International Journal of Engineering Research And Management (IJERM)
ISSN : 2349- 2058, Volume-02, Issue-04, April 2015

STUDY OF TORSIONAL BEHAVIOUR OF RECTANGULAR REINFORCED CONCRETE BEAMS WRAPPED WITH GFRP

Mayank Varshney, Meenu Varshney, Nitesh Gupta

Abstract— **Reinforced concrete (RC) beams have been found to be deficient in torsion resisting capacity and in cases where Torsional moments are substantial there is a need of strengthening these beams to resist these moments. These deficiencies occur for several reasons.**

Investigations have been done on concrete beams retrofitted with glass fiber reinforced polymer (GFRP) composites in order to study the enhancement of strength and ductility, durability, effect of confinement, preparation of design guidelines and experimental investigations of these members.

Index Terms— **GFRP: Glass Fibre Reinforced Polymer RC: Reinforced Concrete**

I. INTRODUCTION

1.1 OVERVIEW

During its whole life span, nearly all engineering structures ranging from residential buildings, an industrial building to power stations and bridges faces degradation or deteriorations. The main causes for those deteriorations are environmental effects including corrosion of steel, gradual loss of strength with ageing, variation in temperature, freeze-thaw cycles, repeated high intensity loading, contact with chemicals and saline water and exposure to ultra-violet radiations. Addition to these environmental effects earthquakes is also a major cause of deterioration of any structure. This problem needs development of successful structural retrofit technologies. So it is very important to have a check upon the continuing performance of the civil engineering infrastructures.

The structural retrofit problem has two options, repair/retrofit or demolition/reconstruction. Demolition or reconstruction means complete replacement of an existing structure may not be a cost-effective solution and it is likely to become an increasing financial burden if upgrading is a viable alternative. Therefore, repair and rehabilitation of bridges, buildings, and other civil engineering structures is very often chosen over reconstruction for the damage caused due to degradation, aging, lack of maintenance, and severe earthquakes and changes in the current design requirements.

Previously, the retrofitting of reinforced concrete structures, such as columns, beams and other structural elements, was done by removing and replacing the low quality or damaged concrete or/and steel reinforcements with new and stronger material. However, with the introduction of new advanced composite materials such as fiber reinforced polymer (FRP) composites, concrete members can now be easily and effectively strengthened using externally bonded FRP composites

Retrofitting of concrete structures with wrapping FRP sheets provide a more economical and technically superior alternative to the traditional techniques in many situations because it offers high strength, low weight, corrosion resistance, high fatigue resistance, easy and rapid installation and minimal change in structural geometry. In addition, FRP manufacturing offers a unique opportunity for the development of shapes and forms that would be difficult or impossible with the conventional steel materials. Although the fibers and resins used in FRP systems are relatively expensive compared with traditional strengthening materials, labour and equipment costs to install FRP systems are often lower. FRP systems can also be used in areas with limited access where traditional techniques would be impractical

Several investigators took up concrete beams and columns retrofitted with carbon fiber reinforced polymer (CFRP) /glass fiber reinforced polymer (GFRP) composites in order to study the enhancement of strength and ductility, durability, effect of confinement, preparation of design guidelines and experimental investigations of these members. The results obtained from different investigations regarding enhancement in basic parameters like strength/stiffness, ductility and durability of structural members retrofitted with externally bonded FRP composites, though quite encouraging, still suffers from many limitations. This needs further study in order to arrive at recognizing FRP composites as a potential full proof structural additive. FRP repair is a simple way to increase both the strength and design life of a structure. Because of its high strength to weight ratio and resistance to corrosion, this repair method is ideal for deteriorated concrete structure.

1.2. TORSIONAL STRENGHTENING OF BEAMS

Early efforts for understanding the response of plain concrete subjected to pure torsion revealed that the material fails in tension rather than shear. Structural members curved in plan, members of a space frame, eccentrically loaded beams, curved box girders in bridges, spandrel beams in buildings, and spiral stair-cases are typical examples of the structural elements subjected to torsional moments and torsion cannot be neglected while designing such members. Structural members subjected to torsion are of different shapes such as

Manuscript received March 26, 2015

Mayank Varshney, Professor, Department of Civil Engg., Jagannath University, Jaipur
Meenu Varshney, Associate Professor, Department of Architecture & Planning, M.N.I.T ,Jaipur
Nitesh Gupta, Junior Civil Engineer, Gyan Prakash Matur & Associates, Jaipur

T-shape, inverted L–shape, double T-shapes and box sections. These different configurations make the understanding of torsion in RC members a complex task.

