BOND BEHAVIOUR OF DEFORMED STEEL REBARS IN STEEL FIBRE HIGH-STRENGTH SELF-COMPACTING CONCRETE

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Civil Engineering
Universiti Teknologi Malaysia

NOVEMBER 2022

ACKNOWLEDGEMENT

First and foremost, I would like to thank God for giving me the strength and grace I needed to complete this thesis. I am nothing without Him.

I would like to express my sincere gratitude to my supervisor Prof. Dr. Ahmad Baharuddin Abd. Rahman for trusting me to conduct the research work and for always supporting, guiding and sharing his wisdom with me. Thank you for believing in me. I am also thankful to my co-supervisors Prof. Ir. Dr. Azlan Adnan and Assoc. Prof. Dr. Roslli Noor Mohamed for their continuous support and guidance throughout my studies.

I am also indebted to Universiti Malaysia Sabah (UMS) for funding my Ph.D. studies and I am especially grateful to Assoc. Prof. Ts. Dr. Ismail Saad, the Dean of Faculty of Engineering, Universiti Malaysia Sabah, for his continuous support. Also, a special thank you to Prof. Ir. Dr. Abdul Karim Mirasa, the former Dean of Faculty of Engineering, Universiti Malaysia Sabah, for giving me the opportunity to pursue my Ph.D. studies.

My thanks and appreciation also goes to all the technicians of the Materials and Structure Laboratories (D04) especially to Ms. Mazlina Binti Ngah and Mr. Muhammad Anwarrasyid Bin Mohd Alwi for helping me a lot in the experimental work. Thank you to all of my postgraduate friends from D04 especially to Ir. Dr. Zuraida, Zanariah, Shariwati, Dianah, Ayun, Azie, Nadirah, Nur Fatin, Fazlin, Nur Suhadah, Annur, Azura and Chiew Shing Mei for assisting me in the experimental work and for their generosity in sharing knowledge and information. Their views and tips were useful indeed.

I also want to thank my family members especially my beloved father, the late Fabian Majain Lajini and to my mother Jovita Moinin, siblings (Genevive, Jonas, Regina, Sr. Marie Carmen and Emily), sister and brothers-in-law, nieces and nephews and also my uncles and aunties for consistently praying for me to complete my studies successfully and also for being so understanding.

I am forever thankful to the most faithful of friends in my life, Melissa Nicholas and Melissa Audrey Francis for their unending prayers, support, and encouragement. Thank you for always being there for me throughout all of my ups and downs in my study life.

Finally, I would like to thank all of my friends in GIFT UTM especially Joanne and Jason for helping me in my research work. Also, my deepest appreciation to all of my friends in Eramaju Synergy Sdn. Bhd., especially to Ir. Dr. Tom Ngui and Ir. Roland Ng for their continuous support and encouragement throughout my studies.

