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Cracking Strength of RCC Beams with Ferrocement "U" Wraps

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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. Limited research is available on the strength enhancement of "U" wrapped concrete elements subjected to torsional loads. Fiber wrapping needs skilled workmanship and suitable for developed countries due to its high cost. Ferrocement on the other hand is a good wrapping material which is suitable for developing countries. 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 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. Failure of a structure takes place after formation of first crack. The strength in the first crack plays a vital role for the designers. In this investigation an attempt is made to quantify the improvement in the cracking torque of "U" wrapped rectangular concrete members subjected to torsional loads. Ferrocement is taken here as wrapping material. Beams were cast with different number of mesh layers with different torsional reinforcement. The beams were analyzed with soft computing method MARS. The results were also compared with the analytical method. Analytical model predicts same cracking torque for all these beams showing zero impact of reinforcement on cracking torque. The predictions by soft computing method are in good agreement with experimental test results.

Index Terms – Cracking torque, MARS, Ferrocement "U" wrap, wrapping.

1. 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 and degradation and more stringent updates in code regulations have also necessitated for the retrofitting of existing structures (Rao and Seshu, 2005; Hii and Riyad, 2007). 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 (Karayannis *et al.,* 2008). FRPs can be effectively used to upgrade such structural deficient reinforced concrete structures. Torsional retrofitting using FRP has received less attention (Ghobarah *et al.,* 2002; Ming *et al.,* 2007; Santhakumar and Chandrasekharan (2007). Strengthening structures with FRP increases the strength in flexure, shear and torsion capacity as well as changes the failure mode and failure plane (Deifalla and Ghobarah, 2010.a). 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 (Ghobarah *et al.,* 2002; Panchacharam and Belarbi, 2002; Salom *et al*.,2004; Hii and Riyad, 2007; Ameli and Ronagh, 2007) with the exception of a few studies that investigated T-beams with U-jacket (Panchacharam and Belarbi,2002; Chalioris, 2008). Few studies regarding torsion strengthening using FRP have shown that the continuous wrapping is much more effective than using the strips (Ghobarah *et al*., 2002; Panchacharam and Belarbi, 2002; Chalioris, 2008; Deifalla and Ghobarah, 2010b). 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 (Hii *et al.,* 2007; Ameli and Ronagh, 2007; Chalioris, 2008).

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 (Bansal *et al.,* 2007). 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 (Li *et al.*, 2013). 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 (ACI Committee 549,1979).

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 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 microcracks in the cement matrix and the transition zone Shannag and Mourad, (2012). The study by (Kumar *et al*., 2007) 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 (Chalioris *et al*., 2014). Torsional behaviour of a beam can be characterized in three stages such as elastic stage, cracking stage and post cracking stage. The wrapped beam behaves linearly up to elastic torque i.e., a shear stress equal to the tensile strength of the mortar of the wrapping or the shear stress at the unwrapped face is equal to the tensile strength of the concrete (whichever is induced earlier). If the tensile strength of the concrete core governs the failure, then the wrapping materials becomes ineffective. Hence the elastic torque is equal to the ultimate torque. Otherwise the wire mesh in the wrapping is effective in the micro cracking as well as in the post cracking stage of wrapped beam.

When the shear stress due to torsion reaches the tensile strength of the mortar of the wrapping, micro cracking in the ferrocement initiates. This stage is referred as "micro cracking stage". In this stage the reinforcement present in the wrapping participate in arresting the crack propagation. This stage is in between the cracking and post cracking stage of the beam. The initiation of the micro cracking starts as and when the shear stress in the wrapping reaches the tensile strength of the mortar. The micro cracking stage ends when the shear stress in the wrapping is equal to the cracking strength of ferrocement (considering the mortar tensile strength as well as that of the mesh reinforcement). Once the shear stress in the wrapping crosses the cracking strength of the ferrocement, the post cracking stage of the beam starts. However during this stage, if the shear stress in the unwrapped face of the concrete reaches the tensile strength of concrete failure of unwrapped portion initiates the ultimate failure of the beam. Otherwise, the ultimate failure of the beam occurs due to the yielding of the reinforcement present in the ferrocement wrapping or failure of the unwrapped portion of the beam. Thus separate equations have to be developed for torque-twist response of the wrapped beams under torsional loads for the three cases viz., elastic stage, micro cracking stage and post cracking stage. Thus the effectiveness of the wrap depends on aspect ratio, tensile strength of the core concrete and the tensile strength of the mortar of the wrapping material. Fig.1 shows the flow chart of the different possibilities of failures in a ferrocement-wrapped (U-Wrap) beam under torsional loads.

