Experimental and Predicted Twist at Ultimate Torque of Ferrocement "U" Wrapped RCC BEAMS: A Comparative Study

Dr. Gopal Charan Behera

Abstract— **Wrapping technology is one of the effective ways of strengthening concrete elements. Several researchers reported the effectiveness of Glass fiber reinforced polymers and carbon fiber reinforced polymers for improving the strength of the concrete elements. Wrapping on three sides is one of the effective methods for strengthening the beams supporting slabs. Scant literature is available on the strength enhancement of "U" wrapped concrete elements subjected to torsional loads. Prediction of torque and twist is reported in literature for wrapping of FRP material. No such calculation is found for ferrocement wrapping materials. In this investigation an attempt is made to quantify the improvement in twist of "U" wrapped rectangular concrete members subjected to torsional loads "U" wraps. Ferrocement is taken here as wrapping material as it is economic and best suited for developing countries. Beams were cast with different number of mesh layers with different torsional reinforcement. The beams were analyzed by soft computing method MARS. The same has been derived by analytical model using softened truss model of Hsu with modification in material properties. Softening of concrete and ferrocement is taken into account. Ferrocement "U" wrapped beams are found to undergo more twist than un-wrapped beams. The plain "U" wrap beam has a twist of 0.0054 rad/m while under reinforced beam U3N undergoes a twist of 0.155 rad/m. This shows "U" wrapped beam undergoes maximum twist in comparison of plain "U" wrapped beams. The predictions for twist at ultimate torque are in good agreement with experimental test results. Soften truss model better predicts over soft computing.**

Index Terms— **ferrocement: U wrap: Twist at ultimate torque: MARS: Softened truss model**

I. Introduction

A reinforced concrete (RC) structural element such as peripheral beams, ring beams at bottom of circular slab, beams supporting canopy and other types of beams are subjected to torsional loading. Strengthening or upgrading becomes necessary for these beams when they are unable to provide the resistance. Increased service loading, diminished capacity through aging, degradation and more stringent updates in code regulations have also necessitated for the retrofitting of existing structures [1,2]. Repair and strengthening of RC members can be done by epoxy repair, steel jacketing or by fibre-reinforced polymer (FRP) composite. Each technique requires a different level of artful detailing. Availability of labour, cost and disruption of building occupancy plays major role to decide type of repair [3]. FRPs can be effectively used to upgrade such structural deficient reinforced concrete structures. Torsional retrofitting using FRP has received less attention [4,5,6]. Strengthening structures with FRP increases the strength in flexure, shear and torsion capacity as well as changes the failure mode and failure plane [7,8]. In practice it is seldom possible to fully wrap the beam cross section due to the presence of either a floor slab, or a flange. However, most of the research on FRP strengthened RC members investigated rectangular section fully wrapped with FRP [2,4,9,10,11] with the exception of a few studies that investigated T-beams with U-jacket [9,12]. Few studies regarding torsion strengthening using FRP have shown that the continuous wrapping is much more effective than using the strips [4,9,12,13,14,15]. Recent studies have shown that the basic deformation of the torsionally strengthened beams is similar to unstrengthened ones, however, the externally bonded limits the crack formation, propagation, widening and spacing between cracks[2,11,12].

Retrofitting by FRP is restricted to developed countries and urban areas of developing countries due to their high cost and skilled workmanship for its application [16]. It is well-known that although common concrete jackets enhance the strength, stiffness and toughness and improve the overall performance, they exhibit substantial shortcomings. These disadvantages are (a) the required labour-intensive procedures and (b) the increase of the member sizes, which reduces the available floor space, increases mass, change in stiffness and alters the dynamic characteristics of the building. Steel jacketing and FRP wrapping have the advantage of high strength and eliminate some of the limitations of concrete jacketing. However, they have poor fire resistance due to strength degradation of resin under moderate temperature. With due consideration on simplicity and constructability, a rehabilitation method for beam–column joints using ferrocement jackets with embedded diagonal reinforcements is proposed. Tests on reinforced concrete columns and beams strengthened by ferrocement have shown significant enhancement in strength [17]. From cost effective point of view and also from strength point of view ferrocement may be a substitute for FRP as it possess high tensile strength , water tightness and easy on application [18].

Ferrocement laminates in the form of Welded Wire Mesh (WWM) when encapsulated with a properly designed thin mortar layer can provide good alternative and low-cost

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technique in strengthening and repairing different structural elements for enhancing their load carrying capacities and ductility. Ferrocement meets the criteria of flowability and strength in addition to impermeability, sulfate resistance, corrosion protection and in some cases frost durability. Such performance is made possible by reducing porosity, inhomogeniety, and micro cracks in the cement matrix and the transition zone [19]. The study by [20]under three different axial load ratios confirmed that confining columns using ferrocement jackets resulted in enhanced stiffness, ductility, and strength and energy dissipation capacity. The mode of failure could be changed from brittle shear failure to ductile flexural failure. Experimental and analytical study of thin concrete jacketing with self compacting concrete and "U" shaped stirrup was found to be beneficial in changing stiffness and altering the dynamic characteristics of the beam [21]. "U" wrapped beams are unable to enhance the torsional capacity to a greater value [22].

I.A. Aim of Present Investigation:

Torsion, due to its circulatory nature, can be well retrofitted by closed form of wrap. Few analytical and experimental studies are found to quantify the torsional strength of FRP bonded full wrap[10,11,23,24, 25]. But inaccessibility and extension of flanges over the web has necessitated strengthening the beams by "U" wrap rather than full wrap [26]. For quantification of torsional strength of "U" wrapped beams very few attempts have been taken by [9,27]. U-jacketed flanged beams exhibited premature debonding failure at the concrete and the FRP sheet adhesive interface [12,28] fond torque is increasing with wrapping. From the above points, it is clear that the "U" wrapped beams cannot perform in the same manner as that of full wrapped beams under torsional loading as it lacks one torsion resisting element(reinforcement) on un-wrapped face.

The mentioned literature in the introduction substantially recommends ferrocement as a retrofitting substitution for FRP. Few studies are available to quantify the torsional strength of ferrocement "U" wrapped beams. Experimental and analytical estimation of torsional strength of "U" wrapped RC beams reported by the author earlier was limited to plain beams only [26]. This paradigm motivated to take up the present investigation. The torque-twist response of reinforced beams is characterized by different salient stages such as elastic, cracking and ultimate stages [26, 29]**.** Elastic and cracking torque of a beam is dependent upon its constituent materials and cross sectional area [29, 30, 31] . The reinforcement provided in longitudinal and transverse direction controls the torque twist response in the post cracking stage [29, 32, 33, 34]. Literature review reveals that the torsional response of a wrapped beam is dependent on aspect ratio, constituent materials of core and wrapping material [23, 35, 36]. A beam if wrapped with ferrocement "U" wrap, then its torque twist response is influenced by ferrocement wrap (ferrocement matrix strength and number of layers along with reinforcement in the core) and states of torsion. The six possible states of torsion (arrangement of reinforcement in longitudinal and transverse direction that can be arranged in a beam) are as follows

1) Only longitudinally reinforced
2) Only transversely reinforced
3) Under Reinforced Beams
4) Longitudinally over reinforced and transversely under reinforced.
5) Longitudinally under reinforced and transversely over reinforced
6) Completely over reinforced.

