UNIVERSITI PUTRA MALAYSIA

ENHANCEMENT OF KNEE BEAM-COLUMN JOINT PERFORMANCE USING HYBRID FIBER-REINFORCED CONCRETE

SHEIKH MOHD IQBAL BIN S. ZAINAL ABIDIN

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

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DEDICATION

This thesis is dedicated to

My Parents;
For their relentless, unwavering dua to see me overcome my difficulties in life. Truly there is nothing more powerful than the dua of our parents.

My wife;
For always being there through good, and very difficult times. I would never have made it if not for your incredible power of empathy and understanding.

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
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The knee beam-column joint is the weakest beam-column configuration in a Reinforced Concrete (RC) structure, particularly when subjected to earthquake vibrations. Current structural design codes dictate the use of high amounts of steel reinforcements in the frame joint to manage the large strain demand in seismic-prone regions. However, this resulted in congestion of steel reinforcements in the limited joint-area and produced numerous construction complications in RC structures. Fibers are known to improve the mode of failure of concrete from brittle to ductile as a result of their crack fiber-bridging effect. Hence, an attempt has been made in this study to improve the performance of the joint region by developing Hybrid Fiber Reinforced Concrete (HyFRC) from the combination of multiple synthetic fibers. For this purpose, sixteen fiber-combinations with different fiber parameters ranging from size, length, volume fraction, bonding power, materials, and form are designed. These parameters were evaluated under flexural residual-strength tests to analyze its hybridization synergistic effect in improving the Average Residual Strength (ARS) of concrete. The results showed positive fiber synergy with an improvement of the ARS from the controlled specimens by 6.12% for the Ferro-Ultra hybrid, 10.2% for the Ferro-Super hybrid, 7.48% for the Ferro-Econo hybrid, and 20.41% for the Ferro-Nylo hybrid. The developed hybrids were also tested under direct shear, resulting in improved shear strength of controlled specimens by Ferro-Ultra (32%), Ferro-Super (24%), Ferro-Econo (44%), and Ferro-Nylo (24%) whilst producing positive fiber synergy under direct shear at large crack deformations. Subsequently, experimental testing in uniaxial compression and tension were conducted to evaluate the behavior of the HyFRC with added High Range Water Reducing Admixture (HRWRA). Constitutive models for each of the materials are formulated to be used as analytical models in numerical analyses. The acquired data are then used to formulate mathematical equations, governing the stress-strain behavior of the proposed HyFRC materials to measure the accuracy of the proposed models. The experimental testing indicated that the Ferro-Ferro mix-combination improved the performance of concrete in the elastic stage while the Ferro-Ultra combination has the highest compressive strain surplus in the plastic stage. In tension, the Ferro-Ferro mix displayed the highest elastic behavior improvement while the Ferro-Ultra designs proved superior in the plastic range, providing additional toughness to conventional concrete. Consequently, six Knee Joint (KJ) specimens were cast using five developed HyFRC materials and one control specimen to be experimentally tested under lateral cyclic loading. The results indicated significant improvements for the HyFRC KJ specimens in energy dissipation capacity, stiffness degradation rate, displacement ductility toughness, steel reinforcement strain, and hysteretic behavior. Six Finite Element (FE) KJ models were then developed using the HyFRC analytical models for verification against the results from the experimental testing. The accuracy of the proposed FE models resulted in an average percentage difference of 25.89% for peak load, 3.45% for peak load displacement, and 0.18% for maximum displacements from the experimental data. This research concluded that the developed HyFRC materials are beneficial in providing cost-efficient alternatives to RC KJ structures in areas with low to moderate levels of seismic risks.

