TORSIONAL BEHAVIOUR OF NORMAL STRENGTH 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. Scant 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 the behaviour of "U" wrapped rectangular concrete members subjected to torsional loads "U" wraps. 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 MARS. The predictions are in good agreement with experimental test results.*

Key words: *ferrocement, U wrap, Ultimate Torque, MARS: ferrocement.*

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 in deciding about 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 external bonding 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 possesses high tensile strength, water tightness and is easy for 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).

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).* For quantification of torsional strength of "U" wrapped beams very few attempts have been made by (Panchacharam and Belarbi, 2002; Deifalla *et al.,* 2013). 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.

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 (Behera *et al.,* 2008).

This paradigm was a motivation 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 experimental study is to evaluate the ultimate torque of a wrapped ferrocement "U" wrap beam using soft computing method MARS.

1.2. Soft Computing by 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.

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 is less than that required for torsionally balanced section. In longitudinally over reinforced sections lower amount of reinforcement in transverse direction and higher amount of reinforcement in the longitudinal direction than the reinforcement required for torsionally balanced sections are provided. In transversely over reinforced sections higher amount of reinforcement in transverse direction and lower amount of reinforcement in the longitudinal direction than the reinforcement required for torsionally balanced sections are provided. In completely over reinforced sections higher 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).

Table 1 Details of Beams

Sl. No.	Series	Designation	Dimensions (mm)	Compressive strength — Ferrocement matrix (MPa)	Compressive strength — Concrete (MPa)	Longitudinal Steel — Diameter, No. of bars	Longitudinal Steel — Yield Strength (MPa)	Transverse steel — Diameter, Spacing	Transverse steel — Yield Strength (MPa)	Outer Wrap — 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 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

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)

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)

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

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 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:

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

Where, Y is a response variable, $X = (X_1, X_{2, \ldots \ldots \ldots} X_n)^{\mathrm{T}}$ 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 ($j = 1, 2, \ldots \ldots p$) with p-dimensional knots $\tau_i = (\tau_{i,1}, \tau_{i2}, \ldots, \tau_{i,p})^{\mathrm{T}}$. Actually, we could even choose the knots $\tau_{i,j}$ more distant 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):

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

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 ultimate torque, ultimate twist, secant stiffness at ultimate and toughness. The values are presented below.

a) For Ultimate Torque
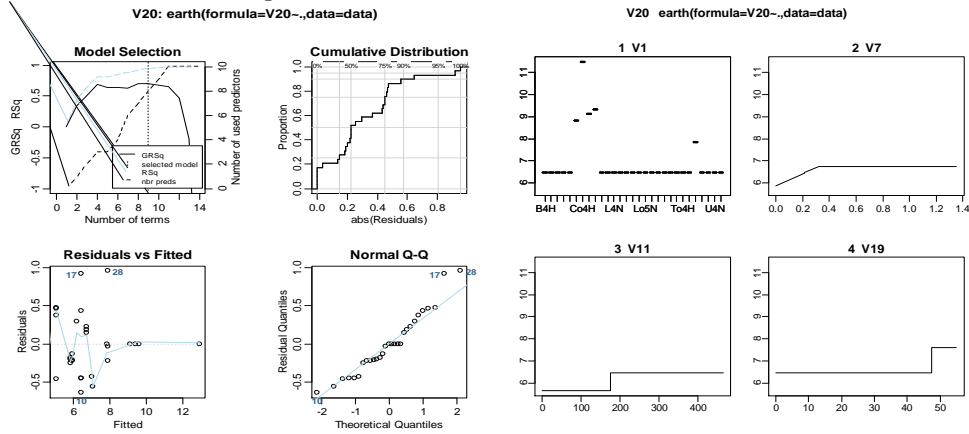
V1Co4H	8	100.0	100.0
V7	6	72.4	71.3
V11	6	52.7	56.9
V19	4	31.3	37.3
V1Co3N	3	29.0	31.2
V1Co4N	3	29.0	31.2
V1Co5N	3	29.0	31.2
V1To5N	1	10.3	15.1

coefficients
(Intercept)	6.7528209
V1Co3N	2.3521791
V1Co4H	5.0055965
V1Co4N	2.6731791
V1Co5N	2.8671791
V1To5N	1.3965373
h(0.322651-V7)	-2.7323212
h(350-V11)	-0.0022761
h(V19-40)	0.0767722

$$T = 6.752 - maximum[0, 0.32265 - spacing\ of\ longitudinal\ reinforcement]$$
$$* 2.7323 - maximum[0, 350 - Fty] * 0.002276$$
$$+ maximum[0, Mortar\ strength - 40] * 0.07677$$

