STRUCTURAL PERFORMANCE OF REPAIRED CIRCULAR REINFORCED CONCRETE COLUMNS USING STEEL STRAPPING TENSIONING TECHNIQUE

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DEDICATION

This thesis is dedicated to my supervisors, my father, my mother, family, and all my beloved friends

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ABSTRACT

Studies on the behaviour of intact reinforced concrete (RC) columns are widely available, however, studies focusing on the behaviour of deteriorated RC columns is quite limited. Deteriorated columns need to be repaired to remain structurally sound. Among the available repairing approaches, confining methods have been extensively researched. Current studies on confining damaged column only focusing on passive-typed confinement, which led to high dependency of the dilation of concrete. This study extends the investigation on repairing RC columns to the active-typed confinement, where confining stress is applied to columns before the concrete dilation. Both experimental and numerical modeling were conducted to investigate the applicability of active confinement in repairing RC columns with varied pre-damaged levels. The applicability of steel strapping confinement in repairing RC columns with the varied pre-damaged levels were confirmed through experimental works, the experimental involved testing of 34 plain concrete cylinders and 21 RC columns under monotonic uniaxial compression. The concrete cylinder tests were performed develop a suitable stress-strain model, which incorporated pre-damaged levels for confined concrete. The empirical stress-strain model was then used in the development of numerical model for the repaired RC columns. The tests on RC column specimens consisted of 3 control columns and 18 repaired RC columns with different confining levels. The overall response of the specimens was investigated in terms of crack pattern, load carrying capacity, axial displacement, stiffness and ductility of repaired columns. The results from the experimental works were then verified by using the numerical modeling before further analysis. The test results have shown that the restorability of confinement was significantly affected by pre-damaged levels. It is also observed that the increase in confining volumetric ratio is able to restore both strength and ductility of repaired RC columns up to 171% and 172%, for the same pre-damaged level. Additionally, the outcome of the finite element modelling also aligned with the experimental results where the average absolute errors (AAE) for both strength and ductility remained are within 15%. Based on this study, a design consideration for repairing columns using confinement was also developed. The design consideration serves as a tool for design engineers in using steel strapping confinement in repairing damaged columns.

ABSTRAK

Kajian memberi tumpuan kepada tingkah laku tiang konkrit bertetulang (KB) dalam keadaan utuh semakin meluas, tetapi fokus dalam tiang-tiang KB yang mengalami kerosakan mekanikal masih sukar didapati. Tiang tersebut mestilah diperbaiki untuk memastikan strukturnya dalam keadaan baik. Dalam kebanyakkan pendekatan dalam membaiki struktur yang ada, balutan sisi telah menjanjikan penyelesaian. Kajian terkini mendapati balutan sisi tiang hanya fokus kepada balutan sisi yang tidak giat yang menjurus kepada pengembangan konkrit. Dalam kajian ini menyambung penyiasatan dalam pembaikan tiang KB bagi balutan sisi aktif di mana tegasan balutan diberikan kepada tiang sebelem konkrit berkembang. Ujikaji makmal dan kaedah berangka telah dijalankan untuk mengkaji kebolehgunaan balutan sisi aktif dalam pembaikkan tiang KB dengan pelbagai tahap pra-kerosakan.Kebolehgunaan besi balutan sisi dalam pembaikkan tiang KB dengan pelbagai tahap pra-kerosakkan ditentukan dengan 34 silinder konkrit biasa dan 21 tiang KB diuji di bawah beban mampatan satu paksi. Ujian silinder konkrit dilakukan untuk membina model tegasan-keterikan yang sesuai bagi menggabungkan tahap pra-kerosakan untuk konkrit berbalut. Model ini kemudiannya digunakan dalam pembangunan model berangka untuk tiang KB yang rosak. Ujian pada spesimen KB terdiri daripada 3 tiang asal dan 18 tiang KB diperbaiki dengan tahap pengasingan yang berbeza telah dijalankan. Tindak balas keseluruhan spesimen disiasat dari segi corak retak, keupayaan menanggung beban, pemendekan paksi, kekukuhan dan kemuluran pembaikan tiang. Hasil ujian menunjukkan tahap pra-kerosakan mempunyai kesan yang signifikan terhadap keupayaan menanggung beban. Peningkatan skema balutan dapat meningkatkan kekuatan dan kemuluran KB yang dibaiki sehingga 171% dan 172% untuk tahap pra-kerosakan yang sama. Selain itu, model berangka telah dibangunkan untuk mengetahui lebih lanjut mengenai tingkah laku tiang yang diperbaiki ini menggunakan balutan sisi. Hasil dari model yang menunjukkan keputusan baik dengan ujikaji makmal di mana purata selisih mutlak untuk kekuatan dan kemuluran berbeza kurang dari 15%. Garis panduan reka bentuk untuk kerja-kerja pembaikan menggunakan balutan sisi telah dibangunkan. Garis panduan reka bentuk ini adalah alat yang menjanjikan bagi jurutera reka bentuk dalam menggunakan balutan sisi dalam kerja pembaikkan kerosakan tiang.