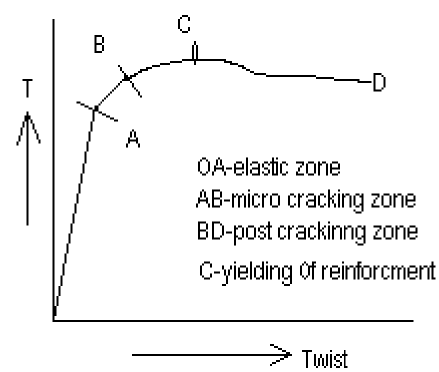


Fig.1 Various Stages of Torque-Twist Diagram of a Wrapped Beam

1.1 Significance 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 (Ming *et al*., 2006; Hii and Riyad, 2006; Salom *et al.*, 2004; Ameli and Ronagh, 2007; Chalioris, 2007). But inaccessibility and extension of flanges over the web has necessitated strengthening the beams by "U" wrap rather than full wrap (Behera *et al.*, 2008). U-jacketed flanged beams exhibited premature debonding failure at the concrete and the FRP sheet adhesive interface Chalioris (2008). 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. Ultimate failure takes place after formation of initial crack. Initiation of first crack plays a vital role in design.

The mentioned literature in the introduction substantially recommends ferrocement as a retrofitting substitution for FRP. Experimental and analytical estimation of cracking torque of “U” wrapped RC beams reported by the author earlier was limited to plain beams only (Behera *et al.*, 2008).

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 (Chalioris, 2006; Behera *et al.*, 2008) **.** Elastic and cracking torque of a beam is dependent upon its constituent materials and cross sectional area (ACI committee 318,2002; Chalioris, 2006; Nei *et al*., 2009). The reinforcement provided in longitudinal and transverse direction controls the torque twist response in the post cracking stage (Liang-Jenq, Leu. and Yu-Shu, 2000; Rao *et al*., 2003; 2005; 2006; Chalioris, 2006). Literature review reveals that the torsional response of a wrapped beam is dependent on aspect ratio, constituent materials of core and wrapping material (Salom *et al*.2003; Rita *et al*., 2003; Ming and Grunberg, 2006). 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

I. Only longitudinally reinforced
II. Only transversely reinforced
III. Under Reinforced Beams
IV. Longitudinally over reinforced and transversely under reinforced.
V. Longitudinally under reinforced and transversely over reinforced
VI. Completely over reinforced.

The objective of the present study is to evaluate the cracking torque of ferrocement “U” wrap beams by soft computing method MARS and analytical model and compare the results with experimental values.

2. 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 transversely over reinforced sections more amount of reinforcement in transverse direction and less 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 Behera *et al*. (2008).

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 The materials used, casting and testing procedure of beams is presented in Behera *et al*. (2014). The experimental results of beams are presented in Table 2.

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

Here soft computing method is employed for the calculation of ultimate Torque, twist, stiffness and toughness 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.

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

Table 1. Details of Beams

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	Only Longitudinal	L3N	125 x 250	40	35	12 mm, 4 nos.	440			3
5		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	Only Transverse	T3N	125 x 250	40	35			8mm @ 100 mm c/c	465	3
8		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	U	U3N	125 x 250	40	35	6 mm, 4 nos.	350	6mm @ 100 mm c/c	350	3
11		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	L	Lo3N	125 x 250	40	35	12 mm, 4 nos.	440	6mm @ 100 mm c/c	350	3
14		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	T	To3N	125 x 250	40	35	6 mm, 4 nos.	350	8mm @ 100 mm c/c	465	3
17		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	C	Co3N	125 x 250	40	35	12 mm, 4 nos.	440	8mm @ 100 mm c/c	465	3
20		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	440			4
26		T4H	125 x 250	55	60			10mm @ 70	445	4
27	U	U4H	125 x 250	55	60	6 mm, 6 nos.	350	6mm @ 70 mm	350	4
28	L	Lo4H	125 x 250	55	60	12 mm, 6	440	6mm @ 70 mm	350	4
29	T	To4H	125 x 250	55	60	6 mm, 6 nos.	350	10mm @ 70	445	4
30	C	Co4H	125 x 250	55	60	12 mm, 6	440	10mm @ 70	445	4