The objective of the present experimental study is to evaluate the twist at ultimate torque of a wrapped ferrocement "U" wrap beam using soft computing method MARS.

II. EXPERIMENTAL PROGRAM

To study the above mentioned parameters, beams are cast and tested under pure torsional loading. The variations considered are the number mesh layers in the ferrocement 'U' wrap, size aspect ratio, mortar strength, concrete strength 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.

Torsional loading induces spiral cracking approximately inclined at 45^0 to the longitudinal direction of the beam. To allow this pattern of cracking and to form two complete spirals in the central test region of the beam, a length 1500 mm is required. In order to hold the specimen and to apply the torque, the end zones are heavily reinforced for a length of 250 mm on either side of the beam. Thus, the total length of the beam is fixed as 2000 mm. In under reinforced section the amount of reinforcement provided in longitudinal and transverse direction are less than that are required for torsionally balanced section. In longitudinally over reinforced sections less amount of reinforcement in transverse direction and more amount of reinforcement in the longitudinal direction than the reinforcement required for torsionally balanced sections are provided. In completely over reinforced sections more amount of reinforcement in transverse direction and longitudinal direction than the reinforcement required for torsionally balanced sections are provided. All details of the beams tested in this investigation are presented in Table 1. Figures of beams cast were shown in [26].

Co5N represents a beam of size (125 mm X 250 mm), Co stands for completely over reinforced, numeric 5 represents number of mesh layer and N stands for concrete of strength 35 MPa. So, Co5N represents a completely over reinforced beam with 5 numbers of mesh layers in ferrocement zone with mortar grade 40 MPa and concrete of 35 MPa in the core.

A. Material and Material Properties

a. Cement:

Ordinary Portland cement of 53 grade conforming to [37]is used throughout the experimental program. The standard consistency is 28% where as the initial and final setting time is 95 min. and 210 min. respectively. The specific gravity of cement is 3.14 and its compressive strength after 28 days is found to be 57 MPa.

b. Coarse Aggregate

Crushed hard granite stone of maximum size 20 mm is used for concrete. The bulk density of aggregates is 16.95 kN/m^3 and specific gravity is found 2.65.

c. Fine Aggregate

IFIC (International Ferrocement Information Centre, 2001) suggests that the size of sand particle in ferrocement matrix should not be more than one half of the opening of mesh. The mesh opening is 6.35 mm. The river sand passing through the 1.18 mm sieve is used in the ferrocement matrix preparation. The specific gravity of sand is 2.65. The bulk density is found 16.05 kN/ m^3. Fine aggregate used for this entire investigation for concrete is river sand conforming to zone-II of [38]. The fineness modulus is 2.81.

d. Water

Potable water is used for casting as well as curing as per [39].

e. Super plasticizer

To achieve both strength and a workable mortar, a regulated dosage of super plasticizer CONPLAST SP-337 of FOSROC chemicals is used.

f. Wire meshes

Galvanized steel woven wire meshes are used for “U” wraps. The diameter of wire is 0.72 mm, yield strength 250 N/mm^2 and centre to centre spacing of wires is 6.35 mm.

g. Reinforcement

6 mm , 8 mm and 10 mm diameter bars with yield stress 350 N/mm^2, 465 N/mm^2 and 445 N/mm^2 respectively are used in the entire experimental study .

The materials used, casting and testing procedure of beams is presented in [4041]. The experimental results of beams are presented in Table 2.

III. SOFT COMPUTING METHOD: MULTIVARIATE ADAPTIVE REGRESSION SPLINE (MARS)

MARS is an adaptive procedure because the selection of basis functions is data-based and specific to the problem at hand. This algorithm is a nonparametric regression procedure that makes no specific assumption about the underlying functional relationship between the dependent and independent variables. It is very useful for high dimensional problems. For this model an algorithm was proposed by Friedman (1991) as a flexible approach to high dimensional nonparametric regression, based on a modified recursive partitioning methodology. MARS uses expansions in piecewise linear basis functions of the form Equation (1)

$$c^{+}(x,\tau)=[+(x-\tau)]_{+}\ ,\ c^{-}(x,\tau)=[-(x-\tau)]_{+} \quad (1)$$

where, [q]=max{0,q} and τ is an univariate knot. Each function is piecewise linear, with a knot at the value τ, and it is called a reflected pair. The points in lustrate the data (x_i , y_i) (i = 1, 2,...N), composed by a p-dimensional

Sl. No.	Series	Designation	Dimensions (mm)	Compressive strength		Reinforcement Details				
						Core Reinforced Concrete				Outer Wrap
						Longitudinal Steel		Transverse steel		
				Ferrocement matrix (MPa)	Concrete (MPa)	Diameter, No. of bars	Yield Strength (MPa)	Diameter, Spacing	Yield Strength (MPa)	No. of mesh layers
1		BQ4N	125 x 250	40	35					
2		BQ3N	125 x 250	40	35					
3		BQ5N	125 x 250	40	35					
4		L3N	125 x 250	40	35	12 mm, 4 nos.	440			3
5	Only Longitudinal	L4N	125 x 250	40	35	12 mm, 4 nos.	440			4
6		L5N	125 x 250	40	35	12 mm, 4 nos.	440			5
7		T3N	125 x 250	40	35			8mm @ 100 mm c/c	465	3
8	Only Transvers e	T4N	125 x 250	40	35			8mm @ 100 mm c/c	465	4
9		T5N	125 x 250	40	35			8mm @ 100 mm c/c	465	5
10		U3N	125 x 250	40	35	6 mm, 4 nos.	350	6mm @ 100 mm c/c	350	3
11	U	U4N	125 x 250	40	35	6 mm, 4 nos.	350	6mm @ 100 mm c/c	350	4
12		U5N	125 x 250	40	35	6 mm, 4 nos.	350	6mm @ 100 mm c/c	350	5
13		Lo3N	125 x 250	40	35	12 mm, 4 nos.	440	6mm @ 100 mm c/c	350	3
14	L	Lo4N	125 x 250	40	35	12 mm, 4 nos.	440	6mm @ 100 mm c/c	350	4
15		Lo5N	125 x 250	40	35	12 mm, 4 nos.	440	6mm @ 100 mm c/c	350	5
16		To3N	125 x 250	40	35	6 mm, 4 nos.	350	8mm @ 100 mm c/c	465	3
17	T	To4N	125 x 250	40	35	6 mm, 4 nos.	350	8mm @ 100 mm c/c	465	4
18		To5N	125 x 250	40	35	6 mm, 4 nos.	350	8mm @ 100 mm c/c	465	5
19		Co3N	125 x 250	40	35	12 mm, 4 nos.	440	8mm @ 100 mm c/c	465	3
20	C	Co4N	125 x 250	40	35	12 mm, 4 nos.	440	8mm @ 100 mm c/c	465	4
21		Co5N	125 x 250	40	35	12 mm, 4 nos.	440	8mm @ 100 mm c/c	465	5
23		BH	125 x 250		60					
24		BO4H	125 x 250	55	60					4
25		L4H	125 x 250	55	60	12 mm, 6 nos.	440			4
26		T4H	125 x 250	55	60			10mm @ 70 mm c/c	445	4
27	U	U4H	125 x 250	55	60	6 mm, 6 nos.	350	6mm @ 70 mm c/c	350	4
28	L	Lo4H	125 x 250	55	60	12 mm, 6 nos.	440	6mm @ 70 mm c/c	350	4
29	T	To4H	125 x 250	55	60	6 mm, 6 nos.	350	10mm @ 70 mm c/c	445	4
30	C	Co4H	125 x 250	55	60	12 mm, 6 nos.	440	10mm @ 70 mm c/c	445	4

