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Energy Absorption Evaluation of CFRP-Strengthened Two-Spans Reinforced Concrete Beams under Pure Torsion

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Abstract

For more than a decade, externally bonded carbon fiber reinforced polymer (CFRP) composites successfully utilized in retrofitting reinforced concrete structural elements. The function of CFRP reinforcement in increasing the ductility of reinforced concrete (RC) beam is essential in such members. Flexural and shear behaviors, ductility, and confinement were the main studied properties that used the CFRP as a strengthening material. However, limited attention has been paid to investigate the energy absorption of torsion strengthening of concrete members, especially two-span concrete beams. Hence, the target of this work is to investigate the effectiveness of CFRP-strengthening technique with regard to energy absorption of two-span RC beams subjected to pure torsion. The experimental program comprises the investigation of two groups; the first group comprises eight un-strengthened beam specimens, while the second group consists of eight strengthened beam specimens tested under torsional forces. The energy absorption capacity measured from the area under the curve of torque-angle of twist for tested beams. Two parameters were studied, the influence of concrete compressive strength and the angle of a twist. Experimental results indicated that all beams wrapped with CFRP sheet display superior torsional energy absorption capacity compared to the control specimens. The energy absorption may consider as a safety index for the torsional capacity of two-span RC beams under service loadings. Therefore, it is possible to avoid structural as well as material damages by understanding the concept of energy absorption that is one of the important experimental findings presented in this study.

Keywords: Two-span Beams; Reinforced Concrete; Torsional Strengthening; CFRP Fabrics; Energy Absorption; Ductility.

1. Introduction

Torsional moments can be developed in many RC members significantly. Bridge elements, horizontally curved members, eccentrically loaded beams and spandrel beams are subjected to torque. Therefore, there is a need for increasing the torsional capacity of such structural members to carry additional load, as well as, avoid structural damage [1].

The ductility of RC members can be described as the ability to withstand plastic deformation without loss in load carrying capacity before failure. In principles, the mechanical energy of the RC element transformed into potential energy. However, this is an indication of inherent ductility acts together with energy absorption of such structures [2,

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3]. Furthermore, the ductility may consider as a suitable parameter for evaluating the flexural behaviour of reinforced concrete beams [4].

In structural design, studying the ductility alone is insufficient to maintain the safety of structures subjected to unexpected or environmental loads. Similarly, to ductility and structural strength, the energy absorption can be considered indicative of structural integrity; energy absorption is also considered to maintain the unity of the system when subjected to unusual physical loads. Multiple complex processes comprise the energy absorption of the RC elements. In fracture mechanics, cracks initiation, cracks propagation and elastic so as plastic deformation are an index for energy absorption process [5-8]. The energy absorption capacity can be calculated as the area under the twist-moment curve. Although, the energy absorption capacity is the level of flexural performance after concrete cracking occurs [9]. Although, different parameters can affect the energy absorption values, such as concrete compressive strength and steel reinforcement ratios. In addition to the research conducted on the energy absorption of unstrengthened simply supported RC beams, limited research has investigated the energy absorption of two-span RC beams upgraded by CFRP fabrics and especially two-span RC beams.

Fiber Reinforced Polymers (FRP) may be carbon, glass, or any synthetic fibers. Considerable advantages gained from retrofitting structural members by FRP. This was attained from the extremely good properties of FRP especially the high tensile strength; corrosion resistance is achievable and superior fatigue behavior [10-12]. Fiber reinforced polymer composites, when externally bonded onto concrete structures, effectively improve the structural performance in terms of load-carrying capacity, flexural stiffness, corrosion resistance and ductility [13]. Over and above these excellent properties, FRP sheet can be installed without difficulty, efforts, and specialized equipment in the site. Researchers studying the upgrading of torsional members by FRP materials are insufficient; however, data so as design procedures are available widely in literature [14, 15]. The increase in attention of the use of FRP composites for the strengthening the RC structures subjected to excessive torsional forces is directed in this study.

Torsional strengthening using FRP has received less attention [16-18]. Retrofitting structures with FRP composites enhanced the flexural, shear, and torsional load carrying capacity, besides, to control the failure mode so as failure planes [19]. It is rarely able to fully wrap the RC beams by FRP composites in practical view. This is due to the occurrence of either a floor slab or beams flange which may prevent completely the wrapping process. Even though numerous researches examine the strengthening of RC members fully wrapped by the FRP, yet few studies focused on retrofitting of RC T-beams by 3-sided wrapping with FRP "U-jackets" [20, 22]. In addition, the latest researches on single-span RC beams clarified that the primary deformation of the upgraded beams subjected to torsion is same as to unstrengthened beams, yet, the externally bonded FRP prevents or limits the crack initiation, extending, widening and spacing in-between [21, 22]. Fully wrapping of RC elements by FRP sheets was found in previous researches on torsion retrofitting is much more effective in producing the required result than using spaced strips [23-26]. Moreover, spiral wrapping at 45° is more efficient than the 90° wrapping [25, 26]. Furthermore, RC beams strengthened by full wrap arrangement have ultimate strength higher than that for RC beam strengthened by 3-sided wrapping [20, 25]. Additionally, mechanical anchoring FRP composites increased the torsion strength substantially [20].

