

PUNCHING SHEAR BEHAVIOUR OF STEEL FIBRE REINFORCED
SELF-COMPACTING CONCRETE FLAT SLABS

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DEDICATION

This thesis is dedicated to my parents, family, and friends,
who encouraged me to fly towards my dreams.

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ABSTRACT

Steel fibre reinforced self-compacting concrete (SFRSCC) consolidates under its own weight and has been shown to have the ability in providing efficient reinforcement mechanism. The research was carried out by leveraging the benefits of the SFRSCC to solve the punching shear problem caused by multiaxial forces in disturbed regions in reinforced concrete (RC) flat slabs. This thesis presents the results of three experimental testing phases to investigate the effectiveness of the SFRSCC, self-compacting concrete (SCC) and the normal concrete (NC) in resisting punching shear in RC flat slabs. Shear reinforcement in the forms of vertical links and welded inclined bars were also investigated in the slabs cast with SCC. The effect of the thickness of the slab, and the limiting area of SFRSCC around the column were also examined. The fresh and hardened properties of these concretes, as well as the optimum content of fibre in the SFRSCC used in the flat slab specimens were determined from the tests in Phase 1. Tests to study on the biaxial behaviour of the concrete to simulate the multi-axial force effects in the RC flat slabs were carried out in Phase 2. Phase 3 deals with the structural testing of slab specimens, tested under a single point load in the middle until failure. The results showed that SFRSCC slabs can withstand higher punching shear load than NC and SCC slabs, with and without shear reinforcement. The failure mode of all fibrous specimens were found to be more ductile as compared to others. The results also revealed that slabs with SFRSCC within a square area around the column can be as efficient in resisting the punching shear as the ones with the SFRSCC cast over the entire slab. These findings were corroborated from biaxial behaviour of concrete in Phase 2. The incorporation of steel fibres into the concrete matrix provides confining pressure, which contributes to an increase in concrete strength under biaxial loading whilst ensuring ductile failure. In term of verification, the numerical analysis with two semi-empirical expressions, namely the strut-and-tie model and the additive model is also presented. The analysis results for the appropriate specimens show good agreement with experimental results, with the additive model giving the closest estimate of the punching shear capacity of the slabs.

ABSTRAK

Konkrit bertetulang gentian keluli terpadat sendiri (SFRSCC) memadat oleh beratnya sendiri dan telah dibuktikan berkeupayaan menyediakan mekanisma tetulang yang cekap. Penyelidikan ini dijalankan dengan memanfaatkan kelebihan SFRSCC untuk menyelesaikan masalah ricih tebuk yang berpunca dari daya pelbagai paksi pada kawasan terganggu di papak rata konkrit bertetulang (RC). Tesis ini memaparkan keputusan ujikaji yang terdiri daripada tiga fasa untuk mengkaji keberkesanan SFRSCC, konkrit terpadat sendiri (SCC) dan konkrit biasa (NC) dalam menghalang ricih tebuk dalam RC papak rata. Tetulang ricih dalam bentuk perangkai pugak dan bar condong berkimpal turut dikaji di dalam papak dengan SCC. Pengaruh ketebalan papak dan keluasan terhad SFRSCC di keliling tiang turut juga diselidiki. Sifat-sifat konkrit tersebut pada peringkat segar dan keras dan kandungan optima SFRSCC yang digunakan dalam spesimen papak rata diperolehi dari Fasa 1 program ujikaji ini. Ujian-ujian ke atas kelakunan dwi-paksi konkrit untuk mewakili kesan-kesan daya pelbagai paksi dalam RC papak rata dijalankan dalam Fasa 2. Fasa 3 melibatkan ujikaji struktur untuk semua spesimen papak rata, diuji dengan satu beban tumpu di tengah papak sehingga berlaku kegagalan. Keputusan kajian menunjukkan papak dengan SFRSCC berupaya menanggung beban ricih tebuk yang lebih besar berbanding daripada papak-papak lain yang dengan NC dan SCC, bertetulang atau tidak mempunyai tetulang ricih. Mod kegagalan bagi papak-papak bergentian adalah bersifat lebih mulur berbanding dengan jenis papak yang lain. Keputusan kajian juga menunjukkan bahawa SFRSCC dalam keluasan empat segi sama di keliling tiang boleh memberikan kesan yang sama dalam merintang ricih tebuk seperti papak dengan keseluruhan keluasannya daripada SFRSCC. Kelakunan dwi-paksi konkrit dalam Fasa 2 menyokong penemuan ini. Campuran gentian keluli dalam konkrit memberikan tekanan mengurung, yang mana menyumbang pada peningkatan kekuatan konkrit di bawah beban dwi-paksi, dan juga memastikan kegagalan yang mulur. Untuk pengesahan, analisis berangka dengan dua ekspresi separa-empirikal iaitu model tujuh-dan-penambat dan model tambahan juga dipaparkan. Keputusan analisis ke atas spesimen-spesimen berkaitan memberikan keserasian yang baik dengan keputusan ujikaji, dengan model tambahan memberikan anggaran ricih tebuk yang terhampir.

