ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC) VOL. 18, NO. 2(2017)
PAGES 173-190

PREDICTION OF TWIST AT CRACKING TORQUE OF FERROCEMENT "U" WRAPPED RCC BEAMS

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Received: 5 June 2016; **Accepted:** 24 August 2016

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. Very less literature is available on the strength enhancement of "U" wrapped concrete elements subjected to torsional loads. 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. Carbon fiber has taken the driver's seat as a wrapping material in developed countries. From cost effective point of view ferrocement can be used as a wrapping material in place of FRP. Beams were cast with different number of mesh layers, different torsional reinforcement, different grades of concrete and mortar. The beams were analyzed with MARS. Analytical model was developed to predict secant stiffness at cracking torque. The predictions for twist at cracking torque are in good agreement with experimental test results.

Keywords: Ferrocement; U wrap; twist at cracking torque; MARS; analytical model.

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, 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

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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]. 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, 8, 9, & 10] with the exception of a few studies that investigated T-beams with U-jacket [8 &11]. Few studies regarding torsion strengthening using FRP have shown that the continuous wrapping is much more effective than using the strips [4, 8, 11 & 12]. 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 [2,10, 11].

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 [13]. 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 [14]. 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 [15].

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 [16]. The study by [17] 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 [18].

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 [9, 10, 19, 20, 21]. But inaccessibility and extension of flanges over the web has necessitated strengthening the beams by “U” wrap rather than full wrap. For quantification of torsional strength of “U” wrapped beams very few attempts have been taken by [8, 22]. U-jacketed flanged beams exhibited premature debonding failure at the concrete and the FRP sheet adhesive interface [11]. 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 [23].

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 [23, 24]**.** Elastic and cracking torque of a beam is dependent upon its constituent materials and cross sectional area [24, 25, 26]. The reinforcement provided in longitudinal and transverse direction controls the torque twist response in the post cracking stage [1, 24, 27, 28, 29]. Literature review reveals that the torsional response of a wrapped beam is dependent on aspect ratio, constituent materials of core and wrapping material [19, 30, 31]. 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.

a) Only longitudinally reinforced
b) Only transversely reinforced
c) Under Reinforced Beams
d) Longitudinally over reinforced and transversely under reinforced.
e) Longitudinally under reinforced and transversely over reinforced
f) Completely over reinforced.

The objective of the present experimental study is to evaluate the twist at cracking torque of a wrapped ferrocement “U” wrap beam using soft computing method MARS and analytical model and comparing the values 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 [23].

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. Beams were tested in torsion test rig.

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 Longit udinal	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 Trans verse	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		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

The materials used, casting and testing procedure of beams is presented in [32, 33]. 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 [34] 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).

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

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 Fig. 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 on the relation between input and response:

$$Y=f(X)+\varepsilon \tag{2}$$

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 $\tau_i = (\tau_{i,1}, \tau_{i2},\dots, \tau_{i,p})^T$. 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:

