AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
STRUCTURAL ENGINEERING DEPARTMENT

SHEAR FLEXURAL BEHAVIOUR OF RC BEAMS STRENGTHENED BY NEAR SURFACE MOUNTED FRP BARS

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STATEMENT

This thesis is submitted to Ain Shams University in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering (Structural).

The work included was carried out by the author.

No part of this thesis has been submitted for a degree or a qualification at any other university or institution.

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IN THE NAME OF ALLAH

ABSTRACT OF THESIS

SHEAR FLEXURAL BEHAVIOUR OF RC BEAMS STRENGTHENED BY NEAR SURFACE MOUNTED FRP BARS

Strengthening with near-surface-mounted (NSM) fiber-reinforced-polymer (FRP) reinforcement has become a well-known technique, which provides a good bond between the FRP element and concrete. However, one of the most common failure modes of NSM-FRP strengthened beams is concrete cover separation (CCS). In this research, the shear flexural behavior of RC beams strengthened with fully and partially bonded NSM CFRP bars was studied. Two different bar configurations with straight and hooked ends were used. The hooked ends were used to act as end anchors, which might delay the CCS failure. The results indicated that the end anchoring was effective in delaying the CCS and increasing the ultimate carrying capacity. The ultimate load of the beams strengthened with two straight NSM CFRP bars increased by 166.2%, while that of the corresponding beam having end anchorage increased by 180.5% compared to the unstrengthened beam. On the other hand, unbonding the NSM bars along the mid-span zone slightly decreased the ultimate load compared with the fully bonded bars, however it slightly increased the beam deformability. Increasing the unbonded length shifted the failure mode from CCS to CCS and anchorage shearing off, which is not preferred from the point of view of the structural safety.

A numerical investigation using the non-linear finite element (FE) modeling was performed using ANSYS®. The developed FE model considered the nonlinear constitutive material properties of concrete, yielding of steel reinforcement, and bond slip of non-anchored NSM bars with adjacent epoxy surface. Progressive continuum damage mechanics (CDM) along with the fracture concepts were employed to simulate the damage initiation and propagation at the epoxy-concrete interface. A strain-based failure criteria was proposed to predict the CCS failure. The developed models were validated by comparing the numerical and experimental results in terms of load-deflection behavior, load-CFRP strain response, and failure modes. Overall, a good agreement was obtained with a Mean Absolute Percentage Error (MAPE) of 6.50% for the ultimate loads. The developed models were then used to study effects of extra parameters. The effect of the NSM CFRP bar length, the diameter of NSM bar, and compressive strength of concrete were evaluated.

With respect to the ultimate load, it was indicated that increasing the bar diameter had a great effect in increasing the ultimate capacity. Increasing the NSM bar length over 175 times the bar diameter did not have a significant effect neither on the ultimate load, or on the beam deformability.

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"May the wind always be on your back and the sun upon your face."

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List of Nomenclature and Symbols

b	Width of RC beam, mm
d_b	FRP bar diameter, mm
a'_e	Distance between center of the NSM strip and edge of the RC beam, mm
h'	Vertical distance between the root of the concrete tooth and the centroid of the FRP bar, mm
h_1	Vertical distance between the centroid of the tension steel and the bottom of the RC beam, mm
h_0	Vertical distance between the compression face of the RC beam and the centroid of the NSM bar, mm
y_0	Neutral axis depth from the compression face of the RC beam, mm
l	Crack spacing, mm
l_{min}	Minimum crack spacing, mm
l_{max}	Maximum crack spacing, mm
L_p	Effective length of the NSM bar in the shear span, mm
L_{p1}	Length of the NSM bar in the shear span, mm
D_a	Maximum aggregate size, mm
b_g	Groove width, mm
d_g	Groove depth, mm
R	Ratio between the groove dimension and the NSM bar diameter
A_b	Cross sectional area of the FRP reinforcement, mm^2
A_e	Cross sectional area of the tensile concrete, mm^2
I_A	Moment of inertia of the concrete tooth cross section, mm^4
I_{cr}	Cracked moment of inertia of the RC beam cross section, mm^4
$\sum O_{bars}$	Total perimeter of the steel bars, mm
$\sum O_{NSM}$	Total perimeter of the NSM bars, mm
n	Number of the NSM bars
n_f	Modular ratio between the FRP and concrete
E_f	Modulus of elasticity of FRP, MPa
E_c	Modulus of elasticity of concrete, MPa
E_a	Modulus of elasticity of epoxy, MPa
G_a	Shear modulus of epoxy, MPa
f'_c	Concrete compressive strength, MPa
f_t	Concrete tensile strength, MPa
G_{ft}	Fracture energy of concrete, N/mm
G_{cn}	Total values of normal fracture energies, N/mm
G_{ct}	Total values of shear fracture energies, N/mm
u_s	Average bond strength between the steel bars and the concrete, MPa
u_{NSM}	Average bond strength between the NSM bars and the concrete, MPa
μ	Coefficient of friction between the epoxy and concrete

Γ	Shear stress, MPa
Γ_{bs}	Local bond strength of NSM strips, MPa
Γ_{b}	Local bond stress at the bar-epoxy interface, MPa
Γ_{t}	Contact shear stress, MPa
$\Gamma_{t, max}$	Maximum shear stress of contact, MPa
σ	Normal tensile stress, MPa
σ_{A}	Tensile stress at the root of the concrete tooth, MPa
$\sigma_{failure}$	Axial stress in the FRP element at the onset of the concrete cover separation, MPa
σ_{n}	Contact normal tensile stress, MPa
$\sigma_{n,max}$	Maximum normal tensile stress of contact, MPa
Γ_{af}	Shear strength of epoxy adhesive, MPa
$\Gamma_{max\ epoxy\text{-}concrete}$	Maximum shear stress at the epoxy-concrete interface, MPa
$\Gamma_{max\ bar\text{-}epoxy}$	Maximum shear stress at the bar-epoxy interface, MPa
$\Gamma_{failure}$	Average interfacial shear stress between FRP and concrete at the onset of the concrete cover separation, MPa
u_{n}	Contact gap, mm
u_{nu}	Contact gap at initiation of debonding, mm
u_{nf}	Contact gap at completion of debonding, mm
δ	Normal interfacial stiffness of the bar-epoxy interface, MPa
δ_{nu}	Contact slip at initiation of debonding, mm
δ_{nf}	Contact slip at completion of debonding, mm
k_{t}	Tangential interfacial stiffness of the bar-epoxy interface, MPa
k_{n}	Normal interfacial stiffness of the bar-epoxy interface, MPa
P	Applied load, kN
P_{cr}	Cracking load, kN
P_{y}	Yielding load, kN
P_{u}	Ultimate load, kN
Δ	Deflection, mm
Δ_{cr}	Cracking deflection, mm
Δ_{y}	Yielding deflection, mm
Δ_{u}	Ultimate deflection, mm
M_{A}	Bending moment at the foot of the concrete tooth, kN.m
ε	Strain
ε_{f}	Strain in the CFRP bar
ε_{fu}	Ultimate or Rapture strain of the FRP bar
ε_{s}	Strain in the tension steel
ε_{c}	Concrete strain
ε_{0}	Strain at maximum concrete compressive strain
ε_{cu}	Concrete crushing strain
K_{e}	Effective pre-yielding stiffness, Kn/m
Ω	Energy absorption, Kn.mm
ζ_{y}	% increase in yielding load