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LIST OF ABBREVIATIONS

ASTM	-	American Society for Testing and Materials
BS	-	British Standard
C-C	-	Compression - compression
CCT	-	Two struts (C) and one tie (T)
C-T	-	Compression - tension
EC2	-	Euro Code 2
EFNARC	-	European Federations of Producers and Contractor of Specialist Products for Structures
HSC	-	High strength concrete
LVDT	-	Linear variable displacement transducers
NC	-	Normal concrete
OPC	-	Ordinary Portland Cement
PL	-	Passing ability
SCC	-	Self - compacting concrete
SF	-	Slump flow
SFRC	-	Steel fibre reinforced concrete
SFRSCC	-	Steel fibre self-compacting concrete
SP	-	Superplasticizer
SR	-	Segregation resistance
SSD	-	Surface dry condition
STM	-	Strut and tie model
RC	-	Reinforced concrete
T-T	-	Tension - tension
VF	-	V-funnel

LIST OF SYMBOLS

ROMAN UPPERCASE LETTER

A	-	Ratio of applied force to the yield force of the flexural reinforcement
A_{bar}	-	Cross- sectional area of bar
A_f	-	Cross-sectional area of calculated steel fibre
A_{sw}	-	Cross-sectional area of shear reinforcement link
B	-	Diameter of column
C	-	Column side dimension
D_b	-	Diameter of the flexural reinforcement
F	-	Fibre factor
F_c	-	Total compression force
L	-	Axis to axis distance between columns
N_1	-	Number of fibre per cross-sectional area
N_f	-	Number of fibre counted on the fractured surface
P_{flex}	-	Flexural ultimate load capacity
S_r	-	Spacing of shear reinforcement in radial direction
V	-	Applied force
$V_{R,ACI}$	-	Predicted punching shear strength of RC flat slab according to ACI 318-11
V_a	-	Strength contribution from aggregate interlock at the crack interface
V_b	-	Strength contribution of fibre
V_c, V_{cd}	-	Strength contribution of concrete
V_{core}	-	Hydrostatic volume of core
V_d	-	Shear strength from dowel action of the flexural reinforcement
V_f	-	Fibre volume fraction
V_m	-	Matrix volume fraction
V_{pun}, V_u	-	Punching shear resistance of RC flat slab

V_s, V_{sd}	-	Shear strength of shear reinforcement
W_f	-	Weight fibre percentage
W_{sf}	-	Weight of fibre
X	-	Neutral axis depth

ROMAN LOWER CASE LETTER

a	-	Length between supports of a square slab
b, b_p	-	Critical perimeter
b_f	-	Modified critical perimeter
d	-	Effective depth
d_f	-	Diameter of fibre
$f_{Rk,4}$	-	Residual flexural tensile strength
f_{cf}	-	Flexural strength of concrete
f_{ck}	-	Compressive cylinder strength of concrete
f_{ct}	-	Tensile splitting strength of concrete
f_{cu}	-	Compressive cube strength of concrete
f_{cu}	-	Maximum strength of concrete in the strut
f_{fu}	-	Ultimate tensile strength of a single fibre.
f_{sw}	-	Link yield strength
f_{yk}	-	Steel yield strength
k	-	Size effect factor
l_{crit}	-	Critical fibre length
l_f	-	Fibre length
m	-	Moment capacity per unit length
r	-	Ratio of the fibre cross-sectional area to the fibre perimeter
s	-	Side dimension of a square slab
u	-	Control perimeter
$u_{out,ef}$	-	Control perimeter at which shear reinforcement is not required
$v_{Rd,c}$	-	Punching shear stress
v_{fd}	-	Shear stress contribution from fibre bridging action
w_c	-	Specific weight of the concrete

y	-	Height of the rectangular compressive stress field Depth of the compression zone
y_f	-	Depth of compression zone at flexure critical section
y_s	-	Depth of the compression zone of the shear critical section at punching