In addition, torsion is usually associated with bending moments and shearing forces, and the interaction among these forces is important. Thus, the behaviour of concrete elements in torsion is primarily governed by the tensile response of the material, particularly its tensile cracking characteristics. Spandrel beams, located at the perimeter of buildings, carry loads from slabs, joists, and beams from one side of the member only. This loading mechanism generates torsional forces that are transferred from the spandrel beams to the columns. Reinforced concrete (RC) beams have been found to be deficient in torsional capacity and in need of strengthening. These deficiencies occur for several reasons, such as insufficient stirrups resulting from construction errors or inadequate design, reduction in the effective steel area due to corrosion, or increased demand due to a change in occupancy. Similar to the flexure and shear strengthening, the FRP fabric is bonded to the tension surface of the RC members for torsion strengthening. In the case of torsion, all sides of the member are subjected to diagonal tension and therefore the FRP sheets should be applied to all the faces of the member cross section. However, it is not always possible to provide external reinforcement for all the surfaces of the member cross section. In cases of inaccessible sides of the cross section, additional means of strengthening has to be provided to establish the adequate mechanism required to resist the torsion. The effectiveness of various wrapping configurations indicated that the fully wrapped beams performed better than using FRP in strips.

1.3. ADVANTAGES AND DISADVANTAGES OF FRP

1.3.1. Advantages

There have been several important advances in materials and techniques for structural rehabilitation, including a new class of structural materials such as fiber-reinforced polymers (FRP). One such technique for strengthening involves adding external reinforcement in the form of sheets made of FRP. Advanced materials offer the designer a new combination of properties not available from other materials and effective rehabilitation systems. Strengthening structural elements using FRP enables the designer to selectively increase their ductility, flexure, and shear capacity in response to the increasing seismic and service load demands. For columns, wrapping with FRP can significantly improve the strength and ductility.

A potent advantage of using FRP as an alternate external confinement to steel is the high strength to weight ratio comparisons. In order to achieve an equivalent confinement, FRP plates are up to 20% less dense than steel plates and are at least twice as strong, if not more. Manufacture of modern composites is, then, possible in reduced sections and allows composite plates to be shaped on-site. The lower density allows easier placement of confinement in application. Design of external confinement to a structure should be made with conservative adjustments to the primary structures dead weight load. Changes of the stiffness of members should be considered when redesigning the structure. The improved behaviour of FRP wrapped members reduces the strains of internal steel reinforcement thereby delaying attainment of yielding. Much like internal steel confinement in longitudinal and lateral axes, external confinement exerts a similar pressure on the concrete as well as to the internal steel. Furthermore, FRP have high corrosive resistance equating to material longevity whilst within aggressive environments. Such durability makes for potential savings in long-term maintenance costs.

1.3.2. Disadvantages

With the above advantages FRP does also have some disadvantages as follows: The main disadvantage of externally strengthening structures with fiber composite materials is the risk of fire, vandalism or accidental damage, unless the strengthening is protected. As FRP materials are lightweight they tend to poses aerodynamic instability. Retrofitting using fiber composites are more costly than traditional techniques. Experience of the long-term durability of fiber composites is not yet available. This may be a disadvantage

for structures for which a very long design life is required but can be overcome by appropriate monitoring. This technique need highly trained specialists. More over there is lack of standards and design guides.

II. RESULTS AND DISCUSSIONS

2.1 EXPERIMENTAL RESULTS

This chapter includes all the experimental results of all beams with different types of configurations and orientation of GFRP. Their behaviour throughout the test is described using recorded data on torsional behaviour and the ultimate load carrying capacity. The crack patterns and the mode of failure of each beam are also described in this chapter. All the beams are tested for their ultimate strengths. Beam No-1 is taken as the control beam. It is observed that the control beam had less load carrying capacity and high deflection values compared to that of the externally strengthened beams using GFRP sheets. All the eight beams except the control beam are strengthened with GFRP sheets in different patterns. In series-1 two beams were fully wrapped, one with unidirectional GFRP and other with bidirectional GFRP. In series-2 two beams were wrapped with 10cm wide GFRP sheets, one with unidirectional GFRP and other with bidirectional GFRP. In series-3 two beams were wrapped with 5cm GFRP sheets, one with unidirectional GFRP and other with bidirectional GFRP. In series-4 two beams were wrapped with 5cm GFRP sheets, one with unidirectional GFRP and other with bidirectional GFRP making 45^0 with the main beam.

2.2 FAILURE MODES

Different failure modes have been observed in the experiments of rectangular RC beams strengthened in torsion by GFRPs.

These include shear failure due to GFRP rupture .Rupture of the FRP strips is assumed to occur if the strain in the FRP reaches its design rupture strain before the concrete reaches its maximum usable strain. GFRP debonding can occur if the force in the FRP cannot be sustained by the substrate. In order to prevent debonding of the GFRP laminate, a limitation should be placed on the strain level developed in the laminate. Load was applied on the two moment arm of the beams which is 0.27m away from the main beam and at the each increment of the load, deflections at L/3, L/2 and 2L/3 is taken with the help of dial gauges. Mid section at L/2 was taken as sec-1 and section 300mm away from sec-1 was taken as section 2.The load arrangement was same for all the beams.

The control beam and GFRP strengthened beam are tested to find out their ultimate load carrying capacity. It is found that all the beams failed in torsional shear.

