Comparative Study on Torsional Strengthening of RC beams using CFRP and BFRP wrapping

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Abstract - *Owing to the unsymmetrical plan and elevation of buildings to enhance the aesthetic appearance, often reinforced concrete (RC) elements such as beams are subjected to torsion especially under seismic forces and lead to collapse of the structure. This lead to the problem of deficiency in torsional capacity. This paper investigates the strengthening of beams deficient in torsional shear capacity by external U wrapping with carbon fibre reinforced polymer (CFRP) and basalt fibre reinforced polymer (BFRP) sheets numerically in ANSYS 16.0APDL. The effect of parameters such as number of layers of FRP sheets and orientation of FRP sheets on torsional resistance and ductility of RC beams is also investigated.*

***Key Words*: ANSYS 16.0 APDL, Reinforced concrete beam, Torsion, Strengthening, CFRP sheets, BFRP sheets**

1.INTRODUCTION

Modern civilization relies upon the continuing performance of its civil engineering infrastructure. For the satisfactory performance of the existing structural system, there is a need for maintenance and strengthening. 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. In such occasions, repair and rehabilitation can be the most commonly used solutions.

Some of the reinforced concrete (RC) elements such as beams may be deficient in torsional shear capacity. Torsion is generally considered as a secondary force, hence generally not considered in design procedure. Reinforced structural elements such as peripheral beams, ring beams at the bottom of circular water tanks, edge beams of shell roofs, beams supporting canopy slabs, helical staircases etc. are subjected to significant torsional loading in addition to flexure and shear. The structural elements subjected to torsion show cracking if they are not designed and detailed properly. Further, a change in loading or deterioration of structural elements cause the deficiency in torsional resistance. Thus torsional resistance is important for structural members.

In current practice, the torsional strengthening of concrete members is achieved by one of the following methods:

- Increasing the member cross-sectional area by adding of transverse reinforcement,
- Externally bonding steel plates and pressure grouting the gap between plate and concrete element and
- Applying an axial load to the member by post-tensioning.

Although these methods will continue to be used in many more instances, fibre reinforced polymer (FRP) composites provide another option for strengthening. These composites can be three to five times stronger, two to three times stiffer and three to four times lighter than metals such as steel and aluminium. In addition, composites are dimensionally stable, aesthetically pleasing and cost effective with better durability and lower maintenance than the conventional materials. FRP composites have shown great promise in flexural and shear strengthening as external reinforcement. Little attention has only been paid to its applicability in torsional strengthening of RC beams in terms of both experimental and numerical research. This is due to the specialized nature of the problem and the difficulties in conducting realistic tests of torsion and representative analyses.

From the literature survey conducted, it could be concluded that structural members are subjected to significant torsion in addition to flexure and shear [3,8,13]. The use of fibre reinforced polymer sheets like carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) as external retrofit can increase the torsional capacity of the RC beams. CFRP sheets are better than GFRP sheets in resisting torsion [4,6,9]. Full wrapping of the beams is more advantageous in terms of increase in torsional capacity than strip wrapping. But complete wrapping of beams is not practically possible due to the presence of slab. The 45^0 diagonal strip or spiral wrapping can improve torsional capacity as the torsional cracks propagate at 45^0 with the longitudinal axis of beams [1,3]. Increase in the number of layers can lead to debonding failure. Unreinforced flange also contributes to torsional capacity [13,15] in T beams. In case of T beams, extended U jacketing is better than regular U jacketing [2,8]. The torsional resistance is more predominant on spandrel beams than in T section beams. Providing anchors to FRP sheets creates a continuous shear flow path and hence, more capacity to resist torsion [5,7,11].

Moreover, anchors prevent the premature debonding of FRPs in T beams and L beams [7,8]. The FRP sheets confine concrete and prevent the propagation of cracks.

FRP sheets such as CFRP, GFRP and aramid fibre reinforced polymer (AFRP) sheets have proved to be excellent in resisting torsional load. CFRP is more advantageous than other FRPs in resisting torsion due to its properties like high tensile strength to weight ratio and high modulus of elasticity. Basalt fibre reinforced polymer (BFRP) is a relative newcomer to FRP composites. The manufacturing process of BFRP is similar to that of GFRP, but with less energy consumed and no additives, which makes it cheaper than glass and other FRPs. BFRP has great potential as strengthening material compared to other FRPs (e.g. CFRP, GFRP, and AFRP) due to its cost effectiveness. The effectiveness of BFRP material in the field of torsion has not been explored yet.

