International Journal of Advanced Research in Engineering and Technology (IJARET)
Volume 11, Issue 3, March 2020, pp. 29-47, Article ID: IJARET_11_03_004
Available online at http://www.iaeme.com/IJARET/issues.asp?JType=IJARET&VType=11&IType=3
Journal Impact Factor (2020): 10.9475 (Calculated by GISI) www.jifactor.com
ISSN Print: 0976-6480 and ISSN Online: 0976-6499

THEORETICAL AND EXPERIMENTAL ON THE BEHAVIOUR OF RECTANGULAR CONCRETE BEAMS REINFORCED INTERNALLY WITH HFRP REINFORCEMENTS UNDER PURE TORSION

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ABSTRACT

Theoretical and Experimental analysis of rectangular concrete beams reinforced internally with Hybrid Fibre Reinforced Polymer (HFRP) reinforcements under pure torsion is carried out in this study. Different parameters like grade of concrete, beam longitudinal reinforcement ratio and transverse stirrups spicing are considered. The basic strength properties of concrete, steel and HFRP reinforcements are determined experimentally. Experimental torque verses twist relationship is established for various values of torque and twist using elastic, plastic theories of torsion. Finally the ultimate torque is determined using experimentaly for different parameters considered in this study. Based on this study, a good agreement is made between theoretical analysis and the experimental behaviour.

Keywords: Pure Torsion; Beam; HFRP Reinforcements; Steel; Experimental Model

Cite this Article: P. Kapildev and G. Kumaran, Theoretical and Experimental on the Behaviour of Rectangular Concrete Beams Reinforced Internally with HFRP Reinforcements Under Pure Torsion, *International Journal of Advanced Research in Engineering and Technology (IJARET),* 11 (3), 2020, pp 29-47.
http://www.iaeme.com/IJARET/issues.asp?JType=IJARET&VType=11&IType=3

1. INTRODUCTION

In this new era, the search of a new material in the construction is a main concern. This is due to the drawbacks in steel reinforcements such as corrosion and high energy wastage. The drawbacks of steel reinforcement can be overcome by using Fibre Reinforced Polymer materials. Since FRP materials occupies an important part in the modern materials. Though FRP materials plays a significant role in construction, its awareness is very less in India compared to developed countries. So there are no recommendations of Indian Standards for FRP materials but the recommendations for FRP are issued in ACI codes. It is not popular in India because of the less awareness to the manufactures and clients. This creates a lag in the commercial success of this material. Based on its performance in the aspects of strength and durability in worst environmental conditions, it has advantages over conventional reinforcement materials. FRP resources are commercially accessible in the form of cables, sheets, plates etc. The availability of FRP materials are possible in the form of reinforced bars in recent days. It is produced by a process called pultrusion for replacing conventional steel reinforcement in concrete members internally. Several imperfections in the surface of FRP bars are made to improve the bonding of FRP bars with concrete. In the modern world, constructions of concrete structures are mainly influenced by Fibre reinforcements. The utilization of FRP reinforcements are in concrete members is significantly increasing throughout the world today. Researches in India are also started to concentrate in FRP bars as replacement for conventional reinforcements for concrete members. The application of FRP reinforcements are mainly adopted in the construction of roof decks in industries, equipment in reactors, floor slabs, electrical base pads and seawalls in worst environmental conditions. Hence the FRP bars are recommended by the structural designers. It is also effective in durable properties of concrete members. Most of the researches, all around the world are focused in the implications of FRP bars in structural components of concrete members such as beams and slabs (Nawy *et al.,* 1997; Faza and GangaRao, 1992; Benmokrane, 1995; Sivagamasundari *et al*., 2008; Deiveegan *et al*., 2010; Saravanan *et al*., 2011). The performance of the HFRP concrete beams under pure torsion are studies in the current research. The hybrid bars are reinforced internally in the HFRP concrete beams. Based on the availability of FRP materials in India, the scope of this research is limited with HFRP reinforcements. This study is mainly divided into two sections such as the theoretical analysis and analytical analysis of HFRP and steel reinforced concrete beams subjected to pure torsion. Space truss formulation application for traditional reinforced beams was used for HFRB concrete beams. Finite element method was adopted for the analytical analysis of HFRP and steel reinforced concrete beams. Finite element analysis is made by using ANSYS software with various parameters (Sivagamasundari *et al*., 2008; Deiveegan *et al*., 2010; Saravanan *et al*., 2011). The analysis results are validated with the existing theories for beams.

2. MATERIALS

2.1. Concrete

Normal Strength Concrete (NSC) of grades M30 and M60 are used in this study. Ordinary Portland cement is used to prepare the concrete. The maximum size of aggregate used is 20 mm and the size of fine aggregate as M-sand ranges between 0 and 4.75 mm. After casting, the specimens are allowed to cure in real environmental conditions for about 28 days so as to attain strength. The test specimens are generally tested after a curing period of 28 days. The strength of concrete under uni-axial compression is determined by loading ‘standard test cubes’ (150 mm size) to failure in a compression testing machine, as per IS 516 - 1959. The modulus of elasticity of concrete is determined by loading ‘standard cylinders’ (150 mm diameter and 200 mm long) to failure in a compression testing machine, as per IS 516: 1959. The mix proportions of the NSC are carried out as per Indian Standards (IS) 10262-1982 and the average compressive strengths are obtained from laboratory tests (Sivagamasundari *et al*., 2008; Deiveegan *et al*., 2010; Saravanan *et al*., 2011) and are depicted in Table 1(a).

Table 1 Properties of Concrete

Material/m^3	**M30 grade of concrete**	**Ratio**	**M60 grade of concrete**	**Ratio**
Cement	368.42kg	1:1.87:3.50	466.67 kg	1:1.36:2.70
Fine aggregate	690.04 kg		629.16 kg	
Coarse aggregate	1290.988 kg		1263.55 kg	
Water/cement ratio	0.38		0.30	
Average compressive strength of concrete cubes	42.00 MPa		76.00 MPa	

