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Torsion Improvement of Reinforced Self-Compacting Concrete Beams Using Epoxy Injection and CFRP

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Abstract

Few researchers have investigated the internal torsional reinforcement of box beams, So, this study aims to find out the possibility of adding a certain percentage of RCA to the NC mixtures, as well as verifying the success achieved in repairing the cracks that occurred as a result of torsion with CFRP or injecting with epoxy, which has not been addressed in previous research and literature reviews. This study reinforces reinforced SCC box beams subjected to complete torsion with CFRP sheets and epoxy resin injections. Four types SCC specimens (the first beam with 0%, the second beams with 33.3%, the third beams with 67.7%, and the fourth beams with 100% RCA by weight) were subjected to pure torsion until failure. The dimensions and reinforcement of every specimen are identical. In addition, the applied torque-twist angle relationship at the midspan and end span was investigated. Bending experiments were performed to establish load-deflection curves and assess failure modes. After structural rehabilitation, all beams exhibited increased rigidity values, according to the results. Epoxy resin and CFRP sheet contributed to the specimens' increased ultimate load. The ultimate strength of RCA beams strengthened with CFRP and injected with epoxy increased. The specimens' flexural strength was considerably enhanced by the combination of surface roughness and fracture injection, and the effectiveness of using RCA was very good; it could be replaced with NCA in concrete mixtures, according to the ratio and need.

Keywords: Reinforced Concrete; Carbon Fiber Reinforced Plastic; Self-Compacting Concrete; Natural Coarse Aggregate; Recycled Coarse Aggregate; Cracking Torque; Ultimate Torque; Cracking Load; Ultimate Load.

1. Introduction

Reinforced concrete (RC) constructions are designed to withstand bending loads under tension and compression. Concrete can only withstand tension between 1/10 and 1/14 of its compressive strength; hence, cracking is inevitable. Apart from tensile cracks, drying shrinkage can break concrete. Damage from corrosion, ASR, or overload can create excessive concrete cracking, affecting serviceability. Cracks can be divided into three distinct categories: those that result from deficient structural performance, those that result from inadequate material performance, and those that are acceptable [1]. Overloading causes structural fractures, shrinkage, and chemical reactions that cause material cracks, and service level loading causes acceptable cracks that distribute tensile stresses along the material [1]. A crack in a structural part can either be dormant or active, depending on the state it is in. Dormant cracks, on the other hand, can be successfully mended, in contrast to active cracks such as those caused by foundation settlement, which cannot be fixed completely.

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Crack repair technologies have been in use for a considerable amount of time. Cementitious and polymer compounds are by far the most frequently used materials for crack repair. Epoxy injection and grouting are the two methods used most frequently. Any material or procedure for repairing cracks must, by ACI 224.1R-93 [2], not only address the source of the crack but also fix the crack itself. This is one of the requirements for passing the test. Epoxy resins are extensively used repair materials with extremely strong bonding and durability qualities. This is according to ACI 546R-96 [3], which states that epoxy resins. According to Calder and Thompson, epoxy resin injection-repaired RC slabs outperformed polyester and methyl methacrylate resins [4]. This study found that broken slabs had 25% of the rigidity of uncracked slabs, whereas repairs restored half. Minoru et al. [5] Explain that a good concrete-injection material connection restores stiffness and prevents chloride ions and water from entering. Dry and clean the crack before injecting. Epoxy injection is impossible if cracks leak or cannot be dried without moisture-tolerant epoxies flushing the fracture surfaces.

Carbon fiber-reinforced plastics are a new way of fixing and fixing up RC systems. These materials have gotten a lot of attention and are being used more and more to fix and improve buildings. Carbon fiber-reinforced plastic (CFRP) fabrics are strong for their weight and have a high stiffness-to-weight ratio [6]. Since CFRP is strengthened by sticking it to RC beams to add flexural and shear reinforcement, the technique's reliability depends heavily on how well the beams join. This study looked at the effects of stress and environmental conditions on epoxy injection with and without bound textiles, as long as all the work materials had a certain amount of recycled aggregates. ACI 440.2R-02 [6] states that cracks wider than 0.25 mm (0.01 in.) can move and delaminate or crush fibers, affecting externally bonded FRP system performance. Resin injection may increase durability and delay steel reinforcement corrosion before FRP is strengthened in harsh conditions for small cracks.

The testing reported in this study helps by figuring out how well resin injections work to fix beam-to-column connections that repeated deformations have broken. The procedure above entails the administration of a thin resin solution into the compromised joint structure by applying pressure [7]. Recent significant earthquakes in Greece have led to the widespread use of resin injections to repair damaged concrete structures. Even though few studies on this procedure's effectiveness have been published to date, it appears to be encouraging [7]. Fiber-reinforced composite sheets, on the other hand, have become more popular in recent years as confining jacketing systems for modernizing under-designed or broken RC elements that would benefit from being surrounded by concrete. Using composite sheets as a jacketing system in these members is especially helpful because confinement avoids brittle shear failure and greatly improves the tensile behavior of the potential plastic hinge zones [8]. Additionally, recent experimental research papers have concentrated on the application of fiber-reinforced plastic to reinforced concrete beams for shear strengthening [9]. Nevertheless, there hasn't been enough experimental or analytical research on how well FRP works for strengthening beam-column connections [10–12]. In previous work, attempts were made to strengthen concrete beams using CFRP sheets. Due to the immediacy and simplicity of the required intervention, there is a developing interest in using these materials, which is the primary impetus for this work. In addition, using resin injections in conjunction with the application of CFRP could demonstrate a highly effective procedure. Torsion stress was applied to ten beam-column sub-assemblies as part of the testing program presented in this study. The investigation program evaluates the effectiveness of fortifying and repair techniques employing sheets of CFRP and epoxy resin.

2. Previous Studies

Imran et al. (2012) [13] conducted a literature review on reinforcing reinforced beams for flexibility, strain, and torque to better comprehend behavior. This review established CFRP as the most popular and practical reinforcing method for RC beams. They concluded that torsion strengthening is challenging and that some research suggests comprehensive packaging, which is practically inapplicable. However, numerous experimental experiments revealed that 45° CFRP wraps can increase the torsional strength of beams.

Al-Bayati & Al-Mahaidi (2013) [14] conducted an exhaustive review of the literature on the torsion performance of reinforced concrete beams strengthened with CFRP. This study is intended to provide an overview of the application and effectiveness of two commonly used techniques, namely Outwardly bound Reinforcement and Near-Surface Mounted (NSM), in improving the torsional behavior of such beams. The optimal configuration for enhancing both resistance and ductility in a beam is found to be the implementation of a full-wrap strengthening arrangement along its span. Such strengthening techniques prevented cracks from spreading. The number and spacing of CFRP layers have a significant impact on the beam's rotational strength. The use of supports causes an extended reaction time and slows disappointment, but it is possible for concrete to collapse in weaker areas. The configuration that utilizes 45-degree inclined spiral segments appears to have been the best option, but there are a number of functional disadvantages. A study of the research shows that there is no information about how reinforced concrete beams strengthened with the NSM method behave when they are turned.

El-Hakimkhalil et al. (2015) [15] examined the behavior of ten RC beams when subjected to pure torsion with and without web opening. The External Prestressing Technique (EPT) was used to reinforce beams both horizontally and vertically. Relevant findings from the investigation include the fact that EPT reinforcement increases rotational ability by 58%, vertical EPT is more productive, and the rotational ability of beams with apertures increases by approximately 13%. Four RC beams of the box section were made by Ma et al. (2016) [11] and forced to total torsion until collapse. The first beam served as the controlling beam, while the second, third, and fourth beams were connected externally using CFRP. The second was reinforced with a single layer of U-wrap, while the third and fourth were reinforced with two layers of U-wrap and diagonal strips, respectively. The ultimate torque of the second, third, and fourth reinforced beams is moderately increased by 16.6%, 15.5%, and 20.5%, respectively. As the torsional rigidity of longitudinally strengthened box beams increased, the fracture torque also increased.