The present study explores numerically the torsional resistance of RC beams strengthened using CFRP and BFRP wrapping. The effect of parameters such as orientation of FRP sheets and number of layers of FRP sheets on torsional resistance and ductility of RC beams is also investigated.

2. MODELLING AND ANALYSIS

The Finite Element Analysis (FEA) is the simulation of any given physical phenomenon using the numerical technique called Finite Element Method (FEM). It is an advanced engineering tool that is used in design and to augment or replace experimental testing. A total of 9 beams of cross section of 150 x 250 mm, and length 2m were modelled in ANSYS 16.0 APDL. ANSYS 16.0 APDL is a general purpose software, used to simulate interactions of all disciplines of physics, structural, vibration, fluid dynamics, heat transfer and electromagnetics for engineers.

2.1 Description of Models and Test Setup

All the beams were designed as per IS 456:2000. All beams were reinforced by two number of 12mm diameter bars at bottom and two number of 10mm diameter bars at top as main reinforcement. The vertical stirrups were 8mm in diameter and placed at 150mm centre to centre. All the reinforcing bars were of 500 grade steel. The cover to reinforcement was given as 25mm. All the beams had same reinforcement pattern. The compressive strength of concrete was taken as 25 N/mm^2. One beam out of 8 beams was modelled as control beam without any external wrapping. All the other beams were provided with CFRP/ BFRP U-wrapping. Table 1 shows the specifications of various models.

Table 1 Specifications of Various Models

Model Name	FRP Used	Wrap Length	Wrap Type	No. of layers	Orientation (deg)
CONTROL BEAM	-	-	-	-	-
C1700FL(1)90	CFRP	1700	Continous	1	90
C1700FL(2)90	CFRP	1700	Continous	2	90
C1700FL(1)45	CFRP	1700	Continous	1	45
C1700FL(2)45	CFRP	1700	Continous	2	45
B1700FL(1)90	BFRP	1700	Continous	1	90
B1700FL(2)90	BFRP	1700	Continous	2	90
B1700FL(1)45	BFRP	1700	Continous	1	45
B1700FL(2)45	BFRP	1700	Continous	2	45

Concrete was assumed to behave as both linear elastic and multilinear inelastic material. Solid 65 is used for the three-dimensional modelling of concrete. Reinforcing bars was assumed to be both linear elastic and bilinear inelastic material. LINK 180 was used to model reinforcing bar. Fig-1 shows the model of reinforcement. Fig-2 shows the complete model of control beam. The CFRP material was assumed to be linear orthotropic. SHELL 181 element was used to model CFRP and BFRP sheets. The steel arm was assumed to be linear elastic. SOILD185 element was used to model the steel lever arm. The material properties for the models were chosen from the literature used for validating the model. The properties of unconfined concrete and confined concrete are different. So due to the confinement effect, the non-linear properties of concrete for wrapped beams and control beam are different. Support condition of the beam was adopted by carefully analysing the behaviour of beam under torsion. The beams were simply supported for a span of 1850mm. A hinge support was created on the left end of the beam and a roller support on the right end of the beam. This supports allows the beam to twist and elongate longitudinally. Load was provided on the ends of lever arm. Lever arm provided for applying torsional load was 0.5m. For the present work, a mesh size of 25mm was adopted for concrete. The mesh size was such that the reinforcement can be drawn through the nodes of concrete. The lever arm was meshed in such a way that the load can be applied to the end nodes of the lever arm. The area of CFRP and BFRP sheets was attached to the surface area of the concrete by defining a as "bonded (always)". Table 2 shows the non-linear properties provided for concrete.

Table 2 Non-linear Properties of concrete

Property	Value
Open shear coefficient	0.3
Closed shear coefficient	0.9
Uniaxial cracking stress (N/mm^2)	3.13
Uniaxial crushing stress (N/mm^2)	-1

The material properties provided are shown in Table 3.