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

PENAMBAHBAIKKAN PRESTASI SENDI RASUK-TIANG BERBENTUK L DENGAN MENGGUNAKAN KONKRIT BERTETULANG GENTIAN HIBRID

Oleh

SHEIKH MOHD IQBAL BIN S. ZAINAL ABIDIN

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Sendi rasuk-tiang berbentuk L adalah konfigurasi rasuk-tiang yang paling lemah di dalam struktur konkrit bertetulang terutamanya jika terdedah kepada getaran seismik. Kod amalan semasa untuk mereka bentuk struktur di kawasan gempa bumi telah menetapkan penggunaan tetulang besi yang tinggi untuk menampung regangan yang akan dihadapi. Hal ini telah menyebabkan kesesakan tetulang besi di ruangan sendi yang sememangya terhad dan akan mencetuskan lagi pelbagai komplikasi di dalam pembinaan struktur konkrit bertetulang. Penggunaan gentian di dalam konkrit dapat memperbaiki mod gagal konkrit yang rapuh kepada mulur hasil daripada efek penyambungan-rekahan gentian. Oleh itu, percubaan telah dibuat dalam penyelidikan ini untuk menambaik baik kemuluran kawasan sendi rasuk-tiang menggunakan konkrit bertetulang gentian hibrid yang diperbuat daripada gabungan gentian – gentian sintetik. Enam belas kombinasi gentian telah direka dengan kajian parametrik seperti saiz bentuk, ukuran kepanjangan, isipadu pecahan gentian, daya ikatan, jenis bahan dan tekstur permukaan. Parameter ini diuji melalui kajian eksperimen kekuatan bakian konkrit di bawah lenturan untuk menganalisa kesan sinergi penghibridan terhadap konkrit dari segi purata kekuatan bakian. Sinergi gentian yang positif dapat dilihat melalui penambahbaikkan purata kekuatan bakian untuk konkrit bertetulang gentian hibrid sebanyak 6.12% untuk hibrid Ferro-Ultra, 10.2% untuk hibrid Ferro-Super, 7.48% untuk hibrid Ferro-Econo, dan 20.41% untuk hibrid Ferro-Nylo berbanding spesimen kawalan. Keupayaan ricih untuk konkrit bertetulang gentian hibrid ini juga telah diuji dan hasil eksperimen yang dilakukan menunjukkan bahawa hibrid yang dikaji telah meningkatkan kekuatan ricih spesimen kawalan sebanyak Ferro-Ultra (32%), Ferro-Super (24%), Ferro-Econo (44%), dan Ferro-Nylo (24%) di samping menghasilkan sinergi gentian yang positif dalam menambahbaikkan keupayaan ricih di bahagian yang mempunyai rekahan yang besar. Seterusnya, ujikaji dalam daya kemampatan dan tegangan ekapaksi telah dijalankan untuk menilai tingkah laku konkrit bertetulang gentian

hibrid dengan campuran konkrit pengurangan kadar air yang tinggi. Model konstitutif untuk setiap hibrid yang dikaji telah diformulasikan dan diguna sebagai model analitik dalam penganalisaan angkaan. Data yang diperolehi kemudiannya diguna untuk mengukur ketepatan model yang telah dihasilkan melalui persamaan matematik yang dirumus sebagai suatu faktor yang mempengaruhi tingkah laku stress-tegasan konkrit bertetulang gentian hibrid. Hasil daripada ujikaji eksperimen yang dijalankan telah menunjukkan bahawa campuran kombinasi Ferro-Ferro telah meningkatkan prestasi konkrit di peringkat anjalan manakala kombinasi Ferro-Ultra telah menghasilkan daya tarikan mempat yang tinggi di peringkat plastik. Untuk daya regangan pula, kombinasi Ferro-Ferro menghasilkan daya tarikan mampat yang tertinggi di peringkat anjalan manakala kombinasi Ferro-Ultra terbukti memberi daya ketahanan tambahan kepada konkrit di peringkat plastik. Dengan itu, enam spesimen rasuk-tiang konkrit berbentuk L telah dituang menggunakan lima konkrit bertetulang gentian hibrid dan satu spesimen kawalan untuk diuji secara eksperimen di bawah bebanan kitaran sisi. Keputusan eksperimen yang diperolehi menunjukkan bahawa konkrit bertetulang gentian hibrid yang dikaji telah meningkatkan prestasi spesimen rasuk-tiang konkrit berbentuk L dari segi kapasiti pelesapan tenaga, kadar kemerosotan kekakuan, ketahanan anjakan kemuluran, keterikan tetulang besi dan juga tingkah laku histeresis. Justeru itu, enam model unsur terhingga untuk spesimen rasuk-tiang konkrit berbentuk L telah dihasilkan untuk disah menggunakan keputusan eksperimen ujikaji yang telah dilakukan. Ketepatan model unsur terhingga yang dihasilkan menunjukkan purata peratus perbezaan sebanyak 25.89% untuk beban puncak, 3.45% untuk beban puncak anjakan, dan 0.18% untuk anjakan maksimum jika dibandingkan dengan data eksperimen. Penyelidikan ini menyimpulkan bahawa konkrit bertetulang gentian hibrid yang dihasilkan mampu untuk dijadikan sebagai alternatif dalam menyediakan kos yang lebih efisien dalam pembinaan struktur konrit bertetulang di kawasan yang mempunyai tahap risiko seismik yang rendah hingga sederhana.