Table 2. Experimental and Predicted Values of Ultimate Torque by MARS

	Ultimate Torque(kNm)			Ultimate Torque(kNm)	
Beams	Expt	MARS	Beams	Expt	MARS
BQ3N	5.443	5.074	To3N	6.899	6.463
BQ4N	5.546	5.074	To4N	7.38	6.463
BQ5N	5.54	5.074	To5N	7.86	7.86
L3N	5.73	5.956	Co3N	9.105	9.105
L4N	5.74	5.956	Co4N	9.426	9.426
L5N	5.82	5.956	Co5N	9.62	9.62
T3N	5.62	5.871	BH	4.612	5.074
T4N	5.67	5.871	B4H	6.52	6.226
T5N	5.69	5.871	L4H	6.55	7.107
U3N	5.816	6.458	T4H	6.59	7.022
U4N	6.01	6.458	U4H	7.68	7.904
U5N	6.01	6.458	Lo4H	7.87	7.904
Lo3N	6.899	6.752	To4H	8.86	7.904
Lo4N	6.939	6.752	Co4H	12.91	12.91
Lo5N	6.979	6.752			

4. INTERPRETATION OF TEST RESULTS

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

4.1. 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.

4.1.1. 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.

4.1.1.1. General Torsional Behavior of Plain Normal Strength Beams

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 of plain concrete beams in column shows that experimental are higher than the predicted values 6.76%, 8.50% and 8.40 % for BQ3N, BQ4N and BQ5N respectively. This shows that the predicted values are well in agreement with experimental values for plain "U" wrapped beams.

4.1.1.2. Effect of Number of Layers:

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 analyzed with

layers from 3, 4 and 5, the ultimate torques are found to be 5.07 kNm for all beams without any variation. 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 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 5.07 kNm for all beams. The variation of ultimate torque with number of layers was shown in Fig. 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 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).

4.1.2. 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 state 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.

4.1.2.1. 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.

4.1.2.2. 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 ultimate torque of these beams L3N,

L4N and L5N were found 5.69 kNm, 5.73 kNm and 5.73 kNm respectively which indicates that there was no such improvement in ultimate torque. The predicted torque of the beams was found to be 5.956 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.
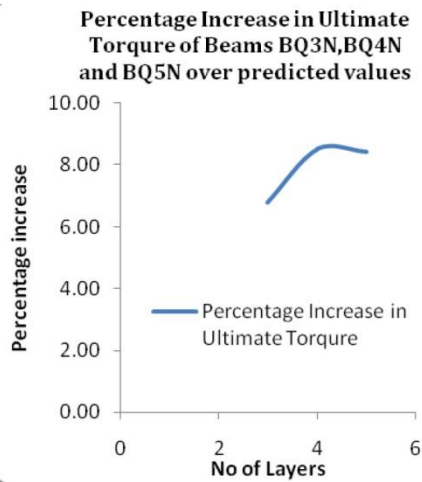

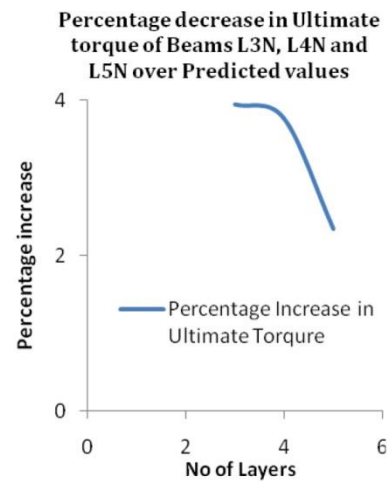**Fig. 1** Percentage Increase in Ultimate Torque and Twist of Experimental Values over Predicted Values

Fig. 2 Percentage variation of torque, twist and Stiffness of only Longitudinally reinforced beams

4.1.2.3. 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 was that the latter were provided with 8 mm diameter bars with 100 mm c/c.

