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Determination of Ultimate Torque and Twist of High Strength RC Beams with Ferrocement "U" Wraps: Different Approaches

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Abstract

Designers are more interested in strength at cracking rather than ultimate strength. Still then beyond cracking, the structures are able to sustain more loads. So, determination of ultimate strength is an important parameter in design field. Evaluation of ultimate torsional capacity of high strength distressed beams with ferrocement "U" wrap has been presented here. The evaluation procedure involves experimental results, results obtained by analytical method. As the above two methods are not providing quick solution, rather than the first one is based on destruction of prototype structure for evaluation of strength. Other methods such as soft computing methods have been employed. Two methods MARS and WASPAS are employed here to compute the torsional strength of "U" wrapped beams. These two methods provide quick solutions to estimate the torque and twist at ultimate stage. Predicted values by these methods are within acceptable limits. At ultimate stage, the "U" wrapped beams are able to resist torque more than 41.37% than the unwrapped beams and a completely over reinforced beam resists 98.01% more than plain "U" wrapped beams. Under reinforced "U" wrap beams have undergone 23.9 times more twist than that of plain "U" wrap beams. This proves effectiveness of "U" wrap on periphery of distressed beams.

Keywords: Ferrocement, U wrap, Ultimate torque, Twist at ultimate torque, MARS, WASPAS

1. Introduction

Torsion is a basic structural load. Torsion occurs in two forms either primary or secondary torsion. Torsion occurs in the structures either individually or with combination of other structural actions. Concrete is most common construction material. The distressed structural reinforced concrete (RC) elements need to be repaired addition of other materials to reinforce concrete with its low tensile strength and poor toughness. Repair can be done with epoxy, steel jacket or FRP. Labour and time availability along with cost decides the retrofitting material to be used for repair. [1]. FRPs can be effectively used to upgrade such structural deficient reinforced concrete structures. Though torsional retrofitting requires a full wrap, 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] with the exception of a few studies that investigated T-beams with U-jacket [2-4].

The deterioration of existing concrete structures in many countries necessitates the need for developing cost-effective and long term repair and retrofit solutions that can be implemented in practice. A practical method of repair should take into consideration, the amount of damage, the shape of the member, materials of repair, construction cost, time and practicality. Several repair/retrofit techniques were used for restoring the load carrying capacity of damaged concrete structural elements. 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 easy on application [5] ACI Committee 549,1979). Ferrocement meets the criteria of flowability and strength in addition to impermeability, sulphate resistance, and corrosion protection and in some cases frost durability. Such performance is made possible by reducing porosity, inhomogeniety, and micro cracks in the cement matrix transition zone of structure [6-7].

1.1 Necessity 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 which quantify the torsional strength of FRP bonded full wrap [8-9]. But inaccessibility and extension of flanges over the web has necessitated strengthening the beams by "U" wrap rather than full wrapping [10]. Methods for quantification of torsional strength of "U" wrapped beams are found to be very few [11]. The mentioned literature in the introduction substantially recommends ferrocement as a retrofitting material and can be

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a substitution for FRP. Few studies are available to quantify the torsional strength of ferrocement "U" wrapped beams. Quantification of torsional strength of "U" wrapped RC beams through experimental and analytical method is reported by the author [12]. No such single equation is derived from the experimental results to predict torsional strength of "U" wrapped RC beams of different sections or with different materials. Analytical method is tedious and needs computation method to predict the torsional strength. So, this paradigm motivated to take up the present investigation. The aim of this investigation is to apply soft computing method to predict torsional strength of ferrocement "U" wrapped RC beams with the help of these experimental results. The objective of the present study is to evaluate the ultimate torque twist of a wrapped ferrocement "U" wrap beam with high strength core concrete using soft computing method MARS and WASPAS.

2. Different Approaches to Predict Torsional Strength

2.1 Experimental Program

Beams tested by the author during his doctoral program are taken into consideration. All the beams are of size (125 mm X 250 mm X 2000 mm).

