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Torsional Strengthening of RC beams using Hybrid CFRP-BFRP External U-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. One of the technique of strengthening of RC beams is through external wrapping with high strength fibre composites. Basalt Fibre Reinforced Polymer (BFRP) has great potential as strengthening material compared to other FRP's due to its cost-effectiveness. This paper investigates the possibility of using hybrid CFRP-BFRP wrapping on RC beams for improving the torsional capacity, using finite element method.*

***Key Words*: ANSYS 16.0 APDL, Reinforced concrete beam, Torsion, Strengthening, Hybrid CFRP - 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 hybrid CFRP-BFRP wrapping. It also compares the torsional resistance and cost effectiveness of RC beams wrapped with CFRP and hybrid CFRP-BFRP sheets.

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 12 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 12 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)
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
C200B50(1)90	CFRP-BFRP	200C/ 50B	Continous strips	1	90
B200C50(1)90	CFRP-BFRP	200B/ 50C	Continous strips	1	90
C125B125(1)90	CFRP-BFRP	125C/ 125B	Continous strips	1	90
C150B100(1)90	CFRP-BFRP	150C/ 100B	Continous strips	1	90
B150C100(1)90	CFRP-BFRP	150B/ 100C	Continous strips	1	90
1700C(1)B(1)90	CFRP-BFRP	17000/ 1700B	Continous Layer	2	90
1700C(1)B(1)45	CFRP-BFRP	1700C/ 1700B	Continous Layer	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. 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. 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