Aghara et al. (2017) investigated both the physical and theoretical behavior of GFRP-laminated RC columns [16]. One was an operator beam, while the other five were GFRP-wrapped with various designs. Casting six rectangular beams with rectangular sections. Non-Linear Finite Element (NLFE) was used to conduct the computation. The article provided a thorough overview of earlier investigations into beam torsional strengthening. They came to the conclusion that a 45º wrapping pattern provides better torsional strength than a 90° wrapping pattern.

Kandekar & Talikoti (2018) looked at the torsional movement of concrete-reinforced beams wrapped in different fiber aramid strip designs [17]. Cast and tested 21 rectangular reinforced concrete pillars that fell under stress. Studying how aramid fiber topologies affect beam rotational capacity, twisting angle, and failure mode. When aramid fiber strands are wrapped around beams, rotational momentum increases. Strip spacing decreases torsional moment capacity, and the twist angle fluctuates slightly. Reinforced beams cracked at larger torsional moments.

In 2018, a study was conducted by Aziz & Hashim to investigate the rotating motion of six box beams made of Self-Compacting Concrete (SCC) that exhibited transverse concrete respiration [18]. The sixth beam was solid, while the first beam was hollow. The second and third beams were strengthened by two folded and opened diaphragms, while the fourth and fifth beams were strengthened by four. The first beam was used as a standard. For the second, third, fourth, and fifth strengthened beams, the peak torque went up by 43%, 61%, 89%, and 94%, respectively. The fourth and fifth beam specimens have 28% and 33% more torque, respectively, than the beam specimen with the heavier piece. When more beams were added, the breakage forces of the second, third, fourth, and fifth beams went up by 57%, 29%, 100%, and 88%.

Zhang et al. investigated the flexural characteristics of injured PRC beams improved with laminates made of CFRP exterior bond and resin injection in 2022 [19]. The impacts of overloading magnitude, overload frequency, and overload after reinforcing were determined on the strengthened beams. The concrete was pulverized after the CFRP laminates were deboned as one of the experiment's frames' failure modes. The initial concrete cracks were successfully prevented from re-cracking or postponed via resin injection. Raising load numbers stiffened the strengthening beam, but the yield load was unaffected. Overload amplitude increased the weakened beam's yielding load but did not affect stiffness.

Vibration tests, a non-destructive test (NDT), were used by Guim et al. (2023) [20] to evaluate beams made of reinforced concrete with CFRP and fracture filling. This study found All specimens had higher fundamental vibration frequencies and stiffness after structural repair. The application of epoxy resin crack injections resulted in the observed enhancement in structural rigidity. The non-injected beams exhibited a stiffness reduction of around 55% compared to the original beam stiffness. In contrast, the crack-injected beams had an average rigidity of 74% relative to the stiffness of the initial, undamaged beams.

Hussein Abdallah & Hameed Aziz (2017) evaluated the improvement of rotational rigidity for strengthened SCC box beams with interior steel bracing [21]. Seven beam prototypes were manufactured and afterward subjected to a comprehensive torsion test. The conventional box beam is the initial design. Applying additional support structures, specifically X-type supports, to the second, third, and fourth specimens increased their twisting moments by 14.4%, 34.3%, and 59.2%, respectively. Furthermore, these reinforcements reduced the twist angles of the specimens by 8.2%, 18.8%, and 30.365%, respectively, and decreased their extension by 8.2%, 21.8%, and 33.2%, respectively. The fifth, sixth, and seventh specimens exhibited concomitant increases in the ultimate twisting moment of 21.9%, 41.8%, and 71.6%. Additionally, the twist angle was reduced by 12.3%, 26.2%, and 32.42% for these specimens, while the length of each specimen decreased by 17.3%, 26.2%, and 40%.

Anbarlouie et al. (2023) [22] tested FRP, NSM, Epoxy Injection, Bacterial Injection, Self-healing Concrete using Polyurethane Coating (100 mm length and 10 cm), metallic material injection, and plaster injection on twenty reinforced concrete beams. The displacements, torsional load, torsional moment, and torsion angle showed that FRP and grout had the greatest and least impact on the repair. FRP standard's influence on cracked concrete sill restoration under torsional strain on ACI (318-08) was also examined, and coefficients were derived to illustrate each method's healing contribution; these Studies have explored that the eco-friendly epoxy resins and recycled CFRP materials are minimized environmental impacts and promote sustainable construction practices [22].

Askar et al. (2022) [23]. Knowledge gaps and research directions about structures reinforced with fiber-reinforced polymers (FRP) were identified, resulting in an enhanced comprehension of the subject matter and the establishment of design standards. The researchers concluded that using FRP laminate strips on the underside of a structure is the most efficient method for enhancing resistance and flexibility, compared to applying an FRP sheet as a jacketing material. The fiber-reinforced polymer (FRP) area in the tension region impacts the flexural strength. Implementing several fiber-reinforced polymer (FRP) layers in an O configuration along the shear span has enhanced strength and flexibility. The utilization of U-shaped and side schemes then follows this. Introducing a Reinforced Polymer (FRP) layer oriented at a 45° angle relative to shear fissures resulted in an enhanced shear strength compared to a 90° angle orientation application. Nevertheless, the process of implementation poses significant challenges.

Hussein (2022) [24] employed CFRP sheets to examine how steel fiber percentage, location, and length affected outcomes in a civil engineering master's thesis. The experimental variables are CFRP sheet placement (internal or exterior), length, and steel fiber volume fraction. The experiment tests thirteen pozzolana concrete reinforced concrete beams configured as supported beams. The empirical study demonstrates a correlation between the proportion of steel fibers and the compressive strength. Over 28 days, steel fibers at 0.5% and 1% have been observed to improve compressive strength by around 4.1% and 37.6%, respectively. The inclusion of steel fibers resulted in a notable enhancement of compressive strength, with increases of 4.9% and 12.8% observed at the 28-day mark compared to the reference specimen. This experiment observed the occurrence of two failure mechanisms in beams reinforced with carbon fiber-reinforced polymer (CFRP). The initial debonding failure generated by intermediate flexure cracks in externally strengthened beams represents a significant phenomenon. The second phenomenon seen is the occurrence of intermediate flexure crack-induced debonding and internal delamination of the CFRP sheet from the mid-span horizontal fracture, resulting in separation and delamination of the concrete cover. The augmentation of the steel fibers proportion for comprehensive external reinforcement resulted in a respective rise of 3.3% and 5.7% in the ultimate load for specimens containing 0.5% and 1% steel fiber, compared to the reference specimen.

Md Nor et al. (2021) [25] assessed the bearing capacity, strength, cracking mechanism, and flexibility of the pre-damaged RC beam repaired by CFRP and epoxy injection must be examined. This study investigates the impact of various restoration techniques on the structural behavior of pre-damaged reinforced concrete beams subjected to monotonic loading till failure. A series of beams were built for the study, including a control beam (S1C), a control beam reinforced with carbon fiber reinforced polymer (CFRP) at the soffit (S2B), a pre-damaged reinforced concrete (RC) beam fixed with epoxy injection and CFRP at the soffit (S3B), a pre-damaged RC beam mended with epoxy injection (S4B), and a pre-damaged RC beam strengthened with CFRP (S5B). Applying carbon fiber reinforced polymer (CFRP) to repair beams results in a notable increase in bearing load capacity, with a significant improvement of 37.24%. Additionally, the strength effectiveness of the restored beams is enhanced by 40%. Nevertheless, the flexibility of the object is comparatively less when compared to the reference beam. The restoration process, including epoxy injection and carbon fiber reinforced polymer (CFRP) for restoring pre-damaged reinforced concrete (RC) beams, is an effective approach. This work holds significance in the context of implementing the technique of repair and maintenance.

Ji et al. (2022) [26] used resin pre-coating to correct CFRP edge separation. The acetone-diluted resin adheres to the surface and penetrates subsurfaces via capillary action. The study tentatively added a Carbon Nanotube (CNT) to RPC to improve bonding. CNT addition did not affect resin curing chemically, according to DSC and FTIR. CNT additions have not modified the surface properties of the RPC solution with five wt% resin and 95 wt% acetone. Compressive tests validated the effect of CNT inclusion (0.5, 1, 1.5, and 2 wt%) on RPC repair. The results show that the 5% RPC solution with 1.5 wt% CNT repairs best, 22% better than RPC alone.