Cross section of the beams and torsion test rig is shown Fig. 1(a) and (b) respectively. Details of beams and material properties are presented in Table 1. All types of beams such as plain beams, beams with single type of reinforcement and beams with both longitudinal and transverse reinforcement were cast and tested.

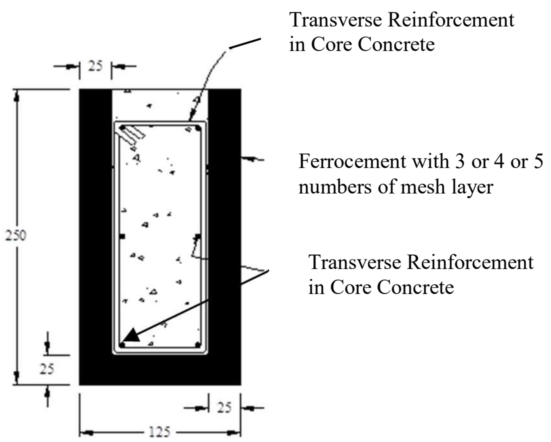


Fig. 1.(a) Cross section of beam

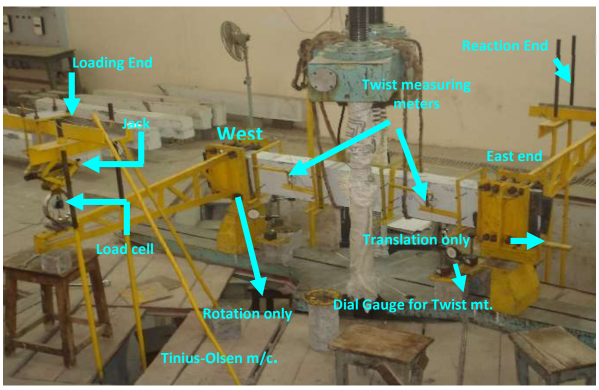


Fig. 1.(b) Torsion test rig

Table-1. Details of the beams tested

	Core Reinforced Concrete			
	Longitudinal Steel		Transverse steel	
	Diameter, No. of bars	Yield Strength (MPa)	Diameter, Spacing	Yield Strength (MPa)
BOH	"-"	"-"	"-"	"-"
BO4H	"-"	"-"	"-"	"-"
L4H	12 mm, 6 nos.	440	"-"	"-"
T4H	"-"	"-"	10mm @ 70 mm c/c	445
U4H	6 mm, 6 nos.	350	6mm @ 70 mm c/c	350
Lo4H	12 mm, 6 nos.	440	6mm @ 70 mm c/c	350
To4H	6 mm, 6 nos.	350	10mm @ 70 mm c/c	445
Co4H	12 mm, 6 nos.	440	10mm @ 70 mm c/c	445

Beam BOH was without any wrap. The grade of concrete is M60 and mortar grade for ferrocement wrap was M55. Ferrocement wrap was provided in "U" shape for all beams except BOH with four numbers of mesh layers. Diameter of mesh was 0.72 mm with square opening 6.35 mm and yield strength was 250 MPa.

2.2 Analytical Model

An analytical model was developed using skew bending theory with modifications to the material properties. The detailed procedure was presented by Behera et al. [10-13].

2.3. Soft Computing method

Determination of torque by experimental method a tedious and time dependent process and involves a destruction of specimen. For prediction of torsional capacity of beams with other dimension and material properties, soft computing is preferred. Different soft computing methods employed to predict torsional strength of ferrocement "U" wrapped beams is described below.

2.3.1 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 [14] as a flexible approach to high dimensional nonparametric regression, based on a modified recursive partitioning methodology. The final values of torque and twist by this method were as folows

$T_{ultimate}$=6.752- maximum[0,0.32265- spacing of longitudinal reinforcement]*2.7323- maximum[0,350-yield strength of transverse steel]*0.002276+maximum[0, mortar strength-40]*0.07677

$\theta_{ultimate}$(rad/m)=0.03558-maximum [0,Fly-350]*0.0003376-maximum[0,350-Fly]*0.00008786+maximum[0,spacing of stirrup]*0.00102665.