2.2. Reinforcements

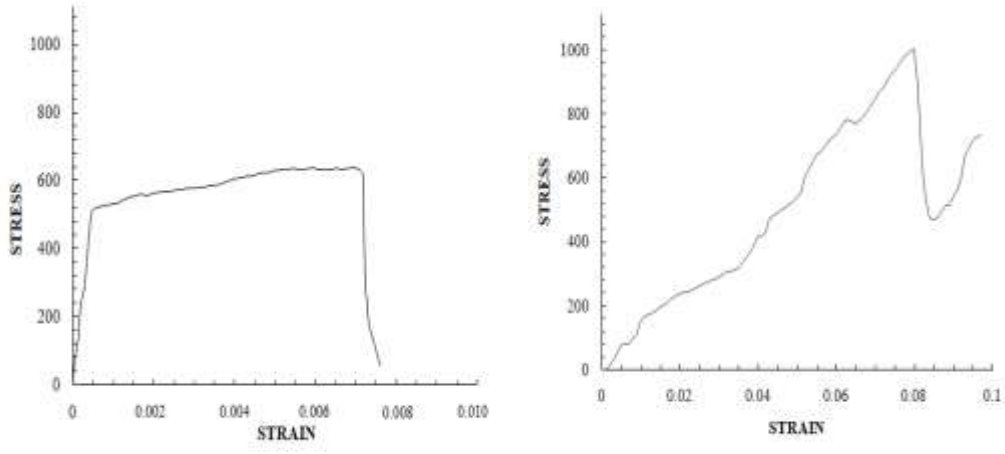
The mechanical properties of all the types of HFRP reinforcements as per ASTM-D 3916-84 Standards and steel specimens as per Indian standards are obtained from laboratory tests and the results are tabulated in Table 1(b). The tensile strength of steel reinforcements (*S*) used in this study, conforming to Indian standards and having an average value of the yield strength of steel is considered for this study. HFRP reinforcements used in this study are manufactured by pultrusion process with the E-glass fibre volume approximately 60% and these fibres are reinforced with epoxy resins. Previous studies were carried out with three different types of GFRP reinforcements (grooved, sand sprinkled & threaded) (ACI 440R-96; Muthuramu , *et al*., 2005; Sivagamasundari *et al*., 2008; Deiveegan *et al*., 2010; Saravanan *et al*., 2011) with different surface indentations and are designated as F_g, F_s *and* F_t. In this study threaded type HFRP reinforcement is used in place of conventional steel. The diameters of the longitudinal and transverse reinforcements are 10 mm and 8 mm respectively. The standard minimum diameters of the reinforcements as per Indian standards are adopted in this study. The tensile strength properties are ascertained as per ACI standards shown in Table1(b) and are validated by conducting the tensile tests at SERC, Chennai. The compressive modulus of elasticity of GFRP reinforcing bars is smaller than its tensile modulus of elasticity (ACI 440R-96; Lawrence C Bank 2006; Sivagamasundari *et al*., 2008). It varies between 36- 47 GPa which is approximately 70% of the tensile modulus for GFRP reinforcements. Under compression GFRP reinforcements have shown a premature failures resulting from end brooming and internal fibre micro-buckling. In this study, GFRP stirrups are manufactured by Vacuum Assisted Resin Transfer Moulding process, using glass fibres reinforced with epoxy resin (ACI 440R-96; Sivagamasundari *et al*., 2008; Deiveegan *et al*., 2010; Saravanan *et al*., 2011). Based on the experimental study, it is observed that the strength of GFRP stirrups at the bend location (bend strength) is as low as 50 % of the strength parallel to the fibres. However, the stirrup strength in straight portion is comparable to the yield strength of conventional steel stirrups. Therefore, in this study, HFRP stirrups strength is taken as 30% of its tensile strength i.e 150 MPa.

Table 2 Properties of reinforcements

Properties	Sand coated Hybrid FRP rod (H_f)	Steel Fe 500 rod (*Fe*)
Tensile strength (MPa)	1052.04	520
Longitudinal Elastic modulus (GPa)	64.70	210
Strain	0.012	0.002
Poisson's ratio	0.236	0.3

Figure 1 HFRP reinforcements with end anchorages for tensile tests

Figure 2 Failure of HFRP reinforcements tensile test



Stress-Strain Curve of Fe 500 steel   Sand coated Hybrid FRP Reinforcements (H_f)

Figure 3 Stress-Strain curve for all the reinforcements involved in the present study

3. THEORETICAL IDEALISATION OF TORQUE –TWIST (*T–θ)* CURVE

3.1. Theoretical Investigation

Theoretical torque verses twist relationship is established for various values of torque and twist using elastic, plastic theories of torsion and also the ultimate torque is determined using space truss analogy (Hsu 1968; MacGregor *et al.*, 1995; Rasmussen *et al*., 1995; Ashar *et al*., 1996; Khaldown *et al*., 1996; Liang et al., 2000; Trahait 2005; Luis *et al*., 2008; Chyuan 2010).

The theoretical investigation consists different rectangular beams and are designated are as follows; $Bp_1m_1S_1Fe$; $Bp_1m_1S_1H_f$; $Bp_1m_2S_1Fe$; $Bp_1m_2S_1H_f$; $Bp_2m_1S_1Fe$; $Bp_2m_1S_1H_f$; $Bp_2m_2S_1Fe$; $Bp_2m_2S_1H_f$; $Bp_1m_1S_2Fe$; $Bp_1m_1S_2H_f$;$Bp_1m_2S_2Fe$; $Bp_1m_2S_2H_f$; $Bp_2m_1S_2Fe$; $Bp_2m_1S_2H_f$; $Bp_2m_2S_2Fe$; $Bp_2m_2S_2H_f$.

These beams are reinforced internally with threaded type Hybrid Fibre Reinforced Polymer Reinforcements and conventional steel reinforcements with different grades of concrete and steel reinforcement ratio under pure torsion is considered in this study. The entire concrete beam is supported on saddle supports which can allow rotation in the direction of application of torsion.

Table 3 Various Parameters involved

Parameters	Description	Designation
Types of reinforcements	Sand coatedHFRP	H_f
	Conventional	F_e
Concrete grade	f_{cu} average cube strength	m_1&m_2
Beam size	160 x 275 mm	B
Reinforcement ratios	0.56% (2-Y12 mm bars top & Bottom) 0.85% (3-Y12 mm bars top & Bottom)	p_1&p_2
Spacing of stirrups	75 mm and 100 mm	S_1&S_2

3.2. Space Truss Analogy

The objective of the current research is to improvise the theoretical prediction of the performance of HFRP reinforcements bars under torsion. The performance of concrete beams under torsion is modelled through T (Torque) — θ (Twist) curves. The improved theoretical prediction to the actual behaviour is developed from the current theories adopted. The relationship is somewhat linear up to failure, which is sudden and brittle, and occurs immediately after the formation of the first torsional crack. Torsion is initiated in a reinforced concrete beams in different ways throughout the progression of load transfer in a structural arrangements. In the design of reinforced concrete, the terms 'equilibrium torsion' and 'compatibility torsion' are frequently utilised to cite to 2 dissimilar torsion-inducing situations. Typically, *equilibrium torsion* is initiated in beams supporting lateral overhanging protrusion, and is provoked by the eccentricity in the loading. Such torsion is also triggered in beams curved in plan and subjected to gravity loads, and in beams where the transverse loads are eccentric with respect to the *shear centre* of the cross-section (Hsu 1984; Pillai & Menon 2010). The current research is pertained to the utilisation of internal HFRP reinforcements in concrete beams. Already sufficient investigations are conceded for flexural members and it has come in the form of codal standards especially in American Standards (ACI440XR 2007). In order to find out the design of concrete structures reinforced with GFRP reinforcements theoretically, it is desirable to understand fundamental constituent properties and their relations with concrete. Consequently, this section explains the essential properties necessary for theoretical formulations of torque capacity expressions.

