*4**	Hybrid	452.16	50.27	50
***H*5**	Hybrid	452.16	12.57	50

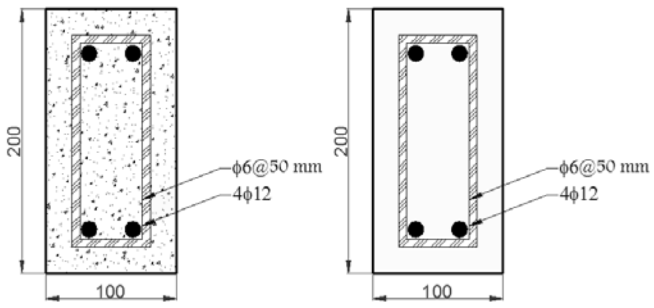


Fig. 1. CC beam and RPC beam.

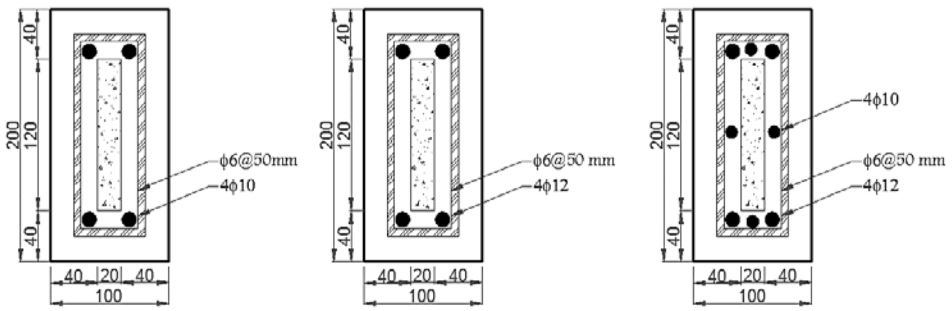


Fig. 2. Hybrid beam with different longitudinal reinforcement.

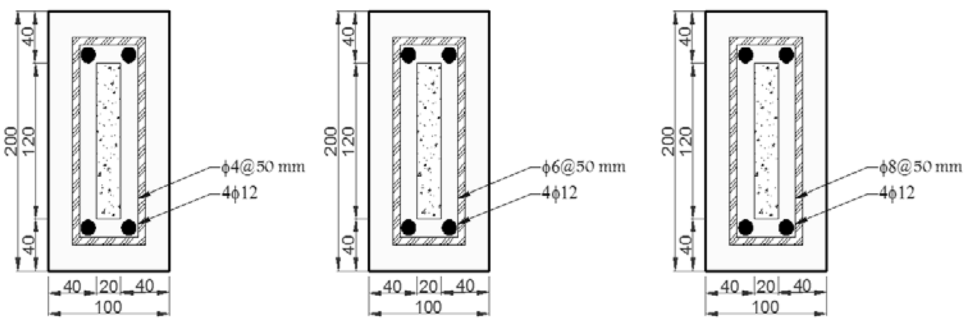
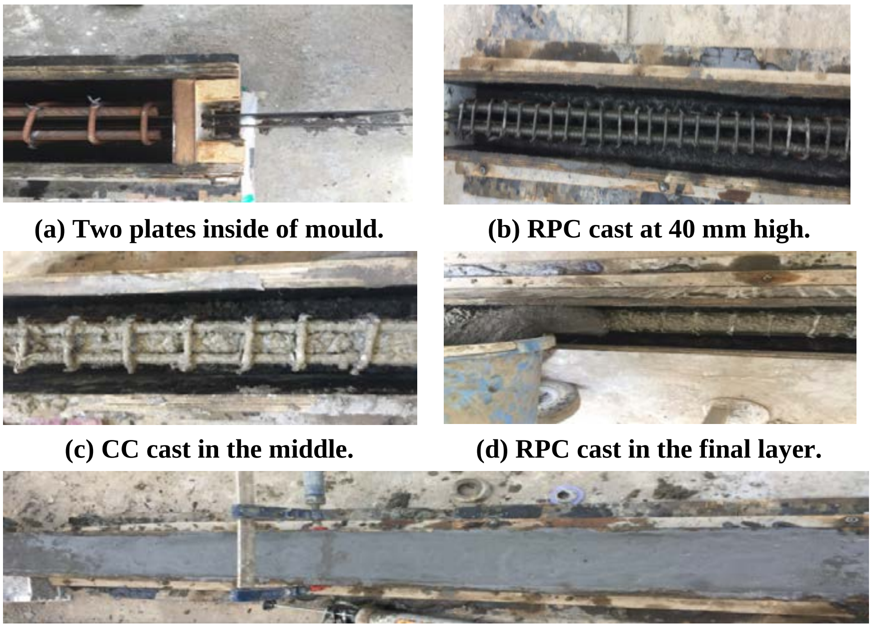


Fig. 3. Hybrid beam with different transverse reinforcement (stirrups).

