BEHAVIOR OF FIBER REINFORCED POLYMER GROUTED SPLICE CONNECTIONS

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A thesis submitted in fulfillment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

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JUNE 2020

DEDICATION

This thesis is dedicated to my beloved father, Abbas Koushfar who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my beloved mother, Fatemeh Razavi who taught me that even the largest task can be accomplished if it is done one step at a time. This thesis is dedicated to my dearest brothers, Kia and Keyarmin Koushfar.

Also, this thesis is dedicated to all those who believe in the richness of learning.

ACKNOWLEDGEMENT

The realization of this research was only possible due to the several people's collaboration, to which desire to express my gratefulness.

I would like to thank my supervisors, Prof. Dr. Ahmad Baharuddin Abd. Rahman, Associate Prof. Dr. Yusof Ahmad and Dr. Sophia C. Alih. I am grateful for the trust deposited in my work and for the motivation demonstrated along this research. Their support was without a doubt crucial in my dedication this investigation. Prof. Dr. Ahmad Baharuddin Abd. Rahman has been the ideal thesis supervisor. Without his inspirational instruction and guidance I was not able to complete this project. His sage advice, insightful criticisms, and patient encouragement aided the writing of this thesis in innumerable ways.

Gratitude is also expressed to my co-supervisor whom without his support this project would not have been possible. Associate Prof. Dr. Yusof Ahmad and Dr. Sophia C. Alih for providing the materials which immensely eased my financial burden. His guidance, support, understanding, and patience throughout my research was greatly needed and deeply appreciated.

Appreciation is extended to all laboratory staff for advices and suggestions of the work, and for the friendship that always demonstrated along these months of this project.

ABSTRACT

Grouted splice connections are widely used in joining precast concrete wall-to-wall and wall-to-column connections. However, not many studies on grouted splice connections could identify and predict their minimum bar embedded lengths and ultimate strength precisely which may lead to catastrophic failures in the structure. Moreover, the majority of the published studies are limited to conventional steel products which could not predict satisfactorily the behavior and performance of the grouted splice connections particularly when new materials and methods are adopted. In this regard, the main aim of this study was to investigate the behavior and performance of grouted splice connections using sleeves manufactured with steel pipes and new sheet materials of Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) sleeves. In order to predict the behavior and performance of the proposed FRP grouted splice connections, empirical relationships, Artificial Neural Network (ANN), and Finite Element Method (FEM) were developed. In Phase 1 of this study, a total of 165 grouted splice connections with different shapes, diameters, embedded lengths, and sleeve materials were tested to failure under incremental tensile load. In Phases 2 and 3, the experimental results obtained from Phase 1 were used as raw data to establish the analytical behavior and performance of the grouted sleeve connections using ANN and FEM, respectively. The results of Phase 1 show that the CFRP sleeves provided better confinement effect, hence contributed higher bond and tensile strengths compared to GFRP sleeves with similar design parameters. New equations were developed based on experimental results in Phase 1 and had shown good prediction of the ultimate tensile strengths of the proposed connections with the reliability ratios close to 1.0. Then in Phase 2, the analytical results demonstrate the superiority of ANN model compared to the other methods in predicting the ultimate tensile strength and behavior of all the proposed connections. The advantage of ANN model is the minimum reliance on the experimental data in estimating the performance of the specimens. The FEM results of Phase 3 indicate that the predicted behaviors of the grouted splices are in line with the experimental results. Also, the FEM results show the importance of providing adequate confinement at regions near the center of the sleeve where the highest stress concentration occurs. In conclusion, CFRP sheets generated the highest confinement, while the embedment length, interlocking mechanism and shape of the FRP sleeves contributed the highest impact on the bond strength, axial stiffness, ultimate tensile strength and ductility of the proposed FRP specimens. Finally, although the proposed empirical relationships predicted acceptable ultimate tensile strength of FRP specimens with high accuracy, the ANN model found to be more superior and it can be used with minimum dependency on experimental data.