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 Figure 4 illustrate the data (x_i , y_i) (i = 1, 2,...N), composed by a p-dimensional 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 (5) on the relation between input and response:

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

Where, Y is a response variable, $X=(X_1, X_2, \ldots\ldots X_n)^T$ 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):

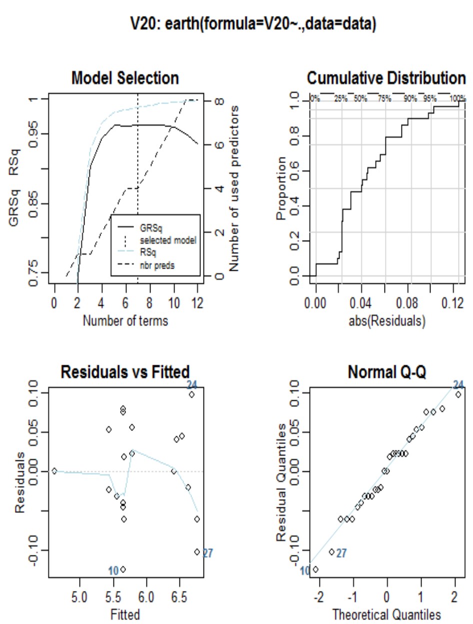
$$\delta := \{(X_j - \tau)_+, (\tau - X_j)_+ \mid \tau \in \{x_{1,j}, x_{2,j}, \ldots\ldots, x_{N,j}\}, j \in \{1,2,\ldots\ldots,p\}\} \quad (3)$$

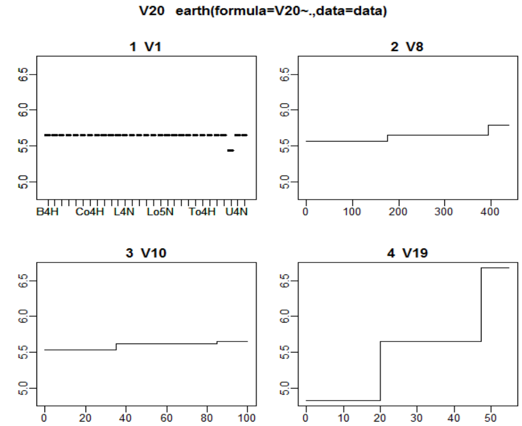
If all of the input values are distinct, there are 2Np basis functions altogether. Thus, we can represent f (X) by a linear combination, which is successively and with the intercept θ built up by the set $_0$, such that Equation (3) takes the form

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

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

3.a For cracking Torque





	nsubsets	gcv	rss
V19	6	100.0	100.0
V8	4	24.8	24.4
V10	3	14.4	15.3
V1U4H	2	2.1	8.5

Coefficients

(Intercept)	5.5324652
V1U4H	-0.2140178
h(V8-350)	0.0015407
h(350-V8)	-0.0002689
h(V10-0)	0.0012240
h(V19-40)	0.0680449
h(40-V19)	-0.0206587

T=5.5324+max (0,Fly-350)*0.00154-max(0,350-Fly)*0.0002689
+max (0, spacing)*0.0012240+max (0, mortar strength-40)*0.0680449
-max (0, 40-mortar strength)*0.0206587

4. 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.

5. RESULTS AND DISCUSSIONS

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

5.1 Torsional Behavior of Normal Strength Beams

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

5.1.1 Torsional Behavior 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.

5.1.1.1 General Torsional Behavior of Plain Normal Strength Beams

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. The beams were designated as BQ3N, BQ4N and BQ5N. The ultimate torque of these beams were found to be experimentally 5.415 kNm, 5.415 kNm and 5.49 kNm respectively for 3, 4 and 5 numbers of mesh layers against the predicted value of 5.438 kNm for all beams by soft computing method MARS. The analytical model predicts the ultimate torque as 5.54 kNm for all the beams BQ3N, BQ4N and BQ5N. 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. Beams BQ3N, BQ4N and BQ5N have shown one value of ultimate torque for Experimental analytical model and soft computing method. Soft computing method underestimates the values while analytical model overestimates ultimate torque. The percentage of variation of ultimate torque with number of layers was shown in Fig. 2. A plain beam without wrapping with ferrocement "U" wrap is found to have cracking torque of 3.66 kNm when analyzed by Hsu's skew bending theory.