3. Casting the Hybrid Beams

The procedure for casting the beams was as follows: Firstly the first layer of RPC was cast in the bottom of the mould up to 40 mm of height, then two plates with 120 mm height were inserted inside the mould to separate the mixes, the second layer contains two types of concrete, the core with CC, 20 mm, and the surrounding RPC, 40 mm, up to 160 mm of height. Finally, the RPC mix was cast up to the top of the mould. As shown in Fig. 4, after 10 minutes, the plates were pulled out of the hybrid beams from the side of the mould.



(a) Two plates inside of mould. **(b) RPC cast at 40 mm high.**

(c) CC cast in the middle. **(d) RPC cast in the final layer.**

(e) Finally, the beams.

Fig. 4. Procedure for casting the beams.

4. Results and Discussion

4.1. Compressive strength (*f*c')

The compressive strength (*f*c') tests were carried out in accordance with ASTM International [5] (100 mm diameter × 200 mm long). The average of three cylindrical specimens was used to determine the compressive strength for RPC and CC mixes, which were 89.6 MPa and 30.1 MPa, respectively.

4.2. Tensile strength (*f*t)

The splitting tests were carried out in accordance to ASTM International [6] (100 mm diameter × 200 mm long), the average of three cylindrical specimens was used to determine splitting tensile strength for RPC and CC mixes. These were 10.22 MPa and 2.84 MPa, respectively.

4.3. Modulus of elasticity

The modulus of elasticity tests were carried out in accordance with ASTM International [7] (150 mm diameter × 300 mm long). The average of three cylindrical specimens was used to determine the modulus of elasticity for RPC mix (49340 MPa) and CC mix (27900 MPa).

4.4. Steel reinforcement

Five nominal deformed steel diameters of 4, 6 and 8 mm were used as shear reinforcement (stirrups) at 50 mm spacing and diameters of 10 and 12 mm were used as flexural reinforcement. The details of the bars are shown in Table 2.

Table 2. Details of bars.

Nominal bar diameter (mm)	Yield stress (MPa)	Ultimate stress (MPa)
4	507.68	546.74
6	416.56	468.63
8	428.00	537.01
10	512.35	533.74
12	519.20	617.15

4.5. Steel fibre

Straight brass coated gold colour short steel fibres 15 mm long with a radius of 0.1 mm and aspect ratio of 75 and tensile strength 2600 MPa, according to the manufacturer [8].

4.6. Cracking torsion capacity

The cracking torsion (T_{cr}) is the load at which, the tensile stress reaches at the beam the tensile strength of the concrete. Table 2 shows the capacity of cracking torsion for all beams. By its nature, cracking torsion is less precise than the ultimate torsion capacity- as the former may be influenced by observation.

4.6.1. Longitudinal reinforcement

Three of the hybrid beams had the longitudinal reinforcement of 314 mm^2, 452.16 mm^2 and 615.44 mm^2, respectively. The cracking torsion was greater by 19.86%, 19.86% and 21.69% compared to the CC beam. On the other hand, the fully RPC beam cracking torsion was 27.85% greater than the CC beam. Therefore, the hybrid beams (all three) were closer to the RPC one than the CC beam, see Fig. 5.

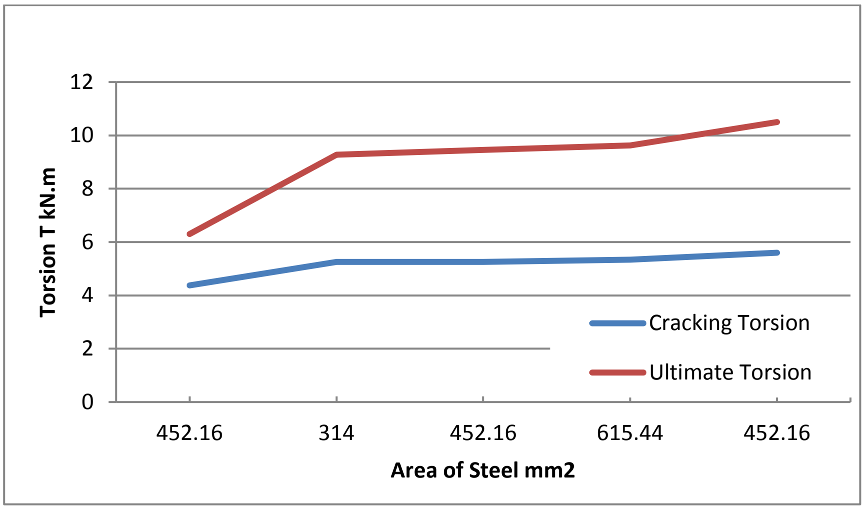


Fig. 5. Capacity of cracking and ultimate torsion by change longitudinal reinforcement.