Table 1 Details of Beams

input specification of the variable x and the corresponding 1-dimensional responses, which specify the variable y.Let us consider the following general model Equation on the relation between input and response:

$$Y = f(X) + \varepsilon \quad (2)$$

Where, Y is a response variable, $X=(X_1 ,X_{2,...........}X_n)^T$ is a vector of predictors and ε is an additive stochastic component, which is assumed to have zero mean and finite variance.

The goal is to construct reflected pairs for each input x_j (j=1,2………p) with p-dimensional knots $\tau_i = (\tau_{i,1}, \tau_{i2},\ldots, \tau_{i,p})^T$. Actually, we could even choose the knots $\tau_{i,j}$ more far away from the input values $x_{i,j}$, if any such a position promises a better data fitting.

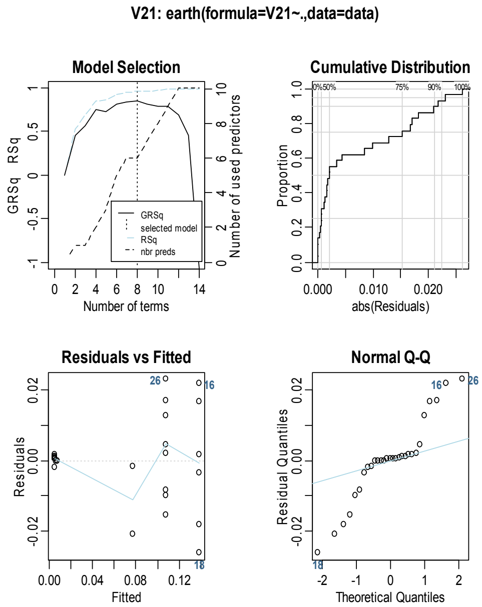
After these preparations, our set of basis functions is Equation (6):

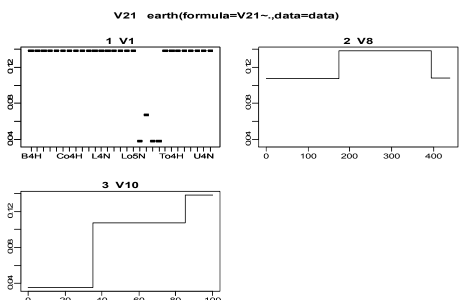
$$\delta := \{(X_j - \tau)_+ , (\tau - X_j)_+ \mid \tau \in \{x_{1,j}, x_{2,j}, \ldots\ldots, x_{N,j}\}, j \in \{1,2,.. \quad (3)$$

If all of the input values are distinct, there are 2Np basis functions altogether. Thus, we can represent f (X) by a linear combination, which is successively built up by the set δ and with the intercept θ_0, such that Equation takes the form

$$Y = \theta_0 + \sum_{m=1}^{M} \theta_m \psi_m (X) + \varepsilon. \quad (4)$$

All the beams tested in the experimental program are analyzed by MARS for obtaining the twist at ultimate torque. The values are presented below.





V10 6 100.0 100.0
V8 5 65.0 67.8
V1T3N 3 40.5 35.3
V1T4H 3 40.5 35.3
V1T4N 3 40.5 35.3
V1T5N 3 40.5 35.3
V13-unused 1 -17.7 13.6

coefficients
(Intercept) 0.035584340
V1T3N -0.100297578
V1T4H -0.071097905
V1T4N -0.100097578
V1T5N -0.099897578
h(V8-350) -0.000337627
h(350-V8) -0.000087864
h(V10-0) 0.001026656

θ=0.03558-maximum [0,Fly-350]*0.0003376-maximum[0,350-Fly]*0.00008786+ maximum[0,spacing of stirrup]*0.00102665

Table 2. EXPERIMENTAL AND PREDICTED VALUES OF TWIST AT ULTIMATE TORQUE

Twist at Ultimate Torque(rad/m)				Twist at Ultimate Torque(rad/m)			
Beams	Expt	Analytical	MARS	Beams	Expt	Analytical	MARS
BQ3N	0.0054	0.0053	0.0048	To3N	0.16	0.15067	0.13825
BQ4N	0.0053	0.0053	0.0048	To4N	0.1348	0.13483	0.13825
BQ5N	0.0052	0.0052	0.0048	To5N	0.112	0.11986	0.13825
L3N	0.0068		0.0051	Co3N	0.125	0.1131	0.107863
L4N	0.0064		0.0051	Co4N	0.11	0.10299	0.1078
L5N	0.0063		0.0051	Co5N	0.098	0.09589	0.107863
T3N	0.0072		0.0072	BH	0.0028	0.0035	0.004832
T4N	0.0074		0.0074	B4H	0.00546	0.0056	0.004832
T5N	0.0076		0.0076	L4H	0.0058		0.005198
U3N	0.155	0.1654	0.1382	T4H	0.0056		0.0056
U4N	0.14	0.13	0.1382	U4H	0.1305	0.13736	0.10745
U5N	0.12	0.0897	0.13825	Lo4H	0.056	0.055	0.077064
Lo3N	0.1207	0.1207	0.107863	To4H	0.0921	0.09158	0.10745
Lo4N	0.1122	0.10973	0.107863	Co4H	0.0754	0.07361	0.077064
Lo5N	0.0995	0.09722	0.107863				

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ANALYTICAL MODEL

Analytical model is developed using Hsu's softened truss model with modifications in the material properties. The detailed procedure is presented by Behera et al. (2014). The values are presented in Table 2.

Here soft computing method is employed for the calculation of twist at ultimate torque using MARS. This method is also known as the dark box method as finally the method of calculations is unknown and only end results were found out by this method.