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LIST OF SYMBOLS

E_f	-	Elastic modulus of confining material
E_0	-	Initial slope of stress-strain curve
$\widetilde{E_0}$	-	Initial slope of stress-strain curve of damaged concrete
E_h	-	Slope of strain hardening
$\widetilde{E_h}$	-	Slope of strain hardening of damaged concrete
f_0	-	Elastic limit
$\widetilde{f_0}$	-	Elastic limit of damaged concrete
f_c	-	Stress of concrete
f_{cc}	-	Damaged concrete compressive strength
f_{cd}	-	Unconfined damaged concrete compressive strength
f_{co}	-	Unconfined undamaged concrete compressive strength
f_l	-	Confinement pressure
f_{ys}	-	Yield strength of steel straps
n	-	Transition parameter
t_f	-	Thickness of confining material
V_c	-	Volume of confined concrete
V_s	-	Volume of steel straps
δ	-	Damaged degree
λ	-	Pre-damaged level
ε_{cc}	-	Ultimate strain of confined concrete
ρ_v	-	Strain of concrete
ε_u	-	Ultimate rupture strain of confining material
ε_c	-	Volumetric confinement ratio
P_o	-	Axial load of original RC columns
P_r	-	Axial load of repaired RC columns
E_s	-	Stiffness of steel reinforcement bar
f_{yk}	-	Yield strength of steel reinforcement

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Over the past years, repairing of damaged concrete structures has become a major part in the construction industry. They contributed nearly half of the total expenditures from total construction activities. Repair is vital, especially for vertical elements such as reinforced concrete (RC) columns since RC columns is the main element that convey axial load of the buildings to the foundations. In practice, RC columns can lose its strength and stiffness especially during its service lifetime due to physical damage. Apart from that, repairs are required for the cases such as: i) arising service loads; ii) altering usage of structure; iii) errors in design or during construction; iv) seismic action; v) corrosion due to humidity; vi) fire effects; and vii) exposure to environmental effects such as the variance of temperature [1].

There are two categories of confinement which are external and internal confinement. Xiong *et al.* [2] claimed that external confinement can be adopted to repair the damaged concrete columns effectively. It can enhance the energy absorption capacity, ductility and significantly restore the strength of damaged structures. The effectiveness of confinement is highly dependent on the cross-sectional area of structure, either the shape is in circular, rectangular or square section. Besides, confinement can be either, active or passive. Passive confinement provides lateral restriction on the dilations of concrete under loading due to the Poisson's ratio and cracking of the structure. Active confinement allows lateral pressure to be applied to the column at the initial stages of loading. Active confinement is relatively recent and is increasingly being researched [3-6]. The steel strap confinement is one of the active confinements that has been studied by previous researchers. The early research of steel straps active confinement was conducted by

Frangou *et al.* [7] and Moghaddam *et al.* [8]. Active confinement increases the concrete strength more efficiently as compared to passive confinement [8]. Subsequently, many researchers studied on steel straps confinement in different perspectives such as strength improvement, ductility enhancement, durability and bond behaviour between steel and confined concrete [9-12].

