Research Report
KTC-02-14/SPR 200-99-2F

KENTUCKY TRANSPORTATION CENTER

College of Engineering

SHEAR STRENGTH OF R/C BEAMS WRAPPED WITH CFRP FABRIC

UNIVERSITY OF KENTUCKY

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SHEAR STRENGTH OF R/C BEAMS WRAPPED WITH CFRP FABRIC

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in cooperation with

Transportation Cabinet
Commonwealth of Kentucky

and

Federal Highway Administration
U.S. Department of Transportation

August 2002

Commonwealth of Kentucky
Transportation Cabinet
Frankfort, Kentucky 40622

James C. Codell, III
Secretary of Transportation

Clifford C. Linkes, P.E.
Deputy Secretary

Paul E. Patton
Governor

August 12, 2002

Mr. Jose M. Sepulveda
Division Administrator
Federal Highway Administration
330 West Broadway
Frankfort, KY 40602

Subject: - Implementation Statement for Final Report entitled "Shear Strength of R/C Beams Wrapped with CFRP Fabric"
- Study number: KYSPR 99-200
- Study title: Implementation of Advanced Composites Technology for Repair and Strengthening of Kentucky Bridges.

Dear Mr. Sepulveda:

This study was conducted to investigate the feasibility of using carbon fiber reinforced polymer (CFRP) fabric in increasing the shear strength of concrete beams. The objective set forth has been achieved by conducting series of experiments in the Structural Engineering Laboratory at the University of Kentucky.

The behavior of concrete beams wrapped with four different configurations of CFRP fabric is experimentally investigated. An analytical procedure is developed to predict the shear capacity of concrete beams wrapped with FRP fabric. Results of the testing show that shear strength is increased up to 33% on concrete beams wrapped with CFRP fabric at an angle of ±45° to the longitudinal axis of the beam.

Sincerely,

for J. M. Yowell, P.E.
State Highway Engineer

JMY/SEG/lg

c: Marcie Mathews
John Carr

EDUCATION PAYS

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
KTC-02-14/SPR 200-99-2F		

4. Title and Subtitle	5. Report Date
SHEAR STRENGTH OF R/C BEAMS WRAPPED WITH CFRP FABRIC	August 2002
	6. Performing Organization Code
7. Author(s): P. Alagusundaramoorthy, I.E.Harik, and C.C.Choo	8. Performing Organization Report No. KTC-02-14/SPR 200-99-2F
9. Performing Organization Name and Address Kentucky Transportation Center College of Engineering University of Kentucky Lexington, Kentucky 40506-0281	10. Work Unit No. (TRAIS) 11. Contract or Grant No. KYSPR 99-200
12. Sponsoring Agency Name and Address Kentucky Transportation Cabinet State Office Building Frankfort, Kentucky 40622	13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Kentucky Transportation Cabinet and the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

The emergence of high strength epoxies has enhanced the feasibility of increasing the shear strength of concrete beams by wrapping with carbon fiber reinforced polymer (CFRP) fabric. The objective of this investigation is to evaluate the increase in shear strength of concrete beams wrapped with different configurations of CFRP fabric. Shear tests are conducted up to failure on two reinforced concrete control beams and twelve reinforced concrete beams wrapped with four different configurations of CFRP fabric. An analytical procedure is presented to predict the shear strength of beams wrapped with CFRP fabric. Comparisons are made between the test results and the analytical calculations. The shear strength is increased up to 33% on concrete beams wrapped with CFRP fabric at an angle of ± 45° to the longitudinal axis of the beam.

17. Key Words	18. Distribution Statement
Reinforced concrete beams; Shear; Strengthening; CFRP fabric; Testing; Analysis.	Unlimited with approval of Kentucky Transportation Cabinet

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	31	

Form DOT 1700.7(8-72) **Reproduction of Completed Page Authorized**

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Notation

A_v = area of transverse reinforcement

b_v = width of closed stirrup

b_w = breadth of concrete beam

d = distance from the compressive fiber to the centroid of tension reinforcements

E_f = Young's modulus of elasticity of FRP fabric

$f_c^{'}$ = specified compressive strength of concrete

f_{fe} = effective stress in FRP fabric

f_{pu} = ultimate stress of FRP fabric

f_y = yield stress of steel

h = height of concrete beam

h_v = height of closed stirrup

t_f = thickness of FRP fabric

R = ratio of effective strain to ultimate strain in FRP fabric

s_f = spacing of FRP fabric

s = spacing of transverse reinforcement

ρ_f = shear reinforcement ratio

θ = angle of fiber orientation

θ_c = angle of crack inclination

Acknowledgments

The financial support for this project was provided by the Kentucky Transportation Center, the Federal Highway Administration, and the National Science Foundation under the grant CMS- 9601674 - ARI program.

The help of Sean Anderson, Dr. Wael Zatar, Emily Delaney, Chen Denglin, Dan Eaton, Dr. Jeff Griffin, Chris Hill, Meg Hopkins, Mario Johnson, Tyler Julliard, Professor Anibal Manzelli, Dr. Vasudevan Krishnappa Naidu, Dr. Chelliah Madasamy, David Ritchie, Laura Schweri, Robin Siddiqui, Tim Taylor, Dr. Michael Whitney, Everett Wilson, Louis Mattingly, Anthony Kordenbrock, Dr. V. Gupta and Mr. Robert Thompson at Fiber Reinforced Systems (FRS), Columbus, Ohio in coordinating, conducting the testing and preparing the manuscript is noteworthy. The authors would like to acknowledge the cooperation, suggestions, and advice of the members of the study advisory committee: Steve Goodpaster, Stewart Goodpaster, Ray Greer, Stephen Halloran and David Steele.

1 Executive Summary

1.1 Introduction

Shear tests are conducted on two concrete control beams and twelve concrete beams wrapped with CFRP fabric. The increase in shear strength of concrete beams due to wrapping of CFRP fabric is calculated from the test results. An analytical procedure is presented to predict the shear strength of concrete beams wrapped with FRP fabric. The shear strength of all tested beams is calculated using the presented analytical procedure and compared with the experimental results.

1.2 Objective and Scope

The main objective of this investigation is to study the effectiveness of unidirectional CFRP fabric supplied by Fiber Reinforced Systems (FRS) in increasing the shear strength of concrete beams. The objective is achieved by conducting the following tasks: (i) Shear testing of concrete beams wrapped with four different configurations of CFRP fabric; (ii) Calculating the effect of CFRP fabric on the shear strength; (iii) Evaluating the failure modes; and (iv) Developing an analytical procedure to calculate the shear strength of concrete beams wrapped with FRP composites; and (v) Comparing the analytical calculations with experimental results.

1.3 Test Specimens

Shear tests are conducted up to failure on two concrete control beams and twelve concrete beams wrapped with four different configurations of CFRP fabric. The CFRP fabric is a stitched unidirectional sheet of 0.18 mm thick supplied by Fiber Reinforced Systems (FRS) of Columbus, Ohio. The length, breadth and depth (ℓ x b x d) of all concrete beams is kept as 2,134 mm x 230 mm x 380 mm. Each concrete beam is reinforced with two 25 mm dia. steel bars for tension and two 9 mm dia. steel bars for compression along with 9 mm dia. Steel bars at a spacing of 300 mm center-to-center for shear reinforcement. The effective span of all beams is kept as 1,830 mm.