2.3.2 WASPAS method

To solve MCDM (Multi-criteria decision-making), Weighted aggregated sum product assessment (WASPAS) method is proposed [15-18]. It is combination of two MCDM methods, Table-2. Ultimate torque and twist of high strength concrete RC beams.

Ultimate torque (kNm)				
Beams	Ext	Analytical	MARS	WASPAS
BOH	4.612	4.34	5.074	
BO4H	6.52	6.52	6.226	6.341
L4H	6.55	NA	7.107	6.395
T4H	6.59	NA	7.022	7.373
U4H	7.68	7.729	7.904	7.472
Lo4H	7.87	7.828	7.904	9.165
To4H	8.86	8.58	7.904	9.165
Co4H	12.91	12.98	12.91	11.264
Twist at ultimate torque(rad/m)				
BOH	0.00280	0.00350	0.00483	0.00351
BO4H	0.00546	0.00560	0.00483	0.00507
L4H	0.00580	NA	0.00520	0.00569
T4H	0.00560	NA	0.00560	0.00589
U4H	0.13050	0.13736	0.10745	0.11063
Lo4H	0.05600	0.05500	0.07706	0.06712
To4H	0.09210	0.09158	0.10745	0.09782
Co4H	0.07540	0.07361	0.07706	0.05431

i.e. weighted sum method WSM and weighted product method WPM. The procedure is as follows.

Step 1. Initial decision matrix is set.

Step 2. Normalization of the decision matrix using following equations for maximization and minimization criteria, respectively [16]

$$\bar{x}_{ij} = x_{ij}/max_i x_{ij} \quad (1)$$

$$\bar{x}_{ij} = min_i x_{ij} \quad (2)$$

Step 3. Calculation of the total relative importance of i^{th} alternative, based on weighted sum method (WSM) using equations.

$$Q_i^{(1)} = \sum_{j=1}^{n} \bar{x}_{ij}.w_j \quad (3)$$

Step 4. Calculation of the total relative importance of i^{th} alternative based on weighted product method (WPM) using equation.

$$Q_i^{(2)} = \prod_j^n \bar{x}_{ij}^{w_j} \quad (4)$$

Step 5: In order to have increased ranking accuracy and effectiveness of the decision-making process, in the WASPAS [17] and [18] method, determination of the total relative importance of alternatives is done using equation.

$$Q_i = \lambda.Q_i^{(1)} + (1-\lambda).Q_i^2 \quad (5)$$

where λ=0,0. 1,1 is coefficient of linear combination and usually takes value of 0.5. By varying values of λ one can observe the change in values of total relative importance of alternatives as well as rankings of alternatives.

The torques and twists at ultimate were determined by experimental, analytical method and by soft computing methods employing MARS and WASPAS method. The computed results are tabulated in Table-2.

3. Interpretation of Test Results

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

3.1 General Behaviour of High Strength Beams

All beams in this phase were replica of beams of BOH with different amount of reinforcement in core concrete. Beam BOH was a high strength beam of M60 grade concrete without any reinforcement and tested under pure torsion. Beam BO4H was cast with a ferrocement "U" wraps of 25 mm thick with four numbers of mesh layer on periphery and without any reinforcement in core concrete. 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 either only in longitudinal or in transverse direction, 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 L4H and T4H were cast to study the effect of singly type of reinforcement on torsional strength. Another four beams U4H, Lo4H, To4H and Co4H were cast as under reinforced, longitudinally over reinforced & transversely under reinforced, transversely over reinforced & longitudinally under reinforced and completely over reinforced beams respectively. So, the beams with all six of states of torsion with control specimen as BOH and BO4H were cast and tested. As torsion induces shear, cracks are found to be 45^0 in all the beams and in all beams crack was initiated on longer face.