Table 3 Material Properties

Materials	Properties	Value
Concrete	Young's modulus (N/mm^2)	25000
	Poisson's Ratio	0.15
Reinforcement	Young's modulus (N/mm^2)	200000
	Poisson's Ratio	0.3
	Yield stress (N/mm^2)	500
Steel Arm	Young's modulus (N/mm^2)	200000
	Poisson's Ratio	0.3
CFRP	Modulus of elasticity in x direction, EX (N/mm^2)	230000
	Modulus of elasticity in y direction, EY (N/mm^2)	17900
	Modulus of elasticity in z direction, EZ (N/mm^2)	17900
	Poisson's ratio in xy direction, PRXY	0.22
	Poisson's ratio in yz direction, PRYZ	0.22
	Poisson's ratio in xz direction, PRXZ	0.3
	Shear modulus in xy direction, GXY (N/mm^2)	11790
	Shear modulus in xy direction, GYZ (N/mm^2)	11790
	Shear modulus in xy direction, GXZ (N/mm^2)	6880
BFRP	Modulus of elasticity in x direction, EX (N/mm^2)	37700
	Modulus of elasticity in y direction, EY (N/mm^2)	5237
	Modulus of elasticity in z direction, EZ (N/mm^2)	5237
	Poisson's ratio in xy direction, PRXY	0.21
	Poisson's ratio in yz direction, PRYZ	0.21
	Poisson's ratio in xz direction, PRXZ	0.2
	Shear modulus in xy direction, GXY (N/mm^2)	3630
	Shear modulus in xy direction, GYZ (N/mm^2)	3630
	Shear modulus in xy direction, GXZ (N/mm^2)	2050