The concrete control beams are designated as SB1 and SB2 respectively. Four beams wrapped with one layer of CFRP fabric inclined at an angle of 90° to the longitudinal axis (SB3-90, SB4-90, SB5-90 and SB6-90), and two beams wrapped with one layer of CFRP fabric inclined at an angle of 90° with an additional layer of CFRP fabric on both sides of the web inclined at an angle of 0° (SB7-90-0 and SB8-90-0) are fabricated. Four beams wrapped with one layer of CFRP fabric inclined at an angle of ± 45° (SB9-45, SB10-45, SB11-45 and SB12-45), and two beams wrapped with one layer of CFRP fabric inclined at an angle of ± 45° with an additional layer of CFRP fabric on both sides of the web inclined at an angle of 0° (SB13-45-0 and SB14-45-0) are also fabricated. The details of the beams are presented in Table 1.1.

1.4 Experimental Results

The failure load is obtained from the load/centerline deflection curves using the "top of the knee method". The failure load according to this method is essentially the maximum load prior to load shedding. The failure loads with their corresponding failure modes are presented in Table 1.2. The average value of failure load of the control beams SB1 and SB2 is calculated (Tables 1.2) and used as a baseline value for comparison with the beams wrapped with CFRP fabric. The percentage increase in shear strength due to wrapping of CFRP fabric is calculated and presented in Tables 1.2. The shear strength is increased up to 33% on concrete beams wrapped with unidirectional CFRP fabric at an angle of ± 45° to the longitudinal axis of the beam.

1.5 Analytical Study

An analytical procedure is developed to predict the shear strength of concrete beams wrapped with FRP fabric. The shear strength of all beams is calculated using the developed analytical procedure and compared with the experimental results (Table 1.2). The mean value of P_e/P_a (Experimental failure load/Analytical failure load) varies from 1.12 to 1.33. The analytical calculations underestimate the failure load of beams by 18% on beams wrapped with CFRP fabric at 90°, 13% on beams wrapped with CFRP fabric at 90° and 0°, 33% on beams wrapped with CFRP fabric at ± 45°, and 30% on beams wrapped with CFRP fabric at ± 45° and 0°.

1.6 Conclusions

The following conclusions are drawn based on the experimental and analytical studies carried out under this investigation.

(i) The shear strength is increased up to 33% on concrete beams wrapped with unidirectional CFRP fabric at an angle of ± 45° to the longitudinal axis of the beam.
(ii) The presented analytical procedure underestimates the shear strength of concrete beams wrapped with CFRP fabric at an angle of ± 45° up to 33%.
(iii) Further tests on the shear strength of concrete beams are to be conducted and the analytical procedure has to be refined.

2 Introduction

The technique of bonding steel plates using epoxy adhesives is recognized as an effective method of improving the structural performance of concrete members. However, the difficulties in preparing, transporting and handling the steel plates, and the possibility of corrosion lead to the need for alternative materials for repair and rehabilitation of concrete structures. Fiber reinforced polymer composites (FRP) with their corrosion resistance, high strength to weight ratio, fatigue strength, and low maintenance cost offer a viable alternative to steel in strengthening applications. The shear strength of concrete beams can be improved by wrapping with thin CFRP fabric in different configurations. The CFRP fabric is durable against temperature, moisture, and chemical attack, and can be easily bonded to the beams. The CFRP fabric considered for repair and rehabilitation should have sufficient test-data demonstrating the adequate performance of the entire system including its method of installation.

Analytical procedures to calculate the shear strength of reinforced concrete beams wrapped with externally bonded FRP sheets have been reported.[1,5] The effect of FRP plates on the crack inclination angle and the shear capacity of concrete beams has been studied analytically.[3] Tests have been reported on the shear strength of concrete beams strengthened with epoxy-bonded unidirectional CFRP strips.[4] The influence of externally bonded GFRP laminates on the failure mechanisms of flexure and shear of both damaged and undamaged concrete beams has been studied experimentally.[6] The effectiveness of composite fabrics made of aramid, E-glass and graphite fibers on the shear capacity of T-beams has been studied.[7] The authors have reported that the ultimate shear strength of tested beams is increased from 60% to 150%. The shear strength of concrete beams bonded with CFRP fabric has been obtained experimentally and theoretically.[8]

The main objective of this investigation is to study the effectiveness of unidirectional CFRP fabric supplied by Fiber Reinforced Systems (FRS) in increasing the shear strength of concrete beams. The objective is achieved by conducting the following tasks: (i) Shear testing of concrete beams wrapped with four different configurations of CFRP fabric; (ii) Calculating the effect of CFRP fabric on the shear strength; (iii) Evaluating the failure modes; and (iv) Developing an analytical procedure to calculate the shear strength of concrete beams wrapped with FRP composites; and (v) Comparing the analytical calculations with experimental results.

3 Research Significance

The problem of shear is a complex phenomenon and both the shear strength and mode of failure are influenced by many factors. The shear capacity and the associated failure modes of concrete beams depend mainly on the configuration of CFRP fabric wrapped to the beam. Strengthening for shear by wrapping the beams with CFRP fabric is less investigated compared to the flexural strengthening. This paper demonstrates both experimentally and analytically the shear strength of concrete beams wrapped with different configurations of CFRP fabric, which will provide guidelines for shear strengthening using CFRP fabric and a database for further research in this field.

4 Test Specimens

Shear tests are conducted up to failure on two concrete control beams and twelve concrete beams wrapped with four different configurations of CFRP fabric. The CFRP fabric is a stitched unidirectional sheet of 0.18 mm thick supplied by Fiber Reinforced Systems (FRS) of Columbus, Ohio. The length, breadth and depth (ℓ x b x d) of all concrete beams is kept as 2,134 mm x 230 mm x 380 mm. Each concrete beam is reinforced with two 25 mm dia. steel bars for tension and two 9 mm dia. steel bars for compression along with 9 mm dia. Steel bars at a spacing of 300 mm center-to-center for shear reinforcement (Fig. 1). The effective span of all beams is kept as 1,830 mm.

The concrete control beams are designated as SB1 and SB2 respectively. Four beams wrapped with one layer of CFRP fabric inclined at an angle of 90° to the longitudinal axis (SB3-90, SB4-90, SB5-90 and SB6-90), and two beams wrapped with one layer of CFRP fabric inclined at an angle of 90° with an additional layer of CFRP fabric on both sides of the web inclined at an angle of 0° (SB7-90-0 and SB8-90-0) are fabricated. Four beams wrapped with one layer of CFRP fabric inclined at an angle of ± 45° (SB9-45, SB10-45, SB11-45 and SB12-45), and two beams wrapped with one layer of CFRP fabric inclined at an angle of ± 45° with an additional layer of CFRP fabric on both sides of the web inclined at an angle of 0° (SB13-45-0 and SB14-45-0) are also fabricated. Beams wrapped with CFRP fabric inclined at an angle of 90°, 0° and 45° are shown in Fig. 2. The details of the beams are presented in Table 1.

