UNIVERSITI PUTRA MALAYSIA

SHEAR STRENGTH OF STEEL-REINFORCED ULTRA-HIGH PERFORMANCE CONCRETE DRY AND EPOXY JOINTS FOR SEGMENTAL GIRDERS

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By

BALAMURUGAN A GOPAL

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

July 2019

DEDICATION

This thesis is dedicated to the memory of my father, A Gopal Arumugam, an inspiring soul whom I miss dearly; and to my lovely mother, Annapoorni Annamalai, whose affection, love and prayers enable my continued success and honour. Along with my dearest wife, Dr. Sumathy Perumal, who leads me through the valley of darkness with light of hope and support. ***I Love You!***

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Associate Professor Farzad Hejazi, PhD
Faculty : Engineering

Joints in precast segmental bridge girders (PSBGs) are the locations of discontinuity and these parts are weaker than those of adjacent monolithic sections within the segment. During the service phase, the compression and shear forces are transmitted at this component. Generally, the keys in this region serve three purposes, namely, to align the segments during erection, to transfer shear force between the sections during service, and to protect the prestressing tendons against corrosion where the tendons pass through the joints. However, as revealed in this study, all the existing provisions tended to significantly over-estimate the ultimate shear capacity of the joint specimens and are developed for normal grade concretes which cannot be used in ultra-high performance fibre reinforced concrete (UHPFRC) joints of PSBGs. The literature review also highlighted that there was no available existing design provision model to calculate the first crack shear capacity of any type of concrete keyed joints.

Therefore, the aim of this research was to investigate the shear capacity loads of typical joints (dry and epoxy) used in PSBGs using UHPFRC concrete and to develop the new design provision models for UHPFRC girders based on the failure criterion of Mohr circle theory. Twelve real full-scale shear key joints of UHPFRC specimens (6 dry keyed joint specimens, 6 epoxy keyed joint specimens) were tested experimentally to fail with three variable parameters namely, number of shear keys, confining stress, and the type of joint (dry or epoxy). Enabling shear was used in the test setup and applied across the shear plane with insignificant moment. The experimental results were also compared with five existing shear capacity design provision models, and a numerical FEM analysis model was developed to compare the results against the experimental data to further confirm the failure pattern of the specimens based on all the three variable parameters.

In all, the results of the study showed that the capacity of the UHPFRC key joints increased with increasing horizontal pressure applied across the joint (confining stress), number of shear keys and the epoxy layers applied on joints. The results of the new UHPFRC design provision model also compared well with the experimental results for both the dry and epoxy keyed joints at both stages (first crack and the ultimate shear capacity loads). The mean and the coefficient of variation (COV) values of the theory/experimental ratio for dry keyed joints were 0.87 and 7.71% at the first crack shear load stage and 0.7 and 9.96% at the ultimate shear load stage. Meanwhile the mean and the coefficient of variation (COV) values for epoxy keyed joints were 0.95 and 5.31% at the first crack shear load stage and 0.87 and 6.12% at the ultimate shear load stage.

In conclusion, this research confirmed that the existing shear capacity design provision models could not be used in the design of UHPFRC precast segmental bridge girder (PSBG) joints. Furthermore, by applying the new UHPFRC shear capacity design provision model in the design of UHPFRC PSBGs, it will ensure both private and governmental bodies that the UHPFRC structures are more affordable, economical, sustainable, and much easier to construct. Lastly, this research will provide an essential contribution to the development of UHPFRC PSBG guidelines in future, particularly in the area of the UHPFRC joint.

Keywords: UHPFRC, shear keys, precast, dry; epoxy; joints; shear strength, bridge.