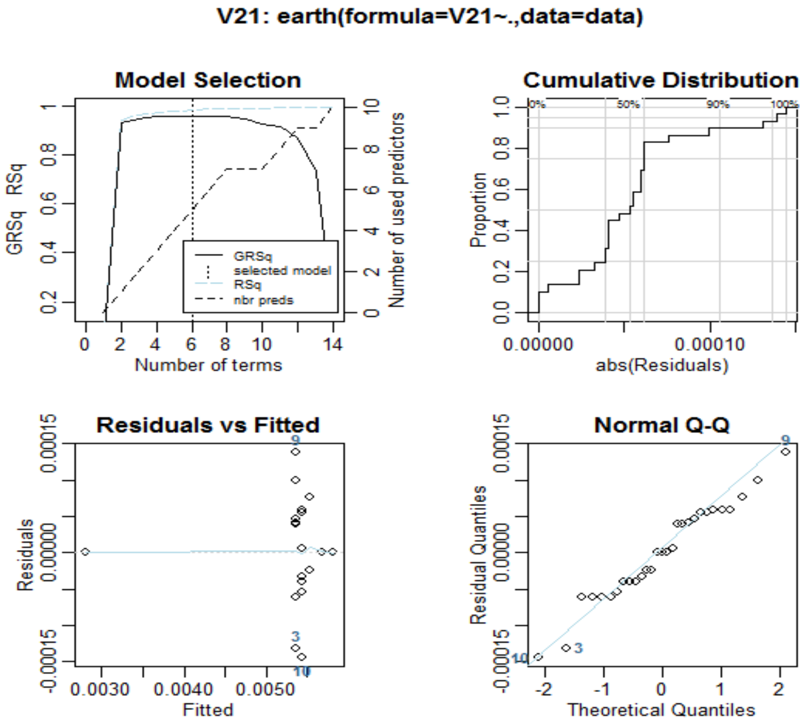
$$\delta:=\{(X_j-\tau)_{+},(\tau-X_j)_{+}\mid \tau\in\{x_{1,j},x_{2,j},\dots\dots,x_{N,j}\},\ j\in\{1,2,\dots\dots,p\}\} \tag{3}$$

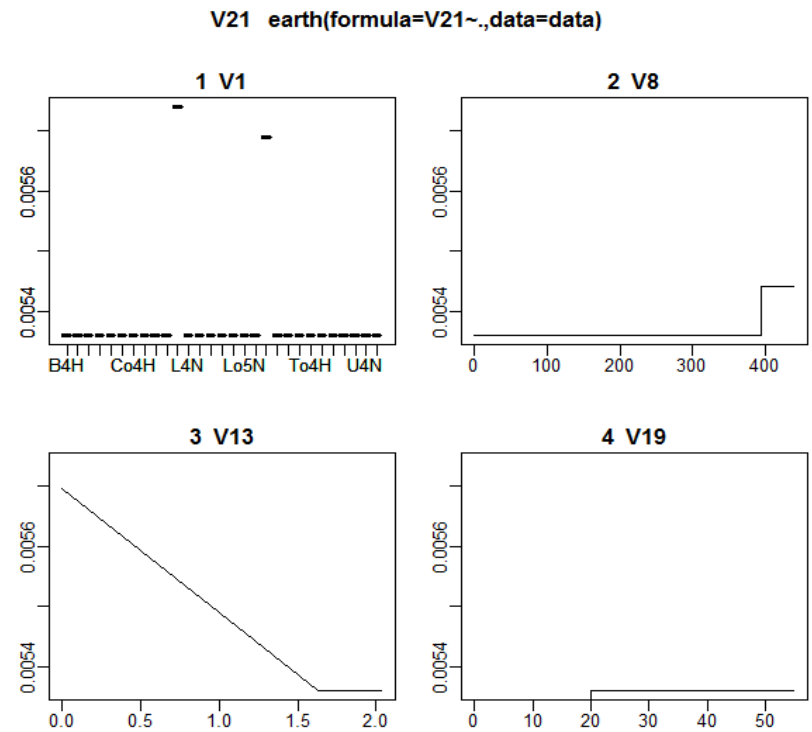
If all of the input values are distinct, there are 2Np basis functions altogether. Thus, we can represent f (X) by a linear combination, which is successively built up by the set δ and with the intercept θ_0, such that Equation (3) takes the form

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

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

For Twist at Cracking


V21: earth(formula=V21~.,data=data)
Model Selection
GRSq RSq
Number of used predictors
Number of terms
GRSq
selected model
RSq
nbr preds
Cumulative Distribution
Proportion
abs(Residuals)
0%
50%
90%
100%
Residuals vs Fitted
Residuals
Fitted
Normal Q-Q
Residual Quantiles
Theoretical Quantiles