5 Material Properties

Concrete with compressive strength of 31 MPa and steel with yield strength of 414 MPa are used. The ultimate tensile stress (f_{fu}) and Young's Modulus (E_f) of CFRP fabric are determined by conducting tension tests on coupons cut from the fabric. The coupons are cut to the size of 1015 mm x 25 mm and tested using a universal testing machine (UTM) with stress control. The Young's modulus and the ultimate tensile stress of CFRP fabric are calculated from the load/strain curves and presented in Table 2. The properties of epoxies used for bonding the CFRP fabric are also presented in Table 2.

6 Bonding of CFRP Fabric

The bonding surface of the concrete beam is made rough to a coarse sand paper texture by scarifying it with a toothed grinder and cleaning it with an air blower. The concrete surface is made free of all apparent moisture. The bonding surface of the CFRP fabric is cleaned with acetone. A two-component epoxy primer is mixed thoroughly and applied to the concrete surface, and allowed to dry for thirty minutes under laboratory ambient conditions. A thick layer of two-component saturating epoxy is applied over the primer on the concrete surface using a paint roller. The CFRP fabric is rolled on the concrete surface, and pressed into place at the center and moved toward the ends. The CFRP fabric is kept tight and wrinkles free. A thick layer of saturating epoxy is applied over the CFRP fabric. The paint roller is used to remove any trapped air pockets and to work the saturating epoxy into the fabric. After thirty minutes an additional layer of saturating epoxy is applied and the above procedure is repeated to bond additional layers of CFRP fabric. The concrete beams, bonded with CFRP fabric, are allowed to cure for seven days at room temperature.

7 Test Details

The test setup shown in Fig. 1(a) is used. The load is applied using a hydraulic jack of 1,800 kN capacity, and transmitted through a rectangular plate (560 mm x 230 mm x 50 mm) to the beam. Hydraulic jacks having 184 mm ram and 150 mm stroke are used for testing. The top of the ram is provided with a spherical cap so that if any tilting of the plate occurs while loading, the spherical cap adjusts in such a way that only a perpendicular load is applied to the beam. A load cell is used to measure the load applied by the jacks. A rubber pad with a thickness of 13 mm is placed between the beam and the steel plate in order to minimize the abrasion between the steel plate and the beam while loading.

Electrical resistance disposable strain gages 6.35 mm long manufactured by Vishay Measurements Group are used on the CFRP fabric. Reusable strain gages 76 mm long manufactured by Bridge Diagnostics are used on the concrete side of the beam to measure the compressive strains. Out-of-plane deflections are measured using Linear Variable Deflection Transducers (LVDT) manufactured by Sensotec, Ohio. The position of strain gages (SG) and LVDTs are shown in Fig. 3. The beams are loaded according to the following sequences: (i) load cycle from zero to 53 kN and back to zero. The cycle is repeated five times to study the response of the beams under cyclic loading; and (ii) load from zero to failure. The strain gages, LVDTs and load cell are connected to a data acquisition system. The data is recorded and stored in a computer at an interval of 1 sec. during loading.

8 Failure Pattern

The reinforced concrete control beams SB1 and SB2 fail due to shear followed by crushing of concrete at the loading point. After failure, flexural and shear cracks are observed in the beams. The failure pattern of the concrete control beam SB2 is shown in Fig. 4.

The concrete beams SB3-90, SB4-90, SB5-90 and SB6-90, and SB7-90-0 and SB8-90-0 fail due to rupture and separation of CFRP fabric followed by shear-compression failure. Hereinafter the term separation implies that, at failure, the carbon fabric separated from the beam with a portion of the concrete cover attached to the fabric. The separation of CFRP fabric is observed near the support B (Fig. 1) and extends towards the mid-span. At failure, the separation of fabric sound is heard followed by load shedding. After failure, the CFRP fabric is cut and removed from the concrete surface to see the crack pattern. Flexural and shear cracks are observed in the beams. No crushing of concrete is observed at the loading point. The separation of CFRP fabric with the concrete cover bonded to the fabric indicates the existence of strong bond between the concrete surface and CFRP fabric. The failure pattern of the beams SB5-90 and SB8-90-0 is shown in Figs. 5 and 6 respectively.

The concrete beams SB9-45, SB10-45, SB11-45 and SB12-45, and SB13-45-0 and SB14-45-0 fail due to separation of CFRP fabric followed by shear failure. The separation of CFRP fabric is observed near the support B (Fig. 1) and extends towards the mid-span. At failure, a blast like sound is heard followed by load shedding. After failure, the CFRP fabric is cut and separated from the concrete surface to inspect the crack pattern. Shear cracks are observed in the beams, and no flexural cracks or crushing of concrete at the loading point were present. The failure pattern of the beams SB9-45 and SB13-45-0 is shown in Figs. 7 and 8 respectively.

9 Test Results and Discussion

9.1 Test Results

The experimental load/centerline deflection curves for beams SB3-90, SB4-90, SB5-90, SB6-90 and SB8-90-0 are shown in Fig. 9, and in Fig. 10 for beams SB9-45, SB10-45, SB11-45, SB12-45, SB13-45-0 and SB14-45-0. The pattern of the curves in Fig. 9 indicates that beams SB3-90, SB4-90, SB5-90 and SB6-90, and SB8-90-0 fail after sufficient warning. The pattern of the curves in Fig. 10 indicates that the beams SB9-45, SB10-45, SB11-45 and SB12-45, and SB13-45-0 and SB14-45-0 fail without sufficient warning. The load/strain curves for cyclic loading and up to failure are plotted for all beams. The typical load/strain curves for cyclic loading for beam SB11-45 is shown in Fig. 11. The pattern of the curves indicates that the stiffness of the beam SB11-45 remains constant at cyclic loading. The stiffness of all other beams also remains constant under cyclic loading.

The failure load is obtained from the load/centerline deflection curves using the “top of the knee method”. The failure load according to this method is essentially the maximum load prior to load shedding. The failure loads with their corresponding failure modes are presented in Table 3. The average value of failure load of the control beams SB1 and SB2 is calculated (Tables 3) and used as a baseline value for comparison with the beams wrapped with CFRP fabric. The percentage increase in shear strength due to wrapping of CFRP fabric is calculated and presented in Tables 3.

The centerline deflection of the beams at a service load of 53 kN, and maximum strain in CFRP fabric at service load and at failure load are presented in Table 4. The average value of centerline deflection under service load of beams wrapped with different configurations of CFRP fabric varies from 0.36 mm to 0.64 mm and at failure load varies from 5.61 mm to 20.65 mm (Table 4). The maximum compressive strain observed in CFRP fabric at service load varies from 2×10^{-6} to 103×10^{-6}, and tensile strain varies from 12×10^{-6} to 55×10^{-6}. The maximum tensile strain observed in CFRP fabric at failure varies from 610×10^{-6} to 7028×10^{-6}.