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

KEKUATAN RICIHAN PADA SENDI KEKUNCI KERING DAN EPOKSI RASUK SEGMENTAL PRA TUANG JENIS KONKRIT BERPRESTASI TINGGI TETULANG BESI

Oleh

BALAMURUGAN A. GOPAL

Julai 2019

Pengerusi : Profesor Madya Farzad Hejazi, PhD
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Bahagian sendi pada mana-mana komponen segmen rasuk jambatan pra tuang (PSBGs) merupakan lokasi yang tidak bersambungan dalam satu komponen segmen rasuk, dan segala daya ricihan dan mampatan akan dipindahkan menerusi bahagian sendi ini. Pada dasarnya bahagian sendi ini merupakan bahagian yang paling lemah berbanding dengan bahagian-bahagian monolitik yang lain dalam segmen rasuk jambatan pra tuang. Bahagian kunci pada sendi rasuk memainkan tiga peranan yang penting dalam rasuk jambatan pra tuang , iaitu (i) selaraskan jajaran pemasangan rasuk semasa kerja-kerja pemasangan di tapak bina, (ii) memindahkan daya ricihan antara dua komponen rasuk jambatan semasa rasuk-rasuk tersebut mula digunakan oleh trafik, (iii) memastikan ketahanlasakan rasuk dengan melindungi komponen tendon pra tegang yang melintas bahagian sendi kunci rasuk daripada sebarang ancaman karat. Pada dasarnya, setakat ini hampir kesemua modal rekabentuk sediada yang digunakan dalam rekabentuk sendi kunci rasuk memberikan anggaran nilai kapasiti ricihan yang tinggi. Selain daripada itu, modal-modal rekabentuk sendi kunci sediada ini dibangunkan untuk konkrit jenis normal dan bukan untuk konkrit jenis berprestasi tinggi tetulang serat besi (UHPFRC) yang pesat digunakan dalam industri pembinaan rasuk jambatan pra tuang pada ketika ini.

Objektif utama kajian ini adalah untuk mengkaji kapasiti daya ricihan sebenar yang dipindahkan pada bahagian sendi kunci (kering dan epoksi) dalam rasuk jambatan pra tuang yang meggunakan konkrit jenis berprestasi tinggi tetulang serat besi dan membangunkan satu modal rekabentuk atau formula baru untuk sendi kunci rasuk jambatan pra tuang yang menggunakan konkrit jenis UHPFRC. Asas pembangunan Modal rekabentuk bagi sendi kunci UHPFRC ini adalah berdasarkan pada kriteria kegagalan teori bulatan Mohr. Bagi tujuan ini, 12 spesimen berskala-penuh sendi kunci UHPFRC disediakan (6 spesimen sendi kering dan 6 spesimen sendi epoksi)

dan diuji sehingga gagal dengan tiga parameter pembolehubah iaitu, bilangan kunci ricihan, nilai daya pra tegangan, dan jenis sendi (kering atau epoksi). Susunatur ujian yang dicadangkan dalam kajian ini membenarkan ricihan dipindahkan merentasi bahagian sendi kunci dengan momen yang boleh diabaikan, dan output dari modal rekabentuk yang baru dibangunkan untuk sendi kunci UHPFRC dibandingkan dengan output yang diperolehi dari ujian makmal. Pada dasarnya, perbandingan kedua-dua keputusan output ini telah menunjukkan persamaan yang baik untuk kedua-dua kapasiti daya ricihan iaitu pada peringkat beban rekahan pertama dan pada peringkat beban ricihan puncak. Selain daripada itu, keputusan ujian makmal juga dibantingkan dengan nilai daya ricihan yang dianggarkan dari lima modal rekabentuk sediada dan keputusan/output dari Analisa FEM. Model FEM ini juga telah digunakan untuk pengesahan lanjut dari segi corak kegagalan spesimen-spesimen yang digunakan dalam ujian makmal berdasarkan pada tiga parameter pembolehubah yang dinyatakan sebelum ini.

