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Torsional Performance of Reinforced Concrete Beams Strengthened with Ferrocement

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ABSTRACT

Reinforced concrete (RC) beams strengthened with ferrocement and exposed to pure torsion are the study's main focus. Ferrocement is utilized for strengthening because it's price-effective. The solution is cost-effective and structurally efficient. Ferrocement is cheaper, more accessible, and has good ductility, durability, and bond performance. Five RC beams were encased with 2.5 cm of ferrocement on each side and subjected to pure torsion for the investigation. The other two beams were references. Each strengthened beam had a cross-section of 100×250 mm and a constant length of 2000 mm. The first control beam without torsional reinforcement has the same reinforcement features as all enhanced beams. This study examined the effects of wrapping beams from three and four sides and the presence or absence of strengthening, plastic, and steel wire mesh layers. All specimens enhanced with the ferrocement layer had better RC beam torsional performance than control beams. Compared to reference beams (b1, b2), b4 (beam strengthened with four faces) had the best torsional moment resistance and the highest ultimate torque moment. Strengthened beams with three faces (U-wrapped) (b4, b5, b6, b7) and different steel and plastic wire mesh layers increase ultimate torque (233%, 233%, 221%, 209%) for b1 and (114%, 114%, 106%, 99%) for b2.

1. INTRODUCTION

The torsional moment results from out-of-plane forces that act offset to the longitudinal axis of the element. Torsion was once considered a minor problem, even though it happens often compared to other types of loading in the event of the ultimate limit state. After the 1960s, torsion was significant in the design of structures that were exposed to offset loading [1, 2]. When using or choosing a material in structural engineering construction, the aim is to use all of its characteristics to make a properly working structure. In most modern civil engineering applications, the building material must be available and used ineffectively in resisting applied loads to produce a durable, strong structure and be easy to work with [3].

A torsional load is a force that is not in the same place as the shear center of a structural member section and is not in the same plane as the section. This causes the member to twist. Simple torsion is caused by just one or two forces in a plane that are orthogonal to the member's axis. Suppose a couple is in a plane that is not orthogonal to the axis of the member. In that case, it can be broken down into a torsional moment in a plane perpendicular to the axis and a bending moment in a plane that goes across the plane of the axis. This is a special kind of load application because, most of the time, uneven loads on beams are balanced out to the point where small differences can be ignored. For example, the spandrel beams that sustain heavy bricks in a building may not be centered on the load, causing torsional stresses. However, these stresses will be largely neutralized by loads of the associated beams, floor, walls, and other restraints not centered on the load. Because of this, torsional stresses rarely cause any kind of defect. Torsion can happen during the building process, usually because of a mistake in how the building is put together. When forms for concrete slabs are put on one edge of a beam (usually the light secondary beam), the weight of the new concrete may be enough to twist the beam. Before building the eccentric wall, the floor ties for spandrels, if there are any, or the slab should be put in place. The problem should be fixed by putting the connectors for the heavy flat roof sheets on the other side of the purlin, which could cause the section to warp [3].

Torsional moments cause shear strains and normal warping in a member.

According to ACI-318, concrete has no resistance to torsion, and the reinforcements must supply the whole nominal torsional strength. To the reinforcements needed for axial force, shear force, and bending moment, torsion reinforcements must be added [4]. Torsion moments are usually added to other internal forces in real structures (axial forces, shear forces, and bending moments). Torsion, on the other hand, can be a very important part of the design of some structures, like bridges. In buildings with multiple forces, the design process is usually based on how the forces interact, and the behavior under pure torsion must be known and measured [5].

Torsional loading is applied to several forms of RC structural elements, including ring beams located at the bottom of the circular slab, peripheral beams, beams supporting the canopy, and other similar beam configurations. When these beams are unable to provide resistance, it becomes necessary to strengthen or upgrade them. The retrofitting of older structures has been required due to increased service loads, reduced capacity caused by ageing and degradation, and stricter modifications in code rules [6, 7].

RC members can undergo repair and reinforcement by several methods, including ferrocement wrapping, steel jacketing, epoxy repair, or the use of fiber-reinforced polymer (FRP) composites. Each approach necessitates a distinct degree of meticulous attention to detail. The type of repair is mostly determined by the availability of labor, cost, and the impact on building occupancy [8].

