UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF STRUT-AND-TIE MODEL FOR CARBON FIBRE REINFORCED POLYMER STRENGTHENED DEEP BEAMS

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By

MOHAMMAD PANJEHPOUR

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2014

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DEDICATION

This work is dedicated to my family members who are always giving me encouragement and support.

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

DEVELOPMENT OF STRUT-AND-TIE MODEL FOR CARBON FIBRE REINFORCED POLYMER STRENGTHENED DEEP BEAMS

By

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March 2014

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Deep beams are commonly used in tall building, offshore structures and foundations. According to many codes and standards, strut-and-tie models (STM) are recommended as a rational approach to analyse discontinuity regions (D-regions) and consequently deep beams. Since the last decade, strengthening of reinforced concrete (RC) beams with carbon fibre reinforced polymer (CFRP) has become a topic of interest among researchers. However, STM is not able to predict shear strength of deep beams strengthened with CFRP sheet. There is a need for a rational model to predict the ultimate strength of CFRP strengthened deep beams is the significance of this research problem.

This thesis elaborates on the STM recommended by ACI 318-11 and AASHTO LRFD using experimental results to point the way toward modifying a strut effectiveness factor in STM for CFRP strengthened RC deep beams. It addresses several ways to enhance our understanding of strut performance in the STM. The purpose of this research is to modify the STM for prediction of shear strength of RC deep beams strengthened with CFRP. Hence, the main objective of this research is to propose an empirical relationship to predict the strut effectiveness factor in STM for CFRP strengthened RC deep beams. Besides, the issue of energy absorption of CFRP strengthened RC deep beams is also discussed in this research. Twelve RC deep beams comprising six ordinary deep beams and six CFRP strengthened deep beams with shear span to the effective depth ratio of 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00 were tested till failure in a four-point bending set up. The values of principal tensile strain perpendicular to strut centreline were measured using demountable mechanical strain gauge (DEMEC).

Finally, a modified STM using an empirical relationship was proposed to predict the ultimate shear strength of CFRP strengthened RC deep beams. The modification of STM was made by proposing an empirical equation to predict the strut effectiveness factor in STM for CFRP strengthened RC deep beams. According to the experimental results the growth of energy absorption of CFRP strengthened RC deep beams varies from approximately 45% to 80% for shear span to effective depth ratio of 0.75 to 2.00 respectively. This research is confined to RC deep beams strengthened with one layer of CFRP sheet installed using two-side wet lay-up system.

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

PEMBANGUNAN MODEL STRUT-AND-TIE BAGI POLIMER DIPERKUKUH GENTIAN KARBON DIPERKUKUHKAN RASUK DALAM

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Rasuk dalam (*Deep beams*) biasanya digunakan dalam bangunan tinggi, struktur luar pesisir, dan yayasan. Menurut kod dan ukuran standard *Strut-and-Tie Models* (*STM*) disyorkan sebagai pendekatan rasional untuk menganalisis wilayah-D dan rasuk dalam (*Deep beam*). Sejak sedekad yang lalu, pengukuhan konkrit bertetulang (*Reinforced Concrete*, *RC*) dengan karbon bertetulang gentian polimer (*Carbon Fibre Reinforced Polymer*, *CFRP*) telah menjadi topik yang hangat di kalangan para penyelidik. Walau bagaimanapun, *STM* tidak dapat meramalkan kekuatan ricih rasuk yang diperkukuhkan dengan kepingan *CFRP*. Keperluan model rasional untuk meramalkan kekuatan muktamad rasuk dalam yang diperkuatkan dengan *CFRP* adalah isu kepentingan dalam kajian ini.

Tesis ini menguraikan tentang *STM* yang disyorkan oleh ACI 318-11 dan AASHTO LRFD dengan menggunakan keputusan eksperimen untuk mengubah faktor keberkesanan topang dalam *STM* bagi rasuk dalam *RC*. Ia juga menunjukkan beberapa cara yang meningkatkan pemahaman kita tentang prestasi topang dalam *STM*. Tujuan kajian ini adalah untuk menambahbaik STM dari segi ramalan kekuatan ricih rasuk dalam *RC* yang diperkuatkan dengan *CFRP*. Oleh itu, objektif utama kajian ini adalah untuk mencadangkan satu hubungan empirikal untuk meramalkan faktor keberkesanan topang dalam *STM* bagi CFRP yang diperkukuhkan rasuk dalam *RC*. Selain itu, kajian ini juga meneliti isu penyerapan tenaga dalam rasuk *RC* yang diperkukuhkan oleh *CFRP*. Dua belas rasuk dalam *RC* yang terdiri daripada enam rasuk dalam biasa dan enam rasuk yang diperkuat dengan *CRFP* bersama dengan bentang geser kepada nisbah kedalaman berkesan 0,75, 1,00, 1,25, 1,50, 1,75, dan 2,00 diuji sehingga kegagalan dalam empat titik lentur mengatur. Nilai-nilai tekanan bersama dan berserenjang dengan tengah topang diukur dengan menggunakan tolok tekanan mekanikal.