Keputusan-keputusan dalam kajian ini juga telah menunjukkan, kapasiti sendi kunci UHPFRC bertambah dengan pertambahan nilai daya pra tegangan yang dikenakan merentasi sendi kunci, pertambahan bilangan kunci ricihan, dan kewujudan lapisan epoksi pada bahagian sendi kunci. Menerusi kajian ini juga didapati, kesemua modal rekabentuk sediada menganggarkan nilai kapasiti ricihan puncak yang tinggi untuk jenis kunci ricihan UHPFRC dan sehingga kini tiada lagi satu model rekabentuk pun yang boleh digunakan untuk menganggarkan nilai kapasiti ricihan pada peringkat daya ricihan rekahan pertama untuk mana-mana jenis konkrit. Anggaran nilai kedua-dua nilai kapasiti ricihan (peringkat rekahan pertama dan peringkat puncak) dari model rekabentuk baru untuk sendi kekunci UHPFRC dalam kajian ini, telah menunjukkan persamaan yang baik dengan keputusan kapasiti ricihan yang diperolehi dalam ujian maklmal untuk kedua-dua jenis sendi kunci (kering dan epoksi) pada kedua-dua peringkat daya ricihan (rekahan pertama dan puncak). Nilai purata dan pemalar pembolehubah (COV) bagi nisbah teori/ujian untuk sendi kekunci kering adalah 0.92 dan 7.1% pada peringkat kapasiti daya ricihian rekahan pertama, manakala 0.72 dan 7.66% pada peringkat kapasiti daya ricihan puncak. Pada masa yang sama, nilai purata dan pemalar pembolehubah (COV) bagi nisbah teori/ujian untuk sendi kunci epoksi adalah 1.18 dan 8.23% pada peringkat kapasiti daya ricihian rekahan pertama, manakala 0.96 dan 8.22% pada peringkat kapasiti daya ricihan puncak.

Oleh yang demikian, menerusi kajian ini, boleh dirumuskan bahawa model-model rekabentuk sediada tidak sesuai digunakan untuk rekabentuk bahagian sendi-sendi rasuk jambatan pra tuang jenis UHPFRC. Dengan mengaplikasikan modal rekabentuk baru bagi menganggarkan nilai kapasiti ricihan (peringkat rekahan pertama dan puncak) untuk sendi rasuk jambatan pra tuang UHPFRC, kedua-dua badan kerajaan dan swasta akan memperolehi manfaat yang optimum dengan memastikan struktur rasuk jambatan UHPFRC yang direkabentuk adalah selamat, ekonomik, dan mudah untuk dibina. Pada masa yang sama, kajian ini juga akan memberikan sumbangan yang penting ke arah pembangunan garispanduan rasuk jambatan pra tuang UHPFRC, khususnya dalam konteks sendi kunci.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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CHAPTER 1

INTRODUCTION

1.1 General overview

Throughout history, bridges have fascinated humanity as symbols of art and science, good architecture, trade, and engineering skill and have also symbolised links between people, culture, communities, and nations. In fact, strategic and tactical bridges have signified their importance towards exercising and displaying power. Bridge building has therefore been a high-ranked profession. The evolution of bridge deck technology can be divided into two major geological era. First, the Arch Earned run average, from 2000 BC to the end of the 18th century, was dominated by the Roman print structures and were practically all stone archway during this period. Secondly, the Contemporary Era that followed and continues today flourished after brand was commercially available as a construction material in the mid-19th century. All Bodoni font bridge types including girder bridge deck , cable-stayed Bridges , abatement Harry Bridges and arch bridges, especially those with larger spans, have been made possible only due to the high enduringness of steel, both in compression and in tension (Tang, 2007). Since the beginning of the 20th century, concrete has become the most widely used construction material in bridge construction with Portland cement being the second most commonly used material, the first being water. According to the U.S. Geological Survey, in 2016, the world production of cement was about 4.35 billion tons (refer to Figure 1.1), compared to just 1.04 million tons in 1990 (Van Oss, 2014 and Van Ruijven et al., 2016).