9.2 Discussion

The failure load of all beams wrapped with CFRP fabric are compared with the baseline values and the percent increase in strength is calculated (Table 3). The average value of shear strength is increased up to 14% on beams SB3-90, SB4-90, SB5-90 and SB6-90, 18% on beams SB7-90 and SB8-90, 33% on beams SB9-45, SB10-45, SB11-45 and SB12-45, and 33% on beams SB13-45-0 and SB14-45-0. Although beams SB13-45-0 and SB14-45-0 are bonded with additional layers of CFRP fabric at an angle of 0° compared to beams SB9-45, SB10-45, SB11-45 and SB12-45, the average value of increase in shear strength, compared to the baseline beams, is the same in both sets of beams. The addition of horizontal layers of CFRP fabric on beams wrapped with CFRP fabric at an angle of ±45° does not increase the strength, but it reduces the centerline deflection at failure load. Based upon the experimental study it is concluded that the shear strengthening of beams with CFRP fabric inclined at an angle of ± 45° is more efficient and the maximum increase in shear strength is up to 33%.

10 Shear Capacity of Beams with Web-Bonded FRP Fabric

The nominal shear strength of a concrete beam wrapped with FRP fabric can be calculated as;

$$V_n = V_c + V_s + V_f \tag{1}$$

in which V_c = shear strength of concrete,
V_s = shear strength of steel stirrups and
V_f = the shear strength of FRP fabric.

The shear strength of concrete is calculated as; [2]

$$V_c = \frac{\sqrt{f_c^{'}}}{6} b_w d \tag{2}$$

in which $f_c^{'}$ = specified compressive strength of concrete,

b_w = breadth of concrete beam (Fig. 12) and

d = distance between the extreme compression fiber to the centroid of tension reinforcement (Fig. 12).

The shear capacity of steel stirrups can be calculated using the equation proposed by Malek and Saadatmanesh[3] as;

$$V_s = f_y A_v \frac{h_v}{s \tan\theta_c} \tag{3}$$

in which f_y = yield stress of shear reinforcement,

A_v = total area of shear reinforcement,

h_v = height of closed stirrup (Fig. 12)

s = spacing of shear reinforcement and

θ_c = angle of crack inclination.

The angle of crack inclination θ_c of the wrapped beam is calculated using the procedures proposed by Malek and Saadatmanesh.[3]

The shear strength of FRP fabric V_f is calculated using the equation proposed by Khalifa et al[1] as;

$$V_f = f_{fe} t_f d (\sin\theta + \cos\theta) \tag{4}$$

in which f_{fe} = effective stress in FRP fabric,

t_f = thickness of the FRP fabric,

d = effective depth of concrete section and

θ = angle of fiber orientation (Fig. 12)

The effective stress f_{fe} of FRP fabric in Eqn. (4) is calculated using the equation proposed by Khalifa et al[1] as;

$$f_{fe} = R f_{pu} \tag{5}$$

in which R = ratio of effective strain to ultimate strain and

f_{fu} = ultimate tensile stress of FRP fabric.

The value R is calculated using the equation proposed by Khalifa et al[1] as;

$$R = 0.5622(\rho_f E_f)^2 - 1.2188(\rho_f E_f) + 0.778 \leq 0.50 \tag{6}$$

in which E_f = Young's modulus of FRP fabric and

ρ_f = shear reinforcement ratio of FRP fabric.

11 Comparison of Analytical Calculations with Experimental Results

The shear strength of all beams is calculated using the presented analytical procedure and compared with the experimental results (Table 3). The mean value of P_e/P_a (Experimental failure load/Analytical failure load) varies from 1.12 to 1.33. The analytical calculations underestimate the failure load of beams by 18% on beams wrapped with CFRP fabric at 90°, 13% on beams wrapped with CFRP fabric at 90° and 0°, 33% on beams wrapped with CFRP fabric at ± 45°, and 30% on beams wrapped with CFRP fabric at ± 45° and 0°.

12 Summary and Conclusions

Shear tests are conducted on two concrete control beams and twelve concrete beams wrapped with CFRP fabric. The increase in shear strength of concrete beams due to wrapping of CFRP fabric is calculated from the test results. An analytical procedure based on the equations proposed by Khalifa et al,[1] and Malek and Saadatmanesh [3] is presented to predict the shear strength of concrete beams wrapped with FRP fabric. The shear strength of all tested beams is calculated using the presented analytical procedure and compared with the experimental results.

The following conclusions are drawn based on the experimental and analytical studies carried out under this investigation.

(iv) The shear strength is increased up to 33% on concrete beams wrapped with unidirectional CFRP fabric at an angle of $\pm 45°$ to the longitudinal axis of the beam.

(v) The presented analytical procedure underestimates the shear strength of concrete beams wrapped with CFRP fabric at an angle of $\pm 45°$ up to 33%.

(vi) Further tests on the shear strength of concrete beams are to be conducted and the analytical procedure has to be refined.

Table 1: Test Specimens

Specimen	Size of the beam (l x b x d) (mm)	Effective span (mm)	STRENGTHENING DETAILS OF CFRP FABRIC			
			Number of Layers			Thickness
			Inclined at 0°	Inclined at 90°	Inclined at ±45°	(mm)
SB1	2130 x 230 x 380	1830	-	-	-	-
SB2	2130 x 230 x 380	1830	-	-	-	-
SB3-90	2130 x 230 x 380	1830	-	1	-	0.18
SB4-90	2130 x 230 x 380	1830	-	1	-	0.18
SB5-90	2130 x 230 x 380	1830	-	1	-	0.18
SB6-90	2130 x 230 x 380	1830	-	1	-	0.18
SB7-90-0	2130 x 230 x 380	1830	1	1	-	0.18
SB8-90-0	2130 x 230 x 380	1830	1	1	-	0.18
SB9-45	2130 x 230 x 380	1830	-	-	1	0.18
SB10-45	2130 x 230 x 380	1830	-	-	1	0.18
SB11-45	2130 x 230 x 380	1830	-	-	1	0.18
SB12-45	2130 x 230 x 380	1830	-	-	1	0.18
SB13-45-0	2130 x 230 x 380	1830	1	-	1	0.18
SB14-45-0	2130 x 230 x 380	1830	1	-	1	0.18

Table 2: Material Properties of CFRP Fabric and Epoxies

	Properties			
CFRP fabric	Thickness (mm)	Ultimate Tensile Stress (σ_u) (N/mm)	Modulus of Elasticity (GPA)	Ultimate Strain (%)
	0.18	490	228	1.80
	Properties			
Structural epoxy	Tensile strength (MPa)	Adhesion (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)
	61	> 2	100	2,140
Saturating epoxy	62	> 2	103	2,410