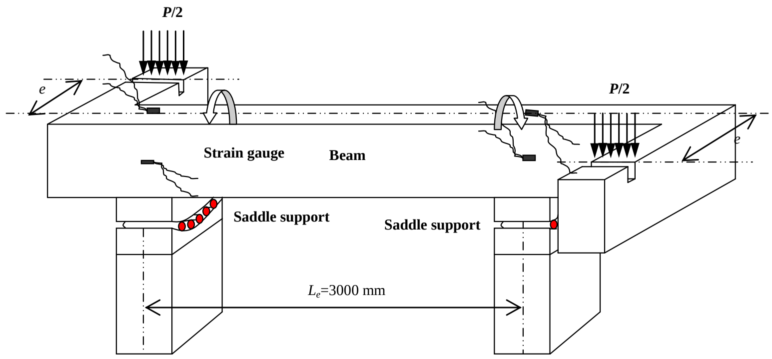


Figure 4 Beam supported on saddle support-Elevation

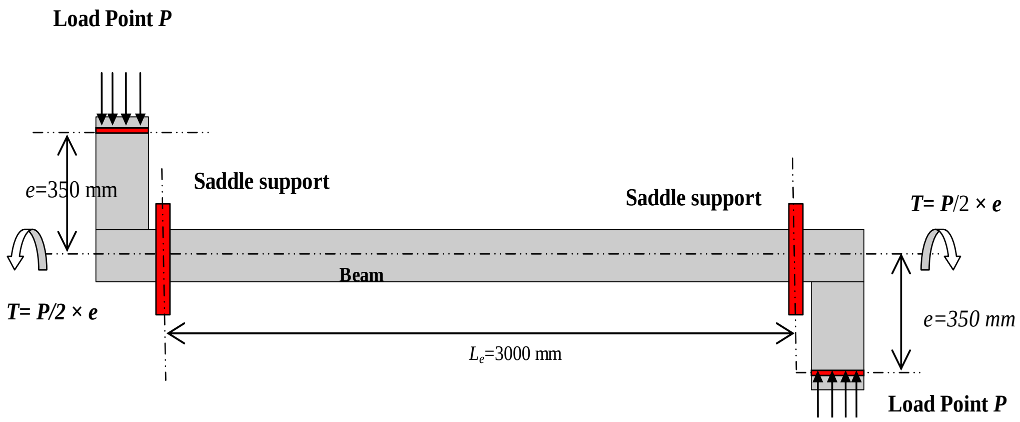


Figure 5 Beam supported on saddle support (plan view)

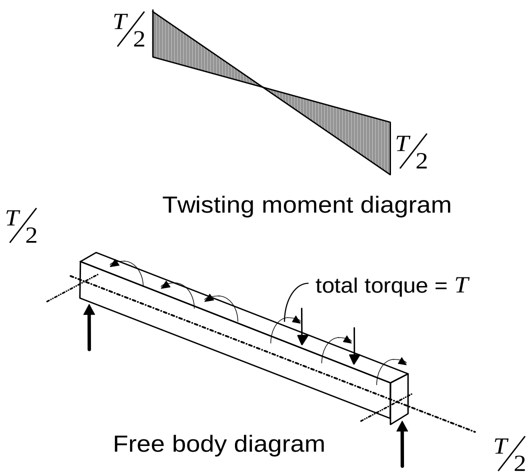


Figure 6 Torsional moment diagram

Fig. 6 shows the torsional moment diagram. The general theoretical torque twist curve T–θcurves are graphed for three stages and are expressed by their (θ;T) coordinates. These coordinates are shown in Fig. 7

Stage 1 constitute the beam's performance prior to cracking. The slope of the curve constitute the elastic St. Venant stiffness $(GC)^{I}$. In this step the curve can be implicit as a straight line with starting point in (0;0) and end in (θ_{el};T_{el}). The theoretical model appraised in this research for this phase depends on Theory of Elasticity.

Subsequent to cracking, the beams endure a impulsive increase of twist after what it resets the linear behaviour. This phase is identified as Stage 2. It starts at (θ_{cr};T_{cr}) and finished at a definite point of twist (θ_{cr}). The slope of stage-2 constitutes the torsional stiffness in cracked stage $(GC)^{II}$. The model observed for stage-2 is based on the space truss analogy with 45° inclined concrete struts and linear behaviour for the materials.

The points of the T–θ curve from which the nonlinear behaviour is expressed by through two dissimilar criterions. The first one corresponds to determine the point for which at least one of the torsion reinforcements (longitudinal or transversal) reaches the yielding point. The second criterion corresponds to determining the point for which the concrete struts starts to behave nonlinearly, due to high levels of loading (this situation may occur before any reinforcement bar yields).

Stage 3 of the curve was plotted by using the Variable Angle Truss-Model, with non linear behaviour of the materials and considering the Softening Effect.

The three stages are identified in the T–θ curve of Fig. 7 are characterized separately.

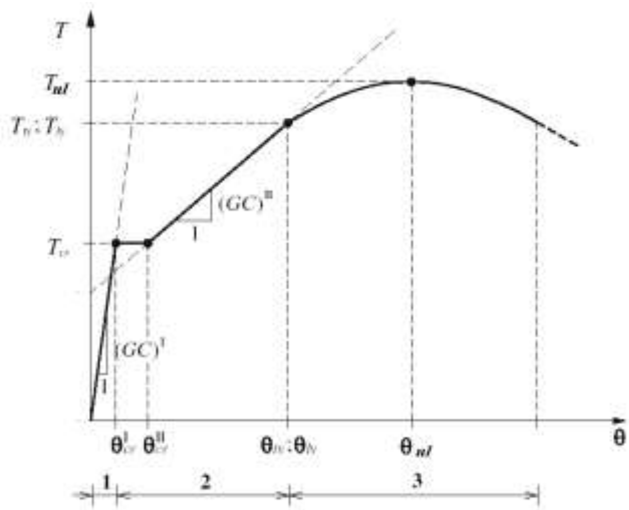


Figure 7 Typical T-θ curve for a reinforced concrete beam under pure torsion

where,

T_{cr} = Cracking torque

θ_{cr} = Twist corresponding to T_{cr} for the stage 1 (limit for linear elastic analysis in non cracked and cracked stage)

T_{ly} = Torque corresponding to yielding of longitudinal reinforcement

θ_{ly} = Twist corresponding to T_{ly}

T_{ty} = Torque corresponding to yielding of transversal reinforcement

θ_{ty} = Twist corresponding to T_{ty}

T_{ul} = Ultimate (maximum) torque

θ_{ul} = Maximum twist at beam's failure.

$(GC)^{I}$ =Torsional stiffness of Zone 1 (for linear elastic analysis in non cracked stage);

$(GC)^{II}$ = Torsional stiffness of Zone 2 (for linear elastic analysis in cracked stage).

3.2.1. Parameters Considered for Analyzing the HFRP /Steel Reinforced Concrete Beams are as follows

B = 160 mm; D = 275 mm; b_1 = 102 mm; d_1 = 217 mm; E_s = 210000 N/mm^2;E_c= $5000\sqrt{f_{ck}}$; E_{HFRP}= 64700 N/mm^2 ;Cube strengths of concrete m_1 = 42.00 MPa; m_2 = 76.00 MPa; m = E_s/E_c; A_l = 113×4= 452mm^2(2 Nos. of top and bottom); A_l = 113×6= 678mm^2(3 Nos. of top and bottom);A_t = 2× 50.3 = 100.6 mm^2; f_y =520 MPa; S_1 = 75 mmS_2 = 100 mm; f_{HFRP-l} =518 MPa ; f_{HFRP-t} =147 MPa.