The purpose of confinement is either to repair, rehabilitate or strengthen a concrete structure. Repairing of a concrete structure is defined as the process to restore the load carrying capacity of a damaged structure to its initial performance. Rehabilitation refers to increasing in the load carrying capacity RC structure for altering the purpose of the existing buildings. While, strengthening refers to the method used to improve the capacity of the structure more than the actual design. There are few types of repairing techniques using confinement which have been reported in open literature such as ferrocement [13-16], Fibre reinforced polymer (FRP) [17-19] and steel jacketing [20-22]. The confinement models developed by previous researchers were dedicated for strengthening and repairing confined concrete works [23-25]. The confinement model developed for repairing works is still scarce and needed to be improvised. In view of this, this study investigates the use of steel strapping tensioning technique (SSTT) as an alternative in repairing the pre-damaged reinforced columns. A finite element model was verified with experimental result and extended for further investigations. Finally, the design equation for the repairing works using SSTT is proposed.

1.2 Problem Statement

Columns are major components in a structure that transfer vertical axial loads to the foundations. This will cause major failures or total collapse of the structure. The restoration of load carrying capacity of damaged columns using external confining method can be considered as one of the most efficient and quickest method. Most of the repairing techniques considered the passive confinement such as FRP concrete and steel jacketing. The study on using active confinements as

repairing techniques is still yet to be attempted by other researchers, to the best knowledge of the author. The understanding of active confinement as repairing techniques is still yet to be discovered. In practice, very less information of the damage assessment can be found in the open literature regarding the design of repairing works respectively. The assessment of pre-damaged levels is particularly important as it will affect the repairing efficiency considerably. Hence, the understanding of damaged level, which has been mostly very limited, is needed to be considered in the design of a confinement in repair works. Most importantly, the majority codes of practice neglected the state of damaged of column prior to repair works and assumed the restoration of load carrying capacity of repaired columns is only up to original capacity of column before it was deteriorated. Therefore, the insight view of the influence of pre-damaged level in the effectiveness of active confinement is required to be examined. These issues are urgently needed to be solved before the confinement can be used confidently in the construction industry.

1.3 Objectives

The aim of this research is to examine the structural performance of repaired RC columns using SSTT. A combination of experimental and modeling methods. The study focused on RC short columns by considering the effects of pre-damaged levels. The more specific objectives of this study are as follows:

i. To investigate the applicability of using SSTT in repairing damaged concrete cylinder in the restoration of the load carrying capacity and ductility through physical testing;

ii. To evaluate the affecting parameters in the restorability of repaired circular RC short columns;

iii. To evaluate the structural performance of SSTT repairing techniques by using finite element modelling;

iv. To develop a design procedure of the load-carrying capacity, ductility and stiffness of damaged structures using SSTT confinement.

1.4 Scope of Works

The study consists of three major parts. The first part is the development of stress-strain model for steel straps repair works, whilst the second part is the experimental work for RC columns. The third part consists of the development of numerical models. In the experimental works, the testing parameters are as follows:

i. A total of 34 normal strength concrete (NSC) and high strength concrete (HSC) cylindrical specimens were prepared with an identical cross-section of 100 mm diameter and 200 mm in height. Three out of 34 specimens are referred as the control specimens without pre-damaged level and unconfined. The strength classes considered were C30/37, C50/60 and C80/95;

ii. All specimens were pre-damaged before the confining works. The pre-damaged levels ranging from +50% to +80%, +80% to -80% and -80% to -50% from its ultimate load carrying capacity of concrete cylinders. The +50% to +80% pre-damaged level represents the damage conditions before it reached ultimate load capacity whilst, -80% to -50% pre-damaged levels indicate the percentage loss after peak load;

iii. The layers of steel strapping used are 1, 2 and 3 layer with 10, 20 and 30 mm of clear spacing between steel straps respectively;

iv. A series of 21 circular RC short columns with the identical size of 150 mm diameter and 600 mm height were fabricated and tested, which three of them were control columns without any repairing works;

