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Improving Behavior of Reinforced Concrete Beams Subjected to Bending and Torsion

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By

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

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وَكَانَ فَضْلُ اللَّهِ عَلَيْكَ
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In the name of Allah, the most compassionate, the most merciful, Praise be to Allah, Lord of all Greation

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Iman Muneam Abd-Zaid

Abstract

The main objective of this research is to investigate the effect of strengthening with ultra-high performance concrete (UHPC) on the load carrying capacity of simply supported RC beams under the combined effect of bending and torsion. The strengthening include many regions, cover, only tension zone, only compression zone and all section. The experimental program consisted of casting and testing thirteen simply supported reinforced concrete beams strengthened by self-compacted concrete with 1 % steel fiber or ultra-high performance concrete under effect of bending and torsion. Dimensions of all specimens were (150 mm) width, (200 mm) depth and (1500 mm) in length.

In general higher loads carrying capacity were obtained for beams strengthened with steel fiber or ultra-high performance concrete as compared with unstrengthened control beam. The beam strengthened using steel fiber in all sections at middle part showed increase in ultimate load capacity by about 21%, while that beam strengthened using ultra-high performance concrete in all sections of the middle part showed excellent result with increase in capacity equal by 95%. Also beams strengthened using ultra-high performance concrete of the cover 2cm in 2-side and 3-side at the middle part showed increase in ultimate load capacity of the 24% and 36% respectively. Furthermore, using ultra-high performance concrete at the compression and tension zones along all entire lengths, showed increase in capacity equal to 17% and 38% respectively. Also beams strengthened using ultra-high performance concrete for cover 3cm in 2-side and 3-side at the middle third zone showed increase capacity equal to 2% and 14% respectively. The beams strengthened using ultra-high performance concrete at the cover 2cm in 2-side and 3-side at the middle third zone and reducing the spacing of stirrups about 15% showed decrease in capacity by -7% and increase in capacity to 31%

respectively. Also beams strengthened using ultra-high performance concrete for the compression and tension zones along all entire length and reducing the bottom reinforcement by 36% showed decrease in capacity equal to -26% and -21% respectively.

The angles of twist decrease when the beam strengthening by steel fiber or by ultra-high performance concrete in compared with control beam. The ratio of angles of twist of all beam with respect to control beam are decreases, and this ratio ranged between 19% to 65%.

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Natation

| Symbol | Description |
|--------|--|
| SCC | Self-compacted concrete |
| UHPC | Ultra-high performance concrete |
| RC | Reinforced concrete |
| FRP | Fiber reinforced polymer |
| GFRP | Glass fiber reinforced polymer |
| FEM | Finite element method |
| SF | Steel fiber |
| ACI | American concrete institute |
| ASTM | American society for testing materials |

Chapter One

Introduction

1.1 Introduction

In many works, due to the fact that the concrete with self-compacting (SCC) and concrete with ultra-high performance (UHPC) can be achieved through various methods, the mixture design overcome all mixture variables.

Today, self-compacting concrete and ultra-high performance concrete is studied all over the world, with many papers presented, the use UHPC is being quickly used in many regions.

1.2 Torsion

Torsion occurs mainly in many parts of structures; beams, slab, columns...etc.

If the concrete without reinforcement is subject to pure torsion, it will crack and fail by forty five degree due to torsional stresses [1]. Similar shape between diagonal tension stresses of shear and torsion, they will appear on all surfaces of a beam. In the region of low moments, maximum shears and torsional forces may be occur.

If external loads act far away from the vertical plane of bending, the beam is subjected to twisting about its longitudinal axis, known as torsion, in addition to the bending and shear. Torsion of members can be divided into two types; determinate, and indeterminate. Figures (1-1(a)) to (1-1(e)) show many types of member subjected to torsion [1]. Also it can be noted that the torsion results from

either loaded element on one side, or supporting forces at distance from center of the beam.

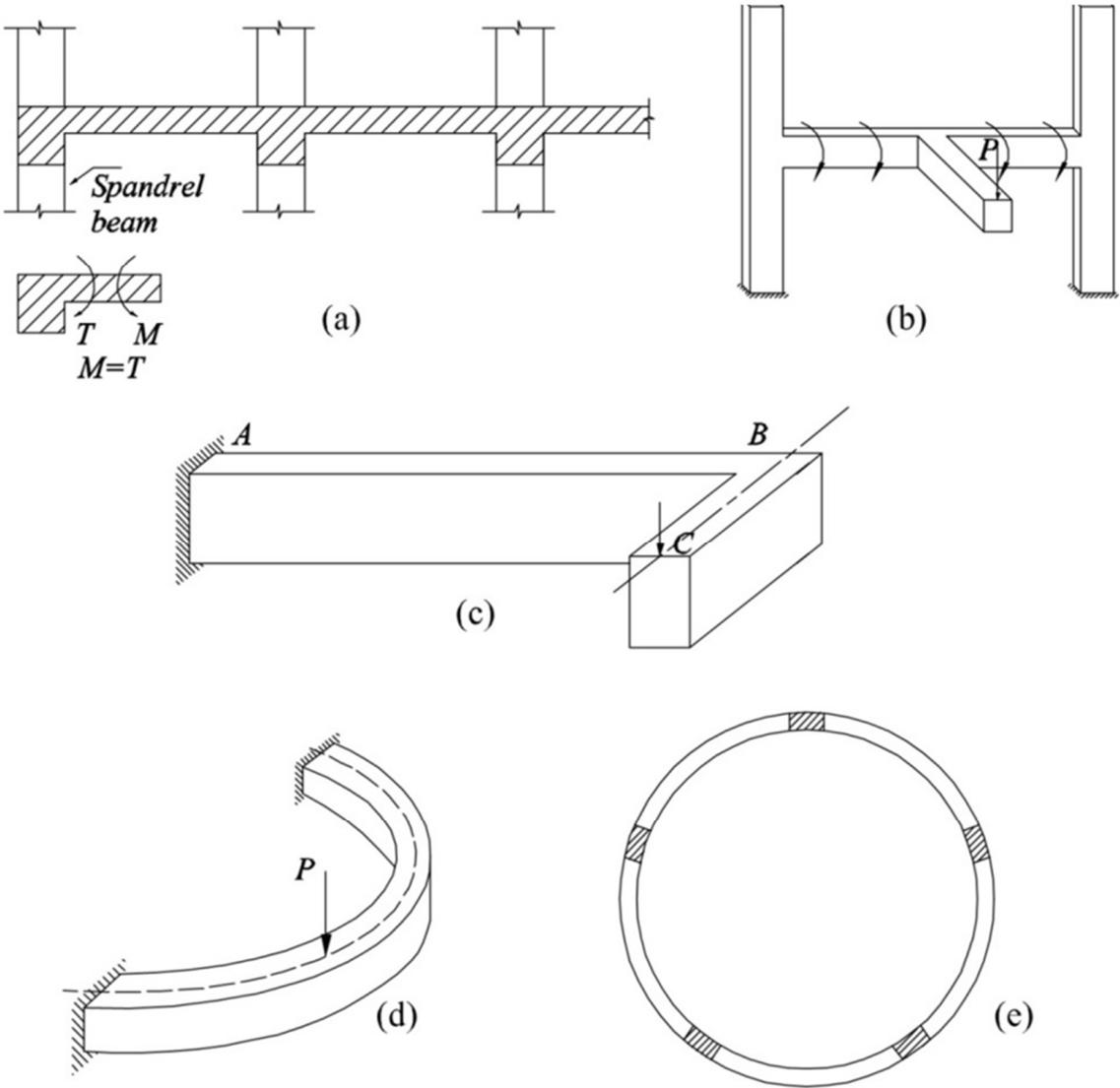


Figure (1-1): Beams subject to torsion: (a) spandrel beam (b)&(c) loads act away from the vertical plane of bending; (d) curved beam; (e) circular beam.

1.3 Combined torsion and bending

Usually torsion occurs in the reinforced concrete members as a secondary effect of bending. RC beams subject to combined torsion and bending should naturally designed in the same method as member subject to beam under bending and shear. If the torsional capacity of the member is inadequate, additional reinforcement for torsional shear should be added and the member must be designed to resist the moments. In practice, generally this steps is rarely used [2].

1.4 Ultra-high performance concrete

UHPC has high compressive strength of concrete which is a cementitious, concrete material, tensile ductility and solidity requirements; in the mixture generally fibers are contained to product specified requirements.

Ultra-high performance concrete UHPC is also defined as RPC (reactive powder concrete). The material is consisted by combining seven items [3]:

- | | | | |
|-------------------|---|-----------------------|------------------------------------|
| 1-Portland cement | 2-supplementary cementitious materials | 3-reactive powders | 4-limestone and or quartz flour |
| 5-fine sand | 6-high-range water reducers | 7-water | |

The material can be fashioning to provide high compressive strengths more than 200 MPa. When mixed with metal, micro fibers it can obtained flexural strengths more than 40 MPa.

The increasing in the concrete compressive strength had become important requirements of the concrete works. For the period greater than 30 years high compressive strength of concrete from 50MPa to 120MPa where used in structure with long spans or buildings in attacker environments. In general the multistory building made of concrete with high strength are heavily reinforced. The low

distances between reinforcement bars may be lead to weakness in concrete shape. For the self-compacting of high strength concrete, the product of densely reinforced concrete member from high strength concrete specification will be easily work. In this study the properties of Ultra high performance concrete with self-compacting and have strength greater than 100 MPa is presented.

Self-compacting concrete is a brittle cementations material as the ordinary concrete. This brittle material can benefit from the addition of steel fibers which can bridge cracks and retard their propagation.

1.5 Objective and scope

The work presented in this research deals with the effect of strengthened beams under effect of bending and torsion by Ultra-High Performance Concrete and includes the following objects:

- Evaluating the adequacy of the mix design with respect to the selected raw materials.
- Study the effect of UHPC on bending and torsion capacity for reinforced concrete members.
- Study the influence of Ultra-High Performance Concrete on deflection and angle of twist of reinforced concrete beams.

In this study an experimental work of many tests has been carried out to achieve the above requirements. These tests consist of compressive strength, splitting tensile strength and modulus of rupture.

1.6 Outline of the study

The work presented in this thesis is covered with five chapters. Present chapter (One) deals with a general development of torsion, combined of bending

and torsion, SCC, UHPC, significance of the study and objective and scope. Chapter Two, presents literature review contain many researches on experimental studies on reinforced concrete members subject to bending and torsion. While chapter three include, mix design, description of the specimens, casting of the specimens, and experimental program. Chapter four includes test results of specimens, crack patterns, load versus mid-span deflection results and torque and angle of rotation of the specimen.

Finally, in chapter five, a general conclusions and perspectives for future works are presented .

Chapter Two

Literature Review

2.1 Introduction

The RC element such as that beams in of multi-story structure, spiral ramps, edge beams of flat slab, and the helical staircases are subjected to a significant torsional moment, flexure and shear.

Due to problem of torsion, repair and handling of bridges, buildings, and other elements have become important due to long age of structure, environmentally induced decomposition, and changes in the design specification. Mainly, there are two reasons for the reduce ultimate capacity to carry the design loads, are the steel reinforcement corrosion and the loads taken in the design lower than code requirements such as earthquake forces.

2.2 Experimental studies on reinforced concrete members subject to bending and torsion and pure torsion.

Ghobara et. al. (2002) [4], an experimental work was conducted on the increasing of the torsional resistance of RC beams using FRP. Eleven tested specimens with dimensions 2440mm length, 150mm width and 350mm height as shown in Figure (2-1). Using testing machine, pure torsional moment was supplied to a 1000 mm length of the beam. The concrete compressive strength for the specimens was 37MPa. Three beams were used as control specimens and eight specimens were strengthened by FRP wrapping of different shapes and tested to up to failure. Both GFRP and FRP were used in the torsional strength development. The RC tested beams were subjected to pure torsional moments. The data recorded were ultimate

load, cracking load, angle of rotation, and strains. It has been shown that improving the torsional strength of RC beams with FRP is viable. The fully wrapped strengthened of beams configurations showed that is better boost of system.

