SHEAR STRENGTHENING AND REPAIR OF DEEP BEAMS WITH AND WITHOUT WEB REINFORCEMENT USING NEAR-SURFACE MOUNTED CFRP BARS

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A thesis submitted in
fulfillment of the requirement for the award of the
Doctor of Philosophy

Faculty of Civil and Environmental Engineering
Universiti Tun Hussein Onn Malaysia

JUNE 2018

ACKNOWLEDGEMENT

I would like to express my utmost gratitude and appreciations to my main supervisor Prof. Ir. Dr. Abdul Aziz bin Abdul Samad for his guidance, encouragement and assistance throughout this amazing research journey. My sincere appreciation also extends to my co-supervisors Assoc. Prof. Dr. Noridah Mohamad and Assoc. Prof. Dr. Ali Naji Attiyah for their assistance and encouragement.

Special thanks to my love and wife Alyaa Abdul Razzaq Azeez for her continuous support throughout my life.

Thanks and acknowledgement to the all lectures at Civil and Hydraulic Structural Engineering department of Kufa Universiti, Specially, Lecturer. Dr. Thaer Matlab Mezher from for his assistance during the experimental works.

Lastly, special thanks to my freind, Raheem Kashan Zahger, friend for his continuous support throughout this journey. My deepest gratitude goes to my late parents Raheem Hassen and Sahira jaafar for their love and support. Finally, also private thankfulness goes to my uncle Abdul Razzaq Azeez and aunt seham nory abood.

ABSTRACT

Shear failure of a reinforced concrete beam is catastrophic because it occurs suddenly and without warning. Recently, CFRP sheets and bars have been rapidly employed in strengthening structural concrete elements including deep beams. In this research, the behaviour of deep beam strengthened with carbon fiber reinforced polymer (CFRP) as Near Surface Mounted (NSM) bars was studied. Five groups of deep beams i.e. G1, G2, G3, G4 and G5 were studied. Each group of deep beams has the same shear span to effective depth ratio at 0.864. Group G1 consists of two beams as a control specimens and each one differs depending on either with web and without web reinforcement. Groups G2 to G5 consists of initially strengthened or pre-cracked and repaired deep beams with CFRP NSM bars with different schemes and orientations. Other variables included beams with and without web reinforcements. The selected orientations for all CFRP NSM bars were either at 0/90 or 45/135 degrees and the two different spacing schemes for the stirrups were at 100 mm or 150 mm. In total, 18 reinforced concrete deep beams with a size of 450 x140 x1200 mm were experimented. A simulation using finite element software ANSYS V.14 was conducted to validate the experimental work. Three existing theoretical equations from ACI 440, Khalifa & Nanni and *fib* were selected for comparison with the experimental findings. From the experimental, all deep beam specimens failed in shear. Experimental results indicated that all deep beams, either with or without web reinforcement, and strengthened or repaired with CFRP NSM bars showed increased shear capacity enhancement from 17% to 141% compared to the control specimens. Finite element analysis by ANSYS software also indicated similar behaviour in terms of shear capacity, crack patterns and mode of failure. In addition, three existing theoretical models; ACI 440, Khalifa and Nanni and *fib* models were applied for theoretical comparison of shear capacity contributed by CFRP NSM bars V_f. The ACI 440 and Khalifa & Nanni model showed good consistency and good agreement with the experimental results. Finally, a modified effective strain limit based on different coefficient (R) values was proposed.

