UNIVERSITI PUTRA MALAYSIA

MODIFIED STRUT-AND-TIE MODELS FOR REINFORCED CONCRETE DEEP BEAMS WITH EXTERNALLY BONDED CFRP SYSTEMS

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By

AMMAR NASIRI HANOON

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

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DEDICATION

This thesis is dedicated to:

The sake of Allah, my Creator and my Master,

My great teacher and messenger, Mohammed (May Allah bless and grant him and his family),

The memory of my parents,

All the people in my life who touch my heart,

I dedicate this research.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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May 2017

Chairman : Professor Mohd. Saleh Jaafar, PhD
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Reinforced concrete (RC) deep beams can be defined as the main structural component used in buildings and bridges to transfer heavy loads. Due to their relatively low shear span to depth ratio (less than 2.0), a linear strain distribution cannot be applied, thus there is a need for a rational model to address this nonlinearity. Numerous codes of practice and research recommended the use of the strut-and-tie model (STM) to analyse the discontinuity regions (D-regions) and consequently deep beams. The STM is an effective shear design method based on the lower-bound plasticity theorem. The significance of this method is that in D- regions, the STM model can predict the shear strength of members with better accuracy than traditional flexure theory.

Since the last decades, using carbon fibre reinforced polymer (CFRP) as strengthening material for RC beams has become a topic of interest among researchers and CFRP has been suggested for structures including concrete deep beams. Moreover, RC structures may be subjected to various dynamic loading types. Considering all these loading types, it is important to understand the effect of loading rate on such structures. Nevertheless, scarce studies have been reported regarding the loading rates effect. In view of these cases, STM is not being able to predict the shear strength of deep beams, effectively.

Thus, the objective of this study is to modify the STM to analyse concrete deep beams for the two cases. This study also highlights the development of an energy absorption capacity model of concrete beams under different loading rates.

An STM of unstrengthened concrete deep beam is modified in two cases: (1) deep beam strengthened with FRP sheet under static loads, and (2) deep beam subjected to different loading rates. Unlike existing STMs, this study implements two FRP failure

modes, namely FRP debonding and tensile rupture failure mode. Moreover, the particle swarm optimization (PSO) algorithm was used to search for the optimum set of unknown coefficients which are stress distribution and concrete tensile reduction factors. The optimum proposed model was built based on the data collected from existing experimental programs and the proposed finite element models.

The proposed models have been verified against experimental data collected from this study and existing literature. The proposed STM approaches exhibit efficiency in assessing ultimate shear strength capacity comparison with the experimental results and can be used as design guides. The experimental results show that the growth of energy absorption of CFRP-strengthened RC deep beams varies from approximately 15% to 51% for shear span-to-effective depth ratios of 1.0 to 1.75 and 15% to 86% for shear reinforcement ratios of 0% to 0.4%, respectively. The results show that the PSO technique is suitable for assessing structural engineering problems and can be used as an efficient tool to explore the optimal solutions for different structural problems.

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

MODEL STRUT-AND-TIE MODIFIED UNTUK RASUK DALAM KONKRIT BERTETULANG DENGAN SISTEM CFRP TERIKAT DI LUARAN

Oleh

AMMAR NASIRI HANOON

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Rasuk dalam konkrit bertetulang (RC) boleh ditakrifkan sebagai komponen struktur utama yang digunakan di dalam bangunan dan jambatan untuk membawa beban berat. Oleh kerana nisbah rentang ricih terhadap ukurdalam yang secara relatifnya rendah (kurang daripada 2.0), agihan terikan linear tidak boleh digunakan, dengan itu terdapat keperluan untuk model rasional bagi menangani ketaklelurusan ini. Banyak kod amalan dan penyelidikan telah mencadangkan penggunaan *Strut-and-Tie Model* (STM) untuk menganalisis kawasan terganggu (kawasan-D) dan seterusnya rasuk dalam. STM adalah kaedah reka bentuk ricih berkesan berdasarkan teorem keplastikan batasan-bawah. Kepentingan kaedah ini adalah bahawa di dalam kawasan-D, model STM boleh meramalkan kekuatan ricih anggota dengan ketepatan yang lebih baik daripada teori lenturan tradisional.

