

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

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## 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 x 140 x 1200 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, penggunaan 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 daripada 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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## LIST OF SYMBOLS

$^{\circ}$	Degree of angle
$\Psi$	FRP strength reduction factor
$\Phi$	Strength reduction factor
$\gamma_f$	Partial safety factor
$\alpha$	Angle of orientation of shear reinforcement
$\theta$	Angle of orientation of FRP reinforcement
$\beta$	Angle of orientation of FRP reinforcement
$\varepsilon$	Strain
$\varepsilon_{fu}$	The ultimate strain in the FRP
$\varepsilon_{fe}$	The effective strain in the FRP
$\Delta$	Deflection
$\mu$	Micro
$\rho_w$	Steel reinforcement ratio
$\rho_f$	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
$f_c'$	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
$L_e$	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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