3.2. Ultimate Torque of High strength Beams

The beam BOH when tested under pure torsion, failed with a singly potential crack initiated on longer face. The beam could not sustain any further torque beyond cracking. Cracking and ultimate torque of beam was found to be same for this plain beam without any reinforcement in core and without any wrap. For other type of beams, after initiation of crack, as reinforcement resists the load, ultimate value was found to be more than cracking. So, ultimate torque depends on amount of reinforcement in both direction and also on ferrocement wrap. The ultimate torque of plain beam BOH was 4.612 kNm, but when the beams are provided with "U" wraps BO4H the ultimate torque was found to be increased much more i.e. 6.52 kNm. Ultimate torque of beams L4H, T4H, U4H, Lo4H, To4H and Co4H was found to be experimentally 6.55 kNm, 6.59 kNm, 7.68 kNm, 7.87 kNm, 8.86 kNm, and 12.91 kNm respectively. Beams L4H, T4H, U4H, Lo4H, To4H and Co4H are replica of BO4H with some reinforcement in core concrete. Fig. 2 presents the details of the torque found by experimentally as well as predicted by analytical, soft computing method MARS and WASPAS.

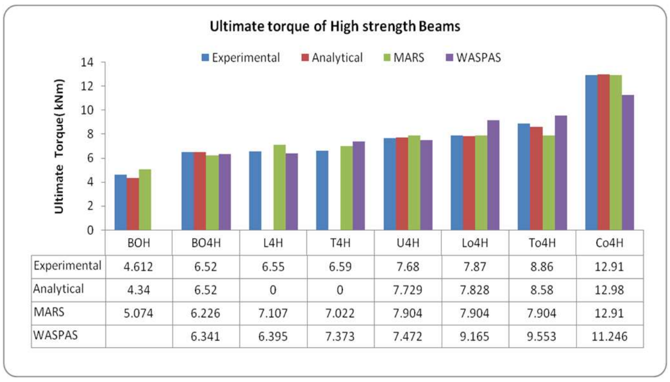
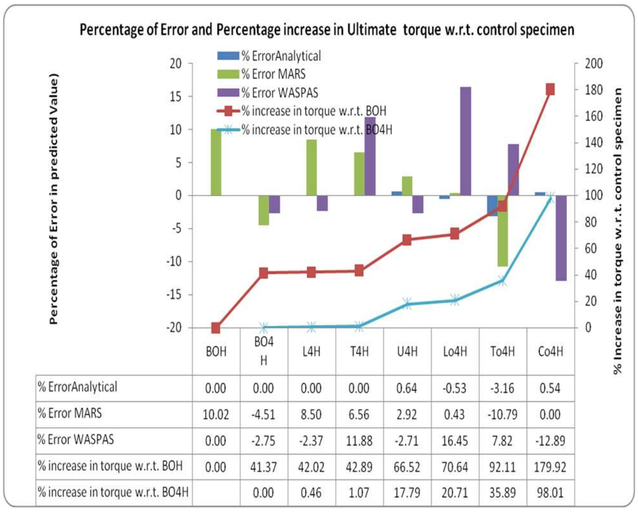


Fig. 2 Experimental and predicted cracking torque of high strength beams



	BOH	BO4H	L4H	T4H	U4H	Lo4H	To4H	Co4H
% ErrorAnalytical	0.00	0.00	0.00	0.00	0.64	-0.53	-3.16	0.54
% Error MARS	10.02	-4.51	8.50	6.56	2.92	0.43	-10.79	0.00
% Error WASPAS	0.00	-2.75	-2.37	11.88	-2.71	16.45	7.82	-12.89
% increase in torque w.r.t. BOH	0.00	41.37	42.02	42.89	66.52	70.64	92.11	179.92
% increase in torque w.r.t. BO4H		0.00	0.46	1.07	17.79	20.71	35.89	98.01

Fig. 3 Percentage of error predicted ultimate torque and percentage increase in ultimate torque over BOH and BO4H of high strength beams

Ultimate torque is more dependent on state of torsion. Completely over reinforced section Co4H resists a torque of 12.91 kNm which is approximately (98.01 %) double value of ultimate torque of control specimen BO4H. After completely reinforced beams, transversely over reinforced beams exhibit better torque resistance over under reinforced and longitudinally over reinforced beams. For singly reinforced beams L4H and T4H, ultimate torque was found to be same as control specimen BO4H. The reason for this already explained in section 3.1.