Table 4 Torque verses twist for various Parameters involved

Beams	T_{el}	θ_{el}	T_{cr1}	θ_{cr1}	T_{eff}	θ_{eff}	T_{yt}	θ_{yt}	T_{ul}	θ_{ul}
$Bp_1m_1F_eS_1$	2.05	0.135	7.35	0.243	8.19	0.541	13.43	5.046	16.27	9.11
$Bp_1m_1H_fS_1$	2.05	0.135	7.35	0.243	8.19	0.541	12.30	14.59	9.91	11.68
$Bp_1m_2F_eS_1$	2.75	0.129	9.89	0.231	11.0	0.515	13.43	5.046	18.27	8.04
$Bp_1m_2H_fS_1$	2.75	0.129	9.89	0.231	11.0	0.515	12.30	14.54	9.91	12.62
$Bp_2m_1F_eS_1$	2.05	0.135	7.35	0.243	8.29	0.547	13.43	3.835	22.93	3.69
$Bp_2m_1H_fS_1$	2.05	0.135	7.35	0.243	8.29	0.547	12.30	10.99	11.26	7.31
$Bp_2m_2F_eS_1$	**2.75**	0.129	9.89	0.231	11.2	0.521	13.43	3.835	32.93	5.60
$Bp_2m_2H_fS_1$	**2.75**	0.129	9.89	0.231	11.2	0.521	12.30	10.94	13.26	7.23
$Bp_1m_1F_eS_2$	2.05	0.135	7.36	0.242	8.04	0.531	10.07	4.088	22.09	9.72
$Bp_1m_1H_fS_2$	2.05	0.135	7.36	0.242	8.04	0.531	9.23	11.85	7.48	13.62
$Bp_1m_2F_eS_2$	**2.75**	0.129	9.89	0.231	11.0	0.505	10.08	4.044	19.10	9.66
$Bp_1m_2H_fS_2$	**2.75**	0.129	9.89	0.231	10.8	0.505	9.23	11.81	8.91	13.52
$Bp_2m_1F_eS_2$	2.05	0.135	7.35	0.243	8.14	0.537	10.07	3.18	24.46	4.45
$Bp_2m_1H_fS_2$	2.05	0.135	7.35	0.243	8.14	0.537	9.23	9.14	14.81	6.67
$Bp_2m_2F_eS_2$	2.75	0.128	9.89	0.231	10.9	0.511	10.07	3.14	27.26	4.17
$Bp_2m_2H_fS_2$	2.75	0.128	9.89	0.231	10.9	0.511	9.23	9.11	18.81	9.60

4. EXPERIMENTAL OBSERVATIONS

4.1. Test Setup

All the test specimens are instrumented to measure their overall twist and axial deformations using dial gauges and LVDTs. The geometry and reinforcement details of test specimens are shown in Figs. 3.17 to 3.18.

Static Loading

Torsion testing frame of capacity 10 tonnes is used for testing the rectangular solid beam specimens. The static monotonically increasing loads are applied at the ends with the help of hydraulic jacks manually (100 kN capacity) and are monitored by pressure gauges. This frame is provided with two plungers along with loading wedges at both the ends in order to induce uniform torque. Torque is induced by applying eccentric loads along the axis of the beam with an eccentricity of 350mm. The deflections or deformations of the beams are measured by dial gauges and Linear Variable Displacement Transducers (LVDT). The schematic diagrams of the torsional beam supported on saddle supports are shown in figs. 8 to 9.

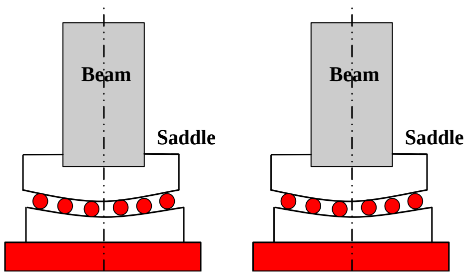


Figure 8 Schematic diagram of saddle support and specimen

Instrumentation

All specimens are pasted with internal and external surface strain gauges. Internal strain gauges are pasted on the surface of the steel/Hybrid FRP reinforcements at the time of casting the specimens with due precaution. External strain gauges are pasted on the surface of the beam specimens near the support at the middle depth (vertically and horizontally) on both ends of the beam. Strains are measured using strain gauges. The twist induced is then calculated on the basis of the measured deformations. The axial extensions are also measured with the help of dial gauges with a least count of 0.01 mm mounted on magnetic base stands at the end of beam specimens at both the ends. A Data acquisition system is used with a sampling rate of 50 samples/s to record all LVDT and electrical strain gauge signals. These electrical signals are converted into strains and are processed with the help of computers. The load is gradually applied with an increment of 1 kN up to the failure of the beams. The experimental set up with instrumentations is shown in fig. 3.20. An arial view of the typical experimental setup with all the instrumentations is shown in fig. 9

Saddle Support

These saddle supports are useful for inducing twisting moments along the beam length with an assumption that both the ends are provided with uniform torque thereby pure torque is applied. The magnitudes of the twisting moments are entirely determinable from statics alone. The entire saddle support unit consists of top plate, rollers and bottom plate. The top and bottom plates are kept in between rollers which can permit rotation along the direction of application of loading.can permit rotation along the direction of application of loading.

a) Top Plate b) Saddle with rollers

Figure 9 Saddle Support

All the test specimens with above said parameters are tested in a torsional testing frame and the corresponding observations are made. The test observations are presented in the form of photographs (Fig. 10 to 13) and graphs in the following sections.

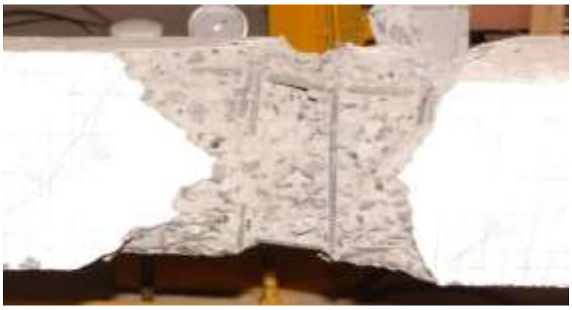
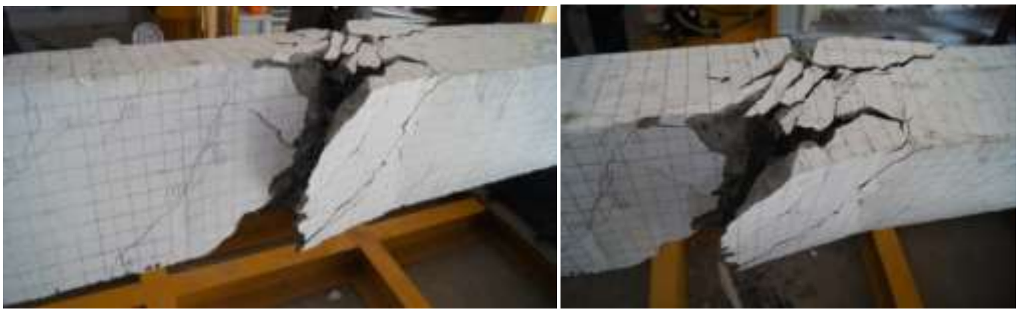


Figure 10 (a, b) Failure of conventional steel reinforced beams due to yielding of longitudinal and transverse steel ($Bp_1m_1F_e$)



(a) (b)

Figure 11 (a, b) Failure of conventional steel reinforced beams due to concrete crushing ($Bp_2m_2F_e$)