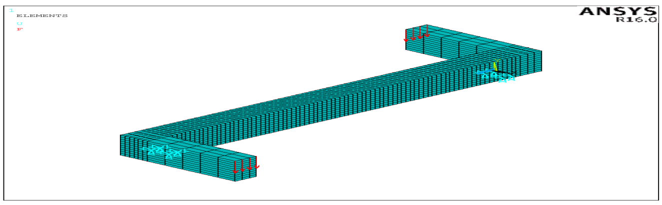

Fig -1: ANSYS Model of Reinforcement

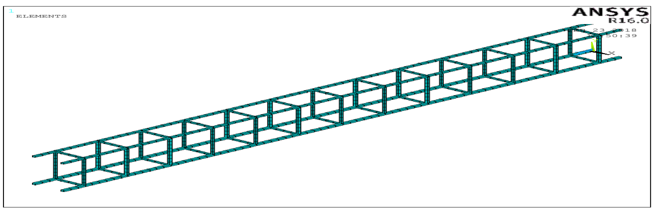

Fig -2: ANSYS Model of Control Beam

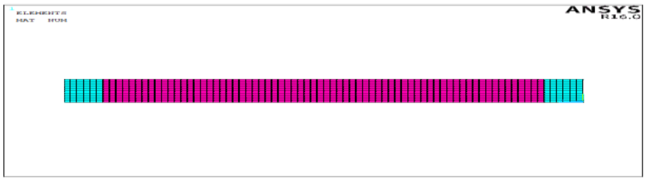

Fig -3 : Wrapping Pattern C1700FL(1)90

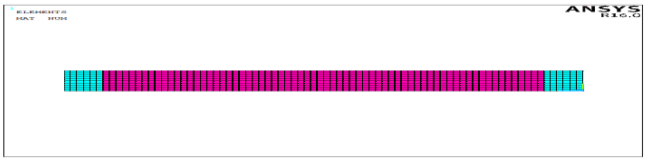

Fig -4: Wrapping Pattern C1700FL(2)90

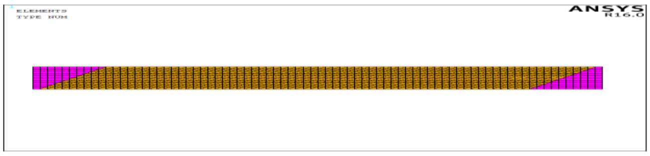

Fig -5 : Wrapping Pattern C1700FL(1)45

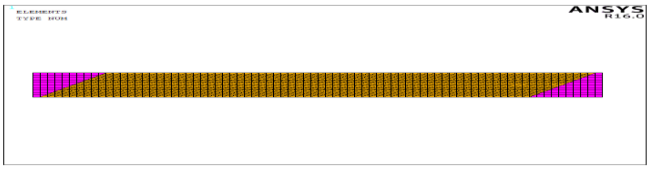

Fig -6 : Wrapping Pattern C1700FL(2)45

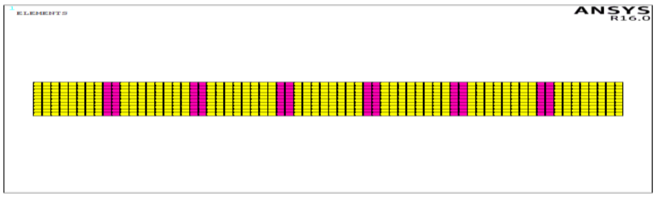

Fig -7 : Wrapping Pattern C200B50(1)90

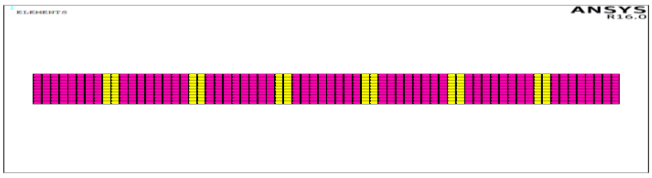

Fig -8 : Wrapping Pattern B200C50(1)90

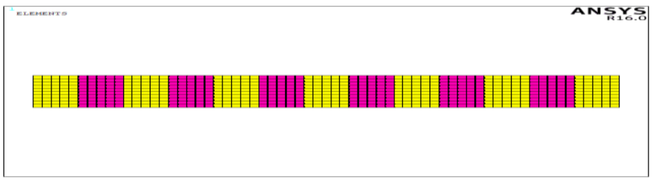

Fig -9 : Wrapping Pattern C125B125(1)90

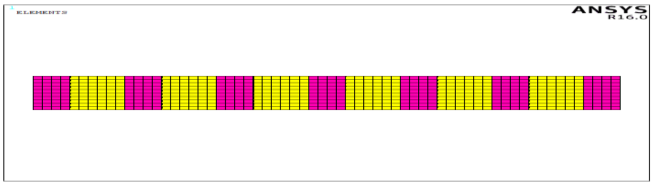

Fig -10 : Wrapping Pattern C150B100(1)90

Fig -11 : Wrapping Pattern B150C100(1)90

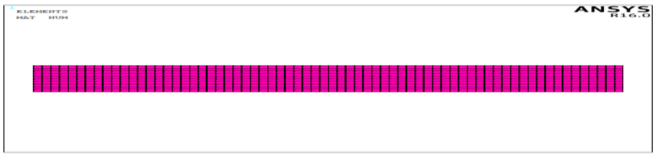

Fig -12 : Wrapping Pattern 1700C(1)B(1)90

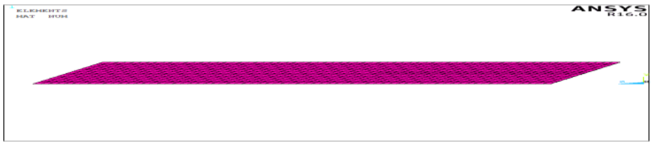

Fig -12 : Wrapping Pattern 1700C(1)B(1)45

Fig -3 to Fig-12 shows the various wrapping patterns.

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 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
C200B50(1)90	16.76	0.000336
B200C50(1)90	13.67	0.000427
C125B125(1)90	15.45	0.000274
C150B100(1)90	16.004	0.000256
B150C100(1)90	13.73	0.000218
1700C(1)B(1)90	19.63	0.000288
1700C(1)B(1)45	24.84	0.000636