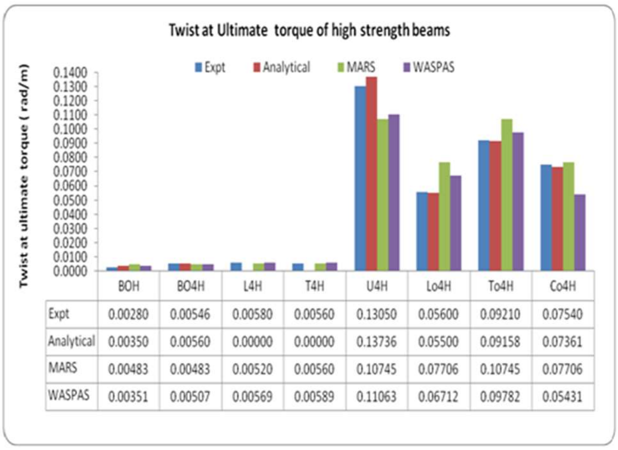
The percentage of error in predicted values of ultimate torque and increase in ultimate torque with respect to control specimen BOH and BO4H were presented in Fig.3. The maximum errors in analytical, MARS and WASPAS were found to be -3.16 %, -10.79 % and -12.89 % respectively. As the error was within 13%, we can utilize these methods for evaluation of ultimate torque of high strength beams.

The percentage of increase of ultimate torque of BO4H, L4H, T4H, U4H, Lo4H, To4H and Co4H over plain beam BOH was found to be 41.37 %, 42.02 %, 42.89 %, 66.52 %, 70.64 %, 92.11 % and 179.92 % respectively. This proves efficacy of ferrocement "U" wrap. Beam BO4H without any reinforcement in core was able to enhance ultimate strength up to 41.37 % over plain beams. The Percentage of increase of ultimate torque of L4H, T4H, U4H, Lo4H, To4H and Co4H over plain ferrocement "U" wrap beam BO4H was found to be 0.46 %, 1.07 %, 17.79 %, 20.71 %, 35.89 % and 98.01 % respectively. These reinforced beams were found to enhance the ultimate torque to a great extent.

3.3 *Twist at Ultimate Torque of High strength Beams*

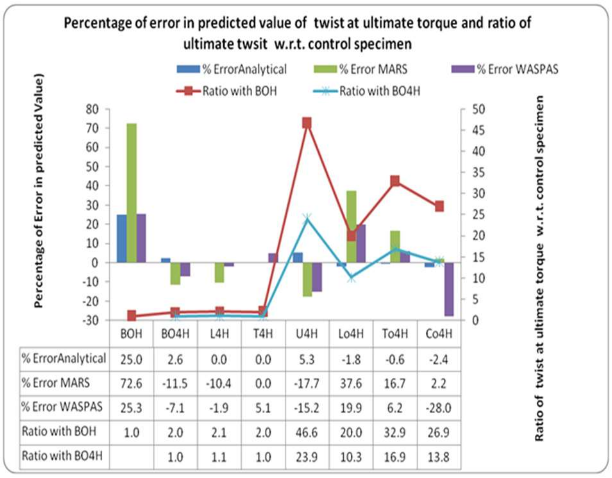
The effect of reinforcement on twist at ultimate torque of high strength ferrocement "U" wrap beams is discussed in this section. When a plain beam BOH was taken, it was able to sustain a twist of 0.0028 rad/m. But when the same beam was provided with a ferrocement wrap, the beam BO4H was able to rotate up to 0.00546 rad/m with high ultimate torque. The beams with reinforcement in core concrete L4H, T4H, U4H, Lo4H, To4H and Co4H sustain twist 0.00580 rad/m, 0.00560 rad/m, 0.13050 rad/m, 0.05600 rad/m, 0.09210 rad/m and 0.07540 rad/ m respectively. The predicted values by analytical model, MARS and WASPAS were presented in Fig.4.