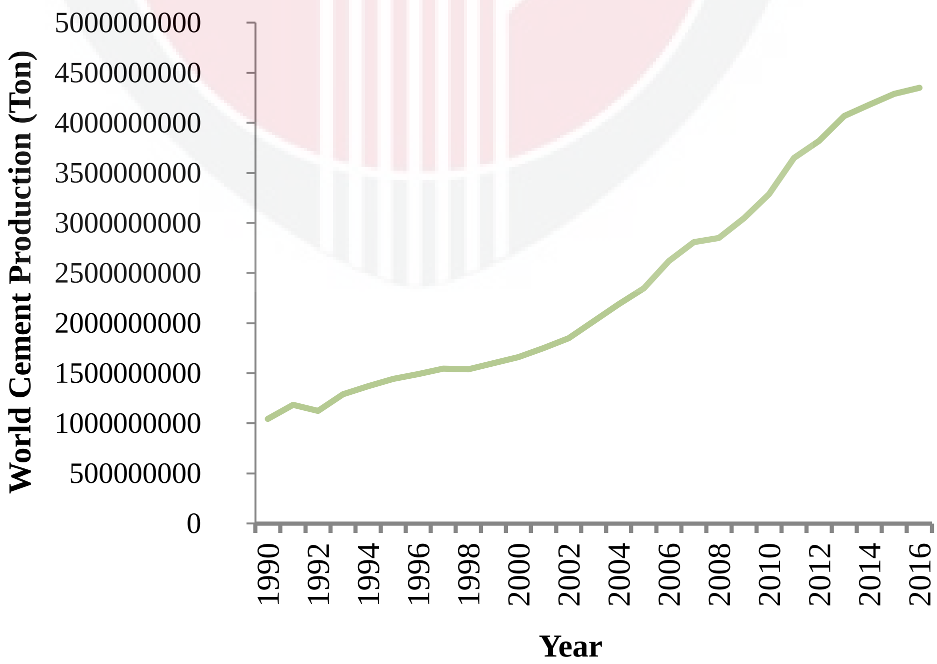

Figure 1.1 : World cement consumption (Van Ruijven et al., 2016)

Traditionally, concrete has been understood to be a mixture of cement, water and aggregate but in modern concrete other constituents may also be present such as mineral components (e.g. fly ash, slag, micro-silica and silica fume), chemical admixtures (e.g. air-entraining agent, superplasticiser, and retarder) and fibres (steel, carbon or synthetic). Figure 1.2 shows the development of concrete through the ages with normal strength concrete (NSC) and high strength concrete (HSC) developed in the early 1900s and 1950s, respectively while the development of ultra-high-performance fibre reinforced concrete (UHPFRC) or reactive powder concrete (RPC) originated during the mid-1990's. When compared with high-performance concrete (HPFRC), UHPFRC tends to exhibit superior properties such as advanced strength, durability, and long-term stability.

Figure 1.2 : Evolution of Concrete Technology (Voo et al., 2012)

In brief compared to NSC, UHPFRC demonstrates exceptional structural durability characteristics such as high fracture energy, low permeability, limited shrinkage, increased corrosion resistance since it is this cementitious material contains a high quantity of cement and silica fume, , incorporates large amounts of steel fibres and low quantity of water. Notably, UHPFRC is characterised by its compression and flexural strengths, more than 150 MPa and 20 MPa respectively. Based on these supreme durability and structural qualities, UHPFRC has ended up commercially accessible in numerous nations, such as Canada, United States, China, Chez republic, Germany, Austria, Italy, Australia, New Zealand, Japan, Malaysia, Netherlands, Singapore, Slovenia, South Korea, Spain, Vietnam and other countries.

The concept, improvement, and the around the world acknowledgment of segmental development within the field of precast segmental bridge girders (PSBGs) represents one of the foremost curiously and vital accomplishments in civil engineering (Poston and Wouters, 1998). Consequently, a large number and varying lengths of PSBGs of have been constructed around the world, due to the demand of safe design, quick, adaptable and practical construction, supreme serviceability and economical in term of cost (Wium and Buyukozturk, 1984). In fact, PSBGs are perceived as an arrangement to numerous bridge issues having superior durability, reasonable low cost cycle and quality control that is promptly accomplished. Generally, the integrity and behaviour of the joints between the segments determines the ultimate strength of segmental bridges. Prior shapes of these bridges ordinarily utilized the single key within the web section, and these can be reinforced are within the key region. However, in contrast with the past, unreinforced multiple keys are widely in use within the key zone, whereby these components would provide improved performance of interlocking (Buyukozturk et al., 1990). Generally, joints between the precast segments are weaker compared to adjacent solid sections within the segments, and during the service stage the compression and shear forces are transmitted through these key components.