Beam-2 continuously fully wrapped with unidirectional fabric did not show any failure in the strengthen part but the unstrengthen cantilever arm transferring moment had failed. Similarly Beam-3 continuously fully wrapped with biidirectional fabric did not show any failure in the strengthen part but the unstrengthen cantilever arm transferring moment had failed. In both cases failure is partial.

Beam-4 & Beam-5 continuously fully wrapped with strips of 10 cm of uni and bi directional fabrics failure occurred in the unstrengthen part. The failure is due to combination of shear and torsion in the region. The diagonal cracks initiated from the concrete portion in between the strips and propagated in the concrete below the fabrics. There was no deboning of GFRP fabrics.

All the beams of series 3 & 4 showed similar types of failure pattern. The failure occurred due to rupture of GFRP fabrics occurred generally at bottom face due to combined action of flexure and torsion. The diagonal cracks developed between the stripes of 5cm width.

2.3 TORSIONAL MOMENT AND ANGLE OF TWIST ANALYSIS

2.3.1 Torsional moment and Angle of twist Analysis of all Beams

Here the angle of twist of each beam is analyzed. Angle of twist of each beam is compared with the angle of twist of control beam. Also the torsional behaviour is compared between different wrapping schemes having the same reinforcement. Same type of load arrangement was done for all the beams.

All the beams were strengthened by application of GFRP in two layers over the beams. It was noted that the behaviour of the beams strengthen with GFRP sheets are better than the control beams. The deflections are lower when beam was wrapped externally with GFRP sheets. The use of GFRP sheet had effect in delaying the growth of crack formation.

When all the wrapping schemes are considered it was found that the Beam-2 with GFRP sheet fully wrapped over full a length of 0.65m in the middle part had a better resistant to torsional behaviour as compared to the others strengthened beams with GFRP.

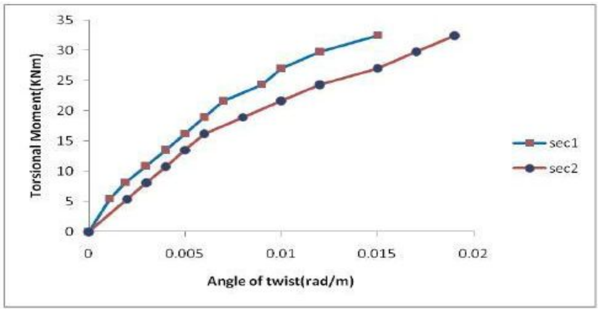

Fig. 2.1 Torsional Moment vs. Angle of Twist Curve for Control Beam-1

Beam 1 is taken as the control beam which is weak in torsion. In Beam1 no strengthening is done. Load was applied on the two moment arm of the beams which is 0.27m away from the main beam and at the each increment of the load, deflection at L/3, L/2 and 2L/3 is taken with the help of dial gauges. Using this load and deflection data, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted.

At the load of 80 KN initial hairline cracks appeared. Later with the increase in loading values the crack propagated further. The Beam1 failed completely in torsion at a load 130KN and torsional moment 35.1KNm. It was observed those cracks were appeared making an angle 40^0-50^0 with the main beam. The cracks were developed in a spiral pattern all over the main beam which later leads to the collapse of the beam in torsional shear.

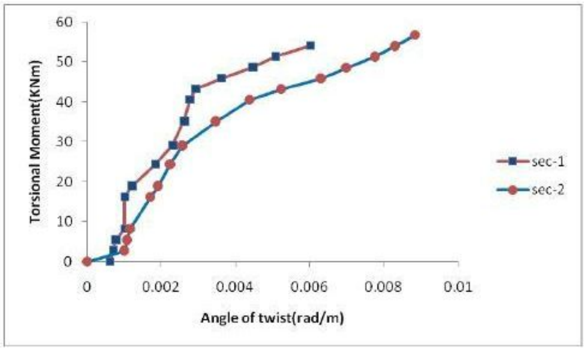

Fig. 2.2 Torsional Moment vs. Angle of Twist Curve for Beam-2

Beam-2 was strengthened by wrapping the full span of the beam under torsion with unidirectional GFRP. Using the load and deflections data from experiment, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted.

At the load of 100 KN cracking sound was heard. The Beam 2 failed completely in torsion at a load 245KN and torsional moment 66.15KNm.The increase strength of beam was 88.46% as compared to control beam. After the test is done the GFRP sheets were removed and the crack pattern was observed. It was found that the crack were appeared making an angle 45^0-50^0 with the main beam on the side faces and top surface.