The ultimate torque of the plain beams with jacketing was presented in the Table-2. A comparison of experimental torque with that of predicted by MARS and analytical model of plain concrete beams in column shows that experimental are less than the predicted values by MARS by 0.43%,0.43% and -0.96% for beams BQ3N, BQ4N and BQ5N respectively. Analytical model overestimates the same by 2.46%, 2.46 % and 1.04% for BQ3N, BQ4N and BQ5N respectively. This shows that the predicted values are well in agreement with experimental values for plain "U" wrapped beams.

5.1.1.2 Effect of Number of Layers:

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 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 torque 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).

5.1.2 Torsional Behavior of RCC Normal Strength Beams

In this phase, the response of ferrocement "U" wrapped reinforced concrete beams with normal strength core concrete is discussed. In a reinforced concrete beam the states of torsion influences the torque-twist diagram. For a wrapped beam the states of torsion and ferrocement influence the torsional behavior. 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. The longitudinal reinforcement and transverse reinforcement were varied in such a way that all possible six states of torsion to occur.

To study the effect of number of layers on all possible arrangements of reinforcement in a reinforced concrete member for torsion, the layers are varied as three, four and five on each possible states of torsion. 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.

5.1.2.1 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.

5.1.2.2 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

Table 2 Experimental and Predicted Values of Ultimate Torque by MARS

Cracking Torque (kNm)				Cracking Torque (kNm)			
Beams	Expt	MARS	Analytical Model	Beams	Expt	MARS	Analytical Model
BQ3N	5.415	5.438347	5.548	To3N	5.735	5.654864	5.548
BQ4N	5.415	5.438347	5.548	To4N	5.73	5.654864	5.548
BQ5N	5.491	5.438347	5.548	To5N	5.73	5.654864	5.548
L3N	5.61	5.671128		Co3N	5.816	5.793526	5.548
L4N	5.61	5.671128		Co4N	5.816	5.793526	5.548
L5N	5.69	5.671128		Co5N	5.85	5.793526	5.548
T3N	5.53	5.560746		BH	4.612	4.612	
T4N	5.53	5.560746		B4H	6.5	6.459021	6.52
T5N	5.53	5.560746		L4H	6.79	6.691801	
U3N	5.53	5.654864	5.548	T4H	6.59	6.5447	
U4N	5.61	5.654864	5.548	U4H	6.4248	6.4248	6.52
U5N	5.615	5.654864	5.548	Lo4H	6.675	6.77748	6.52
Lo3N	5.816	5.793526	5.548	To4H	6.618	6.638818	6.52
Lo4N	5.816	5.793526	5.548	Co4H	6.7163	6.77748	6.52
Lo5N	5.816	5.793526	5.548				

beams BQ3N, BQ4N and BQ5N respectively if the later beams were provided with only longitudinal steel.The cracking torque of these beams L3N, L4N and L5N were found 5.61kNm, 5.61 kNm and 5.69 kNm respectively which indicates that there was no such improvement in cracking torque.

The torques predicted by soft computing MARS of the beams was found to be 5.671 kNm for all the three beams. The predicted values are found to be 3.94%, 3.766% and 2.34% more for beams L3N, L4N and L5N respectively as shown in Fig.2. As one of the reinforcement (Transverse reinforcement) lacks in these beams, analytical model predicts the ultimate torque as beams without reinforcement. The cracking torque was found to be 5.54 kNm for all these three beams. The cracking torque of all these beams L3N, L4N and L5N is plotted in Fig.3.Analytical model predicts the cracking torque same for all beams which shows cracking torque is independent of longitudinal and transverse reinforcement. This contradicts Hsu's statement.

5.1.2.3 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 were analyzed, designated as T3N, T4N and T5N and 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 is that the latter were provided with 8 mm diameter bars with 100 mm c/c.