Hii and Al-Mahaidi carried out experimental tests on torsional strengthening and reported a 40% cracking torque increase and angle of twist for ultimate torque strength [11]. Ameli et al. showed that whereas CFRP sheets fail soon after peak torque capacity, glass fiber reinforced polymer (GFRP) can go for a more extended period thus providing more energy absorption capacity. This enhanced post-peak behavior is more suitable for earthquake-related applications. Research on FRP strengthening shows an important increase in post-cracking strength, besides the ultimate load-bearing capacity, can be achieved under flexural and shear loads [21].

A wide range of researches studied the upgrading of RC beams with CFRP sheets bonded externally and subjected to shear, bending or both. However, there are still many questions concerning the energy absorption of RC beams strengthened in torsion using CFRP sheets, especially for RC two-equal span beams. Thus, this research aims to study the energy absorption capacity of continuous RC beams with different angles of a twist. This article presents the behavior of RC beams fully bonded by CFRP sheets and subjected to torsion. Eight unstrengthened two-span RC beams and eight retrofitted two-span RC beams by CFRP fabrics were utilized to investigate the behavior of continuous RC beams subjected to torsional forces. The results displayed that there is a significant improvement in energy absorption of upgraded beams by CFRP compared to the unstrengthened control beams.

2. The Significance of the Present Investigation

Although extensive studies have been performed on the behavior of RC structures, calculating the energy absorption of such structures with CFRP-strengthening remains the challenge to understand especially for two-span RC concrete beams. Thus, this research focuses on the torsional behavior of continuous RC beams strengthened with CFRP sheets.

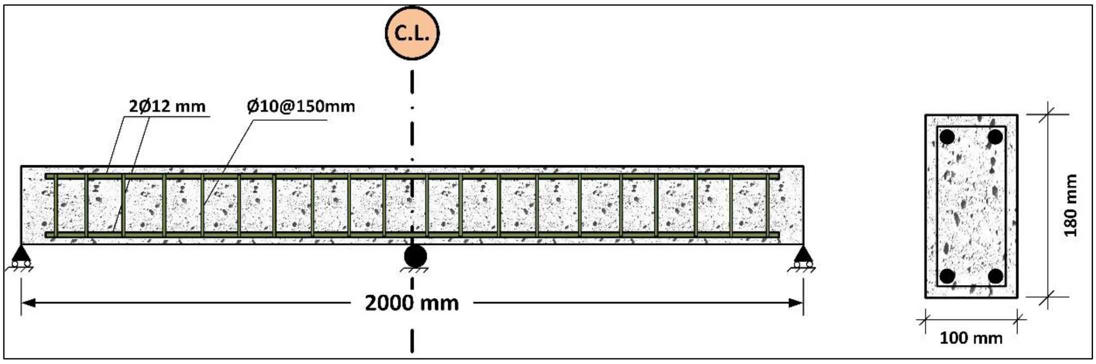
3. Methodology

The study conducted on rectangular beams specimens subdivided into four groups. Two variables were studied, the compressive strength of concrete and angles of twist in relevant to beams strengthening status. Both flexural and shear reinforcements were identical in all studied specimens. All tested RC continuous beams subjected to pure torsion; hence, no effect of shear force and the bending moment has been considered.

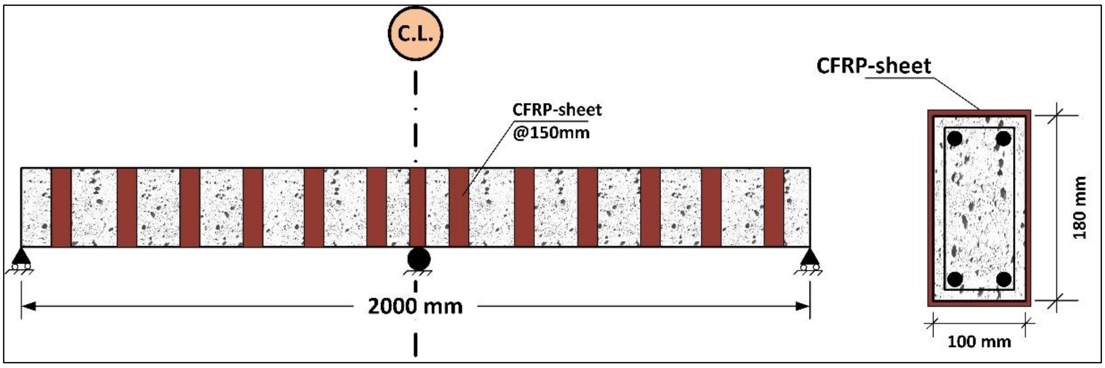
4. Experimental Program

4.1. Specimen Details and Material Characteristics

A total of Sixteen RC two equal spans of rectangular beams specimens tested and evaluated in this study. Eight two-spans RC beams unstrengthened and eight upgraded by CFRP fabrics before testing and subjected to torsional forces. The length of each span was 1000mm and the cross-section of 180mm depth and 100mm width. Four steel bars have 12mm diameter were used as flexural reinforcement, while for the web reinforcement 10mm diameter utilized. Figure 1 illustrates the dimensions of both unstrengthened beams and upgraded beams by CFRP fabrics; furthermore, the arrangements of CFRP fabrics also displayed. RC beams designation system shown in Figure 2, which considers the concrete compressive strength and applied different eccentricities.