Sejak beberapa dekad yang lalu, penggunaan polimer bertetulang gentian karbon (*Carbon Fibre Reinforced Polymer*, CFRP) sebagai bahan pengukuh untuk rasuk RC telah menjadi satu topik yang menarik di kalangan penyelidik dan CFRP telah dicadangkan untuk struktur termasuk rasuk konkrit dalam. Selain itu, struktur RC mungkin tertakluk kepada pelbagai jenis pembebanan dinamik. Mengambil kira semua jenis bebanan ini, adalah penting untuk memahami kesan kadar pembebanan ke atas struktur tersebut. Namun, hanya kajian yang terhad telah dilaporkan mengenai kesan kadar beban. Memandangkan kes-kes ini, STM pada ketika ini tidak dapat meramalkan kekuatan ricih rasuk dalam dengan berkesan.

Oleh itu, objektif kajian ini adalah untuk mengubah suai STM bagi menganalisis rasuk konkrit dalam untuk kedua-dua kes. Kajian ini juga menunjukkan pembangunan model kapasiti penyerapan tenaga rasuk konkrit di bawah kadar-kadar pembebanan yang berbeza.

STM rasuk konkrit dalam yang tidak diperkuatkan diubahsuai di dalam dua kes: (1) rasuk dalam diperkuatkan dengan kepingan FRP di bawah beban statik, dan (2) rasuk dalam tertakluk kepada kadar pembebanan yang berbeza. Tidak seperti STMs sedia ada, kajian ini melaksanakan dua mod kegagalan FRP, iaitu nyahikatan FRP dan mod kegagalan pecah tegangan. Selain itu, algoritma pengoptimuman kumpulan zarah (*Particle Swarm Optimization*, PSO) telah digunakan untuk mencari set optimum bagi pekali-pekali yang tidak diketahui yang berupa faktor-faktor agihan tegasan dan pengurangan tegangan konkrit. Model optimum yang dicadangkan dibina berdasarkan data yang diperoleh daripada program eksperimen sedia ada dan cadangan model unsur terhingga (*Finite Element Model*, FEM).

Model-model yang dicadangkan telah disahkan dengan data eksperimen yang dikumpul daripada kajian ini dan kepustakaan yang sedia ada. Pendekatan STM yang dicadangkan menunjukkan kecekapan dalam menilai kapasiti kekuatan ricih yang muktamad berbanding dengan keputusan eksperimen dan ianya boleh digunakan sebagai panduan reka bentuk. Keputusan eksperimen menunjukkan bahawa pertumbuhan penyerapan tenaga rasuk dalam RC diperkukuhkan-CFRP berbeza dari kira-kira 15% kepada 51% untuk nisbah rentang ricih-ke- ukurdalam berkesan dengan nilai 1.0 hingga 1.75 dan 15% ke 86% masing-masing untuk nisbah tetulang ricih sebanyak 0% hingga 0.4%,. Keputusan menunjukkan bahawa teknik PSO ini sesuai untuk menilai masalah kejuruteraan struktur dan ianya boleh digunakan sebagai kaedah yang cekap untuk menyiasat penyelesaian optimum bagi masalah struktur yang berbeza.

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LIST OF SYMBOLS

a	shear span.
a/d	shear span-to-depth ratio.
A_c	area of concrete section resisting shear transfer.
A_{str}	cross-sectional area at one end of a strut in a strut-and-tie model, taken perpendicular. to the axis of the strut
A_h	total cross sectional area of horizontal steel reinforcement.
A_s	total area of non-prestressed longitudinal steel reinforcement
A_v	total cross sectional area of vertical steel reinforcement.
A_{FRP}	area of FRP sheet.
b_w	web width of the beam.
c_1, c_2	cognitive and social acceleration factors, respectively; "acceleration coefficients".
d	effective depth of cross-section.
$F_1\ to\ F_6$	Set of unknown coefficients for the energy absorption capacity model.
f'_c	characteristic concrete cylinder strength.
f_{ct}	concrete tensile strength.
f_{FRP}	strength of bent portion of FRP bar.
f_t	tensile strength contribution.
f_y	specified yield strength of reinforcement.
f_1	Transverse tensile stress.
f_2	Compressive stress.
$gbest$	best position found by swarm (global best, best of personal
h	overall depth of the beam cross-section.