Akhirnya, STM diubahsuai yang menggunakan perhubungan empirikal yang mencadangkan untuk meramalkan kekuatan ricih yang muktamad daripada CFRP diperkukuhkan RC gelombang-gelombang yang mendalam. Pengubahsuaian STM telah dibuat oleh mencadangkan persamaan yang empirikal untuk meramalkan faktor keberkesanan pemasangan di STM untuk CFRP diperkukuhkan RC gelombang-gelombang yang mendalam. Menurut keputusan

eksperimen, penambahan penyerapan tenaga rasuk dalam *RC* yang diperkukuhkan dengan *CFRP* didapati berbeza kira-kira 45% kepada 80% untuk jangka ricih kepada nisbah kedalaman berkesan 0,75 hingga 2,00 masing-masing. Kajian ini adalah terhad kepada rasuk dalam *RC* yang diperkukuhkan dengan satu lapisan lembaran *CFRP* dengan sistem *lay-up* dua sampingan basah.

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Mohammad Panjehpour

I certify that a Thesis Examination Committee has met on 31 March 2014 to conduct the final examination of Mohammad Panjehpour on his thesis entitled "Development of Strut-and-Tie Model for Carbon Fibre Reinforced Polymer Strengthened Deep beams" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

a	Shear span of deep beams (*mm*)
CFRP	Carbon fibre reinforced polymer
d	Effective depth of deep beam (*mm*)
E	Young modulus of CFRP sheet (*MPa*)
f_{c1}	Principal tensile strain in concrete strut for ordinary deep beams (*mm/mm*)
f_{cr}	Tensile stress of concrete from tensile split test (*MPa*)
f'_c	Specified concrete compressive strength (*MPa*)
f_{cu}	Effective compressive strength of concrete strut from AASHTO LRFD (*MPa*)
IR	Increase ratio, ultimate shear strength of CFRP strengthened deep beam to ordinary deep beam
I	Increase ratio, used in recommended equation for ACI 318-11
$P_{u\text{-}ordinary\text{-}test}$	Ultimate shear strength of ordinary deep beam from the test (*kN*)
$P_{u\text{-}FRP\text{-}test}$	Ultimate shear strength of CFRP strengthened deep beam from the test (*kN*)
$P_{u\text{-}FRP\text{-}recommended}$	Ultimate shear strength of CFRP strengthened deep beam from the proposed method (*kN*)
R	Modification ratio, ratio of $\varepsilon_{1-FRP-test}$ to ε_{1-FRP}
t	Thickness of CFRP sheet (*mm*)
θ	Angle between adjoining tie and strut (*rad*)
υ	Strut effectiveness factor
τ	Average bond strength of concrete-CFRP (*MPa*)
α , β	Reduction factors
ε_1	Principal tensile strain in concrete strut for ordinary deep beams (*mm/mm*)
ε_s	Tensile strain in an adjoining tie (*mm/mm*)
$\varepsilon_{1-ordinary-AASHTO}$	Principal tensile strain of ordinary concrete strut using equation recommended by AASHTO LRFD (*mm/mm*)
$\varepsilon_{1-FRP-test}$	Principal tensile strain in CFRP strengthened concrete strut resulted from the test (*mm/mm*)
$\varepsilon_{1-FRP-recommended}$	Principal tensile strain of CFRP strengthened concrete strut revised using empirical relationship (*mm/mm*)
ε_{1-FRP}	Principal tensile strain in CFRP strengthened concrete strut using equation recommended in this research before the revision with empirical relationship (*mm/mm*)

CHAPTER 1

INTRODUCTION

1.1 Introduction

Deep beams are commonly used in tall buildings, offshore structures, and foundations (Kong, 1990). They mainly occur as transfer girders with single or continuous spans (Wight & Macgregor, 2009). According to ACI 318-11, deep beams have clear spans equal to or less than four times the overall depth. The regions with concentrated loads within twice the member depth from the face of the support are also taken as deep beams into account (ACI, 2011). The experimental results have shown that the addition of web reinforcement beyond the minimum amount is not capable to increase the shear strength of reinforced concrete deep beam owing to the softening behaviour of concrete because it provides only a marginal increase of strength (Islam, Mansur, & Maalej, 2005). Therefore, the application of external reinforcement is necessary to restrain crack widening in shear span of deep beam in order to enhance the shear strength of RC deep beams.