FRPs have achieved global recognition as a retrofitting material due to their exceptional strength, lightweight nature, and favorable fatigue resistance.

Nevertheless, considering the cost-benefit aspect, ferrocement can serve as a viable option for the restoration of degraded or damaged reinforced concrete beams.

Ferrocement, a thin structural composite material, exhibits better crack-arresting capacity, higher tensile strength-to-weight ratio, ductility, and impact resistance.

Hence, it can be used as an alternative for FRPs in repair and rehabilitation [9].

Charan et al. [10] reviewed RC high-strength beams with ferrocement U-wraps' torsional capacity. Seven beams validated the theoretical concept. 5 beams were (125×250) mm, and two were (125×190) and (125×315). The beams were 2 m long to provide two spirals for crack pattern observation, which required 1.5 m for beam size (125×250) millimeter and 250 mm end zones for lever arms. The ends were strongly strengthened to force center zone failure. 25 millimeter-thick ferrocement layer was created on the outer face of the beam with no wrapping on the top face with varied layers of wire mesh 3,4,5 for beams with the same aspect ratio and four layers for the other two beams with a constant mortar compressive strength of 55 MPa. For beams of 125×250, 125×190, and 125×315, the central concrete core was 75×225 mm, 75×165 mm, and 75×290 mm, respectively, to fill with 55, 60, and 70 MPa concrete. The test results demonstrated that elastic torque is not dependent on ferrocement mesh layers. If the wrapped face shear stress governs failure, the jacketed beam's torsional strength increases with the aspect ratio. Tensile strength increases core concrete cracking torque. Its tensile strength and long-face stress determine the ultimate torsional capacity. The strength of core concrete, aspect ratio, and jacketed material determines the capacity for a "U" wrapped plain concrete beam. "U" wrap beams have 59.72% more torque and 91.53% more twist than unwrapped concrete beams.

Behera et al. [9] investigated the torsional strength of ferrocement "U" wrapped normal strength beams using only transverse reinforcement by casting and testing six beams of (125×250) mm and 2 m in length with a 25 mm thick ferrocement shell reinforced with 3, 4, and 5 layers of the wire mesh which is galvanized square grid with a 0.72 mm diameter, a grid spacing of 6.35 mm, the 180 GPa modulus of elasticity and 250 MPa yield stress, three control beams without any reinforcement, and three test specimens with only transverse reinforcement of 8 mm diameter and the yield strength of 100 mm c/c is 465 MPa. Mix proportions for the core concrete were 1:1.5:3 with a water cement ratio of 0.55; the cube strength of concrete was 35 MPa, while the mortar mix was prepared with a 1:1.5 ratio with a w/c ratio of 0.55, giving a compressive strength of 40 MPa. From this experiment, transverse reinforcement increases twist by 21.48% over control specimens. mesh layers, Core concrete, mortar, aspect ratio, and determine ultimate torque. Only transverse reinforcement increases toughness but not torsional capacity.

Al-Obaidy et al. [11] conducted experimental research to explore the enhancement of ferrocement beams in torsion by utilizing Carbon Fiber Reinforced Polymer (CFRP) strips, which improved the mechanical properties of mortar mixed with a superplasticizer at a ratio of 1:1.5. The study involved twelve rectangular beams measuring 50×120 mm and 1 meter in length, which were cast, reinforced, and tested under pure torsion conditions.

The testing program evaluated the impact of the number of wire mesh layers, with configurations including two, three, and four layers integrated with a steel skeleton. Additionally, the study examined the effects of varying the spacing of Carbon FRP strips at intervals of 100, 160, and 200 mm center-to-center.

Results indicated notable influences on torque-twist behavior, ultimate torque, and failure modes. The compressive strength achieved was 65.65 MPa using an optimal superplasticizer dosage of 1.4% of the cement weight. The ultimate torque increased by 13.44% for beams with reinforcement near the section (2-4 layers) and by 3.24% for those with uniformly distributed reinforcement (2-3 layers).

The use of CFRP strips resulted in a significant enhancement of torque performance. Specifically, beams reinforced with four layers of mesh and CFRP strips spaced at 100 mm exhibited a 3.12-fold increase in torque, whereas those with 200 mm spacing achieved a 1.12-fold increase. Among the beams with four units, those with CFRP strips spaced at 100 mm and 160 mm demonstrated 94.34% and 45.28% higher ultimate torque, respectively, compared to those with a 200 mm spacing.