V. INTERPRETATION OF TEST RESULTS

In this phase of investigation, the experimental results obtained were analyzed and compared with the results obtained by MARS.

A. Torsional Behaviour Of Normal Strength Beams With Ferrocement "U" Wrap

In this section, the twist at ultimate torque of normal strength concrete beams with ferrocement "U" wrap, (plain beams and reinforced concrete beams) tested were discussed.

A.I Torsional Behaviour of Plain Normal Strength Beams

Normal strength plain "U" wrap beam with core concrete strength 35 MPa, mortar strength 40 MPa, aspect ratio 2.0 and with 3, 4 and 5 numbers of wire mesh layers in ferrocement shell was cast and tested. The beams were designated as BQ3N, BQ4N and BQ5N. These will act as control specimens.

A.II General Torsional Behaviour of Plain Normal Strength Beams With Ferrocement "U" Wrap

The twist at ultimate torque of the plain beams with jacketing was presented in the Table- 2. In ferrocement wrapped concrete beams, the most important parameters influencing the torque-twist response are number of mesh layers and strength of ferrocement mortar matrix. To study the effect of number of layers, the aspect ratio is kept as 2.0, core concrete and mortar matrix are taken as 35 MPa and 40 MPa respectively. When it is predicted with layers from 3, 4 and 5, the twist at ultimate torques are found to be 0.0048 rad/m for all beams without any variation by MARS. The same was predicted to be 0.0053 rad/m, 0.0053 rad/m and 0.0052 rad/m for beams BQ3N, BQ4N and BQ5N respectively by analytical model. The twists at ultimate torque were found to be experimentally 0.0054 rad/m, 0.0053 rad/m and 0.0052 rad/m for beams BQ3N, BQ4N and BQ5N respectively. This shows "U" wrap beams can sustain more twist than unwrapped beams.

A.III Effect of Number of Layer:

The variation of twist at ultimate torque with number of layers was shown in Figure 1. The twist was found to be same as that of for 3 layers. This is due to the fact that the crack is initiated on un-wrapped face for 3 layers also. Increasing the number of layers beyond three layers only increases the tensile strength of ferrocement, but unable to change the failure plane. The predicted values by MARS underestimate experimental values by 11.11%, 9.43% and 7.69% for beams BQ3N, BQ4N and BQ5N respectively. The analytical model approximately well predicts the values. Variation in twist at ultimate torque is plotted in Figure 1.From the literature it is found strengthening of the longer faces improve the torque carrying capacity.But this way of strengthening shifts the failure plane from longer face to un-wrapped shorter face. Thus any further strengthening of longer face beyond this limit will not improve the rotation capacity of the section. If the grade of core concrete, mortar of the wrapping and the aspect ratio of the cross section are constant, then the increase in the number of layers beyond certain limit may not enhance the rotation carrying capacity of wrapped beams. The similar behavior is noticed in the predicted values also. Increase in the number of layers would be more effective for higher aspect ratio, high strength core concrete and for reinforced concrete sections in the post cracking stage (when the un-wrapped portion contains high strength materials).

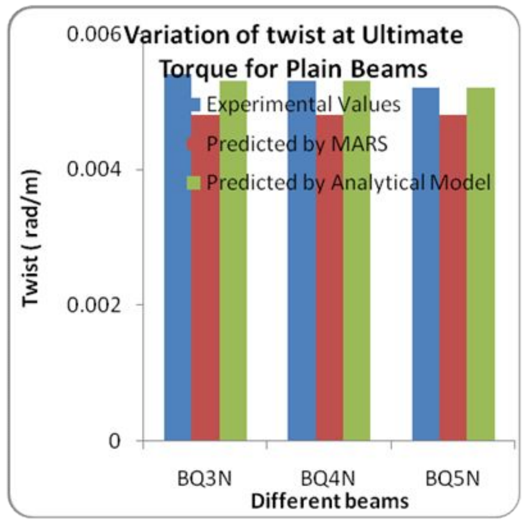

Figure 1. Twist at cracking torque of Plain Beams

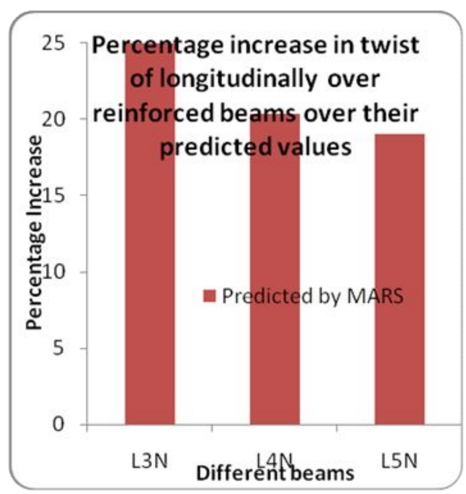

Figure 2. Percentage increase in Twist at Ultimate torque over predicted values for only longitudinally reinforced beams

A.IV Torsional Behavior Of RCC Normal Strength Beams With Ferrocement "U" Wrap

In a reinforced concrete beam the states of torsion influences the torque-twist diagram. For a wrapped beam the states of torsion and wrapping material influence the torsional behaviour. The number of layers present in the ferrocement influences its torsional behavior. So, the variables in this study were taken as states of torsion with respect to one grade of concrete and the number of mesh layers on ferrocement "U" wrap were varied as 3, 4 and 5 layers. The longitudinal reinforcement and transverse reinforcement were varied in such a way that all possible six states of torsion to occur. The aspect ratio, concrete strength and ferrocement matrix strength of the beams were fixed as 2.0, 35 MPa and 40 MPa respectively. So, in this phase total eighteen numbers of beams were tested.

A.V General Behavior of RCC Normal Strength Beams

All beams in this phase were similar to beams of BQ3N, BQ4N and BQ5N with different amount of reinforcement in core concrete.

A.VI Beams with Only Longitudinal Reinforcement

A reinforced concrete member when subjected to torsion, longitudinal reinforcement, transverse reinforcement and the concrete present in the diagonal strut resist the load. For a single type of reinforcement, as one of the load resisting elements is absent, the load carrying capacity is limited to plain beams only. Thus the beams with single type of reinforcement with ferrocement "U" wrap can be analyzed as plain ferrocement "U" wrapped beams. The beams L3N, L4N and L5N were cast to reflect the effect of layers on torque-twist response of "U" wrapped beams with longitudinal steel alone. The beams L3N, L4N and L5N were similar to the beams BQ3N, BQ4N and BQ5N respectively if the later beams were provided with only longitudinal steel.

The twist at ultimate torque of these beams L3N, L4N and L5N were found 0.0068 rad/m, 0.0064 rad/m and 0.0063 rad/m respectively which indicates that there was improvement in twist at ultimate torque. The predicted twist at ultimate torque by MARS of the beams was found to be 0.0051 rad/m for all the three beams. These experimental values are found to be 25.00%, 20.31% and 19.05 % more than predicted values for beams L3N, L4N and L5N values respectively. Twist at ultimate torque of these beams cannot be predicted by Softened truss model as transverse reinforcement is absent. The percentage in variation of twist with respect to experimental values is presented in Figure 2.