Since last decade, strengthening of concrete structures with carbon fibre reinforced polymer (CFRP) has become a topic of interest among researchers, for its advantages of being lightweight and corrosion resistant. Furthermore, its ease of installation and high tensile strength made CFRP a useful tool in strengthening of concrete structures. Numerous studies have attempted to propose a proper model for bonding strength between CFRP and reinforced concrete strengthened in flexure (Lorenzis, B. Miller, & A. Nanni, 2001; X. Z. Lu, Teng, Ye, & Jiang, 2005; Ozden & Akpinar, 2007; Sayed-Ahmed, Bakay, & Shrive, 2009; Wu, Zhou, Yang, & Chen, 2010). Miller et al had recommended a simple equation to predict shear bond strength of CFRP to concrete surface which is used in the calculations throughout this research (Lorenzis, et al., 2001). This empirical equation is related to the shear approach based on the bond between concrete beams surface and CFRP. This equation will be discussed in the next chapter in details.

The strut-and-tie model (STM) has been incorporated into the codes and standards because of its consistency and rationality since last decade. However, it has encountered few challenges during its implementation. The effective compressive strength of strut has been a complex issue among researchers since the emergence of STM. STM is a unified and rational approach which embodies a complicated structural member with a proper simplified truss model. It is commonly utilised to analyse the behaviour of discontinuity regions (D-region) for structural members. It should be noted that B-Regions are portions of a structural element in which Bernoulli's principle of straight-line strain is used. D-Regions are portions of a structural element with complicated variation in strain.

Looking from another vantage point, STM is a model for a portion of structural member which represents a force system including balanced set of loads. In 1899, the original truss model concept was initially recommended by Ritter to analyse the shear problems (Morsch, 1902; Ritter, 1899). It was then developed for tension problems by Rausch in 1929 (Rausch, 1929). Later, the research on the STM was continued and several modified STM were recommended by researchers. In 2002, STM was recommended by ACI code rather than the simple equation which was used to predict the shear strength of reinforced concrete deep beams in previous versions of ACI code. Since last decade, there has been an increasingly growing body of literature published on STM (Bakir & Boduroğlu, 2005; He & Liu, 2010; Kwak & Noh, 2006; Lopes & do Carmo, 2006; Matteo, 2009; Ong, Hao, & Paramasivam, 2006; Perera & Vique, 2009; Tjhin & Kuchma, 2007; Wang & Meng, 2008; N. Zhang & Tan, 2007a). Recent developments for design of deep concrete members such as pile cap and deep beam have heightened the need for using STM. Accordingly, many standards and codes have specified the STM for design and analysis of D-regions for structure members (AASHTO, 2012; ACI, 2011; Bahen, 2007; CAN/CSA-S6-06, 2006; CEB-FIP, 1999; CSA-A23.3-04, 2005; DIN, 2001; Eurocode2, 2008; NZS, 2006).

Strut as an important part of STM is a region in which compressive stresses act parallel together from face to face of two nodes in the structural member. It is commonly idealised into three shapes of prismatic, bottle-shaped, and fan-shaped (AASHTO, 2012; ACI, 2011; Bahen, 2007; CEB-FIP, 1999; CSA-A23.3-04, 2005; DIN, 2001; Eurocode2, 2008; NZS, 2006). According to the prior research, there is not unique strut dimension for one given concrete structural member. The rough estimate of strut dimensions is still an issue among researchers which has caused some challenges for the prediction of concrete strut behaviour in STM. The crushing strength of concrete in case of strut is evaluated by strut effectiveness factor. The available codes and standards which recommended strut effectiveness factor are classified into two groups in this thesis. The former group comprises AASHTO LRFD, CSA-S6-06, and CSA A23.3 which define the strut effectiveness factor as a function of the tensile strain of tie and the angle between the strut and the tie (AASHTO, 2012; CAN/CSA-S6-06, 2006; CSA-A23.3-04, 2005). The original idea of the forgoing effectiveness factor was proposed in 1986 by Vecchio and Collins (Vecchio & Collins, 1986). The latter group comprises ACI 318-11, DIN 1045-1, NZS 3101, and CEB-FIP Model code 1999 which recommend a simple value as the strut effectiveness factor unlike the former group. This value depends on the type of concrete based on the weight as well as the satisfaction of required reinforcements (ACI, 2011; CEB-FIP, 1999; DIN, 2001; NZS, 2006). The equations of strut effectiveness factor recommended by the former group are basically referred to the research conducted on modified compression-field (MCF) theory (J.vecchio & P.Collins, 1986). This research proposed the stress-strain relationship for cracked concrete in compression.