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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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LIST OF ABBREVIATIONS

HyFRC	Hybrid Fiber Reinforced Concrete
RC	Reinforced Concrete
FRC	Fiber Reinforced Concrete
ARS	Average Residual Strength
FF	Ferro Macrofibers
UN	Ultra-Net Microfibers
SN	Super-Net Microfibers
EN	Econo-Net Microfibers
NM	Nylo-Mono Microfibers
FFC	Ferro-Ferro Hybrid Fiber Reinforced Concrete
F6U3	Ferro-Ultra Hybrid Fiber Reinforced Concrete
F6S3	Ferro-Super Hybrid Fiber Reinforced Concrete
F6E3	Ferro-Econo Hybrid Fiber Reinforced Concrete
F6N3	Ferro-Nylo Hybrid Fiber Reinforced Concrete
PP	Polypropylene
UC	Ultra-Net Control Fiber Reinforced Concrete
SC	Super-Net Control Fiber Reinforced Concrete
EC	Econo-Net Control Fiber Reinforced Concrete
NC	Nylo-Mono Control Fiber Reinforced Concrete
LVDT	Linear Variable Displacement Transducer
CDP	Concrete Damaged Plasticity
FE	Finite Element
HRWRA	High Range Water Reducing Admixture
SFRC	Steel Fiber Reinforced Concrete

GFRC	Glass Fiber Reinforced Concrete
NFRC	Natural Fiber Reinforced Concrete
OPSC	Oil Palm Shell Concrete
UTM	Universal Testing Machine
CIP	Cast In Place
KJ	Knee Joint
SCC	Self-Compacting Concrete
HPFRCC	High-Performance Fiber Reinforced Cementitious Composite

CHAPTER 1

INTRODUCTION

1.1 Background

Earthquakes are unpredictable and violent in nature and the resultant tremors can inflict significsingleant damage towards Reinforced Concrete (RC) structures. There have been a lot of cases where buildings collapsed during earthquakes namely the 2001 Gujarat, 2004 Indonesia, 2011 Japan as well as the 2015 Nepal natural disasters. Henceforth, it is of paramount importance to further reinforce structures in seismic-prone regions to limit the structural damage and prevent the total collapse of structures. The beam-column joint is one of the critical points within a structure that is susceptible to excessive damage during earthquakes (Bindhu et al., 2009; Chun & Shin, 2014; Korkmaz & Tankut, 2005; Parastesh et al., 2014). In an RC framed-structure, the forces from columns and adjacent beams are transferred through the beam-column joints. These joints are subjected to compressive, tensile as well as shear forces and consumes the highest damage during earthquakes from the accumulation of these combined forces. Therefore, strengthening these joints would correspond to an increase in structural ductility as more deformation can be resisted before the connection fails.