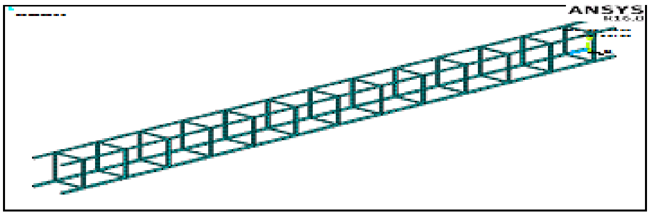

Fig -1: ANSYS Model of Reinforcement

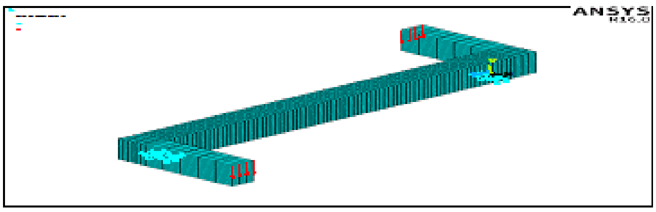

Fig -2: ANSYS Model of Control Beam

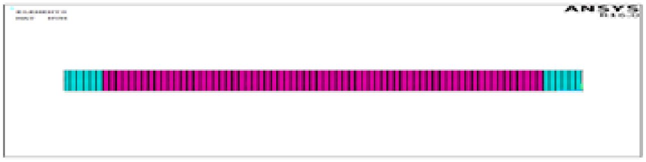

Fig -3 : Wrapping Pattern C1700FL(1)90

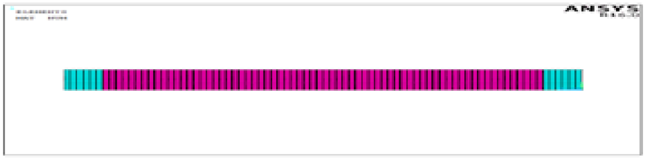

Fig -4: Wrapping Pattern C1700FL(2)90

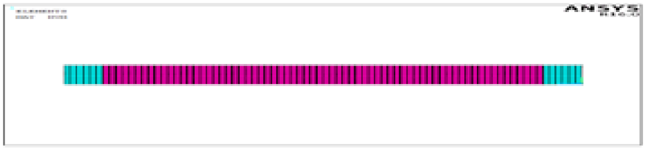

Fig -5 : Wrapping Pattern B1700FL(1)90

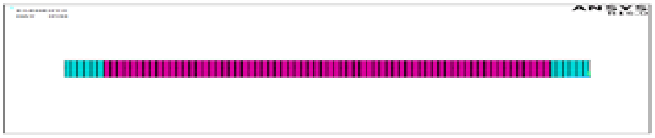

Fig -6 : Wrapping Pattern B1700FL(2)90

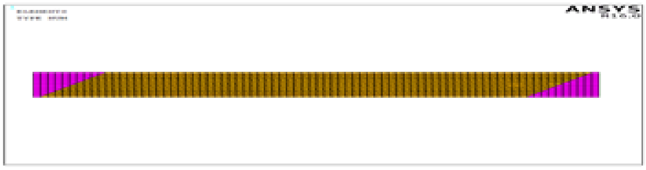

Fig -7 : Wrapping Pattern C1700FL(1)45

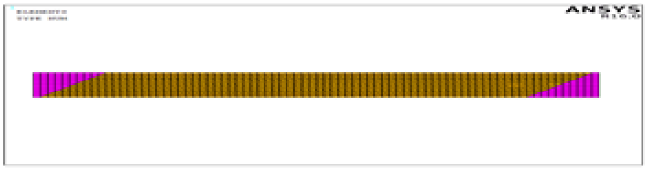

Fig -8 : Wrapping Pattern C1700FL(2)45

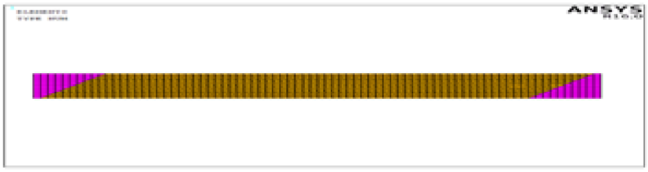

Fig -9 : Wrapping Pattern B1700FL(1)45

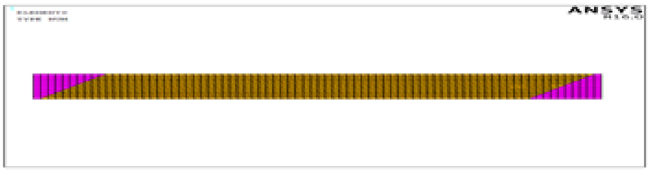

Fig -10 : Wrapping Pattern B1700FL(2)45

Fig-3 to Fig-10 shows various wrapping schemes adopted.

3. RESULTS AND DISCUSSIONS

Static non-linear analysis of beam with and without CFRP and BFRP wraps was done using ANSYS 16.0. APDL. The ultimate torsional moment and maximum rotation at failure of the control beam was compared with that of the CFRP and BFRP wrapped beams. The values for ultimate torsional moment and maximum rotation at failure of the beam due to applied torque were obtained from the general post processing stage in the ANSYS 16.0 APDL.

3.1 Ultimate Torsional Moment and Rotation

The torsional moment and rotation at failure obtained for the control beam and strengthened beams is as shown in the Table 4.

Table 4 Test Results

Model Name	Ultimate Torsional Moment (kNm)	Rotation at Failure (Rad)
CONTROL BEAM	7.35	0.000157
C1700FL(1)90	17.52	0.000264
C1700FL(2)90	23.28	0.000345
C1700FL(1)45	18.15	0.033803
C1700FL(2)45	27.97	0.045635
B1700FL(1)90	13.12	0.000200
B1700FL(2)90	18.47	0.000271
B1700FL(1)45	16.66	0.03272
B1700FL(2)45	21.56	0.041075

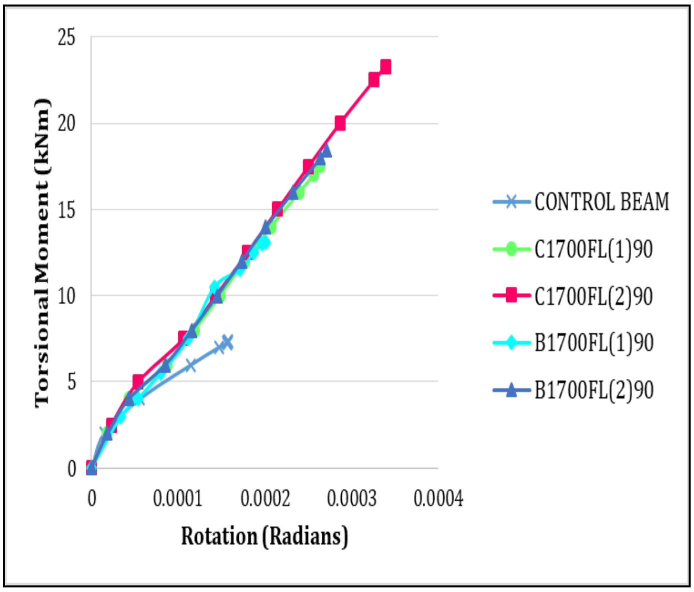

Fig -11: Torsional Moment Vs Rotation Graph of Beams with 90 Degree Oriented Wraps