4.6.2. Stirrups reinforcement

Three of the hybrid beams had the stirrups reinforcement of 12.57 mm^2, 28.27 mm^2 and 50.27 mm^2, respectively. The cracking torsion was greater by 17.81%, 19.86% and 19.87% compared to the CC beam. On the other hand, the fully RPC beam cracking torsion was 27.85% greater than CC beam. Therefore, the hybrid beams (all three) were closer to the RPC one than the CC beam, see Fig. 6.

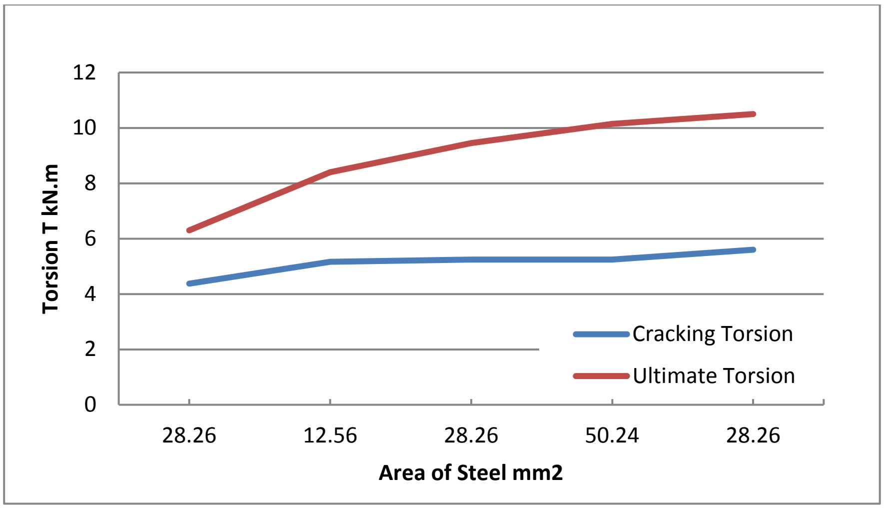


Fig. 6. Capacity of cracking and ultimate torsion by change stirrups reinforcement.

4.7. Ultimate torsion capacity

The ultimate torsion capacity (T_u) can be defined as the test machine reading when the load drops [9] as deformation continues. Table 3 shows the ultimate capacity of torsion for all beams.

Table 3. Cracking and ultimate torsion capacity.

Name of beams	Cracking Torsion kN.m	Ultimate Torsion kN.m	Percentage of increase ultimate Torsion % (longitudinal reinforcement)	Percentage of increase ultimate Torsion% (stirrups)	Angle of twist rad/m	T_u/T_{cr}
NC	4.38	6.3	-	-	0.029	1.44
H1	5.25	9.45	50	50	0.065	1.80
H2	5.25	9.36	48.57	-	0.049	1.78
H3	5.33	9.63	52.86	-	0.038	1.81
H4	5.25	10.15	-	61.11	0.042	1.93
H5	5.16	8.4	-	33.33	0.055	1.62
RP	5.6	10.5	66.67	66.67	0.109	1.88

4.7.1. Longitudinal reinforcement

Three of the hybrid beams had the longitudinal reinforcement of 314 mm^2, 452.16 mm^2 and 615.44 mm^2 respectively. The ultimate torsion was greater by 48.6%, 50.0% and 52.9% compared to the CC beam. On the other hand, the fully RPC beam had 66.7% greater ultimate torsion than the CC beam. Therefore, the hybrid beams (all three) were closer to the RPC one than the CC beam, see Fig. 5.

4.7.2. Stirrups reinforcement

Three of the hybrid beams had the stirrups reinforcement of 12.57 mm^2, 28.27 mm^2 and 50.27 mm^2 respectively. The ultimate torsion was greater by 33.33%, 50% and 61.11% compared to the CC beam. On the other hand, the fully RPC beam had 66.67% greater ultimate torsion than CC beam. Therefore, the hybrid beams (all three) were significantly closer to the RPC one than the CC beam as shown in Fig. 6. When the longitudinal reinforcement ratio or the stirrups reinforcement ratio increased for hybrid concrete beams the ratios of (T_u/T_{cr}) increased, however, the influence of increased stirrups was more significant than increased longitudinal reinforcement. As this percentage increases, the safety of concrete installations increases, see Fig. 7.