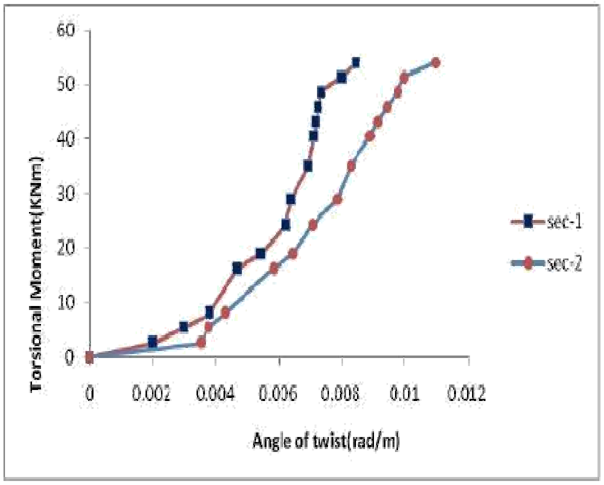

Fig. 2.3 Torsional Moment vs. Angle of Twist Curve for Beam-3

Beam-3 was strengthened by fully wrapping the span of the beam under torsion with bidirectional GFRP. Using the loads and deflections data from experiment, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted. At the load of 140 KN cracking sound was heard. The Beam 3 failed completely in torsion at a load 210KN and torsional moment 56.7KNm. After the test is done the GFRP sheets were removed and the crack pattern was observed. It was found that the crack were appeared making an angle 50^0-60^0 with the main beam on the side faces and top surface.

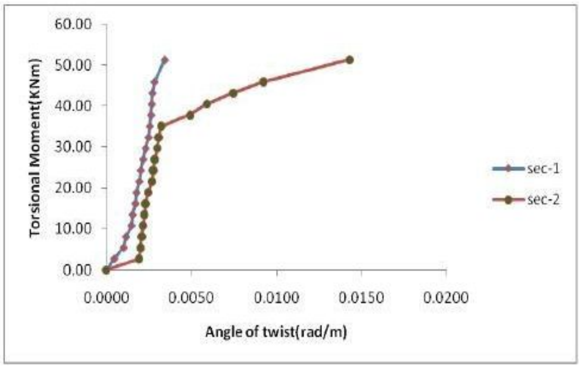

Fig. 2.4 Torsional Moment vs. Angle of Twist Curve for Beam-4

Beam-4 was strengthened by wrapping with four 10cm Unidirectional GFRP strips at a distance 8.3cm from each other over the beam under torsion. Using the loads and deflections data from experiment, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted.

At the load of 140 KN cracking sound was heard. The Beam 3 failed completely in torsion at a load 210KN and torsional moment 56.7KNm. The increase strength of beam was 61.53% as compared to control beam. After the test is done the GFRP sheets were removed and the crack pattern was observed. It was found those cracks were appeared making an angle 60^0 with the main beam on the side faces and top surface

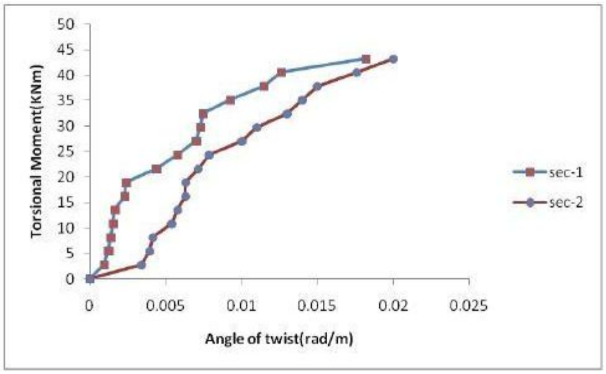

Fig. 2.5 Torsional Moment vs. Angle of Twist Curve for Beam-5

Beam-5 was strengthened by wrapping with four 10cm Bidirectional GFRP strips at a distance 8.3cm from each other over the beam under torsion. Using the loads and deflections data from experiment, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted.

At the load of 100 KN cracking sound was heard. The Beam 3 failed completely in torsion at a load 188KN and torsional moment 50.76KNm. The increase strength of beam was 44.61% as compared to control beam. After the test is done the GFRP sheets were removed and the crack pattern was observed. It was found those cracks were appeared making an angle 55^0-60^0 with the main beam on the side faces and top surface.

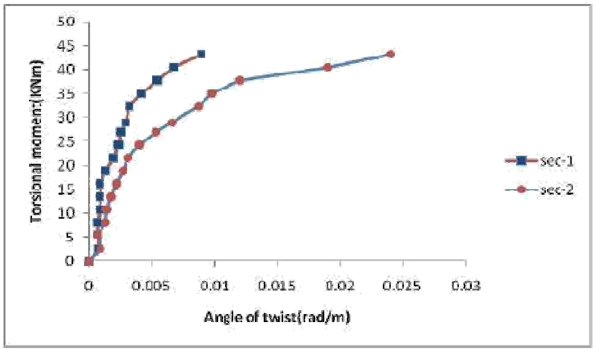

Fig. 2.6 Torsional Moment vs. Angle of Twist Curve for Beam-6

Beam-6 was strengthened by wrapping with four 5cm Unidirectional GFRP strips at a distance 15cm from each other over the beam under torsion. Using the loads and deflections data from experiment, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted.