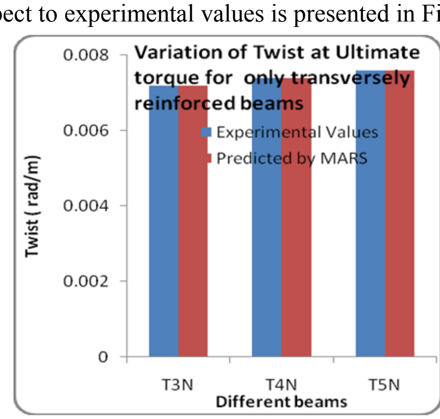

Figure 3. Twist variation of only transversely reinforced beams

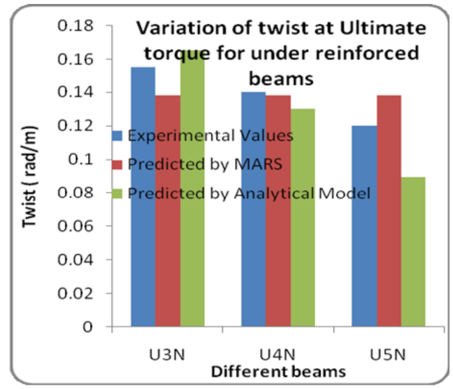

Figure 4. Experimental and Predicted values of twist at ultimate torque for under reinforced beams

A.VII Beams with Only Transverse Reinforcement

To observe the effect of number of layers on the beams those were provided with only transverse reinforcement, three beams designated as T3N, T4N and T5N tested under pure torsional loading. The difference in beams T3N, T4N and T5N to that of plain ferrocement "U" wrapped beams BQ3N, BQ4N and BQ5N were that the latter were provided with 8 mm diameter bars with 100 mm c/c. The ultimate twist for these beams were found to be 0.0072 rad/m, 0.0074 rad/m and 0.0076 rad/m. Provision of only transverse reinforcement in "U" wrapped beams cannot enhance the ultimate torque, but capable of providing better toughness due to increase in twist. The predicted values by MARS are found to be same as experimental values. This proves accuracy of the model. The variation of experimental and predicted torque is shown in Figure 3.

The "U" wrapping beams with single type of reinforcement i.e., transverse reinforcement or longitudinal reinforcement alone able to increase the twist to a considerable amount with respect to plain "U" wrapped beams. The analytical model is unable to predict the twist for these beams as these lack longitudinal reinforcement. Similar observations were reported by earlier researchers for reinforced concrete beams and for steel fiber reinforced beams T.D.G Rao and D.R.Seshu (2006) and Behera (2015)[42].

A.IX Under Reinforced Beams

To study torque-twist response of under reinforced beams with different numbers of mesh layers in the ferrocement "U" wrap, three beams were cast with three, four and five layers of mesh reinforcement and the main reinforcement (longitudinal and transverse) provided is lower than the balanced reinforcement. The beams were designated as U3N, U4N and U5N. The aspect ratio, ferrocement matrix mortar strength and core concrete strength of these beams were kept as 2.0, 40 MPa and 35 MPa respectively. The twist at the ultimate torque of the beams U3N, U4N and U5N were found to be 0.155 rad/m, 0.14 rad/m and 0.12 rad/m experimentally respectively. The same was predicted by soft computing as 0.13825 rad/m for all the three beams. Twist at ultimate torque was found to be 0.1654 rad/m, 0.13 rad/m and 0.0897 rad/m respectively for beams U3N, U4N and U5N by Softened truss model. As reinforcement amount provided in both longitudinal and transverse direction are less than torsionally balanced reinforcement, the twist was noticed more as stiffness of beams are less.U3N, U4N and U5N are found to be experiencing twists at ultimate torque 28.70, 26.42 and 23.08 times more than BQ3N, BQ4N and BQ5N respectively. The variation of twist between experimental and predicted values is presented in Figure 4. Beams undergo more twist while ultimate torque is less.

A.X Longitudinally Over Reinforced Beams

The beams in this series were cast to study the torsional response of longitudinally over reinforced beams with three, four and five number of mesh layers in the wrapping portion, keeping the aspect ratio, mortar strength and concrete grade as 2.0, 40 MPa and 35 MPa respectively. The beams were designated as Lo3N, Lo4N and Lo5N and henceforth will be called as "L" series beams for normal strength beams. The ultimate twists of these beams Lo3N, Lo4N and Lo5N were found to be 0.1207 rad/m, 0.1122 rad/m and 0.0995 rad/m. The ratios of twist at the ultimate to the predicted values by softened truss model are found to be 1.0, 1.022 and 1.023 for beams Lo3N, Lo4N and Lo5N respectively. The same ratio was found to be 1.12, 1.04 and 0.922 for beams Lo3N, Lo4N and Lo5N respectively for values computed by MARS.

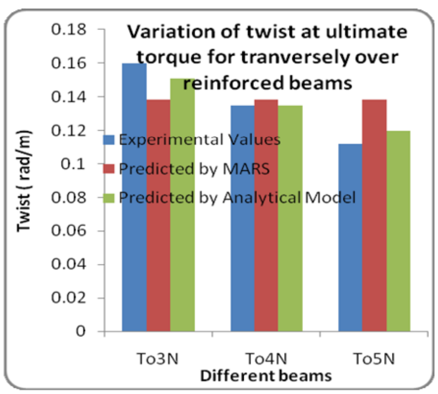

Figure 5. Experimental and predicted twist variation of transversely over reinforced beams

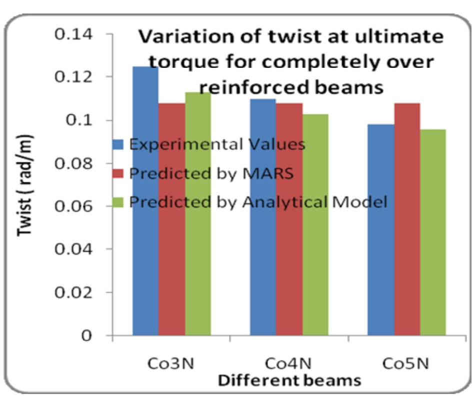

Figure 6 Experimental and predicted values of twist of completely over reinforced beams for different layers

A.XI Transversely Over Reinforced Beams

To examine transversely over reinforced beams, three beams, designated as To3N, To4N and To5N were analyzes and verified with experimental results. The material properties of core and wrap were mentioned in experimental. The beams henceforth will be refereed as "T" series beams. The beams had undergone maximum twist next to the under reinforced series of beams. The ultimate twist of these beams was found to be 0.16 rad/m, 0.1348 rad/m and 0.112 rad/m for beams To3N, To4N and To5N respectively against the predicted values by MARS of 0.13825 rad/m for all beams as shown in Figure 5. The values obtained by analytical model were found to be 0.1506 rad/m, 0.1348 m/rad and 0.11986 rad/m respectively for beams To3N, To4N and To5N. This shows there was a noticeable amount of increase in twist at ultimate torque. The twist at ultimate torque of beam To4N was 18.69% less than that of To3N and To5N was less than 42.86% of beam To3N. The rate of enhancement of twist at ultimate torsional strength of this series with respect to number of mesh layers was more in comparison to other states of torsion. This may be due to the fact that the wire mesh reinforcement in longitudinal direction might have contributed for unwrapped face.