Most or all of the previous studies and literature reviewed did not refer to studying the possibility of treating potential cracks in concrete made wholly or partly from recycled aggregates by CFRP or epoxy injection or both, which is what we did in this study to reach some information and results. New, not previously discussed.

3. Research Significance

There are numerous methods for categorizing structural strengthening strategies, as demonstrated in section 2 above, a literature survey. A review of the literature on rotational reinforcing showed that there have been only a few investigations on the inside rotational reinforcement of box beams. This research uses CFRP and epoxy injection to improve reinforced SCC box beam torsional integrity. External reinforcing boosts reinforced concrete box beam torsional strength. Reinforcing all sides of box beam buildings can also be tricky. Thus, the concept of internal torsional strengthening employing various ways is introduced. As a result, a study on these techniques is being paid attention to even though much research has yet to be done on them, particularly employing SCC. These relatively novel approaches may be cost-effective and safer, particularly when employed in high-raised box girders. The study's main goals can be summed up as follows:

- Investigating experimentally the value of employing CFRP and epoxy injection in strengthening reinforced SCC box beams to repair cracked and damaged prestressed self-concrete box beams.

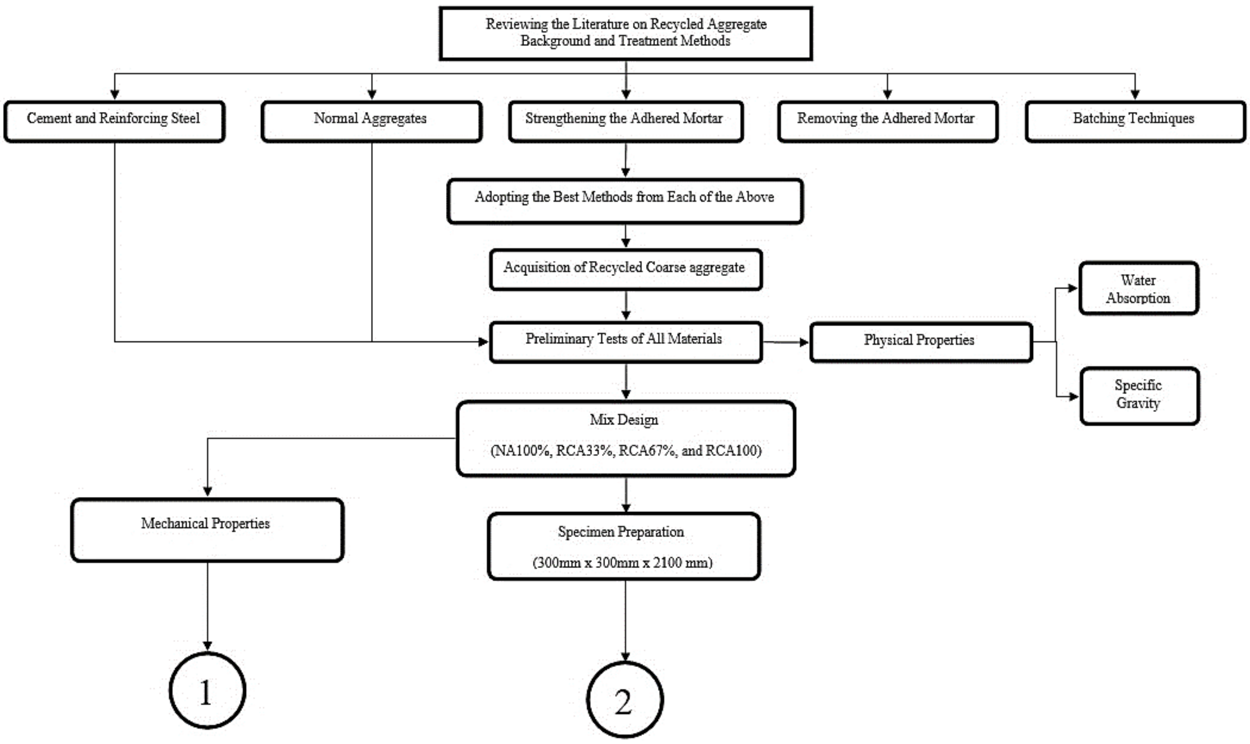
- Investigating the influence of CFRP quantity on the degree of torsion strengthening enhancement. According to a cost analysis, the newly adopted techniques may be employed to reinforce existing or prefabricated box girders.
- Structural Integrity: Prestressed self-concrete box beams are commonly used in structure projects such as bridges and high-rise buildings. Ensuring the structural integrity of these beams is crucial for the safety and longevity of the structures. Repairing damaged cracks using epoxy injection and CFRP can restore structural integrity, preventing further deterioration and potential failure.
- Enhanced Load Capacity: Cracks in prestressed concrete beams can compromise load-carrying capacity. The cracks can be filled and sealed by employing epoxy injection, restoring the column's original load-carrying capacity. Additionally, CFRP can be used to reinforce the repaired sections, increasing the load-bearing capacity of the supports. This study investigates this restoration technique's effectiveness and efficiency in enhancing damaged beams' capacity to support weight.
- Durability and Service Life: Repair damaged cracks using epoxy injection and CFRP contributes to the durability and extended service life of prestressed concrete box beams. Epoxy injection provides a long-lasting solution by effectively sealing cracks and preventing the ingress of moisture and corrosive agents. The application of CFRP reinforces the repaired sections, enhancing the beam's resistance to external forces and improving its durability against future crack formation.
- Cost-effectiveness: Repairing damaged cracks in prestressed concrete box beams using epoxy injection and CFRP can offer a cost-effective solution compared to other repair methods. The research examines this repair technique's economic feasibility and benefits, including material costs, labor requirements, and long-term maintenance savings. Analyzing the cost-effectiveness of this repair approach can aid engineers, contractors, and asset owners in making informed decisions regarding infrastructure maintenance and repair strategies.
- Sustainability and Environmental Impact: Using epoxy injection and CFRP for crack repair in prestressed concrete box beams aligns with sustainability goals. Rather than demolishing and rebuilding, repairing and reinforcing existing structures reduces the use of natural resources and energy.
- Additionally, by extending the service life of damaged beams, the repair technique contributes to minimizing waste generation and environmental impact associated with construction activities.
- Practical Implementation: Investigating the effectiveness of epoxy injection and CFRP as repair techniques for damaged cracks in prestressed concrete box beams provides valuable insights for practical implementation. The research can explore the optimal application procedures, material selection, and performance evaluation methods to ensure successful repair outcomes. These findings can guide engineers and practitioners in the field in effectively executing repair projects and maintaining the structural integrity of prestressed concrete box beams.

In summary, research on repairing damaged cracks in prestressed self-concrete box beams using epoxy injection and CFRP has significant implications for structural integrity, load capacity, durability, cost-effectiveness, sustainability, and practical implementation. This research can contribute to advancing repair techniques, leading to safer and more sustainable infrastructure systems.

