Nonlinear Analysis on Torsional Strengthening Of Rc Beams Using Cfrp Laminates

Asst. Prof. Amer A. H. Al-Nuaimi
aalneaime@yahoo.com

Lect. Dr. Rafa'a Mahmood Abbas
rafaamaa@yahoo.com

Reem Basil Abbas
reembj_86@yahoo.com

Department of Civil Engineering - University of Baghdad

ABSTRACT:

This research is devoted to investigate the behavior and performance of reinforced concrete beams strengthened with externally bonded Carbon Fiber Reinforced Polymer (CFRP) laminates under the effect of torsion. In this study a theoretical analysis has been conducted using finite element code ANSYS. Six previously tested beams are used to investigate reinforced concrete beams behavior under torsion, two of them are solid and the rest are box-section beams. Also, two beams are without CFRP reinforcement, which are used as control beams for the strengthened one, and the other four beams are strengthened with CFRP laminates with different number of layers and spacing. Numerical investigation is conducted on these beams, and comparisons between the available experimental results for these beams and numerical results from the current study are made. Conclusions from these comparisons are presented and discussed. An increase of about 15.6% in the ultimate torque for the solid beam and of about 9.8% in the ultimate torque for the box-section beam is observed after using the CFRP strips. A parametric study is carried out to study the torsional behavior of RC beams having different number of CFRP layers and concrete compressive strength; also U-wrap for the CFRP configuration is investigated.

KEYWORDS: Finite Element Analysis, Torsion, Reinforced concrete, CFRP, Box-section, Beams.

التحليل اللاخطي للعتبات الخرسانية المسلحة المقواة بألياف الكاربون البوليمرية الصفائحية تحت تأثير عزم الألتواء

أ. م. عامر عبد الوهاب النعيمي
aalneaime@yahoo.com

م. د. رافع محمود عباس
rafaamaa@yahoo.com

ريم باسل عباس
reembj_86@yahoo.com

الخلاصة:

ان الغرض من هذا البحث هو التحري عن تصرف و اداء العتبات الخرسانية المسلحة و المقواة بالياف الكاربون البوليمرية و المعرضة الى عزم الألتواء. تم استخدام التحليل اللاخطي ثلاثي الابعاد بالاعتماد على طريقة العناصر المحددة كوسيلة عددية لدراسة تصرف هذه العتبات تحت تأثير عزم الالتواء. في هذا البرنامج جرى الاخذ بنظر الاعتبار التصرف اللاخطي لعلاقة الاجهاد - الانفعال للخرسانة. تمت دراسة ست عتبات تحت تأثير عزم الالتواء. اثنان من هذه العتبات تركت من دون تدعيم بالالياف الكاربونية البوليمرية من اجل ان تتم مقارنتها مع العتبات المدعمة. اربعة عتبات تم تدعيمها بالالياف الكاربونية البوليمرية بعدد مختلف من الطبقات و كذلك بمسافات مختلفة بين الالياف. اجريت عملية تحليل لعدد من العتبات الخرسانية المسلحة المقواة بالياف الكاربون البوليمرية و مقارنتها مع الدراسات العملية المتوفرة. اظهرت نتائج الدراسة المقارنة ان استخدام الالياف الكاربونية البوليمرية اعطى نتائج افضل من عدم استخدامها حيث ازدادت قيمة العزم الاقصى بحوالي 15,6% و 9,8% بالنسبة للعتبات الصلدة و الصندوقية. تمت دراسة تأثير كل من قابلية انضغاط الخرسانة و عدد طبقات الياف الكاربون البوليمرية و طريقة ال U-wrap لتنفيذ الالياف الكاربونية البوليمرية على سلوك و قيمة الحمل الاقصى للخرسانة .

كلمات المفتاح: تحليل العناصر المحددة، عزم الألتواء، الخرسانة المسلحة، ألياف الكاربون البوليمرية الصفائحية، العتبات الصندوقية، العتبات الصلدة.

1. INTRODUCTION

The repair and retrofitting of existing structures has become a major part of construction activity in many countries. To a large extent, this can be attributed to the aging of the infrastructure. Some of the structures are damaged by environmental effects, which include the corrosion of steel, variations in temperature and freeze-thaw cycles. There are always cases of construction-related and design-related deficiencies that need correction. Many structures, on the other hand, need strengthening because the allowable loads have increased or new codes have made the structures substandard. This last case applies mostly to seismic regions, where new standards are more stringent than the old. A new class of structural material known as Fiber Reinforced Polymer (FRP) has become a viable alternative to steel plates. FRP composites can be defined as composite materials consisting of high-strength fibers embedded in a polymer matrix.

Previously, FRP composites have been used, almost exclusively, in aviation and aerospace industries due to their high costs. Recently, the fall in the prices has led to their gradual introduction in the civil construction industry. The stiffness and strength of a composite is generally governed by the embedded fibers. In addition to binding the fibers together, the surrounding matrix acts as a protection against environmental damage. The advantages of composite materials in comparison with traditional construction materials such as steel, wood and concrete are that they are non-corrosive, nonmagnetic, resistant to various types of chemicals, of high strength and light-weight. Fiber reinforced polymer (FRP) has shown great promise as a state-of-the-art material in flexural and shear strengthening as an external reinforcement. However, little attention is paid to torsional strengthening in terms of both experimental and numerical research.