k	stress distribution factor.
L_a	depth of the top nodal zone.
L_b	support-bearing plate width.
L_c	depth of the bottom nodal zone.
N	number of particles in swarm.
n_{FRP}	number of CFRP layers.
$pbest$	best position found by the *ith* particle (personal best).
r_1 , r_2	random variables uniformly distributed within range (*0*,*1*).
t	number of iterations.
t_{FRP}	thickness of each FRP sheet.
V_n	nominal shear strength at section.
V_{exp}	measured shear force at section.
$v_{j,g}^{(t)}$	velocity of particle *j* at iteration *t.*
w	inertia weight factor used to balance the global exploration and local exploitation.
$x_{j,g}^{(t)}$	*gth* components for the position of particle *j* at iteration *t.*
y	actual output value.
y'	predicted output value.
Z_s	lever arm.
θ_s	angle between the axis of a strut and the bars in the *i-th* layer of reinforcement. crossing that strut.
θ_w	web reinforcement angle.
λ	concretes tensile reduction factor.
v	strut effectiveness factor.

ρ_g	longitudinal steel reinforcement ratio.
ρ_w	transverse steel reinforcement ratio.

CHAPTER 1

INTRODUCTION

1.1 Background

Reinforced concrete (RC) deep beams may be utilized in pile caps, bunkers, shear walls, floor diaphragms, and many multistorey RC buildings (Figure 1.1). As the ratio of shear span to effective depth ratio becomes less than two for simply supported beams and 2.5 for continuous beams, the theory of plane section remaining plane after deformation cannot be substantially utilized to determine the bending and shear stresses (Raju (1988); Kong (2006)).

Considering the relatively low shear span-to-depth ratio of deep beams, their structural behavior greatly differs from those of slender beams. In particular, the response of deep beams is characterized by nonlinear stress distribution (Figure 1.2) that occurs even in the elastic load range. In addition, the strength of deep beams with a normal amount of longitudinal reinforcement is usually controlled by shear instead of flexure. Consequently, establishing methods of accurately predicting the shear strengths of deep beams have become an important research topic in this field.


Figure 1.1 : Applications of RC deep beams

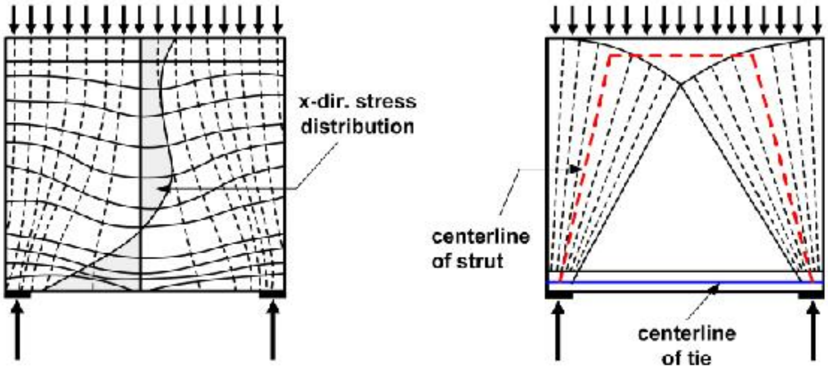

Figure 1.2 : Strain distribution in deep and slender portion of RC beams (Chu and Charles (1979)).

Several studies have been conducted to predict the shear strength of RC deep beams (Kong *et al.* (1978); Mau and Hsu (1989); Park and Kuchma (2007a)). Many researchers used strut-and-tie model (STM) to assess the ultimate shear strength of RC deep beams (Matamoros and Wong (2003); Park and Kuchma (2007a); Arabzadeh *et al.* (2009)). Several codes and standards, such as the American Concrete Institute (ACI318-11 (2011)) and the Canadian Standard Association (CSA-A23.3 (1994)), adopt the STM approach for deep beam design. Additionally, the STM has been applied to predict the capacity of other discontinuity region (D-region) members, such as corbel (Lu and Lin (2009)), dapped-end beams (Lin *et al.* (2003)), or joint in decked bulb-tee bridge (Li *et al.* (2013)). The STM idealizes the complex flow of stresses in a structural member as truss-like members. The flow of concentrated compressive stresses in the concrete can be represented by diagonal struts, whereas the induced concentrated tensile stresses can be represented by tension ties, which are resisted by longitudinal steel reinforcement. The regions where struts and ties intersect each other are called nodal zones.