V21 earth(formula=V21~.,data=data)
1 V1
B4H
Co4H
L4N
Lo5N
To4H
U4N
2 V8
3 V13
4 V19

```
nsubsets   gcv    rss
V19         5 100.0  100.0
V1L4H       4  16.6   20.5
V1T4H       3  10.3   14.5
V8          2   6.2   10.4
V13         1   4.5    7.1

Coefficients
(Intercept)     0.0053610664
V1L4H           0.0003775912
V1T4H           0.0003289336
h(V8-350)       0.0000008816
h(1.62926-V13)  0.0002050043
h(40-V19)      -0.0000723768
```

θ(rad/m)=0.0053610664+max(0,Fly-350)*0.0000008816+max(1.62926-Afl)*0.0002050043- (40-mortar strength)*0.0000723768

Table 2: Experimental and Predicted Values of Twist at Cracking Torque

Twist at Cracking Torque(rad/m)				Twist at Cracking Torque(rad/m)			
Beams	Expt	MARS	AnalyticalModel	Beams	Expt	MARS	Analytical Model
BQ3N	0.00545	0.0054446	0.0053	To3N	0.0055	0.0054446	0.00516
BQ4N	0.0053	0.0053611	0.0053	To4N	0.0054	0.0053611	0.005116
BQ5N	0.00523	0.0053611	0.00525	To5N	0.0054	0.0053611	0.005073
L3N	0.0056	0.0055239		Co3N	0.0055	0.0055239	0.004965
L4N	0.0055	0.0054404		Co4N	0.0054	0.0054404	0.004924
L5N	0.0054	0.0054404		Co5N	0.0054	0.0054404	0.004885
T3N	0.0055	0.0054446		BH	0.0028	0.0028	
T4N	0.0053	0.0053611		B4H	0.00546	0.0053611	0.0056
T5N	0.0055	0.0053611		L4H	0.005818	0.005818	
U3N	0.0053	0.0054446	0.005219	T4H	0.00569	0.00569	
U4N	0.0053	0.0053611	0.005174	U4H	0.005408	0.0053611	0.00548
U5N	0.0053	0.0053611	0.00513	Lo4H	0.005387	0.0054404	0.00521
Lo3N	0.0055	0.0055239	0.005019	To4H	0.005402	0.0053611	0.00531
Lo4N	0.0055	0.0054404	0.004978	Co4H	0.005408	0.0054404	0.00505
Lo5N	0.0055	0.0054404	0.004937				

4. ANALYTICAL MODEL

Analytical model is developed using Hsu's skew bending theory model with modifications in the material properties. The detailed procedure is presented by [32 & 33]. The values are presented in Table 2. Here soft computing method is employed for the calculation of twist at cracking 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.

5. INTERPRETATION OF TEST RESULTS

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

5.1 Torsional behaviour of normal strength beams with ferrocement “U” wrap
In this section, the twist at cracking torque of normal strength concrete beams with ferrocement “U” wrap, (plain beams and reinforced concrete beams) tested were discussed.

5.1.1 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.

5.1.1.1 General torsional behaviour of plain normal strength beams with ferrocement “U” wrap
The twist at cracking 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. The twists at cracking torque were found to be experimentally 0.0054 rad/m, 0.0053 rad/m and 0.00523 rad/m for beams BQ3N, BQ4N and BQ5N respectively. When it is predicted with layers from 3, 4 and 5, the twist at cracking torques are found to be 0.0054446 rad/m, 0.0053611 rad/m and 0.0053611 rad/m respectively 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.

5.1.1.2 Effect of number of layers
The variation of twist at cracking torque with number of layers was shown in Fig. 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 underestimates experimental values by 0.099% for beam BQ3N and overestimates by 1.15% and 2.50 % BQ4N and BQ5N respectively. The analytical model underestimates by 2.75% for beam BQ3N, overestimates by 0.38241% for beam BQ5N and exactly predicts for beam BQ4N.

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).

5.1.2 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.

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 beams BQ3N, BQ4N and BQ5N respectively if the later beams were provided with only longitudinal steel.