Generally, beam-column connections can be divided into two categories – either ductile or rigid connections. Ductile connections are connections where the plastic hinge develops in the joint regions. Henceforth, the connections can plastically-deform to a wide range of displacement due to their ductile nature. Rigid connections are connections that force the plastic hinge to occur outside of the joint region and in the beams. The plastic hinge mechanism would dissipate energy and provide a damping mechanism for the structure to endure seismic vibrations. Most RC beam-column connections are classified as rigid connections due to the seismic detailing. Although the hinge mechanism induces a certain amount of ductility to RC structures, the location of the plastic-hinge often occurs near the face of the columns which have been proven to cause rapid stiffness degradation, loss of strength, and reduces column capacity (Bahrami et al., 2017; Khoo et al., 2006; Priestley & MacRae, 2014).

To retain the strength and stiffness of the joint-area, current design loads require a higher amount of transverse reinforcements in the column encompassing the joint (IS 13920, 1993; Joint ACI-ASCE Committee 352, 2002; NA to BS EN 1998-1:2004, 2008). However, increasing steel reinforcements have caused several problems during construction. The available space in the beam-column joint is limited and having a high percentage of steel reinforcements resulted in steel congestions. These congestions led to on-site complications whereby wet concrete were inadequately compacted and steel reinforcements were not thoroughly covered, due to the space constraints. This caused corrosion in steel thus weakening the performance of steel reinforcements, produced hollow space and cavities inside concrete known as honeycombs, and result in bond-slip failure for the primary reinforcements (Foroughi-Asl et al., 2008; Kadarningsih et al., 2017; Kang et al., 2010). Nevertheless, the elastic behavior of the joint can still be retained by relocating the plastic hinge to the beam instead of on the column face. This would reduce the percentage of transverse reinforcements needed on the joint as well as maintaining the strength and stiffness of the joints.

Consequently, numerous research have been conducted to develop novel beam-column connection designs by relocating the plastic hinge to the beams and subscribing to the weak beam-strong column design philosophy (Fadwa et al., 2014; Weichen Xue & Zhang, 2014; Yuksel et al., 2015). However, this most often produced complex steel designs and difficult construction procedures. Specialized laborers were required for fabrication and transportation which increases the overall cost of construction. Structural behaviors that are commonly observed amongst researchers when improving the performance of moment resisting connections are; displacement ductility, energy dissipation capacity, stiffness and strength degradation, failure modes, drift capacity, flexural strength, and P-Δ hysteretic response.

Furthermore, Nakaki et al. (2014) argued that relocating the plastic hinge region increases the overstrength of the connection and imposes a large amount of stress on the steel reinforcements, causing it to yield. Attempt to strengthen the steel connection using high strength bars resulted in concrete compression failure due to the high strain at yield point which exceeds the concrete crushing strain – the higher the reinforcement stress, the wider the crack width.

Generally, the conventional design of RC employs continuous steel reinforcement to recompense the low tensile, flexural, and shear strain capacity of concrete. The combination between steel and concrete have worked well for decades but its application in seismic-resistant structures can become complex especially on the beam-column joints (Choi et al., 2013; Kabir et al., 2016; Kulkarni & Li, 2014). The steel design requires a high tensile strength ratio of steel, in a limited confinement area subjected to large inelastic deformations; while also taking into consideration the plastic hinge positioning. Henceforth, the design and constructional limitations suggest a more direct approach in addressing the problem – such as using Fiber Reinforced Concrete (FRC) materials for the joint sections.

The term FRC was defined by the ACI 116R, Cement and Concrete Terminology as concrete containing dispersed randomly oriented fibers. These fibers provide 3-dimensional reinforcement in cementitious composites which is advantageous in limiting the inducement of large loads to primary steel reinforcements from all directions (FORTA Corporation, 2017). Reinforcing concrete with high strength and short fibrous material has long been used, and can be dated to approximately 3,500 years ago. Ancient civilization used thatches to reinforced brittle sun-dried bricks, straw fibers to enhance baked-clay mud huts, animal hairs for masonry mortars, and many more, with the aim of improving the mechanical properties of construction materials at that time. Several investigations have already shown FRC improving the performance of conventional concrete in tensile strength, compressive strength, elastic modulus, crack resistance, crack control, durability, fatigue life, resistance to impact and abrasion, shrinkage, expansion, thermal characteristics, and fire resistance (Buratti et al., 2011; Khanlou et al., 2012; Naaman, 2007; Roesler et al., 2006; Thomas & Ramaswamy, 2007).