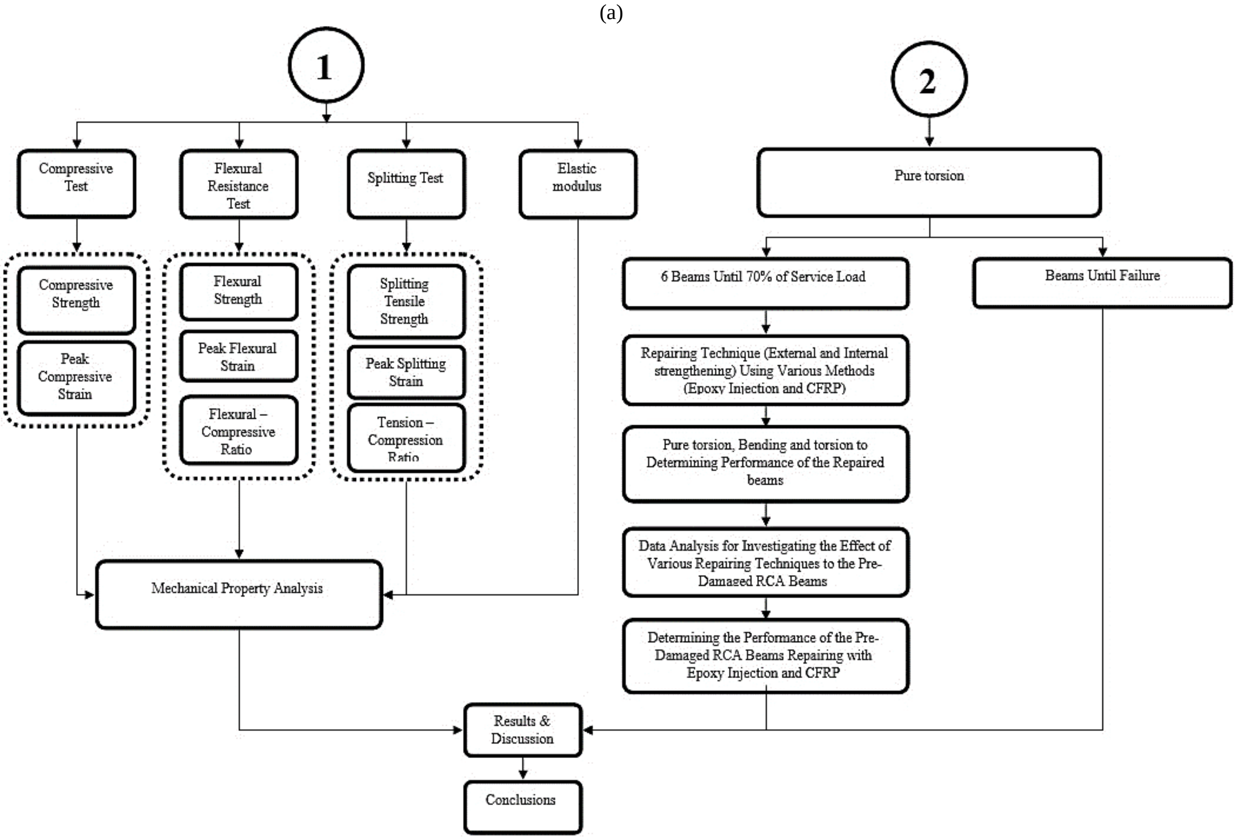
4. Experimental Work

4.1. Experimental Program

As part of the exploratory program, ten reinforced SCC box beam components were poured and tested until torsion-only failure. Four distinct levels of concrete's compressive strength 40.48, 38.32, 35.23, and 34.83 MPa are used in the research to examine the torsional presentation of RC beams composed of natural coarse aggregate (NCA) and recycled coarse aggregate (RCA), concrete mixes contain (one beam with 0, three beams with 33, three beams with 67, and three beams with 100%) by weight of RCA. The same proportion of reward served as the study's primary criterion. The ten specimens included four reference beams with no fortification and six strengthened beams, three with epoxy resin injections, and three with CFRP sheets. In addition to multiple tests for regulating SCC (slump flow, L-box, V-fennel, U-box, and G-ring tests), the experimental schedule includes tests to determine the mechanical properties of reinforced SCC (compressive and tensile strength elasticity). The ultimate strength and yield strength of the reinforcing steel were also evaluated. The visible span, concrete grade, and pressure condition are held constant throughout all specimen experiments. Furthermore, all specimens were held in place by rotatable supports alone. This study examines the torque-angle of twist behavior, fracture and final stresses, modes of failure, and related topics. EFNARC's Standard and Guidance for Self-Compacting Concrete influenced the novel SCC test procedures described in this paper [27]. Figures1-a and 1-b show all the steps and practical tests of the research.



(a)



(b)

Figure 1. (a) Breakdown of this research's experimental testing program, (b) Breakdown of this research's experimental testing program

4.2. Characterization of Beam Specimens

4.2.1. Materials

All specimens have the same dimensions. With a wall thickness of (60) mm, the dimensions are 2100 mm long, 300 mm in width, and 300 mm in height. Torsion requirements from the ACI-318-14 code [28] were used to calculate the necessary quantity of reinforcement. All the beams utilized the same type of reinforcement, which consisted of long bars (210 mm top), (212 mm bottom) and short bars (8@50 mm at both ends of the beam, to a length of 200 mm) and longer bars (8@130 mm spurs alternatively) as closed stirrups (Table 1 lists the properties of steel reinforcement). Box beam dimensions and reinforcement are shown in Figure 2. The physical features of coarse and fine aggregates and their sieve analysis are shown in Tables 2 and 3, and It complies with Iraqi Standard Specification IQS NO. 45/1984 [29] requirements.

Table 1. Features of steel reinforcing

Diameter (mm) Declared	Diameter Size in Measurements (mm)	Theoretical weight (kg/m)	Yield Stress (MPa)	Tensile Stress (MPa)	Elongation%
8	7.86	0.425	712.45	805.47	18.53 %
10	9.84	0.646	600.85	699.36	20.00%
12	11.72	0.888	532.85	648.00	20.00 %

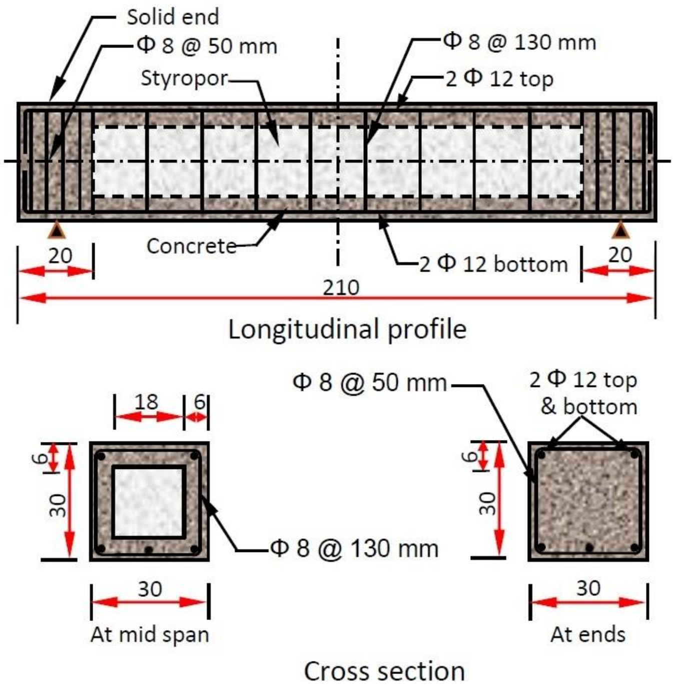


Figure 2. Specifications for the beam's size and reinforcement

Table 2. shows the outcomes of the NFA sieve analysis

Sieve size mm	Cumulative passing %		Limits of Iraqi specification (No.45/1984)			
	NFA		Zone 1	Zone 2	Zone 3	Zone 4
10	100		100	100	100	100
4.75	94.6		90-100	90-100	90-100	95-100
2.36	83.7		60-95	75-100	85-100	95-100
1.18	82.1		30-70	55-90	75-100	90-100
0.6	46.1		15-34	35-59	60-79	80-100
0.3	27.3		5-20	8-30	12-40	15-50
0.15	2.7	4.3	0-10	0-10	0-10	0-15

Table 3. Analysis of the NCA and RCA using a sieve

Size(mm)	Cumulative passing %		Limit of IQS No. 45/1984		
	NCA	RCA	Size (5-14)	Size (5-20)	Size (5-40)
37.5	100	100	-	100	100
20	96.8	96.3	-	95-100	-
14	-	-	-	-	95-100
10	43.3	48.1	100	30-60	35-70
4.75	4.7	6.2	90-100	0-10	-

Pure torsion tests were conducted on the four types of original models. In these tests, steel yielding caused every model to fail. All models had permanent deflection as a result of the tests. To make it easier to see deflections and cracks, the models were shown with the surface under stress facing up, as shown in Figure 3. This image also shows the state of deterioration of the beams following Lima 2017 [30] bending test, prior to rehabilitation efforts.