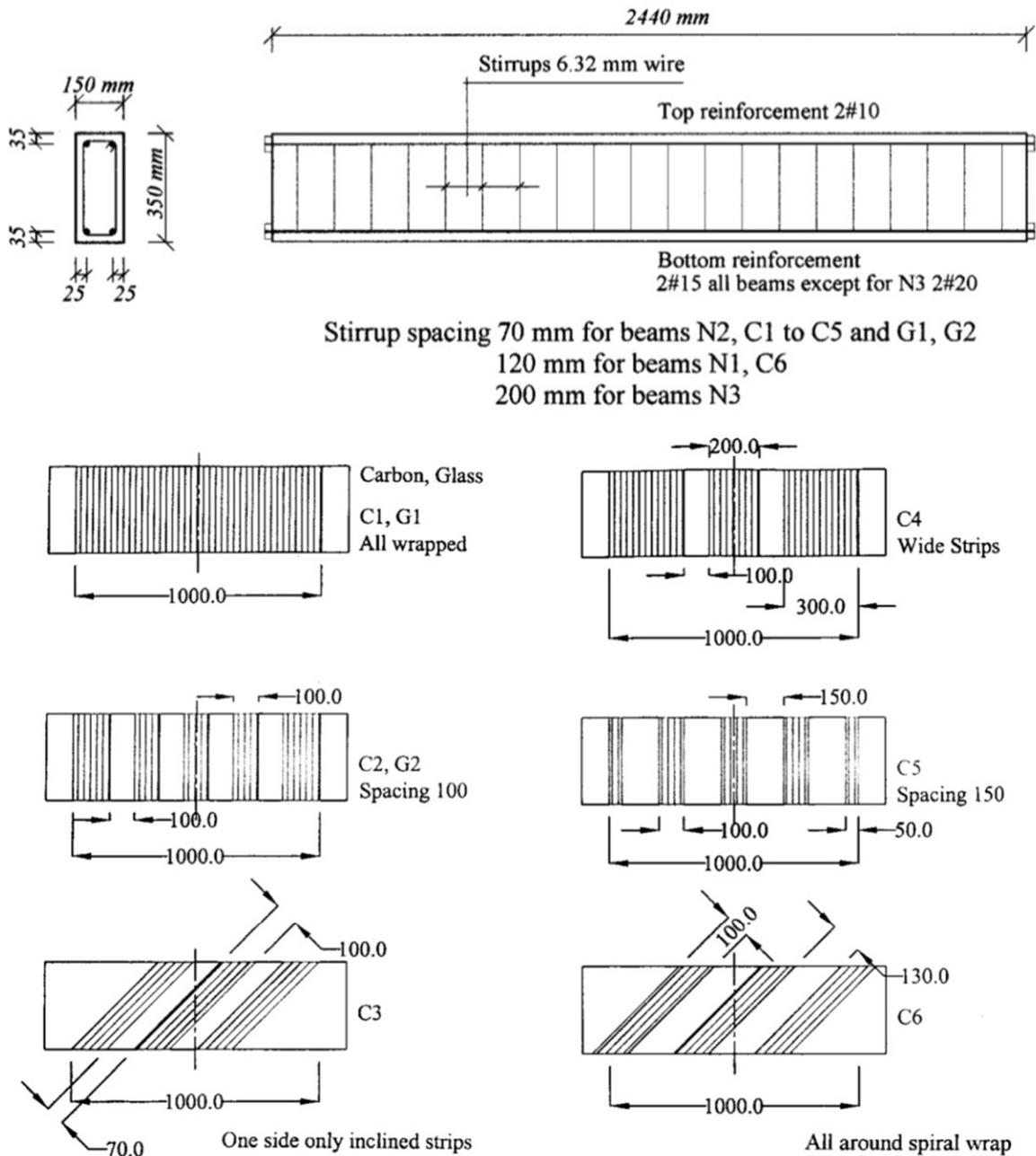


Figure (2-1): Dimensions, reinforcement details and strengthen of the tested beams by Ghobara, et. al. (2002).

Mostofinejad D. and Talaeitaba S. B., (2011) [5], They examined the adequacy of the finite element analysis of reinforced concrete beams subjected to torque. In this research fourteen experimental specimens previously works by other researchers were adopted and modeled using ANSYS software (SOLID65) as shown in Figure (2-2). The specimens consisted of twelve with rectangular sections, one voided section, and one Tee-shaped cross section. The specimens were analyzed in Finite element analysis and subjected to loading up to failure. The results obtained from this program were adequate of making relatively acceptable values of torsional carrying capacity of the concrete beams in addition to cracking and failure moments.

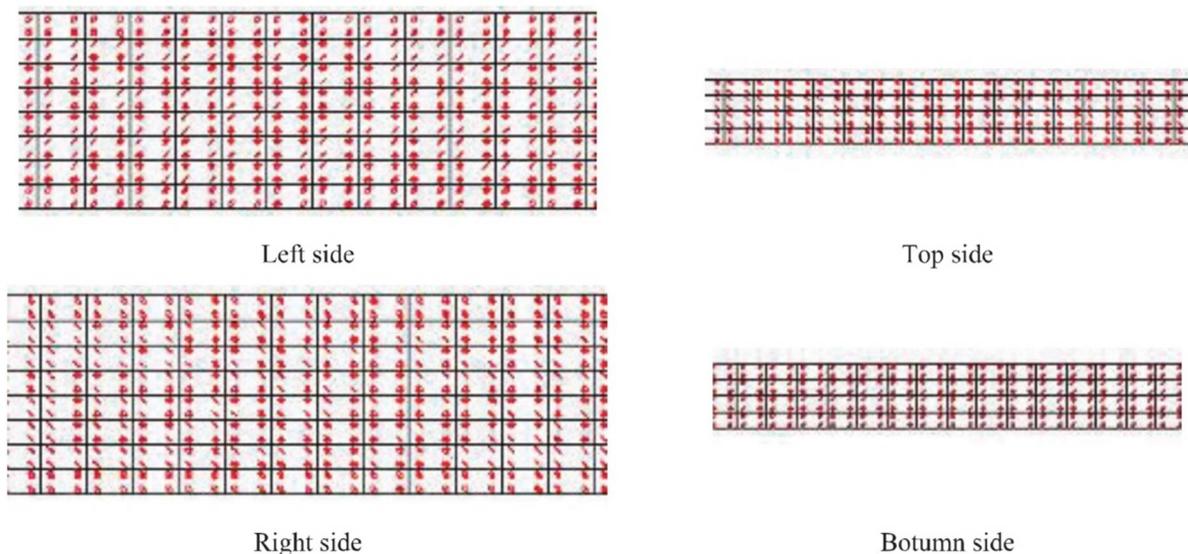


Figure (2-2): Crack at each face of the specimens by Mostofinejad D. and Talaeitaba S. B., (2011).

Vishnu et. al. (2013) [6], tested fourteen reinforced concrete beams with dimensions of 150*150*1700 mm as shown in Figure (2-3). All specimens strengthened by GFRP. These specimens were under effect to combined bending and torsion. All beams were strengthened with GFRP showed good torsional

capacity result compared to the control beam. In comparison with control beam, tested specimen with diagonal and corner strip wrapping showed an increase of 110% in torque at cracking stage and an increase of 117% in ultimate capacity of torque, compared to control specimen. In strengthening of reinforced concrete beam with type of strengthening of GFRP, wrapping of diagonal arrangement was more capacity from vertical strip in resisting torsional carrying moment. Wrapping of corner and 10 cm strip at spacing of 10 cm centers showed better than wrapping formations.

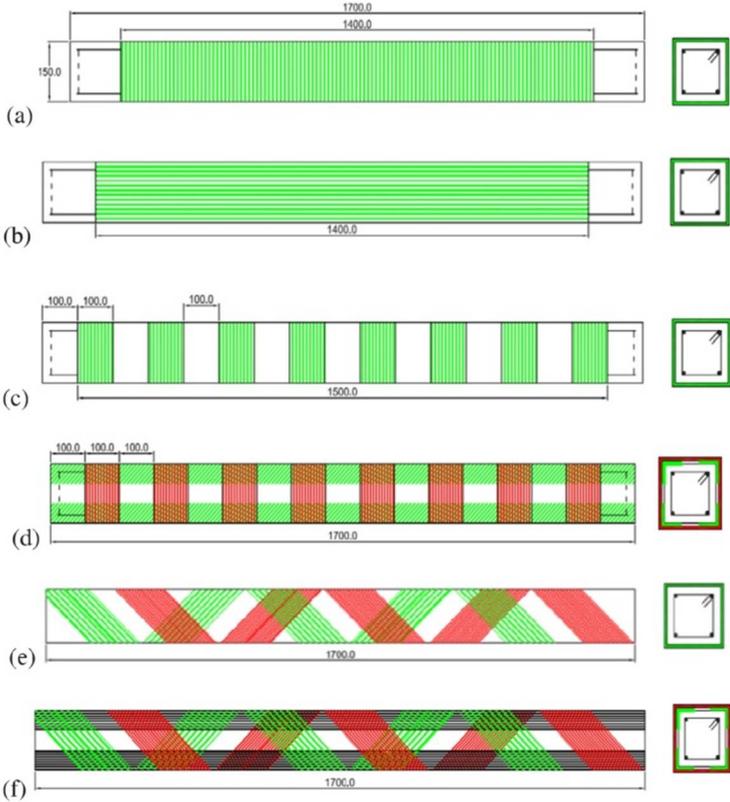


Figure (2-3): The specimens tested by Vishnu et. al. (2013), Schematic representation of different wrapping configurations (a) Full Transverse wrapping (b) Full Longitudinal wrapping (c) 100 mm strip wrapping at 100 mm c/c (d) Corner and 100 mm strip wrapping at 100 mm c/c (e) Diagonal strip wrapping (f) Corner and diagonal strip wrapping.

Gopal et. al. (2016) [7], Wrapping on three sides is one of the effective methods for strengthening the beams supporting slabs. Available literatures on the strength enhancement of “U” wrapped concrete elements subjected to torsional loads do not give a detailed insight, whereas this investigation is an attempt to address the issues with ferrocement “U” wrap. Twelve beams as shown in Figure (2-4) are tested under pure torsional loading. The variations considered are the number mesh layers in the ferrocement ‘U’ wrap and the state of torsion. To study the effect of number of mesh layers on torsional strength of four possible cases of states of torsion, the number of mesh layers is varied as 3, 4 and 5. The other parameters such as ferrocement matrix, core concrete and aspect ratio (2) for all beams are maintained constant. Rectangular beams of dimensions 125 mm width, 250 mm depth and 2000 mm length which includes a 25 mm thick ferrocement wrapping with layers of mesh wire are cast



Figure (2-4): Torsion test of the specimen by Gopal et. al. (2016).

Shraddha B. T. and Vijaykumar R. R., (2016) [8], Experimentally studied the torsional strengthening of RC beams using FRP. The experimental work included cast and test 39 rectangular beams with cross section 150mm × 300 mm and 1200 in length as shown in Figure (2-5). Three specimen were used as control specimens and thirty six specimens were classified into two groups. Using fabric wrapping, first group with CFRP and second group with GFRP. Torsional capacity of beams of two groups is compared with control specimen with respect to torsional moment, angle of twist and ductility factor and it was observed that CFRP fabric bonded beam shows more torsional strength than the GFRP bonded beam. The fully U-wrapped beam of all strengthening in type CFRP and GFRP has showed good increasing in torsional capacity.



Figure (2-5): Specimens tested by Shraddha B. T. and Vijaykumar R. R., (2016)

Ahmed et. al. (2020) [9], investigated the function of continuous spiral stirrups, as a transverse reinforcement with an inclination angle, to increase torsional capacity of hollow and solid reinforced concrete beams. The experimental work included testing of ten reinforced concrete beams with normal strength as shown in Figure (2-6a) and (2-6b). Two solid specimens with closed and spiral rectangular stirrups, and other eight specimens were hollow, one reinforced concrete specimen was reinforced by closed stirrups and other were reinforced concrete specimens reinforced with variable reinforcement ratio of rectangular spiral stirrups. Finite element analysis for all reinforced concrete beams using ANSYS program, was developed to study the possibility of the model to analysis all these beams and compared with experimental results. Good agreement in comparison between the results of ANSYS-15.0 program and experimental results was noticed.

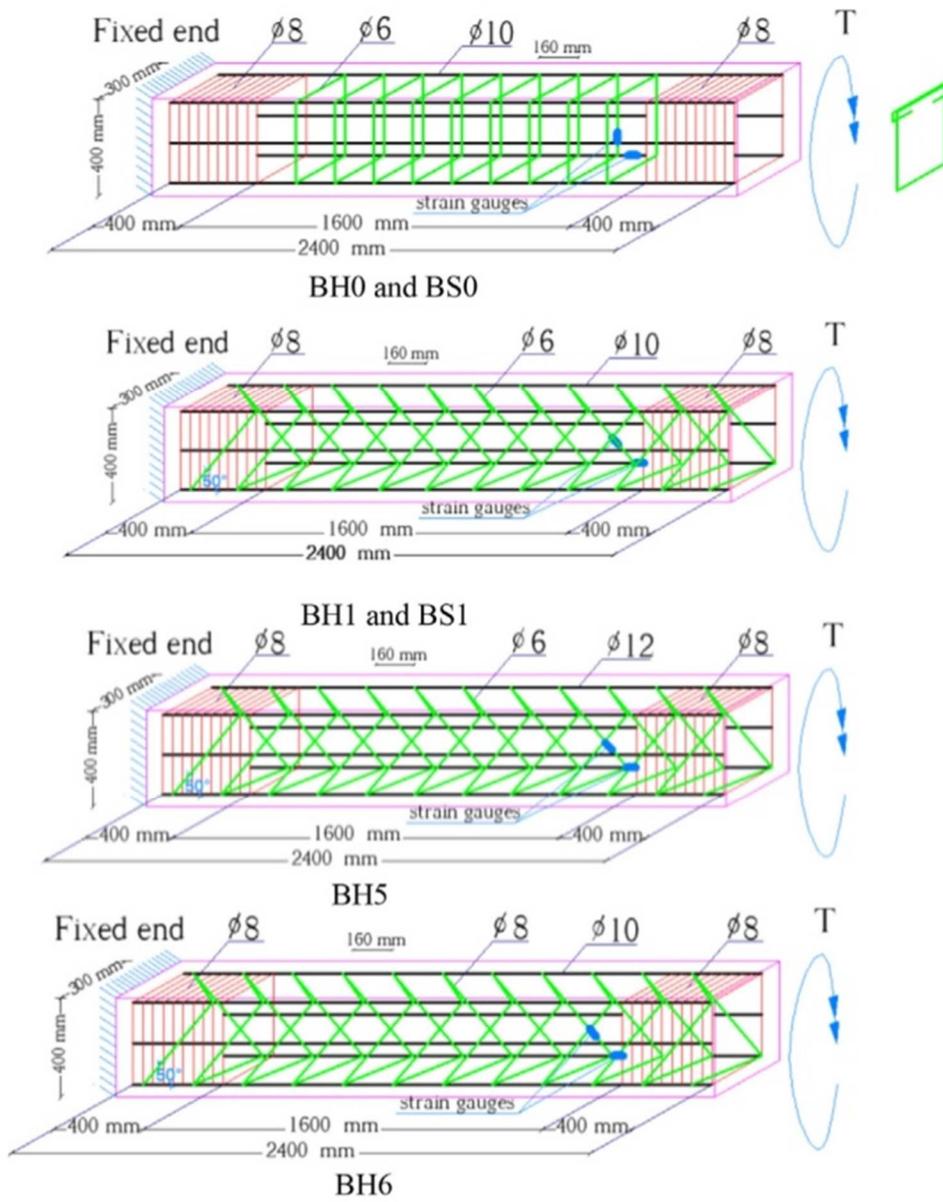


Figure (2-6a): Dimensions and reinforcement details of the tested beam by Ahmed et. al. (2020).