(a) Unstrengthened Beam



(b) Strengthened Beam

Figure 1. Testing Beam Specimens (a) Unstrengthened Beam (b) Strengthened Beam

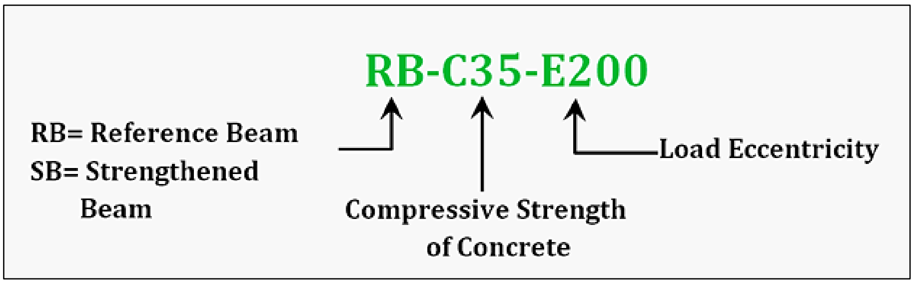


Figure 2. Beams Designation System for the Tested Specimens

For the case of longitudinal reinforcement, steel ratio of 0.12 was used for all the specimens. Two grades of concrete with a specified compressive strength of 35 MPa and 55 MPa was designed, yet concrete mixture proportions are given in Table 1. The concrete compressive strength determined with the aid of concrete cylinders (height of the cylinder 300mm and its diameter is 150mm). The mechanical properties of steel reinforcements were determined following standard tests. The yield strengths of longitudinal so as shear reinforcements were determined experimentally and found to become 510 and 455MPa, respectively.

Table 1. Concrete mix proportions

Parameter	35 MPa	55 MPa
W/C ratio	0.41	0.36
Water, kg/m^3	165	190
Cement, kg/m^3	400	525
Sand, kg/m^3	485	840
Gravel, kg/m^3	980	875
Super-plasticizer, L/m^3	NA	6 liters

The carbon fiber used in this research was made by Sika Group with the trade name "SikaWrap-300C". The CFRP sheet has a unidirectional fibers orientation, and each ply has a thickness of 0.167 mm (based on fibers content). CFRP sheets have an area weight of 304 g/m2 ±10 g/m2 (carbon fibers only). The bonding adhesive also supplied from the same company has a trade name of "Sikadur-330" and used as a bonding agent for dry application of CFRP sheets. The epoxy resin has two components (A & B). The mixing proportion of those components is 4:1 with a pot life of 60 min. The physical properties of these materials were provided by the manufacturer and summarized in Table 2.

CFRP upgrading activity for eight beams specimens was done after 28 days from beam casting. Per manufacturer recommendations according to ambient temperature, a curing time of a minimum seven days was required for CFRP upgrading. CFRP strips with a spacing of 150mm centre-to-centre along the spans bonded to the substrate concrete. Minimum longitudinal overlapping of CFRP strips of 50mm was applied in the beam completely wrapping direction.

Table 2. Physical properties of strengthening components

CFRP Fabrics				Epoxy Resin			
Ultimate rupture, MPa	Elastic modulus, MPa	Ultimate strain, %	Thickness (mm/ply)	Flexural strength (7days), MPa	Ultimate tensile (7days), MPa	Tensile elastic modulus (7days), MPa	Maximum elongation at rupture (7days), %
4000	230000	1.7	0.167	60.6	33.8	3489	1.2

4.2. Instrumentation and Testing

Torque was applied on different eccentricities by means of two external arms attached to both ends as presented in Figure 3. Test done using accurately calibrated hydraulic actuator with a 2000 kN capacity. Additionally, Load cells were fixed under the actuator to measure applied torque. Analog indicators with an accuracy of 0.01mm were used to determine the vertical displacement and hence the angle of twist as shown in Figure 4. The used supports allowed the rotation about the longitudinal axis. Additionally, external arms were connected to the specimen to apply eccentric loading. Therefore, pure torsion condition was achieved as the position of external connected arms coincides with the end supports of the two-span beams. The application of loading at different eccentricities on beams specimen, according to the aforementioned conditions, produced different torsional moments. Representation drawing of the testing setup is presented in Figure 4. Loading by hydraulic jack was transferred to the RC two-span beams through I-beam loaded at its mid-length and positioned at the externally connected arms over end supports.