The under reinforced beam U4H has undergone maximum twist as there is less reinforcement. So, the toughness is greater in this under reinforced beam. The percentage of error in predicted value and ratio of twist with respect to control specimen were presented in Fig. 5. Maximum error in predicted values by analytical method, MARS and WASPAS was found to be 5.3 %, 37.6 % and -28% respectively for ferrocement "U" wrap beams. The predicted values of twist at ultimate torque are found with errors more than 20% for MARS and WASPAS. Here analytical model better predicts the twist at ultimate torque. The ratio of twist at ultimate torque of ferrocement "U" wrap beams of BO4H, L4H, T4H, U4H, Lo4H, To4H and Co4H with control specimen BOH was found to be 2, 2.1, 2.0, 46.6, 20.0, 32.9, and 26.9 respectively. This proves efficiency of providing "U" wrap. The same was found to be 1.1, 1.0, 23.9, 10.3, 16.9 and 13.8 times over control specimen BO4H for L4H, T4H, U4H, Lo4H, To4H and Co4H. The twist of U4H was found to be 46.6 times over BOH and 23.9 times over beam BO4H. Next to under reinforced beam, transversely over reinforced beams has resisted maximum twist.



	BOH	BO4H	L4H	T4H	U4H	Lo4H	To4H	Co4H
Expt	0.00280	0.00546	0.00580	0.00560	0.13050	0.05600	0.09210	0.07540
Analytical	0.00350	0.00560	0.00000	0.00000	0.13736	0.05500	0.09158	0.07361
MARS	0.00483	0.00483	0.00520	0.00560	0.10745	0.07706	0.10745	0.07706
WASPAS	0.00351	0.00507	0.00569	0.00589	0.11063	0.06712	0.09782	0.05431

Fig. 4 Experimental and predicted twist at ultimate torque of high strength beams



	BOH	BO4H	L4H	T4H	U4H	Lo4H	To4H	Co4H
% ErrorAnalytical	25.0	2.6	0.0	0.0	5.3	-1.8	-0.6	-2.4
% Error MARS	72.6	-11.5	-10.4	0.0	-17.7	37.6	16.7	2.2
% Error WASPAS	25.3	-7.1	-1.9	5.1	-15.2	19.9	6.2	-28.0
Ratio with BOH	1.0	2.0	2.1	2.0	46.6	20.0	32.9	26.9
Ratio with BO4H		1.0	1.1	1.0	23.9	10.3	16.9	13.8

Fig. 5 Percentage of error in predicted twist at ultimate torque and ratio of twist over BOH and BO4H of high strength beams

4. Conclusions

Ultimate torques and twist at ultimate torques of plain and reinforced ferrocement "U" wrapped high strength beams were computed by experimental and from other methods. From the results, following conclusions were drawn.

Plain "U" Wrapped Beams

- A significant increase in torsional strength approximately 41.37 % is observed with ferrocement "U" wrapped high strength concrete beams over their plain concrete beam. This proves the effectiveness of "U" wrapped beams.
- Ultimate torque is more dependent upon the states of torsion.

"U" Wrapped Reinforced Concrete Beams

- Single type of reinforcement either in longitudinal or in transverse direction is ineffective in enhancing the torsional strength.
- The enhancement of ultimate torque of completely over reinforced beams is found up to 98.01 % over their control specimen.
- Ultimate torque is dependent on longitudinal and transverse reinforcement.
- There is significant enhancement of twist at ultimate torque for ferrocement "U" wrap high strength beams. Under reinforced beams has undergone an ultimate twist 23.9 times higher over its control specimen.
- The results of soft computing by MARS and WASPAS are well in agreement with experimental results for ultimate torque.

Disclosures

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