Accordingly, during the erection phase, the keys in these regions serve as an alignment tool to align the segments. Meanwhile during the service phase, these components are utilised to transfer shear and compression forces between the segments and to ensure durability of the segments by protecting the prestress tendons which are passing through the joints against corrosion. Nowadays, it is common that the segmental joints can be fabricated and erected either using an epoxy layer between the segments or in a dry condition. Depending on the countries, such as the UK, Australia, USA and Canada the use of a non-epoxied segmental joint is not allowed, whereas, in some countries such as Malaysia, a dry non-epoxied segmental joint is permitted.

1.2 A brief review of earlier works

Exploiting dry keyed joints in the precast segmental bridge girders (PSBGs) are one of the commonly used technique in segmental girders industries. This technique is more suitable than using epoxy joints due to the excellent contribution in accelerating the erection process, and the lack of dependency on weather atmospheric condition during construction. Although, the capacity of the joints increases by applying epoxy layers.

Even though the precast segmental box girder bridges have been extensively used, there is relatively scant knowledge of facts available on the behaviour and design of such bridge structures, especially related to the joints between the segments. The investigation on the behaviour of precast segmental girders with external tendons and dry joints was conducted earlier by MacGregor et al., (1989), Sowlat and Rabbat (1987) and Bu and Wu (2018). More recently researchers who investigated the shear behaviour of the joints included Koseki and Breen (1983), Buyukozturk et al., (1990), Zhou et al., (2005), Han et al., (2017), Jang et al., (2017) and Tawadrous and Morcous (2018). It has been noticed that, all of these previous studies pertaining to PSBG joints are on normal strength concrete (NSC) and most of these works are likely limited to single-keyed joints and are different in detail from the actual use in construction where multiple-keyed joints are dominant.

In a similar vein, Rombach (2004) examined the conduct of NSC multiple-keyed joints in a finite element model while, Zhou et al., (2005), performed a arrangement of experimental tests and examined the conduct of NSC dry single keyed joints and three-keyed joints. Whereas, Turmo et al., (2006a) checked the diverse joint shear capacity details between the distributed experimental data (NSC data) within the published writings and estimated outputs from the ATEP formula (Spanish Design Code) and the AASHTO (American Design Code) equation (both developed for NSC material), and eventually proposed a new formula to be a part of the Eurocode (Turmo etal., (2006b)).

A Finite Element Method (FEM) study investigating the structural behaviour of segmental concrete structures with external prestressing, focusing on the response of these structures under the combined shear and flexure was presented by Turmo et al., (2006c). In this study, they simplified the modelling of interlocking geometry of the keys by not replicating it. Alcalde et al., (2013) examined the fracture characteristic of NSC dry keyed joints under the influence of shear loading, centring on the impact of the number of keys on the joint capacity and its average shear stress. In this study, they summarised that the different design code formulations did not agree to the behaviour of NSC multiple-keyed joints. In a separate study by Hu and Xia (2016), some structural strengthen suggestions on shear keys were suggested, after they investigated and simulated the bending and twisting working conditions between the NSC shear keys and segments.

1.3 Identified gaps

An extensive review of the writing distinguished more than 300 completed bridges (pedestrian and motorway bridges combined) developed around the world utilising UHPFRC in one or more components (Voo et al., 2014 and 2017). The review recognised that both private and legislative bodies are expending consideration and activities toward using UHPFRC as future construction material given the conviction that UHPFRC innovation grasps are the total arrangement for economic developments and sustainable constructions. In Malaysia alone, until 2018 a total of 133 UHPFRC bridge projects (source: Dura Technology Sdn. Bhd.), have been bulided and opened for service. Among these, about 75% of these bridges are made from UHPFRC girders which are assembled or connected using precast segmental bridge girder (PSBG) techniques.

