

**STUDY ON REINFORCED CONCRETE (RC)
BEAMS FLEXURALLY STRENGTHENED
WITH CARBON AND ARAMID FIBER
REINFORCED POLYMER (FRP) STRAND
SHEETS**

PARDEEP KUMAR



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

PARDEEP KUMAR

DEPARTMENT OF CIVIL ENGINEERING

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CERTIFICATE

This is to certify that the thesis entitled “**STUDY ON REINFORCED CONCRETE (RC) BEAMS FLEXURALLY STRENGTHENED WITH CARBON AND ARAMID FIBER REINFORCED POLYMER (FRP) STRAND SHEETS**”, being submitted by **Mr. Pardeep Kumar** to the **Indian Institute of Technology Delhi**, for the award of ‘**Doctor of Philosophy**’ in Department of Civil Engineering is a record of the bonafide research work carried out by him under our supervision and guidance. He has fulfilled the requirements for submission of this thesis, which to the best of our knowledge has reached the requisite standard.

The material contained in the thesis has not been submitted in part or full to any other University or Institute for the award of any other degree or diploma.

(Prof. B. Bhattacharjee)
Emeritus Professor
Department of Civil Engineering
Indian Institute of Technology Delhi
New Delhi-110016, India

(Dr. Shashank Bishnoi)
Associate Professor
Department Civil Engineering
Indian Institute of Technology Delhi
New Delhi-110016, India

Date:

New Delhi

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ABSTRACT

Reinforced concrete members are strengthened with Fiber Reinforced Polymer (FRP) composites in the form of laminates and fabrics, using externally bonded (EB) technique for strengthening. However, the utilisation of FRP composites capacity is limited due to the debonding phenomenon existing in the strengthening system, due to FRP and concrete interfacial shear stress. Presently, prestressing and anchors are in use to avoid or delay FRP debonding. A new type of carbon and aramid FRP, in the form of strand sheets was developed a few years ago and is not been adequately investigated upon for the purpose of strengthening. It may noted that such strand sheets likely to enhance the bond strength due to inherent gap between the fibre strands. These strands are less than 1.0 mm in diameter is woven with thread to make the desired width of sheet. These gaps allow the epoxy (adhesive) to cover the entire out surface of each strand, resulting a better bond mechanism as compared to plate (laminate), which is attached to the concrete surface with one face only. In this study, the effectiveness of CFRP and AFRP strand sheets in the flexural strengthening of RC members with and without CF-anchor were investigated experimentally. The modified procedure was proposed for double lap shear test developed by Larralde *et al.*(2001) and maximum bond widths of double lap shear test have also been proposed in relation to the flexural strength of concrete used in the test. The bond strength improvement was quantified by a modified procedure of double-lap shear test using strand sheets and laminates to establish the improved bonding behavior. A laboratory study to examine the effectiveness of strand sheets and to validate the shear stress obtained from the double-lap shear test was conducted on concrete beam specimens (with and without notch) strengthened with CFRP and AFRP strand sheets. Further, to validate the shear stress obtained from the double-lap shear test by the modified procedure and effectiveness of the strand sheets on reinforced concrete beams, experimental study was conducted using rectangular reinforced concrete (RC) beams with different types of FRP materials and their varying width ratio. The main parameters varied were width ratio (w_f/b) of high strength CFRP strand sheets (0.83 and 0.33) and for high modulus CFRP and AFRP strand sheets, it was kept as 0.33. The reinforced concrete (RC) beams were tested under four-point knife-edge loading. The experimental research includes tests on (1) un-strengthened RC beams, (2) RC beam strengthened with high strength CFRP laminate, high strength and high modulus CFRP strand sheets and AFRP