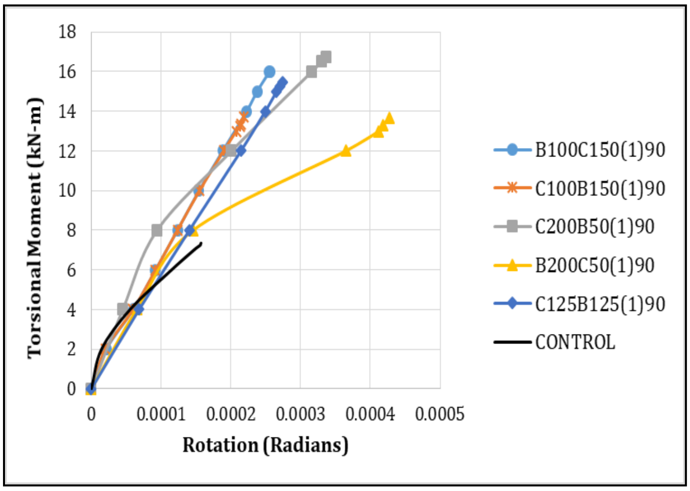

Fig -13 : Torsional Moment Vs Rotation Graph of Hybrid CFRP-BFRP (strips)Beams

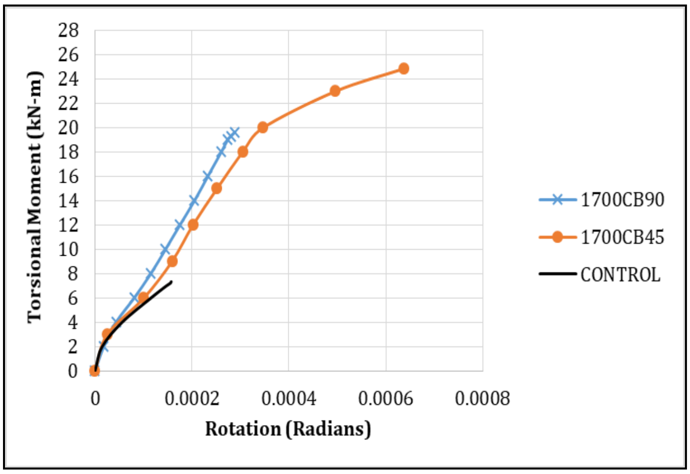

Fig -14 : Torsional Moment Vs Rotation Graph of Hybrid CFRP-BFRP (layer)Beams

Fig -13 and Fig -14 shows the torsional moment-rotation graphs of the control beam and strengthened hybrid 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 continuous wrapping is better than strip wrapping. Also cost of CFRP sheets is very high and it is almost three times as that of BFRP sheets. This leads to the possibility of studying the effectiveness of combined CFRP and BFRP sheets ie, hybrid CFRP-BFRP beams. Instead of wrapping with one single continuous layer of CFRP, some percentage of CFRP sheets was replaced with BFRP sheets. Fig -15 shows the replacement of BFRP strips in between CFRP strips for various percentages for 90 degree orientation.

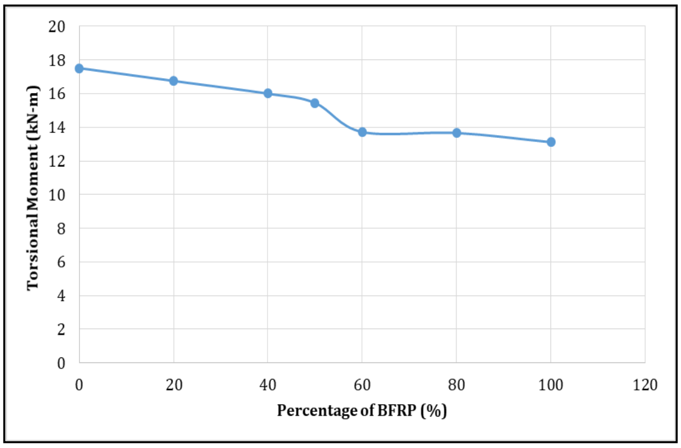

Fig –13 : Replacement of BFRP strips in between CFRP strips

The beam wrapped with continuous sheet of CFRP resisted the maximum torsional moment of 17.52kNm. The percentage increase in C1700FL(1)90 is 138.36% with respect to control beam. When comparing B1700FL(1)90 with CFRP-BFRP hybrid beams ie, C200B50(1)90, B200C50(1)90, C125B125(1)90, C150B100(1)90 and B150C100(1)90 showed increased torsional strength. The percentage increase in torsional strength with respect to control beam for the above mentioned hybrid beams is 128%, 85.95%, 110.20%, 117.74% and 86.74% for 20%, 80%, 50%, 40% and 60% replacement BFRP respectively.