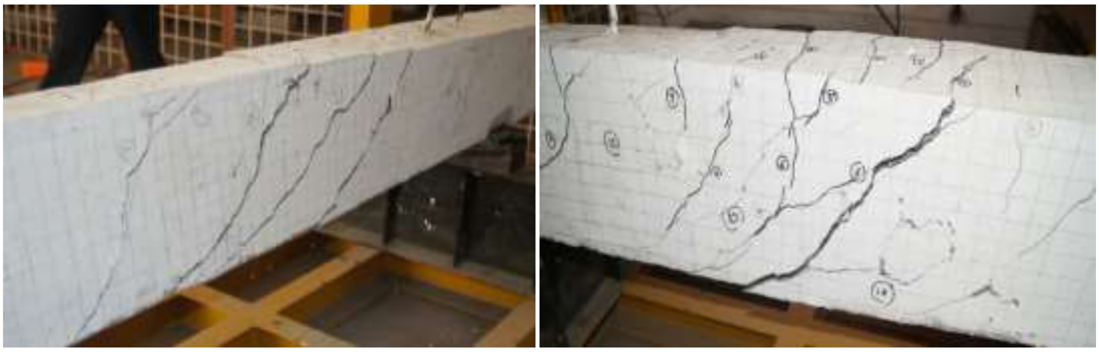


Figure 12 Larger diagonal cracks in Hybrid FRP reinforced beams

Figure 13 Failure of Hybrid FRP reinforced rectangular beam due to excessive spalling of cover followed by concrete crushing ($Bp_1m_1H_f$)