GREEK LETTER

ϕ_{bar}	-	Diameter of the flexural reinforcement
β_c	-	Ratio of the long side to the short side of the column
γ_c	-	Partial safety of concrete
ε_{cu}	-	Ultimate concrete strain
ε_o	-	Concrete strain at the level of the end of the rectangular concrete stress block
η_1	-	Fibre length correction factor
η_θ	-	Fibre orientation factor
λ_f	-	Fibre aspect ratio
ρ_f	-	Bond factor of steel fibre
ρ_{sf}	-	Density of steel fibre
σ_c	-	Uniaxial compressive stress
σ_{cr}	-	Cracking stress of the composites in direct tension
σ_f	-	Ultimate stress in fibre at matrix cracking
σ_{fu}	-	Ultimate strength of the composite concrete is contributed by the fracture strength of the fibre
σ_{mu}	-	Cracking stress of matrix
σ_s	-	Axial tensile stress in the reinforcing bar
σ_{tu}	-	Ultimate post-cracking tensile stress
τ_c	-	Maximum shearing stress
τ_f	-	Fibre-matrix interfacial bond stress
τ_{fd}	-	Design value of increment in shear strength due to steel fibre
α	-	Inclination of the link with the plane of the slab
θ	-	Inclination of crack
λ	-	Size effect factor

ρ	-	Flexural reinforcement ratio
σ	-	Normal stress
τ	-	Shear stress

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Slab-column or flat plate frame system offers numerous construction and architectural advantages, which make them a popular choice in reinforced concrete (RC) construction. This constructive system is the most competitive for residential and commercial buildings with span length between columns varying from 7.0 to 9.0 m and a live load not exceeding 5 kN/m² (PCA–Portland Cement Association, 2005; Delahay and Christopher, 2007). The construction of the flat slab eliminates the use of beam, where the slab is supported directly by columns. It also offers a simpler formwork and greater clear story height as compared to beam-column frame construction, leading to substantial savings in construction costs.

Despite its simple appearance, this slab-column connection is susceptible to punching shear failures, which could lead to substantial floor damage and even the worst scenario of the structural collapse such as the collapse of the Skyline Plaza (Carino *et al.*, 1983), Sampoong department store (Gardner *et al.*, 2002) and 16-storey apartment building at 2000 Commonwealth Avenue (King and Delatte, 2004).

Punching shear failure is a main governing failure mode for a flat slab. It occurs when total shear forces act on the slab is greater than shear resistance of the slab, high bending moment and shear forces at the slab-column connection (Tuan Ngo, 2003), or when the flexural member is unable to develop yield mechanism to fail in a ductile manner (Harajli *et al.*, 1995). On top of that, the structure failed in punching shear failure showed a sudden drop in load-carrying capacity, and the structure collapsed instantaneously without giving people any time to escape (Menétrey, 2002).

Generally, the shear capacity of this connection can be enhanced by increasing the slab thickness or using drop panels or column capitals, which is not an economical or practical option as well as architectural disadvantages. This is because increasing the slab thickness will also increase the cost and the weight of the building. Furthermore, the presence of the drop panel or column head causes the changes in slab cross-section and formwork which result in the non-uniformity in-floor bottom surface and decreasing clear story height. Thus, modifying the geometrical of the slab is not the only method to increase the punching shear capacity.

Therefore, since the 1950s, punching shear has been the subject of an intense experimental effort. Although, several methods have been proposed to increase the punching shear capacity of flat slabs. However, its application is still restricted. For example, traditional shear strengthening using stirrups is only applicable to slabs with a depth greater than 150 mm (ACI Committee 318, 2002), reinforcement using steel section shear head systems (Anderson, 1963; Corley and Hawkins, 1968), stud type reinforcement (Elgabry and Ghali, 1987), shear band system (Pilakoutas and Li, 2003) and lattice shear reinforcement (Park *et al.*, 2007) prolong the duration and increase the cost of construction.