In no case, the replacement with BFRP strips could resist more torsional capacity than the continuous CFRP wrapped beam ie, C1700FL(1)90. The percentage decrease with respect to C200B50(1)90, B200C50(1)90, C125B125(1)90, C150B100(1)90 and B150C100(1)90 is 21.9%, 4.34%, 11.81%, 21.6% and 8.6%. The torsional resistance capacity can be increased by continuous wrapping with CFRP sheets and by replacing some strips of BFRP in between CFRP strips but its ultimate torsional strength can never go above C1700FL(1)90.

The hybrid beams can be more effective when they can resist more torsional strength than a beam wrapped with continuous layer of CFRP sheet. So addition of a continuous layer of BFRP to beam wrapped with a continuous layer of CFRP was studied ie beams 1700C(1)B(1)90 and 1700C(1)B(1)45.

The ultimate torsional strength of 1700C(1)B(1)90 was found to be 167.07% and that of 1700C(1)B(1)45 was 237.95% when compared to control beam. But the percentage increase in ultimate torsional strength of C1700FL(1)90 was 138.36% and that of C1700FL(1)45 was 146.93%. The beams wrapped with continuous layer of BFRP above CFRP sheets could resist more torsional strength than one layer of CFRP sheets.

The percentage increase in ultimate torsional strength of 1700C(1)B(1)90 was found to be 12.04% with respect to C1700(1)90. The percentage increase in ultimate torsional strength of 1700C(1)B(1)45 was found to 36.85% with respect to C1700FL(1)45. The ultimate torsional strength of 1700C(1)B(1)90 was found to be 15.67% decreased with respect to C1700FL(2)90. The ultimate torsional strength of 1700C(1)B(1)45 was found to be 11.19% decreased with respect to C1700FL(2)45.

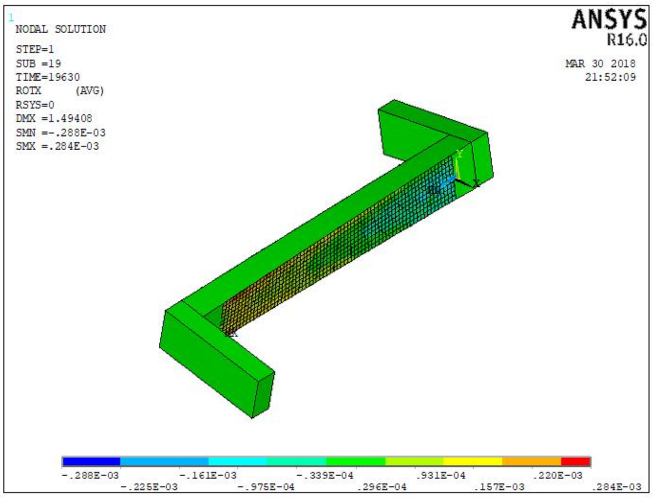

Fig -14 : Result window of 1700C(1)B(1)90

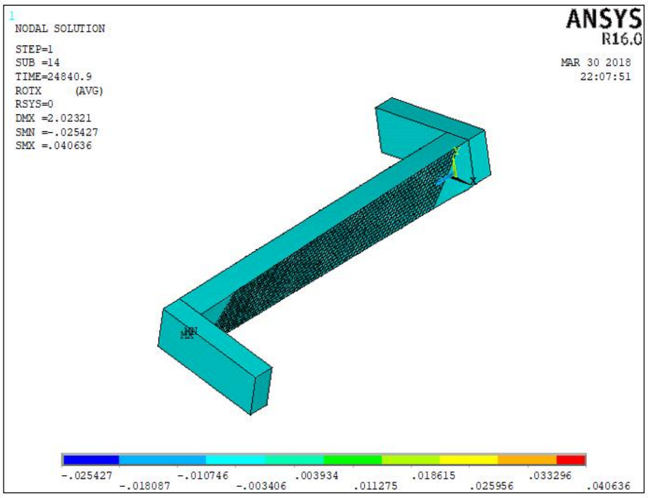

Fig -15 : Result window of 1700C(1)B(1)45

Fig -14 and Fig -15 shows the result window of Hybrid CFRP-BFRP (layer) Beams.