Table 3: Effect of CFRP Fabric on the Shear Capacity of Concrete Beams

Specimen	CENTERLINE DEFLECTION		LOAD		Mode of failure
	At Service Load[2] (mm)	At Failure Load (mm)	Failure Load (kN)	% Increase in Strength	
SB1	-	-	378	-	Shear fai.ure and crushing of concrete at the loading point
SB2	-	-	416	-	Shear failure and crushing of concrete at the loading point
Baseline[1]	-	-	397	-	-
SB3-90	0.13	18.82	463	17	Rupture, delamination of CFRP fabric followed by shear-compression failure
SB4-90	0.41	18.52	435	9	Rupture, delamination of CFRP fabric followed by shear-compression failure
SB5-90	0.53	28.35	469	18	Rupture, delamination of CFRP fabric followed by shear-compression failure
SB6-90	0.74	16.89	436	10	Rupture, delamination of CFRP fabric followed by shear-compression failure
Average	0.45	20.65	451	14	-
SB7-90-0	-	-	482	22	Rupture, delamination of CFRP fabric followed by shear-compression failure
SB8-90-0	0.64	9.88	454	14	Rupture, delamination of CFRP fabric followed by shear-compression failure
Average	0.64	9.88	468	18	-
SB9-45	0.28	9.40	529	33	Delamination of fabric followed by shear failure
SB10-45	0.25	10.34	547	38	Delamination of fabric followed by shear failure
SB11-45	0.53	7.39	509	28	Delamination of fabric followed by shear failure
SB12-45	0.36	8.13	531	34	Delamination of fabric followed by shear failure
Average	0.36	8.82	529	33	-
SB13-45-0	0.53	3.45	513	29	Delamination of fabric followed by shear failure
SB14-45-0	0.28	7.75	542	37	Delamination of fabric followed by shear failure
Average	0.41	5.60	528	33	-

[1] The average values of SB1 and SB2 are used as baseline
[2] Service load = 53 kN

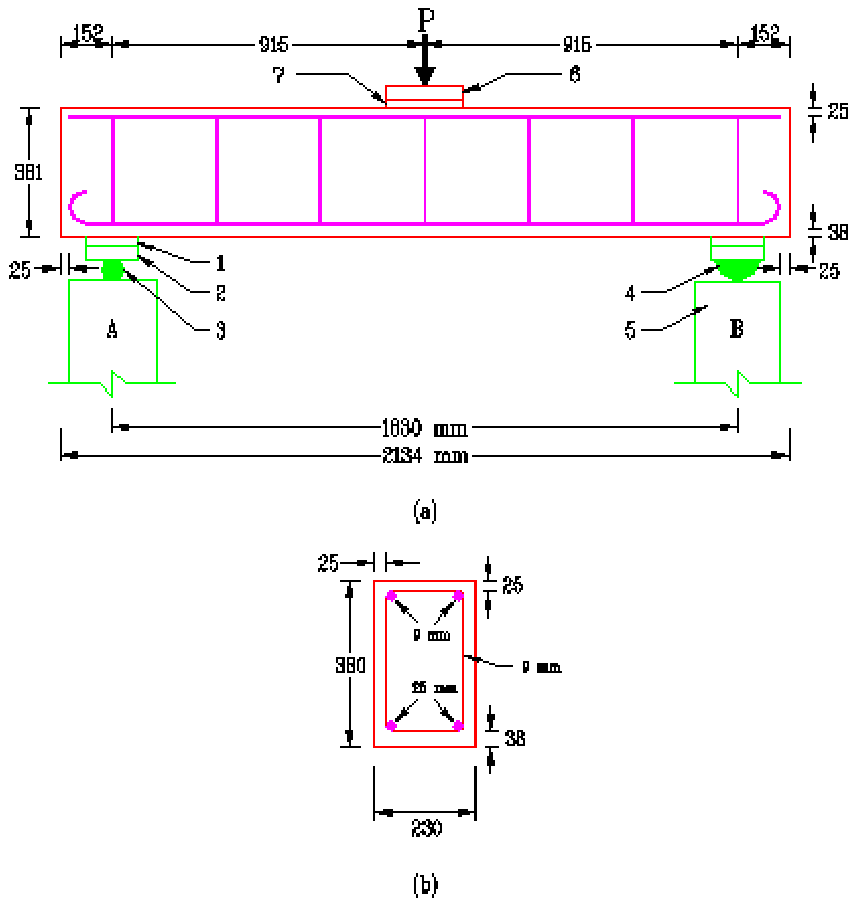
Table 4: Strain in CFRP Fabric at Service Load and at Failure Load

Specimen	Maximum Compressive Strain at Sevice Load	Maximum Tensile Strain at Service Load	Maximum Tensile Strain at Failure Load
SB3-90	0.000005	0.000012	0.001966
SB4-90	0.000007	0.000017	0.004536
SB5-90	0.000004	0.000026	0.001449
SB6-90	0.000005	0.000019	0.001486
SB7-90-0	0.000091	0.000055	0.002187
SB8-90-0	0.000082	0.000010	0.007028
SB9-45	0.000007	0.000018	0.004742
SB10-45	0.000002	0.000028	0.004290
SB11-45	0.000019	0.000026	0.004871
SB12-45	0.000024	0.000015	0.004046
SB13-45-0	-	0.000019	0.000732
SB14-45-0	0.000103	0.000015	0.000610

Table 5: Comparison of Analytical Calculations with Experimental Results

Specimen	FAILURE LOAD			Mean Value
	P_a (kN)	P_e (kN)	$\frac{P_e}{P_a}$	–
SB1	355	378	1.07	1.12
SB2	355	416	1.17	
SB3-90	381	463	1.21	1.18
SB4-90	381	435	1.14	
SB5-90	381	469	1.23	
SB6-90	381	436	1.14	
SB7-90-0	413	482	1.17	1.13
SB8-90-0	413	454	1.10	
SB9-45	397	529	1.33	1.33
SB10-45	397	549	1.38	
SB11-45	397	509	1.28	
SB12-45	397	531	1.34	
SB13-45-0	407	513	1.26	1.30
SB14-45-0	407	542	1.33	

P_e - Experimental failure load
P_a - Analytical failure load



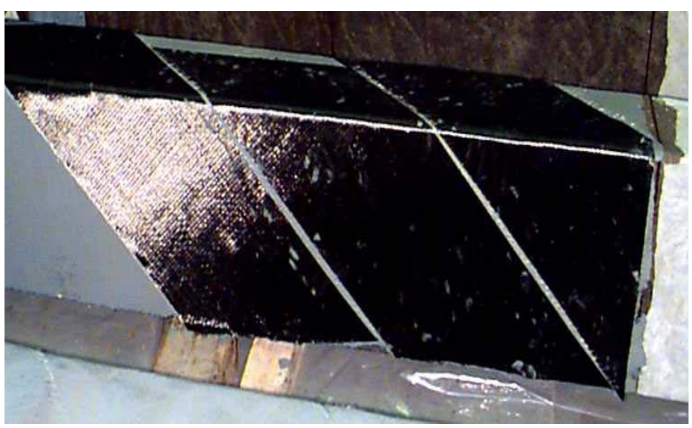
All dimensions are in mm

1. 560 mm x 152 mm x 25 mm A36 Steel plate
2. 560 mm x 152 mm x 13 mm Rubber pad
3. 64 mm dia. A36 Solid steel plate
4. 128 mm dia. A36 Solid steel half round
5. Supporting members
6. 560 mm x 230 mm x 51 mm A36 Steel plate
7. 560 mm x 230 mm x 13 mm Rubber pad