Due to these circumstances, steel fibre reinforced concrete (SFRC) is seen as an alternative in enhancing the punching shear capacity, performance and cracking control of the slab-column connection. Steel fibres in a minimum amount of 30 kg/m³ were found highly useful as an alternative reinforcement (Nguyen-Minh *et al.*, 2012; Ragab, 2013). The addition of steel fibres turns the quasi-brittle concrete into a ductile material. As the maximum tensile strength is improved, the fibre-knitting through the crack enables the transfer of stress even at wide crack openings. Amplitudes of residual strength enhancements depend primarily on the geometry and dosage of the fibres.

Owing to the advantages of including steel fibres in the concrete mix, several studies have tried to increase the volume content of steel fibres (Harajli *et al.*, 1995; De Hanai and Holanda, 2008; Gouveia *et al.*, 2014). Even, Facconi *et al.*(2016) and K. H. Tan and Venkateshwaran (2017) tried to fully replace the conventional reinforcement with the fibre reinforcement. Unfortunately, the specimen failed due to

flexural failure. It should be borne in mind that the efficiency of steel fibres does not only depend on the volume of steel fibres in the concrete mix. The effectiveness of steel fibre reinforcement also relies on the concrete mix proportion, fresh and hardened state of the concrete. Therefore, the study on the correlation of the concrete properties and the effectiveness of steel fibre reinforcement in reinforced concrete flat slab is has become an important issue.

1.2 Problem Statement

Before focusing on a method for enhancing the integrity of the slab-column connection, it should not be overlooked from the structural point of view that it is highly problematic to support a thin slab directly on the column. This static discontinuity is one of the most critical D-regions occurring in concrete structures. The very high moments occur in this D-region of the flat slab and the three-dimensional stress state is extremely complex. In an attempt to find a viable solution to the deficiencies, the issues are outlined in detail.

1.2.1 Disturbed Region of the Reinforced Concrete Flat Slab

In designing a reinforced concrete structure, the component is divided into two parts, which is Beam or Bernoulli region (B-region) and Discontinuity region (D-region). The B-Region is part of a structure in which Bernoulli's hypothesis of straight-line strain profiles applies. The D-Region, on the other hand, is part of a structure with a complex variation in strain. For reinforced concrete, the absence of any transition between column and slab is extremely disadvantageous and the thickness of the slab is often determined by the punching problem. Besides, flat slabs inevitably violate the principle that the safety level of a structure should be equal throughout because, as against any other part of the slab, the D-region with the punching zone is not sufficiently ductile to gain capacity from force redistribution.

Hence, a number of shear reinforcement, such as stirrup, steel section shear head systems (Anderson, 1963; Corley and Hawkins, 1968), stud type reinforcement (Elgabry and Ghali, 1987), shear band system (Pilakoutas and Li, 2003) or lattice shear reinforcement (Park *et al.*, 2007) are provided to improve the ductility in this region. Improper dimensioning and distribution of reinforcing steel in disturbed regions can lead an adverse cracking and failure of the structure. The serviceability limit state is equally important to ultimate strength due to large stress concentrations in the vicinity of bearing surfaces.

However, the installation of any shear reinforcement in a thin element such as flat slab causes the steel reinforcement congestion, particularly within the critical perimeter of slab-column connection. If a lot of hoops overlap within a small space in the joint (as shown in Figure 1.1), the bond between the concrete and the rebar could be weak due to the limited space between the bars to allow the concrete to flow through. Furthermore, the placement and compaction of normal concrete are difficult in the congested area. Consequently, the development of bond between concrete and the bar is interrupted, as well as degrading the quality of concrete due to the existence of voids and honeycombs in the reinforced concrete structure (Mohamed, 2009). It is also affect the strength and durability of concrete, particularly the tensile strength of concrete which is so important in transferring the shear mechanism. On the other hand, increasing the depth of the slab would not be too beneficial, it would only increase the dead load of the structure. Thus, while retaining the comparable strength of the RC flat slab, it is important to minimize the slab depth.