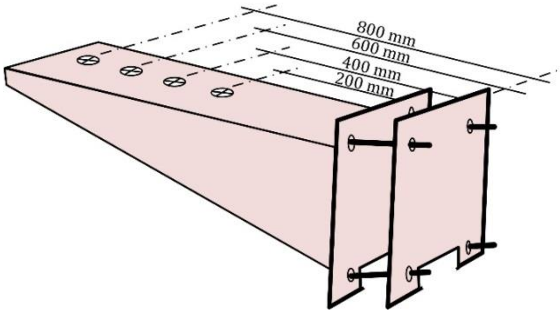


Figure 3. Torsional Load Application Aram for Different Eccentricities

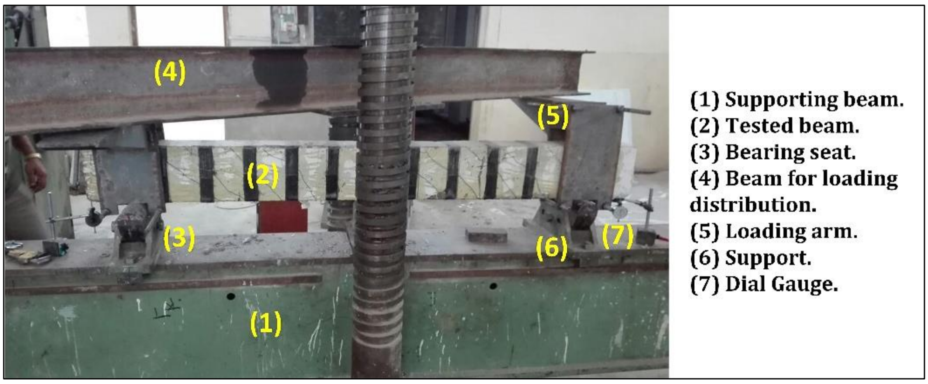


Figure 4. Experimental Test Setup for Two-Span Beam Specimens

5. Results and Discussions

Sixteen two-span RC beams were tested under only torsional loads in order to study the effect of selected parameters. Half of the samples were unstrengthened RC beams. Test outcomes discussed in this section based on torque against longitudinal twisting behavior. The contribution of upgrading RC beams by CFRP strips on resistance the applied torque, at different stages, are summarized in Table 3.

Table 3. Loading stages, concrete strength, and twist angle test results

Group No.	Beam Specimen	Compressive Strength, MPa	Eccentricity mm	Cracking Load kN	Ultimate Load kN	Angle of twist degree
G I	RB-C35-E200	35	200	63.5	79	7.31
	RB-C35-E400	35	400	43	60.5	8.42
	RB-C35-E600	35	600	31	44	9.88
	RB-C35-E800	35	800	13	31.5	11.84
G Π	SB-C35-E200	35	200	69	83	6.92
	SB-C35-E400	35	400	50	63	8.2
	SB-C35-E600	35	600	40	48	9.1
	SB-C35-E800	35	800	18	36	10.76
G III	RB-C55-E200	55	200	82	102	6.45
	RB-C55-E400	55	400	67	86	7.85
	RB-C55-E600	55	600	54	72	9.2
	RB-C55-E800	55	800	38	51	10.65
G IV	SB-C55-E200	55	200	105	119	4.85
	SB-C55-E400	55	400	87	101	5.68
	SB-C55-E600	55	600	72	84	7.43
	SB-C55-E800	55	800	53	64	9.35

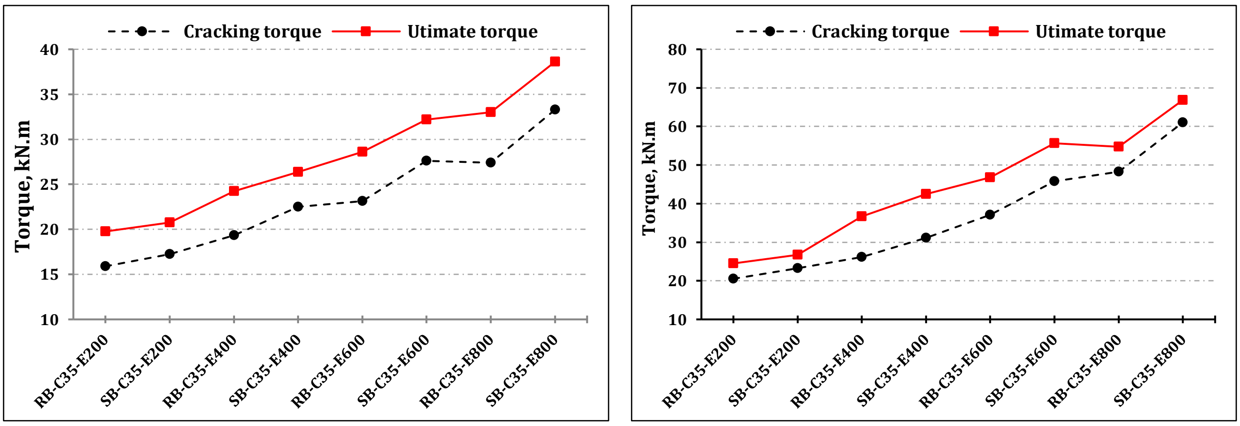
5.1. Failure of Specimens

Failure modes of strengthened RC two equal spans of beam specimens tested under torsional loads are presented in Figure 5. In unstrengthened beams, vertical cracks initiated at the middle of the vertical faces. Furthermore, inclined cracks were generated and propagated. As the applied loading increased, the cracks became wider at both of the spans with clearly observed opposite rotating at both ends and about the centroidal axis of RC beam. The failures of upgraded beams with CFRP strips were somehow slower than the control beams. Moreover, the failure of CFRP observed by debonding of CFRP fabrics.