2. BACKGROUND

In 2003, Taljsten publishes the results of pilot tests conducted on five reinforced concrete beams strengthened with both CFRP and GFRP. The dimensions of the members are 150mm wide by 600mm deep and 6000mm long. It is concluded that strengthening in torsion with externally-bonded FRP was feasible, but continuity of the FRP reinforcement around the section with proper anchorage was critical. Only the torque-twist response of the tests was reported. Salom et al. (2004) present a study that describes an experimental program on the torsional strengthening of reinforced concrete spandrel solid beams using composite laminates. The variables considered in the study include fiber orientation, composite laminates, and effect of anchoring system. The study proved that the FRP laminates could increase the torsional capacity of concrete beams by more than 70%.

Allawi, A. (2006) studies the behavior and performance of nine reinforced concrete members strengthened with externally bonded CFRP laminates in torsion. Two different software have been used, DIANA and P3DNFEA software, to model the tested beams by using FEM. Comparisons of the finite element method results with experimental data show that the maximum difference is 8.2% and 7.3% for cracking and ultimate torque, respectively, when confinement and expansion effects is included in the analysis. While, a difference of 14.3% and 22.7% is obtained for cracking and ultimate torque, respectively, when neglecting these effects.

Al-Mahaidi and Hii (2004, 2005, and 2006) study the behavior and performance of six medium scale reinforced concrete beams. Two specimens were solid sections, while the rest were box-sections strengthened with externally bonded CFRP laminates in torsion. The experimental results show that the bonding of CFRP laminates to beams causes an increase up to 40% and 78% in both cracking and ultimate strengths, respectively compared to the control specimens. DIANA software is used to study numerically tested beams and compare finite element results with experimental outcomes. Good agreement with experiments in terms of torque-twist behavior, steel and CFRP reinforcement responses, and crack patterns is achieved.

3. OBJECTIVE

The main objective of the present study is to investigate the behavior of reinforced concrete beams that have been strengthened by using Carbon Fiber Reinforced Polymers under the effect of torsion forces. Finite element program ANSYS 11.0 is used to model experimentally the tested beams in torsion so that numerical results can simulate tested beams in torque-twist behavior. The torsional behavior of the reinforced concrete beams having different number of CFRP layers, different concrete compressive strength and U-wrap for the CFRP configuration is investigated.

4. VERIFICATION OF THE FINITE ELEMENT IDEALIZATION

The validity and accuracy of the finite element idealization are studied and checked by analyzing concrete beams that have been tested experimentally by Hii and Al-Mahaidi (2006). Six reinforced concrete beams are adopted in this study. Four of these beams are strengthened by using CFRP in torsion, while the other two beams are without strengthening and are used as control beams. The material properties and specimen details of the adopted beams in the main experimental program are shown in **Tables 1, 2, 3, 4 and 5** and **Figs. 1, 2 and 3.**

4.1. Finite Element Idealization Of The Beams

The six concrete beams are modeled using 8-node brick elements (SOLID 65) for the concrete. The reinforcing bars are modeled using 2-node element (LINK 8), and the CFRP strips and the epoxy layer are modeled by using (MEMBRANE 41) and spring elements, respectively. The loading arm is modeled using (SOLID 45) elements, as shown in **Fig. 4** and **Table 6** (ANSYS Help, ANSYS, 2000).

4.2. Boundary Conditions

For the loaded end, a pivot support which is fixed in the lateral and vertical directions is placed. The use of a pivot support allows twist of the cross-section under applied torque. The pivot is free to move in the longitudinal direction to allow elongation or shortening of the beam. During the preliminary analyses, localized concrete crushing around the pivot support is observed. To overcome this, the concrete brick elements around the support are assigned linear elastic properties to distribute the reaction loads uniformly. At the fixed end, the elements at the support are fixed in the longitudinal, vertical and lateral directions.

The constraints reflect the fixity provided by the steel collar in experiments. Loading on the model is achieved by a point load on the loading arm at an eccentricity of 855mm from the centerline of the beam. As accurate stress and strain results from the loading arm are not needed, the use of linear elastic properties ensures no premature termination of analyses occurred from stress concentrations with point loads.

4.3. Finite Element Results Verification

A comparison between the numerical and experimental results has been made to verify the accuracy of the numerical models. The results of the solid beam CS1, as shown in **Figs. 5, 6, and 7**, are chosen to validate finite element results with respect to experimental work. These figures show the relationship between the torque and the angle of twist, the beam extension, and the strain in the stirrups for this beam. These figures reveal that the general behavior for the tested beams in torsion is well established by the adopted numerical model.

5. PARAMETRIC STUDY

The parametric study is carried out to investigate the behavior of reinforced concrete solid and box section beams having:

- Different values of concrete compressive strength.
- Different number of CFRP layers.
- U-wrap CFRP sheets effect is investigated in comparison to fully wrapped sheets.

5.1. Effect of concrete compressive strength

Solid and box-section beams are chosen to investigate the effect of concrete compressive strength (f_c'). Three values for each beam are used in addition to the compressive strength of the concrete used in the experimental work. The results show that the increase in the compressive strength of the concrete (f_c') causes an increase in the load carrying capacity and also an increase in the angle of twist at failure. It also affects the behavior of the strain and longitudinal extension of the beams.