ABSTRACT

Studies on the bond behaviour of deformed steel rebars in conventional concrete have been widely covered. However, the studies on the bond behaviour between deformed steel rebars and high-strength self-compacting concrete (HSSCC), particularly with the addition of steel fibres, are still very limited. Hence, in this research, an in-depth study was conducted to investigate the effects of steel fibres on the bond behaviour of deformed steel rebars embedded in steel fibre high-strength self-compacting concrete (SFHSSCC). Experimental works were carried out in two phases. Phase 1 involved the design of concrete mixes and the testing of fresh and mechanical properties of the normal vibrated concrete (NVC), HSSCC and SFHSSCC. The steel fibres used in SFHSSCC were the hooked-end type with 35 mm length and an aspect ratio of 63.6. The research works in Phase 2 involved the direct pullout testing conducted according to the RILEM RC6 Part 2 standard. A total of 72 pullout specimens with a dimension of 200 mm x 200 mm x 200 mm were prepared and tested at 30 ± 2 days. A few of SFHSSCC specimens were tested at the 6 months of concrete age. The pullout specimens comprised high yield deformed steel rebars of 12, 16, and 20 mm diameters. The pullout specimens were subjected to increasing axial pullout load. The test results in Phase 1 showed the proposed design mix of self-compacting concrete managed to achieve high compressive strength of 60-80 N/mm^2. As compared to HSSCC, the concrete compressive strength of SFHSSCC had increased slightly, but the splitting tensile strength had increased tremendously. The results showed that SFHSSCC with 1.0% of steel fibre volume fraction was the best mix that satisfy the self-compacting and harden concrete requirements and therefore was selected for further study in Phase 2. The test results of Phase 2 showed that the effect of steel fibres in increasing bond strength between rebar and the high-strength self-compacting concrete is seen to be insignificant as the results of bond strength of rebars in HSSCC and SFHSSCC concrete showed small differences only. However, the addition of steel fibres in SFHSSCC had improved the concrete ductility very significantly. At the age of 6 months, the confinement energy of the SFHSSCC improved substantially by about 80% as compared to the confinement energy at 30 ± 2 days. Based on the stress-strain behaviour in concrete, it was observed that the SFHSSCC was able to expand significantly under large stresses with controllable strains which justifies that the presence of steel fibres had contributed to improved confinement effects to the extent that the SFHSSSCC had the ability to provide high confinement energy and good ductility. Subsequently, based on the pullout test results, two new bond strength equations are proposed to predict the bond strengths of deformed steel rebars embedded in HSSCC and SFHSSCC. Finally, it can be concluded that the presence of steel fibres in SFHSSCC could overcome the brittle failure in high strength self-compacting concrete and significantly improves the concrete ductility, which delay the loss of bond between rebars and concrete.

ABSTRAK

Kajian mengenai kelakuan ikatan tetulang keluli berbunga dalam konkrit konvensional telah dilaksanakan dengan meluas. Bagaimanapun, kajian mengenai sifat ikatan antara tetulang keluli berbunga dan konkrit kekuatan tinggi terpadat sendiri (HSSCC), terutamanya dengan penambahan gentian keluli, masih sangat terhad. Oleh itu, dalam penyelidikan ini, kajian lebih mendalam telah dilakukan untuk menyelidik kesan gentian keluli terhadap sifat ikatan tetulang keluli berbunga yang tertanam dalam konkrit kekuatan tinggi terpadat sendiri dengan gentian keluli (SFHSSCC). Kerja-kerja ujikaji dijalankan dalam dua fasa. Fasa 1 melibatkan reka bentuk campuran konkrit dan ujian sifat konkrit segar dan mekanikal bagi konkrit bergetar normal (NVC), HSSCC dan SFHSSCC. Gentian keluli yang digunakan dalam SFHSSCC adalah jenis hujung bercangkuk dengan panjang 35 mm dan nisbah aspek 63.6. Kerja penyelidikan Fasa 2 melibatkan ujian tarik-keluar langsung yang dijalankan mengikut piawaian RILEM RC6 Bahagian 2. Sejumlah 72 spesimen tarik-keluar dengan dimensi 200 mm x 200 mm x 200 mm telah disediakan dan diuji pada 30 ± 2 hari. Beberapa spesimen SFHSSCC juga telah diuji pada umur konkrit 6 bulan. Spesimen tarik-keluar menggunakan tetulang keluli berbunga alahan tinggi berdiameter 12, 16, dan 20 mm. Spesimen tarik-keluar dikenakan beban tegangan paksi yang meningkat. Keputusan ujian Fasa 1 menunjukkan reka bentuk campuran konkrit terpadat sendiri yang dicadangkan dapat mencapai kekuatan mampatan tinggi di antara 60-80 N/mm^2. Berbanding dengan HSSCC, kekuatan mampatan konkrit SFHSSCC meningkat sedikit, tetapi kekuatan tegangan pecah meningkat dengan sangat tinggi. Keputusan menunjukkan SFHSSCC dengan 1.0% pecahan isipadu gentian keluli adalah campuran terbaik yang memenuhi keperluan konkrit terpadat sendiri dan konkrit keras dan telah dipilih untuk kajian lanjut di Fasa 2. Keputusan ujian Fasa 2 menunjukkan kesan gentian keluli dalam peningkatan kekuatan ikatan di antara tetulang keluli dengan konkrit kekuatan tinggi terpadat sendiri dilihat tidak ketara kerana hasil kekuatan ikatan tetulang keluli dalam konkrit HSSCC dan SFHSSCC menunjukkan perbezaan yang sedikit. Bagaimanapun, penambahan gentian keluli dalam SFHSSCC telah meningkatkan kemuluran konkrit SFHSSCC dengan sangat ketara. Pada umur 6 bulan, tenaga pengurungan SFHSSCC meningkat dengan ketara sehingga 80% berbanding tenaga pengurungan pada 30 ± 2 hari. Berdasarkan penyelidikan sifat tegasan-terikan dalam konkrit, telah diperhatikan bahawa SFHSSCC dapat mengembang dengan ketara di bawah tegasan yang besar dengan terikan terkawal yang membuktikan bahawa kehadiran gentian keluli telah menyumbang kepada kesan pengurungan yang lebih baik sehingga SFHSSSCC mempunyai keupayaan untuk memberikan tenaga pengurungan yang tinggi dan kelakuan mulur yang baik. Seterusnya, berdasarkan keputusan ujian tarik keluar, dua persamaan kekuatan ikatan baharu telah dicadangkan untuk meramalkan kekuatan ikatan tetulang keluli berbunga yang tertanam dalam HSSCC dan SFHSSCC. Akhirnya, dapat disimpulkan bahawa kehadiran gentian keluli dalam SFHSSCC dapat mengatasi kegagalan rapuh dalam konkrit kekuatan tinggi terpadat sendiri serta meningkatkan kemuluran konkrit dengan ketara, yang melambatkan kegagalan ikatan di antara tetulang keluli dan konkrit.