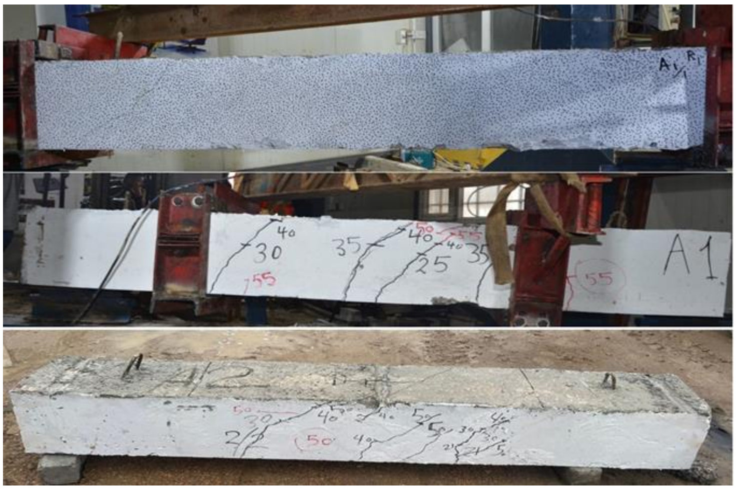


Figure 3. Detail of permanent deflection and fracture of tested beams

The damaged beams were given a preliminary inspection to decide which materials and techniques should be used for the restoration. Similar models have been subjected to a value of 70% of the failure value of the original models (service load) to discover fractures at this stress level and fix them using CFRP sheets and epoxy resin injection. Table 4 lists the broad features of the beams used in this investigation.

Table 4. Specimen characteristics

Mix type	Compressive strength *f*'c (MPa)
NCA	40.48
RCA 33%	38.32
RCA 67%	35.23
RCA 100%	34.83

In the four groups, a beam of each group is subjected to a load until failure. To benefit from it in knowing the maximum value of failure, the amount of bending, and others, the last three groups in Table 2. Each group contains two beams; one beam is repaired with FCRP, and the other is repaired with epoxy resin injection after exposing it to a pregnancy equal to 70% of the value of the pregnancy that led to the failure of the first sample (service load).

4.2.2. Mix and Pour of SCC

The materials listed in Table 5 were utilized to fabricate the necessary test beam specimens, including the SCC, longitudinal and transverse reinforcement, and the Styrofoam required to create section hollowness. The basic components were mixed in a rotary mixer. To create the SCC for each specimen. The beam specimens were cast using ten wooden formworks constructed from 10 mm thick hardwood plates reinforced with steel angle section members. The molds have (2100x300x300) mm internal dimensions. Before casting, the formwork was positioned on stable ground, horizontally level, and properly lubricated, as shown in Figure 4 and Table 6 provides the SCC mix percentages.

Table 5. Details on the material and its characteristics

Material*	Descriptions	
Cement	Common Portland cement (of the Type I variety).	
Fine aggregate (Sand)	Maximum (4.75 mm) all-natural sand grains.	Granular materials
Coarse aggregate (Gravel)	Gravel with a maximum particle size of 14 mm.	
Recycle Coarse aggregate (Gravel)	Maximum particle size of recycled crushed rock is 14 mm.	
Limestone powder	The finest quality limestone powder from Iraq.	
Superplasticizer	The Sika-made Viscocrete-180G.	
Water	In line with the standards for drinking water.	

* All locally sourced materials met or exceeded all relevant Iraqi requirements.

Table 6. mix design proportions

	Materials	Cement	Water	W/C	Super P	LP	Normal Sand	Normal Gravel	Recycled Gravel
Weight for 1 m^3 for NC, Without Replacement	Weight	405	178		4	135	760	845	765
	Specific Gravity	3.1	1	0.4395	1	2.48	2.58	2.64	2.39
	Volume	0.131	0.178		0.004	0.054	0.295	0.320	0
	Materials	**Cement**	**Water**	**W/C**	**Super P**	**LP**	**Normal Sand**	**Normal Gravel**	**Recycled Gravel**
Weight for 1 m^3 for NC, With Gravel Replacement (37%)	Weight	405	178		4	135	760	845	765
	Specific Gravity	3.1	1	0.4395	1	2.48	2.58	2.64	2.39
	Volume	0.131	0.178		0.004	0.054	0.295	0.2144	0.1056
	Materials	**Cement**	**Water**	**W/C**	**Super P**	**LP**	**Normal Sand**	**Normal Gravel**	**Recycled Gravel**
Weight for 1 m^3 for NC, With Gravel Replacement (64%)	Weight	405	178		4	135	760	845	765
	Specific Gravity	3.1	1	0.4395	1	2.48	2.58	2.64	2.39
	Volume	0.131	0.178		0.004	0.054	0.295	0.1056	0.2144
	Materials	**Cement**	**Water**	**W/C**	**Super P**	**LP**	**Normal Sand**	**Normal Gravel**	**Recycled Gravel**
Weight for 1 m^3 for NC, With Gravel Replacement (100%)	Weight	405	178		4	135	760	845	765
	Specific Gravity	3.1	1	0.4395	1	2.48	2.58	2.64	2.39
	Volume	0.131	0.178		0.004	0.054	0.295	0	0.320

Figure 4. Formwork

5. Equipment, Measurements, and Test Methodology

5.1. Equipment and Measurements

A large machine called a hydraulic universal has an amplitude of (3500 kN) A testing machine was used to test how strong a beam is. This machine can apply a very strong force to the beam, and by measuring how the beam reacts to this force, we can learn how strong it showed Figure 5., The experiment aimed to see how much torque a beam could take before it broke. As the strain on the beam increased, using three digital gauges, the torque angle was determined as the tension on the beam increased.

5.2. Protocol for testing

The beam specimen test setup is depicted in Figure 5. The test beam specimen is secured to movable machine supports, allowing it to rotate freely about its longitudinal axis at both ends. The load force is exerted at the precise midpoint of a steel beam that has a wide flange. This equally distributes the force to the loaded arms, resulting in two concentrated loads positioned 800 mm away from the longitudinal axis of the test beam specimens. The utilization of non-uniform spacing at the extremities of the specimen is necessary to induce torsional behavior. This is achieved by enabling the transfer of load to the arms through the application of high torque at the specimen's extremities and the concentration of vertical force immediately transmitted to the support. The applied loads leading to final failures and observing visible fissures were recorded.

Progressive load stages were applied to the beam specimens until failure, at which point displacement and deformations were recorded. The weight was fully removed after each stage, with the actuator suspended for the four groups. The last three groups in Table 2, were subjected to progressive load stages to a pregnancy equal to 70% of the value of the pregnancy that led to the failure of the first sample (service load) after restoring the beam's initial merely supported state. This approach recovers the elastic properties of the element while preserving the inelastic deformation caused by each stage.

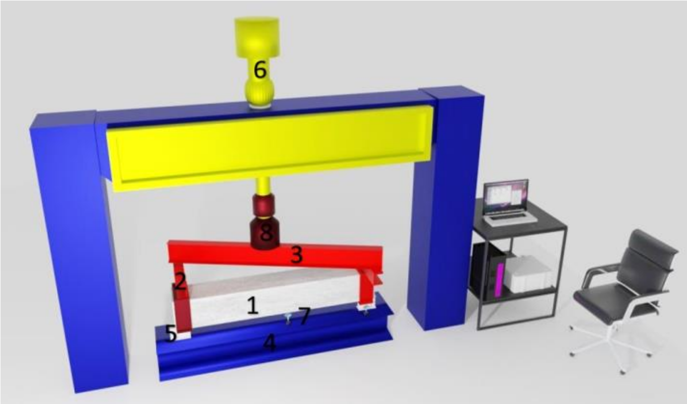


Figure 5. Setup for testing beam specimens, 1. Sample from a beam. 2. Loading Arm. 3. WF-sec for a steel beam., 4. the primary bed area. 5. Support that can be rotated in any direction. 6. A hydraulic jack. 7. A gauge with a dial. 8. A bob of the head.

Three digital instruments were used to measure the rotation angle when increasing weights were applied to the beam. In addition, the total lengthwise displacement at the extremities of the two specimens and the deflections were measured. Having center and middle cross sections fixed with (0.01 mm/division) precision. The readings were taken manually. Shown in Figure 6.

Figure 6. Digital dial gage

6. Characteristics of SCC

6.1. Fresh SCC Control Tests

The production of SCC-type concrete must pass ten separate tests by EFNARC [27] criteria. The slump flow, L-box, V-funnel, U-funnel tests, and the slump flow, L-box, and V-funnel tests were utilized as controls for new SCC in the current study. These four experiments provided information about the features of newly created SCCs, particularly the crucial three SCC traits of filling capacity, passage ability, and segregation resistance. The results of the experiments demonstrated that the SCC in use meets EFNARC requirements [27].