Table 7 shows the values of the concrete strength used in the parametric study, while **Fig. 8** shows the effect of increasing (f_c') on the angle of twist of the solid beam, whereas its effect on the longitudinal extension and strain are shown in **Figs. 9 and 10**, respectively. As for the box-section beam, the effect of f_c' variation is presented in **Figs. 11, 12** and **13**. **Table 8** shows the differences in the ultimate torque among these cases.

5.2. Effect of the number of CFRP layers

The effect of the number of CFRP layers is considered in this study. Different number of layers is used, namely 3, 4 and 5 layers. Two beams are chosen to be tested against this effect, a solid beam and a box-section beam. **Table 9** shows material properties for CFRP strips used in the parametric study**.**

Figs. 14, 15 and **16** show these effects for the solid beam, whereas **Figs. 17, 18** and **19** show these effects for the box-section beam. Concrete compressive strength for the adopted beams is 56.4 MPa. Also, CFRP sheets spacing for both beams is 0.50D. From the figures presented below, it is obvious that when the number of layers is increased the ultimate torque also increased so as for the angle of twist and other factors. **Table 10** shows the effect of increasing the number of CFRP layers on torsion behavior for both solid and box-section beams.

5.3. Effect of CFRP U-wrap style

Two beams have been chosen to investigate this effect. A solid and a box-section beam are tested numerically under U-wrap style for CFRP strips. The results are compared with the fully wrapped beams under the same conditions. Also, a comparison has been made for the two beams (solid and box-section) to investigate the effect of wrap style on them. Concrete strength for the adopted solid and box-section beams is 56.4 MPa, also two layers of CFRP laminates with 0.50D spacing is applied.

The results show that the full-wrap is more viable and bears greater loads than the U-wrap and the solid beam is better than the box-section beam. **Figs. 20, 21** and **22** show these effects for the solid beams, whereas **Figs. 23, 24** and **2**5 show these effects for the box beams.

Figs. 26, 27 and **28** show a comparison between solid and box beams under U-wrap. **Table 11** show the effect of the wrap style on the torque strength for the two beams.

6. CONCLOSIONS

From the numerical analysis carried out in this study, the following conclusions are shown:

1. When comparing the Numerical and experimental results, it is evident that ANSYS finite element models underestimate the angle of twist and the ultimate torsional strength of the adopted beams, especially for the box-section specimens. However, the general behavior for the tested beams is well established.
2. The numerical results revealed that using CFRP laminates generally increases the ultimate torque capacity of the strengthened beams.
3. The ultimate torque at failure is found to increase as the compressive strength of the concrete is increased, Consequently, increasing concrete compressive strength from 25 MPa to 56.4 MPa shows the following :
   - An increase of about 63.6% in the ultimate torque for the solid beam.
   - An increase of about 81.8% in the ultimate torque for the box-section beam.
4. The ultimate torque at failure is found to increase as the number of CFRP layers applied is increased. Increasing the number of CFRP layers from 2 to 5 shows the following :
   - An increase of about 4.7% in the ultimate torque for the solid beam.
   - An increase of about 1.3% in the ultimate torque for the box-section beam.
5. The use of U-wrap for CFRP configuration reduces the ultimate torque capacity as compared to fully wrapped beams. Results show that applying U-wrap style decreases

the ultimate torque by 11.7% as compared to fully wrapped beams for the solid beam, and 0.5% for the box-section beam.

7. REFERENCES

- **Allawi**, A., (2006), "Nonlinear Analysis of Reinforced Concrete Beams Strengthened by CFRP in Torsion". Ph. D. Thesis, University of Baghdad.
- **ANSYS**, "Element References", Release 11, "ASYS Manual", Version (11.0), USA, 2002.
- **ANSYS** (2002), "ANSYS 11.0 Theory Manual". Swanson Analysis Systems Inc., USA.
- ANSYS Help, USA.
- **Hii, A. K. Y. and Al-Mahaidi, R.** (2004), "Torsional Strengthening of Reinforced Concrete Beams Using CFRP Composites". FRP Composites in Civil Engineering - CICE 2004, Adelaide, Australia, Taylor and Francis Group, London, pp. 551-559.
- **Hii, A. K. Y. and Al-Mahaidi, R.** (2005), "Torsional Strengthening of Solid and Box-section RC Beams Using CFRP Composites". Composites in Construction 2005 - Third International Conference, Lyon, France, pp. 59-68.
- **Hii, A. K. Y. and Al-Mahaidi, R.** (2006), "An Experimental Investigation on Torsional Behavior of Solid and Box-section RC beams Strengthened with CFRP using Photogrammetry", *Journal of Composites for Construction*, Vol. 10, No. 4.
- **Hii, K. Y. and Al-Mahaidi, R.** (2006), "An Experimental and Numerical Investigation on Torsional Strengthening of Solid and Box-Section RC Beams Using CFRP Laminates", Ph. D. Thesis, University of Monash. Australia.
- **Salom, P. R., Gergely, J. and Young, D. T.** (2004), "Torsional Strengthening of Spandrel Beams with Fiber-Reinforced Polymer Laminates", *Journal of Composites for Construction*, Vol. 8, No. 2, pp. 157-162.
- Taljsten**, B.** (2003), "Strengthening of Concrete Structures in Torsion with FRP". FRPRCS-6, Singapore, World Scientific Publishing Company, pp. 1167-1176.