A.XII Completely Over reinforced

To observe the effect of number of layers on completely over reinforced beams, three over reinforced beams were analyzed. The beams in this series were designated as Co3N, Co4N and Co5N. The main reinforcement was designed in such a way that there would be no yielding of reinforcement and failure would be due to crushing of concrete**.** The material details of these beams were presented in Table- 1. The twist was decreased as compared to other beams due to participation of more of reinforcement in the post cracking stage. The twists at the ultimate torque of beams Co3N, Co4N and Co5N were found to be 0.125 rad/m, 0.11 rad/m and 0.098 rad/m over their predicted values by MARS 0.1078 rad/m for all beams respectively. The same was found to be 0.1131 rad/m, 0.10299 rad/m and 0.09589 rad/m for beams Co3N, Co4N and Co5N respectively by analytical method. It seems analytical model well predicts the results rather than MARS as twist cannot be same having different amount of reinforcement in longitudinal and transverse direction. The increase in twist at ultimate torque of these beams Co3N, Co4N and Co5N with respect to their companion beams BQ3N, BQ4N and BQ5N were found to be 23.19, 20.74 and 18.85 times more respectively. The experimental values are presented in Figure 6 for these beams. The twist at ultimate torque of Co4N over Co3N was 12% less while the same was 21.6 % less for Co5N over the beam Co3N. The decrease in twist was noticed over more number of mesh layers which might have increased the stiffness.

B. Torsional Behavior of High Strength Beams With Ferrocement "U" Wrap

Torsional behavior of High strength concrete beam differs than the normal strength concrete beams due to change of tensile strength and softening co-efficient factors, so the torsional behavior of high strength concrete beams treated separately.

B.I Torsional Behavior Of Plain High Strength Beams

The torsional behavior of a plain ferrocement "U" wrapped beam is influenced by its core material properties and shell ferrocement material properties. The aspect ratio and core concrete tensile strength are the important factors for core material which influence the torsional behavior of a plain wrapped beam. The number of layers and mortar strength in ferrocement shell are the other important parameters to govern the torsional strength of ferrocement "U" wrapped plain beams. In this section BH and B4H were analyzed.

The twist at ultimate torque of the two beams BH and B4H were found to be 0.0028 rad/m and 0.00546 rad/m respectively. Beam BH is a plain beam without wrapping while B4H has a ferrocement wrap of 4 layers of mesh without ant conventional reinforcement. The increase in twist at ultimate torque of B4H is 1.95 times over beam BH. This is due to wrapping. This shows even the wrapping is on three sides, the beam has more rotational capacity. A plain beam with aspect ratio 2.0 and core concrete strength 60 MPa was cast and tested .The ultimate torque and twist were found to be 4.61 kNm and 0.0028 rad/m respectively. The same calculated by skew bending theory was found 4.34 kNm and 0.003468 rad/m. When the similar beam was provided with a ferrocement "U" wraps with four layers of mesh and even with ferrocement matrix of lower strength (55 MPa) than that of core concrete, the twist at ultimate torque was found to be 0.00546 rad/m. This shows that the beams with "U" wraps have more strength than that of plain beams and their strength cannot be estimated by skew bending theory.

B.II Torsional Behavior of RCC High Strength Beams

Reinforcement gets activated beyond cracking. So, torque-twist response of a reinforced concrete beam beyond cracking is influenced by the reinforcement present in the beam. The post cracking torque-twist response of a ferrocement "U" wrapped beam is characterized by the reinforcement present in the core concrete and the mesh layers in the ferrocement shell. Out of six possible arrangements of reinforcement in the core concrete, the last four types are related to states of torsion. After cracking, the torsional resistance is due to longitudinal reinforcement, transverse reinforcement and the concrete present between the diagonal strut. As the first two categories lack one of the resisting components, they can be analyzed as plain beams. In normal strength "U" wrapped concrete beams, it was proved that the beams with single type of reinforcement was unable to increase the torsional strength over plain beams but capable of increasing the toughness to some extent. To examine the effect of "U" wrapping on the torsional strength of beams containing single type of reinforcement i.e. either only longitudinal or transverse reinforcement with high strength concrete, two beams were cast and tested in third phase of the work. The aspect ratio, core concrete compressive strength and ferrocement mortar matrix of the beams were kept constant as 2.0, 60 MPa and 55 MPa.

B.III Beams with Only Longitudinal Reinforcement

A beam was cast with six numbers of 12 mm diameter bars as longitudinal reinforcement provided in the core area without any transverse reinforcement and four numbers of mesh layers in the ferrocement shell. The beam was designated as L4H. There was increase in twist at the ultimate torque with respect to its plain beam BO4H. The twist at the ultimate torque was found 0.0058 rad/m against the predicted value of 0.005198 kNm. The increase in twist over plain "U" wrapped beam B4H was found to be 39.28%.

B.IV Beams With Only Transverse Reinforcement

To investigate the effect of only transverse reinforcement on torque-twist response of ferrocement "U" wrapped concrete beam, T4H was cast and tested. T4H was cast with stirrups of 10 mm diameter bars at a spacing of 70 mm c/c without longitudinal reinforcement in the test region. The twist at ultimate torque 0.0056 rad/m against the same predicted value.