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LIST OF ABBREVIATIONS

SCC	-	Self-Compacting Concrete
HSSCC	-	High-Strength Self-Compacting Concrete
SFHSSCC	-	Steel Fibre High-Strength Self-Compacting Concrete
NVC	-	Normal Vibrated Concrete
SFRC	-	Steel Fibre Reinforced Concrete
SFSCC	-	Steel Fibre Self-Compacting Concrete
HSC	-	High-Strength Concrete
LWAC	-	Lightweight Aggregate Concrete
NWAC	-	Normal Weight Aggregate Concrete
LVDT	-	Linear Variable Displacement Transducer
VMA	-	Viscosity Modifying Agent
MOF	-	Mode of Failure

LIST OF SYMBOLS

τ - Bond stress

τ_u - Bond strength

τ_{max} - Predicted bond strength

τ_n - Normalised bond strength

s_u - Slip corresponding to bond strength

P - Applied load

$Ø$ - Rebar diameter

d_1, d_2 - Diameter of deformed steel rebar

t - Width of longitudinal ribs

S_r - Distance between inclined transverse ribs

t_r - Maximum width of inclined transverse ribs

r_h - Maximum thickness of inclined transverse ribs

W - Amount of steel fibres

ρ_{sf} - Density of steel fibres

V_f - Fibres volume fraction

V_c - Volume of concrete

x - Fibres factor

V_p - Loading rate

d_s - Rebar diameter for loading rate

c - Minimum concrete cover

d_b - Diameter of bonded rebar

l_d - Rebar embedment length

f'_{cu} - Concrete compressive strength (cube)

f'_c - Concrete compressive strength (cylinder)

f'_{cts} - Concrete splitting tensile strength

A_c - Cross-sectional area of concrete cube

A_{peak} - Area under the bond stress-slip curve from origin up to bond strength

A_{80} - Area under the bond stress-slip curve from origin up to 80% of the bond strength at the post-peak region

A_{50} - Area under the bond stress-slip curve from origin up to 50% of the bond strength at the post-peak region