Figure 5. Failure Modes of Strengthened RC Two-Spans Beams Under Torsional Forces

5.2. Cracking and Ultimate Torque Comparison

First crack torque and ultimate torque for unstrengthened beam specimens and retrofitted beams by CFRP strips tested in torsion for test specimen with compressive strength 35MPa are shown in Figure 6. For tested beams specimens in group (G II) with an eccentric loading of 200mm , 400 mm , 600mm, and 800mm, a maximum exhibited increase in cracking torsional strength of (8.6%, 16.2%, 19.2%, 21.5%) and maximum exhibited increase in ultimate torque of (5%, 8.5%, 12.5%, 16.9%) among all strengthened beams in comparison with group (G I), respectively. Furthermore for tested specimens with concrete compressive strength of 55 MPa, groups (G III) and (G IV), there are increased in cracking torsional strength of (13.4%, 19.1%, 23.4%, 26.3%) while an increase in ultimate torsional strength of (9.2%,15.7%, 18.8%, 22.1%) for group (G IV) for the same aforementioned eccentricities arrangements as shown in Figure 6. Accordingly, derived conclusion that the torsional RC beams wrapped with CFRP sheets displayed a significant increase in their cracking and ultimate strength. Generally, it were concluded that completely wrapping RC two-spans beams with CFRP sheets improved the cracking and ultimate torsional resistance by up to 26.3% and 22.1%; respectively.



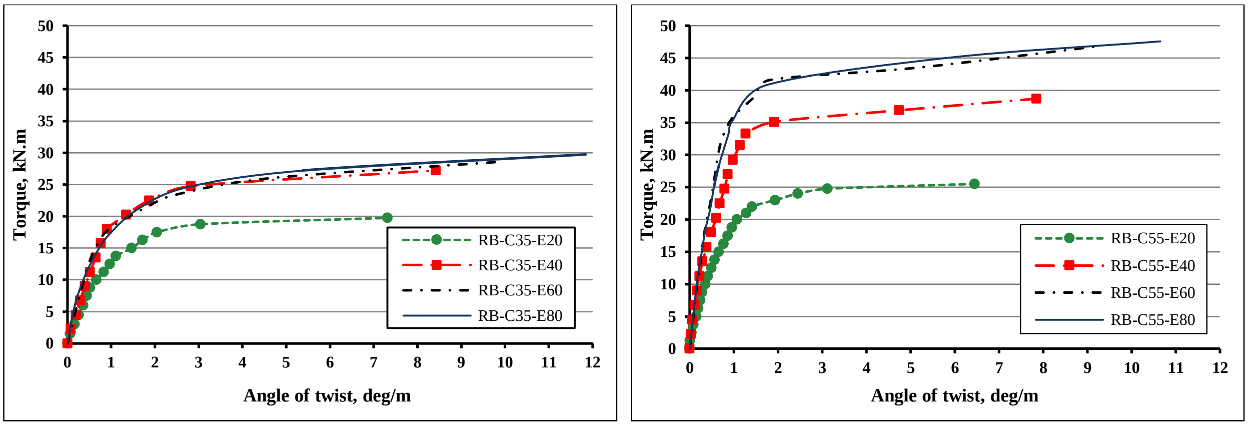
(a) C = 35MPa (b) C = 55MPa

Figure 6. Cracking and Ultimate Torques for Tested Beams

5.3. Torque-Twist Comparison

5.3.1. Unstrengthened RC Concrete Beams

Eight unstrengthened control beam specimens with different load eccentricities (200, 400, 600 and 800mm) were evaluated in this subsection. The torque vs. angle of twist behavior of unstrengthened beams tested under torsion is presented in Figure 7. The tested beams exhibited similar behavior for both torsion and twist angle. Specimens RB-C35-E800 and RB-C55-E800 displayed better ductility compared to other specimens. On the contrary, the least angle of twist is observed from specimens RB-C35-E200 and RB-C55-E200. For different concrete compressive strength, test results exhibited significant increment in torsional strength of specimens for all loading eccentricity. The ultimate torsional strength increased by approximately 44% and 83% for 35 and 55 MPa. Moreover, the angle of twist increased by 62% and 65% for the different studied concrete compressive strength.