Figure 1.1 The overlap stirrup within a small space in the joint may disturb the flow of concrete

Furthermore, when a concentrated force acts on the surface of a member, the compressive stresses fan out from the loaded region. The punching shear problem for a slab–column connection has a three-dimensional nature due to the complex state of the stresses that dictate failure around the connection region (Hallgren, 1996). Figure 1.2 shows the compression zone in the D-region subjected to multiaxial stresses. At such locations, the concrete is loaded with a combination of more than one force action, which induces a field of tensile stresses normal to the line of compression. Diagonal cracking can develop along planes perpendicular to the plane of principal tensile stress due to the low tensile properties of concrete. Therefore, the knowledge of the behaviour of the concrete subject to a multiaxial stress situation is necessary for a better understanding of the process of failure of the concrete.

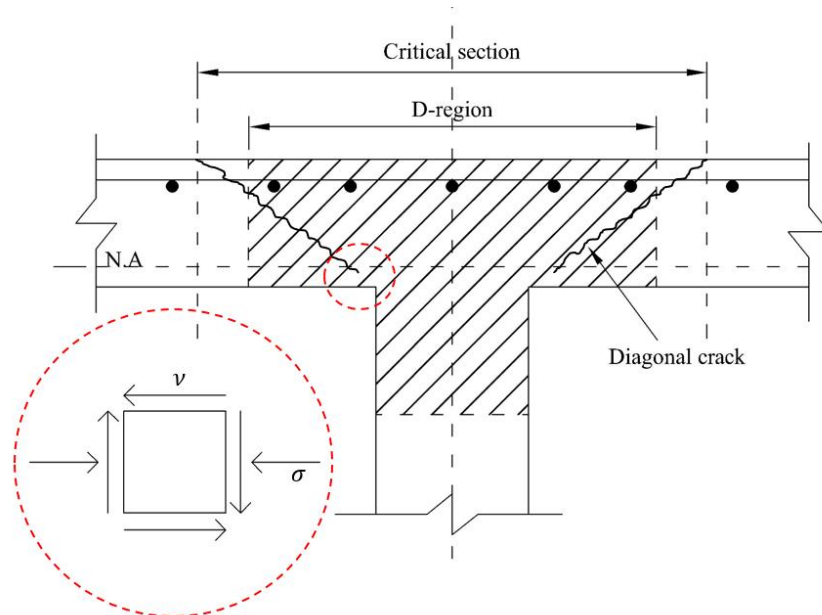


Figure 1.2 The disturbing region (D-region) at the slab-column connection of reinforced concrete flat slab

1.2.2 Application of Steel Fibre Reinforcement in Reinforced Concrete Slab

The steel fibres with an adequate amount has proven its ability to provide efficient reinforcement mechanism through its bridging action and consequently enhance the integrity of the slab-column connection (Nguyen-Minh *et al.*, 2011;

Faconi *et al.*, 2016). Apart from the fibre volume fraction and types of fibre, the efficiency of steel fibres also depends on other factors, such as the casting procedure, and the fresh and hardened state of the concrete. Due to its high specific weight, steel fibre has a higher tendency than other constituents to segregate towards the bottom surface, resulting in a lower fibre content near the top surface of the element (Barros and Antunes, 2003). This can be avoided by using high-flowing concrete matrices such as self-compacting concrete (SCC) as the medium to transport the fibre.

Despite the obvious advantages of SCC, relatively few works have been published related to the application of steel fibre reinforced self-compacting concrete (SFRSCC) to enhance the punching shear resistance of reinforced concrete flat slab (Faconi *et al.*, 2016; Nguyen *et al.*, 2017). Further research on this topic is therefore clearly desirable. On top of that, the use of shear reinforcement remains as a top choice to resist the punching shear issue, even though it is four times as labour-intensive as fibrous concrete in fabrication and casting of the slab (Narayanan and Darwish, 1987). This is because the use of fibrous concrete mix is costly as compared to the normal concrete.