B.V Effect of Number of Layers on Different States of Torsion

In the previous section as the effect of number of mesh layer s could not alter the twist values to a substantial amount, so the number of mesh layers is kept constant as four layers. To study the effect of a particular mesh layer on different states of torsion, aspect ratio, ferrocement mortar matrix and concrete strength of beams were kept as

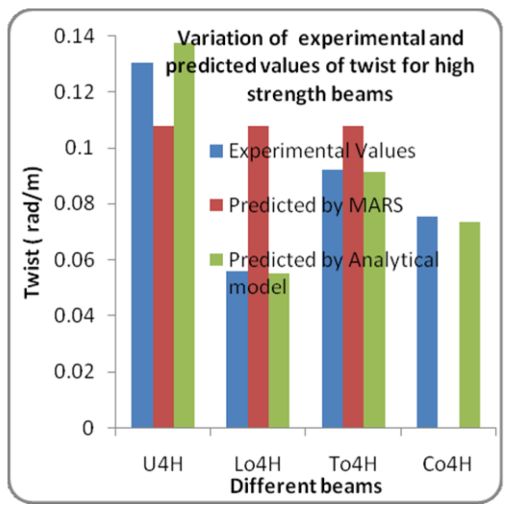

Figure 7. Comparison of twist at ultimate Torque of high strength Beams for 4 layers for different states of torsion

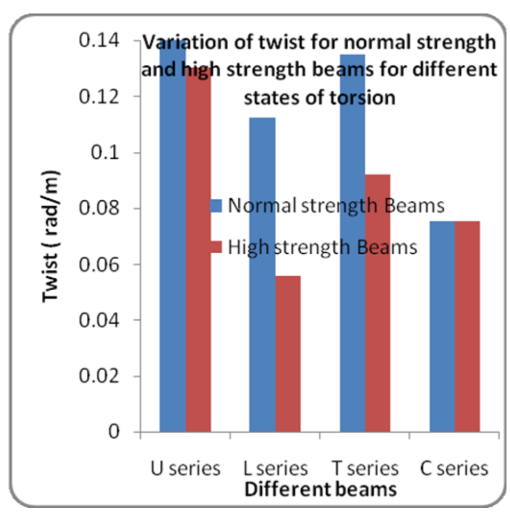

Figure 8. Comparison of twist at ultimate Torque between normal strength and high strength Beams for 4 layers between different states of torsion

2.0, 55 MPa and 60 MPa, mesh layer was kept as 4 and beam were U4H, Lo4H, To4H and Co4H.Twist at ultimate torque were found to be 0.1305 rad/m, 0.056 rad/m, 0.0921 rad/m and 0.0754 rad/m against their predicted values by soft computing was 0.10745 rad/m, 0.077064 rad/m, 0.10745 rad/m and 0.077064 rad/m for beams U4H, Lo4H, To4H and Co4H respectively. The same was found to be 0.1373 rad/m, 0.055 rad/m, 0.0915 rad/m and 0.0736 rad/m for beams U4H, Lo4H, To4H and Co4H respectively by softened truss model. The twist at ultimate torque for different states of torsion was plotted in Figure7. The twist was found to be more for under reinforced beams than completely over reinforced beams. This is due to less torsional stiffness of under reinforced beams. The experimental and predicted twist at ultimate torque was found to be more for normal strength reinforced beam for same number mesh layers in the ferrocement zone than high strength beams. The longitudinally over reinforced beams were found to have the less twist at ultimate torque in comparison to other states of torsion. This may be due to less stiffness of normal strength beams than high strength beams. The comparison is shown in Figure8.

CONCLUSIONS

From the soft computing model MARS and experimental study for torsional behavior of "U" wrapped plain and reinforced concrete beams, the following conclusions were drawn.

Plain "U" Wrapped Beams

I. A significant increase in twist at ultimate torque is observed with ferrocement "U" wrapped normal and high strength concrete beams over their plain concrete beams. This proves the effectiveness of "U" wrapped beams.

II. Twist at ultimate torque is dependent upon the core concrete, mortar strength, mesh layers, reinforcement in core concrete and aspect ratio combinedly.

Reinforced Concrete Beams

I) The decrease in twist at ultimate torque over the number of layers for any state of torsion is very less.

II) Under reinforced and transversely over reinforced concrete beams showed overall increase twist at ultimate torque over longitudinally over reinforced beams.

III) Soft computing model and the experimental results reveal that the twist at ultimate torque of a ferrocement "U" wrap beam is more influenced by the state of torsion than the amount of ferrocement reinforcement.

IV) The results of soften truss model are well in agreement with experimental results tan predicted by MARS.

REFERENCE

[1] T. D. G. Rao, and D.R. Seshu, " Analytical model for torsional response of steel fiber reinforced concrete members under pure torsion," *Concrete and Cement Composites*, Vol. 27,pp.493-501, 2005.

[2] A. K. Y. Hii, and A.M. Riyad, " Torsional capacity of CFRP Strengthened reinforced concrete beams," *Journal of Composites for construction ASCE*, pp. 71-80, Jan-Feb 2007.

[3] C.G. Karayannis, C.E. Chalioris,.and G.M. Sirkelis, " Local Retrofit of Exterior RC Beam-Column Joints using Thin RC Jackets - An Experimental Study," *Earthquake Engineering and Structural Dynamics*, Vol. 37, No. 5, pp. 727-746, 2008.

[4] A. Ghobarah, M.N. Ghorbel, and S.E. Chidiac, " Upgrading Torsional Resistance of Reinforced Concrete Beams Using Fiber-Reinforced Polymer," *ASCE Journal of composites for Construction*, Vol- 6, No.4, pp. 257-263, November-2002.

[5] J. Ming, R. Werasak, and Li Zhongxian, "Torsional strengthening of reinforced concrete box beams using carbon fiber reinforced polymer," *Science Direct,Composite structures* ,Vol.78, pp.264-270,2007.

[6] D. R. Santhakumar, and E.Chandrasekharan, "Behaviour of reinforced concrete beams under combined bending and torsion: A numerical study," *Electronic Journal of structural Journal*, pp. 1-7, 2007.

[7] Asiim, "Analytical study on torsional behavior of RC flanged beams using glass FRP, " *International Journal of Advance Research In Science And Engineering*, 2015.

[8] A. Deifalla, and A. Ghobarah, "Full Torsional Behavior of RC Beams Wrapped with FRP: Analytical Model," *Journal of Composites for Construction*, Vol.14,No.3,pp.289-300,2010-a.

[9] S. Panchacharam, and A. Belarbi, "Torsional Behavior of Reinforced Concrete Beams Strengthened with FRP Composites," in *Proceedings of First FIB Congress, Osaka, Japan*, 13-19, October 2002,pp. 1-11.

[10] P.R. Salom, J. Gergely, and D .T. Young, "Torsional Strengthening of Spandrel Beams with Fiber-Reinforced Polymer Laminates,"*Journal of composites for construction, ASCE*, pp.157-162, March- April 2004.

[11] M. Ameli, and H. Ronagh, "Analytical model for evaluating torque of FRP strengthened reinforced concrete beams." *Journal of Composites for construction*, pp. 384-390, July-Aug 2007.

[12] C.E. Chalioris, "Torsional Strengthening of Rectangular and Flanged Beams using Carbon Fibre-Reinforced-Polymers - Experimental Study," *Construction and Building Materials*, Vol. 22, No. 1, pp. 21-29, 2008.

[13] A.R. Avinash, B. Karthik, Padigela Abhinai and K. Kamath, , "Torsional response of structures retrofitted with Fluid viscous dampers in different configurations Subjected to bi-directional seismic excitations " in *Proceedings of 23rd IRF International Conference*, Bengaluru, India, 1st May, 2016, ISBN: 978-93-86083-05-0, pp.15-18.