The cracking and ultimate torsional strength of all these beams were found to be 5.62 kNm, 5.67 kNm and 5.69 kNm experimentally. The predicted ultimate torques of all these beams is found to be 5.871 kNm for all these beams as shown in Fig.3. The torque increased by 3.25%, 2.24% and 2.71% 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 "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].
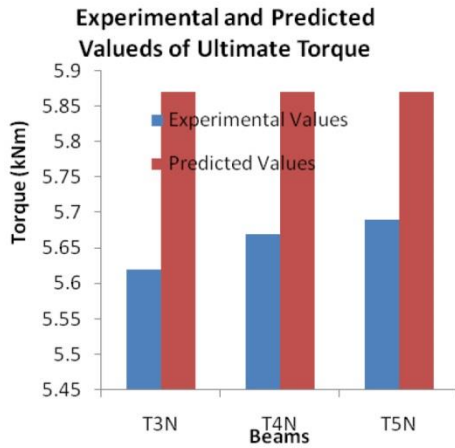
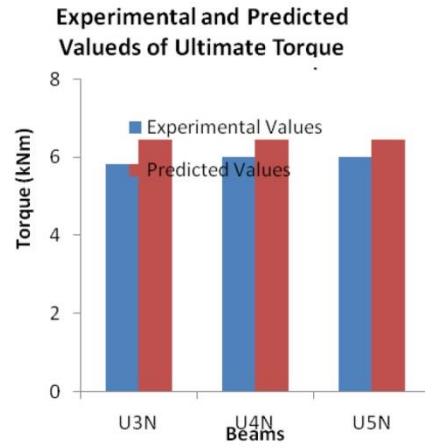**Fig. 3** Percentage variation of torque of only Transverse reinforced beams

Fig. 4 Experimental and Predicted values of Torque for under reinforced beams

4.1.2.4. 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 ultimate torque values were found to be 5.816 kNm, 6.01 kNm and 6.01 kNm against predicted values of 6.45 KNm for three, four and five layers respectively as shown in Fig.4. The predicted value overestimates by 7.31% for beam U5N.

4.1.2.5. 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 experimental and predicted values are shown in Table 2. The ultimate torques of the beams was found to be 6.899 kNm, 6.939 kNm and 6.979 kNm for beams Lo3N, Lo4N and Lo5N respectively against the predicted values 6.752 kNm for all the three beams. As there is shortage of reinforcement in transverse direction on the unwrapped face, increase the number layers cannot enhance the ultimate torque. The same was revealed from the soft computing method MARS. The predicted values are well in agreement with experimental values as shown in Fig.5.
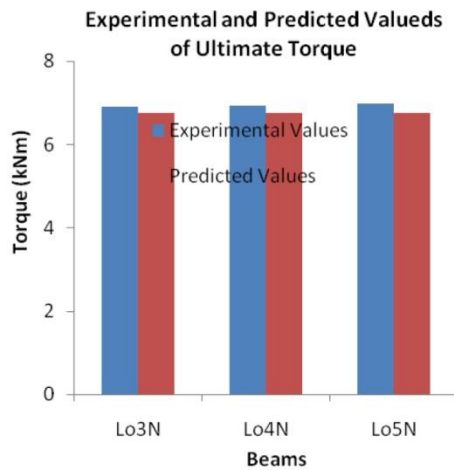
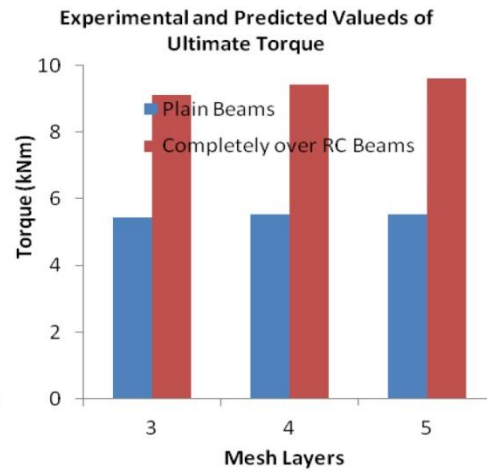**Fig. 5** Experimental and Predicted Torque variation of longitudinally over reinforced beams