Furthermore, the importance of this study is because, while many experimental researchers have studied various parameters in the punching capacity of fibre-reinforced slab-column connection, in most cases, concrete is only distinguished by its compression strength (Harajli *et al.*, 1995; Nguyen-Minh *et al.*, 2011; K H Tan and Venkateshwaran, 2017). The increment of the compressive strength of concrete due to the fibre addition is not significant (Olivito and Zuccarello, 2010; Iqbal *et al.*, 2015; Soulioti *et al.*, 2011). Therefore, the equations developed using compressive strength may not accurately represent the actual contribution of fibrous concrete to structural capacity enhancement. Only a few researchers addressed the concrete strength characteristic by its flexural tensile strength, which is the dominant strength of the fibrous concrete (Gouveia *et al.*, 2014; Barros *et al.*, 2015; Facconi *et al.*, 2016). Furthermore, most of the researchers neglected the crucial information on the fibre dispersion and orientation in large-scale steel fibre concrete elements. Stähli and van Mier (2007) confirmed the result that the moulded smaller sized prism shows higher bending stresses than the geometrical specimens cut off from bigger cast specimens.

This so-called 'wall effect' has a significant effect when there is a huge difference in size or two different structural elements.

Meanwhile, the established design standard or codes such as ACI Building Code (ACI Committee 318, 2008), British standard (BS 8110-1, 1997), the Fib Model Code 2010 (Du Béton, 2010) and Euro code 2 (BS EN 1992-1-1, 2004) present various formulas to estimate the punching shear capacity of the reinforced concrete flat slabs. However, these formulas were developed for a normal reinforced concrete flat slab, thus, its applicability to predict the punching shear resistance of SFRC flat slab is debatable. Therefore, a solution for predicting the punching shear resistance is seen as a crucial issue.

1.3 Aim and Objectives of Research

The general aim of the investigation was to determine the possible benefits of using steel fibres in reinforced concrete flat slab. In more specific terms, the objectives of the study are as follows:

- i. To develop an optimum mix design of SFRSCC by investigating the performance of the concrete in terms of fresh and hardened concrete properties.
- ii. To study the behaviour of SCC and SFRSCC specimens subjected to the biaxial loads due to the multiple types of forces existed at a slab-column connection.
- iii. To investigate the punching shear and deformation behaviour of RC flat slab made of SFRSCC.
- iv. To relate the improvement in punching shear strength and ductility due to the inclusion of steel fibres into possible design equations for strength prediction of RC flat slab.

1.4 Scope of Research

The research would be experimental in nature, beginning with the development of SCC and SFRSCC with the addition of fibres at volume fractions of 0.5%, 0.75%, 1.0%, and 1.25%. In this study, hooked-end steel fibre with a length of 35 mm and an aspect ratio of 60 was used in SFRSCC mixes. To compare the properties of normal concrete (NC) and SCC, NC of the same grade as the SCC was also casted. Phase 1 focuses on the investigation of the properties of fresh and hardened concrete. The fresh properties included the filling ability, passing ability and the segregation resistance of concrete. Meanwhile, the hardened concrete properties included compressive, flexural tensile, splitting tensile and residual flexural tensile strengths, as well as the flexural toughness and modulus of elasticity.

The optimum fibre content determined in Phase 1 was investigated further in Phases 2 and 3. The second phase focuses on the investigation of concrete under biaxial loading in the compression–tension and tension – tension regions with variation in stress ratios. The last phase involved the use of fibre reinforcement in RC flat slabs. Eight RC flat slabs with a dimension of 1.65 m x 1.65 m were casted with an effective span of 1.4 m and simply supported on all edges. The RC flat slabs were provided with identical main reinforcement, which were designed to fail in punching shear. The variables considered were concrete types, shear reinforcement, slab thickness, and the effective area of SFRSCC. Lastly, new semi-empirical equations were proposed to predict the punching shear resistance of RC flat slabs with various parameters. The experimental results were used to validate the accuracy of the proposed equations.

1.5 Significance of Research

Punching shear is still a polemic topic and advancements in the state of the art are still required. This work intends to contribute with the additional results regarding the test of SFRSCC flat slabs, with a different approach from the previous works. As been mentioned earlier, the rheological properties of high-flowing concrete play an important role in determining the effectiveness of the steel fibre reinforcement,

therefore, this study was focusing on understanding the material behaviour, by including the finding from the fresh and hardened concrete properties, hence an adequate mix composition of SFRSCC could be decided before structure testing. In addition, the behaviour of concrete under uniaxial and biaxial loading was further discussed in order to determine the actual behaviour of the SFRSCC specimens. This knowledge is scarce and is therefore of interest to the engineering and scientific community.