Nowadays, compared with normal strength concrete (NSC), the investigation about the structures and structural components constructed with UHPFRC as a bridge building material in many countries, is still in its early stage. Over the last decade, many experimental studies have been conducted and published on the structural behaviour of UHPFRC structural members subjected to different loadings. However, the focus of the experimental studies regarding shear strength response at the keyed joints of the actual completed UHPFRC bridges is almost non-existent. Further, the existing provisions of shear capacity are all for NSC prestressed bridge girders, and based on the literatures, all these provisions tend to significantly over-estimate the ultimate shear capacity of the joint specimens. Therefore, there is no design provision model available to calculate the first crack shear capacity loads of any kind of concrete keyed joints, and to estimate ultimate shear capacity loads of UHPFRC shear keyed joints (dry and epoxy). Accordingly, this research study aims to close these gaps regarding the lack of or non-existence of data on such connections for this ultra-high performance fibre reinforced concrete (UHPFRC) material.

1.4 Problem statements

The growing use and application of precast segmental bridges as a solution to bridge problems has resulted in the need to increase the current knowledge of the behaviour of joints in PSBGs. This is because, in PSBGs, shear and compression forces are passed hrough the joints, and generally, these parts are weaker than those of the adjacent monolithic sections.

In spite of the fact that UHPFRC has gotten to be commercially accessible in numerous nations, there has been no comprehensive and detailed international or even European standardisation work on the design of UHPFRC structures. In early 2016, the first UHPFRC standard, (i.e. French standard NF P18-710) was published which can be considered as a national extra feature to Eurocode 2 in the design of UHPFRC structures. Nonetheless, there is no mathematical formula or design provision model to estimate the strength and shear capacity of dry and epoxy UHPFRC joints in this recently released French code.

Therefore, based on the extensive review of the literature, it is observed that there are crucial unresolved gaps in the understanding and assessment of UHPFRC PSBGs including:

i. All the experimental tests available in the literatures, investigated the behaviour of normal strength concrete (NSC) keyed joints. Therefore, there is no comprehensive and full-scale experimental test data available to investigate the shear capacities of the dry and epoxy UHPFRC keyed joints.
ii. All the existing mathematical models and empirical formulae from different researchers and design standard codes for calculating the ultimate shear capacity of dry keyed joints are only dedicated to normal strength concrete (NSC) precast segmental bridges which lead to different and uncertain values (Tawadrous et al. (2018) and Zhou et al. (2005). Hence, there are no mathematical and empirical design provision models, to estimate the failure shear capacities (first crack and ultimate) of the dry and epoxy UHPFRC keyed joints.
iii. In the technical review of the literatures, there are some exploratory studies, FE models and numerical models are accessible to explore the characteristic of NSC dry keyed joints. Be that as it may, a reasonable comparative analysis is troublesome to realise, since the setups of both the experimental studies, numerical models and FE models are exceptionally distinctive.
iv. There is no numerical or FE model yet to simulate the failure pattern of the UHPFRC shear key joint specimens under different variable parameters (i.e. number of shear keys, confining stress (prestressed strength), and kinds of joint keys (dry and epoxy).
v. It can be observed from undertaking literature reviews that, particularly at low confining stress condition, the ultimate shear capacity of the multiple-dry keyed joints are overestimated. This is due to, the formulation proposed by AASHTO was inferred from the single-keyed joints exploratory data. This equation does not consider the diminished capacity in multiple-keyed joints due to consecutive failure.
vi. Most of the existing design provision models are created to calculate the ultimate shear capacity of NSC dry keyed joints. It was found that all the existing provisions tend to greatly over-estimate the ultimate shear capacity of the dry keyed joint of Precast Segmental Bridge Girders (PSBGs). Therefore, there are no comparison studies between:

    a) Existing design provision data and experimental results for UHPFRC keyed joints (dry and epoxy).
    b) FEM model and experimental data on UHPFRC keyed joints (dry and epoxy).

1.5 Objective of the study

The primary objective of this study is to investigate the shear strength and behaviour of typical joints used in PSBGs using UHPFRC without conventional steel reinforcement in the shear key zones. In addition, this research will check the applicability of the available shear design provisions for structural members that have been used in the design for PSBGs. Therefore, the objectives of this research are summarised as:

1. To conduct experimental tests on twelve UHPFRC real full-scale shear joint key specimens up to failure with three variable parameters namely, number of shear joint keys, amount of prestress strengths or confining stresses, and types of joint keys (dry or epoxy).
2. To develop new design provision models for dry and epoxy keyed joints of UHPFRC segmental girders based on the Mohr-Circle theory.
3. To develop a new numerical and finite element model (FEM) to compare the shear capacity load values against the experimental data and confirm the failure pattern of the UHPFRC shear keyed joint specimens based on all three variable parameters.
4. To perform a comparison study between existing shear capacity design provision models and the newly developed UHPFRC shear capacity design provision models with the UHPFRC experimental shear joint experimental results.