3.2 Cost Analysis of Hybrid CFRP-BFRP Beams

To find out a cost effective solution for torsional strengthening, the concept of hybrid CFRP-BFRP beams were introduced.

- Cost of CFRP – 1600/m^2
- Cost of BFRP – 390/m^2

The cost analysis considering the ultimate torsional-moment for hybrid CFRP-BFRP beams (strips) compared to C1700FL(2)90 is shown in the Table 5.

Table 5 Cost analysis of hybrid CFRP-BFRP(strips) beams

Model Name	Cost/ Specimen (Rs)	Ultimate Torsional Moment (kNm)	% increase/ decrease in torsional moment (%)	% increase/ decrease in cost (%)
C1700FL(2)90	3536	23.28	-	-
C200B50(1)90	1501	16.76	-28.00	-57.55
B200C50(1)90	1233	16.004	-31.25	-65.13
C125B125(1)90	1100	15.45	-33.63	-68.89
C150B100(1)90	967	13.73	-41.02	-72.65
B150C100(1)90	700	13.67	-41.28	-80.20

The percentage decrease in torsional strength for hybrid CFRP-BFRP beams (strips) with respect to C1700FL(2)90 is about 28% to 41.28% and that in cost is about 57.55% to 80.20%. That means, while using combination of CFRP-BFRP strips, there is a considerable reduction in cost and the reduction in the ultimate torsional moment is only less when compared to cost. So hybrid CFRP-BFRP (strips) beams can be an effective strengthening technique for torsional strengthening. The cost analysis considering the ultimate torsional moment for hybrid CFRP-BFRP (layer) beams compared to C1700FL(2)90 and C1700FL(2)45 is shown in the Table 6.

Table 6 Cost analysis of hybrid CFRP-BFRP (layer) beams

Model Name	Cost/ Specimen (Rs)	Ultimate Torsional Moment (kNm)	% increase/ decrease in torsional moment (%)	% increase/ decrease in cost (%)
C1700FL(2)90	3536	23.28	-	-
1700C(1)B(1)90	2200	19.63	-15.67	-37.78
C1700FL(2)45	3636	27.97	-	-
1700C(1)B(1)45	2200	24.84	-11.19	-37.78

The percentage decrease in torsional strength for 1700C(1)B(1)90 is 15.67% and that in cost is 37.78% when compared to C1700FL(2)90. The percentage decrease in torsional strength for 1700C(1)B(1)45 is 11.19% and that in cost is 37.78% when compared to C1700FL(2)45. The percentage reduction in torsional moment while using hybrid CFRP-BFRP (layer) is less when compared to the cost reduction. The percentage reduction in torsional moment is only 11.19% for 1700C(1)B(1)45 and that for 1700C(1)B(1)90 is 15.67%. While considering the percentage increase in torsional strength with respect to control beam, the percentage increase in torsional strength 1700C(1)B(1)45 is about 237..95% and that for 1700C(1)B(1)90 is only 167.07%. So the pattern 1700C(1)B(1)45 can be considered as an economic viable strengthening scheme for beams deficient in torsional strength.

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 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.
- The percentage decrease in torsional strength for hybrid CFRP-BFRP beams (strips) with respect to C1700FL(2)90 is about 28% to 41.28% and that in cost is about 57.55% to 80.20%.
- So hybrid beams are economically viable since there is a considerable reduction in cost as compared to torsional strength.
- The percentage decrease in torsional strength for 1700C(1)B(1)45 with respect to C1700FL(2)45 is about 11.19% and that in cost is about 37.78%.

- The best pattern considering economic efficiency is continuous wrapping with BFRP above the CFRP wrapped beams oriented at 45 degrees ie, 1700C(1)B(1)45.

- The pattern 1700C(1)B(1)45 has a percentage increase in ultimate torsional moment of about 237.95% with respect to the control beam.

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