Apart from the investigation on the contribution of steel fibres as a secondary reinforcement, this study also investigated the boundary area of SFRSCC need to be provided to produce superior structural performance. This concept is similar to the concept of the use of high strength concrete in the column head area only. Thus, it was possible to minimize the economic impact of using SFRSCC and enhance its competitiveness. On top of that, the simple semi-empirical equation was proposed to predict structural performance. Thus, the experimental result and the proposed semi-empirical equation could contribute to future development and improve the phenomenological understanding of reinforced concrete flat slab using steel fibres as the secondary reinforcement.

1.6 Thesis layout

This thesis is made up of nine chapters. The outline of the thesis and the details of each chapter are as follows:

Chapter 1 describes the background, problem statements, the study objectives, the scope of the study and the significance of the study.

Chapter 2 and 3 present the compilation of literature data related to materials properties of SCC, SFRC, SFRSCC, and reinforced concrete flat slabs. Chapter 2 discusses the properties and behaviour of the steel fibres in the concrete matrix in order to broaden the perspective on the advantages of the steel fibres to be used in the structural system. In the continuation of Chapter 2, Chapter 3 is related to the previous

studies and methods applied to enhance the punching shear capacity of a reinforced concrete flat slab, as well as considering the potential use of steel fibres as the replacement of conventional reinforcement.

Chapter 4 deals with the research methodology used to achieve the objectives of the study. The procedures and methods are described in detail in this chapter. Three phases of experimental work have been integrated into this study. Phase 1 and phase 2, which are mainly focused on the properties of concrete, explain the procedure in preparation of the NC, SCC, and SFRSCC. It also describes the testing procedures for the fresh and hardened concrete (e.g. test under uniaxial load and biaxial load). The last phase presented the experimental work related to the application of concrete in the structure system (namely: the reinforced concrete flat slab).

Chapter 5 reports the experimental findings from the fresh and hardened concrete tests. Objective 1 and 2 are discussed in this chapter. The results give the optimum fibre content evaluated based on its fresh and hardened concrete properties. It also produces the biaxial envelope, which is correlated to the concrete matrix behaviour in the structure system.

Chapter 6 presents the experimental findings retrieved from the punching shear test of a reinforced concrete flat slab. In this chapter, the related experimental parameters are discussed to determine the impact of the steel fibre reinforcement on the structural behaviour, such as punching shear capacity, steel and concrete strain, and mode of failure. The inter-connection of the results of concrete behaviour under biaxial loading to the behaviour of reinforced concrete flat slab is discussed.

Chapter 7 presents the development of the semi-empirical equation used to predict the punching shear capacity of reinforced concrete flat slab. The failure influencing factors, post cracking shear behaviour of SFRSCC flat slab and contribution from other factors such as the contribution of concrete, fibre bridging, compressive resistance and dowel action are considered in the development of the semi-empirical equation.

Chapter 8 presents the validation of the proposed semi-empirical equations, which are validated against experimental results and further compared to existing equations proposed by other researchers. In this chapter as well, the contribution of fibre in enhancing the shear strength is further analysed and discussed. The implication of the results of the tests on the use of steel fibres as a replacement for conventional reinforcement in the punching shear capacity of reinforced concrete flat slab is also presented.

Chapter 9 concludes the study by highlighting the significant outcome of the study and the achievement of the objectives mentioned in Chapter 1. Several recommendations for further research are suggested.

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- a) **Zamri, N. F.**, Mohamed, R. N., Khalid, N. H. A., Mansor, S., Shukri, N. A., Mahmoor, M. S. N. and Awalluddin, M. D. K. (2018) ‘Performance of medium strength of steel fibre reinforced self-compacting concrete (SFRSCC)’, *IOP Conference Series: Materials Science and Engineering*, 431, 1-8. **(Indexed by SCOPUS)**
- b) **Zamri, N. F.**, Mohamed, R. N. and Awalluddin, D. (2020) ‘The experimental studies of punching shear behaviour of reinforced concrete flat slab with the inclusion of steel fibre: Overview’, *IOP Conference Series: Materials Science and Engineering*, 849, 1–10. **(Indexed by SCOPUS)**