8. NOTATION

D	Depth of section
E_c	Young’s modulus of concrete
E_f	Young’s modulus of FRP
E_s	Young’s modulus of steel reinforcement
f_c'	The compressive strength of concrete at the relevant age
f_y	Yield strength of steel reinforcement.
φ	Angle of twist from torsion
υ	Poisson’s ratio.
CFRP	Carbon fiber reinforced polymer composites
FRP	Fiber reinforced polymer composites
GFRP	Glass fiber reinforced polymer composites
RC	Reinforced concrete.

Table 1: CFRP Material Properties

Properties	Values
Young's modulus in longitudinal direction (MPa)	240000
Young's modulus in lateral direction (MPa)	24000
Poisson's ratio υ	0.3
Shear modulus G (MPa)	12000
Thickness of sheet (mm)	0.176

Table 2: Material Properties for the Epoxy

Element	Elastic Modulus (MPa)	υ
Epoxy	2028	0.3

Table 3: Basic Properties of the Concrete Material [Hii and Al-Mahaidi 2006]

Specimen / Properties	f'_c (MPa)	E_c (MPa)	f_t (MPa)	υ
CS1	52.5	37370	3.79	0.21
FS050D2	56.4	38270	4.01	0.21
CH1	48.9	36490	3.58	0.21
FH075D1	48.9	36490	3.58	0.21
FH050D1	52.8	37440	3.81	0.21
FH050D2	56.4	38270	4.01	0.21

Table 4: Specimen details in the experimental program [Hii and Al-Mahaidi 2006]

No.	Beam designation	CFRP strengthening scheme		
		Layout scheme	No. of layers	Strip spacing
1	CS1	None, Control beam	None	None
2	FS050D2	Full strips	2	0.50D
3	CH1	None, Control beam	None	None
4	FH075D1	Full strips	1	0.75D
5	FH050D1	Full strips	1	0.50D
6	FH050D2	Full strips	2	0.50D

Table 5: Reinforcing bar Properties in the Experimental Program [Hii and Al-Mahaidi 2006]

Sample	Stirrups φ6mm			Longitudinal bars φ10mm		
	E_s (MPa)	f_y (MPa)	f_u (MPa)	E_s (MPa)	f_y (MPa)	f_u (MPa)
1	227300	432	537	208000	393	470
2	214600	427	538	207000	390	466
3	209800	426	528	204500	413	526
4	205000	416	523	203900	401	471
5	210500	431	547	211800	394	476
Average	**213 400**	**426**	**535**	**207000**	**398**	**482**

Table 6: Finite elements representation of structural components

Structural Component	Finite Element Representation	Element Designation in ANSYS
Concrete (Beam)	8-node Brick Element (3 Translation DOF per node)	SOLID 65
Reinforcement (Longitudinal and Stirrups Steel)	2-node Discrete Element (3 Translation DOF per node)	3D-SPAR 8 (LINK-8)
CFRP (Carbon Fiber Reinforced Polymers)	4-node Element (3 DOF element)	SHELL 41
Epoxy	2-node Nonlinear Spring Element with three Translations DOF per node	COMBINATION
The Arm (Steel Arm)	8-node Element (3 Translation DOF per node)	SOLID 45

Table 7: Concrete compressive strength values in the parametric study

Parameters	Case 1	Case 2	Case 3	Case 4
Concrete compressive Strength f'_c (MPa)	25	35	45	56.4

Table 8: Effect of f'_c on the ultimate torque for both solid and box-section beams

Beam	Number of CFRP Layers	Cases of f'_c (MPa)		Torque (kN.m)	% Difference From Case1
Solid	2 layers (0.5D)	Case 1	25	44.46	-
		Case 2	35	59.85	+34.7
		Case 3	45	70.97	+59.7
		Case 4	56.4	72.7	+63.6
Box-Section	2 layers (0.5D)	Case 1	25	22.23	-
		Case 2	35	29.07	+30.8
		Case 3	45	35.91	+61.6
		Case 4	56.4	40.4	+81.8

Table 9: Material Properties for CFRP strips used in the parametric study

No. of Layers	Thickness (mm)	Young's Modulus E_f (MPa)	Poisson's ratio v
3	0.528	240000	0.3
4	0.704	240000	0.3
5	0.880	240000	0.3

Table 10: Effect of CFRP number of layers on torque for the solid and box-section beams

Beam	Cases of Thickness		Torque (kN.m)	% Difference From Case1
Solid	Case 1	2 layers CFRP	72.7	-
	Case 2	3 layers CFRP	75.3	+3.6
	Case 3	4 layers CFRP	73.6	+1.3
	Case 4	5 layers CFRP	76.1	+4.7
Box-Section	Case 1	2 layers CFRP	40.4	-
	Case 2	3 layers CFRP	40.2	-0.5
	Case 3	4 layers CFRP	40.4	0
	Case 4	5 layers CFRP	40.9	+1.3

Table 11: Effect of wrap style on torque for the solid and box-section beams

Beam	Full-wrap torque (kN.m)	U-wrap torque (kN.m)	% Difference
Solid	72.7	64.2	-11.7
Box-Section	40.4	40.2	-0.5