Figure 1: (a) Test Setup; (b) Reinforcement Details

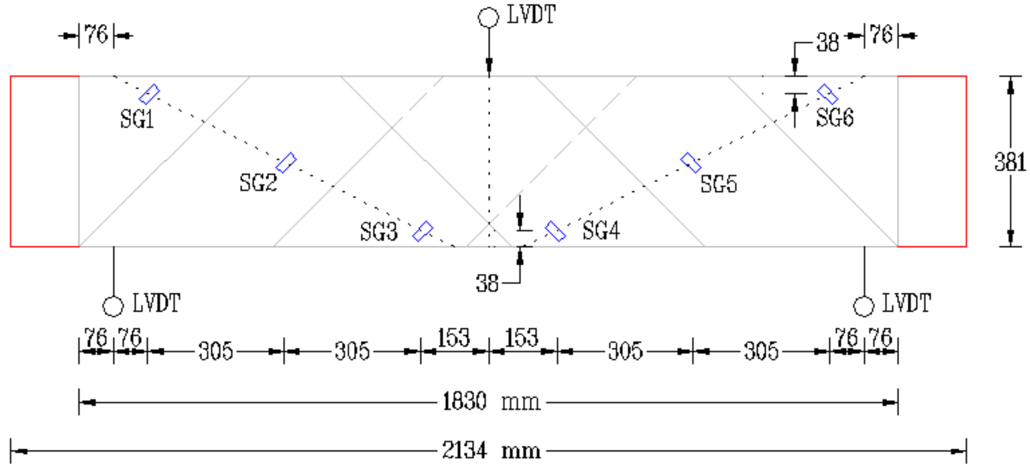
(a)

(b)



(c)

Figure 2: Strengthening Details: (a) CFRP Fabric Inclined at 90°; (b) CFRP Fabric Inclined at 0°; and (c) CFRP Fabric Inclined at 45°



All dimensions are in mm
SG1 to SG6 - Strain Gages
LVDT - Linear Variable Deflection Transducers

Figure 3: Position of Strain Gages and Linear Variable Deflection Transducers

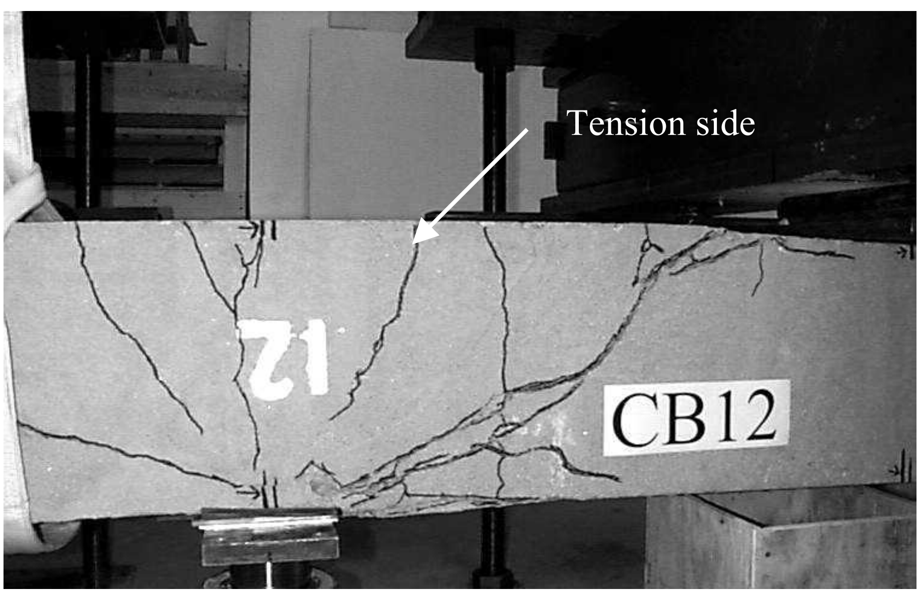


Figure 4: Failure Pattern of the Control Beam SB2

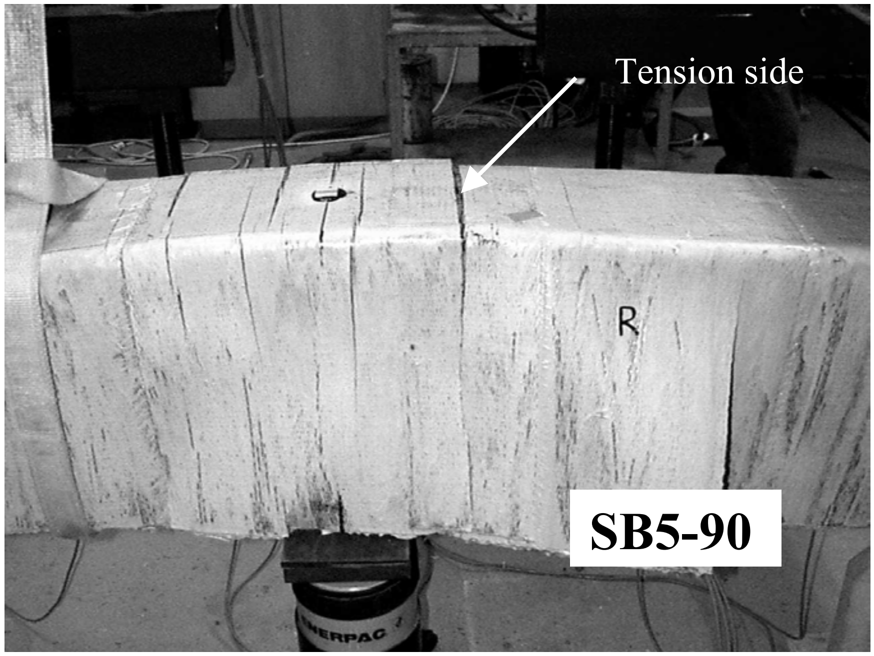


Figure 5: Failure Pattern of the Beam Bonded with CFRP Fabric inclined at 90°; Rupture and Delamination of CFRP Fabric

Figure 6: Failure Pattern of the Beam Bonded with CFRP Fabric Inclined at 90°and 0°; Rupture and Delamination of CFRP Fabric

Figure 7: Failure Pattern of the Beam Bonded with CFRP Fabric Inclined at ±45°; Shear and Delamination of CFRP Fabric

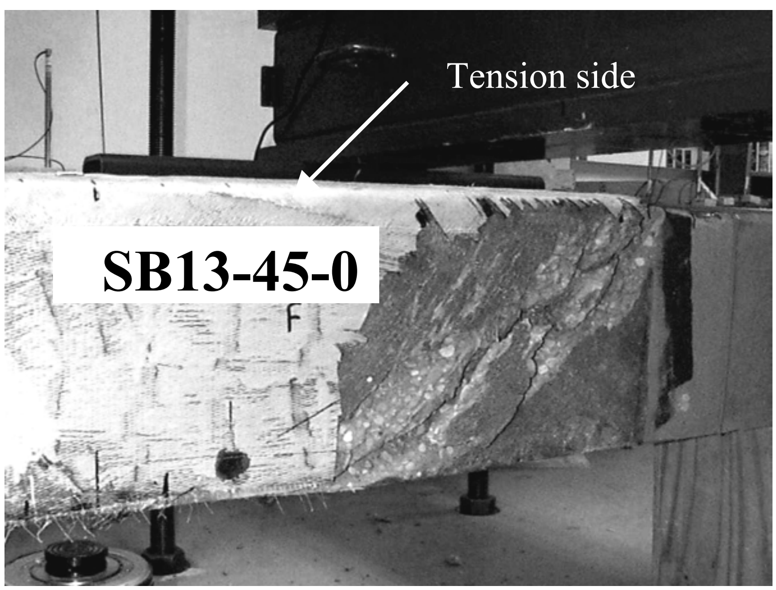


Figure 8: Failure Pattern of the Beam Bonded with CFRP Fabric inclined at ± 45° and 0°; Shear and Delamination of CFRP Fabric