strand sheets, (3) CF-anchors as end anchorages on RC beams strengthened with CFRP and AFRP strand sheets keeping the width ratio as 0.33. The proposed modified procedure of double-lap shear test was validated successfully in the strengthened specimens. The relative contribution of the CFRP and AFRP strand sheets to the bending moment capacity was observed to be significantly higher than that in the case of the CFRP laminate. The failure mode debonding (FD) shifted to concrete cover separation (CCS) with increase in width ratio (w_f/b) from 0.33 to 0.83 in high strength CFRP strand sheets, The specimen strengthened with high modulus CFRP strand sheets had a failure mode of rupture (FR). Further, CF-anchors successfully delayed the debonding of CFRP and AFRP strand sheets. Based on the observed failure modes, models for predicting the mechanical behavior of various systems were recommended. Overall, it was seen that the bending-moment capacity and ductility of the beams increased when strand sheets were used in comparison with laminates as a result of the improved bond. A further improvement was observed with the use of CF-anchors.

KEYWORDS: CFRP, AFRP, strand sheets, laminates, CF-anchors, end anchorage, PC beam, RC beam, double-lap shear test (DLST), FRP tensile strain, debonding.

सारांश

सुदृढ़ीकरण के लिए बाहर से चिपकाने वाली तकनीक के द्वारा फाईबर प्रबलित पोलिमर (FRP) मिश्रण की प्लेट व फेब्रिक का प्रयोग करके कंक्रीट के विभिन्न अवयवों को प्रबलित किया गया। हालाँकि FRP एवं कंक्रीट की अंतर्सतहों (interfacial) पर कर्तन (shear stress) दबाव के कारण सुदृढ़ीकरण की प्रणाली में जोड़ /चिपक हटने के कारण FRP मिश्रण के प्रयोग की कुछ सीमाएँ हैं। वर्तमान में जोड़/चिपक खत्म होने से बचने के लिए प्रबलन एवं एंकर का प्रयोग किया गया। कुछ वर्षों पहले ही कार्बन और एरामिड FRP की स्ट्रैंड शीट (strand sheets) विकसित की गयी जिसके सुदृढ़ीकरण में प्रयोग पर प्रयाप्त रूप से अनुसंधान नहीं किया गया। यह पाया गया है कि इस तरह की स्ट्रैंड शीट में प्रयुक्त फाईबर रेशों में उचित फासला होने के कारण जोड़ की सामर्थ्य को बढ़ाता है। स्ट्रैंड शीट की वांछित मोटाई बनाने के लिए 1 मिमी से कम व्यास के रेशों को धागों के साथ बुना जाता है। स्ट्रैंड के बीच उचित फासले होने की वजह से प्रत्येक स्ट्रैंड की बाहरी सतह पर पूरी तरह से इपोकसी (चिपकाने वाल पदार्थ) पहुँच जाती है, क्योंकि प्लेट की केवल एक सतह ही कंक्रीट से चिपकाई जाती है, जिसके कारण प्लेट (परत) की अपेक्षा CFRP तथा AFRP के स्ट्रैंड शीट का कंक्रीट से बेहतर जोड़ उत्पन्न होता है। इस अध्ययन में CFRP तथा AFRP की स्ट्रैंड शीट को एंकर व बिना एंकर के प्रबलित कंक्रीट की आनमनी सामर्थ्य (Flexural strength) की प्रभावशीलता पर प्रयोग किया गया है। लैरालदे आदि 2001 (Larralde et al. 2001) द्वारा विकसित डबल लैप कर्तन परिक्षण के लिए परिशोधित विधि को प्रस्तावित किया गया है और परिक्षण में प्रयोग की गयी कंक्रीट की आनमनी सामर्थ्य (Flexural strength) के अनुसार डबल लैप कर्तन परिक्षण की अधिकतम जोड़ क्षेत्र को प्रस्तावित किया गया है। जोड़ के बेहतर व्यवहार को स्थापित करने के लिए तथा एक परिभाषित जोड़ सामर्थ्य में सुधार के लिए लेमिनेट्स तथा स्ट्रैंड शीट का प्रयोग करते हुए डबल लैप अपरूपण परिक्षण की एक संशोधित विधि को अपनाया गया है। प्रयोगशाला में स्ट्रैंड शीट को जांचा गया है तथा प्रबलित कंक्रीट बीम को CFRP एवं AFRP द्वारा सुदृढ़ करके (कटाव और बिना कटाव के) डबल लैप कर्तन परिक्षण किया गया तथा प्राप्त कर्तन दबाव की पुष्टि की गयी और साथ ही स्ट्रैंड शीट की प्रभावशीलता को परखा गया। इससे आगे विभिन्न प्रकार की FRP पदार्थों का प्रयोग करके आयताकार