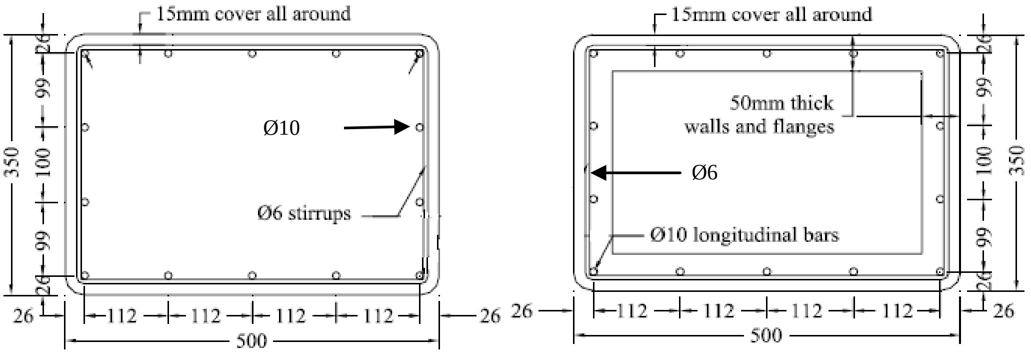

Fig. 1: Reinforcement Layout of Solid and Box-Section Beams [Hii and Al-Mahaidi 2006]

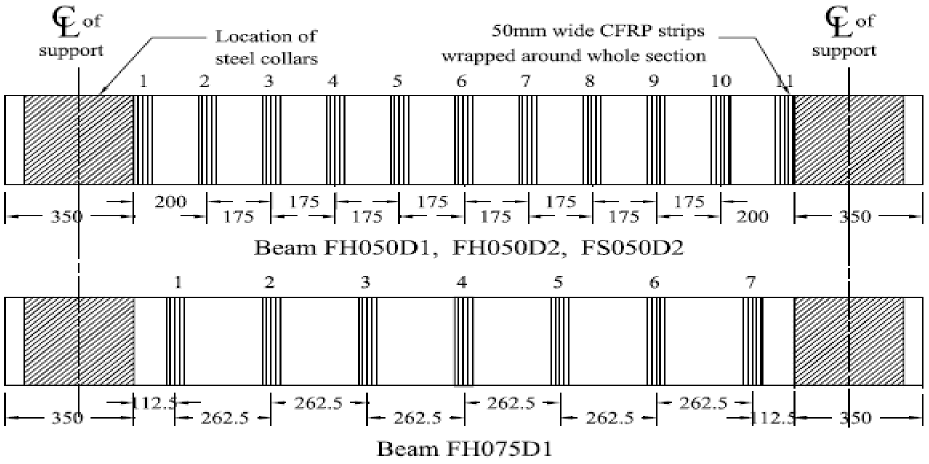

Fig. 2: CFRP layout of strengthened specimens [Hii and Al-Mahaidi 2006]

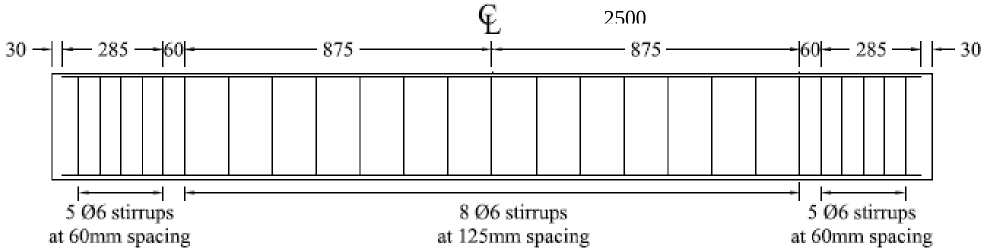

Fig. 3: Hoop Reinforcement Layout [Hii and Al-Mahaidi 2006]

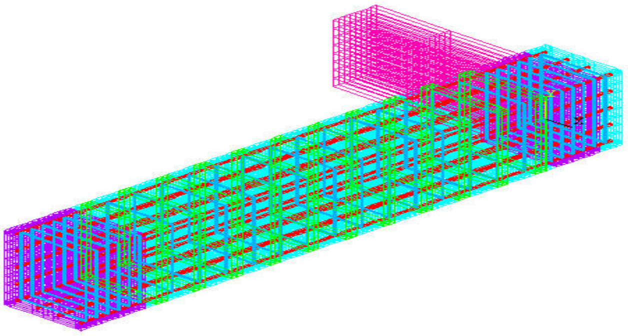

Fig. 4: Finite Element Modeling of the RC Beams

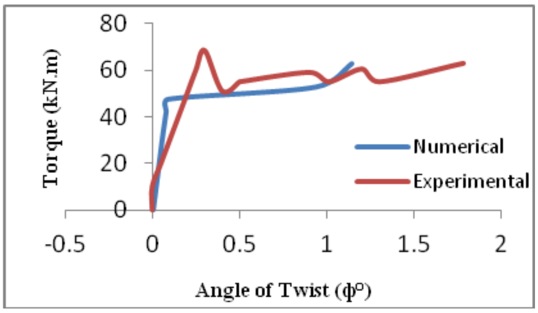

Fig. 5: Relationship between angle of twist and the torque for Beam CS1

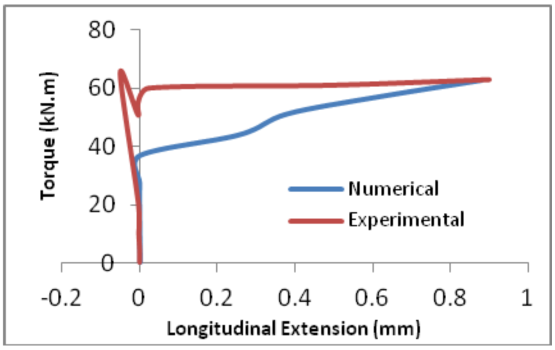

Fig. 6: Relationship between angle of twist and longitudinal extension for Beam CS1