At the load of 80 KN cracking sound was heard. The Beam 3 failed completely in torsion at a load 174KN and torsional moment 46.98KNm. The increase strength of beam was 65.38% as compared to control beam. After the test is done the GFRP sheets were removed and the crack pattern was observed. It was found those cracks were appeared making an angle 50^0 with the main beam on the side faces and top surface

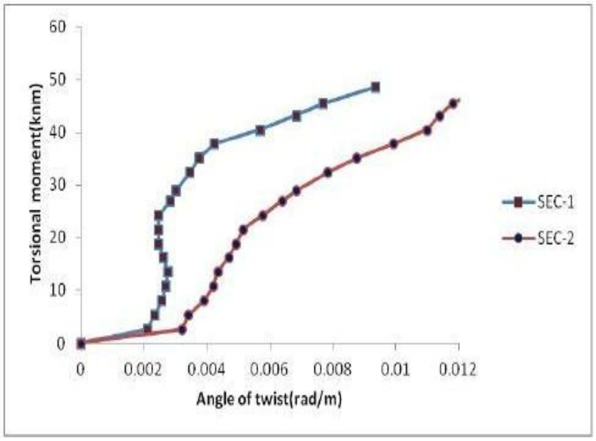

Fig. 2.7 Torsional Moment vs. Angle of Twist Curve for Beam-7

Beam-7 was strengthened by wrapping with four 5cm Bidirectional GFRP strips at a distance 15cm from each other over the beam under torsion. Using the load and deflection data from experiment, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted.

At the load of 100 KN cracking sound was heard. The Beam 3 failed completely in torsion at a load 216KN and torsional moment 58.32KNm. The increase strength of beam was 66.15% as compared to control beam. After the test is done the GFRP sheets were removed and the crack pattern was observed. It was found those cracks were appeared making an angle 55^0-65^0 with the main beam on the side faces and top surface.

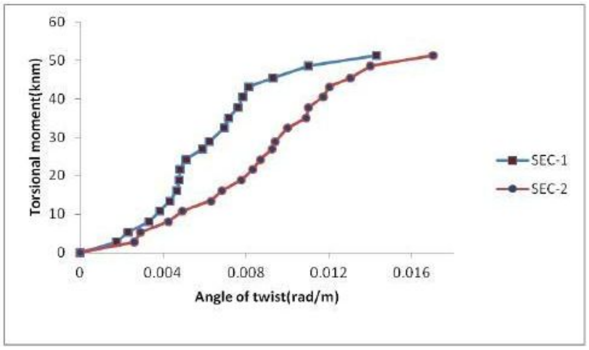

Fig. 2.8 Torsional Moment vs. Angle of Twist Curve for Beam-8

Beam-8 was strengthened by wrapping with four 5cm Bidirectional GFRP strips at a distance 15cm from each other over the beam under torsion. The GFRP strips were wrapped over the beam by making an angle 45^0 with the main beam. Using this loads and deflections data from experiment, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted.

At the load of 110 KN cracking sound was heard. The Beam 3 failed completely in torsion at a load 202KN and torsional moment 54.54KNm. The increase strength of beam was 53.84% as compared to control beam. After the test is done the GFRP sheets were removed and the crack pattern was observed. It was found those cracks were appeared making an angle 70^0 with the main beam on the side faces and 60^0 at the top surface.

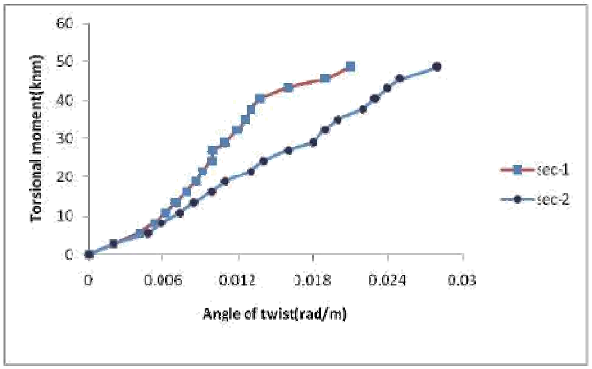

Fig. 2.9 Torsional Moment vs. Angle of Twist Curve for Beam-9

Beam-9 was strengthened by wrapping with four 5cm Bidirectional GFRP strips at a distance 15cm from each other over the beam under torsion. The GFRP strips were wrapped over the beam by making an angle 45^0 with the main beam. Using the loads and deflection data from experiment, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted.

At the load of 100 KN cracking sound was heard. The Beam 3 failed completely in torsion at a load 188KN and torsional moment 50.76KNm. The increase strength of beam was 55.38% as compared to control beam. After the test is done the GFRP sheets were removed and the crack pattern was observed. It was found those cracks were appeared making an angle 40^0 with the main beam on the side faces and 40^0 at the top surface.

It was observed from the test that with unidirectional fabrics cracks initiated making an angle between 40^0 to 60^0 with the axis of beam and with bidirectional fabrics steep cracks was developed by making an angle between 50^0 to 70^0 with the axis of the beam.

