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TORSIONAL CAPACITY OF HIGH STRENGTH CONCRETE BEAMS JACKETTED WITH FERROCEMENT U – WRAPS

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Abstract

Jacketing with composites on the outer periphery is one of an effective way to enhance the torsional capacity of distressed reinforced concrete structures and to change the mode of failure from brittle to ductile. Ferrocement due to its better crack arresting capacity and better strain distribution across the section make it one of the suitable composite materials in the field of strengthening reinforced concrete members. An experimental programme consisting of casting and testing of beams with “U” wraps (more commonly used strengthening technique) was conducted in the laboratory to study the effect of aspect ratio (ratio of depth to breadth), constituent materials of ferrocement (viz., number of mesh layers, yield strength of mesh layers and compressive strength of mortar) and concrete strength on ultimate torsional strength and twist. This experimental results briefly recounts that wrapping on three sides enhance the ultimate torque and twist. This strengthening scheme is more effective for higher aspect ratios with high strength jacketing material. An analytical model proposed in this paper for prediction of torque and twist response of jacketed beams is in good agreement with experimental results.

Keywords: Ferrocement; jacketing; shear modulus torsional capacity; torque; twist; torsional toughness

1. Introduction

Increased service loads, diminished capacity of structures through aging and environmental ingress and need from architectural point of view have necessitated many structures either to be retrofitted or to be demolished. It is cost effective to rehabilitate the deficient structures before replacement becomes an economically viable consideration. In the field of retrofitting, a large number of studies have been reported in shear and flexure while the torsional effects were not considered due to its complex nature and occurrence with other basic structural actions for a long period [1], [2], [3] and [4]. FRPs have capacity to alter the failure mode of structural members from brittle to ductile apart from increasing the load

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carrying capacity and hence dominated the field of retrofitting material. On the other hand ferrocement is also another composite material having thorough dispersion, high volume fraction of reinforcement with small thickness, closer and uniform distribution of reinforcement which yields in better strain distribution and crack arresting capacity. This material will be a substitute for FRP in jacketing or retrofitting from cost benefit point of view. Circulatory torsion induces significant shearing stresses on the periphery of the beam cross section. Hence, the most efficient way of retrofitting torsionally distressed beams is to strengthen in all four sides. But due to the inaccessibility and extension of flanges over the web, U wrap is the practical solution over full wrap [5].

The present investigation addresses the effect of aspect ratio; strength of core concrete and number of layers present in the jacketing and the influence of jacketing on the torsional response of the U wrapped concrete beams.

2. Analytical Solution

A plain homogeneous concrete beam with skinning on four sides when subjected to pure torsion experiences a prestressing force on concrete due tensile stress produced on skinning material [5], [6]. This prestressing effect increases the torque carrying capacity of concrete beams.

The skinned concrete beam behavior can be studied in three phases i.e. elastic stage, micro cracking stage and post cracking stage. The beam behaves elastically up to elastic torque i.e., a shear stress equal to the tensile strength of the mortar of the jacketing or the shear stress at the unwrapped face is equal to the tensile strength of the concrete (whichever cracking shear stress reaches earlier). If the tensile strength of the concrete governs the failure then the jacketing materials becomes ineffective hence the elastic torque is equal to the ultimate torque. Otherwise the wire mesh in the jacketing is effective in the micro cracking as well as post cracking stage of skinned beam.

