FORMULATION OF THE THEORY OF CRITICAL DISTANCE FOR FATIGUE CHARACTERISTIC IN CONCRETE INCORPORATING VARIOUS WATER-CEMENT RATIOS

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DEDICATION

This thesis is dedicated to whomever that passionate with knowledge; it is not the completion that is vital. The struggle is real. The hardship is real. The sacrifice is real. But do not fear as fear is not real. It is only in our head. The tears that come out from our eyes, turn them gold – never let it as it is. Stay focus. Endure. Take control of every moment in our life. Remember, war comes without knowing our ups and downs. Push ourselves. Don't settle. *Be with only Allah and everything will be fine*.

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ABSTRACT

The employment of the Theory of Critical Distances (TCD) in the research of fatigue damage in concretes is a fairly recent development. TCD is primarily used to characterise fatigue and fracture behaviours of concrete. Previous research have discussed on the accuracy of TCD application in concrete under high-cycle fatigue conditions. The research tested the TCD formulation on two batches of concrete mix differs in terms of their water-cement ratio. In comparison, the accuracy of TCD is proven judging exceptionally small errors that occurred between the theoretical and tested outcomes for both batches. However, although TCD is proven to be accurate, the percentage errors display severe inconsistency when being compared side-by-side between two batches of concrete. Thus, TCD seems to be susceptible to the change of water-cement ratio. It is beneficial to comprehend that fatigue and fracture assessment method like TCD relies chiefly on the tensile characteristics. Unfortunately, the effects of water-cement ratio has been overlooked since the resulted difference in tensile strength is commonly small and often considered insignificant for concrete. Moreover, there are no documented standard procedures on fatigue test in plain concretes, and thus the studies of fatigue and fracture in concrete become stumbled and slow. Accordingly, the theoretical establishment of linking the static behaviours, which are surely less cumbersome to characterise, to those of fatigue is necessary. Therefore, this research aims to study in detail the numerical characterisation of cracks in concrete governed by water-cement ratio through a proposed linkage relationship between the static and fatigue condition. Three important outputs were obtained to achieve the aim of this research. First objective is to conduct the fatigue testing in analysing the fatigue properties in concrete. Secondly, a unified linkage is formulated using Buckingham's Pi technique for achieving the third objective. Thirdly, a closed-form TCD formulation covering the variation of the water-cement ratio is then proposed. Since fatigue testing method of concrete has no officially developed, both ACI 215-75R and RILEM TC 89-FMT were utilised complimentarily. For static testing of the concrete's tensile properties, the methodology presented by Xiao Zhi Hu was adopted. A three-point bending test configuration is utilised onto plain concrete beam following the static and fatigue respective methodologies since both testing configuration are similar. ABAQUS computational engineering software is used to formulate TCD covering the variation of the water-cement ratio. By proving mathematically the linkage between static and fatigue parameters of concrete, it may cause TCD formulation remained unstable towards different water-cement ratio in concrete mix more intelligible. From the analysis of fatigue property in concrete, the increasing fatigue limit of 2.883 MPa, 3.022 MPa, and 3.903 MPa with the increment of water-cement ratio 0.3, 0.4, and 0.5 respectively is significant and non-linear. Hence, fatigue limit of concrete is not simply obtained by converting it from static strength by a single magnitude. Using Buckingham's Pi, the connection between static and fatigue properties is revealed in terms of Π_1 and Π_2. The Π_1 and Π_2 represent a group of static and fatigue properties of concrete respectively. The link established shows that Π_2 is equal to approximately half of Π_1. Yet, individual linkage between parameters remained for future research. Consequently, the research has solved the issue by incorporating water-cement ratio in TCD by introducing equations in the form of polynomial which is $K_{Ic} = 0.7826f_t - 309.935W_c^4 + 495.999W_c^3 - 289.485W_c^2 + 72.31W_c - 8.5516$ and Power Law $K_{Ic} = 0.77 f_t - 2.3W_c^{0.102}$. Both of the equations are identical but in different forms. The equations formed are related to TCD and incurring water-cement ratio elements. Hence, provide better understanding of how TCD can be utilised for fatigue analysis on concrete structure.