ABSTRAK

Sambungan sambat berturap digunakan secara meluas bagi menyambungkan konkrit pratuang dinding-ke-dinding dan dinding-ke-tiang. Bagaimanapun, tidak banyak kajian mengenai sambungan sambat dapat mengenal pasti dan meramalkan minimum panjang tambatan dan kekuatan tegangan muktamad dengan tepat yang boleh menyebabkan kegagalan bencana dalam struktur. Lebih-lebih lagi, sebahagian besar kajian yang diterbitkan hanya terhad kepada produk keluli konvensional dapat tidak meramalkan tingkah laku dan prestasi dengan memuaskan terutamanya apabila bahan dan kaedah baru digunakan. Dalam hal ini, objektif utama kajian ini adalah untuk mengkaji tingkah laku dan prestasi sambungan sambat berturap menggunakan selonsong daripada paip keluli dan bahan kepingan baru Karbon Tetulang Gentian Kaca (CFRP) dan Polimer Tetulang Gentian Kaca (GFRP). Untuk meramalkan tingkah laku dan prestasi sambungan FRP yang dicadangkan hubungan empirical, Rangkaian Neural Buatan (ANN) dan Unsur Terhingga (FEM) telah dibangunkan. Dalam kajian Fasa 1, sejumlah 165 sambungan sambat berturap dengan bentuk, diameter, dan selongsong bahan yang berbeza telah diuji sehingga gagal di bawah beban tegangan bertambah untuk menyiasat kelakuan dan prestasi sambungan. Dalam Fasa 2 dan 3, keputusan ujikaji yang diperolehi dari Fasa 1 telah digunakan sebagai data mentah untuk menentukan kelakuan analitikal dan prestasi sambungan selonsong menggunakan kaedah ANN dan FEM. Keputusan kajian Fasa 1 menunjukkan selonsong CFRP memberikan kesan pengurungan lebih baik, serta menghasilkan kekuatan ikatan dan kekuatan tegangan yang lebih tinggi berbanding GFRP bagi konfigurasi yang sama. sambat lain. Persamaan baru juga telah dibangunkan berdasarkan keputusan ujikaji Fasa 1 dan telah menunjukkan ramalan yang baik dalam menentukan kekuatan tegangan muktamad bagi sambungan yang dicadangkan dengan nisbah kebolehpercayaan menghampiri 1.0. Kemudian dalam Fasa 2, hasil analitikal menunjukkan keunggulan model ANN berbanding kaedah lain dalam meramalkan kekuatan tegangan muktamad dan tingkah laku semua sambungan yang dicadangkan. Kelebihan model ANN adalah pergantungan minima data ujikaji dalam menganggarkan prestasi sambungan. Keputusan FEM bagi kajian Fasa 3 pula menunjukkan tingkah laku yang diramalkan FEM adalah sejajar dengan keputusan ujikaji. Selain itu, keputusan FEM menunjukkan kepentingan menyediakan pengurungan yang mencukupi di kawasan pertengahan selongsong di mana penumpuan tegasan tertinggi berlaku. Kesimpulannya, lembaran CFRP memberikan pengurungan tertinggi, manakala panjang tambatan, mekanisme saling mengunci dan bentuk sambungan FRP menyumbang kesan tertinggi pada kekuatan ikatan, kekukuhan paksi, kekuatan tegangan muktamad dan kemuluran spesimen FRP yang dicadangkan. Akhirnya, walaupun hubungan empirikal yang dicadangkan meramalkan kekuatan tegangan muktamad mutlak spesimen FRP dengan ketepatan yang tinggi, model ANN didapati lebih unggul dan dapat digunakan dengan pergantungan minimum pada data eksperimen.

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LIST OF ABBREVIATIONS

2D	-	Two Dimensional
3D	-	Three Dimensional
ANN	-	Artificial Neural Network
CFRP	-	Carbon Fiber Reinforced Polymer
CIDB	-	Construction Industry Development Board
DCDT	-	Direct Current Differential Transformers
DTP-BT	-	Direct Tension Pullout Bond Test
FE	-	Finite Element
FRP	-	Fiber Reinforced Polymer
GFRP	-	Glass Fiber Reinforced Polymer
IBS	-	Industrialized Building Systems
LVDT	-	Linear Variable Differential Transformers
MSE	-	Mean Squared Error
NN	-	Neural Network
R	-	Regression value
WS	-	Welded and Bolted Specimens

LIST OF SYMBOLS

μ_d	-	Ductility ratio
μ_s	-	Strength ratio
μ_y	-	Yield ratio
A_b	-	Steel bar cross sectional area
$A_{b,p}$	-	Contact surface area of the bar
A_{sl}	-	Contact surface area of the sleeve
$A_{sl,c}$	-	Contact surface area of cylindrical sleeve
$A_{sl,t}$	-	Contact surface area of tapered head sleeve
$A_{T,sl}$	-	Effective transverse cross sectional area of the sleeve
c	-	Constant
d_i	-	Inner diameter at mid-length of sleeve
d_o	-	Inner diameter at the end of sleeve
E	-	Modulus of elasticity
E_g	-	Modulus of elasticity of grout
E_{sl}	-	Modulus of elasticity of the sleeve
f_{bt}	-	Bond stress
f'_c	-	Concrete compressive strength
f'_g	-	Grout compressive strength
f_n	-	Lateral confining pressure
F_n	-	Confinement force
$F_{n,c}$	-	Confinement force generated in cylindrical sleeve
$F_{n,t}$	-	Confinement force generated in tapered head sleeve
k_1	-	Pre-yield stiffness
k_2	-	Post-yield stiffness
l_e	-	Embedded length
$l_{opt,cr}$	-	Minimum embedded length (ultimate method)
$l_{opt,gr}$	-	Minimum embedded length (graphical method)
l_s	-	Sleeve length