प्रबलित कंक्रीट बीम पर प्रयोगात्मक अध्ययन किया गया ताकि परिशोधित विधि द्वारा डबल लैप परिक्षण से प्राप्त कर्तन दबाव का पुष्टिकरण किया जा सके तथा कंक्रीट बीम पर स्ट्रैंड शीट की प्रभावशीलता को जांचा जा सके | इस प्रयोग में अलग अलग FRP पदार्थ तथा चौड़ाई अनुपात का प्रयोग किया गया | मुख्य मानदंड उच्च सामर्थ्य वाली CFRP स्ट्रैंड शीट का चौड़ाई अनुपात 0.83 और 0.33 एवं उच्च गुणांक वाली CFRP तथा AFRP की स्ट्रैंड शीट के लिए चौड़ाई अनुपात 0.33 रखा गया | प्रबलित कंक्रीट बीम का चाकू की धार वाले 4-पॉइंट वाली लोडिंग से परिक्षण किया गया | प्रयोगात्मक अनुसंधान में निम्नलिखित भी सम्मिलित हैं (1) बिना सुदृढ़ की कंक्रीट बीम, (2) सुदृढ़ की हुई कंक्रीट बीम जिसमें उच्च सामर्थ्य वाली CFRP स्ट्रैंड शीट का प्रयोग किया गया साथ ही उच्च सामर्थ्य व उच्च गुणांक वाली CFRP की स्ट्रैंड शीट तथा AFRP स्ट्रैंड शीट का भी प्रयोग किया गया, (3) CFRP व AFRP की स्ट्रैंड शीट (चौड़ाई अनुपात 0.33 रखते हुए) से सुदृढ़ की हुयी प्रबलित कंक्रीट बीम के सिरों पर CF एंकर का प्रयोग किया गया | डबल लैप कर्तन परिक्षण की संशोधित प्रणाली को प्रस्तावित करके सफलतापूर्वक सुदृढ़ किये हुए नमूनों को विधिमान्य किया गया | CFRP तथा AFRP स्ट्रैंड शीट का परस्पर सम्बंधित योगदान में यह पाया गया है की CFRP परत का बालन गुरुत्व (Bending Moment) क्षमता सार्थक रूप अधिक थी | उच्च सामर्थ्य वाली CFRP स्ट्रैंड शीट की चौड़ाई अनुपात 0.33 से 0.83 करने पर फेल होने की घटना कंक्रीट के कवर अलग होने की शक्ल में बदल गया | जिन नमूनों में उच्च सामर्थ्य वाली CFRP स्ट्रैंड शीट का प्रयोग करने से फेल होने की प्रक्रिया CFRP स्ट्रैंड शीट टूटने से हुई है | CFRP व AFRP स्ट्रैंड शीट के जोड़ को CF एंकर के प्रयोग से विलंबित किया जा सकता है | Failure mode को देखने के बाद विभिन्न उपायों के मेकेनिकल व्यवहार की भविष्यवाणी हेतु मॉडल की संस्तुति की गयी है | कुल मिलाकर यह देखा गया है कि जब स्ट्रैंड शीट का प्रयोग संपीडन में किया गया तो बीम की नमित सामर्थ्य तथा तन्यता बढ़ गयी | CF एंकर के प्रयोग से और अधिक सुधर हुआ है |

संकेत शब्द : - CFRP, AFRP, स्ट्रैंड शीट, प्लेट, CF एंकर, end एंकरेज, कंक्रीट बीम, प्रबलित कंक्रीट बीम, डबल लैप कर्तन परिक्षण, प्लेट का हटना, FRP तन्य तनाव।

