EFFECT OF END ANCHORAGE ON CFRP STRENGTHENED CONCRETE BEAMS

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DECLARATION

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ABSTRACT

Reinforced concrete structures are often being subjected to modifications and improvements during their service life. The main causes for improvements are design errors, changes in use, degradation due to corrosion of reinforcing steel, damage due to seismic loads, vehicular impact and excessive wear and excessive loading. Precautions for these issues are mainly in two types; repair and strengthening. Restoring the structures which became structural malfunction is known as repair. Improvements done in structures in order to achieve higher service loads or longer service lives are known as strengthening. As far as strengthening techniques are concerned, concrete jacketing, steel jacketing, precast concrete jacketing, prestressed concrete jacketing and external application of Fibre reinforced polymer (FRP) composite materials are the available upgrading methods.

Structural strengthening with fibre reinforced polymers is a popular strengthening technique worldwide, due to its extensive advantages. The important properties of FRP's are high strength, light weight, good rigidity, corrosion resistance, high elastic modulus etc. FRP's are used to improve structures by means of increasing flexural capacity, enhancing shear capacity and confining concrete columns to improve axial compression load carrying capacity. When flexural strengthening with FRP is concerned, research studies show that a significant strength increment can be achieved with use of CFRP sheets as an external reinforcement. It also improves serviceability of structures.

Failure of a CFRP strengthened beam for flexure can be due to flexure, shear, concrete crushing or debonding. The failure modes can be categorized in to two main types; classical failure and premature failure. Failure of an element due to yielding of steel bars, tensile failure of FRP sheets and crushing of concrete in compression zone are known as classical failure. Failure of element in any other method such as debonding of FRP, peeling off of FRP and concrete cover separation are premature failure modes.

End debonding is the most common failure mode which has been experienced in practice. This mode of failure, limits the capacity by 60% to 80% of ultimate capacity (Mostofinejad 2014, Xiong 2007) of the system and induce sudden failure without prior warning. Different methods have been proposed in literature to delay end debonding. They are Mechanical fasteners, FRP pin and pan shape anchors, Near Surface Mount reinforcement, End wraps and use of wire mesh–epoxy composite. Among these techniques, end wraps are more beneficial since it contribute to shear capacity of the beam and help to improve ductility apart from preventing debonding failure. Although these techniques are advantages, they are not popular in the industry due to lack of technical data to quantify the effects.

Previous research studies emphasise the need of proper design method to predict the strength enhancement gained due to end wraps. There are few studies (Sawada et al,2003 Hawileh et al. 2013) carried out to investigate the interaction between resistance to debonding and the strength gain. Moreover, studies conducted in tropical countries are even less. This has lead to less confidence of using this technique by practicing engineers. Although there are several design guides available on design of externally bonded FRP systems, none of these guides address the effect of end anchorage on flexural strength gain. This study investigates the effect of end anchors on enhancing flexural capacity of reinforced concrete members, flexural strengthened with CFRP sheets.

An extensive experimental program was carried out using reinforced concrete beams to understand the failure behaviour, stress distribution, deflection behaviour and flexural strength enhancement. It was observed that 98.53% strength increment could achieved by the specimens flexural strengthened with CFRP external reinforcement over control specimens. When the flexural strengthened beams were anchored at the ends, the strength enhancement was 145% compared with that of unstrengthened beams. It was also observed that strain levels at the ends of longitudinal CFRP strips reduces significantly, when end wrap anchorage is provided. End debonding can be fully prevented by providing sufficient amount of end anchorage. The failure mode of beams changed from cover debonding to CFRP rupture, in existence of end wraps.

A new theoretical model was developed based on experimental observations, design guidelines and data collected literature. It is capable of predicting both failure load and failure mode of flexural strengthened and end anchored beams. The model was compatible with experimental results of current study as well as experimental results collected from literature.

Two papers were published from the work of this study and are attached in appendix E.