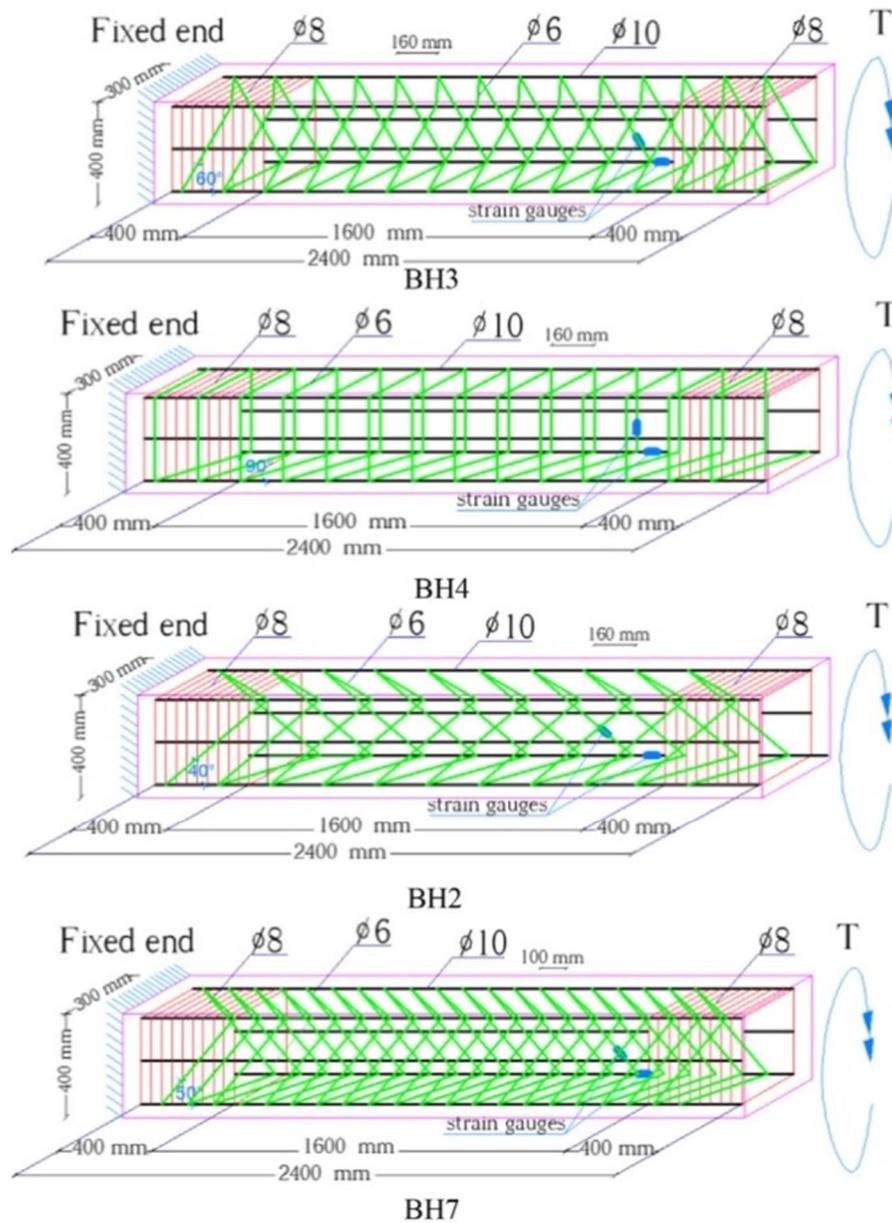


Figure (2-6b): Dimensions and reinforcement details of the tested beam by Ahmed et. al. (2020).

Milad A. H. and Shatha D. M, (2021) [10], studies the behavior of hooked and straight steel fiber reinforced concrete beam under the influence of combined torsional-flexural load. The experimental program included three fixed supported fiber reinforced concrete beams with dimensions 250mm width, 300mm depth and 1800mm length as shown in Figure (2-7).. All beams were of volume fraction

(1.5%) and same details, except their fibers type (no fiber, hook fiber, and straight fiber). From hardened concrete test results, it was concluded that beam of hooked steel fiber gave the best enhancing where the increase in the compressive reached to 33.37% and tensile strength to 55.08%, while straight fiber's improving was in the second order. Hooked steel fibers was more advanced to improve the strength against combined bending and torque forces. Also the considered types of fibers improved significantly the overall structural behavior of the reinforced concrete beams. Adding fibers increased the concrete ductility, the main first cracks in all fiber reinforced beams arisen after the reference beam (without fibers).

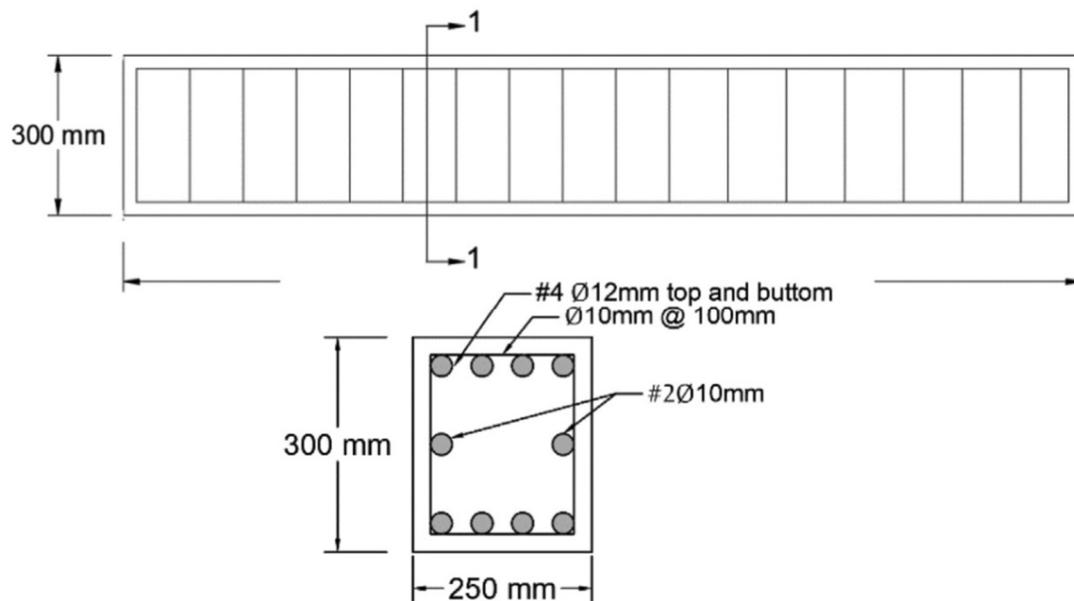


Figure (2-7): The specimens by Milad A. H. and Shatha D. M, (2021)

Sachin B. K. and Rajshekhar S. T, (2021) [11], Reinforced concrete beam strengthened with aramid fiber tested for torsional moment using two opposite lever arm subjected to equal point load which transfer equal torsional moment to the beam cross section. The dimensions of beam is 150 mm width 300 mm depth

and of 1000 mm in length as shown in Figure (2-8). In that three beams were designed for torsional reinforcement and nine as conventional beams. The study is restricted to aramid fiber fully wrapped and wrapped in strips at width 100 mm of U shape on three faces of beam by using epoxy resin. Experimental result includes ultimate loads capacity and first cracking loads, angle of twist and twisted shape of the beam. Result shows that fully wrapped reinforced concrete beam gives more torsional strength as compared to controlled beam and there is significant improvement in torsional strength of beams wrapped in strips.

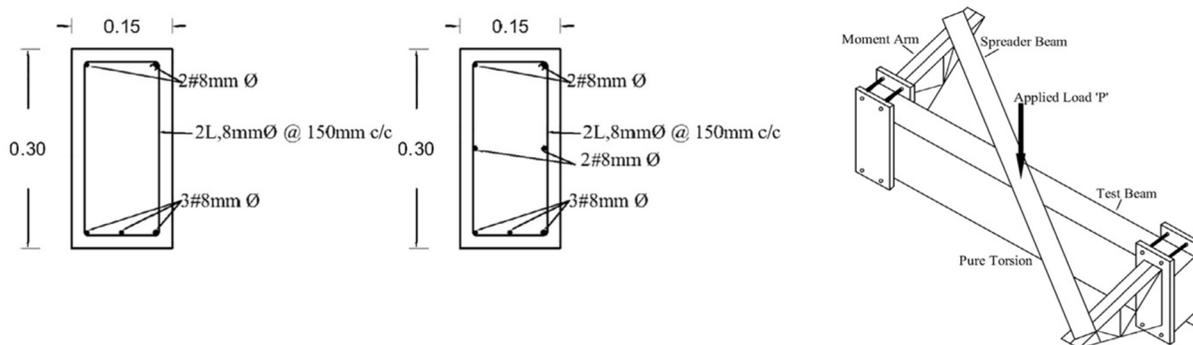


Figure (2-8): Dimension and detailed of tested beam by Sachin B. K. and Rajshekhar S. T, (2021)

2.3 Beam strengthening with ultra-high performance concrete

In-Hwan Yang et. al. (2013) [12], studied the torsional behavior of ultra-high performance concrete reinforced concrete specimens. Thirteen specimens with dimensions 300mm width and 300mm depth and 3000 mm length as shown in Figure (2-9). The specimens cast using from ultra-high performance concrete with strengths of concrete more than 150 MPa. The variables were the specimens quantity of steel fibers (SF) and ratio of longitudinal and transverse reinforcement. From tested results we indicated that the initial cracking and torsional capacity

increased when the quantity of SF increased. The cracking and ultimate torsional strength of beam with ratio of stirrup of 0.70% and longitudinal rebar ratio of 0.56% increased by 19% and 27%, respectively, when it contained a percent equal to 2% steel fiber compared to beam containing 1% steel fiber. Beam with a steel fiber content of 1%, a longitudinal rebar ratio of 0.56%, and a stirrup content of 0.70% showed improved ultimate torsional strength of 18% compared to that containing no stirrups.

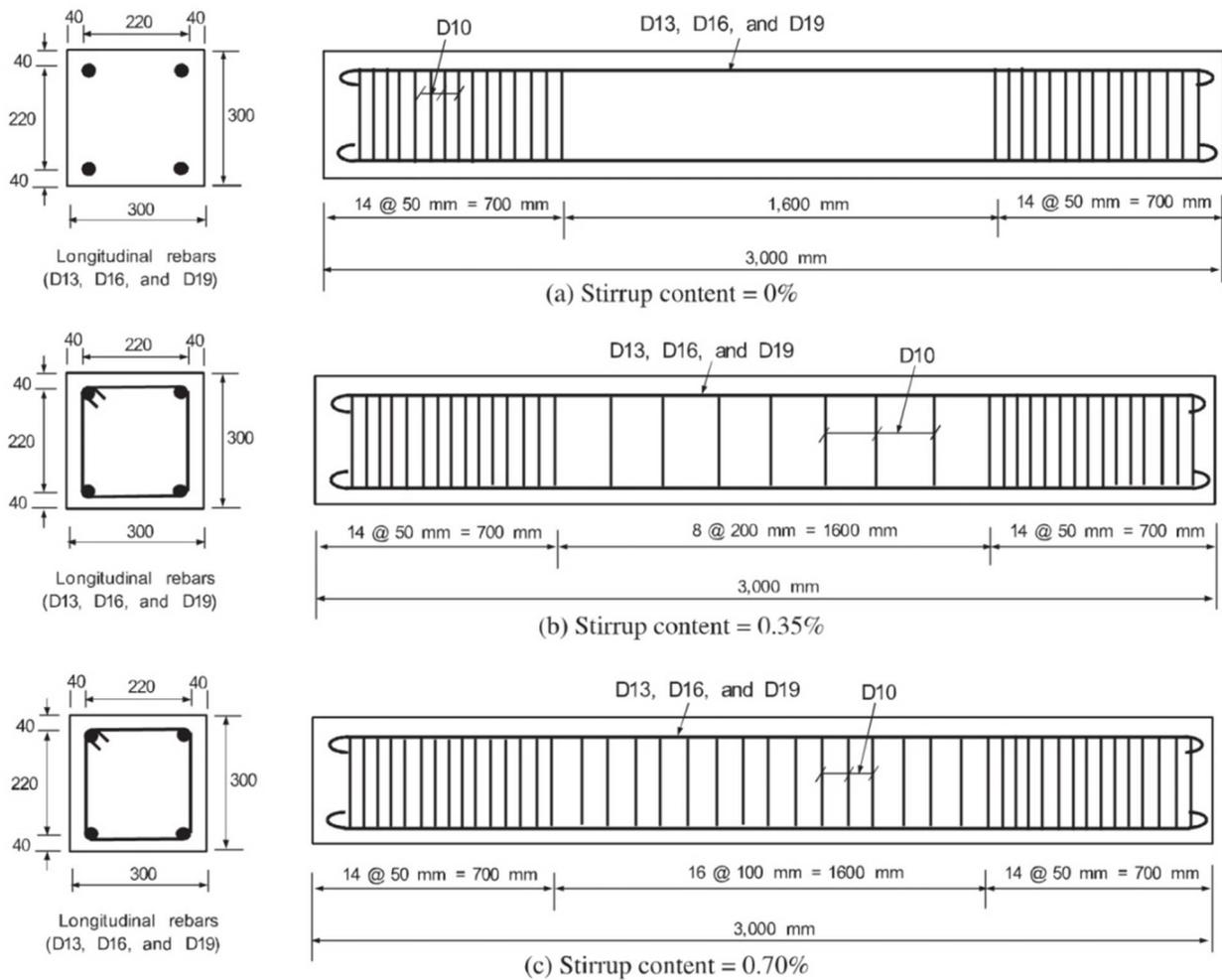


Figure (2-9): Beams detail tested by In-Hwan Yang et. al. (2013)

Mohammed I. and Ekkehard F., (2016) [13], tested a square cross section beams with dimensions of either 180*180 mm*2400 mm or 280*280 mm*1500 mm as shown in Figure (2-10). Experimental tests on small notched UHPC prisms cast simultaneously with the test beams for torsion in order to determine the efficiency of steel fiber showed that the values obtained from these tests may not necessarily reflect the actual fiber efficiency of the torsion test beams at the cracking surface. Experimental tests on notched prisms cut from the torsion test beams at the cracking surface after conducting the torsion tests showed values of fiber efficiency between 50 % to 65 % of the results from the first specimens of tests. The values obtained from the second specimens of tests were used in an analytical and FEM to determine the torsional carrying capacity of the beam. The comparison between the experimental and analytical results showed very good agreement.