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LIST OF SYMBOLS

A strength reduction factor	=	ϕ
Additional reduction factor	=	ψ_f
Anchorage length	=	$l_{b,max}$
Applied bending moment	=	M
Applied cracking bending moment	=	$M_{cr,exp}$
Applied cracking load	=	$P_{cr,exp}$
Applied load	=	P
Applied ultimate bending moment	=	$M_{u,exp}$
Applied ultimate load	=	$P_{u,exp}$
Applied yielding bending moment	=	$M_{y,exp}$
Applied yielding load	=	$P_{y,exp}$
Area of compression steel	=	A_{s1}
Area of compression steel	=	A_{sc}
Area of FRP composites	=	A_f
Area of shear reinforcement	=	A_{sv}
Area of tensile steel	=	A_s
Area of tension steel	=	A_{st}
Area of tension steel	=	A_{s2}
Average crack spacing	=	S_{rm}
Centre of the gravity of the cross-section at stage of first crack	=	$y_{c,I}$
Characteristic Cube Compressive Strength of Concrete after 28 days (measured)	=	f_c
Characteristic cylindrical Compressive Strength of Concrete after 28 days (measured)	=	f'_c
Compression force in concrete	=	f_c

Compression forces in concrete	=	C_c
Compressive strain of concrete	=	ε_c
Concrete ultimate strain	=	ε_{cu}
Considered Cover for reinforcement	=	c
Cracked Moment of Inertia	=	I_{cr}
Depth of FRP composites from extreme compression zone	=	d_f
Depth of neutral axis	=	c
Depth of Neutral axis from top extreme compression zone of RC beams	=	N.A.
Depth to tensile reinforcement from the extreme compression fiber d'	=	d
Design strain of FRP	=	ε_{fd}
Design thickness of FRP composites	=	$.t_f$
Distance of neutral axis from the top extreme compression zone	=	x
Displacement ductility index	=	μ_{Δ}
Effective strain in FRP	=	ε_{fe}
Elastic modulus of FRP composites	=	E_f
Elastic modulus of steel	=	E_s
Energy absorption upto applied ultimate load	=	$EA_{u,exp}$
Energy absorption upto applied yielding load	=	$EA_{y,exp}$
Energy absorption after applied yielding load	=	EA_{yu}
energy absorption ductility index	=	μ_E
Environmental reduction factor	=	C_E
Experimental deflection at cracking load	=	$\Delta_{cr,exp}$
Experimental deflection at ultimate load	=	$\Delta_{u,exp}$
Experimental deflection at yielding load	=	$\Delta_{y,exp}$
Flexural resistance due to RC beam and FRP	=	M_r
Flexural strength of concrete	=	f_r
Glass transition temperature	=	T_g

Initial strain when bonding FRP was applied	=	ε_{bi}
Maximum crack spacing	=	$S_{r,max}$
Mean axial tensile strength of the concrete	=	f_{ctm}
Mean axial tensile strength of the concrete	=	f_{ctk}
Micro-strain	=	$\mu\varepsilon$
Modulus of Elasticity of Concrete	=	E_c
Modulus of elasticity of FRP composites	=	E_f
Modulus of rupture (Flexural Strength of Concrete)	=	f_b
Moment capacity	=	M_{Rd}
Moment contributed form FRP composite	=	M_{nf}
Moment contributed form steel	=	M_{ns}
Moment due to dead load	=	M_{DL}
Moment of inertia for the conversion section	=	I_o
Neutral axis form the top	=	k
Nominal flexural strength of the RC beam	=	M_n
Normalised BM contributed by FRP	=	$M_{FRP,exp}$
Numbers of layer of FRP composites	=	n
Observed shear stress between FRP composite and concrete substrata from double-lap shear test (DLST)	=	τ_{pre}
Observed shear stress between FRP composite and concrete substrata in RC beam	=	τ_{exp}
Overall depth of beam	=	h
Overall Depth of the Beam	=	D
Position of FRP from Top fiber compression	=	d_f
Prism compressive strength of concrete	=	f_c
Ratio of steel	=	ρ_s
Ration of FRP composites	=	ρ_f
Reduced cross-section of the strengthened beam	=	A_{red}
Reduced moment of the inertia of the total cross-section	=	$I_{I,red}$