1.2 Problem Statement

The strengthening of concrete structural elements using CFRP sheet is on the increase because of CFRP advantages which have been mentioned in the preceding section. The need for CFRP strengthening of concrete structural elements including B-regions and D-regions has been on the increase since the last decade. Crucially, the cost of CFRP will be competitive with steel for strengthening because of its mass production within the next five years (Ahmad, 2012). D-Regions are parts of the structure with complicated variation in strain. In essence, D-Regions contain the parts of structure which are near to the concentrated forces or steep changes in geometry which are so-called geometrical discontinuities or static discontinuities. Strut-and-tie model (STM) is very convenient for analysis of D-regions. According to the literature review, the main challenge in STM is the calculation of the value of the strut effectiveness factor for design purposes. However, strengthening of D-regions using CFRP exacerbates the forgoing issue.

By and large, the problem is that the STM is not able to predict shear strength of RC deep beams strengthened with CFRP sheet. The need for a rational method to predict the ultimate strength of CFRP strengthened D-regions particularly in RC deep beams is the significance of this research problem. This thesis aims to modify the STM for analysis of CFRP strengthened RC deep beams with various shear to the effective depth ratios. It also discusses the issue of ductility and energy absorption of ordinary and CFRP strengthened RC deep beams.

1.3 Research Aims and Objectives

This thesis elaborates on the STM recommended by ACI318-11 and AASHTO LRFD using experimental results to point the way towards modifying strut effectiveness factor in STM for CFRP strengthened RC deep beams. It addresses several ways to enhance our understanding of strut performance in the STM. The main purpose of this research is to modify the STM for prediction of ultimate shear strength of RC deep beams strengthened with CFRP. To date, no research has been conducted about the value of strain along and perpendicular to the strut centreline in D-region to achieve the strut effectiveness factor in STM. Hence, the objectives of this research are as follows:

- To propose modified STM using an empirical relationship to predict the ultimate shear strength of CFRP strengthened RC deep beams.

    i. To obtain an empirical relationship to predict the value of principal tensile strain in strut for CFRP strengthened deep beams.

ii. To establish an empirical relationship between the growths of energy absorption of CFRP strengthened RC deep beams and shear span to effective depth ratio.

iii. To identify the failure mode of ordinary and CFRP strengthened deep beams as well as the maximum crack width of deep beams with different shear span to the effective depth ratios.

1.4 Scope and Limitations

This research is confined to the ordinary concrete deep beams strengthened with one layer of unidirectional CFRP sheet with two-side wet lay-up system. The experimental concrete deep beams constructed in this experiment consist of two groups according to control deep beams and CFRP strengthened deep beams. Each group consisted of six deep beams with shear span to the effective depth ratio of 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00.

The beams were cast using a single batch of ready mixed concrete. The cylindrical compressive strength and cylinder splitting tensile strength of concrete were 37.02 MPa and 3.31 MPa respectively. The beams were tested to failure under four-point bending set-up. The CAST (computer aided strut-and-tie) design tool were utilised to facilitate the iterative calculation method for STM and draw the three parts of STM with different amounts of stress in colour (D. A. Kuchma & T. N. Tjhin, 2001). Ultimate shear strength of control deep beams and CFRP strengthened deep beams, shear span to effective depth ratio, the value of principal strain perpendicular to the strut centreline and the energy absorption of deep beams were the main factors in this research.

1.5 Layout of Thesis

This research consists of five chapters. These chapters were formatted according to the Style 1 of the Guide to Thesis Preparation-March 2014, provided by the School of Graduate Studies, University of Putra Malaysia. Chapter 1 comprises the concise literature review, problem statement, objectives and scope of current study. Chapter 2 explores the background research regarding deep beam, carbon fibre reinforced polymer (CFRP), and the strut-and-tie model (STM). Chapter 3 presents the methodology of this research comprising application of CAST design tool (Kuchma & Tjhin, 2005) as well as material and method used in this experimental work. Chapter 4 provides the results of this research and related discussion. Finally, in chapter 5, the conclusion of this research is drawn and subsequently the recommendations for further research are presented.

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