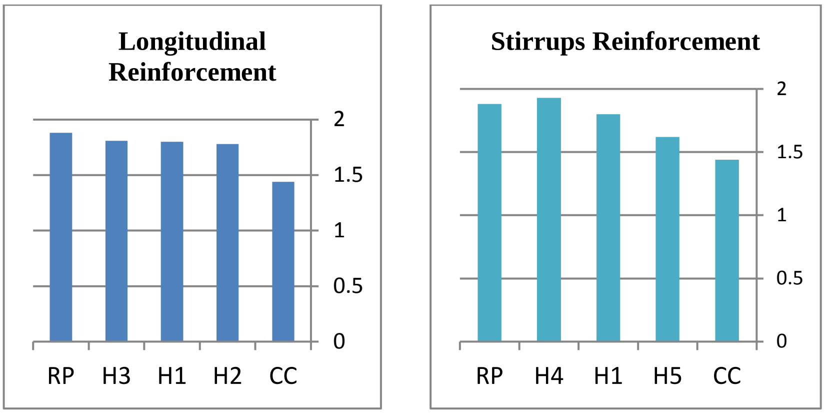


Fig. 7. (T_u/T_{cr}) with all beams.

4.8. Angles of twist

This is the angle through, which the free end of a beam rotates with respect to the fixed end. The twisting of a body by the exertion of force tending to turn one end or part about a longitudinal axis while the other is turned in the opposite direction. For the measurement of the angle of twist two LVDTs were attached to the steel plate at the end of the beams.

The CC beam (NC) reached maximum torque of 6.3 kN.m with a maximum rotation of 0.029 rad/m. While the first cracking torsion was 4.38 kN.m at rotation 0.025 rad/m, the beam had a larger angle of twist at failure. The RPC beam (RP) had a rotation of 0.008 and 0.109 rad/m at cracking and ultimate torsion capacity respectively. On the other hand, the five hybrid beams behaved more closely at the beginning of the test. Even at later loading all 6 beams (RPC and 5 hybrid beams) were still close in behaviour. They are shown in Table 3 and Figs. 8 to 10. Based on the results of this work, hybridization did not significantly change the behaviour from the full RPC beam.

Fig. 8. Show the LVDT, steel arms and machine test.

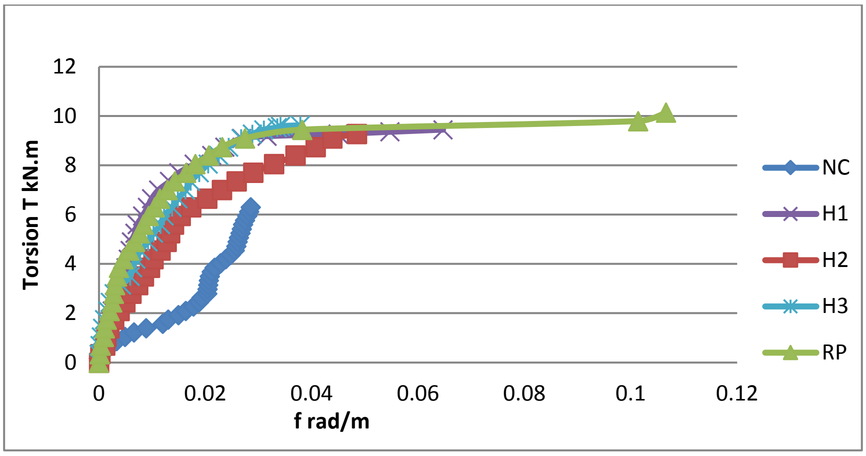


Fig. 9. Angle of twist by change longitudinal reinforcement.

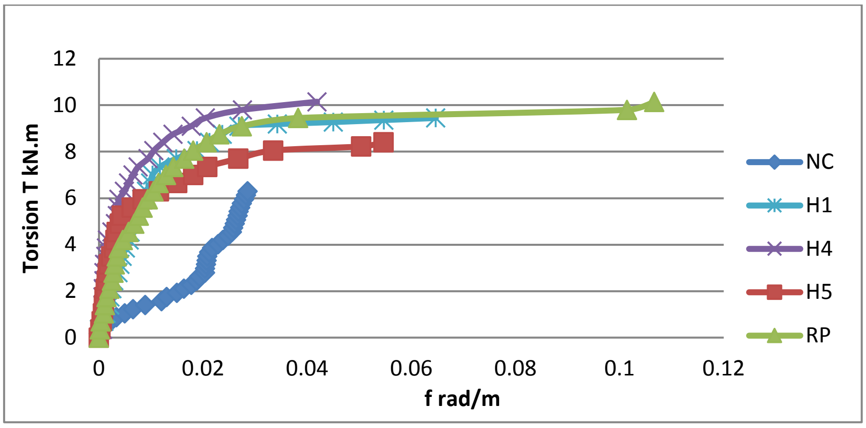


Fig. 10. Angle of twist by change stirrups reinforcement.