2.3.2 Torsional moment and Angle of twist Analysis of Beams Wrapped with Different Series of wrapping

Series-1 (Unidirectional & Bidirectional GFRP fully wrapped over the beam)

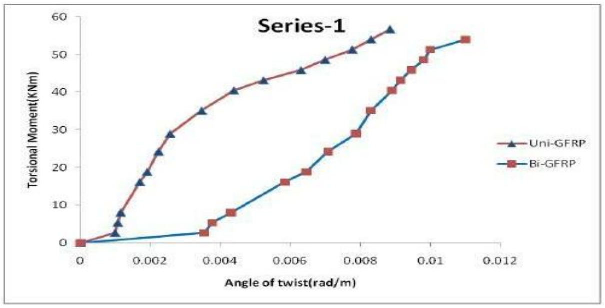

Fig. 2.10 Torsional Moment vs. Angle of Twist Curve for Beam-2 and Beam-3

Torsional reinforced concrete beams strengthened with GFRP sheets exhibited significant increase in their cracking and ultimate strength as well as ultimate twist deformations. Both, the Beam 2 & Beam 3 had partially collapsed without achieving the ultimate load. The failure occurred in the unstrenghtened part of the specimens. The torsional strength of the retrofitted beams exceeded that of the control specimen by up to 88.46% for Beam 2 with unidirectional FRP and up to 61.5% for Beam 3 with bidirectional FRP. Test result reveals that strengthening using bidirectional GFRP sheets had not enhanced the ultimate strength but had increased the ductility of the beam.

Series-2 (Unidirectional & Bidirectional GFRP 10cm strips wrapped over the beam)

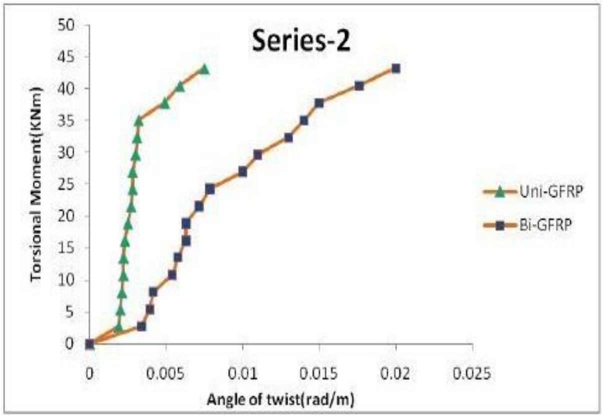

Fig. 2.11 Torsional Moment vs. Angle of Twist Curve for Beam-4 and Beam-5

The torsional strength of the retrofitted beams exceeded that of the control specimen by up to 44.61% for Beam 4 with unidirectional FRP and up to 65.38% for Beam 5 with bidirectional FRP. From the above graph it is observed that wrapping with Bidirectional GFRP is more efficient to arrest the crack and enhance the strength of the beam.

Series-3 (Unidirectional & Bidirectional GFRP 5cm strips wrapped over the beam)

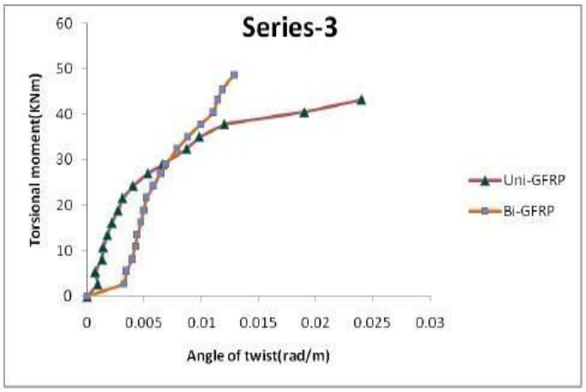

Fig. 2.12 Torsional Moment vs. Angle of Twist Curve for Beam-6 and Beam-7

Rupture and debonding of GFRP occurred in both of the beams. Both strips of Unidirectional and Bidirectional GFRP undergone rupture before ultimate failure of the beam. The torsional strength of the retrofitted beams exceeded that of the control specimen by up to 33.84% for Beam 6 with unidirectional FRP and up to 66.15% for Beam 7 with bidirectional FRP. From the above graph it is observed that wrapping with Bidirectional GFRP is more efficient to arrest the crack and enhance the strength of the beam.

Series-4 (Unidirectional & Bidirectional GFRP 5cm strips wrapped over the beam making an angle 45^0 with beam)