6.2. Hardened SCC Control Tests

The concrete mixtures for the compressive, splitting tensile, and flexure strengths tests were cast using twenty-four 150 × 150 × 150 mm cubes to determine the compressive test (The American Society for Testing and Materials (ASTM C39-01, 2001). According to ASTM C496-96 [31], Twelve 100 mm in diameter by 200 mm tall cylinders were manufactured and examined for fracturing tensile strength. (ASTM Designation C496-96, 1996), According to ASTM C78-02 [32], twelve additional prism molds with a loading of 100 × 100 × 500 mm were used to measure the flexural strength by ASTM Designation C78-02 [33]. Respectively. Before casting, the inside surfaces of the molds were greased to prevent concrete adherence. Molds were removed after 24 hours, and samples were placed in a water receptacle until the test began 28 days later. The samples underwent water curing in a controlled laboratory setting at a temperature of 20 +/- 5 °C after being de-molded 24 hours from the casting time. All segments of concrete that met the curing criteria have been completed, as have the four beams that were cured under identical conditions. Table 7. depicts the properties of hardened concrete mixtures based on the standard deviations of the three samples tested at 28 days.

Table 7. qualities of hardened concrete at 28 days

Mix type	Compressive strength $f'c$ (MPa)	Modulus of elasticity Ec (MPa)	Splitting tensile strength ft (MPa)	Flexural strength fr (MPa)
NCA	40.48	29725	2.09	9.23
RCA 33%	38.32	28972	2.07	8.52
RCA 67%	35.23	27805	1.91	8.22
RCA 100%	34.83	27405	1.79	7.68

6.3. Crack Injections

The chemical compositions and mechanical characteristics of the resins employed in fracture injections, specifically Sikadur® -52 Injection Type N and LP, are presented in Table 8 and Figure 7, respectively.

Table 8. Characteristics of resins

Product Description	Sikadur®-52 Injection Category N and Category LP are two-component, solvent-free, low viscosity epoxy-based injectable fluids. Between +5°C and +30°C, Type N (= Natural Potlife) is utilized for substrate temperatures. For material temperatures among +25°C and +40°C, type LP (= Long Potlife) is utilized.	
Mechanical / Physical Properties		
Compressive Strength	The normal value for this kind is 52 N/mm^2 after 7 days at +23 degrees Celsius.	(According to ASTM D695-96)
	Long-Potential Type: 34 N/mm^2 (after 7 days at +30°C)	(According to ASTM D695-96)
Flexural Strength	The normal type value is 61 N/mm^2 (measured after 7 days at +23°C).	(According to DIN 53452)
	Long-Potential Type: 41 N/mm^2 (after 7 days at +30°C)	(According to DIN 53452)
Tensile Strength	The normal value for this kind is 37 N/mm^2 after 7 days at +23 degrees Celsius.	(According to ISO 527)
	Long-Potential Type: 24 N/mm^2 (after 7 days at +30°C)	(According to ISO 527)
Bond Strength	To concrete: > 4 N/mm^2 (inability in concrete) (after 7 days at +23°C) after 7 days at +23°C	(According to DafStb-Richtlinie, part 3)
E-Modulus	The normal value for this type is 1800 N/mm^2 after 7 days at +23 degrees Celsius.	(According to DIN 53 452)
	Long-Potential Type: 1100 N/mm^2 (after 7 days at +30°C)	(According to DIN 53 452)

Figure 7. the resins employed in the crack injections (Sikadur® -52 Injection Type N and LP)

Surface packers were used in the injection process Figure 8. Due to the small scale of the models, the same method employed by Ekenel & Myers [34] was utilized, Nikopour & Nehdi [35], and Griffin et al. [36]. An invasive approach that might harm the models and jeopardize the eventual restoration process would be using borehole packers as a substitute.

Figure 8. Surface packers

Epoxy resin makers frequently recommend a distance between surface packing less than the structural member's thickness for a single fracture. The transversal portion of the models used in this investigation had cracks that covered its entire tiny width. Because of this, only one surface packer was applied to each fracture, which let the resin penetrate. The packers were pasted to the specimen and then fastened with a nail. Figure 9. shows where the surface packers are situated.

Figure 9. Surface packers secured with nails

After cleaning the beams, Surface spacers were secured with epoxy glue and nails. Cracks were then filled. The surface packers were adhered to, and each crack that ran the length of the lateral portion was only superficially sealed. All cracks seen with the unaided eye were filled with resin on the model's surface where the strain was applied. Epoxy resin was injected into the fissures after the sealing adhesive had fully dried. As depicted in Figure 10., The two components of the resin were combined and then injected into each crevice.

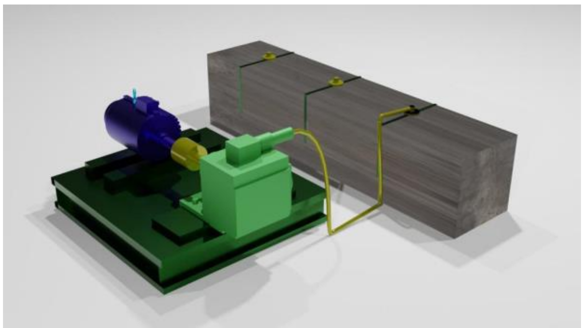


Figure 10. General crack injection schematics in the models and technique for injecting cracks

Pressures between 35 and 100 bar were used during the whole injection procedure, which is lower than the manufacturer's suggested maximum pressure of 200 bar for crack injection. When the injected material overflowed, each crack's injection process was complete.

6.4. Reinforcement with CFRP Sheet

FRP sheet was used to reinforce the structure. The Teknowrap 300 CFRP sheets were the kind utilized in this project. The thickness is th=0.17 mm. Before carrying out the CFRP structural reinforcement, all surface packers were removed. Using a grinding machine, the adhesive used to glue surface packers and seal cracks was also removed, as shown in Figure 11.

Figure 11. removed surface packers with the use of a grinding machine for carrying out the CFRP sheet

The ACI 440.2R [37] was used to guide the design of the torsion reinforcement. Each specimen from Lima's [30] work's ultimate load was incorporated as a design criterion. A single layer of CFRP was strengthened perpendicularly to each crack. Table 9. displays the physical and mechanical properties of the reinforcement CFRP sheet's materials. Table 10. details the Epoxy Based Adhesive and Lamination Resin (Teknobond 300 Tix).

Table 9. Characteristics of CFRP sheet

General information	
Color	Black
Structure of Material	Carbon
Unit Weight	300 g/m^2
Package	50 cm × 100 cm roll
Shelf Life	Unlimited in dry storage conditions
Nominal Wall Thickness	0.17 mm
Performance Information	
Tensile Strength	≥ 4,900 MPa
Modulus of Elasticity	≥ 230,000 MPa
Elongation at Break	2.1 %

Table 10. Characteristics of the Epoxy Based Adhesive and Lamination Resin (Teknobond 300 Tix)

General information	
Color (Resin and Hardener Mixture)	Off-White
Density (A + B)	1.27 ± 0.03 kg/t
Shelf Life	12 months in unopened original packaging
Package	Package 5 kg
Application Information	
Consumption	1-1,5 kg/m² for 300 gr/m²
Applicable Ground Temperature	(+5ºC) – (+35ºC)
Mixture Ratio (Weight)	3,85 units A: 1,15 units B
Pot Life	~30 minutes
Performance Information	
Concrete Adhesion	≥ 4.0 N/mm² (Rupture from Concrete)
Bending Strength	≥ 40 N/mm²
Pressure Resistance	≥ 80 N/mm²
Tensile Strength	≥ 30.0 MPa
Full Strength	7 days

The CFRP sheets were polished using a sander in the regions where anchorage was applied. This was done to facilitate the opening of concrete pores and enhance the adhesion of the thixotropic adhesive. Subsequently, the concrete surface underwent a cleaning process to eliminate any detritus, oil residues, or other impurities that could impede the establishment of adhesion. After the thixotropic glue has dried and the sheets have been joined, the resin coating is applied. The carbon fiber sheet was thoroughly covered with resin using a foam paint roller to apply the laminating resin to the CFRP sheet. Figure 12 depicts a portion of the beam specimens following repair.