5. Testing Procedure and Failure of Beams

Curing of all specimens lasted for 60 days. Drying lasted about 30 days, and then all specimens were cleaned and painted white in order to obtain clear observation of cracks and their spread patterns. Steel arms were placed at both ends of each beam in opposite directions. At the earlier stages of loading, hairline cracks were formed in the areas between supporting arms. With further increase in load, multiple cracks widened and began to form in a diagonal orientation. These cracks continued to propagate with increasing load until reaching the failure point.

All tested beams failed in torsion as the inclined cracks were about 45 degrees to the beam axis. This cracking angle that appeared in the surface of beams led to a redistribution of internal stresses. The failure in CC beam was beyond just cracking and reached to the crushing of the concrete cover, which is more dangerous than the other six beams at failure. All six beams (five hybrid beams plus RPC) failed by cracking on the surface. Thus, hybrid beams are more reliable in terms of failure, than the CC one. This work indicates that concrete strength has a significant influence on torsional strength, unlike practically all codes (except the BS code) [10]. The beams CC, *H*1, *H*2, *H*3, *H*4, *H*5 and RP are shown in Figs. 11 to 16.

Fig. 11. Show the CC beam (*NC*) and RPC beam (*RP*).

Fig. 12. Hybrid beam (*H*1).

Fig. 13. Hybrid beam (*H*2).

Fig. 14. Hybrid beam (*H*3).

Fig. 15. Hybrid beam (*H*4).

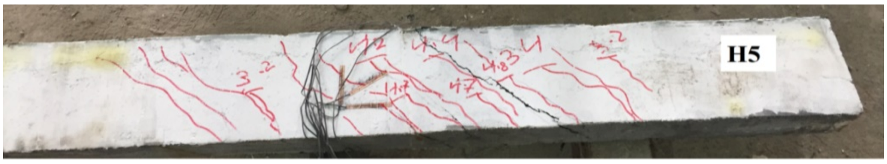


Fig. 16. Hybrid beam (*H*5).

6. Conclusions

A total of seven beams are tested for pure torsion, in order to determine the effect of the reinforcement on the strength of hybrid beams. The following conclusions are given below:

- Two mix procedures used in this research present a successful way to produce hybrid beams with different reinforcement.
- Unlike practically all codes (except the BS code), this work indicates that concrete strength has a significant influence on torsional strength.
- The ultimate torsion capacity compared to the CC beam (NC) was increased by 48.57%, 50%, 52.86% and 66.67% respectively, depending on increasing longitudinal reinforcement.
- The ultimate torsion capacity compared to the CC beam was increased by 33.33%, 50%, 61.11% and 66.67% respectively, depending on increasing transverse reinforcement.
- The cracking torsion capacity increased with increasing longitudinal reinforcement by 19.86%, 19.86%, 21.69% and 27.85% respectively as percentages to conventional concrete (NC).
- The cracking torsion capacity increased with increasing transverse reinforcement (stirrups) by 17.81%, 19.86%, 19.86% and 27.85% respectively percentages to conventional concrete (NC).
- In general, the cracking and ultimate torsion capacities in hybrid beams are larger than CC and only slightly less than RPC beam.
- The angle of twist decreased significantly in hybrid beams when compared with normal concrete beam (CC).
- The CC beam failure was beyond just cracking and reached to crushing into cover concrete, which is more dangerous than the other beams at failure. All 6 other beams, non-CC ones, failure was represented by cracks on the surface of each beam. Thus, hybrid beams are more reliable in terms of behaviour.

One possible future research may be for columns under large eccentricity of loading, where the stronger concrete may be on the outside of the columns.

Nomenclatures

T_{cr}	Cracking torsion, kN.m
T_u	Ultimate torsion, kN.m

Greek Symbols

ϕ	Angle of twist, rad

Abbreviations

ASTM	American Society for Testing and Materials
CC	Conventional Concrete
LVDT	Linear Variable Differential Transformer
RPC	Reactive Powder Concrete

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