During their service life, RC structures may suffer from various deteriorations, such as cracks, concrete spalling, large deformation, and sometimes may collapse. Various factors are causing these deteriorations, such as aging, corrosion of steel reinforcement, increased loads, and environmental effects (Wang *et al.* (2006); El Maaddawy and Sherif (2009); Dong *et al.* (2010)). Therefore, strengthening such structures to resist possible high loading is necessary (CSA-A23.3 (1994); Sundarraja and Rajamohan (2009); Wang and Hsu (2009); Dong et al. (2010)). Several options are available for retrofitting the damaged structural elements. Fiber-reinforced polymer (FRP) has been widely used to retrofit or repair damaged structural elements; FRP was also utilized to increase the loading capacity, ductility and stiffness of the structures because of its corrosion resistance, light weight, high tensile strength, durability, and simple installation (Zwicky and Vogel (2006); Deng and Lee (2007); Wang *et al.* (2008); Tanarslan *et al.* (2012)).

In spite of the extensive research on the STM, few models applicable to CFRP-strengthened RC deep beams have been achieved, such as the modification proposed by Zhang *et al.* (2004), Park and Aboutaha (2009), Godat and Chaallal (2013), and Panjehpour *et al.* (2014). Some of these models did not consider the effects of FRP scheme and its orientation. For instance, the STM proposed by Panjehpour et al. (2014) was established based on the strength of deep beams with side wrapping. However, the effects of CFRP scheme and orientation were not considered. Therefore, further studies were required to develop an improved understanding of the behavior of CFRP-strengthened RC deep beams and to develop a modeling technique that accurately predicted the static shear capacity. As mentioned previously, the assumptions of bending theory cannot be used for RC deep beams. Thus, some assumptions are necessary, such as the value of stress distribution along the cross section. This study presents the difficulty to solve such problem by conventional analytical methods. Therefore, using an optimization technique is important to solve this complex problem.

Engineers design structures that fulfill design requirements at optimum possible cost. Optimization provides engineers with a variety of techniques to deal with these problems (Kaveh and Talatahari (2010)). These techniques can be classified into two main groups, namely, classical and metaheuristic approaches (Kaveh *et al.* (2008)). Classical approaches are based on mathematical programming, whereas metaheuristic approaches depend on ideas inspired from nature. Metaheuristic approaches are not affected by the conflicts of mathematical programming, such as the continuous objective function or requirement for calculating the gradients of objective function and constraints.

Genetic algorithms (Holland (1992)), ant colony optimization (Dorigo *et al.* (2006)), harmony search (Lee and Geem (2004)), cuckoo search (Gandomi, Talatahari, *et al.* (2013)), bat algorithm (Gandomi, Yang, *et al.* (2013)), krill herd (Gandomi and Alavi (2012)), and particle swarm optimization (PSO) (Eberhart and Kennedy (1995)) are common metaheuristic techniques to address engineering problems. Researchers used PSO technique in engineering applications because of its few parameters and easy to carry out (Schutte and Groenwold (2003); Li *et al.* (2009); Hadidi *et al.* (2011)). PSO is based on the simulation of the social behavior of bird flocking.

PSO is effective in solving engineering problems (Eslami *et al.* (2012)). Given its few parameters, this method provides high accuracy in finding suboptimal solutions in a reasonable amount of time. Thus, researchers are encouraged to utilize PSO for different optimization problems in diverse branches of knowledge. PSO has been successfully used in optimization problems in structural engineering (Zhang et al. (2004); Islam *et al.* (2005); Benachour *et al.* (2008); Jalali *et al.* (2012)). Chen *et al.* (2013) developed a method based on PSO and finite element (FE) analysis for the reliability-based design of composite structures. Kazunori Fujikake *et al.* (2009) developed a program using PSO algorithm for the cost-optimum design of RC beams.