Keywords: *CFRP/concrete, flexural performance, de-bonding failure, end anchorage*

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
ACI	American Concrete Institute
AFRP	Aramid Fibre Reinforced Polymer
BRE	Building Research Establishment
CEB	Comité euro-international du béton
CFRP	Carbon Fibre Reinforced Polymer
EBR	Externally Bonded Reinforcement
EMI	Electromagnetic Interference
FIB	Fédération internationale du béton
FIP	Fédération internationale de la précontrainte
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
GI	Galvanized Iron
HIT	High Heat Treatment
HM	High Modulus
HT	High Tensile
IHT	Intermediate Heat Treatment
IM	Intermediate Modulus
JCI	Japanese concrete institute
LHT	Low Heat Treatment
NSMR	Near Surface Mount Reinforcement
RC	Reinforced concrete
SHT	Super Heat Tensile
UHM	Ultra High Modulus

LIST OF SYMBOLS

Symbol	Description	Units
A_f	$nt_f w_f$, area of FRP external reinforcement	[mm^2]
A_{fv}	area of FRP shear reinforcement	[mm^2]
A_s	area of non pre-stressed steel reinforcement	[mm^2]
a_s	cover to steel tension reinforcement	
a_u	effective bond length	
A_{sv}	provided area of shear reinforcement	[mm^2]
A_{s1}	area of tensile steel reinforcement	[mm^2]
A_{s2}	area of compressive steel reinforcement	[mm^2]
b	width of beam	[mm]
b_f	width of the FRP strip	[mm]
b_w	minimum width of cross section over the effective depth	[mm]
c	distance from extreme compression fiber to the neutral axis	[mm]
C_1	Factors obtained through calibration of test results (for CFRP strips, the value is 0.64)	
C_2	Factors obtained through calibration of test results (for CFRP strips, the value is 2)	
d	effective depth of the member	[mm]
d_f	depth of FRP shear reinforcement	[mm]
d_2	distance from centroid of compressive steel to extreme compressive fibre	[mm]
E_f	modulus of elasticity of FRP	[N/mm^2]
E_{fu}	elastic modulus of FRP in the principal fibre orientation	[N/mm^2]
E_{s2}	modulus of elasticity of steel	[N/mm^2]
f_c	prism compressive strength of concrete	[N/mm^2]
f_{ctm}	mean value of the concrete tensile strength	[N/mm^2]
f_{cu}	characteristic strength of concrete	[N/mm^2]

F_d	tensile force before the debonding of CFRP sheets	
f_f	stress level in the FRP reinforcement	[N/mm^2]
f_{fe}	effective stress in the FRP	[N/mm^2]
f_s	stress in non pre-stressed steel reinforcement	[N/mm^2]
F_t	force in main tension reinforcement	[N]
F_u	effective shear force	[N]
f_y	characteristic strength of main reinforcement	[N/mm^2]
f_{yd}	design value of the steel yield strength	[N/mm^2]
f_{yv}	characteristic strength of shear reinforcement	[N/mm^2]
G_f	interfacial fracture energy	[Nmm]
h	overall thickness of a member	[mm]
k_b	geometry factor	
k_c	factor accounting for the state of compaction of concrete	
l	length of specimen	[mm]
$l_{b,max}$	maximum anchorable length	[mm]
L_e	active bond length of FRP laminate	[mm]
L_{ue}	effective bond length of FRP shear wraps	[mm]
M	expected maximum moment	[N mm]
M_n	nominal moment strength	[N mm]
M_{Rd}	resisting design moment	
$N_{fa,max}$	maximum anchorable FRP force in tensile steel reinforcement	
P	externally applied force	[N]
s_f	spacing FRP shear reinforcing	
t_f	thickness of FRP	
V_f	nominal shear strength provided by FRP stirrups	
W	applied external point load	[N]
w	uniformly distributed self-weight of concrete element	[N/mm]
x	depth of the compression zone	
α	reduction factor, (approximately equal to 0.9)	

α	angle between principal fibre orientation and longitudinal axis of member
β_1	ratio of the depth of the equivalent rectangular stress block to the depth of the neutral axis
δ_f	interfacial slip
δ_G	stress block centroid coefficient
ε_f	FRP strain
$\varepsilon_{fd,e}$	design value of effective FRP strain
ε_{s2}	compressive steel strain
θ	angle of diagonal crack with respect to the member axis
τ_f	interfacial shear stress at failure
τ_{max}	maximum interfacial shear stress
φ_f	additional FRP strength-reduction factor
λ	a factor depends on δ_f, τ_f, elastic modulus of FRP and thickness of FRP