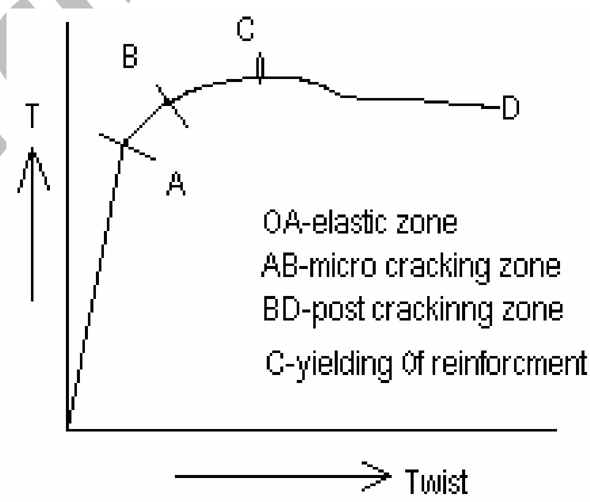

Figure 1. Typical torque twist response of a wrapped beam

Micro cracks appear on ferrocement jacket, when the shear stress due to torsion reaches the tensile strength of ferrocement. This stage is referred as "micro cracking stage", since the reinforcement present in the jacketing participate in arresting the crack propagation. This stage is in between the cracking and post cracking stage of the beam. The initiation of the micro cracking can be taken as the shear stress in the jacketing equal to the tensile strength of the mortar. The micro cracking stage ends when the shear stress in the jacketing is equal to the cracking strength of ferrocement i.e. considering the mortar tensile strength as well as that of the mesh reinforcement. Once the shear stress in the jacketing crosses the cracking strength of the ferrocement, the post cracking stage of the beam starts. During this stage, if the shear stress in the unwrapped face of the concrete reaches the tensile strength of concrete, failure of unwrapped portion initiates the ultimate failure of the beam. Otherwise, the ultimate failure of the beam occurs due to the yielding of the reinforcement present in the ferrocement jacketing or failure of unwrapped portion of the beam. Thus separate equations have to be developed for torque twist response of the wrapped beams under torsional loads for the three cases viz., elastic stage, micro cracking stage and post cracking stage. Thus the effectiveness of the wrap depends on aspect ratio, tensile strength of the core concrete and the tensile strength of the mortar of the jacketing material. Figure1 shows the different stages of behavior in a ferrocement-skinned beam under torsional loads.

2.1 Elastic response

Cracking takes place in a concrete beam subjected to torsion when the shear stress exceeds the tensile stress of plain concrete. Due to prestressing effect on jacketed beams the tensile strength can be taken a higher value as

$$f_{tp} = f_{tc}\sqrt{(1+\frac{\sigma}{f_{tc}})} \quad \text{Given by Hsu [6]} \tag{1}$$

f_{tp}=tensile strength of concrete due prestressing stress σ
f_{tc}=tensile strength of high strength concrete

The prestressing stress (σ) can be taken as stress induced in shorter side (f_{tc}) due to torsion.

$$\text{Taking } f_{tc} = 0.44\sqrt{f_{ck}} \text{ as per [7]} \tag{2}$$

f_{ck}=cube strength of concrete (150mm cube)

$$f_{tp} = 0.44\sqrt{2}f_{ck} \text{ for full wrap} \tag{3}$$

$$f_{ck} = 0.91 * F_{ck} + 3.92 \text{ from [8]} \tag{4}$$

F_{ck} = compressive strength of concrete (100mm cube)

For "U" wraps the prestressing effect is half the full wrap **[5]**. Thus, f_{tp} for U wrap

$$f_{tp} = 0.44\sqrt{1.5}f_{ck} \tag{5}$$

The elastic torque T_e of a skinned plain concrete member can be expressed as

$$T_e = \alpha X^2 Y f_{tm} \text{ if } f_{tpe} \le f_{tp} \tag{6}$$

$$T_e = T_{cr} = T_{ult} = \alpha_2 XY^2 f_{tp} \text{ If } f_{tpe} > f_{tp} \tag{7}$$

X and Y shorter and larger dimensions of skinned sections

f_{tm}=tensile strength of mortar

f_{tpe} = shear stress of concrete face when stress on longer ferrocement face f_{tm}

$$f_{tpe} = \frac{\alpha X}{\alpha_2 Y} f_{tm} \tag{8}$$

α, α_2 are St. Venant's constants depend on aspect ratio.

$$f_{tm} = 0.678(f_{cm})^{0.5} \text{ as given in [9]} \tag{9}$$

f_{cm}=compressive strength of mortar 100 mm cube

The elastic twist (θ_e) during this elastic regime can be evaluated from the Saint Venant's elastic equations modifying the rigidity modulus (effective rigidity modulus).

$$\theta_e = \frac{T_e}{\beta X^3 YG} \tag{10}$$

β is St.Venant's constants.

$$G = \frac{G_m G_c}{G_m V_c + G_c V_m} \text{ (Law of mixtures)} \tag{11}$$

G= Equivalent shear modulus of composite section

G_c ,G_f,G_m are shear modulus of concrete,ferrocement and mortar respectively.