Fig. 6 Torque of Plain and over reinforced beams for different layers

4.1.2.6. Transversely Over Reinforced Beams

To examine transversely over reinforced beams, three beams, designated as To3N, To4N and To5N were analyzed and verified with experimental results. The material properties of core and wrap were mentioned in experimental section. The beams henceforth will be referred to as "T" series beams. The torque-twist responses of individual beams, both experimental and predicted are presented below. The ultimate torque of these beams To3N, To4N and To5N was found to be 6.899 kNm, 7.38 kNm and 7.86 kNm. The increases in ultimate 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 ultimate torque. The ultimate 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 ultimate torsional strength of this series with respect to number of mesh layers was more in comparison to other states of torsion. The predicted values are found to be 6.463 kNm,6.463 kNm and 7.86 kNm respectively. The predicted values are lower by 6.32%, 12.42 % and 0 % than their experimental values.

4.1.2.7. 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 ultimate torques of these beams was 9.015 kNm, 9.426 kNm and 9.62 kNm respectively for beams Co3N, Co4N and Co5N over the same predicted values. The increase in ultimate torque of these beams Co3N, Co4N and Co5N with respect to their companion beams BQ3N, BQ4N and BQ5N were found to be 66.38%, 74.23% and 75.22% respectively. The experimental values are presented in Fig. 6 for these beams. These beams showed maximum increase in ultimate torque over their respective plain "U" wrapped beams BQ3N, BQ4N and BQ5N in

comparison to all states of torsion. The increase in ultimate torque of Co4N over Co3N was 4.5% while the same was 6.71% for Co5N over the beam Co3N. Here absolutely the predicted values are exactly equal to the experimental values.

4.2. Torsional Behavior of High Strength Beams

Torsional behavior of High strength concrete beam differs from 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 are analyzed in this section.

4.2.1. 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 ultimate torque of the two beams BH and B4H was found to be 4.612 kNm and 6.52 kNm respectively. Beam BH is a plain beam without wrapping while B4H has a ferrocement wrap of 4 layers of mesh without any conventional reinforcement. The increase in ultimate 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.

4.2.2. 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 were 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.

4.2.2.1. 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.

Ultimate torque of beam L4H was found to be 6.55 kNm. The increase in torque of beam L4H over its plain "U" wrap beam B4H is 4.46%. The predicted value 8.51% more than the experimental values.

4.2.2.2. 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 ultimate torque of the beam was found to be 6.59 kNm against the predicted value of 7.02 kNm. The increase in cracking torque over the beam B4H was 1.38% only.

4.2.2.3. 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 beams were U4H, Lo4H, To4H and Co4H. The designations of the beams were already explained earlier. The beams U4H, Lo4H, To4H and Co4H have ultimate torque of 7.68 kNm, 7.87 kNm, 8.86 kNm and 12.91 kNm respectively. The predicted values 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. A comparison of normal strength and high strength beams shown in Fig.8.
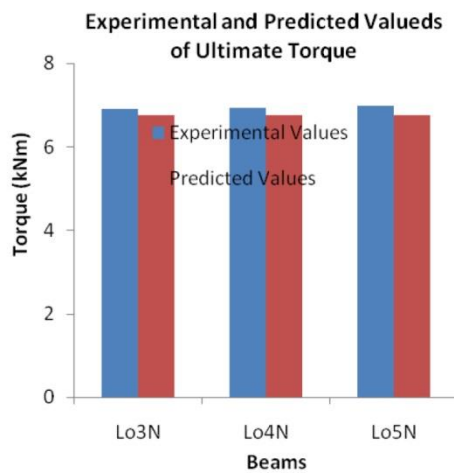