m	-	Slope of the regression line
P	-	Load
P_{cr}	-	Minimum requirement for the tensile strength
P_{exp}	-	Load recorded in experiment
P_{NN}	-	Load predicted by neural network
$P_{T,sl}$	-	Transverse tensile force
P_u	-	Ultimate tensile strength
$P_{u,exp}$	-	Experimental ultimate tensile strengths
$P_{u,FE}$	-	Fe analysis tensile strength
$P_{u,Pre}$	-	Ultimate tensile strengths predicted by proposed equations
$P_{u,NN}$	-	Ultimate tensile strengths predicted by neural network
P_y	-	Yield point
S_l	-	Slippage corresponding to the bond stress
t	-	Thickness
t_{frp}	-	Thickness of fiber reinforced polymer
t_{sl}	-	Sleeve thickness
T	-	Bond strength
T_c	-	Bond strength of cylindrical specimen
T_s	-	Tangential force
T_t	-	Bond strength of tapered specimen
U	-	Bond strength of concrete
x	-	Normalized data
X_{max}	-	Minimum value of variable
X_{min}	-	Maximum value of variable
Δl	-	Small longitudinal length
Δ_u	-	Ultimate displacement
$\Delta_{u,Exp}$	-	Experimental ultimate displacement
$\Delta_{u,FE}$	-	FE Analysis ultimate displacement
Δ_y	-	Displacement at yield
ε_s	-	Tangential strain
$\varepsilon_{T,sl}$	-	Tensile strain of sleeve
ϑ	-	Poisson's ratio

ϑ_s	-	Poisson's ratio of grout
ρ	-	Mass density
σ_n	-	Normal confinement stress
$\sigma_{n,b,c}$	-	Normal confinement stress of cylindrical sleeve
$\sigma_{n,b,t}$	-	Normal confinement stress of tapered sleeve
σ_{sy}	-	Yield stress
$\sigma_{T,sl}$	-	Transverse tensile stress of sleeve
σ_u	-	Ultimate tensile stress
σ_y	-	Specified yield strength
τ	-	Bond stress
τ_{cr}	-	Ultimate bond stress
τ_{max}	-	Maximum bond strength
$\tau_{u,Exp}$	-	Experimental bond stress
$\tau_{u,NN}$	-	Bond stress predicted by neural networks
φ	-	Bar diameter

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Numerous advantages of precast concrete systems made them a promising alternative choice to their conventional reinforced concrete counterparts in the construction industry. Precast concrete systems have the potential to increase the quality of building components by producing them under the controlled environment. Moreover, the precast systems can provide significant benefits for engineers, labors, and public by improving the quality, constructability, work zone safety and minimizing the environmental impacts, construction costs, and traffic disruptions. In this regard, the main objective of Construction Industry Development Board (CIDB) of Malaysia is to develop the capacity and capability of the construction industry through enhancing the quality and productivity by expanding the employment of precast concrete systems [1].

The chronology of the Industrialized Building Systems (IBS) in Malaysia goes back to 1960s. Sufficient exposure and incentives are pouring in to encourage industry players to make a paradigm move – from conventional to IBS construction. In this regard, about 22.7 acres of land in Jalan Pekeliling, Kuala Lumpur was dedicated to the first IBS project during the 1st and 2nd Malaysian Plan (1960–1965 and 1966–1970) to build quality and affordable houses in a shorter period of time. This project comprised of 7 blocks of 17 stories flat consisted of 3000 units of low-cost flat and 40 shops lot [2-4]. Due to the problems related with some of the foreign prefabricated systems in 1960s and 1970s, identifying newer, better, and innovative technologies which are suitable with Malaysian climate and social practices has been the main objective for the construction industry in Malaysia. To promote the IBS

usage in the industry, the IBS Strategic Plan was introduced in 1999 [2]. This was followed by developing IBS Roadmaps 2003-2011 and 2011-2015 to enhance the efficiency, quality, sustainability, competency and research and development programs. To increase the contribution of the IBS industry, the Malaysian government mandated that all public-sector projects must attain no less than 70% IBS-content under the Treasury Circular SPP 07/2008 [1].