Behera et al. [12] conducted experimental and theoretical research on eight rectangular beams with cross-sections of 125×250 mm and lengths of 2000 mm. The study focused on varying configurations of longitudinal and transverse reinforcements in the beams. Two of the beams were plain, without any reinforcement, and one was encased in four layers of wire mesh. The other six beams were designed to represent different torsional reinforcement scenarios: solely longitudinal, solely transverse, under-reinforced and over-reinforced in both longitudinal and transverse directions, under-reinforced longitudinally with over-reinforcement transversely, and vice versa.

The longitudinal reinforcements consisted of six bars with diameters of 6 and 12 mm, with yield strengths of 350 and 440 MPa, respectively. Transverse reinforcements were 6 and 10 mm diameter bars spaced 70 mm apart, center-to-center, with yield strengths of 350 and 445 MPa. After a curing period of 28 days, the compressive strengths of concrete cubes and ferrocement mortar were measured at 60 MPa and 55 MPa, respectively.

Experimental findings showed that beams with only longitudinal reinforcement exhibited significant increases in torque, twist, and toughness—4.46%, 39.28%, and 73.5%, respectively—compared to a plain-wrapped beam. Beams with only transverse reinforcement showed improvements of

1.38%, 28.57%, and 51.14% in the same metrics over the control wrapped beam. Torque improvements ranged from 39% to 179% across various reinforcement strategies, with under-reinforced beams demonstrating the highest toughness due to their greater capacity to twist under lower torsional stiffness.

Further experiments by Behera et al. [13] examined the torsion behavior of beams with specific longitudinal or transverse reinforcements wrapped in "U" shaped, galvanized steel square woven wire mesh. The mesh had a wire diameter of 0.72 millimeters and a yield strength of 250 MPa, with a spacing of 6.35 mm center-to-center. The core concrete used in these beams had a strength of 35 MPa, while the ferrocement layer was rated at 40 MPa Fc'. The results indicated that any single type of reinforcement, whether longitudinal or transverse, significantly enhanced the torsional strength and toughness compared to both unwrapped and "U" wrapped plain beams, with longitudinally reinforced beams showing higher cracking torque and toughness than those reinforced transversely.

Behera et al. [14] conducted experiments on twelve beams to study the effects of torsion. These beams were tested under pure torsional forces to assess the influence of varying the number of 'U' wrap wire mesh layers within four distinct torsion states: under-reinforcing, longitudinal over-reinforcing, transverse over-reinforcing, and complete over-reinforcing. Despite changes in the number of mesh layers from three to five, no significant improvement in torsional strength was noted. The experiments revealed that torsion conditions more significantly affect the torque-twist response of a ferrocement 'U' wrap beam than the amount of ferrocement reinforcement. Under-reinforced beams demonstrated superior rotation capacity, transversely over-reinforced beams showed greater toughness, and completely over-strengthened beams exhibited the highest torque resistance compared to other conditions.

Behera [15] examined the torsional stiffness of twenty-nine U-wrapped reinforced concrete beams. These beams, measuring 125 by 250 by 2000 millimeters, were subjected to pure torsion tests. The study differentiated between 21 beams made from normal-strength concrete (35 MPa) and ferrocement mortar (40 MPa) and nine beams made from high-strength concrete (60 MPa) and mortar (55 MPa). The research focused on variations in the number of mesh layers (3, 4, 5) and six torsional states. Results indicated that high-strength concrete beams wrapped with ferrocement U demonstrated greater secant stiffness at cracking torque than those with normal-strength concrete, affirming the effectiveness of U-wrapped beams. The secant stiffness at cracking torque was found to depend on the number of mesh layers, the strengths of the mortar and core concrete, and the aspect ratio, with high-strength beams achieving higher values at ultimate torque.