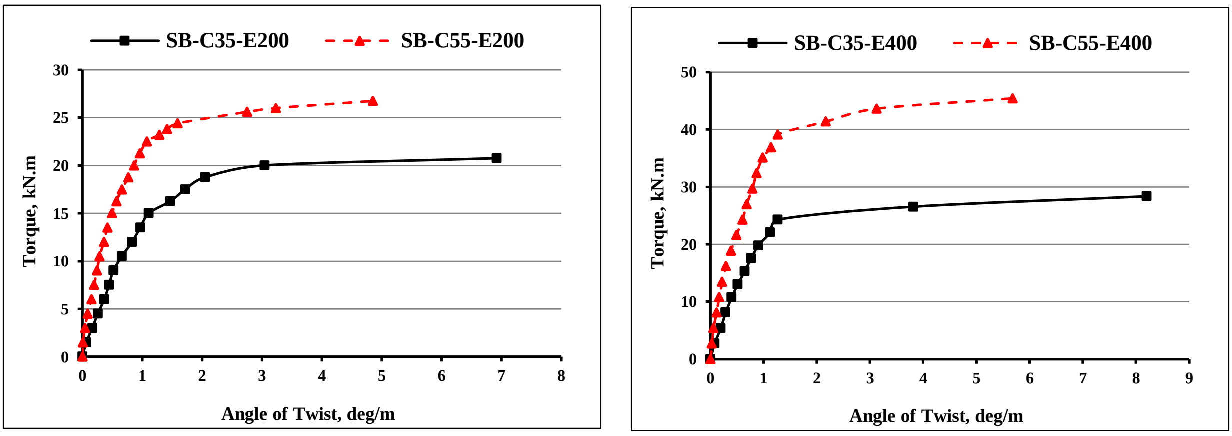


(a) C = 35MPa (b) C = 55MPa

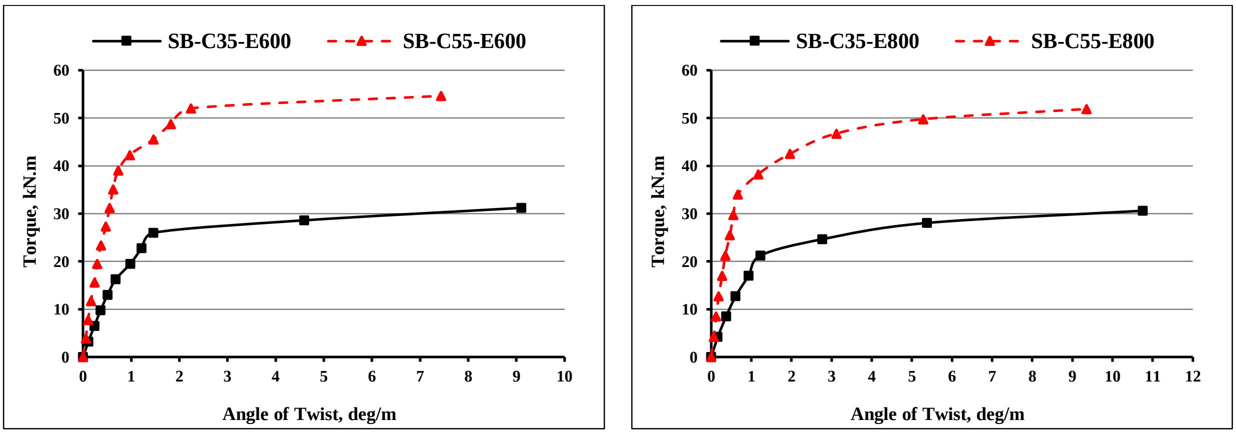
Figure 7. Torsional Strength of Unstrengthened RC Beams under Different Loading Eccentricities

5.3.2. Strengthened RC Concrete Beams with CFRP Fabrics

Comparison of the torque-twist behavior of CFRP-strengthened tested specimens based on the grades of concrete are presented in Figure 8. All tested beams behave similarly for torque and twist angle. SB-C35-E800 and SB-C55-E800 reveal better ductility compared to other specimens. For different concrete compressive strength, the results showed considerable increment in torque of specimens for all the eccentricities. The ultimate torque capacity increased by approximately (31% and 54%) for 35 and 55 MPa, respectively. Moreover, the angle of twist increased (10.76% and 9.35%) for the studied concrete grades.



(a) Eccentricity E=200 mm (b) Eccentricity E=400 mm

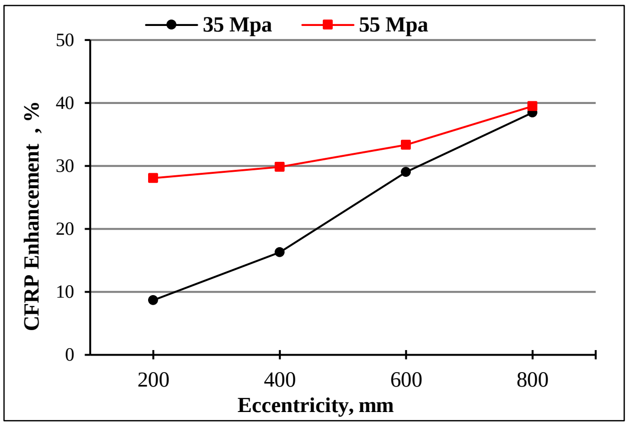


(c) Eccentricity E=600 mm (d) Eccentricity E=800 mm

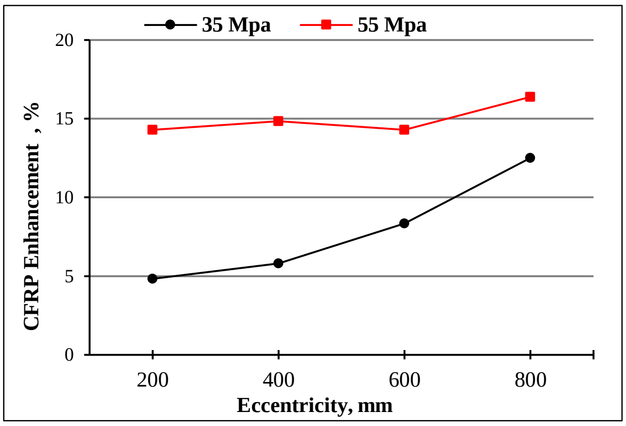
Figure 8. Torsional Behaviour of CFRP-Strengthened RC Beam Specimens with Different Compressive Strength