In recent years, IBS precast components are used in construction projects to offer solutions to overcome the increasing demands for schools, hospitals, colleges, universities and private buildings. It was only possible through expanding knowledge through intensive research on local IBS technologies.

The connections are the most important components of precast concrete systems, as the overall integrity of the precast structure is largely governed by its connections. Connections alone can dictate the type of precast frame, the limitations of that frame, and the erection progress which emphasizes the importance of connections in precast concrete systems [5,6]. Hence, addressing the effectiveness of precast connections in transferring the forces between individual building components (is a research area that) needs further investigations. In this regard, current research is carried out to develop and study grouted splice connections to join precast concrete components.

There are different ways to have a satisfactory connection, such as welding, bolting, or grouting. The used method should be simple and applicable on site. Grouted splice connections can be completed much faster with significant reduction in the required embedded length of the reinforcement bars compared to conventional methods such as cast-in-place concrete [4]. This fact makes the splice connections a good choice for heavily reinforced structures.

There are two different types of connections: conventional method or lapping reinforcement bar, and mechanical connections. Grout filled splices connection is a form of mechanical connection which have been used to connect precast members

and they have been used to overcome the issues related to the long embedded length of lapping systems. During the fabrication, sleeves are pre-embedded in one end of the precast member and projecting steel bars are inserted into the sleeves to fit two sides of the members. Then, the space between the bars and sleeves is filled with non-shrink grout (see Figure 1.1). By having a good installation of the connection, the sleeves can withstand applied forces and they can develop the full strength of the bars to have a monolithic behavior as cast in situ concrete.

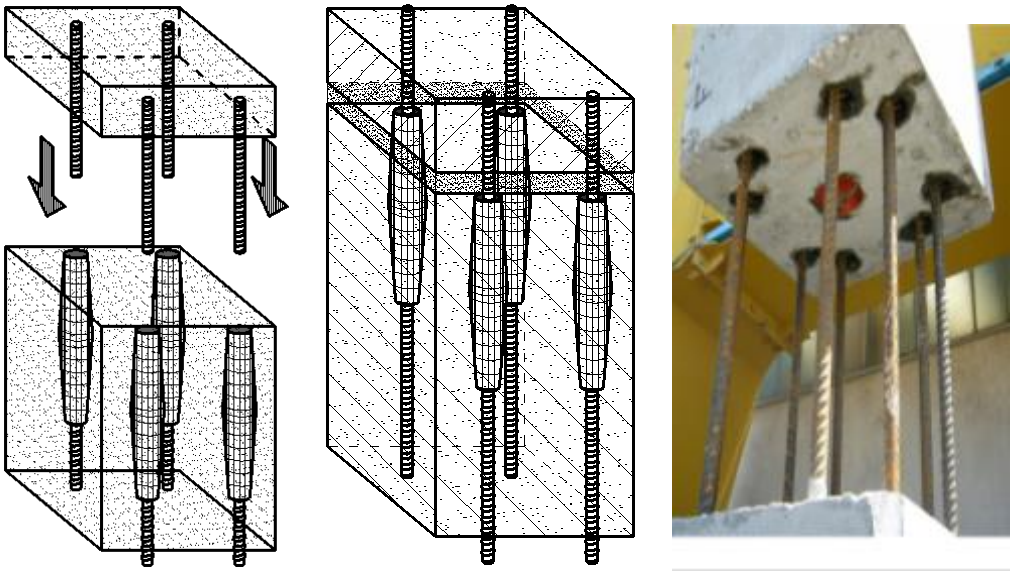

Figure 1.1 Installation of grouted splice connections [6]

Several types mechanical connections are available on the market such as Lenton Interlok® [7, 8], NMB Splice-Sleeve® [9], Quick-Wedge©, BarSplice Products Inc, etc. The main problem related to such proprietary products is that little information has been published about the mechanism of the connection system. Moreover, they could only be purchased from certain companies which belong to foreign countries, therefore developing a new type of sleeve connection which could be cost effective and simple to produce is necessary for countries like Malaysia.

The effectiveness of the splice connection largely depends on the generated bond between reinforcement bar and the surrounding grout. Hence, a satisfactory splice connection should be able to provide structural continuity by providing

adequate bond strength with short development length. In this regard, six types of splice connections were introduced in this research to study the factors that might affect their behaviors and feasibility under incremental tensile load.