1.6 Scope and limitation of the work

To ensure that the above objectives are achieved, the present study is organised as follows:

1. Twelve real full-scale shear joint key specimens are casted and tested experimentally up to failure with three variable parameters namely, number of shear joint keys, amount of confining stress, and the type of joint keys (dry or epoxy)
2. New design provision models are developed for UHPFRC dry and epoxy joints. The reliability of the new design provision models is established through comparison with experimental results.
3. A finite element model (FEM) is developed to compare the validity of the experimental data against the FEM outputs, and simulate the failure pattern.
4. Comparison study is performed between the outputs of existing shear capacity design provision models against the experimental data.

Furthermore, the limitations of the present study are presented as follows:

1. The effects of prestress losses are not considered in finite element formulations.
2. Further investigations are needed to determine the effect of epoxy layer on residual frictional shear capacities ($V_{j,fric,exp}$) and the static friction coefficients (μ) of the UHPFRC keyed joints.
3. A comprehensive investigation on overall behaviour of the dry or epoxy keyed joints on actual PSBGs are yet to be conducted.

1.7 Organisation of the thesis

The thesis comprises five chapters, of which are summarised below.
In Chapter 1, the significance and definition of the problem statement of the present investigation have been highlighted, along with the overall objective and scope of the study.

In Chapter 2, the existing knowledge on the application of PSBGs and the design models of conventional segmental bridges is reviewed. Subsequently, the shear transfer mechanism of the segmental joints is also presented. The literature review will also cover the overview on the background of UHPFRC and case studies or projects where UHPFRC has been used in segmental bridge construction.

In Chapter 3, the detailed methodology of this study will be discussed. A new provision design model for UHPFRC precast segmental girders is developed and presented in this chapter. This model is used to calibrate against the experimental data on the full-scale UHPFRC specimens in this study on both non-epoxied (dry) segmental joints and the epoxied segmental joints. Notably, this model is also used as the design tool mainly for the design of UHPFRC precast segmental prestressed girder in shear. The procedure for development of the FE shear keyed joint models is also explained. This chapter further reports on the experimental program of this study which includes (i) the mix design and mechanical properties of UHPFRC and fabrication of full-scale shear joint keys specimens, and (ii) experimental setup and testing methodology for the material testing program and the shear joint specimens.

In Chapter 4, the mechanical property results of the UHPFRC used in the experimental test program are presented. Subsequently, the experimental test results and observations of the shear joint strength tests are reported. Furthermore, the experimental results on the tested UHPFRC specimens are compared to both the existing design models and a shear joint model as proposed in Chapter 3.

Lastly, Chapter 5, presents the major conclusions from the experimental and numerical results of this study. The scope of future work and recommendations are also discussed.

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LIST OF PUBLICATIONS

A.Gopal, Balamurugan; Hejazi, Farzad; Hafezolghorani, Milad; VOO, Yen Lei. "Shear strength of dry and epoxy joints using ultra-high performance fibre reinforced concrete" *Journal of ACI Structural and material Journal* (***Accepted & under publication process**)

A.Gopal, Balamurugan; Hejazi, Farzad; Hafezolghorani, Milad; VOO, Yen Lei. "Finite-Element analysis of ultra-high performance fibre reinforced concrete keyed dry and epoxy joints in precast segmental bridge girders" *International Journal of Advanced Structural Engineering* (***Accepted & under publication process**)

Voo,Yen Lei; Behzad, N.; Abu Bakar bin M.S; Balamurugan A.G.; Yee,T.S; (2012). "Application of ultra-high performance fibre reinforced concrete – The Malaysia perspective", *International Journal of Sustainable Construction Engineering & Technology*, Vol.3, No.1, ISSN : 2180-3242, pp : 26 – 44 (***Published**)

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