4.2. Torque and Twist Relationships for various Designation of Beam

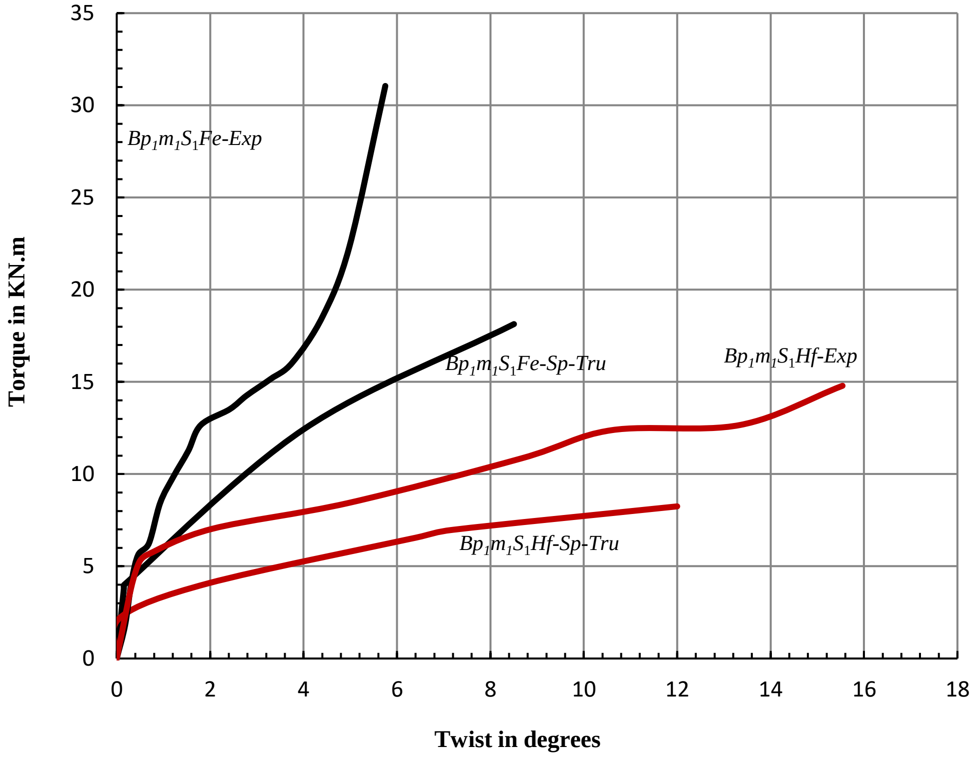


Figure 14 Torque verses twist for $Bp_1m_1F_eS_1$ and $Bp_1m_1H_fS_1$

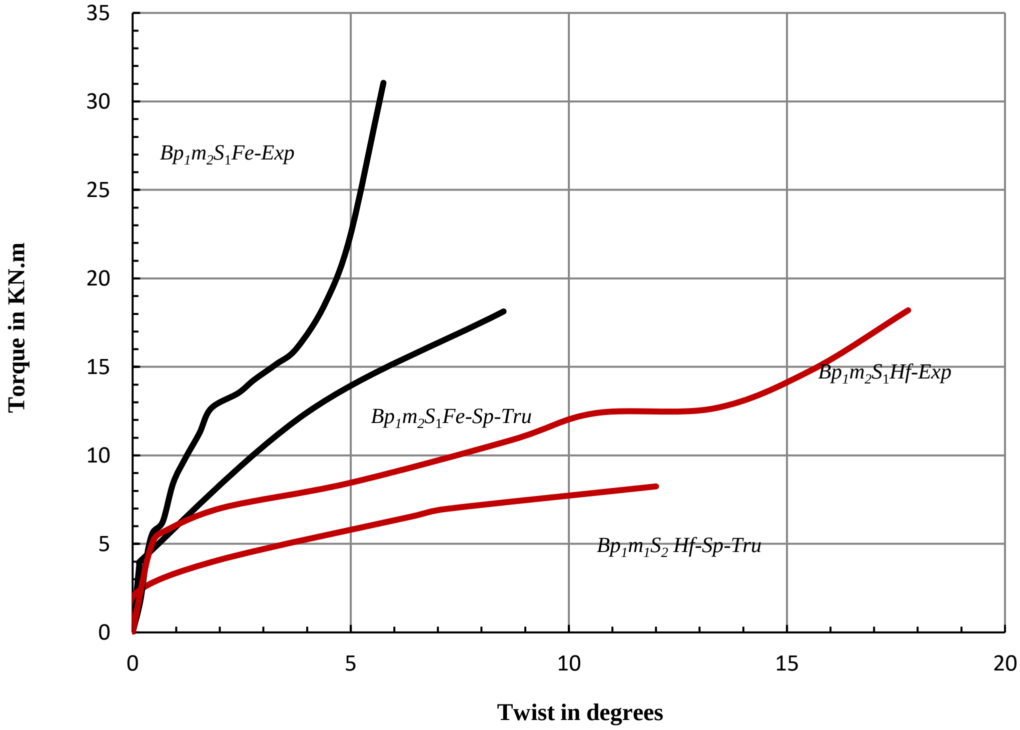


Figure 15 Torque verses twist for $Bp_1m_2F_eS_1$ and $Bp_1m_2H_fS_1$

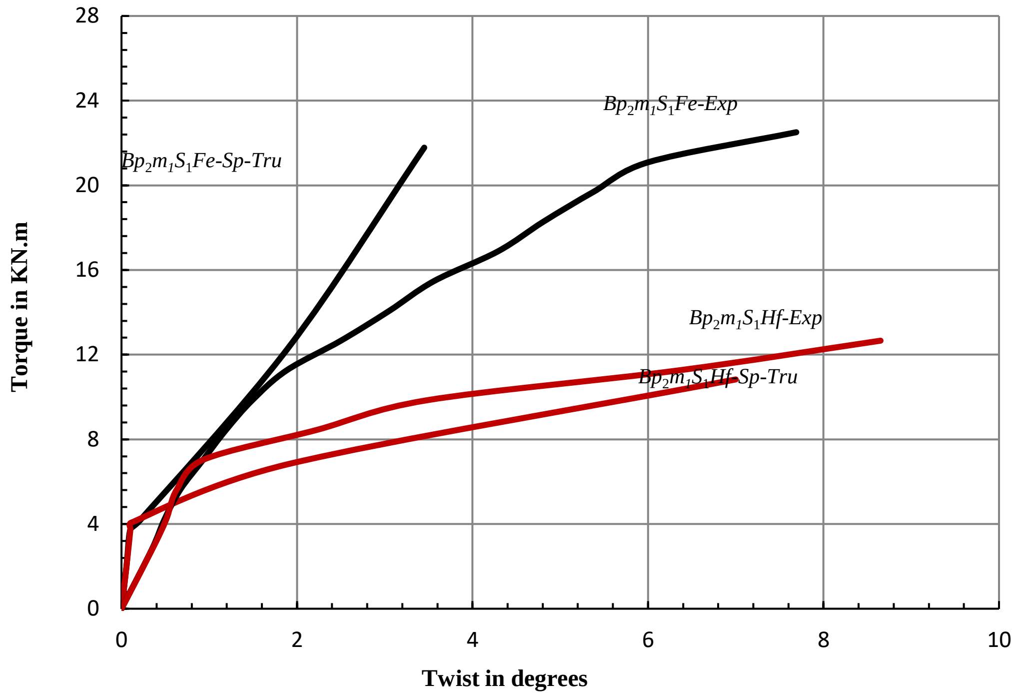


Figure 16 Torque verses twist for $Bp_2m_1F_eS_1$ and $Bp_2m_1H_fS_1$

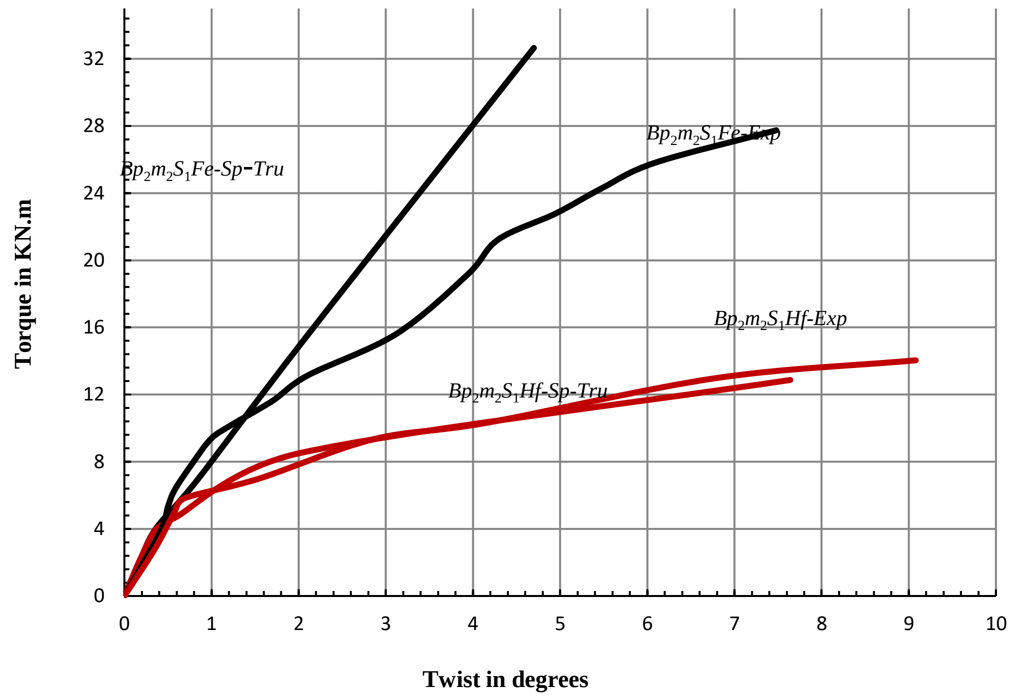


Figure 17 Torque verses twist for $Bp_2m_2F_eS_1$ and $Bp_2m_2H_fS_1$

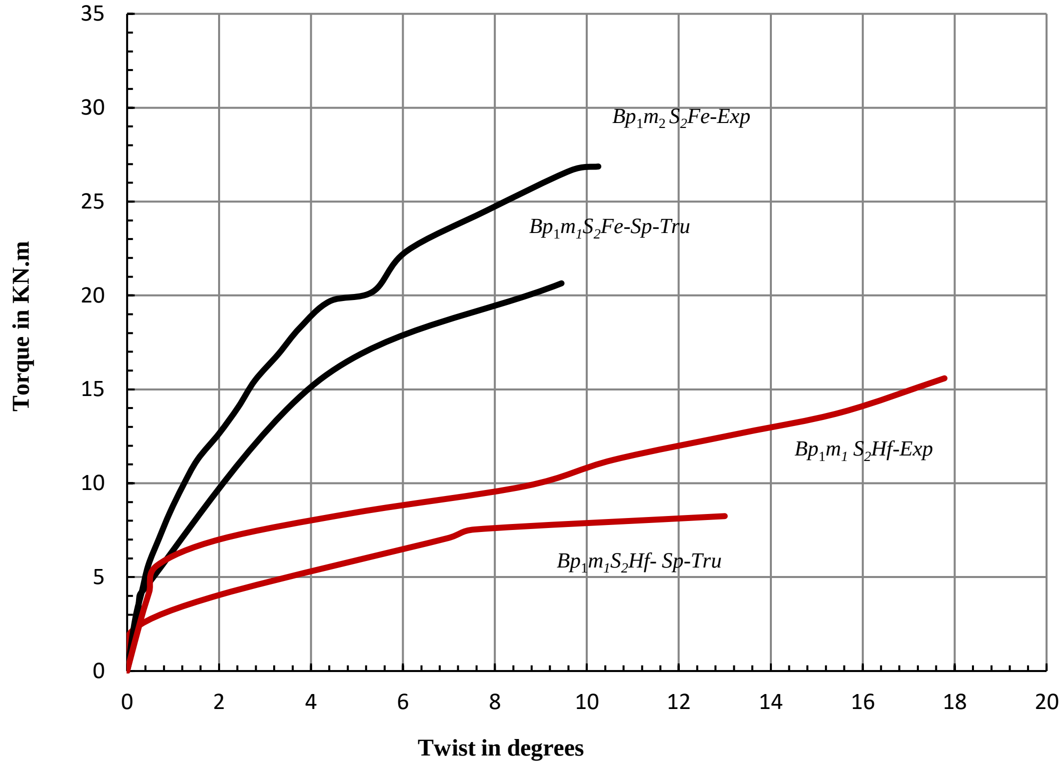


Figure 18 Torque verses twist for $Bp_1m_1F_eS_2$ and $Bp_1m_1H_fS_2$

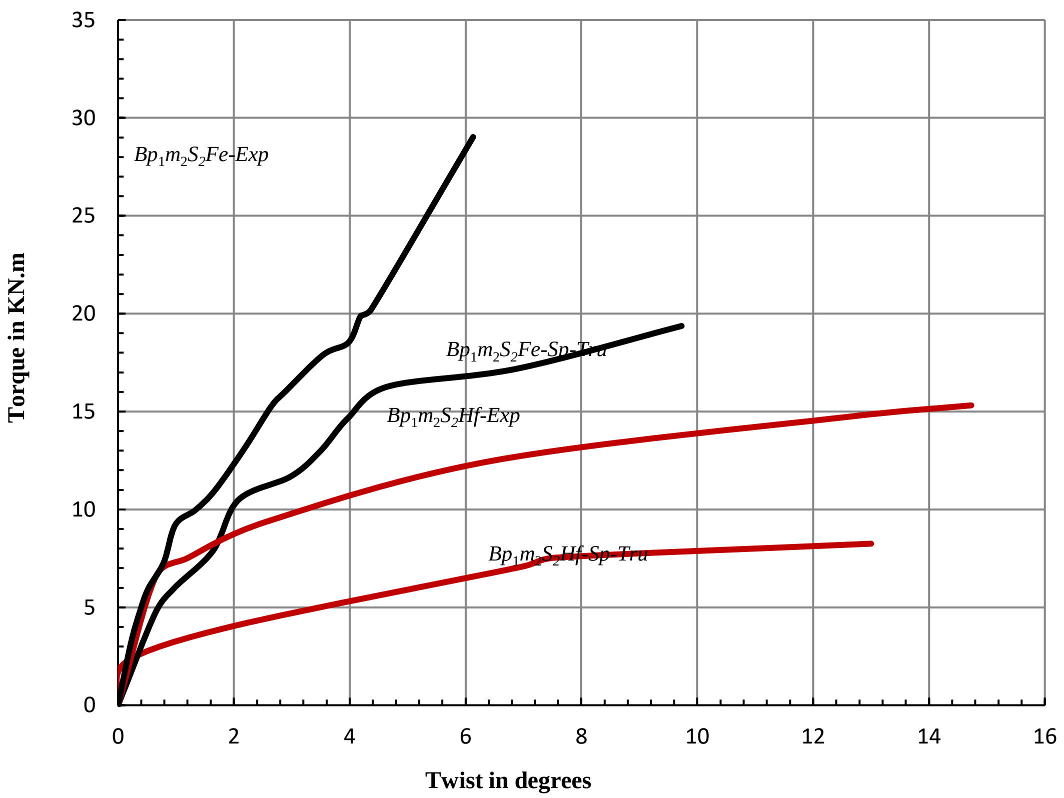


Figure 19 Torque verses Twist for $Bp_1m_2F_eS_2$ and $Bp_1m_2H_fS_2$

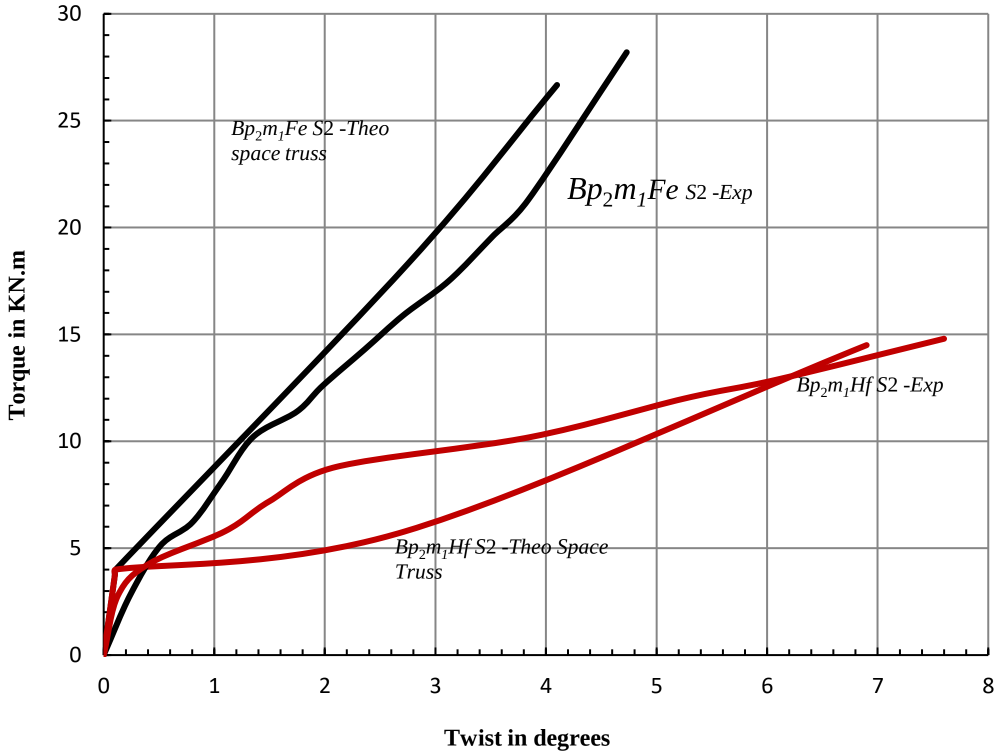


Figure 20 Torque verses twist for $Bp_2m_1F_eS_2$ and $Bp_2m_1H_fS_2$

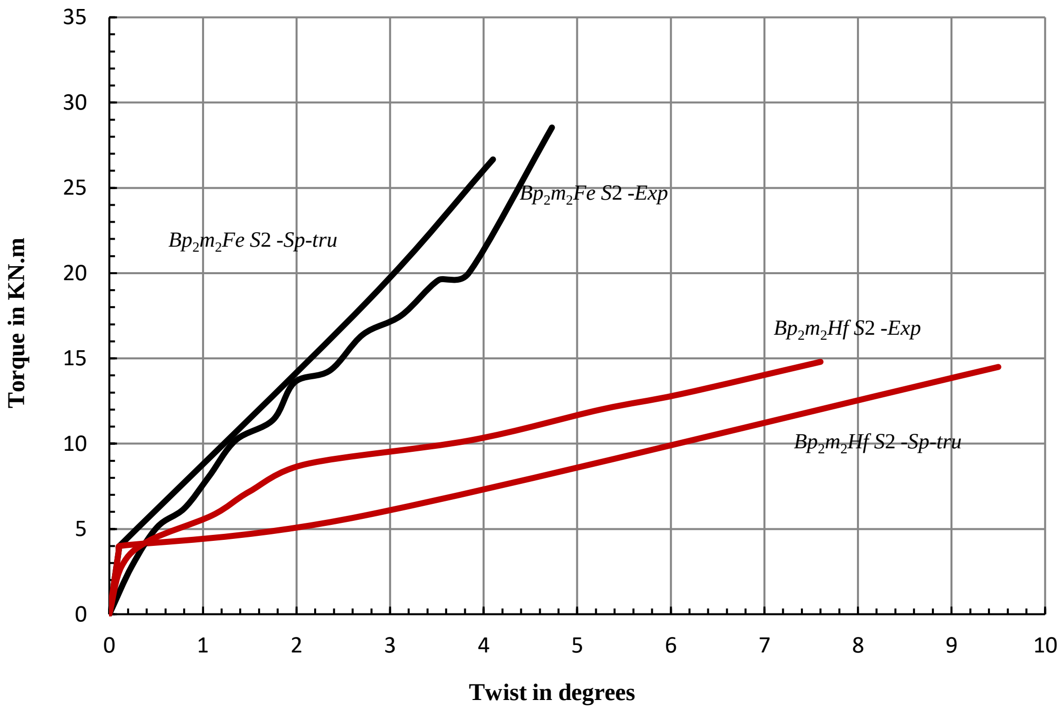


Figure 21 Torque verses twist for $Bp_2m_2F_eS_2$ and $Bp_2m_2H_fS_2$

Table 5 Results obtained from Experimental and Theoretical values

Beam	($T_{cr\text{-}EXP}/T_{cr\text{-}Sp\ Tr}$)	($\theta_{cr\text{-}EXP}/\theta_{cr\text{-}Sp\ Tr}$)	($T_{ul\text{-}EXP}/T_{ul\text{-}Sp\ Tr}$)	($\theta_{ul\text{-}EXP}/\theta_{ul\text{-}Sp\ Tr}$)
$Bp_1m_1\ F_eS_1$	1.08	1.84	1.08	1.79
$Bp_1m_1H_fS_1$	1.08	1.84	1.21	1.38
$Bp_1m_2\ F_e\ S_1$	0.86	1.13	1.08	1.79
$Bp_1m_2H_fS_1$	0.86	1.13	1.13	1.01
$Bp_2m_1\ F_e\ S_1$	1.08	1.84	0.87	1.67
$Bp_2m_1\ H_fS_1$	1.08	1.84	0.92	1.44
$Bp_2m_2\ F_e\ S_1$	0.86	1.13	0.93	1.34
$Bp_2m_2H_fS_1$	0.86	1.13	1.66	1.00
$Bp_1m_1\ F_eS_2$	1.08	1.84	0.87	1.07
$Bp_1m_1H_fS_2$	1.08	1. 84	1.27	0.85
$Bp_1m_2\ F_e\ S_2$	0.86	1.13	0.94	0.68
$Bp_1m_2H_fS_2$	0.86	1.13	1.25	0.50
$Bp_2m_1\ F_e\ S_2$	1.08	1. 84	1.00	1.05
$Bp_2m_1H_fS_2$	1.08	1. 84	1.16	1.40
$Bp_2m_2\ F_e\ S_2$	0.86	1.13	0.97	0.85
$Bp_2m_2H_fS_2$	0.86	1.13	1.06	0.62

5. CONCLUSIONS

The experimental results in the form of torque verses twist diagrams are shown in Fig. 13 to Fig. 20 and the results are compared with the reference beams.

- The torque value of the steel reinforced beams in all the cases are 30 to 45% higher than the Hybrid FRP reinforced beam specimens. The specimens of M 60 grade exhibits lesser value of torque as compared to M 30 grade specimens invariably for all the specimens.
- The twist value of the Hybrid FRP reinforced beams in all the cases are 20 to 50% higher than the conventionally reinforced beam specimens. The specimens of M 60 grade exhibits higher twist value of torque as compared to M 30 grade specimens invariably for all the specimens.