The twist at cracking torque of these beams L3N, L4N and L5N were found 0.0056 rad/m, 0.0055 rad/m and 0.0054 rad/m respectively which indicates that there was improvement in twist at cracking torque. The predicted twist at cracking torque by MARS of the beams was found to be 0.005523 rad/m, 0.0054404 rad/m and 0.0054404 rad/m for all the three beams L3N, L4N and L5N respectively. These experimental values are found to be 1.35 %, 1.08 % and -0.74 % more than predicted values for beams L3N, L4N and L5N values respectively. Twist at cracking torque of these beams cannot be predicted by analytical model as transverse reinforcement is absent. The percentage in variation of twist with respect to experimental values is presented in Fig. 2.

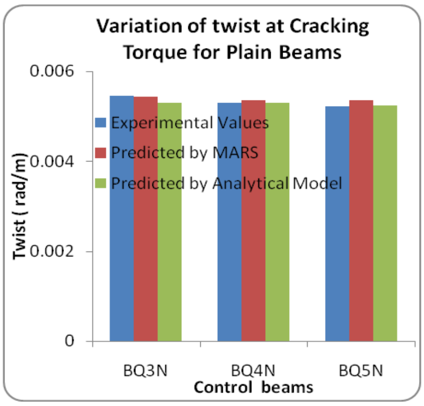


Figure 1. Twist at cracking torque of control specimens

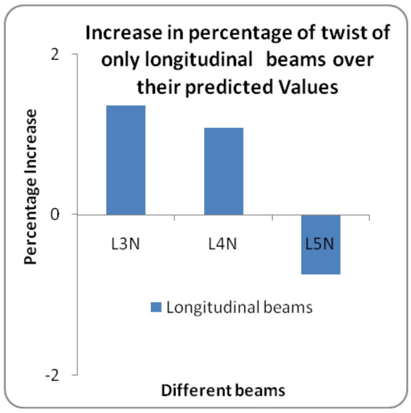


Figure 2. Percentage increase in twist at cracking torque of only longitudinally reinforced beams over their predicted values

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 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 cracking twist for these beams was found to be 0.0055 rad/m, 0.0053 rad/m and 0.0055 rad/m for beams T3N, T4N and T5N respectively. The predicted values by MARS are found to be 0.00544 rad/m, 0.0053611 rad/m and 0.0053611 rad/m T3N, T4N and T5N respectively. This proves accuracy of the model. The variation of experimental and predicted torque is shown in Fig. 3.

The twist values over plain beams are presented in Fig. 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 [29].

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 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 cracking torque of the beams U3N, U4N and U5N were found to be 0.0.0053 rad/m experimentally for all beams. The same was predicted by soft computing as 0.0.0054446 rad/m, 0.005311 rad/m and 0.0053611 rad/m for U3N, U4N and U5N respectively for these three beams. Twist at cracking torque was found to be 0.005219 rad/m, 0.005174 rad/m and 0.00513 rad/m respectively for beams U3N, U4N and U5N by analytical model. As reinforcement amount provided in both longitudinal and transverse direction are less than torsionally balanced reinforcement, the cracking torque was found same as control specimens BQ3N, BQ4N and BQ5N. The variation of twist between experimental and predicted values is presented in Fig. 4.

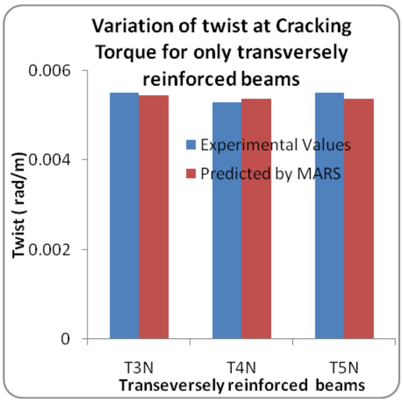


Figure 3. Experimental and predicted twist variation of transversely reinforced beams