A number of experimental studies works on strength and ductility capacity of RC structures have been carried out in the previous, which indicated that the ductility capacity was substantially affected by loading types and conditions (loading rates). As far as such as earthquake motion is concerned, the design based on ductility capacity is not almost reasonable. Thus, the previous studies proposed that the energy absorption capacity of concrete structures is well proper index for seismic safety. This study attempts to propose an energy absorption model by using PSO algorithm.

1.2 Problem statements

The weakness of many existing concrete structures has been demonstrated by various incidents over the last half century. Many of these structures were not designed to withstand severe loading because of various factors, such as aging, corrosion of steel reinforcement, and dynamic loading (Wang et al. (2006); El Maaddawy and Sherif (2009); Dong et al. (2010)). Several options are available for retrofitting or repairing structural members of the existing RC structures to overcome the design error or unexpected loads. The commonly used options are to bond carbon fiber reinforced polymer (CFRP) sheets into the damaged members to restrain cracks and to increase the load carrying capacity, strengthening stiffness of structures (Deng and Lee (2007); Wang et al. (2008)).

The need for FRP strengthening of RC structural elements including B and D regions (as presented in section 2.3.2) has been on the increase since the last decade. Regions are parts of the structure with a complicated variation in strain. In essence, D regions contain the geometry. D regions are near to the concentrated forces or step changes in geometry, which are so-called geometrical discontinuities. The STMs are widely used in certain types of structural elements in reinforced concrete and in regions with complexity of the stress state, called regions ‘‘D’’, where the distribution of deformations in the cross section is not linear.

Based on the above finding, the following problems have been drawn.

1. Aside from research conducted on the behavior of RC deep beams using FRP as strengthening, few studies were carried out on the energy absorption and ductility of FRP-strengthened RC deep beams with different shear spans to effective depth ratio and FRP sheet scheme and orientation.

2. FRP-strengthened RC deep beams under static loads.
   (a) The current design codes and guides (CSA-S806-02 (2002); ACI-440 (2006); ISIS (2007)) provide no shear design method specifically for deep concrete members strengthened with FRP sheets. Designers only have guidance on using sectional models, which may result in uneconomical designs in instances where large members are used, as is the case when RC deep beams are designed using sectional models.
   (b) Despite the ease of its use and spread, the problem is that the STM is not able to predict shear strength of RC deep beams strengthened with FRP sheet. Moreover, very few models are applicable to FRP-strengthened RC

deep beams. In addition, most of these models did not consider the FRP scheme and its orientation. The need for rational method to predict the shear strength in RC deep beams with FRP strengthening is the significance of this research problem. However, most of the STMs proposed did not take inconsideration the effect of FRP failure modes, such as debonding and FRP tensile rupture failure modes.

(c) The stress distribution along the diagonal strut of deep beam cannot be determined directly by the assumptions of the beam theory because of its nonlinearity. Therefore, more assumptions are needed to find the stress distribution factors. However, assuming these factors requires exhaustive traditional trial-and-error procedure to find the optimum assumption. Therefore, this study estimates the values of stress distribution factors using an optimization technique to address these nonlinearity problems.

3. Unstrengthened RC deep beams under wide range of loading rates.
   Strain rate effects at the constitutive level of structural material have been well documented in the literature. However, investigation into the structural behavior under varying loading rates is very limited (Somraj et al. (2013)). To the best knowledge of the researcher, less STMs are currently available in the literature especially for RC deep beams subjected to various loading rates.

4. Energy absorption capacity of RC beams under different loading rates.
   A number of experimental studies on strength and ductility capacity of RC structures were performed. These studies displayed that the ductility capacity was substantially influenced by loading types and rates. For instance, the design based on ductility capacity is very conservative in structures subjected to earthquake motion. Thus, the energy absorption capacity of RC structures is a proper index for seismic safety. Apart from research conducted on the energy absorption of concrete beams, there is no research was conducted on the energy absorption of RC deep beams subjected to different loading rates with different parameters, such as shear span to effective depth ratio, concrete compressive strength, and steel reinforcement ratios.