ABSTRAK

Penggunaan Teori Jarak Genting (TCD) adalah suatu perkembangan terkini dalam penyelidikan kegagalan konkrit disebabkan oleh kelesuan. Pada dasarnya, TCD digunakan untuk mengenalpasti ciri-ciri tabiat konkrit yang mengalami kelesuan dan keretakan. Kejituan penggunaan TCD pada konkrit yang mengalami kelesuan kitaran tertinggi pernah diperbincangkan dalam kajian-kajian lepas, di mana dua campuran konkrit yang berbeza nisbah air-simennya telah diuji untuk mengkaji pembentukan TCD. Hasil kajian tersebut mendapati kejituan TCD yang didapati melalui dua kaedah iaitu pengiraan berdasarkan persamaan secara teori dan ujikaji makmal terbukti wujud ralat dalam peratusan yang rendah. Ralat tersebut adalah bukti yang jelas bahawa tahap kepersisan di antara kedua-dua campuran konkrit tersebut adalah lemah. Hasil kajian tersebut memberi gambaran jelas yang menunjukkan bahawa TCD sangat dipengaruhi oleh nisbah air-simen konkrit. Kaedah pentaksiran kelesuan dan keretakan konkrit seperti TCD bergantung kepada ciri-ciri kekuatan tegangannya. Malangnya, impak nisbah air-simen setakat ini sering diabaikan kerana perbezaan ujian kekuatan tegangan konkrit yang terhasil kebiasanya rendah dan tidak mustahak. Lebih malang lagi apabila tiada usaha untuk mendokumenkan secara rasmi langkah-langkah piawai bagi ujian kelesuan konkrit, natijahnya penyelidikan berkenaan kelesuan dan keretakan konkrit akhirnya terbantut dan perlahan. Oleh yang demikian, pembentukan teori menghubungkaitkan tabiat pegun dengan kelesuan konkrit adalah suatu keperluan memandangkan komplikasinya yang rendah. Justeru, matlamat kajian ini adalah untuk mengkaji secara terperinci sifat-sifat berangka pada keretakan konkrit bergantung kepada nisbah air-simen dalam keadaan pegun melalui suatu cadangan hubungkait antara keadaan pegun dan kelesuan. Tiga hasil penting telah diperolehi untuk mencapai tujuan kajian ini. Objektif pertama adalah menjalankan ujian kelesuan dalam menganalisis sifat kelesuan konkrit. Kedua, menghasilkan hubungkait terpadu yang dirumuskan menggunakan teknik *Buckingham's Pi* untuk mencapai objektif ketiga. Ketiga, rumusan TCD terhad yang merangkumi variasi nisbah air-simen kemudian dicadangkan. Oleh kerana tiada kaedah dan langkah-langkah piawai yang rasmi untuk menjalankan ujian kelesuan konkrit, kedua-dua ACI 215-75R dan RILEM TC 89-FMT digunakan untuk tujuan timbangtara. Untuk ujian sifat tegangan konkrit pegun, kaedah yang dikemukakan oleh Xiao Zhi Hu diamalkan. Ujian lenturan tiga titik dikenakan pada rasuk konkrit biasa berdasarkan perspektif kaedah pegun dan kelesuan memandangkan penstrukturan ujian yang serupa. Perisian komputer kejuruteraan ABAQUS telah digunakan untuk merumuskan TCD meliputi beberapa variasi nisbah air-simen. Pembuktian hubungkait faktor-faktor pegun dan kelesuan konkrit secara matematik menjadikan isu pembentukan rumusan TCD kekal tidak stabil jika wujud perubahan nisbah air-simen dalam campuran konkrit lebih menyeluruh. Daripada analisis sifat kelesuan konkrit, peningkatan had kelesuan sebanyak 2.883 MPa, 3.022 MPa, dan 3.903 MPa masing-masing bergantung kepada nisbah air-simen 0.3, 0.4, dan 0.5 adalah signifikan dan tidak berkadar langsung secara semulajadi. Oleh sebab itu, had kelesuan konkrit tidak hanya diperoleh semudah mengubah kekuatan pegun dengan suatu nilai. hubungkait antara sifat pegun dan kelesuan dengan menggunakan *Buckingham's Pi* dinyatakan dalam bentuk Π_1 dan Π_2. Π_1 dan Π_2 masing-masing mewakili kumpulan sifat pegun dan kelesuan konkrit. Hubungkait yang terbentuk mempamerkan bahawa Π_2 adalah hampir separuh dari Π_1. Setakat ini, hubungkait antara faktor-faktor secara individu diserahkan kepada penyelidikan akan datang. Dua persamaan berjaya diterbitkan di mana satu persamaan di dalam bentuk polinomial iaitu $K_{Ic} = 0.7826f_t - 309.935W_c^4 + 495.999W_c^3 - 289.485W_c^2 + 72.31W_c - 8.5516$ dan satu lagi persamaan di dalam bentuk kuasa, $K_{Ic} = 0.77\ f_t - 2.3W_c^{0.102}$. Kesimpulannya, kajian ini telah menyelesaikan masalah dengan memperkenalkan faktor berserta unsur-unsur nisbah air-simen dalam penerbitan rumusan TCD dengan harapan dapat menyediakan tapak bagi meningkatkan pemahaman ke tahap yang lebih baik tentang penggunaan TCD untuk menganalisis kelesuan pada struktur konkrit.