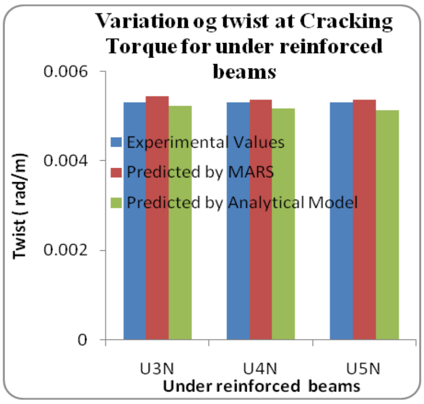


Figure 4. Experimental and predicted values of twist at ultimate torque for under reinforced beams

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 twists of these beams Lo3N, Lo4N and Lo5N were found to be 0.0055 rad/m for all these beams. The ratios of twist at the cracking to the predicted values by MARS are found to be 0.9891 for all beams Lo3N, Lo4N and Lo5N respectively. The same ratio was found to be 0.9125, 0.9050 and 0.8976 for beams Lo3N, Lo4N and Lo5N respectively for analytical model.

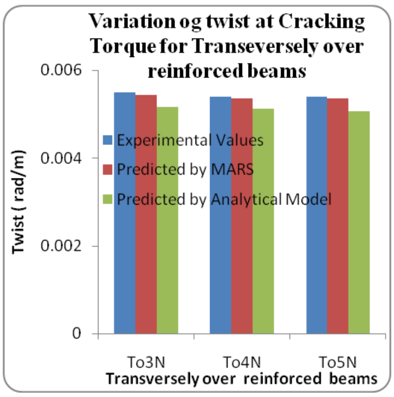


Figure 5. Experimental and Predicted twist variation of transversely over reinforced beams

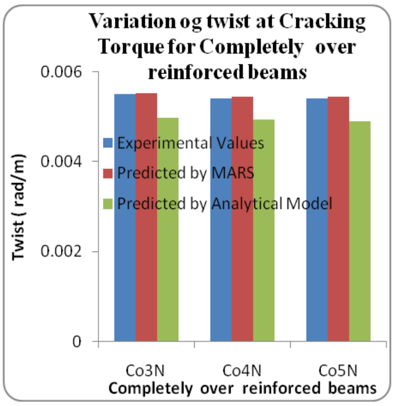


Figure 6. Experimental and predicted values of twist of completely over reinforced beams for different layers over

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 beams had undergone maximum twist next to the under reinforced series of beams. The cracking twist of these beams was found to be 0.0055 rad/m, 0.0054 rad/m and 0.0054 rad/m for beams To3N, To4N and To5N respectively against the predicted values by MARS of 0.0054446, 0.0053611 rad/m and 0.0053611 rad/m for all beams as shown in Fig. 5. The values obtained by analytical model were found to be 0.00516 rad/m, 0.00516 m/rad and 0.005073 rad/m respectively for beams To3N, To4N and To5N.

This shows there was a no noticeable amount of increase in twist at cracking torque. The cracking torque of beams is well predicted by MARS rather than analytical model.

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 twist was should decrease as compared to other beams due to participation of more of reinforcement in the post cracking stage. The twists at the cracking torque of beams Co3N, Co4N and Co5N were found to be 0.1250.0055 rad/m, 0.0054 rad/m and 0.0054 rad/m over their predicted values by MARS 0.0055239 rad/m, 0.005404 rad/m and 0.005404 rad/m for all beams respectively. The same was found to be 0.004965 rad/m, 0.004924 rad/m and 0.004885 rad/m for beams Co3N, Co4N and Co5N respectively by analytical method. It seems soft computing method MARS well predicts the results rather than analytical model. The experimental values are presented in Fig. 6 for these beams. The twists at cracking torque of all these beams are found to be less in analytical model than that of control specimen as more amount of reinforcement participated after cracking increasing the stiffness. There is no such wide variation of twist observed in experimental and prediction by MARS.