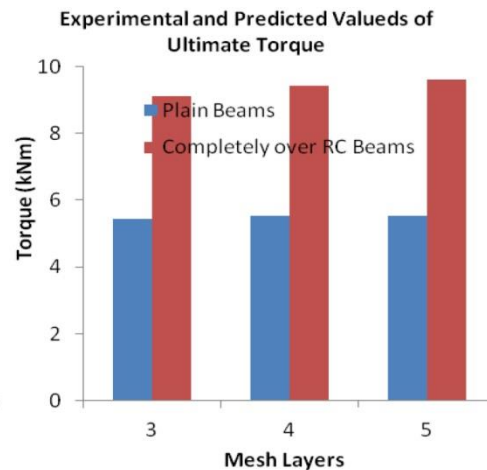**Fig. 7** Comparison of Torque between Experimental and Predicted Values for high strength Beams

Fig. 7 Comparison of Torque between normal strength and high strength Beams for 4 layers

5. 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
1. A significant increase in torsional strength is observed with ferrocement "U" wrapped normal and high strength concrete beams over their plain concrete beams.
2. Ultimate torque is dependent upon the core concrete, mortar strength, mesh layers and aspect ratio combinedly.
3. 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
1. The increase in torsional strength over the number of layers for any state of torsion is very less.
2. Single type of reinforcement either longitudinal or transverse reinforcement is ineffective in enhancing the torsional strength.
3. Transversely over reinforced concrete beams showed overall increase in torque over longitudinally over reinforced beams.
4. Soft computing model and the experimental results reveal that the torque twist response of a ferrocement "U" wrap beam is more influenced by the state of torsion than the amount of ferrocement reinforcement.
5. The results of soft computing by MARS are well in agreement with experimental results.

References

1. ACI committee 318, (2002). Building code requirements for structural concrete and commentary, *ACI 318R-02*: Farmington Hills, Michigan.
2. ACI Committee 549. (1979). Ferrocement-Materials and Applications. ACI Symposium Proceedings SP-61: *American Concrete Institute* 549, Farmington Hills, Michigan.
3. Ameli, M., and Ronagh,H.(July-Aug 2007). "Analytical model for evaluating torque of FRP strengthened reinforced concrete beams." *Journal of Composites for construction*, pp. 384-390.
4. Bansal,P.P., Kumar, M. and Kaushik,S. K.(2007). " Effect of mesh orientation on strength of beams retrofitted using ferrocement jacket." *International Journal of Engineering,* Vol- 20 Issue-(1),pp.8-19.
5. Behera, G. C. Rao, T. D. G. & Rao, C. B. K. (August-2008). " Torsional Capacity of High Strength Concrete Beams jacketed with ferrocement U wraps." *Asian Journal of Civil Engineering*, Volume -9 Number 4, pp. 411-422.
6. Behera, G. C. Rao, T. D. G. & Rao, C. B. K"A study on post cracking torsional behaviour of high strength reinforced concrete beams with ferrocement "u" wraps" Vol. 22, 2014, No. 3, DOI: 10.2478/sjce-2014-0012, Slovak Journal of Civil Engineering,pp.1 – 12.
7. Behera, G. C. Rao, T. D. G. & Rao, C. B. K "Analytical model for torsional response of RC beams strengthened with ferrocement U-Wraps" DOI: 10.2749/101686614X13854694314847, SEI Vol.24, No.4, Nov-2014, IABSE Structural Engineering International, pp.509-520.
8. Chalioris, C.E.(2006). "Experimental Study of the Torsion of Reinforced Concrete Members." *Structural Engineering and Mechanics*, Vol. 23, No. 6, pp. 713-737.
9. Chalioris, C.E.(2007). "Analytical Model for the Torsional Behaviour of Reinforced Concrete Beams Retrofitted with FRP Materials." *Engineering Structures*, Vol. 29, No. 12, pp. 3263-3276.
10. Chalioris, C.E.(2008). "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.

