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

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by

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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.

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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

सुद्रढ़ीकारण के लिए बाहर से चिपकाने वाली तकनीक के द्वारा फाईबर प्रबलित पोलिमर (FRP) मिश्रण की प्लेट व फेब्रिक का प्रयोग करके कंक्रीट के विभिन्न अवयवो को प्रबलित किया गया |हालाँकि FRP एवं कंक्रीट की अंतर्सतहों (interfacial) पर कर्तन (shear stress) दबाव के कारण सुद्रढ़ीकारण की प्रणाली में जोड़ /चिपक हटने के कारण FRP मिश्रण के प्रयोग की कुछ सीमाएं हैं |वर्तमान में जोड़/चिपक खत्म होने से बचने के लिए प्रबलन एवं एंकर का प्रयोग किया गया |कुछ वर्षो पहले ही कार्बन और एरामिड FRP की स्ट्रांड शीट (strand sheets) विकसित की गयी जिसके सुद्रढ़ीकारण में प्रयोग पर प्रयाप्त रूप से अनुसंधान नहीं किया गया |यह पाया गया है कि इस तरह की स्ट्रांड शीट में प्रयुक्त फाईबर रेशों में उचित फासला होने के कारण जोड़ की सामर्थ्य को बढाता है | स्ट्रांड शीट की वांछित मोटाई बनाने के लिए 1 मिमी से कम व्यास के रेशों को धागों के साथ बुना जाता है |स्ट्रांड के बीच उचित फासले होने की वजह से प्रत्येक स्ट्रांड की बाहरी सतह पर पूरी तरह से इपोक्सी (चिपकाने वाल पदार्थ) पंहुच जाती है, क्योंकि प्लेट की केवल एक सतह ही कंक्रीट से चिपकाई जाती है , जिसके कारण प्लेट (परत) की अपेक्षा CFRP तथा AFRP के स्ट्रांड शीट का कंक्रीट से बेहतर जोड़ उत्पन्न होता है |इस अध्धयन में CFRP तथा AFRP की स्ट्रांड 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 स्ट्रांड शीट का प्रयोग करते हुए डबल लैप अपरूपण परिक्षण की एक संशोधित विधि को अपनाया गया है |प्रयोगशाला में स्ट्रांड शीट को जांचा गया है तथा प्रबलित कंक्रीट बीम को CFRP एवं AFRP द्वारा सुद्रढ़ करके (कटाव और बिना कटाव के) डबल लैप कर्तन परिक्षण किया गया तथा प्राप्त कर्तन दबाव की पुष्टि की गयी और साथ ही स्ट्रांड 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 स्ट्रांड शीट की प्रभावशीलता को जांचा जा सके |इस प्रयोग में अलग अलग FRP पदार्थ तथा चौडाई अनुपात का प्रयोग किया गया |मुख्य मानदंड उच्च सामर्थ्य वाली CFRP स्ट्रांड शीट का चौडाई अनुपात 0.83 और 0.33 एवं उच्च गुणांक वाली CFRP तथा AFRP की स्ट्रांड शीट के लिए चौडाई 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 सम्मलित हैं (1) बिना सुदृढ की कंक्रीट बीम, (2) सुदृढ की हुई कंक्रीट बीम जिसमे उच्च सामर्थ्य वाली CFRP स्ट्रांड शीट का प्रयोग किया गया साथ ही उच्च सामर्थ्य व उच्च गुणांक वाली CFRP की स्ट्रांड शीट तथा AFRP स्ट्रांड शीट का भी प्रयोग किया गया, (3) CFRP व AFRP की स्ट्रांड शीट (चौडाई अनुपात 0.33 रखते हुए) से सुद्रढ़ 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 सुद्रढ़ किय हुए नमूनों को विधिमान्य किया गया |CFRP तथा AFRP स्ट्रांड शीट का परस्पर सम्बंधित योगदान में यह पाया गया है की CFRP परत का बालन गुरुत्व (BendingMoment) क्षमता सार्थक रूप अधिक थी |उच्च सामर्थ्य वाली CFRP स्ट्रांड शीट की चौडाई 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 स्ट्रांड शीट का प्रयोग करने से फेल होने की प्रक्रिया CFRP स्ट्रांड शीट टूटने से हुई है |CFRP व AFRP स्ट्रांड 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 हेतू मॉडल की संस्तुति की गयी है |कुल मिलाकर यह देखा गया है कि जब स्ट्रांड 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, स्ट्रांड 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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Applied cracking load	=	$P_{cr,\exp}$
Applied load	=	P
Applied ultimate bending moment	=	$M_{u,\exp}$
Applied ultimate load	=	$P_{u,\exp}$
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Applied yielding load	=	$P_{y,\exp}$
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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