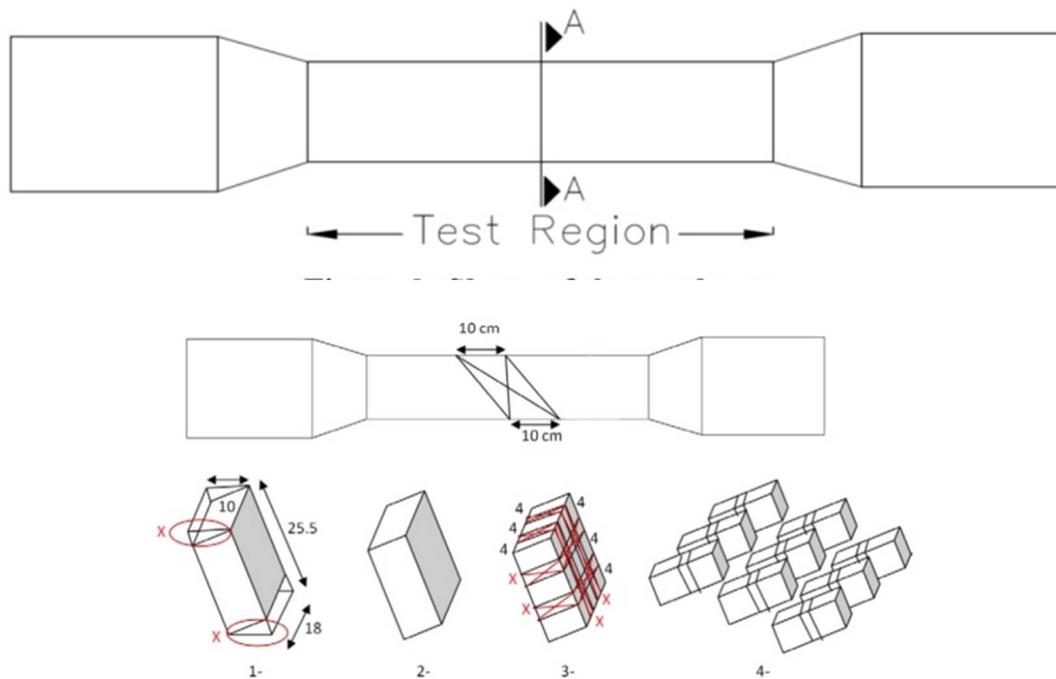


Figure (2-10): Tested beams by Mohammed I. and Ekkehard F., (2016).

Thaer Jasim Mohammed et. al. (2016) [14], investigated the efficiency work using UHPC reinforced concrete to strengthened RC beams under effect of torsion. Important advantages of the application of the applied ultra-high performance fiber jack...ets, are excellent rheological properties and high compressive and tensile strength. This study included strengthen all samples have different types of formations and thickness UHPC. Ten RC specimens with only longitudinal reinforcement (without any shear reinforcement) were strengthened with UHPC fiber on two, three, and four sides as shown in figure (2-11). Experimental results showed procedure of the this procedure at final torque for different specimens strengthening, behavioral curves and crack types.

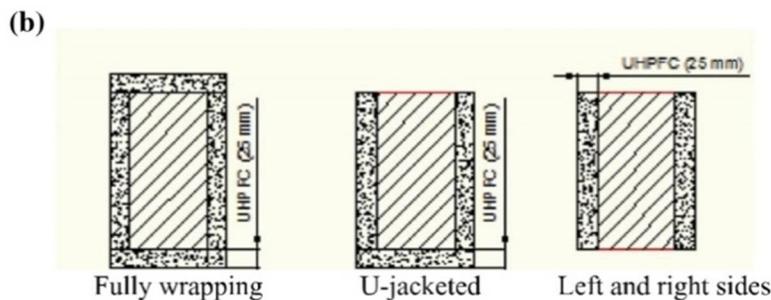
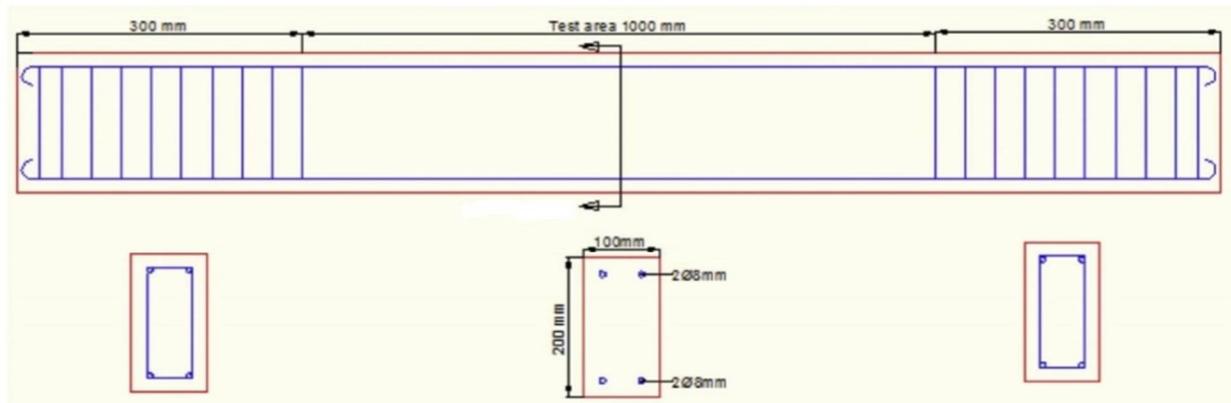


Figure (2-11): Geometry and strengthened details of tested beam by Thaer Jasim Mohammed et. al. (2016)

Sarah Jabbar et. al. (2019) [15], studied effects of a square opening in the solid reinforced concrete beam with different size dimensions on the behavior of beams under effect of loading. Materials with two types were used in this work, UHPC and high strength concrete. The FEM was developed to represent simply supported reinforced concrete beams under of flexural load. Four specimens were modeled: the solid section without opening and solid beams with openings of 100×100 mm, 200×200mm, and 300×300 mm as shown in Figure (2-12). Beams dimensions were clear span 6000mm, depth 600mm, and width 600 mm. Four RC beams were modeled using ultra-high-performance concrete and high strength concrete with openings in different dimensions, and nonlinear analysis was conducted by applying load steps. From the analysis, the results showed that web holes in the solid specimens reduced the capacity of the member, The small aperture of the solid in the specimens can also withstand almost the same load of the solid specimen without any aperture.

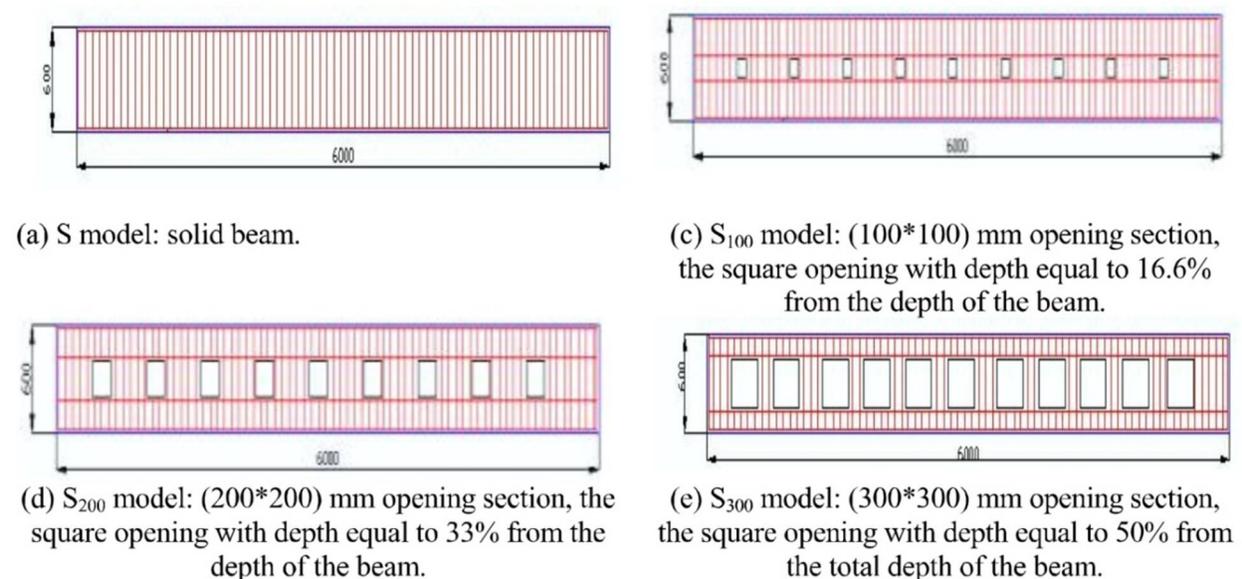


Figure (2-12): Modeled beams by Sarah Jabbar et. al. (2022).

2.4 Summary

This chapter is adopted to review many researches on subjects of RC beams under either torsion and combined bending and torsion. These researches are experimental works and theoretical solutions using many methods. The experimental strengthening made by general methods to increase torsional capacity of member.

In this research the experimental work including investigating the effect of strengthening by ultra-high strength concrete on the the behavior of reinforced concrete beam under combined bending and torsion.

Chapter Three

Experimental work

3.1 General

The object of this research is to investigate the effect of steel fiber and ultra-high performance concrete (UHPC) on ultimate loading capacity of simply supported reinforced concrete beams under effect of bending and torsion. The strengthening included many regions, cover, tension zone, compression zone and all section. Most of experimental investigation and researches have been suggested using UHPC in strengthening and repairing of reinforced concrete beams because of its good engineering properties [12], [13], [14] and [15].

3.2 Mix design and material properties.

According to ACI 211.4R 93 (Neville 2002) [16], three types of mix design used in this work are:

- Self-compacted concrete (SCC).
- Self-compacted concrete with 1% steel fiber (SCC+SF).
- Ultra-high performance concrete (UHPC).

The percentages of materials used in these mix design are shown in Tables (3-1) to (3-3).

Table (3-1): Mix design of self-compacted concrete

| Material | Quantity | Unit/m ³ |
|------------------|----------|---------------------|
| Cement | 500 | kg |
| Sand | 775 | kg |
| Gravel | 825 | kg |
| Water | 190 | Liter |
| Super stabilizer | 4.5 | Liter |

Table (3-2): Mix design of self-compacted concrete with 1% steel fiber

| Material | Quantity | Unit/m ³ |
|------------------|----------|---------------------|
| Cement | 500 | kg |
| Sand | 775 | kg |
| Gravel | 825 | kg |
| Water | 190 | Liter |
| Super stabilizer | 4.5 | Liter |
| Steel fiber | 79 | kg |

Table (3-3): Mix design of ultra-high performance concrete

| Material | Quantity | Unit/m ³ |
|------------------|----------|---------------------|
| Cement | 950 | kg |
| Sand | 1050 | kg |
| Water | 152 | Liter |
| Super stabilizer | 3.5 | Liter |
| Steel fiber | 158 | kg |
| Silica fume | 210 | kg |

Super stabilizer (Hyperplast PC200) is a high super plasticizing admixture with long chains can be used in high strength concrete, to achieve highest concrete durability and performance.

Steel fiber with specific gravity of 7800kg/m³ were used in mix design to increase concrete compressive strength, the characteristics of steel fiber are (0.2 mm) diameter, (13 mm) length and 2200 MPa tensile strength.

Micro silica fume, also known as silicon dioxide, silica. The main used of application for high performance concrete.

The reinforcement properties used in this experimental work are listed in Table (3-4), This table shows the degree of ultimate and yielding strength for every bar size, and depending on (ASTM A615-86).

Table (3-4): Reinforcement steel properties.

| Bar size | Actual diameter mm | Yield stress MPa | Ultimate strength MPa |
|----------|-----------------------|---------------------|--------------------------|
| 6 | 5.9 | 408 | 600 |
| 8 | 7.8 | 425 | 621 |
| 10 | 9.7 | 435 | 631 |

3.3 Description and details of the specimens

The experimental work consisted the testing of thirteen RC beams under bending and torsion strengthened by self-compacted concrete with steel fiber or ultra-high performance concrete. All beams had the same dimensions, the specimens cross section were (150 mm) width, (200 mm) depth and (1500 mm) length.

The control beam design for shear and flexural moments and checked for torsion capacity [17] and [18], as shown in appendix A.

The descriptions of these beams, flexural reinforcement, shear reinforcement and strengthening region by self-compacted concrete with steel fiber or ultra-high performance concrete are shown in the Table (3-5) and Figure (3-1).