1.3 Objectives of the study

The overall objective of this study is to ascertain the behavior of strengthened RC deep beams with unidirectional CFRP sheets. Specifically, the objectives of this research are summarized as follows:

1. To identify the failure modes, ultimate capacity, ductility, energy absorption and cracks width of unstrengthened and CFRP-strengthened RC deep beams with different shear spans to the effective depth ratios, CFRP scheme and orientation, and various shear reinforcement ratios.
2. To propose modified STM for CFRP-strengthened RC deep beams based on PSO algorithm and new strut effectiveness factor for CFRP-strengthened RC deep beams subjected to static loads.
3. To propose modified STM and new strut effectiveness factor for unstrengthened RC deep beams under different loading rates.

4. To propose an empirical relationship for the energy absorption capacity of RC deep beams under different loading rates with different parameters, such as shear span-to-depth ratio, concrete compressive strength, longitudinal reinforcement ratio, and web reinforcement ratio based on PSO technique.
5. To assess the effectiveness of the proposed models by changing some parameters considered especially important to set suitable range of application.

1.4 Approaches of the proposed STM modification

Two approaches of STM modification are proposed and investigated. The first approach deals with the modified STM of RC deep beam strengthening with CFRP under static load. The second approach considered the effect of various loading rates on the modification of the STM of unstrengthened RC deep beams. The proposed models consider the effect of the combined tensile strength of longitudinal and transverse reinforcements, FRP sheets, and the tensile strength of concrete. A linear failure criterion based on modified Mohr–Coulomb theory is adopted in this study. The proposed model is simulated using MATLAB environment.

1.4.1 RC deep beam strengthening with CFRP under static load

The STM of unstrengthened RC deep beams proposed by Tan *et al.* (2001) is extended and modified to account the ultimate shear strength of FRP-strengthened RC deep beams. Tan et al. model is adopted in this study because it considers the effects of various shear reinforcement configurations vertical and horizontal, or inclined. Other than defining the stress limits for the STM components, the model uses a failure criterion from the Mohr–Columb theory for nodal zones (tension–compression stress state). The effects of FRP sheets are represented by the equivalent external forces, which are built in the model explicitly. In addition, the assumptions on the stress distribution factor acting along the diagonal strut are necessary to add the CFRP effect to the original unstrengthened STM because to assess the exact value of the principal tensile stress is difficult. Moreover, the plane section of plane theory does not hold for deep beams. Thus, this study aims to estimate the value of the stress distribution (k) and concrete tensile stress reduction (λ) factors by using PSO algorithm to address the nonlinearity problems and to find the optimum solution of these unknown coefficients.

1.4.2 Unstrengthened RC deep beams under different loading rates

In this approach, the STM introduced by Tan et al. (2001) is modified to account for the ultimate shear strength of RC deep beams under a wide range of loading rates. A simple and refined interaction formula to predict the ultimate dynamic shear strength of RC deep beams is derived. To imply and integrate the dynamic effect, the proposed constitutive relationships of concrete and reinforcing steel (K. Fujikake *et al.* (2009)) are considered.

1.5 Research hypothesis

Based on the current design codes, such as American Concrete Institute building code (ACI318-14 (2014)), a RC deep beam should be analyzed using the STM considering the complex stresses flow in D regions (discontinuity regions). Based on the best author knowledge, studies on the ultimate shear strength and behavior of RC deep beams strengthened with CFRP sheet under static loads and unstrengthened deep beams subjected to different loading rates are scarce. As a result, the necessity to propose rational methods to estimate the ultimate shear strength of the RC deep beams has become significant in current literature topics. Therefore, this study aims theoretically to propose STM to assess the ultimate shear strength and suggests a new model using STM to design RC deep beams.

Therefore, to develop the applicability of the STM concept for RC deep beams under both static with FRP strengthening and dynamic without strengthening, the following hypothesis are assumed:

(a) The concrete strut is subjected to a uniaxial compressive stress f_2 (Figure 1.3) inclined at an angle θ with respect to the beam axis.
(b) The proposed model considers the effect of crushing and diagonal splitting concrete failure.
(c) Perfectly, plastic behavior is assumed for the materials and for the bond at the FRP-concrete interface. In particular, the failure of the external reinforcement occurs after yielding of the internal steel reinforcement, wherein the steel yielding/concrete crushing takes place before FRP fracture or debonding failure.
(d) The external tension FRP sheet is treated like conventional shear reinforcement.
(e) The external shear reinforcement in the form of continuously bonded sheet or discontinuously bonded vertical strips is treated like conventional internal stirrups in terms of distributed forces. Its quantitative evaluation depends on the failure mode, i.e., bond slip or tensile fracture.
(f) The failure of shear tension caused by the inadequate anchorage of flexural reinforcement is not considered.
(g) The constitutive relationships for the stress–strain of concrete and steel reinforcement proposed by K. Fujikake et al. (2009) is considered in the current study.