5.3.3. Comparison between Unstrengthened and CFRP-strengthened Concrete Beams

All the specimens completely wrapped with CFRP showed enhancement in torque resistance compared to the unstrengthened RC two-spans beam specimens. Figure 9 describes the results which showed that the cracking torque capacity increased by a range of (8%-38%) and (28%-39%) for 35 MPa and 55 MPa concrete strength, respectively. Moreover, the ultimate torque capacity enhanced by (5% -12%) and (14%-16%) for both studied concrete compressive strength.



(a) CFRP Enhancement for Cracking Torque



(b) CFRP Enhancement for Ultimate Torque

Figure 9. Enhancement of CFRP Fabrics for; (a) Cracking, (b) Ultimate Torsional Strength

6. The Ductility and Energy Absorption

The intrinsic nature of RC members is the conversion of mechanical energy into the internal potential energy which is due to the inherent ductility and energy absorption of those members. Absorbing energy by concrete members involves complicated processes such as including the fracture mechanics corresponding to cracking of concrete in additional to elastic and plastic deformations [27].

Considerable studies have shown a proportionate correlation for energy absorption and the ductility of RC members. In this study, the areas under energy absorption curve were computed using Simpson's rule for all RC two-beams. The ductility ratio (μ_ϕ) is usually defined as the ratio of the angle of twist corresponding to ultimate torque to the angle of twist corresponds to yield torque as in the following equation:

$$\mu_\emptyset = \frac{\mu_P}{\mu_Y} \quad (1)$$

Where (μ_P) and (μ_Y) are the angle of twist at both ultimate and yield torque, respectively. This ratio represents the amount of energy that a member can absorb during when undergoing plastic deformations and so represents the ductility as well as energy absorbing capacity of the RC elements. In accordance with this concept for ductility, the adoption for strengthened RC members may be utilized in similar manner.

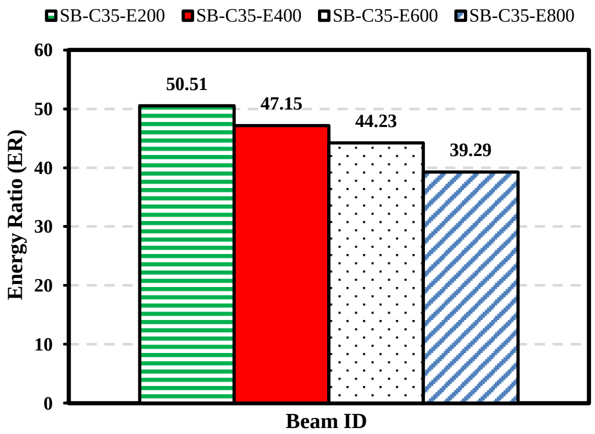
The ductility of the upgraded RC beams with CFRP sheets was also enhanced. According to the experimental observations, bonded CFRP sheets lead to an increase in ultimate torque capacity and ductility of the upgraded beams compared with the unstrengthened RC specimen. In Table 4, the ductility ratios for all beam specimens are presented. The maximum ductility ratios by both unstrengthened and strengthened beams are exhibited by RB-C35-E800 and SB-C35-E800 with values of 7.26 and 11.55, respectively. These values show an enhancement of in ductility index of (12.89% - 70.40%) for strengthened beams of group GII compared with group GI for the same grade of concrete (35 MPa). Similarly, for group GIV, the contribution of strengthening fabrics enhanced the ductility index within a range of (11.77% - 40.90%) compared with group GIII for the same grade of concrete (55 MPa). Therefore, a conclusion was highlighted, beams with higher concrete strength exhibited less ductility than beams with lower compressive strength. This is reflected from that fact that the higher concrete strength, the higher brittleness tendency.

Generally, the energy absorption in CFRP upgraded beams was much more than that for beams without strengthening. This was due to the ability of the CFRP fabrics to prevent the growth of the cracks. The increases in cracking and ultimate loads were observed to be adversely affected by eccentricity. In pure torsion, the maximum increase in cracking loads was noted. Post-cracking energy deformation and energy absorption capacity of the CFRP strips were more than in the reference beams.