The ACI Committee 544 (2002) classify fibers into four categories – Type I (steel), Type II (synthetic), Type III (glass), and type IV (natural). The use of steel fibers have been popular since the 1970s because of the substantial improvement it imparts on concrete. However, recent advancement in petrochemical and textile industries has led to the widespread use of synthetic materials because of its fast manufacturing process, economical price, new types of organic fibers and versatile applications (Sadrmomtazi & Haghi, 2008; Salvador Cesa et al., 2017; Zheng & Feldman, 1995). Several companies have begun manufacturing macro synthetic fibers, a synthetic fiber in a macro-sized scale, which has been claimed as a replacement for secondary steel reinforcements (Alani & Beckett, 2013; McCraven, 2002). In addition, the application of FRC in different beam-column joint have been studied by several researchers and the results showed improvement on the beam-column structural ductility (Abbas et al., 2014; Oinam et al., 2014; Röhm et al., 2012; R. Zhang et al., 2015). The fiber application in cement matrix harbors great potential by the possible reduction of steel reinforcements in the beam-column joint regions while providing a more straightforward connection design, without the ductile detailing complications that commonly ensues.

1.2 Problem Statements

The beam-column joint is considered as one of the most critical location in a Reinforced Concrete (RC) structure when subjected to earthquake vibrations. Loads are transferred from beams to columns via the joints and since the load-path is discontinuous, the joint consumes the highest damage during vibrations. For non-seismic steel detailing, it has been observed that RC structures fail because of the huge shear demand on the joint, as a result of concrete crushing and weakening of the concrete-steel reinforcements bond (Kotsovou & Mouzakis, 2012). Concrete is brittle and does not have a large deformation capacity in its plastic stage. After achieving peak stress, it fails and would not be able to endure the formation of diagonal cracks in the joint caused by the slippage of steel reinforcements in the beam during the flexural yielding of reinforcements (Siva Chidambaram & Agarwal, 2014). The compressive and tensile stresses acting on the face of the joint section further contribute to the formation of diagonal shear cracks (Antonopoulos & Triantafillou, 2002). Hence, current structural design codes dictate the use of high amounts of steel reinforcements in the frame joint to manage the large strain demand in seismic-prone regions. This is known as seismic steel detailing and are used worldwide in RC structures located in areas with high seismic risk. However, the increase in steel reinforcements resulted in congestion of steel reinforcements in the limited joint-area and produced numerous construction complications (Tsonos, 2007). In fact, the weak link in the beam-column joint remained even after satisfying the minimum requirement for seismic steel detailing according to the design codes (Khose et al., 2012). Sharma & Bansal (2019) even reported that all the various beam-column joints in RC structures exhibited different levels of damage pattern. Therefore, it can be deduced that the life safety and structural failure cannot be guaranteed during seismic vibrations despite satisfying the minimum requirements established by the various structural design codes (Siva Chidambaram & Agarwal, 2018).

The strengthening of the beam-column joint using FRC is dependent on the capacity of the fibers inside concrete to retain excessive loads and reduce the damage on steel reinforcement connections. The mechanical properties of FRC in compression, flexure, tension, and shear can be determined from experimental tests but the results should not be used as a basis for the material to be applied universally on all structural components, particularly for the beam-column joints. This is because the performance of the beam-column joint differs with different structural configurations. Positive results of using steel-FRC in external beam-column joints should not fundamentally translate to improved performance in the external, T, or knee beam-column joints. In fact, it has been shown that the knee-type beam-column arrangement performed the weakest among the interior, exterior, and T-type connections (Xue & Yang, 2014). The absence of lateral and vertical restraints due to its discontinuous L-shaped assembly resulted in an unbalanced structure. Henceforth, the knee-type connection is susceptible to more damage compared to the rest of the joints during seismic vibrations and might require a tougher FRC in the joints compared to steel-FRC.