Table (3-5): Reinforcement and material strengthening of casted beams.

| No | Beam Notation | Top reinf | Bottom reinf | Stirrups | Strengthening | |
|----|---------------|-----------|--------------|-------------|---------------|---------------------------|
| | | | | | Material | Region |
| 1 | CB1 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 56 mm | SC | ----- |
| 2 | FB2 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 56 mm | SC+SF | all middle third |
| 3 | UAB3 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 56 mm | UHPC | all middle third |
| 4 | U2SB4 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 56 mm | UHPC | 2-side (2cm) middle third |
| 5 | U3SB5 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 56 mm | UHPC | 3-side (2cm) middle third |
| 6 | UCB6 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 56 mm | UHPC | Comp zone all beam |
| 7 | UTB7 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 56 mm | UHPC | Ten zone all beam |
| 8 | U2SB8 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 56 mm | UHPC | 2-side (3cm) middle third |
| 9 | U3SB9 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 56 mm | UHPC | 3-side (3cm) middle third |
| 10 | U2SB10 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 66 mm | UHPC | 2-side (2cm) middle third |
| 11 | U3SB11 | 2 Ø 8 mm | 2 Ø 10 mm | Ø 6 @ 66 mm | UHPC | 3-side (2cm) middle third |
| 12 | UCB12 | 2 Ø 8 mm | 2 Ø 8 mm | Ø 6 @ 56 mm | UHPC | Comp zone all beam |
| 13 | UTB13 | 2 Ø 8 mm | 2 Ø 8 mm | Ø 6 @ 56 mm | UHPC | Ten zone all beam |

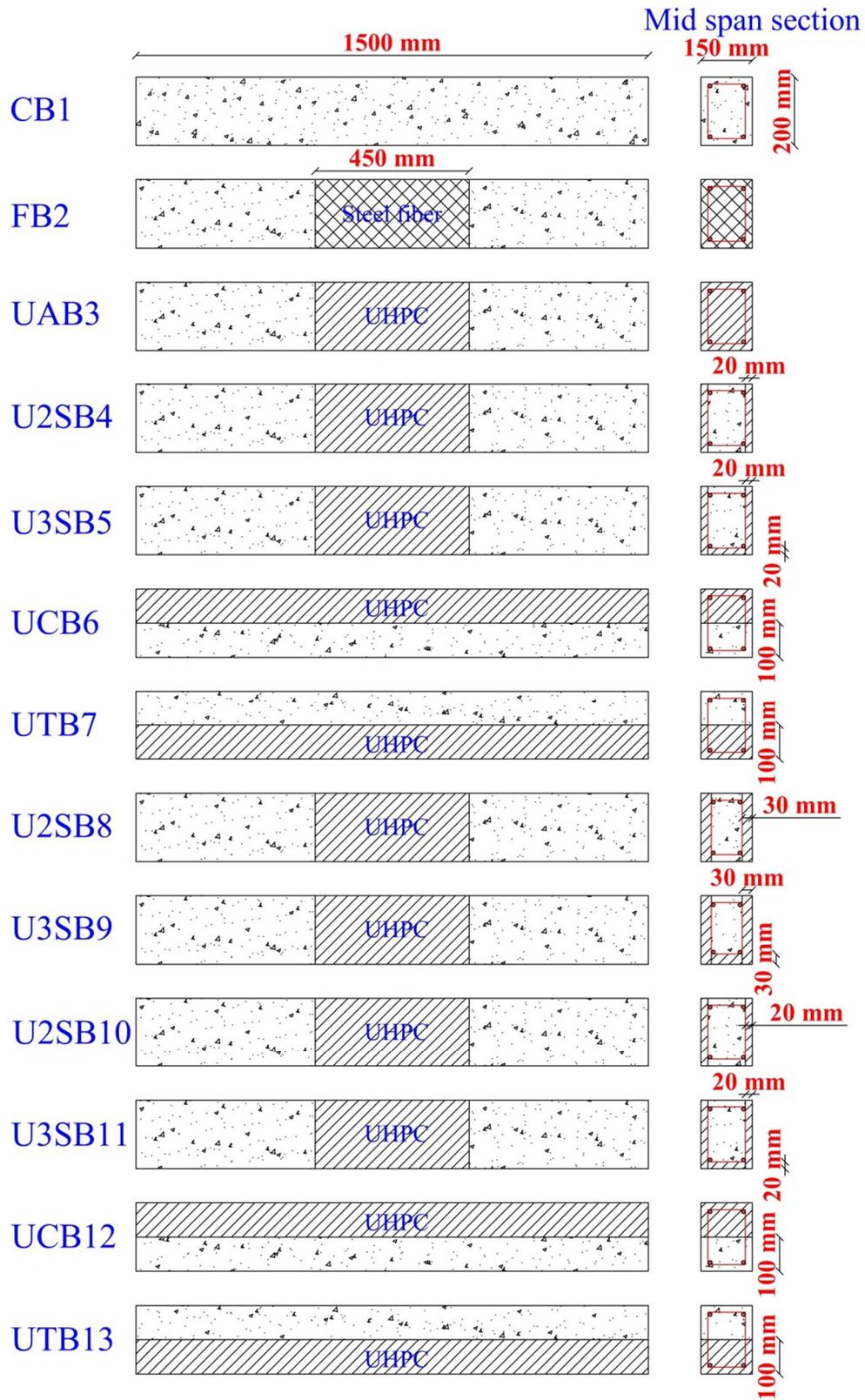


Figure (3-1): Region of strengthening of the casted beams

3.4 Casting of the specimens

In this work, wood moulds were used to cast all specimens as shown in Figures (3-2) and (3-3).



Figure (3-2): Reinforcement of casted beams



Figure (3-3): Wood mould of casted beams

The method of casting can be listed by the following stages.

- Before each casting, the wood moulds were oiled and put on horizontal surface.

- Put longitudinal reinforcement in the wood mould and use plastic cover under bars to maintain the designed cover for all the beams.
- The concrete was poured in the moulds, then electrical vibrator was used to vibrate the fresh concrete.
- The specimens were covered by sheet to prevent water evaporation during time of curing.

Cylinders, cubic and prisms were casted to find concrete compressive strength and rupture modulus as shown in Table (3-6).

Table (3-6): Compressive strength of concrete and modulus of rupture.

| Concrete type | Cylinder compressive strength of concrete MPa | Modulus of rupture MPa |
|--|--|---------------------------|
| Self-compacted concrete (SC). | 35 | 4.2 |
| Self-compacted concrete with 1% steel fiber (SC+SF). | 50 | 4.9 |
| Ultra-high performance concrete (UHPC). | 130 | 8.0 |

The first stage of casting includes prepare wood moulds and put the reinforcement, where the second stage includes casting by self-compacted concrete with steel fiber or ultra-high performance concrete according to strengthening region. Figures (3-4) to (3-6) show the specimens before and after strengthening by ultra-high performance concrete.



Figure (3-4): Specimens before strengthening by ultra-high performance concrete



Figure (3-5): Specimens after casting the ultra-high performance concrete



Figure (3-6): Specimens after complete curing and prepare to casting

3.5 Experimental program

All specimens were tested using one point load divided to two point load by steel beam one on each lever arm, where lever arm of 500 mm length as shown in Figures (3-7) to (3-9). The beam divided to three equal parts, the middle part were under bending and torsion due to location of lever arm. Rollers used at supports. Also, bearing plates under each load and support to avoid any crushing in concrete. Figures (3-10) and (3-11) show the machine used to test all the specimens.

Three dial gages used to record data, one at mid span to record deflection, other dial gages were put at ends of beam to record angle of twist as presented in the Figure (3-11).

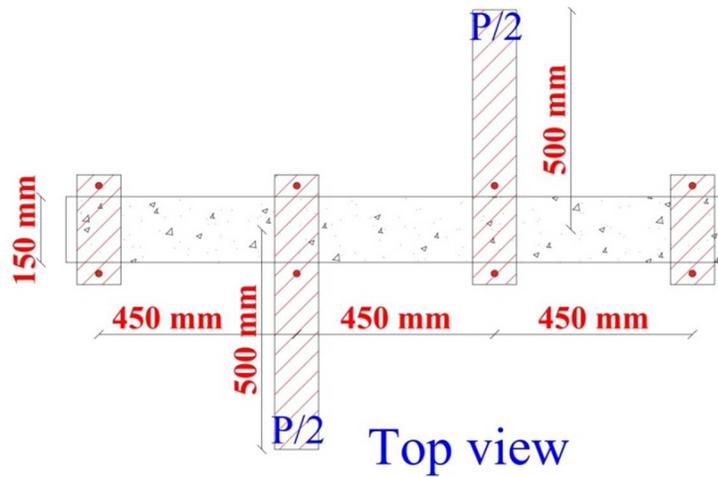


Figure (3-7): Top view of tested beam (details and dimensions)

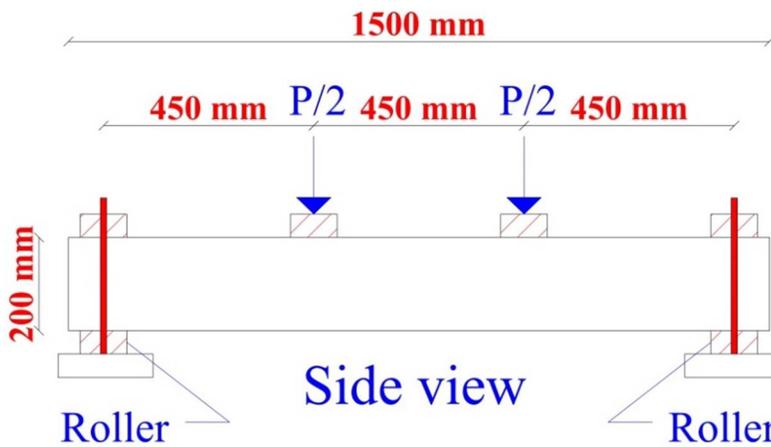


Figure (3-8): Side view of tested beam (details and dimensions)

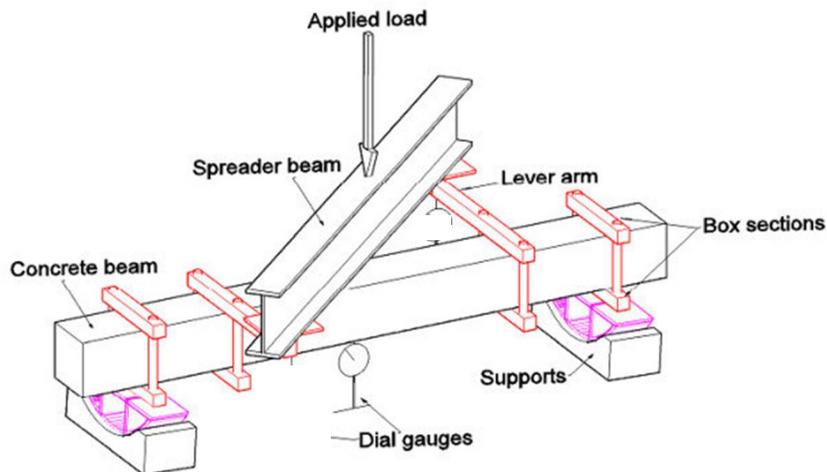


Figure (3-9): Isometric view for the tested beam



Figure (3-10): Middle part under bending and torsion



Figure (3-11): Setting the specimens in the testing machine

Chapter Four

Experimental Result and Discussion

4.1 Introduction

This chapter includes the results of thirteen beams tested under the combined effect of bending and torsion. The results recorded from the tested beams are cracking load, mid-span deflections at first cracking load, ultimate load and final mid-span deflections at ultimate load. Also crack patterns, load versus deflection curves and torque versus angle of twist at beam end are indicated in this chapter.

4.2 Test results

For the thirteen beams tested in this study, cracking load, mid-span deflections at first crack, ultimate load and final mid-span deflection are listed in Table (4-1).

From results of testing beams shown in Table (4-1) one can be noticed that:

- The beam number 1 named CB1 was control specimen.
- The beam number 2 named FB2 which strengthened using steel fiber in all sections of the middle third zone shows increase in loading carrying capacity of about 21% with respect to control specimen.
- The beam number 3 named UAB3 which strengthened using UHPC in all sections of the middle third zone shows excellent result in comparison with results of all strengthened beams, the increase in loading carrying capacity of about 95% with respect to control specimen.
- The beams number 4 and 5 named U2SB4 and U3SB5 which strengthened the cover (2cm) by UHPC in 2-side and 3-side respectively at the middle third zone

show an increase in loading carrying capacity of about 24% and 36% with respect to control specimen.

- The beams number 6 and 7 named UCB6 and UTB7 which strengthened the compression zone and tension zone along length of beam by UHPC respectively, show an increase in loading carrying capacity of about 17% and 38% with respect to control specimen.
- The beams number 8 and 9 named U2SB8 and U3SB9 which strengthened the cover (3cm) by UHPC in 2-side and 3-side respectively at the middle third zone show an increase in loading carrying capacity of about 2% and 14% with respect to control specimen.
- The beams number 10 and 11 named U2SB10 and U3SB11 which strengthening the cover (2cm) by UHPC in 2-side and 3-side respectively at the middle third zone and reducing the spacing of stirrups from $\text{Ø } 6 @ 56 \text{ mm}$ to $\text{Ø } 6 @ 66 \text{ mm}$ show a decrease in loading carrying capacity of by -7% for beam U2SB10 and an increase in loading carrying capacity of about 31% for beam U3SB11 with respect to control specimen.
- The beams number 12 and 13 named UCB12 and UTB13 which strengthened the compression zone and tension zone along length of beam by UHPC respectively and reducing the bottom reinforcement from $2 \text{ Ø } 10 \text{ mm}$ to $2 \text{ Ø } 8 \text{ mm}$ show a decrease in loading carrying capacity by -26% and -21% with respect to control specimen.