- The specimens having the spacing of stirrups 75mm show identical values of torque and twist value in the ultimate load capacity, both for the steel and Hybrid FRP reinforced concrete beams, inspite of the concrete grade and the reinforcement ratios.
- The increased percentages of (0.86%) reinforcements show better performance in the load carrying capacity, both for the steel and Hybrid FRP reinforced specimens 10% to 15%. The same kind of variation has been noticed for the specimens having the spacing of stirrups 75mm.
- The torque-twist behaviour of concrete beams reinforced with HFRP reinforcements are similar to that of concrete beams reinforced with steel reinforcements until the formation of the first torsional crack. The value of first crack (T_{cr}) is insensitive to the type of reinforcement used. When cracking occurs, there is an increase in twist under nearly constant torque, due to a drastic loss of torsional stiffness. Beyond this, however, the strength and behaviour depend on the amount and type of longitudinal and torsional reinforcement present in the beam.
- From the experimental study it is seen that two types of failures are observed for beams reinforced with steel reinforcements, namely, yielding of longitudinal and transverse reinforcements and concrete crushing. It is also observed from the present study that for beams reinforced with conventional steel reinforcements having a

reinforcement ratio lesser than 1% (ie.0.56%) are failed by yielding of longitudinal and transverse reinforcements before crushing of concrete in compression (Fig.3.26) but beams with approximately closer to 1% (ie.0.86%) of steel reinforcement ratio are failed by crushing of concrete in compression before yielding of longitudinal or transverse reinforcements (Fig.3.27).

- Also it is seen that two types of failures are observed for beams (Figs.3.25 to 3.30) reinforced with Hybrid FRP reinforcements, namely, concrete crushing and rupture of Hybrid FRP stirrups under tension. Hybrid FRP reinforced concrete beams are failed due to crushing of concrete followed by rupture of Hybrid FRP stirrups when the reinforcement ratio lesser than 1% (0.56%). It is probably due to the fact that the ultimate tensile strains of Hybrid FRP stirrups (generally HFRP pultruded reinforcements have higher ultimate strains in fact higher than conventional steel, but HFRP stirrups are not manufactured by pultrusion process and are indeed, manufactured by vacuum resin bath method which are having lesser ultimate strains but slightly greater than concrete ultimate strains) and are slightly higher than the ultimate compressive strains of concrete. Such mode of failure is invariably observed for all Hybrid FRP reinforced beams with a reinforcement ratio lesser than 1% and approximately closer to 1%. But none of beams failed due to rupture of Hybrid RFP reinforcements prior to concrete strain reaches ultimate. It is probably due to the fact that the ultimate tensile strains of Hybrid FRP reinforcements are greater than the ultimate compressive strains of concrete.