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Self-compacting concrete (SCC) originated in Japan and was first developed in 1988 by Okamura. The innovation of SCC aimed to produce durable concrete structures that do not require compaction by skilled labours. SCC is a type of concrete that flows and is compacted under its own weight without the need for any mechanical vibration (European Project, 2005). SCC offers substantial benefits in the construction industry due to its ability to naturally fill in the highly congested reinforced concrete formwork and thus reduce the number of workers required for the concrete works. Besides, the elimination of compaction works also helped reduce noise and provide better safety conditions for construction workers (Siddique, 2011; Dehwah, 2012; Kamal *et al.*, 2013). Hence, SCC becomes the preferred alternative material against the traditional vibrated concrete (Pajak and Ponikiewski, 2013; Santos *et al.*, 2016). The application of SCC was extended to high-rise buildings, including the construction of the world tallest building, the Burj Khalifa in Dubai, as shown in Figure 1.1 (Bajic and Vasovic, 2009; Baker *et al.*, 2009).

As known, concrete is a brittle material with limited ductility, and this is more evident for concrete with a high-strength grade (Sulaiman *et al.*, 2017). The use of high-strength concrete in modern construction industry is getting popular due to the economic advantages. The reason is that high-strength concrete avoids the design of oversized structural members, which is uneconomical to the industry (Song and Hwang, 2004). Similar to high-strength conventional concrete, HSSCC also exhibits brittle behavior in both compression and tension, which gets more apparent as its strength increases (Schumacher, 2006; Pajak and Ponikiewski, 2013). Therefore, various research works have been carried out to overcome the brittle behaviour of high-strength concrete so that the concrete ductility can be improved.

Figure 1.1 Super high-rise building, Burj Khalifa, Dubai constructed using SCC material (Baker *et al.*, 2009)

To improve ductility and crack resistance, steel fibres are added to normal concrete to produce the steel fibre reinforced concrete (SFRC). However, the vibration work used to facilitate the concrete compaction in SFRC may cause uneven distribution of steel fibres and hence affect the quality of the reinforced concrete structure. Therefore, by using the same concept in SFRC, researchers have started to explore the possibility of adding steel fibres in SCC to eliminate the issue of compaction work and at the same time to increase the hardened properties of SCC. Hence, a sufficient amount of steel fibres are added into the fresh SCC mixtures, resulting in steel fibres self-compacting concrete (SFSCC), an innovation to the plain SCC. It was found that the addition of steel fibres in SCC dramatically improved the material behaviour in terms of tensile strength, flexural strength, toughness, ductility, and resistance towards cracking and dynamic load (Gouri *et al.*, 2010). These effects are attributed to the capacity of steel fibres to transfer tensile stress across crack surfaces, a process known as crack- bridging (Lu *et al.*, 2018; Mahmod *et al.*, 2018; Khan and Ahmad, 2018).

Despite the fact that SCC was introduced at the end of the 1980s, the research on the bond behaviour only commenced toward the end of the 1990s (Valcuende and Parra, 2009; Santos *et al.*, 2016). The bond studies in reinforced concrete design are crucial because they are the key element for concrete and steel reinforcement to function as a composite structural material. This composite action which formed the bond involved a load transfer between the concrete and the reinforcement steel. Consequently, the bond may be considered as a continual stress distribution that occurs along the steel-concrete interface (Bilek *et al.*, 2017). If the bond resistance is insufficient, the reinforcing rebar will slip, disrupting the composite action and hence causing failure, which is detrimental to the whole structural system. Therefore, bond studies in reinforced concrete are crucial as they can influence the ultimate failure of reinforced concrete members.

The addition of steel fibres in reinforced concrete is known to improve the anchorage bond between reinforcing rebars and the surrounding concrete. Steel fibres in reinforced concrete can delay crack propagation and increase the ductility of reinforced concrete components. This improved performance is believed to be associated with the confinement effects provided by the steel fibres.