11. Chalioris C.E., Thermou, G.E. and Pantazopoulou, S.J. (2014). "Behaviour of Rehabilitated RC Beams with Self-Compacting Concrete Jacketing - Analytical Model and Test Results." *Construction and Building Materials*, Vol. 55, pp. 257-273.

12. Deifalla, A., Awad, A. and Elgarhy, M. (2013). " Effectiveness of externally bonded CFRP strips for strengthening flanged beams under torsion; An experimental study."*Engineering structure* (56),pp.2065-2075.

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

14. Deifalla, A. and Ghobarah, A.(2010 b). " 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.

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

16. Hii A, K. Y. and Riyad, A.M.(2006)."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.

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

18. Karayannis, C.G., Chalioris, C.E.and Sirkelis, G.M.(2008). " 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.

19. Kumar, P.R., Oshima, T, M. and Yamazaki, T.(2007). " 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.

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

21. Liang-Jenq, Leu. and Yu-Shu, Lee.(February 2000). " Torsion design charts for reinforced concrete rectangular members." *journal of structural engineering ASCE*,pp.210-218.

22. Ming, J. and Grunberg, J.(2006). "Mechanical analysis of reinforced concrete box beam Strengthened with carbon fiber sheets under combined actions." *Composite Structures,* vol.73,pp. 488-494.

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

24. Nie, J., Liang, T. and Cai,S. C.(2009). " Performance of steel- concrete composite beams under combined bending and torsion". *journal of structural* Engineering,ASCE,pp.1049-1057.

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

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

27. Rao, T. D. G. and Seshu, D.R.(2006). " Torsional Response of fibrous reinforced concrete beams; Effect of single type reinforcement." *Construction and Building materials,* Vol.20,pp.187-192.

28. Rao,T. D. G. and Seshu, D.R. (2003). "Torsion of steel fiber reinforced concrete members." *Cement and Concrete Research*, pp. 1783-1788.

29. Rita, S. Y., Wong, F. and Vecchio, J. (January-Feb-2003). "Towards Modeling of Reinforced Concrete Members with Externally Bonded Fiber-Reinforced Polymer Composites." *ACI Structural Journal,* pp.47-55.

30. Salom, P.R., Gergely, J., and Young, D.T.(January 2003). "Torsional retrofit of Spandrel Beams with composite Laminates." In: *Proceedings of Institution of Civil Engineers, Structures and Buildings*, 157 Issues SBI,pp. 69-76.

31. Salom,P.R., Greeley, J.R. and David,Y.T.(March-April 2004)."Torsional Strengthening of Spandrel Beams with Fiber-Reinforced Polymer Laminates."*Journal of composites for construction, ASCE*, pp.157-162.

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

33. Shannag, M.J. and Mourad, S.M.(2012). "Flowable high strength cementitious matrices for ferrocement applications." *Construction and Building Materials*, Vol. 36, pp. 933-939.

TORZIONO PONAŠANJE GREDA OD ARMIRANOG BETONA OJAČANIH ZAŠTITNIM OBLOGAMA U OBLIKU „U" KOŠULJICA

Tehnologija oblaganja je jedan od efikasnih načina za ojačanje betonskih elemenata. Više istraživača je izveštavalo o ojačavanj betonskih elemenata polimerima of fiberglasa ili ugljeničnih vlakana. Oblaganje sa tri strane je jedan od efikasnih metoda za ojačavanje greda koje nose međuspratne konstrukcije. Dostupno je malo literature koja se bavi ojačavanjem betonskih elemenata oblogama "U" oblika koji su izloženi torzionim opterećenjima. U ovom istraživanju, pokušano je da se kvantifikuje napredak u ponašanju četvorouglih betonskih elemenata obloženih "U" košuljicama a koji su izloženi torzionom opterećenju. Ferocement je uzet za material obloge. Grede su izlivene sa različitim brojem mrežnih slojeva i različitim torzionim ojačanjima. Grede su analiziranje korišćenjem MARS-a. Dobijeni rezultati se slažu sa rezultatima eksperimentalnog ispitivanja.

Ključne reči: *ferocement: „U" obloga, Moment loma, MARS, ferocement*