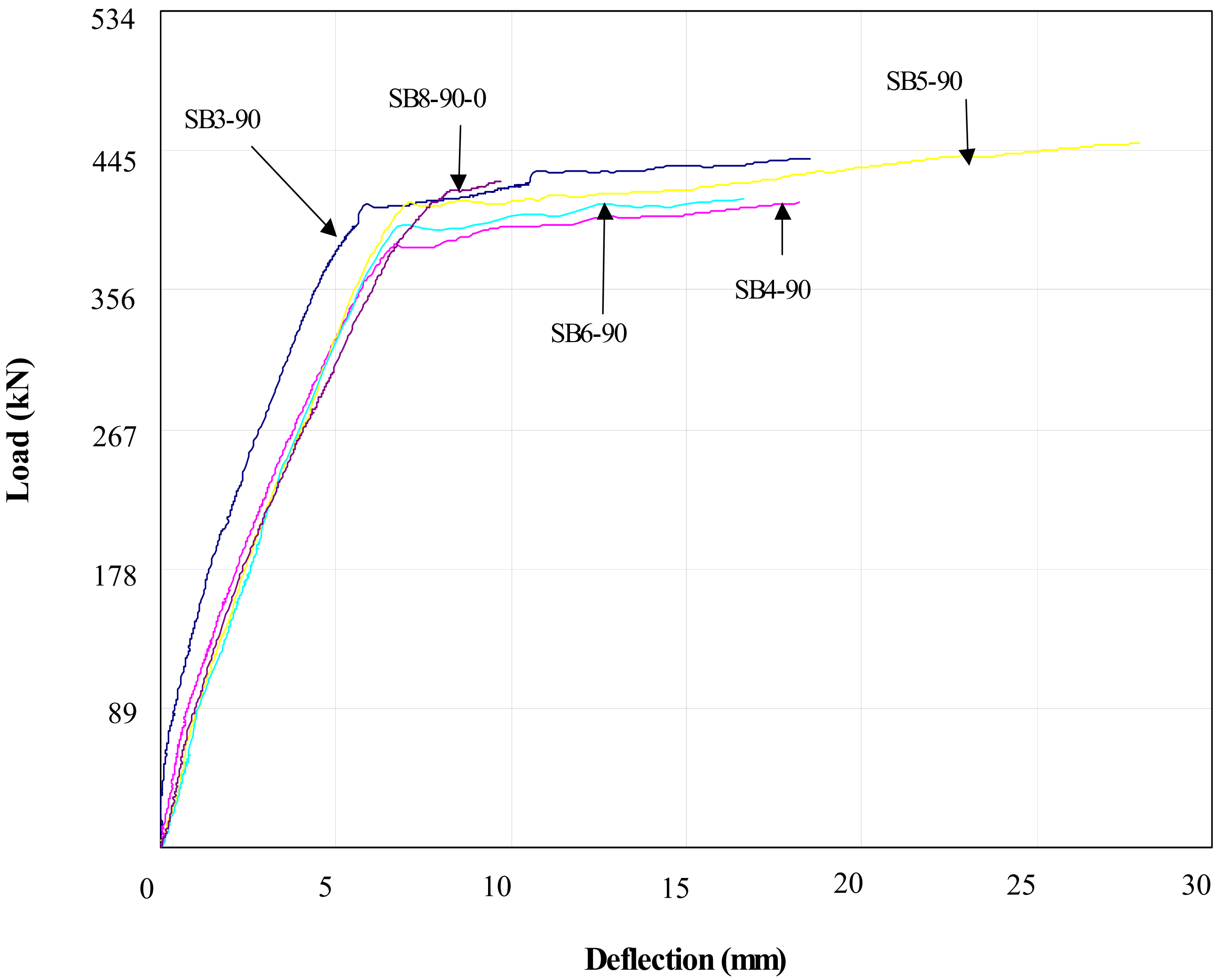


Figure 9: Load/Centerline Deflection Curves for Beams Wrapped with CFRP Fabric Inclined at 90°, and 90° with 0°