1.2 Problem Statement

In literature, numerous information on the bond of reinforcing rebar in normal vibrated concrete (NVC) is available, and some researchers have developed model formulae to predict the bond strength (Goto, 1971; Orangun *et al.*, 1977; Eligehausen *et al.*, 1982; Hassan *et al.*, 2010; Garcia-Taengua *et al.*, 2016). However, the bond studies between SCC and deformed steel rebars only started in the late 90s. Some of the earlier studies were conducted by Sonebi and Bartos (1999) and then followed by Zhu *et al.* (2004), Valcuende and Parra (2009), Desnerck *et al.* (2010a), Pop *et al.* (2013), Sfikas and Trezos (2013) and Khayat and Desnerck (2014). In general, most researchers agreed that the SCC bond shows better performance than the NVC.

According to some researchers, HSSCC tends to be brittle due to the high strength concrete (Sonebi and Bartos, 1999; Valcuende and Parra, 2009; Pop *et al.*, 2013). Therefore, without sufficient concrete confinement, the high compressive strength in HSSCC can cause sudden and brittle failures in concrete, which causes abrupt loss of bond between rebar and the surrounding concrete. Some methods used before to increase concrete confinement are transverse reinforcement, external wrapping materials, or fibres. The use of fibres, in particular steel fibre, has gained popularity due to economics, reinforcing effects, and resilience to environmental aggression.

Taengua (2013) stated that passive confinement provided by steel fibres affects bond performance in terms of bond strength and bond failure ductility. However, data on the effects of steel fibre confinement are very limited, particularly the effects of steel fibre confinement on the bond behaviour of deformed steel rebars in SFHSSCC. So far, only a few studies have been conducted to investigate the bond between deformed steel rebars and the SFHSSCC. These studies focus more on the influence of specific parameters such as fibre volume, fibre aspect ratio, concrete cover, concrete compressive strength, and early concrete ages on the bond behaviour of deformed steel rebars in SFHSSCC.

Hence, based on the limited information obtained from the previous studies, there are three main issues that have not been addressed. The first issue is how the steel fibre confinement affects the mode of failure in SFHSSCC and the second issue is the effectiveness of the steel fibre confinement in increasing the ductility of SFHSSC. Meanwhile, the third issue is the development of the bond strength equations. Various bond strength equations have been developed quite extensively over the last few decades to predict bond strength. However, the bond strength equations for HSSCC and SFHSSCC still require some refinement and improvement as it is still at the initial stage of development. Therefore, there is a need to review and refine the existing bond strength models to produce a more reliable and accurate bond strength equation to predict the bond strength of rebar in HSSCC and SFHSSCC.

1.3 Objectives of the Study

This study aims to investigate the bond behaviour of deformed steel rebars embedded in SFHSSCC. In an attempt to solve the issues stated in the problem statement, the following outlines the objectives of this study, which are:

i. To investigate the fresh and mechanical properties of NVC, and the proposed HSSCC and SFHSSCC.

ii. To investigate the behaviour and performance of bond between deformed steel rebars and HSSCC without steel fibres and with steel fibres (SFHSSCC).

iii. To investigate the effects of steel fibre confinement on the bond behaviour of deformed steel rebars in SFHSSCC.

iv. To make a recommendation of bond strength equations to predict the bond strength of deformed steel rebars in HSSCC and SFHSSCC.

1.4 Scope of Study

The scopes of works are limited to the study on:

i. the fresh and hardened properties of NVC, HSSCC without steel fibres and SFHSSCC with fibres volume fraction of 0.5% and 1.0%.

ii. bond between rebars and concrete based on experimental pullout tests of 12 mm, 16 mm and 20 mm diameter deformed steel rebars embedded in NVC, HSSCC without steel fibres and SFHSSCC with fibres volume fraction of 1.0%, and

iii. SFHSSCC using 35 mm length and 0.55 mm diameter of hooked-end steel fibres only.

1.5 Significance of Study

This study provides information on the key properties of the SFHSSCC through the investigation of the fresh and hardened properties of the material. More importantly, this study shows the benefit of adding steel fibres in HSSCC to improve the bond performance between deformed steel rebars and the surrounding concrete through the passive confinement effect provided by the steel fibres. The findings of the in-depth investigation on the pullout test are discussed thoroughly in this study, which further enriches and contributes to the knowledge of the bond behaviour between deformed steel rebars and SFHSSCC. This study also proposes improved bond strength equations to predict the bond strength of deformed steel rebars embedded in HSSCC and SFHSSCC. Additionally, this study can also be used in the construction industry, especially for construction materials that involve the use of HSSCC and SFHSSCC.