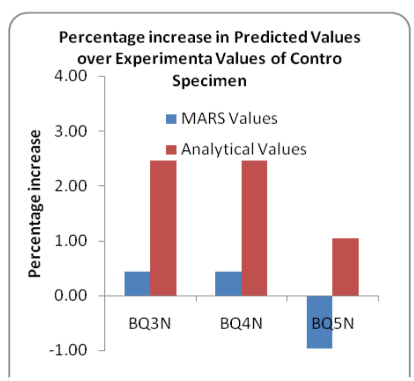


Fig.2 Percentage Variation in Cracking Torque of predicted values by analytical model and MARS over Experimental Values

nd to be 5.53 kNm. The torque increased by 2.21%, 2.21% and 0.72% for beams T3N, T4N and T5N over their plain "U" wrapped beams BQ3N, BQ4N and BQ5N respectively. This shows that the improvement is very marginal. The predicted cracking torques of all these beams by MARS and analytical method are found to be 5.56 kNm and 5.548 kNm respectively for all these beams as shown in Fig.4.

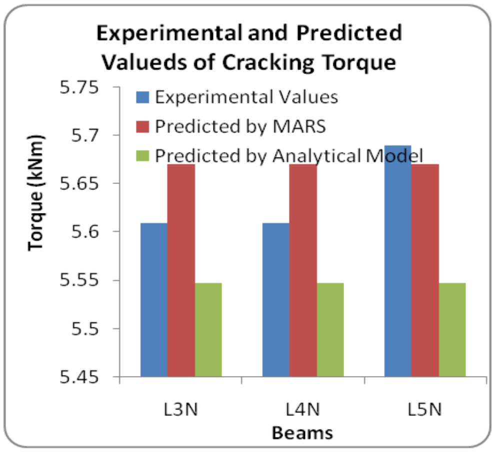


Fig. 3 Variation of Cracking torque of only longitudinally reinforced beams

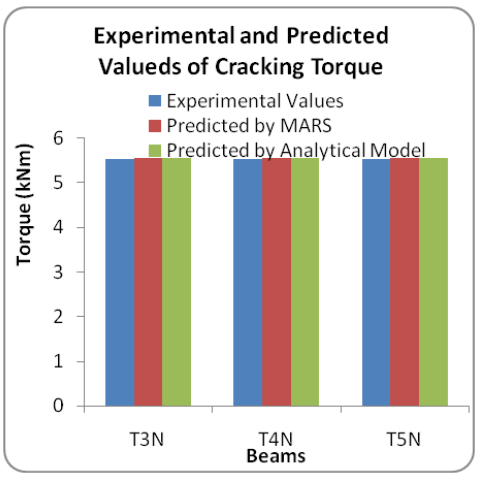


Fig.4 Cracking Torque variation of only Transverse reinforced beams

The "U" wrapping beams with single type of reinforcement i.e., transverse reinforcement or longitudinal reinforcement alone cannot enhance the torsional capacity of beams to a substantial amount, but are able to increase the toughness to a considerable amount with respect to plain "U" wrapped beams. 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].

5.1.2.4 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 analyzed and experimental data are compared. 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 companion specimens for these reinforced beams are BQ3N, BQ4N and BQ5N. Henceforth these beams will be called as U series beams. The experimental cracking torque values were found to be 5.53 kNm, 5.61 kNm and 5.615 kNm against predicted values of 5.65KNm for three, four and five layers respectively by MARS. The predicted value overestimates by 2.25% for beam U3N. The same was predicted by MARS as 5.654 KNm for all the beams. The analytical model predicts the same values 5.548 kNm for beams U3N, U4N and U5N respectively. The predicted values are found to be same for all types of states of torsion showing the cracking torque independent of amount of steel. The cracking torque values of under reinforced beams are presented in Fig.5. From the figure it is clear that predicted values are well in agreement with experimental values.

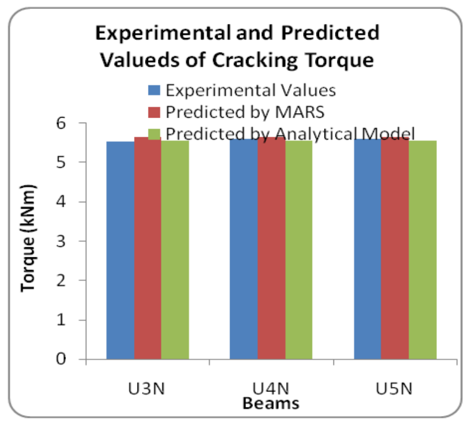


Fig.5 Experimental and Predicted values of Cracking Torque for under reinforced

5.1.2.5 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 cracking torques of the beams was found to be 5.816 kNm for beams Lo3N, Lo4N and Lo5N respectively against the predicted values 5.793526 kNm for all the three beams. The predicted values by analytical model were found 5.548 kNm for beams Lo3N, Lo4N and Lo5N respectively.