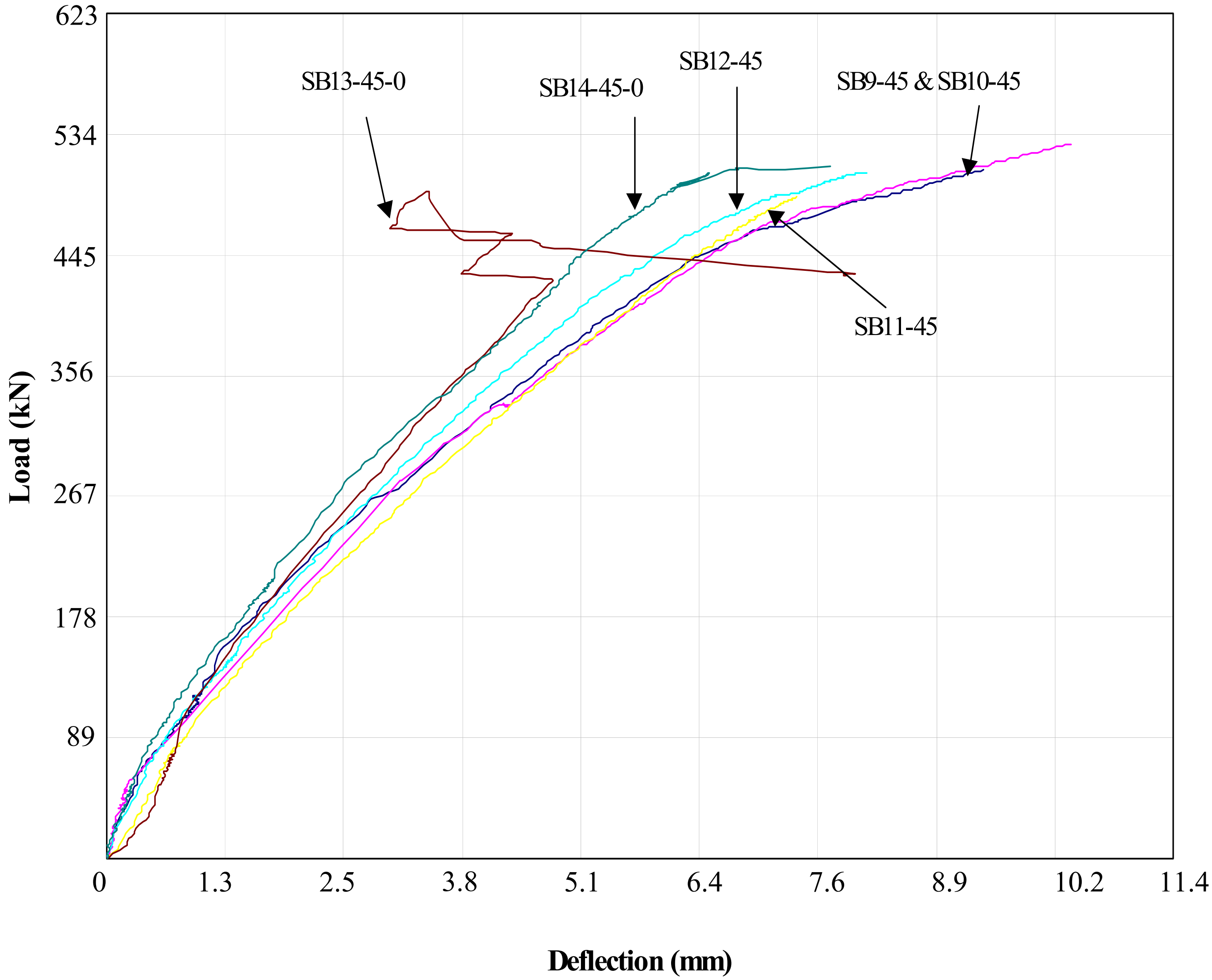


Figure 10: Load/Centerline Deflection Curves for Beams Wrapped with CFRP Fabric Inclined at 45°, and 45° with 0°

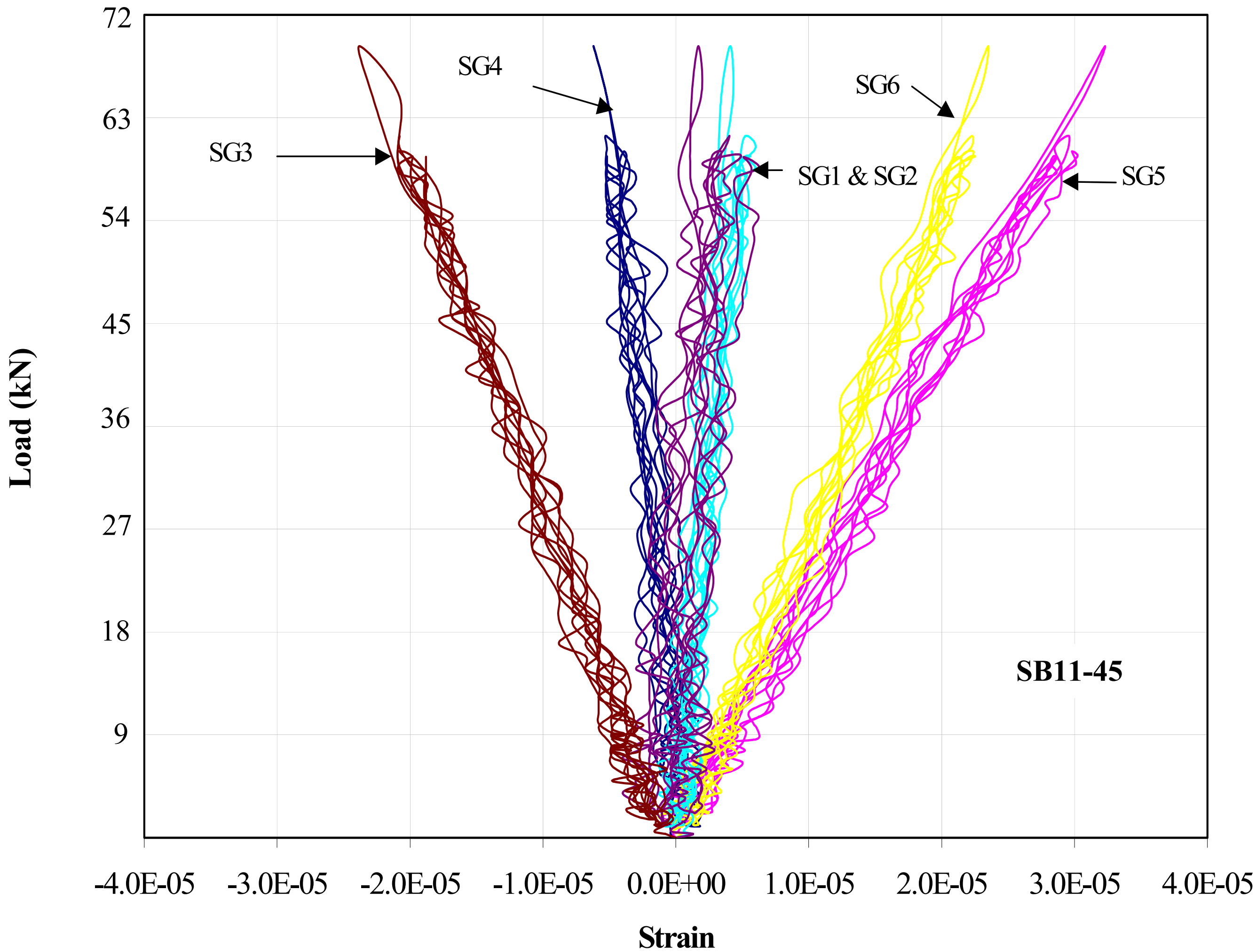
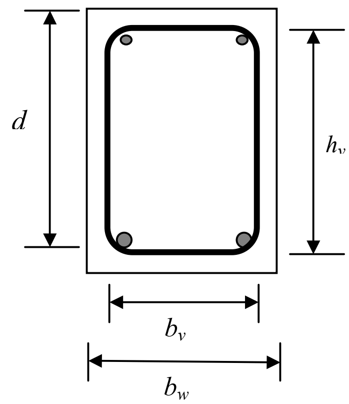
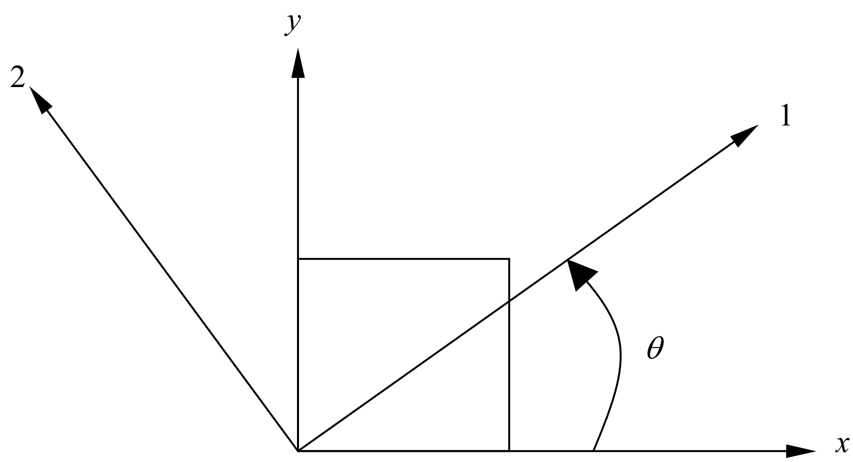


Figure 11: Typical Load/Strain Curves for Beams Wrapped with CFRP Fabric Inclined at ±45°



(a)



(b)

Figure 12: (a) Beam Cross Section; (b) Fiber Orientation Angle

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