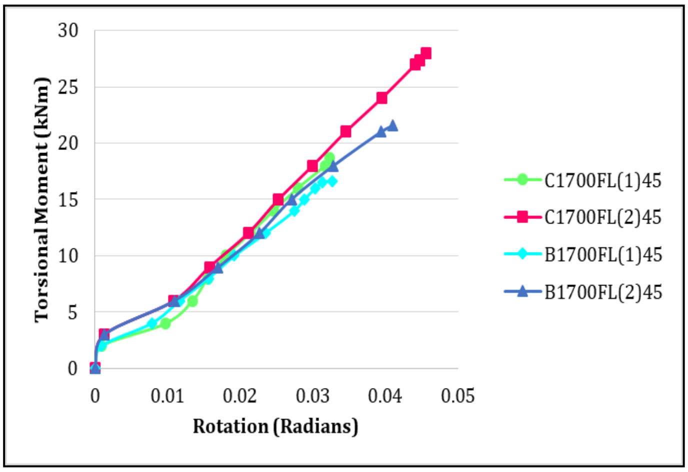

Fig -12: Torsional Moment Vs Rotation Graph of Beams with 45 Degree Oriented Wraps

Fig -11 and Fig -12 shows the torsional moment-rotation graphs of the control beam and strengthened beams. The torsional moment-rotation relationship is almost linear up to first cracking in concrete. After cracking, a sudden increase in the rotation occurred and the relationship becomes non-linear up to failure. The wrapped sections have almost the same first cracking torsional strength of the control beam. The torsional moment-rotation was studied to know the behaviour of the beams.

All the wrapped beams exhibited more ductility than the control beam. More the ductility, less chance of failing in brittle manner. The beams wrapped for the full length with CFRP and BFRP at 90degree orientation, exhibits small rotations. It provides maximum confinement. The beams wrapped for the full length with CFRP and BFRP at 45 degree orientation, exhibits large rotations. The 45 degree orientation shows less confinement than 90 degree orientation in U wrapping.

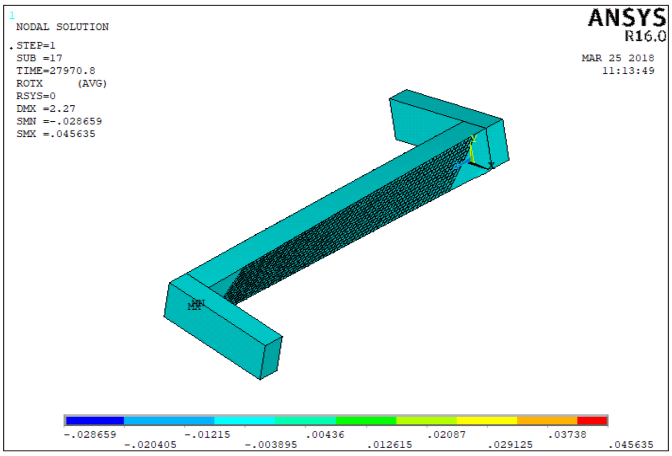

Fig –13 : Beam strengthened at 90 degree oriented sheets at failure

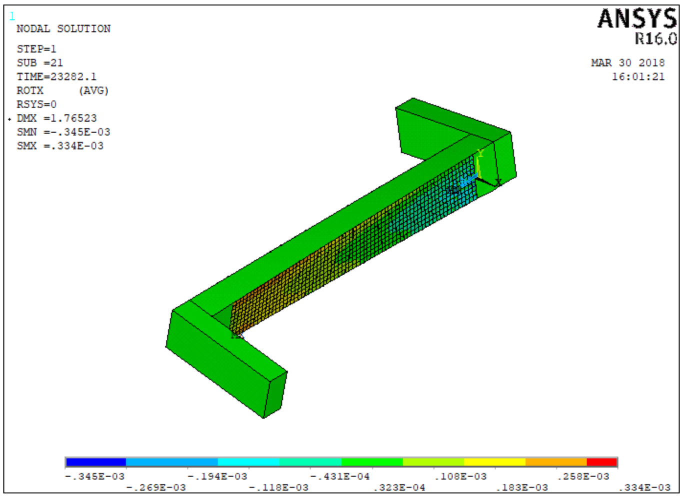

Fig -14 : Beam strengthened at 90 degree oriented sheets at failure

Fig -13 and Fig -14 shows the typical view of beams strengthened at 45 degree and 90 degree oriented sheets at failure.