As there is shortage of reinforcement in transverse direction on the unwrapped face, increase the number layers could not enhance the cracking torque. The same was revealed from the two predicted values. The predicted values by MARS are well in agreement with experimental values as shown in Fig.6 rather than analytical values.

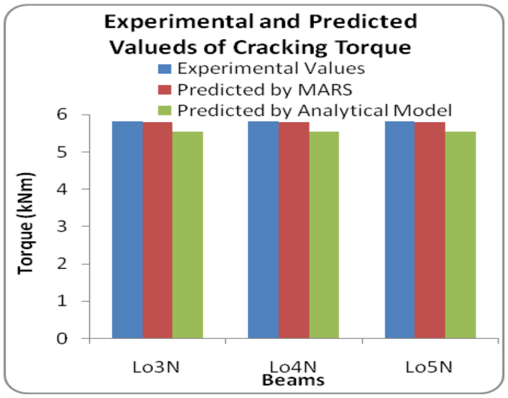


Fig.6 Experimental and Predicted Torque variation of longitudinally over reinforced beams

5.1.2.6 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 torque-twist response of individual beams both experimentally and predicted are presented below. The cracking torque of these beams To3N, To4N and To5N were found to be 5.735 kNm, 5.73 kNm and 5.73 kNm. The increases in cracking torque of these beams To3N, To4N and To5N over their companion beams BQ3N, BQ4N and BQ5N were found to be 27.35%, 36.41% and 43.16% respectively. This shows there was a noticeable amount of increase in cracking torque. The cracking torque of beam To4N was 7.11% more than that of To3N and To5N was more than 14.07% of beam To3N. The rate of enhancement of cracking torsional strength of this series with respect to number of mesh layers was more in comparison to other states of torsion. The predicted values by MARS are found to be 5.654864 kNm respectively. The predicted values by analytical model are found to be 5.548 kNm for all the beams. This shows MARS better predicts over analytical model for torsionally transversely over reinforced beams. Longitudinally over reinforced beams have more cracking torque.

5.1.2.7 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 cracking torques of these beams was 5.816 kNm, 5.816 kNm and 5.85 kNm respectively for beams Co3N, Co4N and Co5N respectively. The increase in cracking torque of these beams Co3N, Co4N and Co5N with respect to their companion beams BQ3N, BQ4N and BQ5N were found to be 7.4 %, 7.4 % and 6.4 % respectively. These beams showed maximum increase in cracking torque over their respective plain "U" wrapped beams BQ3N, BQ4N and BQ5N in comparison to all states of torsion. The increase in cracking torque of Co4N over Co3N was 0 % while the same was 0.58 % for Co5N over the beam Co3N. The cracking torque of these beams Co3N, Co4N and Co5N are found to be 5.793 kNm by MARS. The predicted values by analytical model were found to be 5.548 kNm for all beams Co3N, Co4N and Co5N respectively as shown in Fig.7. The values by soft computing well predict the cracking torque for completely over reinforced beams.

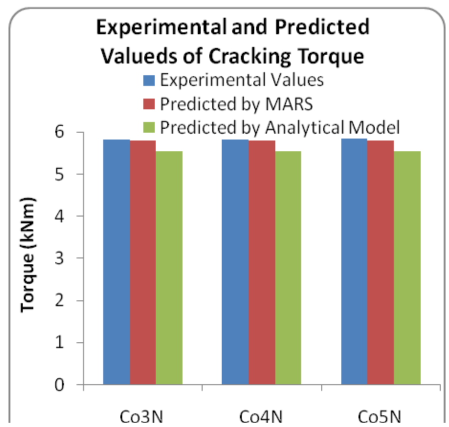


Fig.7 Experimental and Predicted cracking Torque of completely over reinforced beams for different layers

5.2 Torsional Behavior of High Strength Beams

Torsional behavior of High strength concrete beam differs than the normal strength concrete beams in respect of brittleness and toughness. Also due to change of tensile strength and softening co-efficient factors, the torsional behavior of high strength concrete beams should be treated separately. Thus high strength concrete beams containing plain concrete and reinforced concrete beams analyzed in this section.