Rajguru and Patkar [16] reported findings from an experimental study on the torsional capacity of ten RC beams externally strengthened with U ferrocement at various mortar strengths. The beams, sized 150, 200, and 1500 millimeters, featured a concrete compressive strength of 25 MPa and were reinforced longitudinally and transversely with 6 mm diameter bars at 100 mm center-to-center spacing. The study aimed to assess the impact of torsion on the ferrocement strengthening system across mortar strengths of 32.95, 36.87, 41.49, and 46.45 MPa, maintaining consistent wire mesh layers and thickness throughout the experiments.

A variety of mortar mixes with varied strengths can be produced by altering the ratio of water to cement in the range of 0.400–0.475 with stepped increments of 0.025. As a result, there was less of an increase in the beam's ultimate torsional strength, and the twist angle increased by an average of 10.33% more than typical beams.

After analyzing the literature reviews on the techniques used to strengthen reinforced concrete beams by using ferrocement, it’s observed that there are many considered and effective approaches. The variables considered in the past research were changing the torsional reinforcement, number of mesh layers, concrete compressive strength, mortar compressive strength, and aspect ratio. The best result was shown when aspect ratio of 2 was maintained while the concrete and mortar were of normal compressive strength. It has seemed that the torsional strength enhancement is very marginal with layer number for any state of torsion, so the most important difference that will be worked out in this study can be mentioned:

- Using plastic and steel ferrocement wire mesh;
- Strengthening beams by three and four sides;
- Applying the minimum torsional reinforcement to observe the effectiveness of the strengthening layer;
- Place the strengthening layer after 28 days of casting beams, which is closer to real-world application.

2. EXPERIMENTAL PROGRAM

Seven beams were cast and tested to study the torsional behavior of reinforced concrete beams strengthened with ferrocement. The size was (100×250) mm and 2000 mm in length without any jacketing. The end zone of 300 mm was heavily reinforced to induce a failure within the intermediate region. Eight millimeters in diameter reinforcement was used in the longitudinal and transverse direction, yielding 357.33 MPa, with normal-strength concrete having a compressive strength of 30 MPa. After 28 days of curing, five beams were strengthened with a 25 mm thick ferrocement layer with different variables in the design (refer to Tables 1 and 2).

Table 1. Beams details

Beam Symbol	Strengthening	Cross-Section Dimensions (mm)	Wire Mesh Layers
B1	None	100*250	None
B2	None	100*250	None
B3	Four sides	150*300	4 steel
B4	Three sides	150*275	4 steel
B5	Three sides	150*275	3 steel+1 plastic
B6	Three sides	150*275	2 steel+ 2 plastic
B7	Three sides	150*275	4 plastic

*percentage= $\frac{x_2-x_1}{x_1}$ *100%

Table 2. Increase in ultimate torque [1, 2]

Beam	Ultimate Torque Tu (KN.m)	Increase in Tu with R1	Increase in Tu with R2
B1	1.5525	R1	/
B2	2.415	/	R2
B3	5.365	245.5716586	122.1532091
B4	5.18	233.6553945	114.4927536
B5	5.18	233.6553945	114.4927536
B6	4.995	221.7391304	106.8322981
B7	4.81	209.8228663	99.17184265

3. CONSTRUCTION MATERIALS

3.1 Cement

Ordinary Portland cement (type I) used during this experimental work for concrete and mortar mix, produced by Lafarge company (Bazian), classified according to Iraqi Standard Specification No. 5 [17].

3.2 Fine aggregate

This study uses natural sand from the (Al-Akhaidher) region of Karbala, Iraq, for concrete and mortar mixtures. The fine Aggregate passed through a 4.75 mm sieve with rounded-shape particles and a smooth texture, with a fineness of 4.9% and a sulfate concentration of 0.37%.

According to the obtained results, the fine aggregate grading was zone 3 and within the limits of Iraqi Specification No. 4 [18].

3.3 Coarse aggregate

Crushed gravel with a maximum size of 20 mm obtained from Diyala's (AL-Sodour) region is used throughout this work. The results show that the coarse aggregate contains 0.002% finer than 0.075 mm of materials and 0.05% of sulfate content. The rough aggregate grading satisfies Iraqi Standard No. 4 [18].

3.4 Water

Regular tap water free from impurities and mud was used in casting and curing specimens [19].

3.5 Reinforcement

Iranian steel bars with 8 mm diameter were used in transverse and longitudinal reinforcement throughout this investigation. Table 3 shows the test result of steel bars' tensile strength, which conformed to ASTM A615-86 [20]. The test was carried out in the laboratory of the Civil Engineering Department at Al-Nahrain University, Baghdad, Iraq.

