

**SHEAR STRENGTHENING OF REINFORCED CONCRETE BEAMS USING  
EXTERNALLY BONDED BI-DIRECTIONAL CARBON FIBRE REINFORCED  
POLYMER**

**By**

**J. JAYAPRAKASH**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in  
Fulfilment of the Requirement for the Degree of Doctor of Philosophy**

**August 2006**

**Dedicated to  
My Beloved Mother**

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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**Chairman: Professor Abdul Aziz Abdul Samad, PhD**

**Faculty: Engineering**

Shear failure of Reinforced Concrete (RC) beams is catastrophic and could occur without any forewarning. Many existing reinforced concrete (RC) members are found to be deficient in shear strength and need to be repaired. Shear deficiencies in reinforced concrete beams may crop up due to many factors such as inadequate shear reinforcement, reduction in steel area due to corrosion, use of outdated design codes, increased service load, poor workmanship and design faults. The application of Carbon Fibre Reinforced Polymer Composite material, as an external reinforcement is a viable technology recently found to be worth for improving the structural performance of reinforced concrete structures.

This study was conducted to investigate the shear strengthening capacity and modes of failure of reinforced concrete beams using externally bonded bi-directional Carbon

Fibre Reinforced Polymer (CFRP) strip. To accomplish the objectives, an experimental program was conducted within laboratory environment where a specimen lot comprised of eighteen rectangular (18 Nos) beams and sixteen (16 Nos) T-beams were tested until failure. The specimens comprised of rectangular and T-beams of length 2980mm were fabricated and tested in the Structural Laboratory at Universiti Putra Malaysia. The rectangular beams were strengthened without any internal shear reinforcement but the T-beams were strengthened with internal shear reinforcement. The beams were classified into three categories: control, precracked/repared and initially strengthened specimens. The variables investigated in this experimental program included (i) longitudinal reinforcement ratio, (ii) shear span to effective depth ratio, (iii) spacing of CFRP strip and (iv) orientation of CFRP strips. Test results showed that the externally bonded bi-directional Carbon Fibre Reinforced Polymer (CFRP) significantly enhances the shear enhancement of both the rectangular (without steel stirrups) and T-beam (with steel stirrups). The study also revealed that the contribution of externally bonded CFRP strips to the shear capacity was significantly influenced by the variables investigated.

A design equation was developed to compute the shear contribution of CFRP to the shear capacity of RC beams. The experimental results were compared with the existing models of Triantafillou, 1998; Khalifa 2002; and ACI 440, 2003 to verify the proposed design equation. The theoretical values calculated by the proposed model for rectangular beams without internal shear reinforcement showed good agreement with those of the T-beams with internal shear reinforcement. The study observed that the predicted results of the existing models by Khalifa (2002) and ACI 440 were slightly higher than that of the proposed one. However it was also observed that the model by

Triantafillou shows poor agreement in comparison to Khalifa (2002) and ACI 440 models. While the study contributed insights in terms of shear strength and modes of failure of reinforced concrete CFRP strengthened beams with respect to the variables such as shear span to effective depth ratio, longitudinal reinforcement ratio, spacing, and different orientations of CFRP strips, it developed a design equation and few recommendations.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doctor Falsafah

**PENINGKATAN DAYA KEKUATAN REGANGAN PADA BINAAN KONKRIT  
YANG KUKUH MENGGUNAKAN IKATAN LUARAN BI-DIRECTIONAL  
CARBON FIBRE REINFORCED POLYMER**

Oleh

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Kegagalan daya regangan pada binaan konkrit yang kukuh merupakan satu malapetaka dan boleh terjadi tanpa sebarang amaran awal. Terdapat banyak komponen binaan konkrit yang wujud kini perlu diperbaiki kerana kurang daya kekuatan regangan. Kekurangan kekuatan regangan ini boleh berlaku akibat beberapa faktor seperti pengukuhan kuasa regangan yang tidak mencukupi, bahagian besi atau keluli terhakis, penggunaan kod rekabentuk yang lama, penambahan beban servis, kekurangan kemahiran dan kesalahan rekabentuk. Penggunaan bahan Carbon Fibre Reinforced Polymer (CFRP) sebagai pengukuhan luaran adalah teknologi bernilai yang ditemui untuk mempertingkatkan kekuatan struktur binaan dan hayat bangunan.

Kajian ini telah dijalankan untuk menyelidik tahap kemampuan kekuatan regangan dan penyebab kegagalan binaan konkrit yang telah diperkukuhkan menggunakan pendekatan ikatan luaran bi-directional Carbon Fibre Reinforced Polymer (CFRP). Bagi mencapai