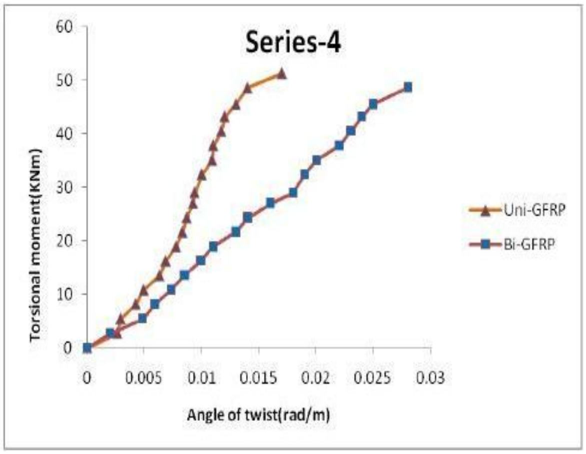

Fig. 2.13 Torsional Moment vs. Angle of Twist Curve for Beam-8 and Beam-9

Rupture and debonding of GFRP occurred in both of the beams. Both strips of Unidirectional and Bidirectional GFRP undergone rupture before ultimate failure of the beam. The torsional strength of the retrofitted beams exceeded that of the control specimen by up to 53.84% for Beam 8 with unidirectional FRP and up to 55.38% for Beam 9 with bidirectional FRP. Both the beam 8 and Beam 9 were strengthened by applying the GFRP by making an angle 45^0 with the beam surface. From the above graph it is observed that wrapping with Bidirectional GFRP is more efficient to arrest the crack and enhance the strength of the beam if the beam is strengthened with GFRP at an angle 45^0 with the beam.

2.3.3 Torsional moment and Angle of twist Analysis of Beams Wrapped with Unidirectional GFRP

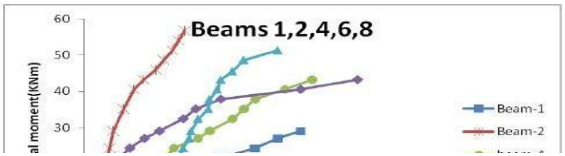

Fig. 2.14 Torsional Moment vs. Angle of Twist Curve for Beam-1, Beam-2, Beam-4, Beam-6 and Beam-8

Here all the beams strengthened with Unidirectional GFRP are compared with respect to their torsional moment and angle of twist. And it can be interpreted that beam 2 which was strengthened with full wrap double layered GFRP sheet for a length of 0.65 m in the main beam , a series of closely spaced cracks were visible on the concrete indicating torsional shear failure. And Beam 2 has the highest load carrying capacity among all the Beams strengthened with Uni-GFRP.

2.3.4 Torsional moment and Angle of twist Analysis of Beams Wrapped with Bidirectional GFRP

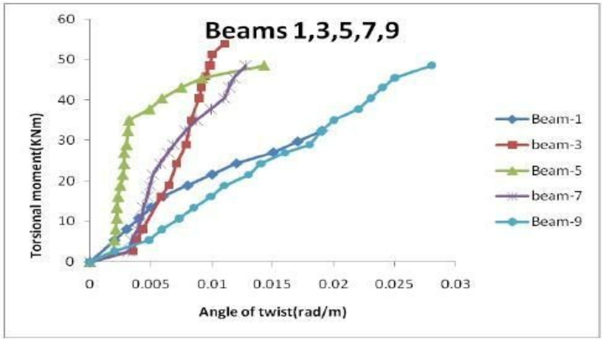

Fig. 2.15 Torsional Moment vs. Angle of Twist Curve for Beam-1, Beam-3, Beam-5, Beam-7 and Beam-9

Here all the beams strengthened with Bidirectional GFRP are compared with respect to their torsional moment and angle of twist. And it can be interpreted that beam 3 which was strengthened with full wrap double layered GFRP sheet for a length of 0.65 m in the main beam where most of the cracks are occurring has minimum angle of rotation value as compared to others. And Beam 3 has the highest load carrying capacity among all the Beams strengthened with Bi-GFRP.

2.3.5 Torsional moment and Angle of twist Analysis of All Beams

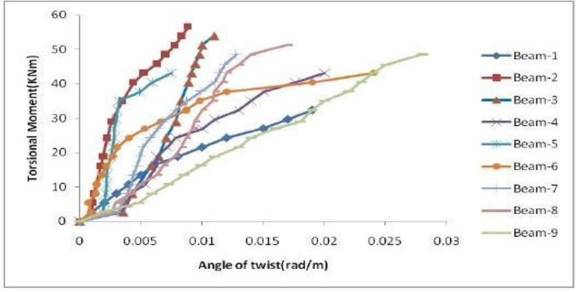

Fig. 2.16 Torsional Moment vs. Angle of Twist Curve for All Beams

In fig. 2.16 all the beams strengthened with Unidirectional GFRP are compared with respect to their torsional moment and angle of twist. And it can be interpreted that beam 2 which was strengthened with full wrap double layered GFRP sheet for a length of 0.65 m in the main beam gives the highest strength to the beam.