ABSTRAK

Sifat kegagalan ricihan rasuk konkrit bertetulang secara tiba-tiba tanpa amaran adalah satu sifat yang sangat merbahaya. Oleh itu, pengunaan lembaran CFRP dan bar CFRP adalah kaedah yang telah kerap digunapakai dalam usaha untuk mengukuhkan elemen konkrit struktur termasuk rasuk dalam. Dalam kajian ini, ciri-ciri rasuk dalam yang diperkukuh dengan polimer bertetulang gentian karbon (CFRP) secara *Near Surface Mounted* (NSM) telah di kaji. Lima kumpulan rasuk G1, G2, G3, G4 dan G5 telah dilaksanakan. Setiap kumpulan rasuk mempunyai nilai rentang ricih dengan nisbah kedalaman yang berkesan pada 0.864. Kumpulan G1 terdiri daripada dua rasuk sebagai spesimen kawalan dan masing-masing berbeza bergantung sama ada dikukuh dengan tetulang web atau tanpa tetulang web. Kumpulan G2 hingga G5 terdiri daipada rasuk yang telah dikukuh awal dengan bar CFRP NSM, atau rasuk pra-retak yang kemudiannya diperbaiki dengan bar CFRP NSM. Pembolehubah untuk rasuk kumpulan G2 dan G5 merangkumi rasuk bertetulang web dan rasuk tanpa tetulang web. Ini di susuli pula dengan pemilihan orientasi bar CFRP NSM pada sudut 0/90 darjah atau 45/135 darjah dan susunan jarak tetulang web pada 100 mm atau 150 mm. Lapan belas rasuk dalam konkrit bertetulang dengan saiz 450 mm x 140 mm x 1200 mm telah diuji. Simulasi dengan menggunakan perisian elemen terhingga ANSYS V.14 telah dijalankan untuk mengesahkan hasil kajian. Tiga teori model iaitu ACI 440, Khalifa & Nanni dan *fib* telah dipilih untuk perbandingan dengan kajian. Semua spesimen telah gagal secara ricih. Kajian menunjukkan bahawa semua rasuk yang bertetulang web atau rasuk tanpa tetulang web dan dikukuh awal atau diperbaiki dengan bar CFRP NSM menunjukkan peningkatan kapasiti ricih dari 17% hingga 141% berbanding spesimen kawalan. Perisian ANSYS menunjukkan kapasiti ricih, corak retak dan kegagalan mod yang serupa dengan kajian. Di samping itu, sumbangan bar CFRP NSM (V_f) terhadap kapasiti ricih dari tiga teori model dari ACI 440, Khalifa dan Nanni dan *fib* telah dibandingkan. Dari analisis tersebut, model ACI 440 dan Khalifa & Nanni telah menunjukkan konsistensi dan persetujuan yang baik dengan keputusan kajian. Akhirnya, had keterikan berkesan yang diubahsuai berdasarkan nilai pekali (R) yang berbeza telah dicadangkan.

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^{o}	Degree of angle
Ψ	FRP strength reduction factor
Φ	Strength reduction factor
γ_{f}	Partial safety factor
α	Angle of orientation of shear reinforcement
θ	Angle of orientation of FRP reinforcement
β	Angle of orientation of FRP reinforcement
ε	Strain
ε_{fu}	The ultimate strain in the FRP
ε_{fe}	The effective strain in the FRP
Δ	Deflection
μ	Micro
ρ_{w}	Steel reinforcement ratio
ρ_{f}	FRP reinforcement ratio
a_{v}/d	Shear span to effective depth ratio
A_{s}	Area of longitudinal tension reinforcement
A_{s}	Area of shear reinforcement
A_{f}	The area of FRP shear reinforcement
A_{fv}	The area of FRP shear reinforcement
b	Width of section
b_{w}	Web width
C	Celsius
d	Effective height of section
d_{f}	The effective depth of FRP at section
E_{f}	The modulus of elasticity of the FRP
I	Moment of inertia
fc'	Concrete compressive stress
f_{y}	Yield strength of longitudinal tension reinforcement

f_v	Yield strength of shear reinforcement
f_{fe}	The effective stress in the FRP
f_{fu}	The ultimate stress in the FRP
Gpa	Giga Pascal
Kg	Kilo grams
K_v	The bond-reduction coefficient
K_{vm}	The modified bond-reduction coefficient
k_1	Modification factor for concrete strength
k_2	Modification factor for wrapping scheme
kN	Kilo-Newton
Le	The effective length of FRP reinforcement
n_f	Number of layer of FRP reinforcement
M	Bending moment
m^3	meter of cube
Mpa	Mega Pascal
M_u	Factored moment at section
$P_{u,FEM}$	Ultimate load of simulation results
$P_{u,exp}$	Ultimate load of experimental results
s	Spacing centre-to-centre between reinforcement
s_f	Spacing centre-to-centre between FRP strips reinforcement
t_f	Thickness of FRP sheet
V	Shear force
V_c	Shear resistance of the uncracked concrete
V_a	Aggregate interlock force
V_d	Dowel action
V_n	Nominal shear strength
V_c	Shear strength contributed by concrete
V_s	Shear strength contributed by shear reinforcement
V_f	Shear strength contributed by CFRP
V_{cz}	Shear resistance of uncracked concrete
V_a	Interface shear transfer
V_{us}	Ultimate shear strength of web steel
V_{Rd}	The shear resistance of a member with shear reinforcement
V_{fd}	The FRP contribution to shear capacity
V_u	Factored shear force at section

V_{FEM}	Shear strength of simulation results
V_{exp}	Shear strength of experimental results
V_{theory}	Shear strength of theoretical value
V_u	Ultimate shear strength
$V_{f,exp}$	Shear strength of experimental results contributed by CFRP
$V_{f,theory}$	Shear strength of theoretical value contributed by CFRP
w_f	Width of FRP strips
w_{fe}	The effective width of FRP strips
SC1- SC6	Strain gauge at concrete surface
SF1-SF8	Strain gauge at CFRP bars

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