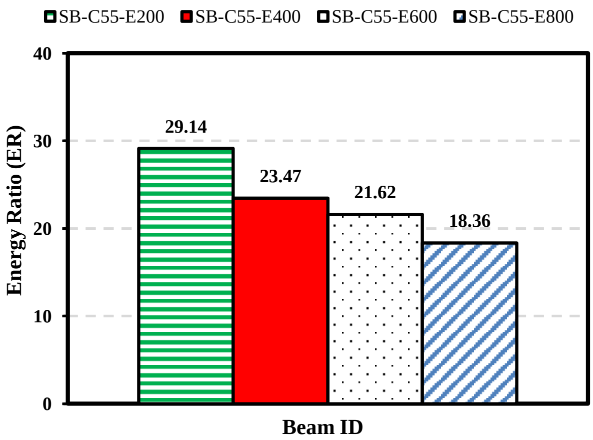
Experimental results displayed that the development of energy absorption capacity corresponding to the RC beams externally bonded with CFRP sheets is higher than those of unstrengthened beams. The development of energy absorption capacity ranged from 39.29% to 50.51% for CFRP-strengthened beams with 35 MPa concrete compressive strength while the development ranged from 18.36% to 29.14% were found for CFRP-strengthened beams with 55 MPa concrete compressive strength as illustrated in Figure 10. However, the governing mode of failure was debonding of CFRP strips. Furthermore, CFRP strips provided stronger post-cracking stiffness and better confinement, which increased ultimate torque.

Table 4. Comparison of ductility ratios for tested specimens

Group No.	Beam Specimen	Angle of twist, degree/m	Torque kN.m	Ductility ratio	Ductility increasing, (%)
G I	RB-C35-E200	7.31	19.75	3.57	-
	RB-C35-E400	8.42	27.23	4.51	-
	RB-C35-E600	9.88	28.65	5.44	-
	RB-C35-E800	11.84	29.75	7.26	-
G II	SB-C35-E200	6.92	20.75	4.03	12.89
	SB-C35-E400	8.24	26.35	7.29	61.64
	SB-C35-E600	9.13	32.24	9.27	70.40
	SB-C35-E800	10.76	38.63	11.55	59.31
G III	RB-C55-E200	6.45	24.52	3.33	-
	RB-C55-E400	7.85	36.70	4.11	-
	RB-C55-E600	9.24	46.84	5.09	-
	RB-C55-E800	10.65	54.75	6.17	-
G IV	SB-C55-E200	4.85	26.75	3.72	11.77
	SB-C55-E400	5.68	42.45	5.79	40.90
	SB-C55-E600	7.43	55.62	6.97	36.77
	SB-C55-E800	9.35	66.85	7.98	29.29



(a) Groups G I & G II



(b) Groups G III & G IV

Figure 10. Effect of Eccentricity and Concrete Compressive Strengthened Beams

Table 5. Energy absorption capacity and energy ratios for beam specimens

Specimens Groups	Beam ID	Energy absorption	Energy ratio (ER)
G I	RB-C35-E200	14.02	-
	RB-C35-E400	15.68	-
	RB-C35-E600	30.95	-
	RB-C35-E800	103.86	-
G II	SB-C35-E200	21.1	50.51%
	SB-C35-E400	23.07	47.15%
	SB-C35-E600	44.64	44.23%
	SB-C35-E800	144.67	39.29%
G III	RB-C55-E200	21.86	-
	RB-C55-E400	29.44	-
	RB-C55-E600	54.76	-
	RB-C55-E800	142.95	-
G IV	SB-C55-E200	28.23	29.14%
	SB-C55-E400	36.35	23.47%
	SB-C55-E600	66.6	21.62%
	SB-C55-E800	169.2	18.36%

7. Conclusions

An experimental program comprised sixteen concrete tow equal span beams was conducted to investigate the energy absorption of CFRP-strengthened two equal spans of concrete beams under pure torque using various eccentricities values. Based on the results obtained from the experimental work, the following conclusions are reported.

- Retrofitting with epoxy-bonded CFRP strips is a feasible strengthening technique for two-span beams under torsion.
- The results showed an increase in the ultimate torque capacity, by approximately (16.9 and 22.1) % for 35 and 55 MPa concrete compressive strength; respectively. Moreover, a considerable increase in the angle of twist about (62 and 65) % for the different concrete compressive strength.
- Failure of wrapped beams by CFRP strips delayed relative to the failure of the control specimens as the fabrics prevented cracking at initial stages. However, torsional diagonal cracks eventually appeared and widened in the unwrapped part of the beams, while fibers debonding were noticed for some specimens.
- All the tested beams showed similar behavior, under loading, for torque -twist angle relation. Unstrengthened specimens (RB-C35-E800 and RB-C55-E800) and strengthened beams (SB-C35-E200 and SB-C55-E200) displayed better ductility compared to other specimens.
- For 35 MPa concrete strength RC 2-span beams, the CFRP-strengthened beams exhibited a considerable increase in energy absorption capacity ranged (39.29–50.51) % than unstrengthened beams for a similar grade of concrete.
- The growth of energy absorption for strengthened specimens with 55 MPa concrete strength was increased by (18.36–29.14) % compared with unstrengthened beams have the same concrete grade.
- Once the energy absorption capacity has been calculated using the presented method in this study, the structural safety under severe loads may be judged through comparing the applied external energy imparted by loadings and the beams energy absorption capacity.

8. Acknowledgements

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9. Conflicts of Interest

The authors declare no conflict of interest.

10. References

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