4. PARAMETRIC STUDY

The effect of parameters such as orientation of FRP sheets and number of layers of FRP sheets on torsional resistance and ductility of RC beams were studied.

4.1 Number of Layers of FRP Wrap

The number layers from one to two was investigated. Increasing the number of layers from one to two increased the torsional strength of both CFRP and BFRP wrapped beams.

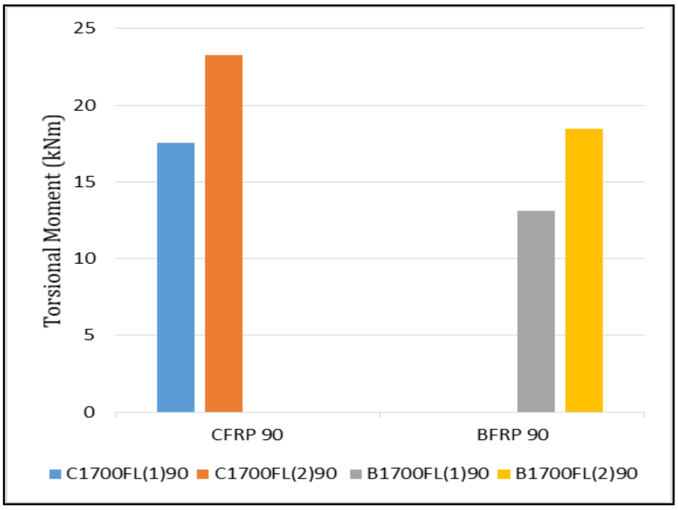

Fig -15 : Comparison of beams wrapped with one layer and two layer of CFRP/BFRP oriented at 90 degrees

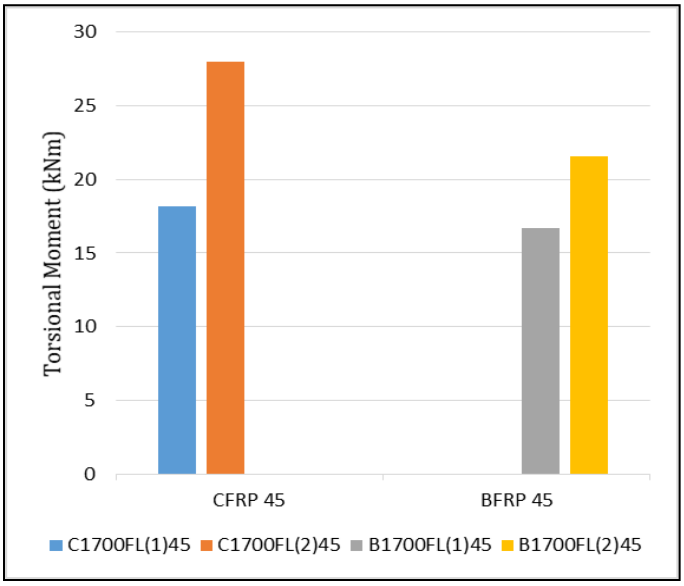

Fig –16 : Comparison of beams wrapped with one layer and two layer of CFRP/BFRP oriented at 45 degrees

Fig -15 and Fig -16 shows the comparison on the number of layers of wraps. In case of wraps oriented at 90 degrees, C1700FL(2)90 had a percentage increase of 32.87% from C1700FL(1)90in torsional strength. Similarly B1700FL(2)90 had a percentage increase of 40.77% from B1700FL(1)90 in torsional strength. In case of wraps oriented at 45 degrees, C1700FL(2)45 had a percentage increase of 54.10% from C1700FL(1)45 in torsional strength. Similarly B1700FL(2)45 had a percentage increase of 29.41% from B1700FL(1)45 in torsional strength .

4.2 Orientation of FRP Wrap

The effect of 90 degree orientation and 45 degree orientation of wraps was investigated. All the beams showed an increase in torsional strength when the orientation of wrap changed from 90 degree to 45 degree.