3.6 Plastic and steel wire mesh

A square grid wire mesh with a diameter of 0.72 mm and grid spacing for steel of 13 mm and 14 mm for plastic was taken from a roll width of 1200 mm and then cut into the desired shape to fit in the molds (refer to Figure 1).

Table 3. Reinforcement test results

Diameter of Bars (mm)	Yield Stress fy (MPa)	Ultimate Strength fu (MPa)	Elongation %
8	357.33	552.4	18.1

Figure 1. Plastic and steel chicken wire

Table 4. Concrete mix

Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	Superplasticizer (l/m^3)
300	850	1050	100	2

Table 5. Mortar mix

Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Superplasticizer (l/m^3)
648	1620	290	3

3.7 Add mixture

A superplasticizer, Hyperplast PC175 (high range water reducing admixture), was used in concrete and mortar mix from DCP Company Baghdad, Iraq. To achieve the highest concrete and mortar durability and performance and maintain the workability retention of fresh concrete and mortar mixes.

3.8 Bonding material

Epoxy resin bonding agent sikadur-32 LP was used during this experimental work to connect the old concrete with the new ferrocement layer. The bonding agent consisted of two parts: A: white color and B: black color mixed by a ratio of 2A:1B.

3.9 Concrete mix

For this research, the mix design was utilized to get a compressive strength of 30 MPa or higher in 28 days. The quantities of construction ingredients needed to make ready-mix concrete were prepared by Capital Gate Company and given in Table 4.

3.10 Mortar mix

Many trial mixes were conducted in mixed proportions to achieve a compressive strength for mortar of about 35 MPa after 28 days of curing. Cement: sand ratio was 1:2.5, and the water: cement ratio was 0.45. The materials quantities are listed in Table 5.

4. BEAMS PREPARATION

4.1 Wooden work

To cast the concrete beam specimens, seven rectangular molds, each measuring 2 meters in length and having a cross-section measuring 100 by 250 millimeters, were created. The molds were constructed using sheets of plywood with a thickness of 15 millimeters. The two molds were fastened together, and each mold's total number of components was four (base and three similar side parts). The base part was bolted to the three corresponding side portions.

4.2 Reinforcing work

Steel bars were cut and formed in the shape of longitudinal and transverse reinforcement according to design of beams and then placed inside the wooden molds. Beam reinforcement contained hooks to transfer them by crane.

4.3 Concrete casting

After the wooden and reinforcing work was completed, molds were cleaned and prepared for casting. Concrete materials were prepared by weight according to the quantities listed before; a rotary concrete mixer was used in mixing and pouring concrete. A vibrator was used during the casting operation to compact concrete and force the trapped air out of the mixture.

Prisms, cylinders, and cubes were cast to test hardened concrete properties.

4.4 Curing of specimens

After 48 hours of casting work, molds were removed from beams and control specimens. Beams were covered with thick fabric to keep the water after the hardening of specimens, then sprinkled with water during the curing period (28 days). Control specimens were submerged in a water tank to achieve the desired compressive strength.

5. BEAMS STRENGTHENING

5.1 Wooden work

Four plywood molds of size (150×275) mm cross-section and 2000 mm length were made for casting the strengthening layer of ferrocement from three sides, and one plywood mold of size (150×300) mm cross-section and 2000 mm length was used for jacketing the beam from all sides.

5.2 Roughening operation

The surface of the five beams was roughened by using a drill machine to increase adhesion between the old concrete and the new mortar.

5.3 Shear connectors placement

The center third of U-shaped reinforced beams were grooved with a drill machine to accommodate bolts measuring 7.5 cm in length (5 cm inside concrete and 2.5 cm inside mortar) and 1 cm in diameter. The spacing between bolts was constant at 15 cm c/c, varying distances from the beam's edge to the bolt's center on each side as shown in Figures 2 and 3. Sikadur-32LP epoxy resin binding material was utilized to insert bolts into the grooves.

5.4 Applying bonding material

Parts (2A+1B) were mixed for at least 3 minutes with a mixing spindle fitted to a slow-speed electric drill until the material was smooth and grey. It was mixed without air. The mixture was poured into a clean container and stirred for another minute at low speed. After mixing, a brush was used to apply the material on the surface of the beam. The casting operation started after four hours of epoxy resin application.