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LIST OF ABBREVIATIONS

TCD	-	Theory of Critical Distance
EPFM	-	Elastic-Plastic Fracture Mechanics
LEFM	-	Linear-Elastic Fracture Mechanics
FPFM	-	Fully-Plastic Fracture Mechanics
MCCM	-	Manson-Coffin Curve method
EC	-	Eurocodes
ACI	-	American Concrete Institute
LWAC	-	Lightweight aggregate concrete
NDC	-	Normal density concrete
RILEM	-	*Reunion Internationale des Laboratoires et Experts des Materiaux Systemes de Construction et Ouvrages* (French/English: International Union of Laboratories and Experts in Construction Materials, Systems, and Structures)
BEM	-	Boundary Effect Model
FPZ	-	Fracture Process Zone
ITZ	-	Interfacial Transition Zone
PM	-	Point Method (TCD)
LM	-	Line Method (TCD)
HCF	-	High Cycle Fatigue
FFM	-	Finite Fracture Mechanics
ICM	-	Imaginary Crack Models
SEM	-	Size Effect Method
FEA	-	Finite Element Analysis
BS	-	British Standard
ASTM	-	American Society for Testing and Materials
EET	-	Element Elimination Technique
X-FEM	-	Extended Finite Element Method
LHS	-	Left Hand Side
RHS	-	Right Hand Side

LIST OF SYMBOLS

ΔK_{th}	-	Fatigue Crack Growth Threshold
$\Delta\sigma$	-	Stress range
$\sigma_{amplitude}$	-	Stress amplitude
σ_{mean}	-	Mean stress
σ_{min}	-	Minimum Stress magnitude in cyclic loading
σ_{max}	-	Maximum Stress magnitude in cyclic loading
σ_{nom}	-	Nominal stress
$\sigma_{0,max}$	-	Plain-specimen Fatigue/Endurance Limit
$\sigma_{0\text{-}n}$	-	Maximum Bending Stress amplitude ("*n*" is referring to percentage from ultimate tensile strength. Say 60% of σ_{UTS}, thus n=0.6) – *plotting S-N curve*
σ_U or f_t	-	Ultimate Tensile Stress
σ_{xx}	-	Linear-elastic stress field in the direction of perpendicular to the notch/crack tip – also represent Maximum Principal Stress
$a_{o,n}$	-	Notch Depth of Beam specimen
B	-	Width of Beam specimen
c	-	Farthest distance from neutral axis for cross section
E	-	Young's Modulus of Elasticity
f_{ck}	-	Maximum Compressive Strength
G	-	Average grain size
G_f	-	Fracture Energy
I	-	Area Moment of Inertia about corresponding axis
K_I	-	Fracture Toughness
K_t	-	Stress concentration factor
ℓ_n	-	Length of Beam specimen
L_f	-	Critical Distance under fatigue condition
L_s	-	Critical Crack Distance under static condition
M_b	-	Bending Moment
N_f	-	Number of Cycle to Failure
R	-	Load Ratio

r	-	Distance from notch/crack tip
r_n	-	Notch Width of Beam specimen
S_n	-	Span of Beam specimen
W_c or w/c	-	Water-to-cement ratio
W_n	-	Depth of Beam specimen
Y	-	Shape factor in linear-elastic fracture mechanics (LEFM)

"*n*" represent water-cement ratio.
n:1 for water-cement ratio 0.3
n:2 for water-cement ratio 0.4
n:3 for water-cement ratio 0.5