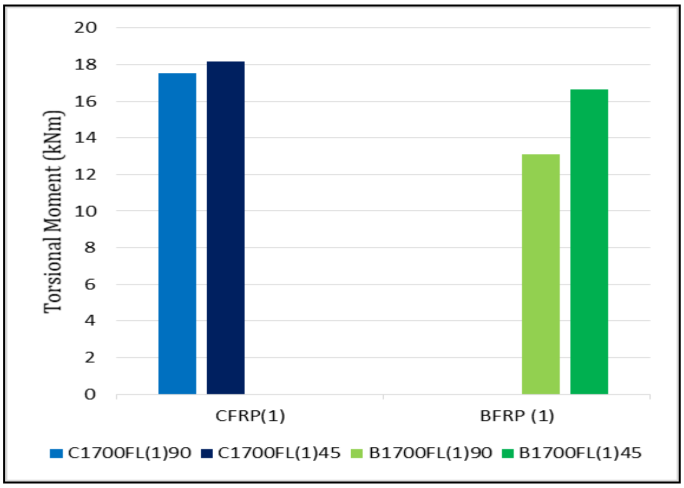

Fig –17 : Comparison of beams wrapped with one layer of CFRP/BFRP oriented at 90 degrees and 45 degrees

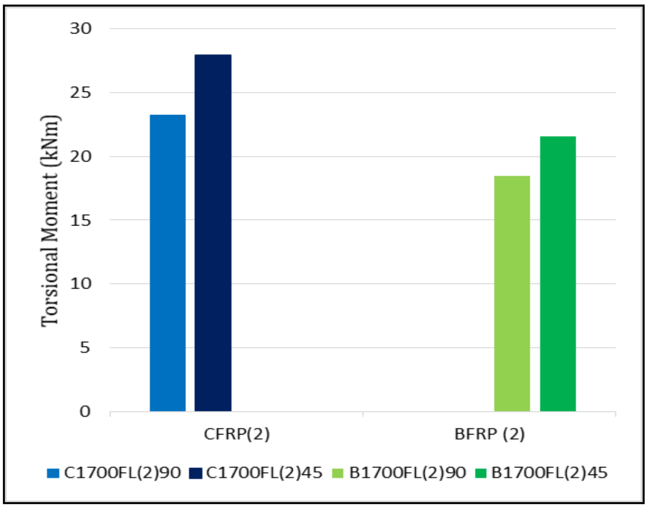

Fig -18 : Comparison of beams wrapped with two layer of CFRP/BFRP oriented at 90 degrees and 45 degrees

Fig -17 and Fig -18 shows the comparison on the orientation of wraps. In case beams wrapped with one layer of CFRP/BFRP, C1700FL(1)45 had a percentage increase of 3.5% from C1700FL(1)90 in torsional strength. Similarly B1700FL(1)45 had a percentage increase of 26.98% from B1700FL(1)90 in torsional strength. In case beams wrapped with two layers of CFRP/BFRP, C1700FL(2)45 had a percentage increase of 20.14% with respect to C1700FL(2)90 in torsional strength. Similarly B1700FL(2)45 had a percentage increase of 16.72% with respect to B1700FL(2)90.

5. CONCLUSIONS

The non-linear finite element models were found to be capable of predicting the behaviour of strengthened RC beams subjected to torsion using CFRP and BFRP wrapping. The torsional behaviour was investigated by finding out the ultimate torsional moment and rotation at failure of the beams. The parametric study was done to account for various strengthening variables in terms of orientation of FRP wraps and number of layers of FRP wraps.

Following are the conclusions derived from the studies conducted as a part of this study:

- Some of the reinforced concrete elements such as beams may be deficient in torsional shear capacity and is in need of strengthening.
- The external wrapping with CFRP/BFRP sheets can increase the torsional capacity of RC beams.
- The 45 degree orientation of CFRP/BFRP is much effective than 90 degree oriented CFRP/BFRP sheets in resisting torsion.
- Increasing the number of layers of CFRP/BFRP sheets from one to two, can increase torsional strength.
- The maximum ultimate torsional moment is obtained is for continuous wrapping with two layers of CFRP sheets oriented at 45 degrees i.e. C1700FL(2)45 and is about 280.5% with respect to control beam.
- BFRP is promising material for strengthening beams under torsion.
- On comparing the CFRP sheets and BFRP sheets, torsional capacity is more for CFRP sheets but from economic point of view, BFRP sheets are more beneficial than CFRP sheets.
- Wrapping the beam with two layers of BFRP sheets can give more torsional strength than that with one layer of CFRP sheets.

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