5.5 Wire mesh placing

To start the casting process, the beams were wrapped with wire mesh and placed inside the molds.

5.6 Casting of strengthening layer

After inserting the wrapped beams into the molds, mortar materials were manufactured by weight by the previously mentioned quantities; a rotary concrete mixer was utilized for mixing and pouring mortar. During the casting process, a vibrating machine was used to compact the mortar and drive out the trapped air. Cylinders and cubes were cast to evaluate the properties of hardened mortar.

5.7 Strengthening beams curing

Following 48 hours of casting, the beams and control specimen molds were removed. During the curing process (14 days), water was sprayed on beams coated with thick fabric to retain moisture after the specimens had hardened. Control specimens were submerged in a water tank.

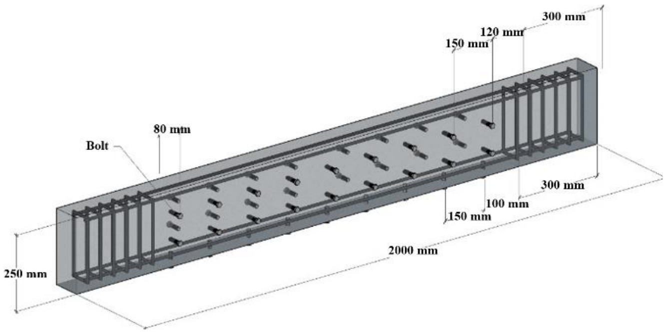

Figure 2. Side 1 and bottom bolts 3D design

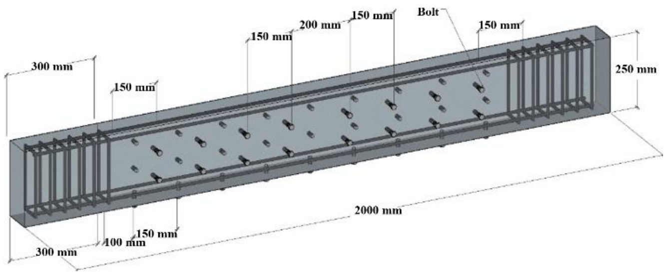

Figure 3. Side 2 and bottom bolts 3D design

Figure 4. Testing machine

5.8 Testing

Seven reinforced concrete beams are torsion-tested in the experiment. The ferrocement layer strengthened five samples. The civil engineering lab tested a 2000-KN device. To establish pure torsion, two arms (25 cm wide, 2.5 cm thick, and 39 cm long) were bolted to the ends of the sample to be tested. A 260-cm-long, 15-cm-wide girder follows.

To ensure even distribution of the load, it is positioned directly above the loading arms, as shown in Figure 4. Instead of using a dial gauge, the load arms on both the right and left sides are equipped with Linear Variable Differential Transformers (LVDTs).

6. TEST RESULTS

The test uses data on ultimate torsional capacity, cracking capacity, mode of failure, stiffness, and torsional moment versus angle of twist behavior to explain the behavior. All of the beams are tested until they attain their maximum torsional strength. The reference beam is designated as B1. Compared to the strengthened beams, the reference beam has less torsional capacity and a higher angle of twist. All seven beams are undergoing torsional moment testing, where the angle of twist was taken into consideration and recorded at each (5kN) load increase.

Table 6. Results of experimental work of beams

Beam	Crack Load Pcr (KN)	Ultimate Load Pu (KN)	Crack Torque Tcr (KN.m)	Ultimate Torque Tu (KN.m)	Tcr/Tu %
B1	6	9	1.035	1.5525	66.66667
B2	8	14	1.038	2.415	42.98137
B3	20.86	29	3.86	5.365	71.94781
B4	25.4	28	4.7	5.18	90.73359
B5	24.84	28	4.6	5.18	88.80309
B6	23.7	27	4.38	4.995	87.68769
B7	25.4	26	4.7	4.81	97.7131

6.1 Crack and ultimate torque

Table 6 shows that the reference beams (B1, B2) crack torque of about 66.6% and 42% of the ultimate torque, while strengthened beams vary from 71.9% to 90.7%.