- Torsional strength and angle of twist increases with the increase in grade of concrete and percentage of longitudinal and transverse reinforcements. But Hybrid FRP reinforced concrete beams showed higher angle of twist than the conventional reinforcements. This fact is primarily due to higher tensile strain values for Hybrid FRP reinforcements than the steel reinforcements.
- It is also noted that by replacing main and transverse steel reinforcements by an equal percentage of Hybrid FRP reinforcements, reduced their torsional capacities by 30% for lower grade concrete but their increase is reduced by 20% for higher grade concrete and higher percentage of steel.
- It is also observed that for steel reinforced concrete beam, the yielding of reinforcement leads to a larger increase in twist with little change in torque, whereas Hybrid FRP reinforced beams show no yielding of reinforcements and the twist continues to increase with the increase in torque, there by exhibiting some ductility despite the brittle nature of Hybrid FRP reinforcements.
- Higher grade of concrete and higher percentage of steel, the torque–twist diagrams show a increase in torque together with a rapid increase of beam twist. The failures were characterized by crushing of the concrete at the compressive face, followed by the yielding of steel stirrups and rupture of Hybrid FRP stirrups. This qualitative behaviour is observed in Hybrid FRP/steel beams; consequently the overall behavior of the Hybrid FRP beam is similar to the behavior of conventionally reinforced concrete beams except that the failure of Hybrid FRP stirrups even after concrete crushing.
- The post peak values of torsional strength of beams have greater influence on the spacing of stirrups. The minimum spacing of stirrups are arrived based on the Indian Standards. An examination of the curves reveals that the slope of the curves at the initial stages of loading is mild for Hybrid FRP reinforced specimens whereas for

conventionally reinforced specimen it is steeper. This is primarily due to lower elastic modulus than conventional steel reinforcements.

- During test all specimens exhibited satisfactory ultimate torsional behaviour, however the post-peak behaviour differs for Hybrid FRP reinforced beam than the conventionally reinforced beams.

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