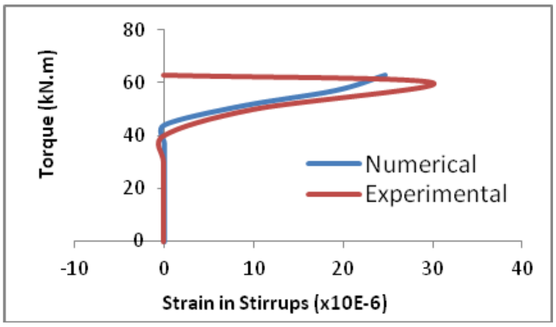

Fig. 7: Relationship between angle of twist and stirrups strain for Beam CS1

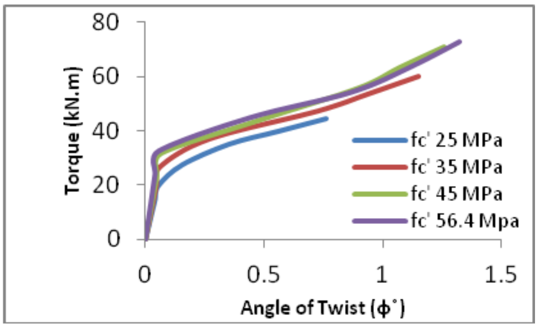

Fig. 8: Effect of f_c' variation on angle of twist for the solid beam

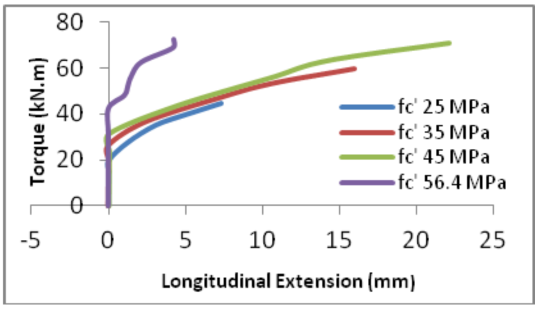

Fig. 9: Effect of f_c' variation on the longitudinal extension for the solid beam

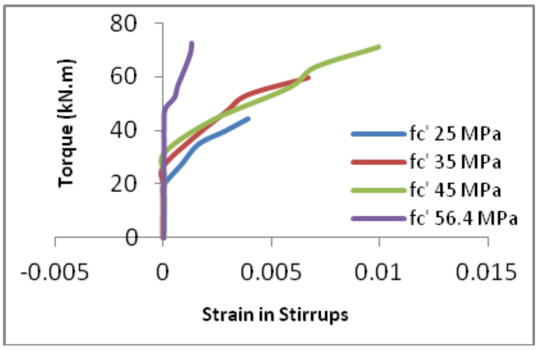

Fig. 10: Effect of f_c' variation on the strain in the stirrups for the solid beam

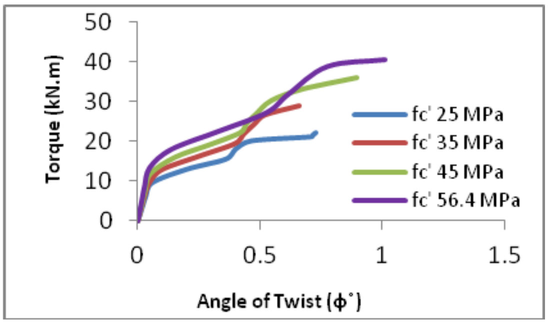

Fig. 11: Effect of f_c' variation on angle of twist for the box-section beam

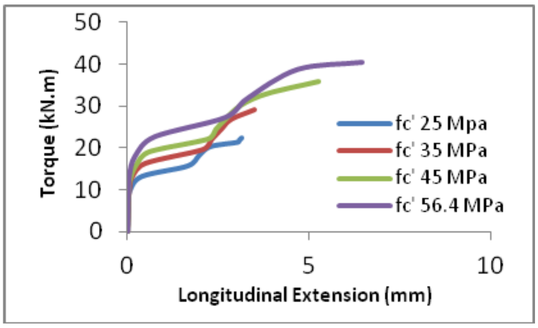

Fig. 12: Effect of f_c' variation on the longitudinal extension for the box-section beam

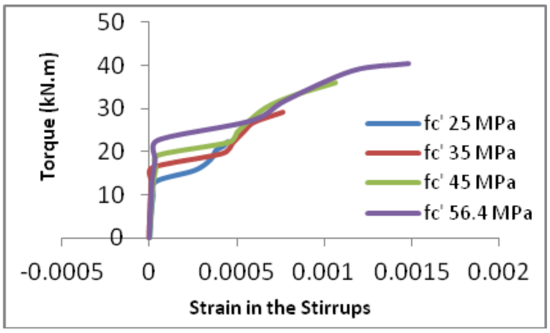

Fig. 13: Effect of f_c' variation on the strain in the stirrups for the box-section beam