Table (4-1) Experimental results of all tested beams

| No | Beam Notation | Cracking load Pcr (kN) | Mid-span deflection at cracking load (mm) | Ultimate load Pu (kN) | Final mid-span deflections (mm) | $\frac{P_{cr}}{P_u}$ | Increase in ultimate load with respect to control beam |
|----|---------------|------------------------|---|-----------------------|---------------------------------|----------------------|--|
| 1 | CB1 | 12 | 0.90 | 42 | 7.20 | 29% | ----- |
| 2 | FB2 | 19 | 1.40 | 51 | 6.40 | 37% | 21% |
| 3 | UAB3 | 24 | 1.63 | 82 | 9.65 | 29% | 95% |
| 4 | U2SB4 | 15 | 1.48 | 52 | 5.86 | 29% | 24% |
| 5 | U3SB5 | 29 | 3.70 | 57 | 7.50 | 51% | 36% |
| 6 | UCB6 | 16 | 2.13 | 49 | 8.43 | 33% | 17% |
| 7 | UTB7 | 22 | 2.5 | 58 | 7.02 | 38% | 38% |
| 8 | U2SB8 | 18 | 0.81 | 43 | 4.52 | 42% | 2% |
| 9 | U3SB9 | 19 | 2.45 | 48 | 5.81 | 40% | 14% |
| 10 | U2SB10 | 14 | 1.30 | 39 | 6.95 | 36% | -7% |
| 11 | U3SB11 | 19 | 2.23 | 55 | 7.00 | 35% | 31% |
| 12 | UCB12 | 13 | 1.92 | 31 | 7.10 | 42% | -26% |
| 13 | UTB13 | 12 | 0.72 | 33 | 7.45 | 36% | -21% |

The experimental results for torques and angles of twist at end beams are shown in Table (4-2). From the results showed in this tables one can notice that the angles of twist decrease when the beam strengthening by steel fiber or by ultra-high performance concrete in comparison with the control beam.

The ratio of angles of twist of all beams with respect to the control beam decreases, which are ranged between 19% to 65%.

Table (4-2) Experimental results torque and angle of twist

| No | Beam Notation | Ultimate load at failure (kN) | Ultimate torque at failure (kN.m) | Angle of twist at failure (degree) | Ratio of angles of twist with respect to control beam |
|----|---------------|-------------------------------|-----------------------------------|------------------------------------|---|
| 1 | CB1 | 42 | 21 | 3.96 | ----- |
| 2 | FB2 | 51 | 25.5 | 0.92 | 23% |
| 3 | UAB3 | 82 | 41 | 2.22 | 56% |
| 4 | U2SB4 | 52 | 26 | 1.31 | 33% |
| 5 | U3SB5 | 57 | 28.5 | 1.79 | 45% |
| 6 | UCB6 | 49 | 24.5 | 1.89 | 47% |
| 7 | UTB7 | 58 | 29 | 2.59 | 65% |
| 8 | U2SB8 | 43 | 21.5 | 0.80 | 20% |
| 9 | U3SB9 | 48 | 24 | 1.87 | 47% |
| 10 | U2SB10 | 39 | 19.5 | 1.47 | 37% |
| 11 | U3SB11 | 55 | 27.5 | 1.26 | 32% |
| 12 | UCB12 | 31 | 15.5 | 1.83 | 46% |
| 13 | UTB13 | 33 | 16.5 | 0.77 | 19% |

4.3 Crack patterns

All tests of specimens were carried out using a hydraulic machine, the steel frame used in test divided the specimens to three parts, the first and last part are under effect of bending and shear without torsion, while the middle part under effect of bending and torsion with zero shear.

The crack patterns for all tested strengthened beams show approximately same behavior from first cracking to final cracking at failure as shown in Figures (4-1) to (4-6) and good behavior than control beam without strengthening.

At starting steps of loadings, cracks appear in middle third of beam starting by vertical flexural crack at bottom face then diagonal torsional crack where maximum bending and torsion in this region zone.

After increasing loading value during testing, these cracks for bending and torsion at middle part increased in length and numbers, then another flexural cracks appear at first and last parts where these region under effect of bending and shear.

At final steps of loadings up to failure, another shear cracks appear at first and last parts, finally failure occurs by combined flexural and shear cracks at middle part.



Figure (4-1): Crack pattern at middle third of tested beam



Figure (4-2): Crack type of CB1



Figure (4-3): Crack type of UAB3



Figure (4-4): Crack type of U2SB4



Figure (4-5): Crack type of U3SB5



Figure (4-6): Crack type of UCB6

4.4 Load versus mid-span deflection results

Experimental inquiry at the behavior of load against mid-span deflection curves for all specimens are presented in this section.

Figure (4-7) shows the comparison of the load deflection curves between the control beam CB1 and two strengthening beams FB2 and UAB3, which strengthened by SF and UHPC respectively. From this figure, it can be concluded that the beam strengthening by UHPC showed more stiffness of control beam CB1, also the beam strengthening by SF showed more stiffness from control beam CB1

but less than the beam strengthening by UHPC. This behavior due to agreed properties of UHPC and SF concrete.

Figure (4-8) shows the comparison of the load deflection curves between the control beam CB1 and three strengthening beams; U2SB4, U2SB8 and U2SB10, which strengthened includes 2-side for these beams by 2 cm cover (UHPC) ($\text{Ø } 6 @ 56 \text{ mm}$), 3 cm cover (UHPC) ($\text{Ø } 6 @ 56 \text{ mm}$) and 2 cm cover (UHPC) ($\text{Ø } 6 @ 66 \text{ mm}$) respectively. This figure shows approximately same behavior in linear stage and more stiffness at final stage for beam strengthened by UHPC.

Figure (4-9) shows the comparison of the load deflection curves between the control beam CB1 and three strengthening beams; U2SB5, U2SB9 and U2SB11, which strengthened includes 3-side for these beams by 2 cm cover (UHPC) ($\text{Ø } 6 @ 56 \text{ mm}$), 3 cm cover (UHPC) ($\text{Ø } 6 @ 56 \text{ mm}$) and 2 cm cover (UHPC) ($\text{Ø } 6 @ 66 \text{ mm}$) respectively, one can see an approximately same behavior in linear stage and more stiffness at final stage for beam strengthened by UHPC.

Figure (4-10) shows the comparison of the load deflection curves between the control beam CB1 and two strengthening beams UCB6 and UCB12. These beams strengthened the compression zone along length of beam by UHPC and reducing the bottom reinforcement from 2 $\text{Ø } 10 \text{ mm}$ to 2 $\text{Ø } 8 \text{ mm}$ for beam UCB12. It can be noted that the beam UCB6 shows more stiffness of control beam CB1 and UCB12 due to the effect of strengthening by UHPC. While UCB12 shows lower stiffness due to reducing bottom reinforcement.

Figure (4-11) shows the comparison of the load deflection curves between the control beam CB1 and two strengthening beams; UCB7 and UCB13, these beams strengthened the tension zone along length of beam by UHPC and reducing the bottom reinforcement from 2 $\text{Ø } 10 \text{ mm}$ to 2 $\text{Ø } 8 \text{ mm}$ for beam UCB13. It can be

noted that the beam UCB7 shows more stiffness of control beam CB1 and UCB13 due to the effect of strengthening by UHPC, while UCB13 show low stiffness due to reducing bottom reinforcement.