V_c=Volume of concrete

V_m=Volume of Mortar=Volume of ferrocement

$$G_c = \frac{E_c}{2(1+\nu)} \tag{12}$$

Where ν=0.15 for concrete

$$G_m = \frac{E_m}{2(1+\nu)} \tag{13}$$

$$E_m = 9500(f_c)^{0.3} \text{ As given in [8]} \tag{14}$$

f_c= Compressive strength of mortar in (150 × 300) mm cylinder

$$f_c = 0.8(0.9)f_{cm} \tag{15}$$

The twist (θ) within the elastic regime corresponding to a Torque(T) can be evaluated

$$\theta = \frac{T}{\beta X^3 yG} \tag{16}$$

2.2 Cracking stage

Cracking of a jacketed beam takes place when the shear stress induced due to torsion crosses the tensile strength of concrete f_{tp} (top face of the beam) or ferrocement jacketing (f_{tf}) (on any one of the three sides). If the unwrapped potion of the beams cracks before the jacketing, no post cracking stage exists for the beam. The failure of the beam is catastrophic. If (τ_l) is the shear stress induced in longer face when f_{tp} is the stress in shorter face and τ_l can be estimated as

$$\tau_l = \frac{\alpha_2 Y f_{tp}}{\alpha X} \tag{17}$$

If (τ_l) < (f_{tf}=tensile strength of ferrocement), crack occurs in concrete face and ultimate stress in concrete is the tensile stress of concrete and the stress on ferrocement is as calculated above.

If (τ_l) > (f_{tf}=tensile strength of ferrocement), first the crack takes place on ferrocement face and finally the ultimate failure is by cracking of the unwrapped portion.

$$f_{tf} = f_{tm}(1 - V_f) + V_f m f_{tm} \tag{18}$$

m=modular ratio ferrocement to mortar=Ef/Em

V_f=Volume fraction of ferrocement reinforcement

Applying Bredt's thin tube theory of variable thickness the cracking torque can be evaluated .The thickness of tube on longer side (t_f) at the time of cracking can be taken as 0.75(A/P) and same thickness can be assumed on all sides of ferrocement "U" wrap face and thickness of top concrete face (t_c) can be evaluated from principle of equal shear flow through out the periphery.

$$q = \tau_l t_f = f_{tp} t_c \tag{19}$$

The cracking torque T_{cr} is evaluated from [6]

$$T_{cr} = 2A_0 q = 2(X - t_c)(Y - \frac{t_c}{2} - \frac{t_f}{2})q \tag{20}$$

A_0=Area of shear flow=bh

$$b = X - t_f,\ h = Y - t_c/2 - t_f/2 \tag{21}$$

The twist angle can be calculated at cracking (θ_{cr})

$$\theta_{cr} = \frac{T_{cr}}{4A_0^2}\left(\frac{2h+b}{G_f t_f} + \frac{b}{G_c t_c}\right) \ [6] \tag{22}$$

Where $G_f = \frac{E_f}{2(1+\nu)}$

$$E_f = E_m(1 - V_r) + E_s V_r \text{ From law of mixture} \tag{23}$$

ν=0.15 upto cracking of ferrocement $\tau_l * f_{tf}$, ν=0.25 [10] after cracking of ferrocement $\tau_l > f_{tf.}$
V_r= effective volume fraction of mesh reinforcement in crack direction=0.35* V_f

2.3 Microcracking stage

The micro cracking stage is the zone between post elastic stages to pre cracking stage. The angle of twist in between elastic torque and cracking torque (micro cracking regime) can be calculated using linear interpolation

$$\theta = \frac{T}{\left(\frac{T_{cr}}{\theta_{cr}}\right)} \tag{24}$$

3. Experimental Program

3.1 Test beams

Seven beams were cast for validation of the proposed theoretical model .The size of five beams are (125×250) mm and other two are of size (125×190) mm and (125×315) mm. The lengths of the beams were kept 2000mm long with a view to allow two spirals for observation of crack pattern which requires a length of 1500mm for beam size (125×250) mm and the end zones of 250mm were kept for fixing lever arms. The ends were reinforced heavily to force the failure to the central zone. 25 mm thick ferrocement shell was prepared on outer perimeter without wrapping on top face. The central concrete core of size (75×225) was taken for beams of dimension (125×250), (75×165) mm for beam size (125×190) mm and (75×290) mm for beam of size (125×315) to fill up with different grades of concrete.