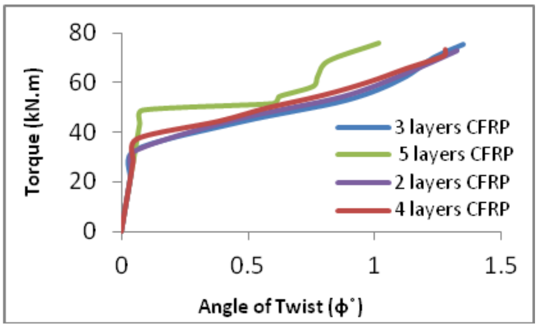

Fig. 14: Effect of number of CFRP layers on the angle of twist for the solid beam

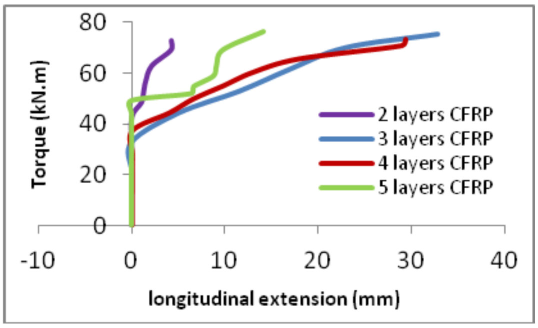

Fig. 15: Effect of number of CFRP layers on the longitudinal extension for the solid beam

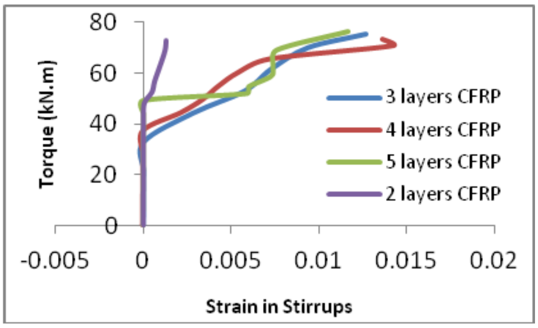

Fig. 16: Effect of number of CFRP layers on the strain in the stirrups for the solid beam

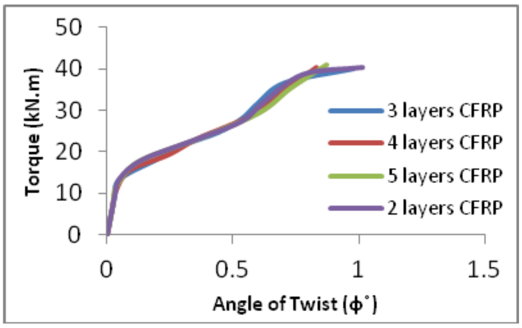

Fig. 17: Effect of number of CFRP layers on the angle of twist for the box-section beam

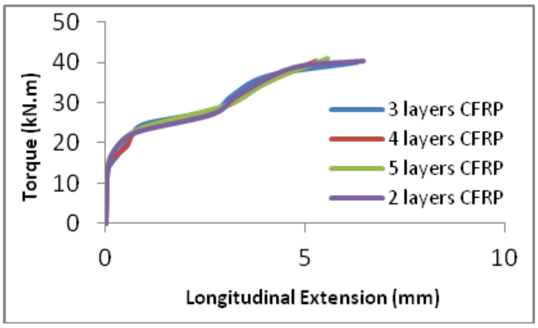

Fig. 18: Effect of number of CFRP layers on the longitudinal extension for the box-section beam

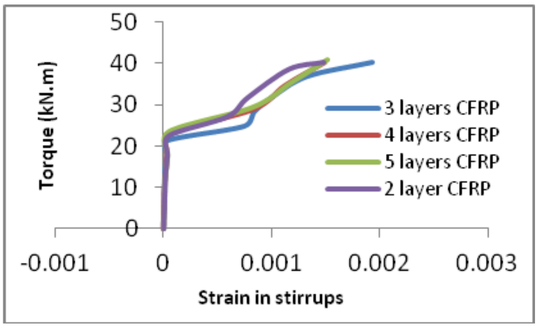

Fig. 19: Effect of number of CFRP layers on the strain in the stirrups for the box-section beam