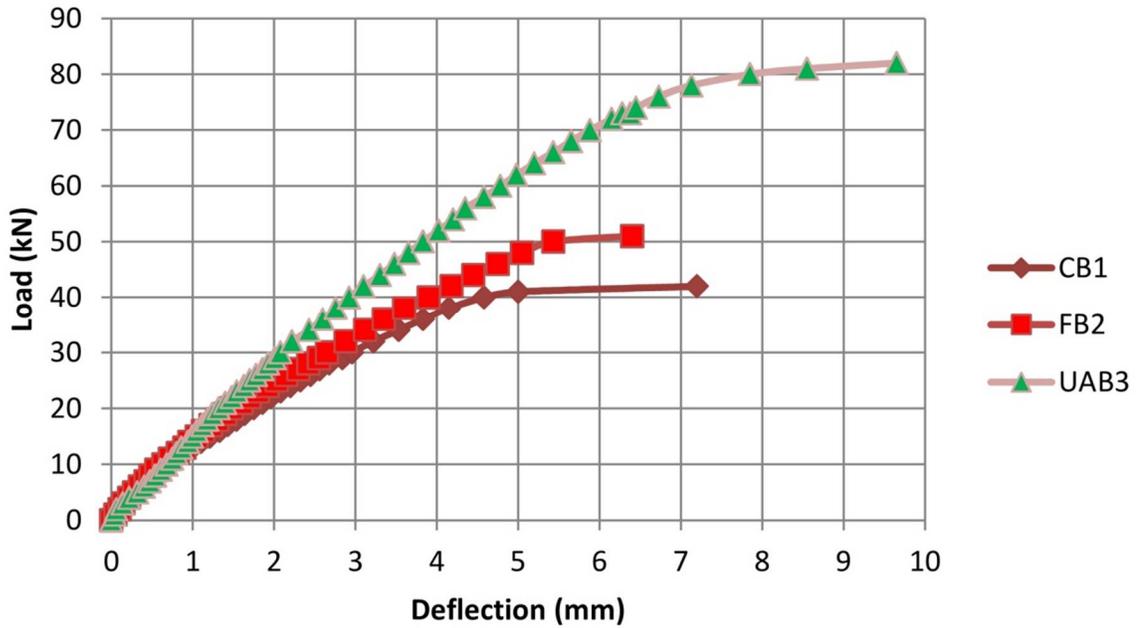


Figure (4-7): Load against mid-span deflections for CB1, FB2 and UAB3

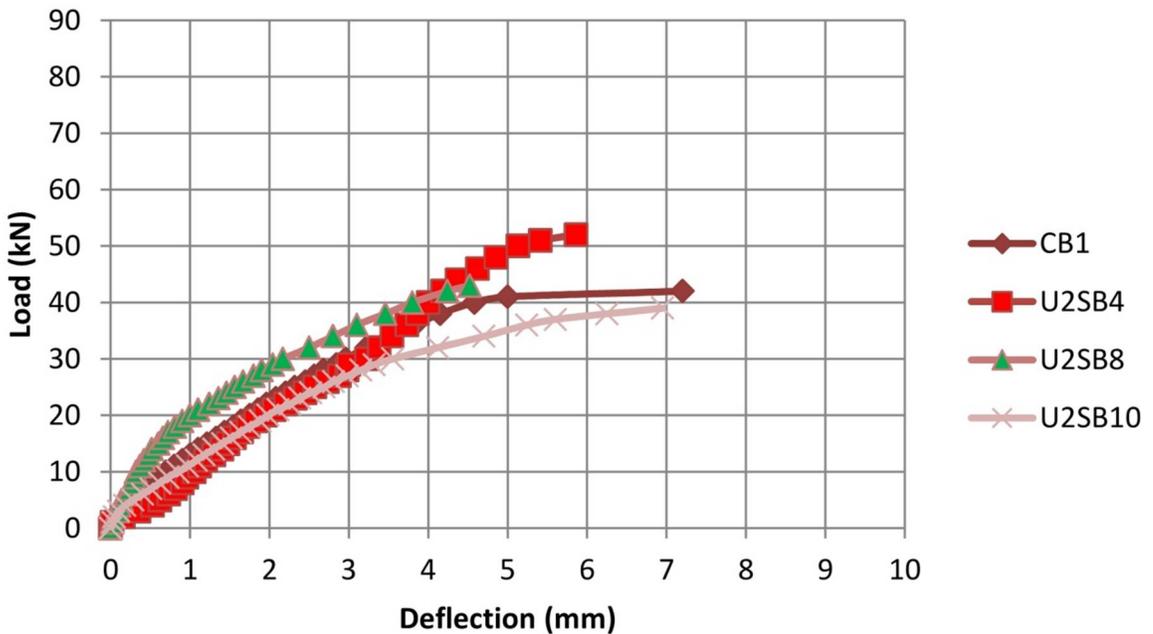


Figure (4-8): Load against mid-span deflections for CB1, U2SB4, U2SB8 and U2SB10

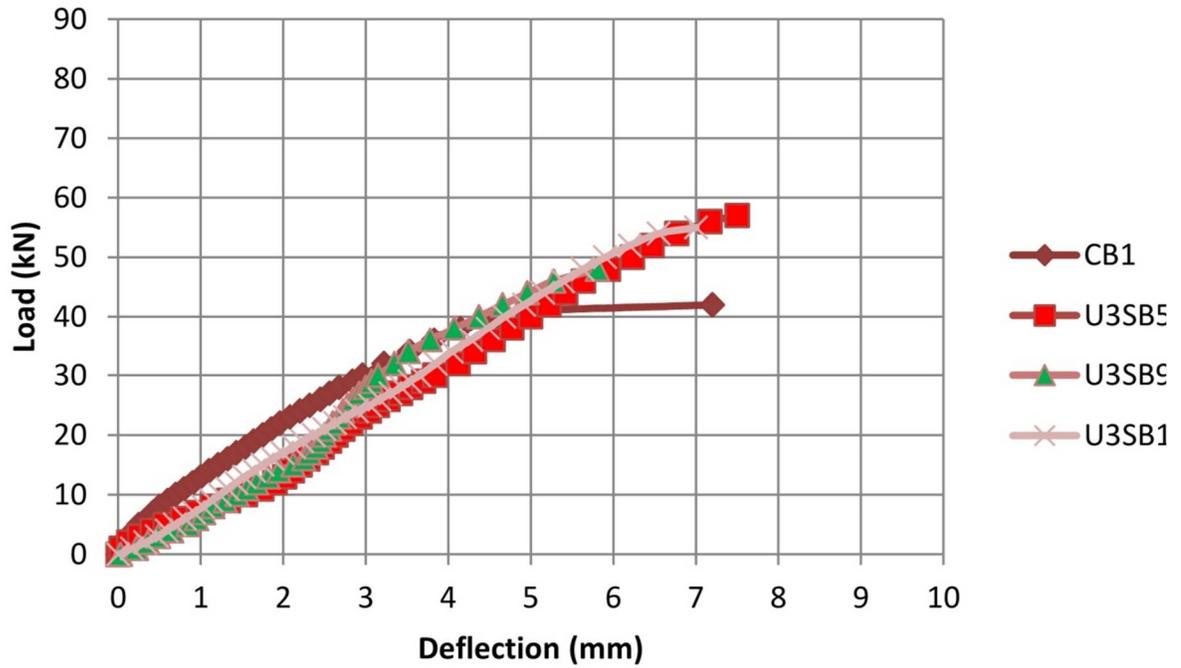


Figure (4-9): Load against mid-span deflections for CB1, U3SB5, U3SB9 and U3SB11

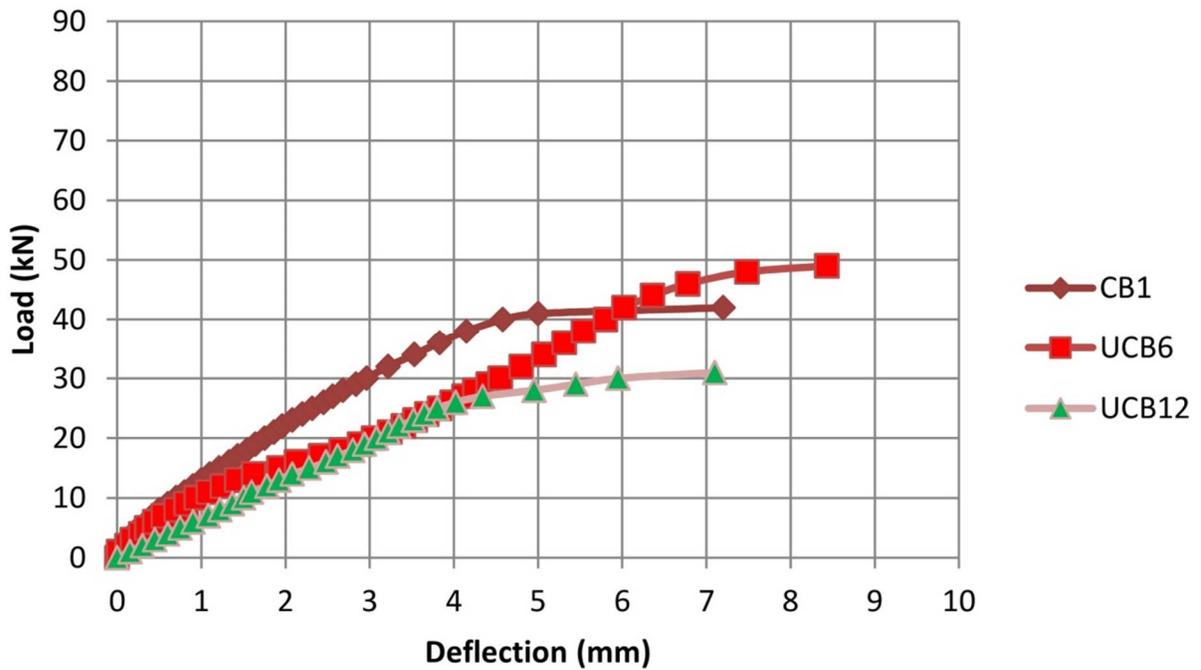


Figure (4-10): Load against mid-span deflections for CB1, UCB6 and UCB12

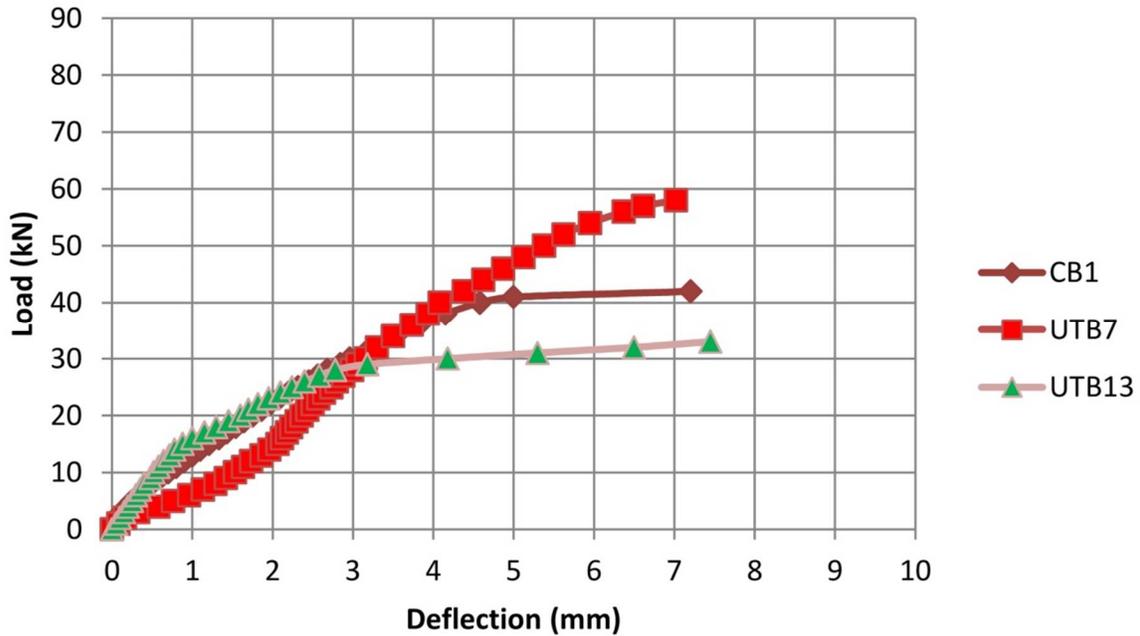


Figure (4-11): Load against mid-span deflections for beams CB1, UTB7 and UTB13

4.5 Torque and angle of twist results

Thirteen reinforced concrete beams under effect of bending and torsion were strengthened by SF and UHPC to examine the effect of strengthening on angle of twist of the beams. Experimental investigation on the behavior of torque versus angle of rotation for these beams are presented in this section.

Figures (4-12) to (4-16) show a comparison for the torque versus angle of twist curves for all specimens. From these figures, it can be noted that the angle of twist decrease for strengthened beams in comparison with the control beams.

Also from these figures it can be noted that approximately same behavior in first stage for all beams and at other stages of loading, the effect of strengthening of angle of twist begin to appear.

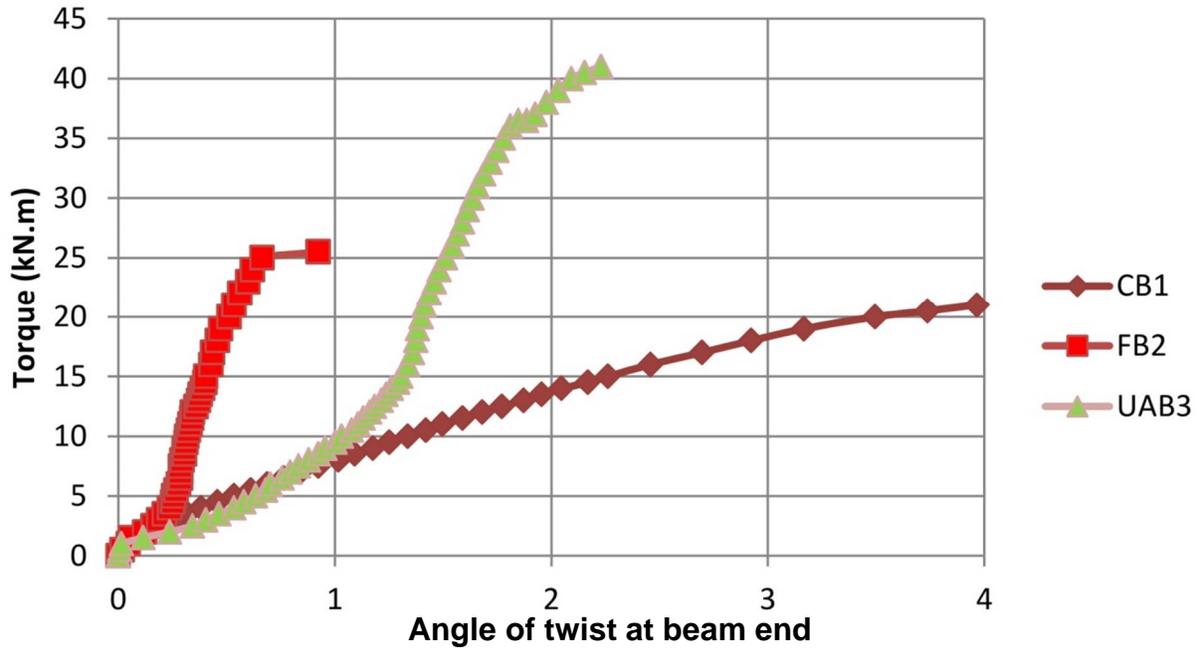


Figure (4-12): Torque against angle of twist at beams end CB1, FB2 and UAB3

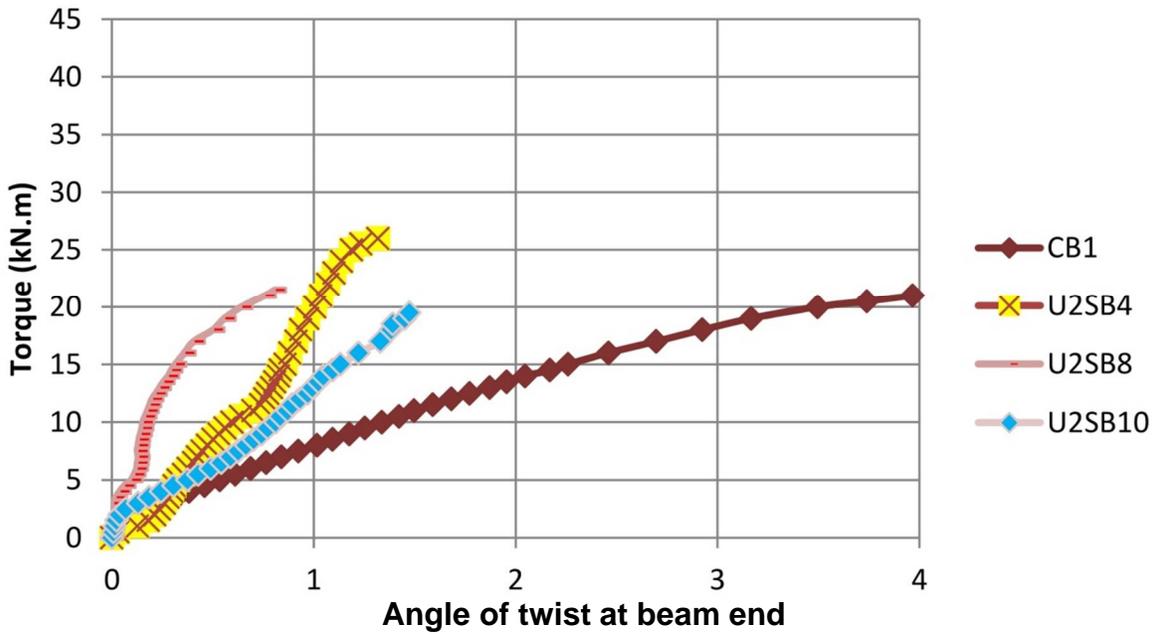


Figure (4-13): Torque against angle of twist at beams end CB1, U2SB4, U2SB8 and U2SB10

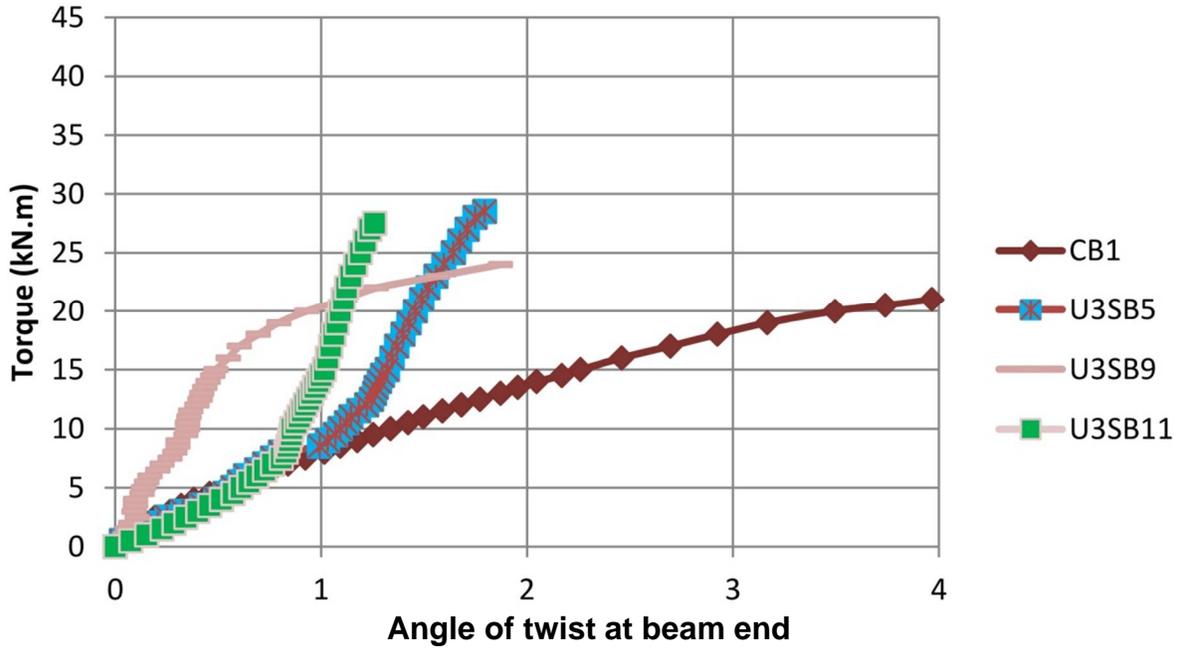


Figure (4-14): Torque against angle of twist at beams end CB1, U3SB5, U3SB9 and U3SB11