2.3.6 Load and angle of twist Analysis of Beams Wrapped with GFRP in Different Orientation

2.3.6.1 Beams Wrapped with Unidirectional GFRP at 90^0 and 45^0 angle making with Beam

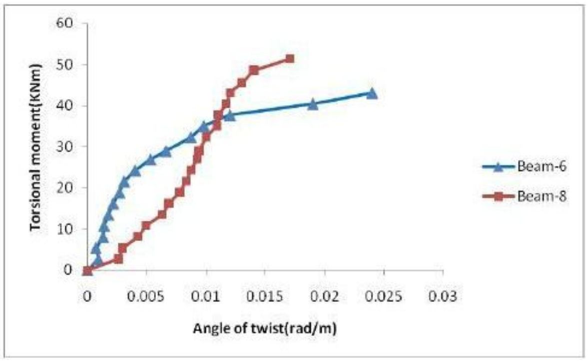

Fig. 2.17 Torsional Moment vs. Angle of Twist Curve for Beam-6 and Beam-8

2.3.6.2 Beams Wrapped with Bidirectional GFRP at 90^0 and 45^0 angle making with Beam

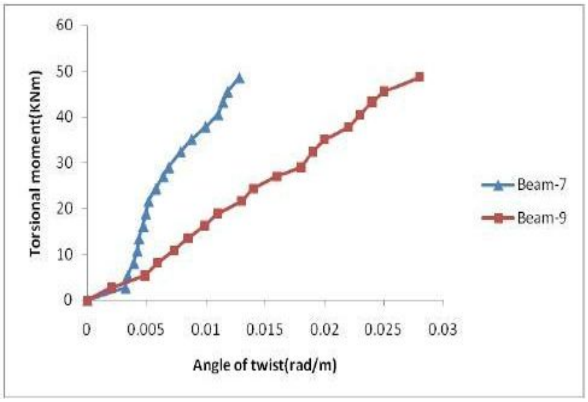

Fig. 2.18 Torsional Moment vs. Angle of Twist Curve Beam-7 and Beam-9

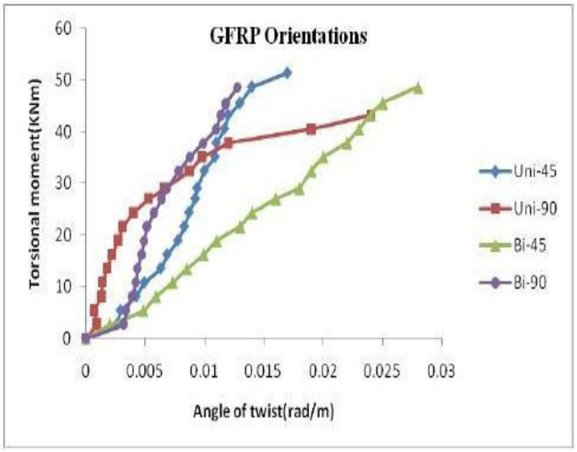

Fig. 2.19 Torsional Moment vs. Angle of Twist Curve for beams where GFRP applied in different orientations

From the above graph it can be observed that GFRP applied at an angle 45^0 to the beam gives more strength to the beam. Both Uni-GFRP and Bi-GFRP strips applied at 45^0 gives more strength to the beams compared to beam wrapped with Uni-GFRP and Bi-GFRP at an angle with 90^0 with the beam.

EXPERIMENTAL SETUP

CONCLUSION

The use of glass fiber reinforced plastics (GFRPs) for torsional strengthening of reinforced concrete beams has been scrutinized to a considerable depth in the paper with the results of an experimental investigation .It can be concluded that the reinforced concrete beams subjected to torsion can be strengthened with GFRP wraps in a variety of configurations.

REFERENCES

[1] ACI Committee 440 (1996) State Of Art Report On Fiber Reinforced Plastic

[2] Ameli, M. and Ronagh, H.R. (2007). “Behavior of FRP strengthened reinforced

[3] concrete beams under torsion”,*Journal of Composites for Construction*, 11(2), 192-200.

[4] Ameli, M., and Ronagh, H. R. (2007), “Analytical method for evaluating ultimatetorque of FRP strengthened reinforced concrete beams” ,*Journal of Composites forConstruction* **,11**, 384–390.

[5] Amir, M., Patel, K. (2002).“Flexural strengthening of reinforced concrete flangedbeams with composite laminates”,*Journal of Composites for Construction*, 6(2), 97-103.

[6] Andre, P., Massicotte, Bruno, Eric, (1995). “Strengthening of reinforced concretebeams with composite materials : Theoretical study”, *Journal of compositeStructures*,33,63-75.

[7] Arbesman, B. (1975). “Effect of stirrup cover and amount of reinforcement on shearcapacity of reinforced concrete beams.” MEng thesis, Univ. of Toronto.

[8] Arduini, M., Tommaso, D. A., Nanni, A. (1997), “Brittle Failure in FRP Plate andSheet BondedBeams”, *ACI Structural Journal,* 94 (4), 363-370.

[9] Belarbi, A., and Hsu, T. T. C. (1995). “Constitutive laws of softened concrete inbiaxial tension-compression.” *ACI Structural Journal,* 92, 562-573.

[10] Chalioris, C.E. (2006). “Experimental study of the torsion of reinforced concretemembers”, *Structural Engineering & Mechanics*, 23(6), 713-737.

[11] Chalioris, C.E. (2007a). “Torsional strengthening of rectangular and flanged beamsusing carbon fibre reinforced polymers – Experimental study”, *Construction &Building Materials*, in press (available online since 16 Nov. 2006).