1.6 Outline of the Thesis

This thesis consists of seven chapters. Chapter 1 presents the introduction of the topic, problem statement, objectives of the study, scope of the study, significance of the study, and the outline of this thesis.

Chapter 2 presents the literature review on various aspects of the bond behaviour between deformed steel rebars and the SFHSSCC. In this chapter, the background of SCC and SFSCC are discussed in detail. Subsequently, reviews of the previous research works related to bond studies are presented and discussed. This includes the bond mechanism, factors influencing the bond behaviour, confinement effect, and bond testing method.

Chapter 3 discusses the research methodology used in this study. This entails the methodology used to achieve the objectives of this research. At the beginning of this chapter, an overview of the research methodology framework is presented, which consists of two phases. The first phase is the investigation of the fresh and mechanical properties of the concrete mixtures, while the second phase is the experimental pullout test works. This chapter also detailed the method used to prepare specimens for fresh and mechanical properties testing, and also for the pullout testing.

Chapter 4 presents the results of the fresh and mechanical properties of the NVC, HSSCC and SFHSSCC. The results of the fresh concrete testing, which consists of slump test, slump flow, V-funnel and L-Box are presented and discussed. Subsequently, this chapter also analysed and discussed the results of the mechanical properties of the concrete mixes.

Chapter 5 reports the findings of the experimental pullout test conducted. The overall results of the pullout specimens are presented and discussed in detail, which emphasise the mode of failure and the bond stress-slip relationship. The effects of rebar sizes, concrete cover thickness and rebar embedment length on the mode of failure are discussed at length in this chapter. Subsequently, the effects of the concrete compressive strength, tensile strength and top-rebar effect on the bond performance are also analysed and presented. Additionally, analysis of the bond strength using the normalised bond strength is also discussed in this chapter.

Chapter 6 discusses the analysis of the steel fibre confinement mechanism in SFHSSCC. The discussion includes the bond mechanism and the analysis of the steel fibre bridging and sewing effects in SFHSSCC. The distribution of steel fibres in concrete obtained from the coring samples of the SFHSSCC pullout specimens is also shown in this chapter. Subsequently, the analysis of the steel fibre confinement effects is presented using the graph that shows the stages of pullout behaviour. The confinement energy and the stress-strain analysis of pullout specimens are also discussed. Then the detailed analysis of selected existing bond strength equations, which leads to the development of new equations to predict the bond strength of HSSCC and SFHSSCC is presented.

Chapter 7 presents the conclusion which highlights the significant contribution of this study. The outcomes of this study are compared to the objectives to show the accomplishment of the objectives. This chapter ends with some recommendations for future works that are expected to benefit this field of study.

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LIST OF PUBLICATIONS

International ISI Indexed Journal

1) **Nelly Majain,** Ahmad Baharuddin Abd. Rahman, Azlan Adnan and Roslli Noor Mohamed (2022), 'Bond behaviour of deformed steel bars in steel fibre high-strength self-compacting concrete', *Construction and Building Materials*, 318, 125906, 1-18, Publisher: Elsevier, Journal Impact Factor 2020 (Web of Science): 4.375, Q1 Journal.

Indexed Conference Proceeding

1) **N. Majain,** A. B. A. Rahman, R. N. Mohamed and A. Adnan (2019) 'Effect of steel fibers on self-compacting concrete slump flow and compressive strength, *IOP Conference Series: Materials Science and Engineering*, 513, 1-8. **(Indexed by SCOPUS)**

2) **Nelly Majain,** Ahmad Baharuddin Abdul Rahman, Azlan Adnan and Roslli Noor Mohamed (2021) 'Pullout behaviour of ribbed bars in self-compacting concrete with steel fibers', *Materials Today: Proceedings*, 39, 1034-1040. **(Indexed by SCOPUS)**