Table 1. Tested beam details

Designation of the beam	Aspect ratio	Concrete compressive strength (MPa)	Number of layers in the jacketing	Section dimensions	
				Breadth (mm)	Depth (mm)
AO4H	1.5	60	4	125	190
BO4H	2.0	60	4	125	250
CO4H	2.5	60	4	125	315
$BO4H_1$	2.0	70	4	125	250
$BO4H_2$	2.0	55	4	125	250
BO3H	2.0	60	3	125	250
BO5H	2.0	60	5	125	250

3.2 Ferrocement material properties

The beams are wrapped with different numbers of layers of galvanized square grid wire mesh. The diameter of wire 0.72mm, spacing of grid 6.35mm with yield stress of 250 MPa and modulus of elasticity of 180 GPa. The required strips were taken from a roll of width 1200 mm. The compressive strength of mortar was 55 MPa with flow value more than 80 with proportion 1:1:0.30 (30ml of SP-337 per kg of binder with 10% addition of silica fume) for all beams.

3.3 Specimen preparation

Three moulds of size (125×190)mm, (125×250)mm and (125×315)mm were prepared for casting of seven beams. The U shape mesh layers were put in mould. Mortar was filled upto 25mm in bottom and then a closed hollow box of core concrete size was put as shown in Figure 2. Mortar was poured from top to fill up outside the closed box section in bottom and side face with continuous vibration through a needle vibrator to allow mortar to insert through mesh layers properly. After the initial setting time hollow box section was taken outside and the ends were provided with reinforcement cage and concrete was filled up in the core. After 24 hours the mould was removed and the specimen was put in curing tank. The casting of ferrocement shell was shown in Figure 3 and Figure 4.

Figure 2. Placement of wire mesh with solid mould for pouring mortar.

Figure 3. Mortar is filled through wire mesh leaving the core portion

Figure 4. Ferrocement shell in the mould ready for casting of core concrete

Figure 5. Torsion test rig along with twist meter

3.4 Test setup

The specimens along with companion specimens were kept for curing for 28days. After 28 days of curing the beams along with companion specimens were taken out of curing tank and made dry, properly white washed and marked for fixing the twist meters and loading frames. The jacketed beams were tested in the test rig as shown in Figure 5. Rollers in the lateral direction at the reaction end were provided to allow the beam to slide freely along the longitudinal direction to avoid any axial restraint. The loading end was supported on a circular roller placed to allow the beams to twist under pure torsion. The twist was measured with the help of the twist meter frame. The loading frame was kept perpendicular to longitudinal axis of beam to avoid bending. Neoprene pads were provided between beam sides and loading frame plates to avoid crushing of ferrocement at longer faces at ends. The load was applied gradually through the load cell. The companion specimens related to the beams were tested on the same day.

4. Discussion on Test Results

The first crack for plain concrete beams jacketed with ferrocement "U" wraps appeared on the unwrapped concrete face. The beams failed with single potential crack on the top of concrete face shown in Figure 6 and similar observations are reported by earlier researchers also **[11]**. However first crack appeared on wrapped longer faces for beams $BO4H_1$,CO4H and on further loading few more small segmental cracks were noticed. The ultimate failure was found to be due to the formation of single crack on unwrapped face with inclination of approximately 45º to the longitudinal axis. De-bonding was noticed at the interface of concrete and ferrocement at failure.