6.2 Torque-angle of twist behavior

Figures 5-9 show the relationship between the angle of twist and torque for all beams (T-Diagram). These diagrams were made by calculating each beam's test run and inspection results. The curves are linear until the first fracture, then inelastic until failure as the twist angle rises.

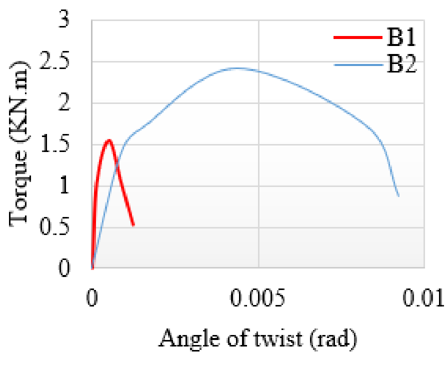

Figure 5. B1, B2 torque twist curve

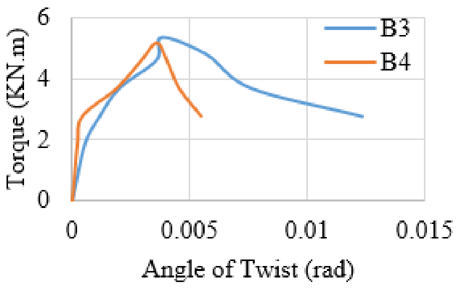

Figure 6. B3, B4 torque twist curve

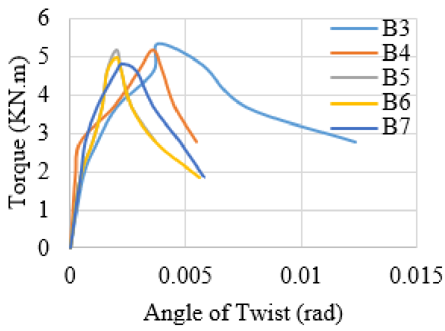

Figure 7. B3, B4, B5, B6, B7 torque twist curve

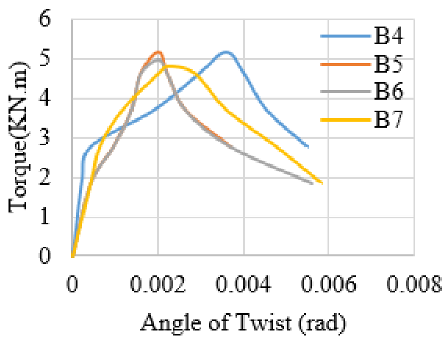

Figure 8. B4, B5, B6, B7 torque twist curve

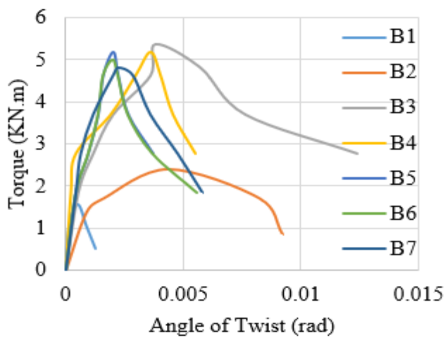

Figure 9. All beams torque twist curve

Table 7. Toughness and stiffness of beams

Beam	Tu	Toughness	Stiffness
B1	1.5525	1.3225	3113.3
B2	2.415	16.73	553.48
B3	5.365	45.55	1408
B4	5.18	36.81	1440
B5	5.18	30.25	2577.41
B6	4.995	30.78	2485.36
B7	4.81	19.4	2165.38

6.3 Toughness and stiffness

Torsional toughness is defined as the capacity to resist crack development. It could be considered a ductility indicator. Torsional toughness can also be considered a measure of energy absorption capability. The energy absorption capacity of tested beams was calculated using the area under the torque angle of the twist curve. The area under the curve of torque-angle twist by the Simpson rule was used to calculate the region bounded by the torque-angle twist curve.

For each beam, the application Microsoft Excel was used to find the area under the torque-angle twist.

Torsional stiffness is the torque required to twist an object by one radian. It is also known as the applied torque-to-twist angle ratio. It displays how much stiffer an object is to sustain a torsional load.