5.2.1 Torsional Behavior 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 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 cracking torque of the two beams BH and B4H were found to be 4.612 kNm and 6.5 kNm 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 cracking torque of B4H is 41.37% over beam BH. This is due to wrapping. This shows even the wrapping is on three sides, the torsional strength increases a lot. 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 torsional strength was found to be 6.50 kNm. 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.

5.2.2 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.

5.2.2.1 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. Cracking torque of beam L4H was found to be 6.79 kNm. The increase in torque of beam L4H over its plain “U” wrap beam B4H is 4.46%. The predicted value 1.41% more than the experimental values.

5.2.2.2 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 cracking torque of the beam was found to be 6.54 kNm against the predicted value of 6.5447 kNm. The increase in cracking torque over the beam B4H was 1.38% only.

5.2.2.3 Effect of Number of Layers on different States of Torsion

To study the effect of a particular mesh layer on different states of torsion, aspect ratio, ferrocement

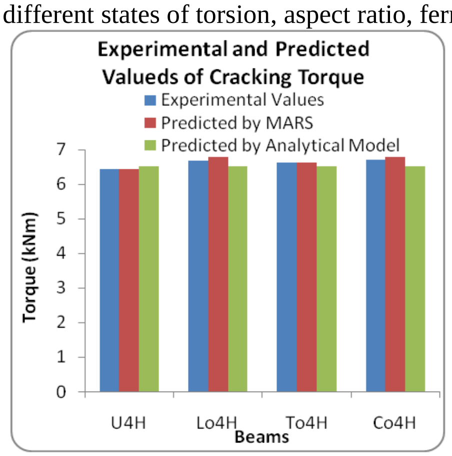


Fig.8 Comparison of Cracking Torque between Experimental and Predicted Values for high strength Beams for different states of Torsion

mor
2.0,
were U4H, Lo4H, To4H and Co4H. The designations of the

beams were already explained earlier. The beams U4H, Lo4H, To4H and Co4H have cracking torque of 6.4248 kNm, 6.675 kNm, 6.618 kNm and 6.7163 kNm respectively. The predicted values by MARS are 7.68 % less, 2.91 % more, and 0.43% more and exactly same with their experimental values for the beams U4H, Lo4H, To4H and Co4H respectively. The initial torque for different states of torsion was plotted in Fig.8.

The high strength beams are having more cracking strength than that of normal strength beams. A comparison of cracking torque for high strength and normal strength for four layers has been presented in Fig.9.

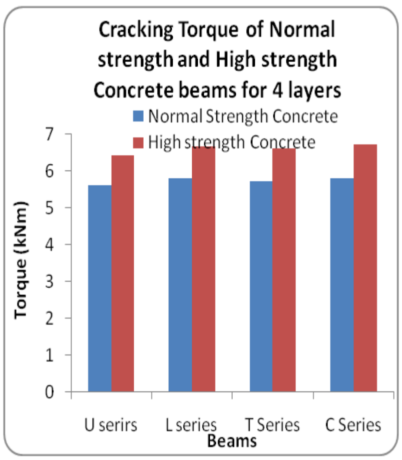


Fig.9 Comparison of Torque between normal strength and high strength Beams for 4 layers

6. CONCLUSION

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

Plain "U" Wrapped Beams

a. A significant increase in torsional strength is observed with ferrocement "U" wrapped normal and high strength concrete beams over their plain concrete beams.

b. Cracking torque is dependent upon the core concrete, mortar strength, mesh layers and aspect ratio combinedly.

c. The "U" wrap can increase the torsional capacity of a plain beam. This proves the effectiveness of "U" wrapped beams.

"U" Wrapped Reinforced Concrete Beams

a. The increase in torsional strength over the number of layers for any state of torsion is very less.

b. Cracking torque is increases with increase in longitudinal reinforcement.

c. Soft computing model and analytical model predicts approximately same cracking torque for all states of torsion. They are silent about effect of reinforcement on cracking torque.

d. The results of soft computing by MARS are well in agreement with experimental results.

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