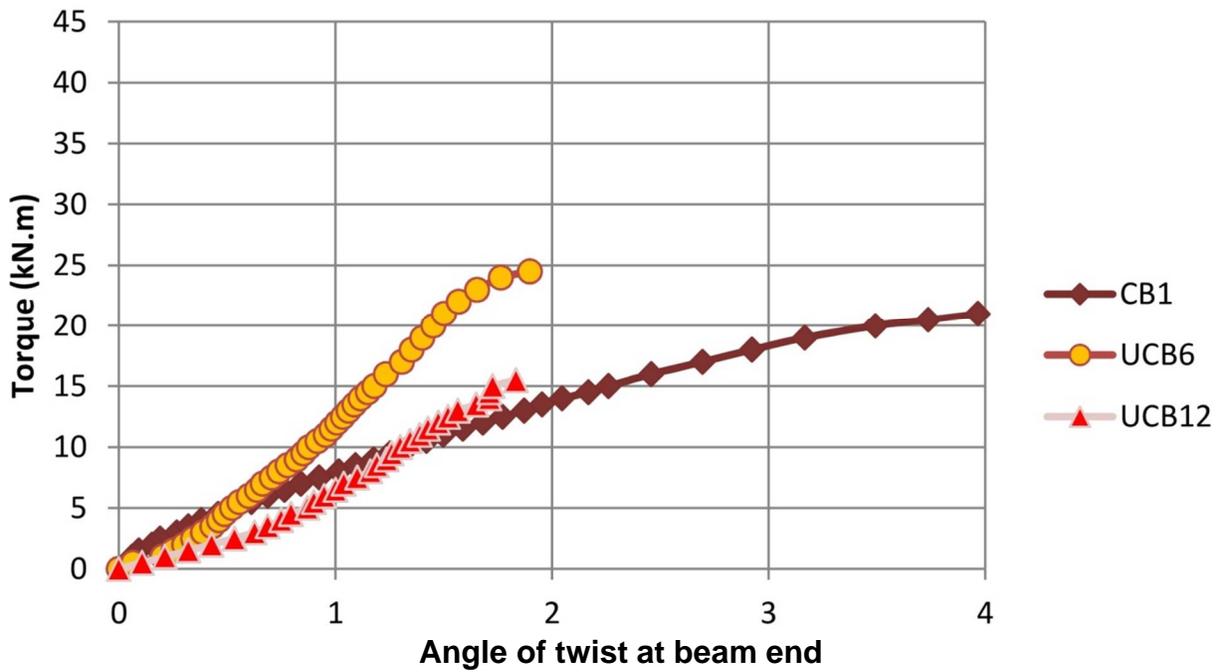


Figure (4-15): Torque against angle of twist at beams end CB1, UCB6 and UCB12

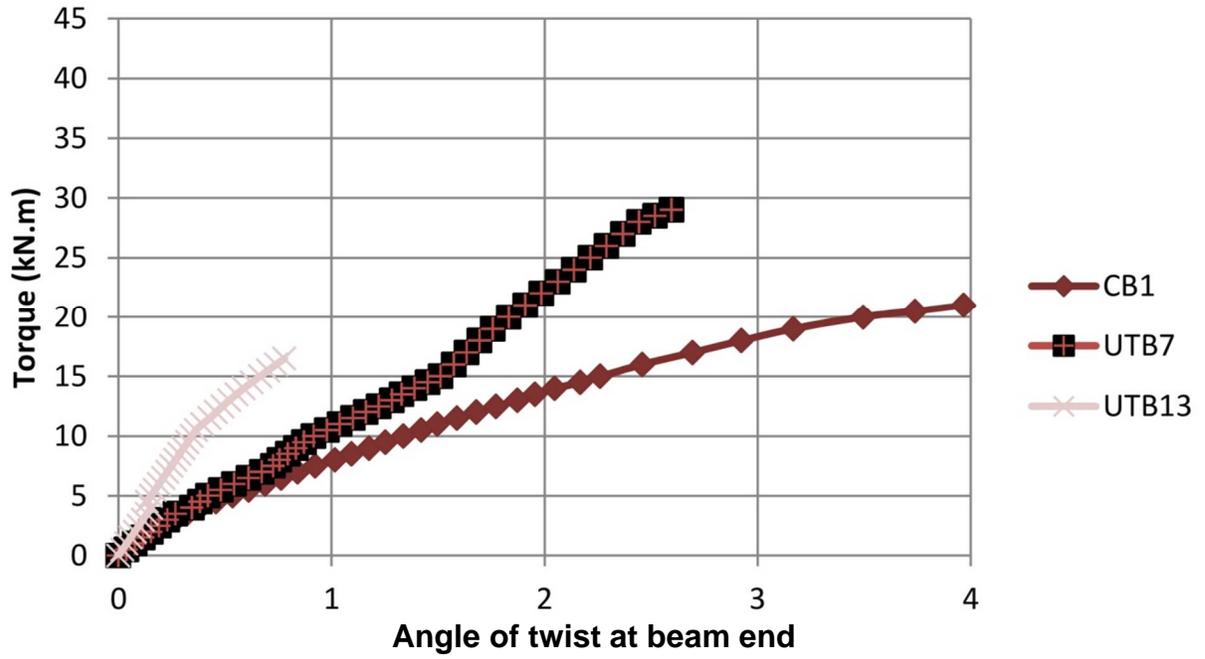


Figure (4-16): Torque against angle of twist at beams end U2SB8 CB1, UTB7 and UTB13

Chapter Five

Conclusion and Recommendation for Future Work

5.1 General

The work contained in this research is at the first place concerned on studying ultimate load capacity of RC beams strengthened by self-compacted concrete with steel fiber or ultra-high performance concrete. The experimental work consisted of testing thirteen simply supported beams under combined the effect of bending and torsion. The beams dimensions were 150mm width, 200 mm depth and 2000mm length. The results indicated that the strengthening adopted in this research significantly increases the ultimate torsion capacity of the considered specimens.

5.2 Conclusion

Based on the overall experimental results obtained for reinforced concrete beams strengthened by self-compacted concrete with steel fiber or ultra-high performance concrete in different configurations the following conclusions can be drawn as follows:

1. The beam strengthened using steel fiber in all sections of the middle third zone show increase in capacity of up to 21% with respect to the control beam.
2. Specimens strengthened using ultra-high performance concrete in all sections of the middle third zone showed excellent result in comparison with the results of all strengthened beams, the increase in capacity up to 95% with respect to the control beam.

3. The beams strengthened using ultra-high performance concrete with cover 2cm in 2-side and 3-side at the middle third zone showed increasing capacity of about 24% and 36% respectively with respect to the control beam.
4. Specimens strengthened by ultra-high performance concrete the compression zone and tension zone along all lengths, showed increase in capacity equal to 17% and 38% respectively with respect to the control beam.
5. Specimens strengthened using ultra-high performance concrete for cover 3cm in 2-side and 3-side at the middle third zone showed increase in capacity equal to 2% and 14% respectively with respect to the control beam.
6. Ultra-high performance concrete strengthened beams for cover equal to 2cm in 2-side and 3-side at the middle third zone and reducing the spacing of stirrups from $\text{Ø } 6 @ 56 \text{ mm}$ to $\text{Ø } 6 @ 66 \text{ mm}$ showed decrease in load carrying capacity equal to -7% and increase capacity to 31% respectively with respect to the control beam.
7. Ultra-high performance concrete for the compression zone and tension zone along all length and reducing the bottom reinforcement from 2 $\text{Ø } 10 \text{ mm}$ to 2 $\text{Ø } 8 \text{ mm}$ showed decrease in load carrying capacity equal to -26% and -21% respectively with respect to the control beam.
8. The ratio of angles of twist of all strengthening beams with respect to the control beam decreased, the reductions ranged between 19% to 65%.

5.3 Future work recommendations

The behavior of reinforced concrete beams repaired or strengthened by ultra-high performance concrete requires further investigation. The following recommendations are suggested:

- 1- Studying the behavior of strengthening reinforced concrete beams by UHPC under effect of bending, shear and torsion.
- 2- Studying the behavior of strengthening reinforced concrete beams by UHPC containing opening with different sizes and locations under effect of bending torsion.
- 3- A similar experimental program can be conducted for strengthened reinforced concrete T-section beams.
- 4- Same experimental program can be extended to repair reinforced concrete beams exposed to fire.
- 5- Repairing of damage reinforced concrete beams using ultra-high performance concrete in zone under maximum shear.

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Appendix A

Beam dimensions (150 mm) width, (200 mm) depth and (1500 mm) length

Clear span=1350 mm

Assume

Top reinforcement (2 Ø 8 mm), bottom reinforcement (2 Ø 10 mm), Stirrups Ø 6 @ 56 mm, $f_y=420$ MPa and $f_c=35$ MPa.

Beam with two point load lies at distance $L/3$ from each support (450 mm).

Lever arm for torsion =500mm

Total load=P,

From analysis maximum moment= $0.225P$, maximum shear = $0.5P$ and maximum torque = $0.25P$.

$d= 169$ mm, $b=150$ mm, $\rho=0.00619$

$M_n = \rho b d^2 f_y \left(1 - 0.59 \rho \frac{f_y}{f_c'}\right) = 10.64$ kN.m, **P=47.28 KN**

$0.5P = V_c + V_s$, $V_c = V_c = 0.16 \sqrt{f_c'} b_w d = 25.49$ kN, $V_s = \frac{d}{s} A_v f_y = 71$ kN, **P=192 KN**

$T = (2 * 0.85 * A_{oh} A_t f_y c o t \theta) / s = 0.5P$, **P=11.63 kN**

خلاصة

الهدف الرئيسي من هذا البحث هو التحقيق في تأثير الخرسانة فائقة الأداء (UHPC) على قدرة تحمل الاعتاب الخرسانية المسلحة المسندة البسيطة تحت تأثير الانحناء والالتواء سويًا. التقوية تشمل عدة مناطق، الغطاء، منطقة الشد، منطقة الضغط وكل المقطع. يتكون البرنامج العملي من صب وفحص ثلاثة عشر نموذج من الاعتاب الخرسانية المسلحة المسندة البسيطة المقواة بخرسانة مرصوفة ذاتيا بألياف فولاذية أو خرسانة فائقة الأداء تحت تأثير الانحناء والالتواء. ابعاد تلك العينات هي 150 ملم عرض و 200 ملم ارتفاع و 1500 ملم طول.

بشكل عام ، تم الحصول على قدرة تحميل أعلى للأعتاب المقواة بألياف فولاذية أو الخرسانة فائقة الأداء مقارنة بالعتب النموذجي. ، ان الاعتاب المقواة باستخدام الألياف الفولاذية في كل المقطع للجزء الوسطي تظهر زيادة في التحمل بحوالي 21%، في حين أن العتب المقواة باستخدام الخرسانة فائقة الأداء في كل المقطع للجزء الوسطي تظهر نتيجة ممتازة بزيادة في التحمل بنسبة 95% بالمقارنة مع العتب النموذجي. كما أن الاعتاب المقواة باستخدام الخرسانة فائقة الأداء للغطاء 2 سم في جانبيين وثلاث جوانب في الجزء الوسطي تظهر زيادة في التحمل بنسبة 24% و 36% على التوالي. علاوة على ذلك ، فإن استخدام الخرسانة فائقة الأداء في مناطق الضغط والشد بطول كامل العتب يظهر زيادة في التحمل تعادل 17% و 38% على التوالي. كما أن الاعتاب المقواة باستخدام الخرسانة فائقة الأداء للغطاء 3 سم في جانبيين و ثلاث جوانب في المنطقة لوسطى تظهر زيادة في التحمل تساوي 2% و 14% على التوالي. بينما تم تقوية الاعتاب باستخدام الخرسانة فائقة الأداء عند الغطاء 2 سم في جانبيين و ثلاث جوانب في المنطقة الوسطى وتقليل تباعد حديد تسليح القص حوالي 15% تظهر انخفاضاً في التحمل بنسبة 7% وزيادة في التحمل إلى 31% على التوالي. كما تم تقوية الاعتاب باستخدام الخرسانة فائقة الأداء لمناطق الضغط والشد بطول كامل وتقليل حديد التسليح الاسفل بنسبة 36% يظهر انخفاض في التحمل يساوي -26% و -21% على التوالي.

تنخفض زوايا الالتواء عند تقوية الاعتاب بألياف فولاذية أو بالخرسانة فائقة الأداء مقارنة بالعتب النموذجي. تتناقص نسبة زوايا الالتواء لكل عتب بالنسبة للعتب النموذجي، والتي تتراوح بين 19% إلى 65%.



جمهورية العراق

وزارة التعليم العالي والبحث العلمي

جامعة بابل

كلية الهندسة

قسم الهندسة المدنية

تحسين تصرف الاعتاب الخرسانية المسلحة المعرضة للانحناء والالتواء

بحث

مقدم الى كلية الهندسة / جامعة بابل كجزء من متطلبات نيل درجة الدبلوم العالي في الهندسة/

الهندسة المدنية / الانشاءات

من قبل

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