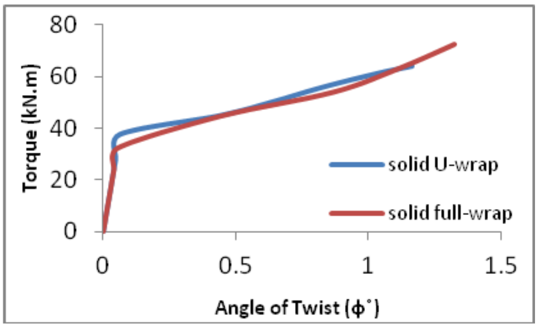

Fig. 20: Effect of CFRP U-wrap and full wrap on solid beam angle of twist

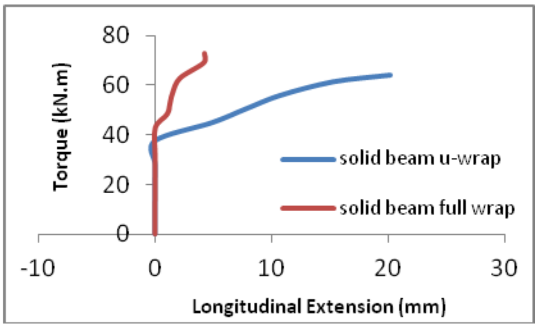

Fig. 21 Effect of CFRP U-wrap and full wrap on solid beam longitudinal extension

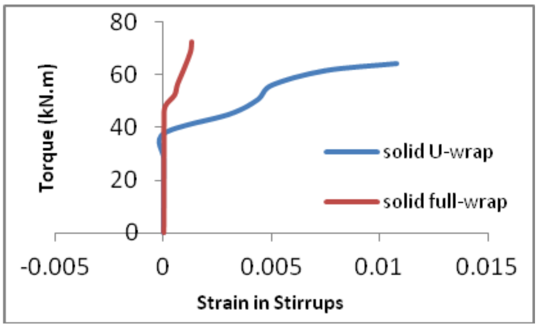

Fig. 22: Effect of CFRP U-wrap and full wrap on solid beam strain in the stirrups

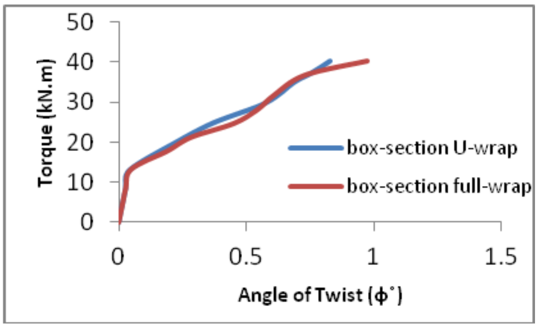

Fig. 23: Effect of CFRP U-wrap and full wrap on box-section beam angle of twist

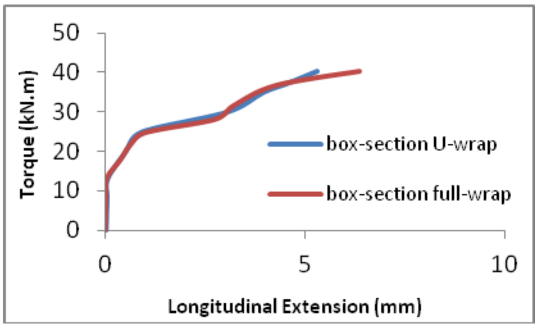

Fig. 24: Effect of CFRP U-wrap and full wrap on box-section beam longitudinal extension

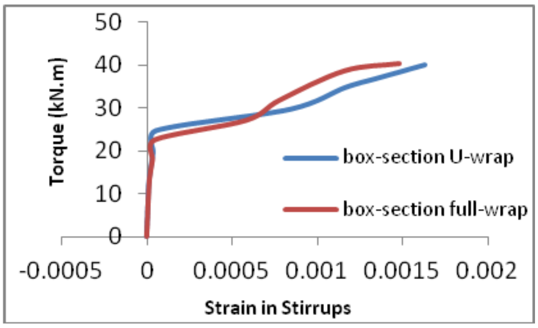

Fig. 25: Effect of CFRP U-wrap and full wrap on box-section beam strain in the stirrups

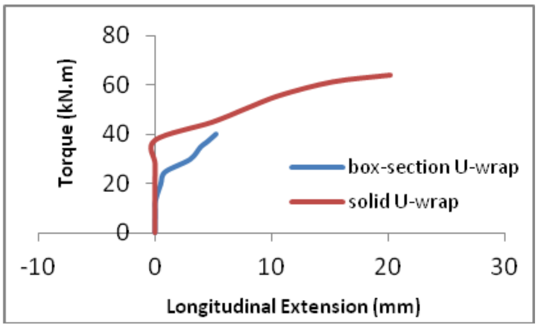

Fig. 27: Effect of CFRP U-wrap on the box-section and solid beam longitudinal extension

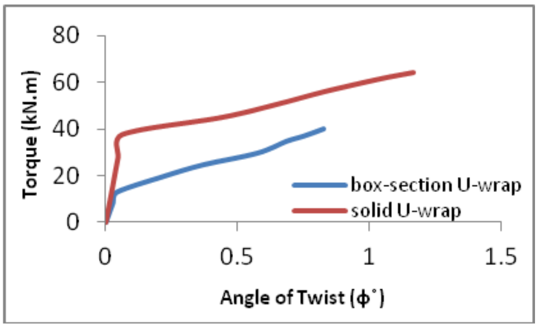

Fig. 26: Effect of CFRP U-wrap on the box-section and solid beam angle of twist

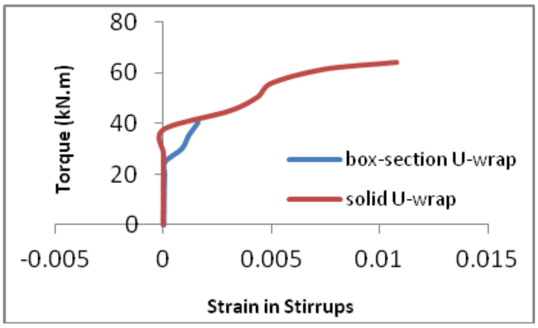

Fig. 28: Effect of CFRP U-wrap on the box-section and solid beam strain in the stirrups