[14] A. Deifalla, and A. Ghobarah, " Strengthening RC T-beams Subjected to Combined Torsion and Shear using FRP Fabrics: Experimental study,", *Journal of Composites for Construction*, Vol. 14, No. 3, pp. 301-311, 2010-b.

[15] H. Dehghani, and M.J. Fadaee, " Optimum resistance factor for reinforced concrete beams retrofitted with U wrap, " *International Journal of Optimization in Civil Engineering*, 5(2),pp. 227-240, 2015.

[16] P.P. Bansal, M. Kumar, and S.K. Kaushik, "Effect of mesh orientation on strength of beams retrofitted using ferrocement jacket," *International Journal of Engineering,* Vol- 20 Issue-(1), pp.8-19, 2007.

[17] B. Li, E.S.S.Lam, B. Wu, and Y.Y. Wang, " Experimental Investigation on Reinforced Concrete Interior Beam-Column Joints Rehabilitated by Ferrocement Jackets," *Engineering Structures,* Vol. 56, pp. 897-909,2013.

[18] ACI Committee 549, Ferrocement-Materials and Applications. ACI Symposium Proceedings SP-61: *American Concrete Institute* 549, Farmington Hills, Michigan, 1979.

[19] M.J. Shannag, and S.M. Mourad, "Flowable high strength cementitious matrices for ferrocement applications," *Construction and Building Materials*, Vol. 36, pp. 933-939,2012.
[20] P.R. Kumar, T.M. Oshima, and T.Yamazaki , " Studies on RC and ferrocement jacketed columns subjected to simulated seismic loading" *Asian Journal of Civil Eng (Build Housing)*, Vol.8(2), pp.215–225, 2007.
[21] C.E. Chalioris, G.E. Thermou, and S.J. Pantazopoulou, "Behaviour of Rehabilitated RC Beams with Self-Compacting Concrete Jacketing - Analytical Model and Test Results," *Construction and Building Materials*, Vol. 55, pp. 257-273, 2014.
[22] N. Sure,A. Patel and B. Jena "Study on Torsional Behavior of RC T- Beams Strengthened with Glass FRP, " *Research Journal of Recent Sciences*, ISSN 2277-2502 Vol. 4, pp.57-64,2015.
[23] J. Ming, and J. Grunberg, "Mechanical analysis of reinforced concrete box beam Strengthened with carbon fiber sheets under combined actions," *Composite Structures,* vol.73,pp. 488-494,2006.
[24] A. K. Y. Hii, and A.M. Riyad, "An experimental and numerical investigation on torsional strengthening of solid and box- section RC beams using CFRP laminates," *Composite structures,* vol.75, pp. 213-221, 2006.
[25] C.E. Chalioris, "Analytical Model for the Torsional Behaviour of Reinforced Concrete Beams Retrofitted with FRP Materials," *Engineering Structures*, Vol. 29, No. 12, pp. 3263-3276,2007.
[26] G.C.Behera, T.D.G. Rao, and C. B. K. Rao, "Torsional Capacity of High Strength Concrete Beams jacketed with ferrocement U wraps," *Asian Journal of Civil Engineering*, Volume.9, Number 4, pp. 411-422, August-2008.
[27] A. Deifalla, A. Awad, and M. Elgarhy, "Effectiveness of externally bonded CFRP strips for strengthening flanged beams under torsion; An experimental study," *Engineering structure,* (56), pp.2065-2075, 2013.
[28] S. Rathi, S. Kandekar and R.S. Talikoti " Strengthening of R.C. Beam using Carbon and Aramid Fibre for its Torsional Behaviour," *International Journal of Research Studies in Science, Engineering and Technology*, Volume- 2, Issue 9, pp. 65-71, Sept-2015.
[29] C.E. Chalioris, "Experimental Study of the Torsion of Reinforced Concrete Members." *Structural Engineering and Mechanics*," Vol. 23, No. 6, pp. 713-737, 2006.
[30] ACI committee 318, Building code requirements for structural concrete and commentary, *ACI 318R-02*: Farmington Hills, Michigan,2002.
[31] J. Nie, T. Liang, and S.C. Cai, " Performance of steel- concrete composite beams under combined bending and torsion," *journal of structural Engineering,ASCE*,pp.1049-1057, 2009.
[32] Liang-Jenq Leu, and Yu-Shu Lee, " Torsion design charts for reinforced concrete rectangular member," *journal of structural engineering ASCE*,pp.210-218 ,February 2000.
[33] T. D. G. Rao, and D.R. Seshu, "Torsion of steel fiber reinforced concrete members," *Cement and Concrete Research*, pp. 1783-1788, 2003.
[34] T. D. G. Rao, and D.R. Seshu, " Torsional Response of fibrous reinforced concrete beams; Effect of single type reinforcement," *Construction and Building materials* , Vol.20,pp.187-192,2006.
[35] P.R. Salom, J. Gergely, and D .T. Young, "Torsional retrofit of Spandrel Beams with composite Laminates," in *Proceedings of Institution of Civil Engineers, Structures and Buildings*, 157 Issues SBI, January 2003,pp. 69-76.
[36] S. Y. Rita, F. Wong, and J. Vecchio, "Towards Modeling of Reinforced Concrete Members with Externally Bonded Fiber-Reinforced Polymer Composites," *ACI Structural Journal,* pp.47-55, January-Feb-2003.
[37] IS: 12269-1987 "Specification for 53 Grade ordinary Portland cement". Bureau of Indian Standard, Manak Bhavan, Bahadurshah Zafar Marg, New Delhi,1987.
[38] IS 383-1970: "Specifications for Coarse and Fine Aggregates from Natural Sources for Concrete" (Second Revision), Bureau of Indian Standard, Manak Bhavan, Bahadurshah Zafar Marg, New Delhi,1970.
[39] IS 456-2000, "Code of Practice for Plain and Reinforced Concrete Structures", Bureau of Indian Standard, Manak Bhavan, Bahadurshah Zafar Marg, New Delhi, 2000.
[40] G.C.Behera, T.D.G. Rao, and C. B. K. Rao, "Analytical model for torsional response of RC beams strengthened with ferrocement U-Wraps" *IABSE Structural Engineering International*, DOI: 10.2749/101686614X13854694314847, SEI Vol.24, No.4, pp.509-520, Nov-2014.
[41] G.C.Behera, T.D.G. Rao, and C. B. K. Rao, "A study on post cracking torsional behaviour of high strength reinforced concrete beams with ferrocement "u" wraps, " *Slovak Journal of Civil Engineering,*Vol. 22, 2014, No. 3, DOI: 10.2478/sjce--0012, pp.1 – 12, 2014.
[42] G.C.Behera, T.D.G. Rao, and C. B. K. Rao, "Experimental study on torsional behaviour Of singly type of reinforcement With ferrocement "U" wraps, " *IJISET - International Journal of Innovative Science, Engineering & Technology*, Vol. 2 Issue 4,pp.1195-1203,2015.

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