Figure 12. Experimental Beams reinforced with CFRP

6.5. Torsion Test

The torsion test adhered to the same protocol as the reference investigations. After utilizing displacement control methods to load the specimens through a spreader beam, 360 mm extending torsion arms were installed at the extremities of the specimens. The beams had an unobstructed span of 2100 mm and were supported at either end by free rollers within the machine. A 3 m long by 300 mm deep steel girder was used to transport the weights from the machine's center to the two arms of the frame, which is 80 cm long, as shown in Figure 4. The burden was applied using continuous displacement control at a rate of 0.01 mm/s. The steel support beam was strategically positioned above the conventional testing apparatus to provide structural reinforcement for the specimens, spanning a distance of 2100 cm. Three digital gauges were used to measure the twist angle when the beam was loaded with increasing weights. Also, overall lengthwise displacement was determined at the extremities of both specimens and deflections. Having center and middle cross sections that are precisely fixed (0.01 mm/division). The measurements were collected manually. The torque was steadily increased until the beam broke, as depicted in Figure 5., which depicts the positions of antiquated dial gauges.

7. Results of Tests and Discussion

7.1. Cracking and Maximum Pressure

Tests on beam specimens were conducted using only gradually applied torsion force. The loading procedure went on until the eventual failure mechanism appeared. After recording the fracture and ultimate loads (Pcr and Pu), torsional moments (torques) were calculated for more information.

Following structural rehabilitation using epoxy resins, parts that underwent injection (RCA 33%, RCA 67%, and RCA 100%) showed ultimate torques (Tu) that were, respectively, 23.75%, 19.84%, and 16.39% higher than those of the original beams. These findings are depicted in (Table 11 and Figure 13).

Table 11. Cracking and maximum allowable load while using epoxy resins (Tcr and Tu)

Specimen Designation	NCA	RCA 33%	RCA 67%	RCA 100%
Pcr (kN)	22.51	20	15	13.53
Pu (kN)	61.33	45.11	42	40.13
Pu (kN) with Epoxy Resins		59.16	52.41	48.02
Arm (m)		0.8		
Tcr (kN.m)	9	8	6	5.41
Tu (kN.m)	24.53	18.04	16.8	16.06
Tu (kN.m) with Epoxy Resins	—	23.66	20.96	19.21
Increasing* (%), Tu		23.75	19.84	16.39

* Increasing % is relative are with Epoxy Resins and without Epoxy Resins.

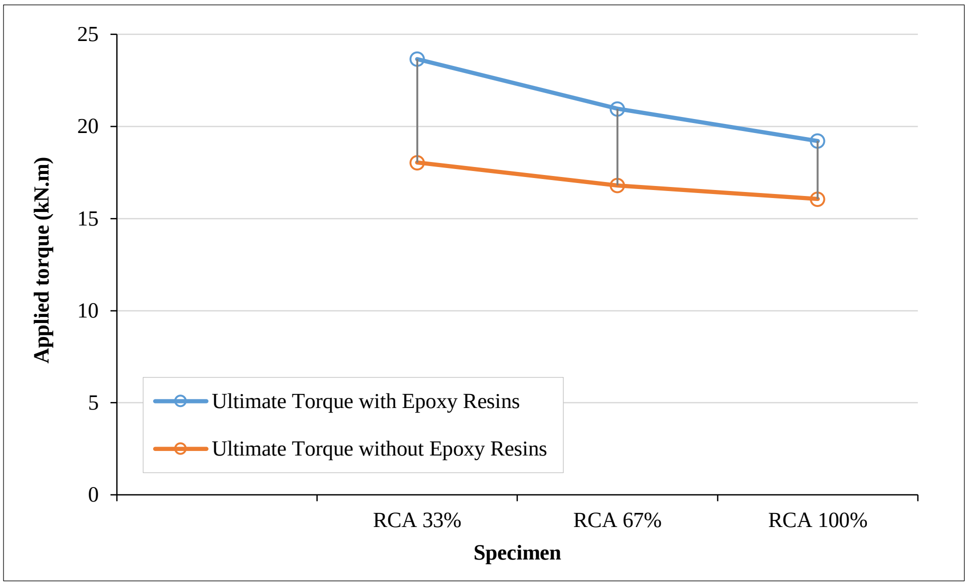


Figure 13. Cracking, maximum, and applied torque capacities while using epoxy resins

On the other hand, the sections that were only strengthened with CFRP (RCA 33%, RCA 67%, and RCA 100%) exhibited Tu values that were 19.75%, 14.85%, and 11.95% greater than those of the initial beams, as shown in (Table 12 and Figure 14).

Table 12. Cracking and maximum allowable load while using CFRP (Tcr and Tu)

Specimen Designation	NCA	RCA 33%	RCA 67%	RCA 100%
Pcr (kN)	22.51	20	15	13.53
Pu (kN)	61.33	45.11	42	40.13
Pu (kN) with CFRP	——	56.22	49.33	45.6
Arm (m)			0.8	
Tcr (kN.m)	9	8	6	5.41
Tu (kN.m)	24.53	18.04	16.8	16.06
Tu (kN.m) with CFRP	——	22.48	19.73	18.24
Increasing*(%), Tu	——	19.75	14.85	11.95

*Increasing % is relative are with CFRP and without CFRP.

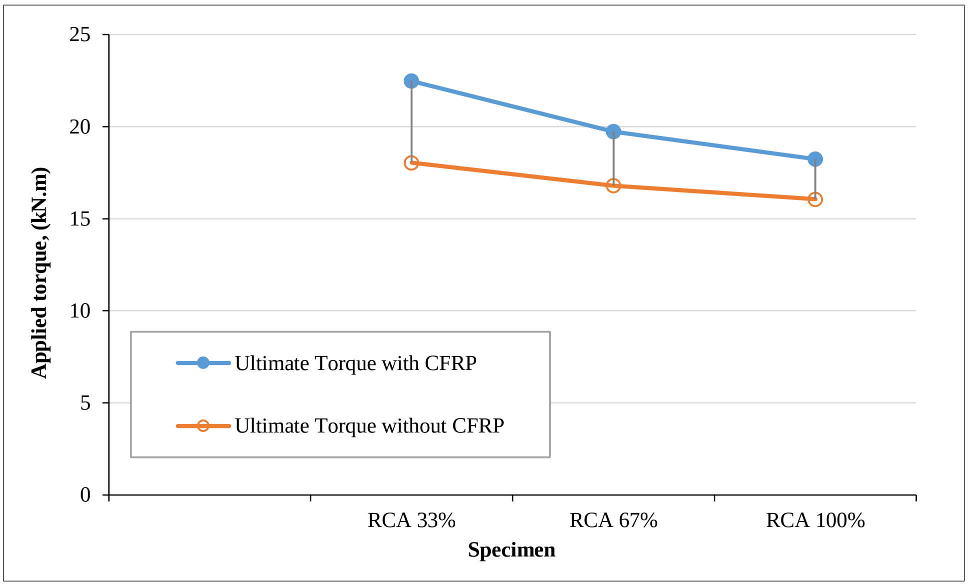


Figure 14. Cracking, maximum, and applied torque capacities while using CFRP

Furthermore, the specimens with crack injection (RCA 33%, RCA 67%, and RCA 100%) had a superior Tu than the RCA 33%, RCA 67%, and RCA 100% specimens reinforced with CFRP. The growth rates are significant. This indicates that the presence of CFRP or fracture injection reinforcement improves the resistance of the box section to extra torsional stress. In addition, it should be noted that the rates of growing cracking torque (Tcr) vary little, whereas the percentages of Tu vary considerably. The observed phenomenon could be attributed to the fact that the applied load was predominantly borne by the concrete, leading to the initial fracture originating at the center of the outermost fiber of the box section side. Subsequently, the reinforcing steel commences its role in augmenting the capacity to withstand stress. During the concluding stages of the loading process, the primary resistance against the applied load will be provided by either CFRP (carbon fiber reinforced polymer) or epoxy resin reinforcement. The TCR (Total Compressive Resistance) rating is predominantly influenced by the concrete's ability to withstand the externally applied load. On the other hand, the Tu value is contingent upon the combined influences of the concrete, reinforcement steel, and CFRP or epoxy resins. Hence, the utilized fortification technique significantly enhances the torsional ultimate capacity.