Figure 6. Crack pattern on beam BO_4H

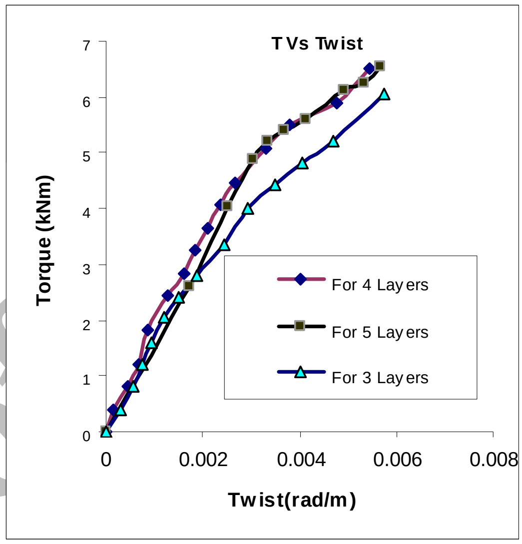

Figure 7. Torque twist response for different layers

4.1 Effect of number of layers

The torque twist response of tested beams having different layers of wire mesh in the jacketing portion, keeping all other parameters same were presented in Figure 7. The beam jacketed with ferrocement having three layers of wire mesh, showed cracking on top as well as on longer faces of the beam. The reason for this can be attributed to the fact that the shear stress at the top face (where concrete is present) and the shearing stress on the longer face (where ferrocement wrapping is present) reached their capacities simultaneously. Even the analytical model also predicted the same behavior. In the torque twist response of these three beams, deviation was noticed only in the post elastic regime due to participation of wire mesh. As grade of mortar and concrete is same for all three beams there is no change in torque twist response due to same torsional rigidity upto elastic torque. The twist decreased with increases of number of layers beyond the elastic torque. There is no improvement in the ultimate torque of beams wrapped with ferrocement having five layers compared to four layers. The reason for this behavior is due to the fact that the increase in the strength of skinning no way improves the over all strength as one of the face of the beam was not wrapped. Thus it can be concluded that the wrapping on the three sides can improve the strength of the beam to a limited extent only. If the grade of core concrete, mortar strength of ferrocement and the aspect ratio of the cross section are same then the increase in the number of layers beyond certain limit may not enhance the torque carrying capacity of skinned beams. Increased number of layers may be more effective for higher aspect ratio, high strength core concrete and for reinforced concrete sections in the post cracking stage, as the difference of the shearing stresses on the longer face and the un-skinned face depend greatly on these quantities. The ratios of predicted to experimental torque for BO3H, BO4H and BO5H are 1.073, 1.00 and 0.9957 respectively. This indicates that the proposed analytical model fairly estimates the torsional capacity of the jacketed beam.

4.2 Effect of aspect ratio on cracking torque and twist

The beams AO_4H, BO_4H and CO_4H were cast to study the effect of aspect ratio on torque and twist, keeping all other parameters same. The cracking, ultimate torque and corresponding twist were reported in Table 2. The torque twist response is shown in Figure 8. In the lower aspect ratios, the crack appeared on the center of the unwrapped portion with an angle approximately 45º. At lower aspect ratios, the wrapping has become ineffective as the unwrapped portion of the beam initiates the failure. With increase in aspect ratio the cracks appeared on longer jacketed ferrocement face. From the above observations it can be concluded that jacketing would be more beneficial for higher aspect ratios of the beams as noticed on beam CO_4H. The increase in torsional strength depends upon tensile stress of skinned material, tensile strength of core material and number of layers. The ratios of ultimate torque predicted from the proposed analytical model to experimental are found to be 1.01, 1.00 and 1.01 for beams AO_4H, BO_4H and CO_4H respectively. The ultimate twist is found to be dependent on the formation of potential crack on wrapped face or unwrapped face.

Table 2. Experimental and analytical results

Beam Designation (→)	**AO_4H**	**BO_4H**	**CO_4H**	**BO_4H_1**	**BO_4H_2**	**BO_3H**	**BO_5H**
Torque (Exp)(kNm)	4.188	6.500	8.680	6.947	6.180	6.057	6.538
Theta (Exp)(rad/m)	0.0062	0.00546	0.00588	0.006241	0.0058	0.00575	0.00567
Torque if only concrete Beam (kNm)	3.300	4.340	5.434	4.560	4.230	4.340	4.340
Increase in Torque % with Respect to concrete Beam	26.91	49.77	59.72	52.34	46.10	39.56	50.65
Theta if only concrete beam (rad/m)	0.003942	0.003468	0.00307	0.003468	0.003468	0.003468	0.00347
Increase in Theta with respect to Concrete beam	57.281	57.439	91.531	79.960	67.243	65.802	63.495
Torque (Analytical) (kNm)	4.23	6.5151	8.751	6.843	6.245	6.5	6.51
Torque Ratio (Analytical/Exp)	1.01	1.00	1.01	0.985	1.01	1.073	0.995
Theta (Analytical)(radian per mt)	0.005700	0.005600	0.005938	0.006200	0.005470	0.005722	0.005680
Theta (Analytical/Exp)	0.919	1.026	1.010	0.993	0.943	0.995	1.002