1.2 Problem Statement

Components in precast concrete systems are prefabricated, so lapping length may not be appropriate for precast concrete systems as the lapping method requires significant lapping length. Although the general structural behavior of precast components is similar to members that are monolithically cast in place, the major difference is the nature of connections. Hence, details of precast concrete connections are especially important to ensure equivalent behavior of a conventionally designed, cast-in-place, monolithic concrete structure [10]. While the continuity in cast-in-place systems is achieved by providing lapped reinforcement bars to have a monolithic system, it can be achieved by utilizing grouted splice connections with shorter anchorage lengths in precast systems.

However, limited information is provided by design codes as practical solutions for designing a splice connection which might be due to the proprietary and confidential nature of these products. On the other hand, available studies about the performance of the spliced connections are restricted to the small scale experimental studies with limited design parameters which might not be suitable to predict the acceptability of the connections [11-13].

Furthermore, the majority of the published articles are mainly focused on grouted splices produced from steel pipes. Steel pipes cannot generate required interlocking mechanism between their inner surface and the grout. Hence, several methods have been used by previous researches to provide adequate interlocking mechanism. Among the proposed methods, welding gained more attention due to its advantage over other methods like threading. This might be due to this fact that compared to best-quality thread, providing interlocking mechanism by welding is

cost effective and it permits the use of thinner pipes as it does not cause mechanical weakening.

The issues related to the research are:

1. The embedded lengths used in precast grouted splice connections are much shorter than the embedded lengths offered by design standards. Hence, ensuring the ability of the grouted splice to develop the full strength capacity and maintaining the structural continuity of the spliced bars is a critical issue in practice. In this regard, further research is required to study the acceptability of the short embedded lengths and subsequently identifying the minimum bar embedded lengths of the grouted splices able of developing full tensile strengths of the spliced bars.
2. During the design process, if the ultimate strength of the grouted splice connection is not determined precisely, it may lead to catastrophic failures in the structure. In order to obtain reliable predictions of the ultimate strength of the grouted splices with different design parameters, analytical research are conducted and equations are derived by analyzing the experimental results of the current study.
3. In practice, predicting the behavior of the grouted splice is the key issue to assure designers and contractors in using grouted splices. To do this, an extensive experimental and analytical research is carried out to justify the load responses of the grouted splices with different design parameters under incremental tensile load.
4. The majority of the published studies are limited to conventional steel products and they did not cover the practicality of the alternative materials and design parameters. Hence, further investigation is required to understand the effects of different combination of confining materials on the performance and behavior of the spliced connections.

1.3 Objectives

The specific objectives of the research are:

1. To study experimentally the behavior, performance, and satisfactory design parameters of the proposed grouted splice connections using FRP sheets as the confinement and subjected to incremental tensile load.
2. To develop empirical relationship of the behavior of the proposed grouted splices based on the experimental results.
3. To predict the behavior and performance of the proposed FRP grouted splice connections using Artificial Neural Network (ANN).
4. To investigate the behavior of the FRP grouted splice connection such as load-displacement, types of failure, and ultimate tensile strength using Finite Element Method (FEM).
5. To compare the results of the proposed empirical relationship, neural network model, and finite element method with the experimental results of the proposed FRP grouted splice connections.

1.4 Scopes of Research

The scope of the research program is limited to the following:

1. Steel reinforcement bars with diameter of 16 mm were used for all grouted splices.
2. The sleeve diameter of the proposed grouted splices ranging from 37 mm to 75 mm.
3. The embedded lengths of 75 mm, 125 mm, and 175 mm were considered for the proposed grouted splices.
4. One type of grout was used to prepare the proposed grouted splices.

5. Mild steel pipes, two types of aluminum tubes (rigid and flexible corrugated tubes), glass and carbon fiber reinforced polymers were used to prepare the proposed grouted splices.
6. Grouted splices were subjected to incremental tensile load and other load cases were not considered.
7. Artificial neural network and finite element methods were used to predict the behavior and performance of FRP grouted splice connections only.

1.5 Thesis Outline

The general aim of this thesis was to study the behavior of the grouted splice connections under incremental tensile load until failure. This thesis comprises of eight chapters covering three phases of this study.

A brief introduction of the grouted splice connections, relative problem statement, the objectives and scopes of this study are presented in Chapter 1.

Chapter 2 presents the review of the available literature and the present state of knowledge regarding grouted connections and proposed methods for studying and analyzing the behavior of these type of connections.

Chapter 3 describes the experimental program, including the details of test specimens, different variables considered in the proposed connections, material specifications, instrumentations, test setup and procedures.

Chapter 4 covers Phase 1 of this study and presents the results and discusses the effects of various designs on the responses of the grouted splice connections when subjected to incremental tensile load. Moreover, an empirical relationship was developed in this phase of research to verify and predict the ultimate strength as well as the load-displacement responses of the grouted splices under incremental tensile load.

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