objektif kajian, satu eksperimen telah dijalankan dalam persekitaran makmal di mana banyak spesimen mengandungi lapan belas (18) kerangka/rasuk segi empat tepat dan enam belas (16) kerangka/rasuk-T diuji sehingga gagal. Kesemua spesimen yang mengandungi kerangka/rasuk segi empat tepat dan kerangka/rasuk-T berukuran 2980 mm telah dibina dan diuji di Makmal Struktur, Universiti Putra Malaysia. Kerangka/rasuk segi empat tepat telah diperkukuhkan tanpa sebarang pengukuhan regangan dalaman dan sebaliknya bagi kerangka/rasuk-T. Rasuk/kerangka tersebut dibahagikan kepada 3 kategori: kawalan, pembaikan dan kekuatan awal spesimen. Pembolehubah-pembolehubah yang dikaji dalam eksperimen ini termasuklah nisbah peneguhan membujur (longitudinal reinforcement ratio), jarak dan kuantiti rakap besi dalaman atau peneguhan melintang, nisbah jangka hayat kekuatan regangan kepada kedalaman berkesan, jalur-jalur CFRP serta kuantiti dan orientasi jalur CFRP. Hasil kajian menunjukkan bahawa ikatan luaran bi-directional Carbon Fibre Reinforced Polymer (CFRP) berupaya dalam meningkatkan kapasiti regangan bagi kerangka/rasuk segi empat tepat dan juga kerangka/rasuk-T. Hasil penemuan daripada eksperimen yang dilakukan didapati bahawa tahap kemampuan kekuatan regangan bagi rasuk CFRP yang telah diperkukuhkan adalah sangat bergantung kepada pembolehubah-pembolehubah yang digunakan dalam kajian ini. Persamaan empirik untuk menentukan kemampuan ketegangan kekuatan regangan bagi ikatan luar CFRP telah dihasilkan. Perbandingan daripada hasil kajian dari model sedia ada seperti Triantafillou (1998), Khalifa (2002), dan ACI 440 (2003) untuk mengesahkan persamaan empirik yang dicadangkan. Berdasarkan teori, nilai yang dihasilkan oleh model yang digunakan untuk kerangka/rasuk segi empat tepat tanpa kekuatan regangan dalaman menunjukkan keputusan yang baik bersama dengan kerangka/rasuk-T dengan kekuatan regangan

dalaman. Kajian juga membuktikan bahawa keputusan jangkaan bagi model Khalifa (2002) dan ACI 440 adalah sedikit tinggi daripada yang dicadangkan. Bagaimana pun, ini telah membuktikan bahawa model Triantafillou menunjukkan keputusan yang agak rendah jika dibandingkan antara model Khalifa (2002) dan ACI 440. Semasa kajian dilakukan untuk mencari pengertian dalam daya kekuatan regangan dan kaedah kegagalan kekuatan regangan bagi CFRP adalah sangat bergantung kepada pembolehubah seperti jarak dan kuantiti rakap besi dalaman atau peneguhan melintang, nisbah peneguhan membujur, jalur dan orientasi jalur CFRP yang berbeza, ia menghasilkan persamaan dan sedikit cadangan.



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J. Jayaprakash

I certify that an Examination Committee has met on 14<sup>th</sup> August 2006 to conduct the final examination of J. Jayaprakash on his Doctor of Philosophy thesis entitled “Shear Strengthening of Reinforced Concrete Beams using Externally Bonded Bi-Directional Carbon Fibre Reinforced Polymer” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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## DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

---

J. Jayaprakash

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## ACRYNOMS

|                    |   |
|--------------------|---|
| $a_v$              | Shear span  |
| $A_v$              | Area of internal shear reinforcement within a distance $s$  |
| $A_s$              | Area of tensile reinforcement   |
| $A_f$              | Area of CFRP reinforcement = $2nt_f w_f$  |
| $f'_c$             | Concrete cylinder compressive strength of concrete  |
| $b_w$              | Width of beam cross section   |
| $d$                | Effective depth of beam   |
| $d_f$              | Effective depth of the FRP shear reinforcement (usually equals to $d$ for rectangular cross section and $d-t_s$ for T-section)                  |
| $E_f$              | Elastic modulus of FRP  |
| $f_{fe}$           | Effective average stress in the FRP sheet at ultimate   |
| $f_{fu}$           | Tensile strength of FRP   |
| $f_y$              | Yield strength of steel reinforcement   |
| $k_v$              | Bond reduction coefficient relies on the modification factor $k_1$ (account for concrete strength); $k_2$ (account for type of wrapping scheme) |
| $L_{eff}$ or $L_e$ | Effective bond length   |
| $R$                | ( $R_1$ , $R_2$ , and $R_3$ ) reduction coefficient,  |
| $M_u$              | Factored bending moment at the section  |
| $s$                | Spacing of internal shear reinforcement   |
| $s_f$              | Spacing of FRP strip  |
| $s_{f,max}$        | Maximum spacing of FRP strip  |
| $t_f$              | Thickness of FRP strip  |

|                                      |   |
|--------------------------------------|---|
| $V_c$                                | Nominal shear strength provided by concrete                                 |
| $V_f$                                | Nominal shear strength provided by FRP shear reinforcement                  |
| $V_n$                                | Nominal shear strength  |
| $V_s$                                | Nominal shear strength provided by steel stirrups                           |
| $V_u$                                | Factored shear force at the section   |
| $w_f$                                | Width of FRP strip  |
| $w_{fe}$                             | Effective width of FRP  |
| $\alpha$                             | Angle of inclination of internal shear reinforcement                        |
| $\beta$                              | Angle between principal fibre orientation and longitudinal axis of the beam |
| $\gamma_f$                           | Partial safety factor for FRP in uniaxial tension (taken 1.15 for CFRP)     |
| $\psi$ or $\psi_f$                   | Reduction factor applied to the shear contribution of the FRP               |
| $\phi_f$                             | Material reduction factor for the FRP (0.8)                                 |
| $\epsilon_{fe}$                      | Effective strain of FRP at failure  |
| $\epsilon_{fu}$ or $\epsilon_{fu}^*$ | Ultimate tensile strain of FRP.   |
| $\epsilon_{V_{cu}}$                  | Ultimate vertical strain of concrete  |
| $\rho$                               | Ratio of longitudinal tensile reinforcement                                 |
| $\rho_f$                             | FRP fraction area= $(2nt_f/b_w)(w_f/s_f)$                                   |
| AvgM1/M2                             | Average strain of M1 and M2   |
| AvgM3/M2                             | Average strain of M1 and M2   |
| AvgS1a/S1b                           | Average strain of S1a and S1b   |
| AvgS2a/S2b                           | Average strain of S2a and S2b   |
| AvgS3a/S3b                           | Average strain of S3a and S3b   |