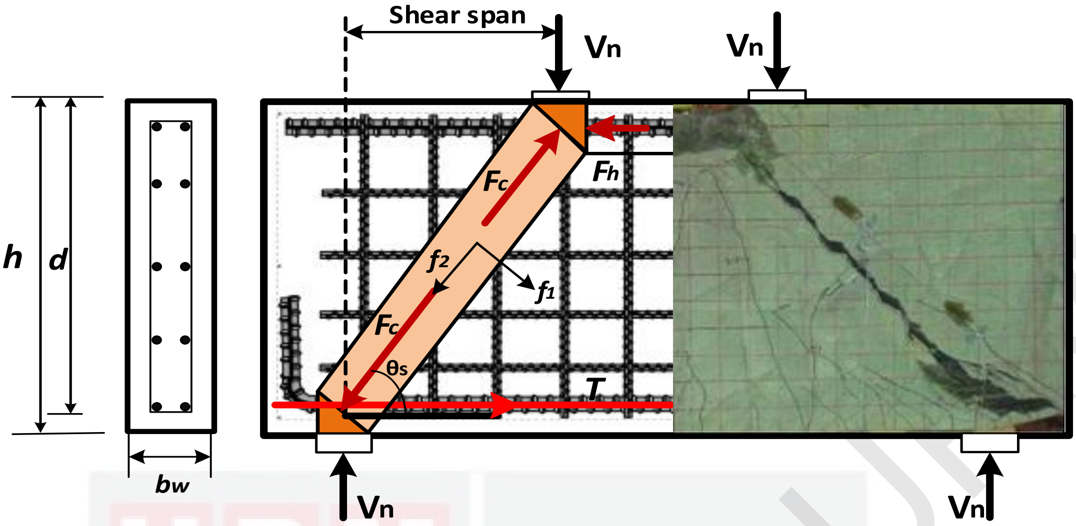

Figure 1.3 : Strut-and-tie model for simply supported deep beams

1.6 Scope and research approach of the study

The research approach followed in this study comprised a literature survey, extensive experimental program, theoretical analysis using rational model and numerical simulations using FE analysis. Figure 1.4 shows a schematic representation of the research approach adopted in this study.

A state-of-the-art literature survey was achieved to collect information on RC deep beams. Research gaps and limitations were categorized. The experimental program comprised deep beam specimen testing to examine the performance of CFRP-strengthening technique.