v. The steel reinforcement ratio considered is 1.78 %, 2.56 % and 4.55 %;

vi. The strength classes considered were C30/37, C50/60 and C80/95. C50/60 was set as boundary between NSC and HSC columns;

vii. The testing variables also include difference confining schemes, which are the layer of steel straps (1, 2 and 3 layer) and the clear spacing between the strapping (10, 20 and 30 mm);

viii. A finite element (FE) model is developed by using Abaqus V.6.14. The concrete and steel reinforcement bars were simulated with 3D–eight node solid reduced integration element (C3D8R) and 2-node linear displacement (T3D2) elements. Plasticity theory was considered in the material properties of steel and concrete;

ix. The boundary condition was considered as fixed at one-end. Embedded interaction was applied between concrete and steel bars. An axial compressions displacement was applied. Then, the model developed was validated with experimental results.

1.5 Significance of Study

The main objective of this study is to determine the applicability of pre-tensioning confinements in repairing damaged columns. In order to identify the parameters that affect the effectiveness of confined columns, several damaged columns were prepared and then repaired with different confining schemes. Most importantly, the existing design guidelines for repair works considering the pre-damaged level has not yet been addressed. Therefore, numerical approach will be developed to simulate the effects of pre-damaged level, concrete compressive strength, longitudinal volumetric ratio and confinement effects towards repaired columns. The design equation is then developed for the repaired columns using steel straps. The overall view of this research is to capture the effectiveness of this confinement method so that it can be applied in practice.

1.6 Thesis Layout

This thesis was divided into nine chapters. This chapter gives an insight into the background information on the importance of repairing the structure in RC columns. Based on the Chapter 1, the fundamental and parameter of this research were identified based on the existing literature review from previous researcher.

In Chapter 2, a brief discussion was presented to explain mechanism of active and passive confinement. Previous research on the use of various confining materials to repair or strengthen existing structures was reviewed. At the end of this chapter, the focus of this research was presented by identifying the main variables that affect the repair works. The literature review was extended to Chapter 3 to review comprehensively the effects of pre-damaged level in concrete cylinder and RC columns.

The damage assessment from other researchers' perspectives and design considerations were presented in Chapter 3. It addressed each type of damage, according to behaviour of cracks formation for plain cylinder and RC columns. The overview of the damage conditions was summarized for visual assessment purposes. From this chapter, the different pre-damaged levels were classified.

The experimental methodology was presented in Chapter 4. The chapter was divided into two parts, which is experimental and numerical studies. It contains the information about mix proportion of NSC and HSC. It also shows the details specimen with the full experimental setup procedure. The repairing techniques were also elaborated. The formation for the numerical model considered in this study was presented at the end of this chapter.

Chapter 5 outlines the development of stress-strain models. The results of stress-strain relationship were analyzed. After that, the stress-strain model for steel straps confinement was proposed. Other than that, the strength and stiffness models were proposed for design considerations of repair columns.

In Chapter 6, it shows the results of an experimental program where the effects of the test parameter were analyzed and discussed. The failure modes and load-deformation behaviour were detailed out based on different parameter configurations. Subsequently, the experimental data were compared to predict the effects of the variables in strength, stiffness and ductility of repairing RC columns.

The Chapter 7 presents the prediction based on numerical analysis. Finite element analysis model was developed with elasto-plastic approach. The prediction of load-deformation behaviour of finite element were compared with experimental studies. The accuracy of the model was reported. Conclusions were drawn based to the parametric study conducted.

Chapter 8 reviews existing design consideration for repair works. The design consideration of repair work using SSTT was proposed in consideration the axial capacity of repaired columns. The example of calculations was shown in this chapter with step by step process of repair works.

Chapter 9 summarizes the outcome of the experimental test for development of stress-strain model from cylindrical specimens and results of RC columns. It also concludes the findings from finite element analysis and proposed design considerations for repaired RC columns. Consequently, the future recommendations from this research study were stated at the end of this thesis.

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