7.2. Angle of Twist and Deflection

In the present study, only one category of deformation was considered: angle of twist ϴ. The attitude of twist was determined at two points: the right end spread twist angle (ϴES) and the midspan twist angle (ϴMS) of the test specimens. These deformations were listed in Table 13 for Tu. Note that the degree value represents the complete twist angle. ϴES and ϴMS represent the final and intermediate spans, respectively.

Table 13. Deformations under a cracking strain (Tu)

Specimen	Deformation at cracking Tu (normal beam)		Deformation at cracking Tu (beam Reinforcement with Epoxy Resins)		Deformation at cracking Tu (beam Reinforcement with CFRP)	
	ϴES	ϴMS	ϴES	ϴMS	ϴES	ϴMS
NCA	1.68	0.62	-	-	-	-
RCA 33%	1.61	0.53	1.65	0.54	1.64	0.54
RCA 67%	1.53	0.54	1.71	0.55	1.58	0.54
RCA 100%	1.63	0.5	2	0.51	1.67	0.51

Consequently, the reinforcement with CFRP and Reinforcement with Epoxy resin alters the deformation capacity of every box beam specimen tested. The magnitude of the angle of twist remains quite low before the onset of the initial observable crack. Subsequently, the entity's values progressively escalate until they hit a critical threshold, ultimately deteriorating. This phenomenon is observed in all instances when measurements of rotation angles were conducted.

ϴES of reinforced specimens rises with Reinforcement with Epoxy Resins by (2.4%), (10.5%), and (18%) for RCA 33%, RCA 67%, and RCA 100%, respectively, in comparison to RCA specimen without Reinforcement. ϴES of strengthened specimens increases, with Reinforcement with CFRP by (1.82%), (3.16%) and (2.39%) for RCA 33%, RCA 67% and RCA 100%, respectively. ϴMS of strengthened specimens increases Reinforcement with Epoxy Resins by (1.58%), (1.82%), and (2.39%) for RCA 33%, RCA 67%, and RCA 100%, respectively, when compared to RCA specimen without Reinforcement. ϴES of strengthened specimens increases with Reinforcement with CFRP by (1.85%), (0.08%), and (1.96%) for RCA 33%, RCA 67%, and RCA 100%, respectively.

Even though (ϴMS) must have a value of zero due to the test setup, it has some exceedingly tiny numbers in the loading region up to Tcr. The reason may be the nonhomogeneous character of the concrete or the violation of one or more conditions of the symmetry of the test setup, even if the violation is minor. As fractures grow larger beyond Tcr, the behavior alters so that ϴMS has large values at the Tu level.

7.3. The Failure Mechanisms

The propagation of fractures along the length of the specimen beam during the test provided useful data surrounding the malfunctioning mechanism. The first obvious crack of all specimens happened near the center of the span at some location on the midheight of the outer face of the beam specimen, indicating the weakest point, and then grew progressively. As the force being applied moment increased, the fractures expanded progressively on all sides and ultimately spiraled. Typically, the primary fractures, including the initial, observable break, originated and progressed within the central third of the span, exhibiting a diminishing breadth as they neared the extremities of the beam specimen. Furthermore, the extremities of the specimen were vertically limited through the application of concentrated torque at the supports. At the same time, longitudinally, they experienced forces resulting from loading the steel arm fixation. However, they retained the ability to rotate. This phenomenon could be attributed to the fact that both ends of the specimen were solid and possessed a higher degree of longitudinal reinforcement than the overall span. The occurrence of the ultimate failure point for the majority of beam samples is typically concentrated near the center of the span.

7.4. A Pattern of Cracks

Fractures propagated across the specimens of reference beams devoid of reinforcing CFRP and Epoxy resin. The fissures in the center third of the span exhibited a slight increase in width compared to those found in the end thirds. However, the fissures situated near the supports demonstrated a significantly narrower width. Typically, the number of fractures increases as loading increases, and failure occurs somewhere in the middle of the span. At failure, excessive parallel fractures were observed on all sides of the beam's span.

After reinforcing with CFRP and Reinforcing Epoxy Resins, cracks develop more slowly in the zones where the reinforcing CFRP and Epoxy Resins were applied because they reduce the rate at which cracks grow. This is because the reinforcing CFRP and Epoxy resin delay the rate at which cracks grow. The angle of reference beam specimen fractures relative to the longitudinal axis ranged from 45º to 50º for NCA, 47º to 53º for RCA 33%, 46º to 55º for RCA 67%, and 48º to 56º for RCA 100%. As anticipated, all cracks measure between 30º and 60º, Figure 15. The spiral-shaped fractures were present on all surfaces of each tested specimen. Approximately the same number of full cracks could be found in each of the analyzed beam specimens. This suggests that the strengthening procedure has less of an effect on the rate of cracks compared to the cracking values and final torques.

Figure 15. Tested specimens of beams

8. Conclusions

This study investigated the durability performance and behavior of crack-reinforcing CFRP and Epoxy Resin infusions on RC beams comprised of NCA and RCA. Based on the investigation conducted, the following inferences can be made:

- As part of the experimental program, ten reinforced SCC box beam specimens were poured and tested until torsion-only failure. The torsional behavior of RC beams composed of NCA and RCA is investigated using four distinct levels of the compressive strength of concrete (40.48, 38.32, 35.23, and 34.83 MPa). Concrete mixes contain varying amounts of RCA by weight (one beam with 0%, three beams with 33.3%, three with 67.7%, and three with 100%).
- Reinforcing CFRP, or Epoxy Resin was used to repair the fracture specimens that contained the breach of external beam-column connections as a limiting jacketing system. This action was taken to stop the breach from spreading.
- Repaired specimens had better load-carrying ability and energy absorption than controls. The CFRP- or epoxy-repaired specimens survived compression. All repaired specimens had non-joint damage.
- Crack epoxy injection and CFRP reinforcement increased rigidity in the linear region of the load–displacement curves for all RC beams by as much as 23.7% relative to control specimens. However, there was no significant improvement in flexural capacity.
- Crack epoxy injection has been shown to enhance the ultimate strength and initial stiffness of load versus deflection curves when compared to CFRP-reinforced specimens. Injected fractures in epoxy-reinforced specimens displayed minimal crack opening displacement.
- The CFRP-reinforced specimens exhibited some fracture opening displacement, but not as much as the epoxy-reinforced specimens. Epoxy injections were used, resulting in less tension in the reinforcement steel and a slower crack propagation rate. The use of epoxy injections can explain this. Epoxy injection of cracks is recommended when cracking is severe and durability is a significant concern.
- The use of crack epoxy injection resulted in a notable increase in the flexural capacity of the specimens and a reduction in the breadth of fracture openings, as compared to other specimens improved with CFRP. This improvement can be attributed to the effect of surface roughness.
- Following structural rehabilitation using epoxy resins, Ultimate Torsional moments (torques) capacity increased significantly, and parts that underwent injection (RCA 33%, RCA 67%, and RCA 100%) showed Tu that were, respectively, 23.75%, 19.84%, and 16.39% higher than those of the original beams. In contrast, the beams' Tu of elements that were merely reinforced with CFRP revealed 19.75%, 14.85%, and 11.95% greater than those of the original beams. These elements were RCA 33%, RCA 67%, and RCA 100%, respectively.
- Following structural rehabilitation using epoxy resins and CFRP, the Ultimate angle of twist capacity ϴES and ϴES increased significantly.

9. Declarations

9.1. Author Contributions

Conceptualization, A.E., A.S.A., and S.K.A.; methodology, A.E., A.S.A., and S.K.A.; analysis, A.S.A. and S.K.A.; investigation, A.S.A. and S.K.A.; resources, A.S.A. and S.K.A.; data curation, A.S.A. and S.K.A.; writing—original draft preparation, A.S.A. and S.K.A.; writing—review and editing, A.E., A.S.A., and S.K.A.; supervision, A.E. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available in the article.

9.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

9.4. Conflicts of Interest

The authors declare no conflict of interest.

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