The use of single-fiber in FRC also limits the fiber-bridging capabilities because they are bounded by crack-zones and volume fraction limitations. Cracking is a multiscale and gradual process, microcracks coalescent into macrocrack which propagates at a stable rate until instability occurs and fractures the cementitious composites. The use of only one type of fiber implies that the fiber would only be able to reinforce one level of crack and within its cracking-strain limit (Fu et al., 2018; Guler, 2018; Swolfs et al., 2014; Yao et al., 2019). Hence, high-volume fractions of fiber are typically designed to overcome the strain-limit, but then this caused problems such as workability complications during concrete casting (Siva Chidambaram & Agarwal, 2018). In general, micro and macro synthetic fibers are fibers manufactured from synthetic materials that have diameters smaller than 0.3mm and larger than 0.3mm, respectively. By hybridizing micro and macro synthetics from two or more different materials in cement matrix, the Hybrid Fiber Reinforced Concrete (HyFRC) can reinforce higher range of crack levels, reduce applied damage and achieve equal or greater performance capability than using single-FRC. HyFRC combinations were also more effective than traditional FRC in bridging micro-crack and result in strain-hardening of concrete as well as improving the post-cracking mode of failure (Nayar & Gettu, 2015; Sahoo et al., 2014; Soutsos et al., 2012; Yap et al., 2014).

Fibers are usually hybridized between a primary load-bearing fiber and a secondary fiber. Steel fibers are widely popular in being considered as the load-bearing fiber in any combination mix because of its high strength, stiffness, ductility, and large macro-size compared to the other types of fiber (Mo et al., 2017; Thomas & Ramaswamy, 2007; Wille & Naaman, 2012; F. Zhang et al., 2016). However, recent developments in producing macro synthetic fibers might break the over-dependency on steel fibers as the primary choice for the load-bearing fiber. Macro-sized synthetic fibers are more advantageous to be used because it is more economical than steel fibers and have been reported to achieve similar reinforcing capabilities (Buratti et al., 2011; Yin et al., 2015), produce a significantly lower carbon footprint (Shen et al., 2010; Strezov & Herbertson, 2006), and non-corrosive compared to steel, which was known to deteriorate in performance over time. The use of steel fibers more than 2% in concrete also led to fiber segregation and air entrapment which affects the tensile and flexural stress-resisting capabilities of the fibers (Chidambaram & Agarwal, 2015). Furthermore, there is currently limited literature available on the shear behavior of concrete with different fiber hybridization especially for synthetic fibers, and this warrants further research.

Conjointly, conducting numerical analyses for unconventional materials proved challenging as most commercial FE software material libraries are constrained to conventional concrete. Most of the studies that have been conducted in the reviews performed small-scale experimental testing in compression, tension, and flexure while large-scale tests were narrowed to using steel fibers hybrid combinations as it has higher chances of obtaining favorable results, thus lowering the cost of experimental testing. This poses a problem as combinations of other types of fibers in large-scale tests were limited to steel fiber hybrids due to the possible risk of unfavorable or mediocre results. Hence this paper attempts to develop non-steel HyFRC synthetic fiber combinations and formulate constitutive modeling of these materials for FE modeling and numerical analyses. This would lower the costs of experimental testing while broadening the opportunity for these materials to be numerically tested in various structural applications, unconstrained by overhead costs.

In summary, it can be deduced that the most advantageous type of fibers to be used in RC structures are synthetic fibers due to their resultant ductility improvements. Hybridizing multiple different types of synthetic fibers would improve the crack fiber-bridging effect in cementitious composites, allowing it to absorb more energy than single-fibers. Therefore, it can be hypothesized that the developed HyFRC in this research would undertake the steel congestion problems in beam-column joints by reducing the need for more steel reinforcements. Moreover, it might also improve the overall performance of the weakest beam-column connections – the knee joint, under reversed cyclic loading. Numerical models would then be developed using commercial FE software and verified against the experimental results for future applications using the developed novel materials.