5.2 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.

5.2.1 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 ferrocement shell material properties. 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 cracking 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 cracking 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 cracking 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 cracking torque was found to be 0.00546 rad/m. This shows that the beams with "U" wraps have more strength and resists more twist 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. There was increase in twist at the cracking torque with respect to its plain beam B4H. The twist at the cracking torque was found 0.005818 rad/m against the same predicted value by MARS. The increase in twist over plain "U" wrapped beam B4H was found to be 6.15 %.

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 twist at cracking torque was found to be 0.00569 rad/m against the same predicted value.

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 mortar matrix and concrete strength of beams were kept as 2.0, 55 MPa and 60 MPa, mesh layer was kept as 4 and beam were U4H, Lo4H, To4H and Co4H.Twist at cracking torque were found to be 0.005408 rad/m, 0.005387 rad/m, 0.005402 rad/m and 0.005408 rad/m against their predicted values by soft computing was 0.0053611 rad/m, 0.0054404 rad/m, 0.0053611 rad/m and 0.0054404 rad/m for beams U4H, Lo4H, To4H and Co4H respectively . The same was found to be 0.00548 rad/m, 0.00521 rad/m, 0.00531 rad/m and 0.00505 rad/m for beams U4H, Lo4H, To4H and Co4H respectively by analytical model. The twist at cracking torque for different states of torsion was plotted in Fig. 7. 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 cracking torque was plotted for normal strength and high strength reinforced beam for four number mesh layers. The comparison is shown in Fig. 8. As amount of reinforcement, core concrete strength and ferrocement mortar strength are different, no conclusions could not be drawn.

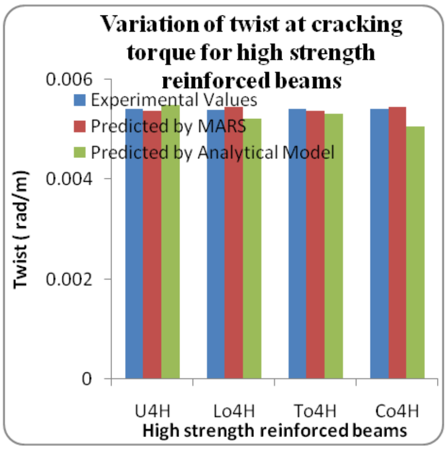


Figure 7. Comparison of twist at Cracking Torque of high strength Beams for 4 layers for different states of torsion

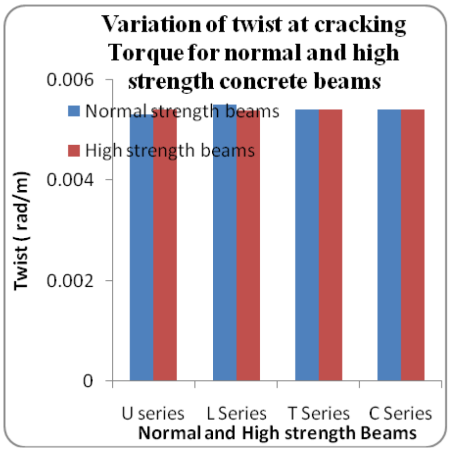


Figure 8. Comparison of twist at cracking torque between normal strength and high strength Beams for 4 layers between different states of torsion

6. 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.

<u>Plain "U" Wrapped Beams</u>

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

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

Reinforced Concrete Beams

1. The decrease in twist at cracking torque over the number of layers for any state of torsion is very less.
2. Twist at cracking torque for ferrocement "U" wrapped beam is approximately same for all states of torsion as it is revealed by the results of Soft computing model, analytical model and the experimental values.
3. The results of soft computing by MARS better predicts than analytical model with experimental results.

Acknowledgement: The authors are grateful to the Director, National Institute of Technology, Warangal, and Andhra Pradesh, India for encouragement and granting permission for this project and also to publish this project.

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