Resistance factor of concrete	=	ϕ_c
Resistance factor of FRP composites	=	ϕ_{frp}
Resistance factor of steel	=	ϕ_s
Rupture strain	=	ε_{fu}
Self Weight of the Beam	=	W
Shear modulus of the adhesive	=	G_a
Spacing of shear Reinforcement	=	S
Span of the beam - Effective	=	l_{eff}
Static moment of the reduced cross-section of the strengthened beam	=	S_{red}
Strain at bottom level of FRP composite of strengthened RC beam at mid-span	=	SG_F
Strain at extreme top compression fiber zone of RC beam at mid-span	=	SG_C
Strain at level of reinforcement at bottom tension zone of RC beam at mid-span	=	SG_T
Strain at level of reinforcement at top compression zone of RC beam at mid-span	=	SG_{CB20}
Strain at mid-level of RC beam at mid-span	=	SG_M
Strain corresponding to f'_c	=	ε'_c
Strain in compression steel	=	ε_{s2}
Strain in steel reinforcement	=	ε_s
Strain in tension steel	=	ε_{s1}
Stress levels in FRP	=	f_{fe}
Stress levels in steel	=	f_s
Tensile force in steel	=	f_t
Tensile force, before debonding	=	F_d
Tensile strength corresponding to a strain value of 0.005	=	N_b
Tensile Strength in the FRP reinforcement at 1% strain	=	P_{frp}
Tensile strength of concrete	=	f_{ct}
Tensile Strength of Concrete	=	f_{ctm}

Tensile strength of concrete (Brazilian Test)	=	f_t
Tension forces in FRP	=	T_{frp}
Tension forces in steel	=	T_s
Tension forces in steel and FRP	=	T
The distance of tension reinforcement from extreme compression zone	=	d
Theoretical cracking moment	=	$M_{cr,theo}$
Theoretical ultimate bending moment	=	$M_{u,the}$
Analytical yielding bending moment	=	$M_{y,ana}$
Analytical ultimate bending moment	=	$M_{u,ana}$
Thickness of FRP composites	=	t_f
Total area of the conversion section	=	A_o
Total moment contributed from steel and FRP composites	=	M_{rd}
Ultimate compressive strain of concrete	=	ε_{cu}
Ultimate strain in FRP	=	ε_{fud}
Ultimate strain in FRP composites	=	ε_{frpu}
Ultimate tensile strain in FRP	=	f_{fu}
Ultimate Tensile Strength of CFRP Strand Sheet	=	f_{fu}
Width CFRP strand sheet	=	w_f
Width of FRP composite	=	b_{frp}
Width of the Beam	=	B
Width of the RC beam	=	b
Yield strain in steel	=	ε_y
Yield stress of steel (design)	=	f_{yd}
Young modulus of compression steel	=	E_{s2}
Young modulus of concrete	=	E_c
Young modulus of tension steel	=	E_{s1}

LIST OF ACRONYMS

Linear variable displacement transducer	=	LVDT
Reinforced concrete	=	RC
Plain concrete	=	PC
Electrical Strain gauge	=	SG
Fiber reinforced polymer	=	FRP
Carbon fiber reinforced polymer	=	CFRP
Glass fiber reinforced polymer	=	GFRP
Aramid fiber reinforced polymer	=	AFRP
Advance composite material	=	ACM
Double-lap shear test	=	DLST
Single lap shear test	=	SLS
Carbon fiber anchor	=	CF-anchor
Externally bonded	=	EB
Near surface mounted	=	NSM
Intermediate crack	=	IC
Critical diagonal crack	=	CDC
Plate-end	=	PE
Rupture of fiber composite	=	FR
Debonding of fiber composite	=	FD
Concrete cover separation	=	CCS
Yielding of steel followed by crushing of concrete	=	YS-CC
Iterative analytical procedure	=	IAP