1.3 Aim and Objectives

This research aims to develop several novel HyFRC combinations by hybridizing different types of synthetic fibers with HRWRA. The developed HyFRC would be used on the joint-region of a knee beam-column structure to limit the inducement of excessive strains to the primary steel reinforcements and improve its structural performance under reversed cyclic loads. The objectives are specified further below;

1. To develop HyFRC with improved Average Residual Strength (ARS) and shear strength as well as to verify the adequacy of the hybridization synergy between the synthetic fiber combinations.
2. To evaluate the mechanical properties of the HyFRC with High Range Water Reducing Admixture (HRWRA) and determine the optimal fiber volume fraction in providing adequate slump, compressive and tensile strengths.
3. To improve the constitutive models and develop the CDP for the HyFRC while also proposing FE analytical models from the derived data.
4. To evaluate the performance of HyFRC beam-column knee joint experimentally under reversed cyclic loads and verify the accuracy of the proposed FE models by comparing the numerical analyses with the experimental results.

1.4 Scope of Research

This study consists of developing new synthetic HyFRC from FORTA-manufactured fibers to enhance the post-crack behavior of conventional concrete in flexure and shear. The fiber content for hybridization was limited to 0.4% to 0.6% for the primary fiber and 0.2% to 0.3% for the secondary fibers, with a total of sixteen hybrid-combinations between five different fibers. The improvements in the developed HyFRC were tested using methods from accredited test-standards.

Subsequently, five hybrid-combination cases representing each of the different types of fibers used were selected to ascertain their hybridization efficacy with the addition of HRWRA. Incremental admixture dosage from 0.2% to 1.0% was applied to the selected cases, to assess its impact on HyFRC compressive and tensile strength at 28-days as well as their wet concrete workability through slump tests. The objective is to obtain adequate slump result without significant reduction in compressive and tensile strength.

Uniaxial tests were then conducted to develop Concrete Damaged Plasticity (CDP) constitutive models in Abaqus FE software. The results were also used to calculate the improvement in strength and toughness of the HyFRC in compression as well as tension. Consequently, six knee RC beam-column joint analytical models were proposed based on the constitutive data and were further evaluated using numerical analyses. The accuracy of the models was then verified using data obtained from experimental testing of quasi-static cyclic load reversals on RC knee beam-column HyFRC joints.

The knee beam-column joint is selected to be investigated because it is the weakest type of all the beam-column structures. The main aim of this study has always been to develop five novel synthetic hybrid fibrous concrete for experimental tests in beam-column joints. Conducting FE analyses and verifying the results with experimental testing using the developed HyFRC would provide a more detailed and insightful finding on the knee beam-column joints as compared to widening the scope and testing it on all internal, external, and T beam-column structures.

1.5 Thesis Layout

This thesis can be divided into five chapters.

Chapter one presents the background problems encountered in RC beam-column connections and the potential application of FRC on beam-column joints. The problem statements, aim, and objectives, as well as the research scope limitations, are all defined in this chapter.

Chapter two is a collection of reviews from existing literature. It is subdivided into two parts – the materials and applications section. The materials section studies the available fibers currently on the market for the development of HyFRC while the application part reviews past experimental tests conducted on similar fiber-hybridization ideas.

Chapter three describes the methodology employed in this research; outlining standards, codes, and procedures undertaken in this study. Details of the HyFRC development, experimental tests procedure, damage plasticity constitutive modeling, and numerical computational methods are presented in detail.

Chapter four discusses the results obtained from the experimental tests in sequential order. The post-crack Average Residual Strength (ARS), shear-resisting capabilities, admixture parametric study, constitutive modeling, knee beam-column cyclic tests, and the verification of the models are all elaborated in this chapter.

Chapter five concludes the research outcome from the obtained results. The overall research is summarised with regards to prior aims and objectives while further recommending future investigation in certain aspects of the study.

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