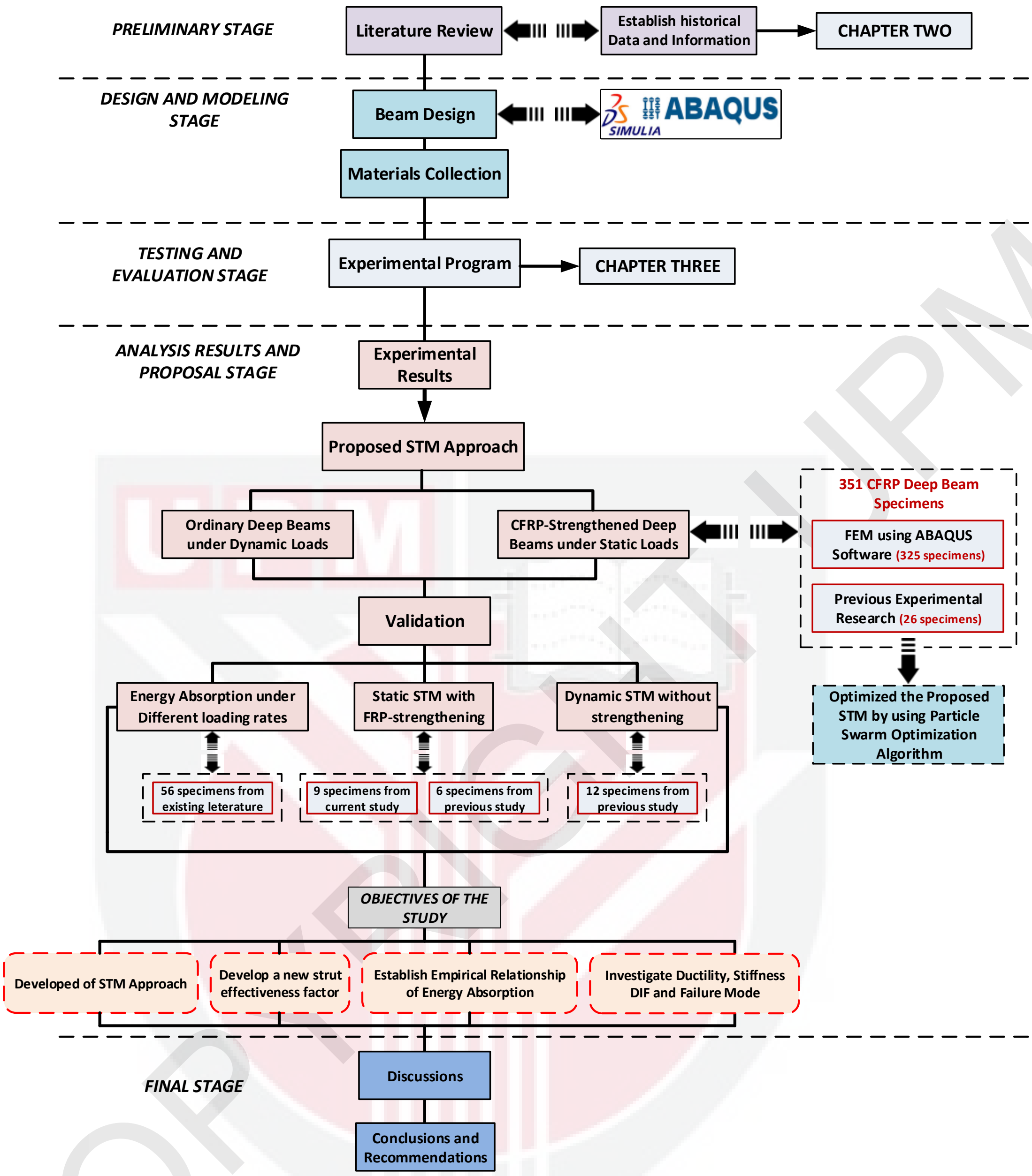

Figure 1.4 : Schematic representation of research approach

The current study is limited to the CFRP-strengthened RC deep beams strengthened with one layer of unidirection CFRP sheet. A total of 12 RC deep beam specimens were tested until failure under static loads. These specimens comprise unstrengthened and CFRP-strengthened RC deep beams. The CFRP-strengthened RC deep beams were side wrapping, 45° and 90° strips. The beams were cast using a single batch of ready-mixed concrete. The cylindrical compressive strength and cylinder splitting tensile strength of concrete were 41.6 and 4 MPa, respectively. Chapter 3 discusses in details the experimental program.

1.7 Thesis outline

This research with six chapters was formatted in accordance with the guide to Thesis Preparation-March 2004, provided by the School of Graduate Studies, Universiti Putra Malaysia.

Chapter 1 contains the brief literature review, statement of problem, objectives, research hypothesis, and scope of current study.

Chapter 2 covers the background research regarding deep beams behavior, carbon fiber polymer (CFRP), loading rates, strut-and-tie model (STM), and particle swarm optimization (PSO) technique.

Chapter 3 presents the details of the experimental program and the testing procedure, as well as geometrical and material properties and test setup used in this program.

Chapter 4 presents the derivation steps of the proposed STMs and finite element (FE) analysis.

Chapter 5 addresses the experimental and the theoretical results of this research and the related discussion.

Finally, Chapter 6 presents a general conclusion of the results obtained from the experiments and theoretical aspect with regard to the problems and observations discussed throughout the thesis in addition to the recommendations for further research.

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