4.3 Effect of concrete strength

The beams BO_4H_2, BO_4H and BO_4H_1 were cast to study the effect of core concrete strength on torque and twist keeping all other parameters same. The torque twist response for the different grades of concrete is shown in Figure 9. The increase in concrete strength increases the ultimate torque provided the stress in the longer face is less than the tensile strength of jacketed material while there is no change in the elastic torque. As seen in beam $BO4H_1$ the maximum shear stress in the ferrocement face at the time of cracking of concrete is more than the tensile strength of ferrocement, hence the first crack was observed in the longer face. The maximum shearing stresses are induced in middle of longer faces due to torsion and increases with increase of aspect ratio. Hence there is a need for high strength materials on longer faces for higher aspect ratio. There is a large difference in torsional strength between M55 and M70 grade concrete. The strength of M70 grade was not in its optimum use due to early cracking of jacketed material. The increase in torsional strength over the plain concrete beams (unwrapped) for $BO4H_2$, BO4H and $BO4H_1$ are 46.10%, 49.77% and 52.34% respectively.

The ratios of predicted to experimental ultimate twist for above beams are found 0.943, 1.02 and 0.993 The ratio of predicted to experimental ultimate torque are 1.01, 1.00 and 0.99 respectively, which indicates the experimental results are in good agreement with analytical results.

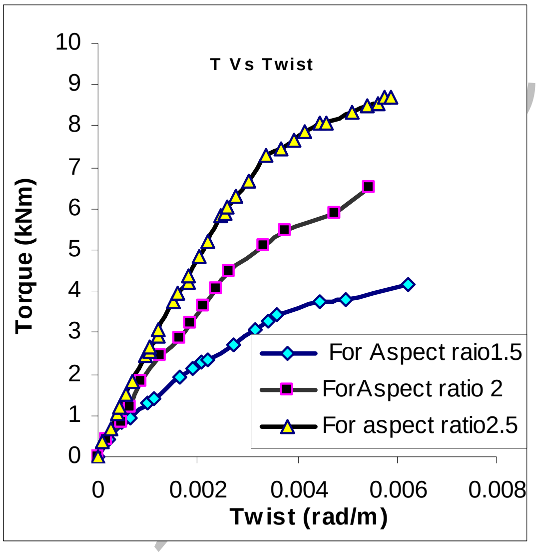

Figure 8. Torque twist response for different aspect ratio

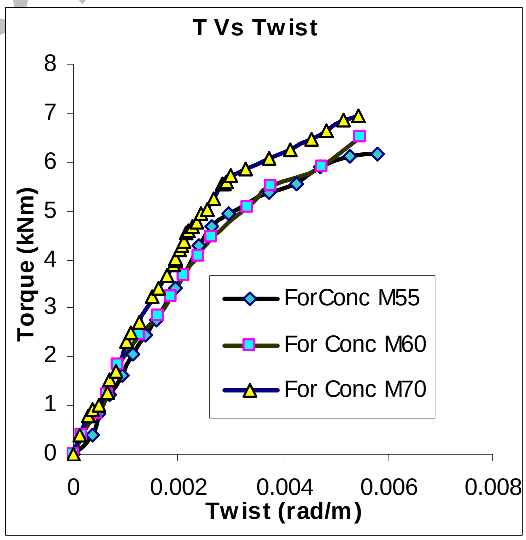

Figure 9. Torque twist response for different grade of concrete

5. Summary and Conclusions

From the analytical model developed and experiments conducted in this investigation, the following conclusions were drawn.

1. The elastic torque is independent of number of mesh layers in ferrocement.
2. The torsional strength of jacketed beam increases with increase of aspect ratio provided the failure is governed by the shear stress developed on the wrapped face.
3. Increase in core concrete strength increases the cracking torque due to increase in the tensile strength. The ultimate torsional capacity is again not only dependent on this tensile strength, but depends on the stress induced on the longer face. The ultimate capacity of a "U" wrapped plain concrete beam is governed by strength of core concrete, strength of jacketed material and aspect ratio.
4. The torque and twist of "U" wrap beam increases by 59.72% and 91.53% respectively compared to an unwrapped concrete beam.

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