Rotational stiffness can be given by:

$K=\frac{m}{\theta}$

K: stiffness (KN.m/rad)

m: applied torque (KN.m)

θ: angle of twist (rad)

Beams' toughness and stiffness can be represented in Table 7.

6.4 Mechanism of failure

The progression of cracks revealed important information on the failure mechanism of studied specimens. It was discovered that all of the tested beams failed in torsion. The first crack in all specimens occurred in the weaker zone and subsequently increased. As the torque moment increased, cracks developed on each side, forming a spiral shape. The failure mechanisms for the tested beams are depicted in Figures 10 to 16. Due to significant diagonal concrete cracks (torsional spiral cracks), all beams failed.

Figure 10. Beam B1 mode of failure

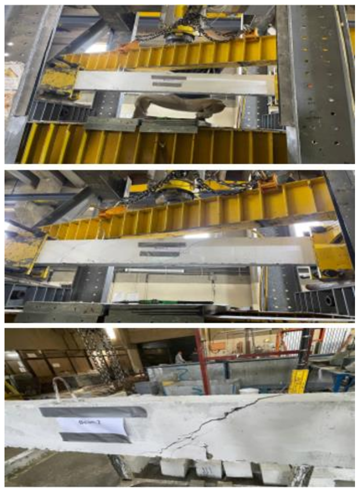

Figure 11. Beam B2 mode of failure

Figure 12. Beam B3 mode of failure

Figure 13. Beam B4 mode of failure

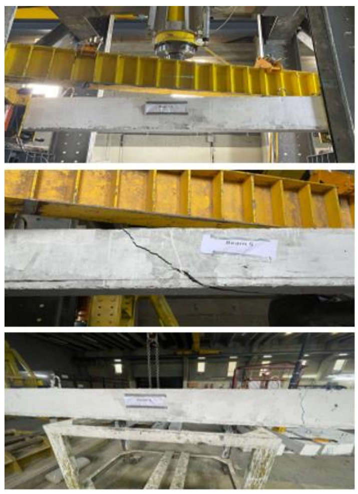

Figure 14. Beam B5 mode of failure

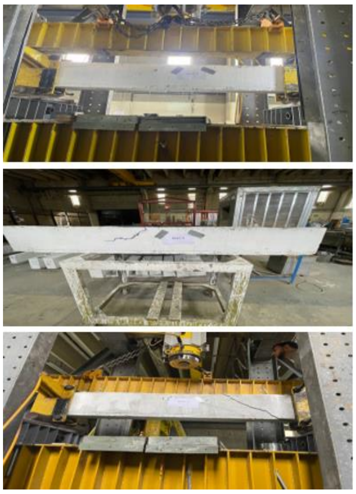

Figure 15. Beam B6 mode of failure

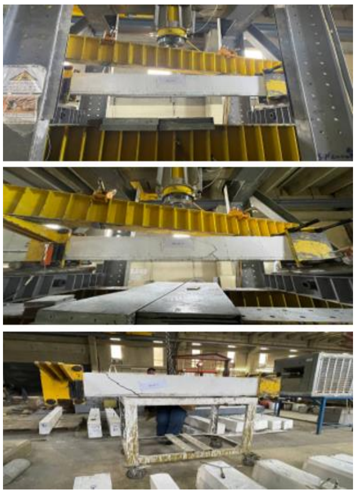

Figure 16. Beam B7 mode of failure

Beam B1, serving as the reference beam with neither torsional reinforcement nor strengthening, failed due to a single, wide potential crack located at the middle of the span. In contrast, Beam B2, which included torsional reinforcement, exhibited multiple thin, branched cracks upon failure.

The strengthened beams (B3, B4, B5, B6, B7) cracks cannot be observed because they appear first on the inner surface of the concrete and extend to the outside surface of the concrete.

7. CONCLUSION

All specimens that were strengthened with ferrocement showed improved torsional performance in RC compared to plain beams.

Variations in the layers of steel and plastic wire mesh did not significantly impact the torsional capacity.

Beams that were reinforced on all four sides demonstrated better performance than those reinforced on three sides, as evidenced by the torque-twist responses shown in Figure 6 for beams B3 and B4.

There was an observed increase in ultimate torque, ranging from 99% to 122%, for beams strengthened with ferrocement but lacking torsional reinforcement, compared to reference beams that were torsionally reinforced.

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