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CHAPTER 1

INTRODUCTION

1.1 Overview

Fatigue is a process of a material being weaken due to cyclic loading. Cyclic loading that cause fatigue failure is a repeated load and unloads progression in a period of time on a material. "The Versailles Train Crash of 1842" tragedy is the departure point in understanding the mechanism of fatigue. At that time, people did not realise that a build-up of small stress cycles could lead to a crack and sudden failure (1). Following the tragedy, the study related to fatigue is going on until now. Fatigue is dominantly known as the culprit to the long term integrity of ductile materials like steel and metal (2). There are steady guidelines and formulations established for fatigue and fracture in ductile materials such as steel and metal components. Comprehensive research in fatigue especially on metal and steel make the engineers today have high confidence to use and incur fatigue element in their design since it is rather easy to understand and implement.

In reality, not only ductile material experiences fatigue. Brittle material like concrete also continually encounter repeated loading that can lead to fatigue failure. Undeniably, researches on concrete have broadly branched and it is progressing well until current (3,4). Though, there are some fragment of concrete study is noticed to be deficit, which is fatigue and fracture mechanics. Although at the very beginning of the last century to the latest study in fatigue and fracture has attracted attention tremendously, there are still no recognized agreements in methods to perform the fatigue assessment of concrete. Moreover, not much organized works were done to cultivate specific method or standard to suit the condition of detrimental effect of notches on plain concrete subjected to cyclic loading (5). Back in 1920s where the industrial age was, many engineers remained the fatigue issue in concrete as a textbook discussion – the realisation started to exist after 50 years as the engineers only realised fatigue is a long-term failure process (6).

1.2 Background of Study

A proper research in fatigue on concrete initiated quite late, which was at the end of 1980s compared to steel and metal. For example, one of the initial researches was in 1991 which was related to the size effect of concrete towards the fatigue fracture (7). The reasons of the adjournment are due to the employment of additional safety factor in designing concrete structure that make a structure over-designed and the lack of advancement in high-rise concrete structures back then.

Firstly as mentioned above, every calculation in designing concrete structures has already been utilised the safety factor as early as 1930s (8). The safety factor was applied either it was direct or indirect manner (9). The safety factor incorporates additional value on top of concrete's ultimate strength. Hence, the final value to design concrete structure after adding safety factor is more than its ultimate strength. Consequently, the final value will correspond directly to the dimension of a concrete structure. Having said that, bigger safety factor will result higher final value, which finally will enlarge the dimension of concrete structure. At that moment, engineers presume larger concrete structure can discourage the fatigue failure caused by continual cyclic loading (10). However, as the standards that associated to the concrete design evolved towards adopting green building codes and embraces sustainability in construction, many calculations that involve safety factor has been optimised and trimmed to avoid over-designed structures. By optimising the factor by lowering it in concrete design will result reduction of concrete usage and size of concrete structures. Although it is still safe, reducing the size of concrete has exposed the structure with one of the infamous factor of failures for concrete which is fatigue. It is because quasi-brittle material like concrete only allows minimal crack before it ruptures and fail. The propagation of cracks due to cyclic loading is not elastic – the crack links from one to another. The inelastic crack linkage is strongly influenced by the structural size factor (11).

The second factor of adjournment is while engineers were looking forward into the matter involving safety factor, at that era there was less tall buildings being built. Tall building is understood to be the structures that vulnerable to the fatigue fracture. But nowadays, there are many concrete-based skyscrapers, high-rise building, and flyovers are built across the globe. The higher it goes, more gesticulation of the structures that has to be considered. Yet, one might claim that in the Eurocodes or British Standards, there is already wind load factor that has been considered in constructing tall buildings. It has to be understood that the wind load factor is meant to defy the ultimate strength whereas fatigue failure happens at the amplitude which did not need to reach the ultimate strength (10).

Research on fatigue in concrete is not a straight-forward task. Fatigue is being very subjective on its application on concrete. Hence, the research of fatigue in concrete needs more tremendous exploration.

1.3 Statement of Problem

Recently, researches related to fatigue on concrete are growing but the depth of study is still shallow and lack compared to metal and steel (11). It could be said that the study of fatigue in concrete is still in its infancy stage. One of the factors that deter the research related to fatigue in concrete is due to its complications in configuring fatigue test on concrete specimen. While inquiring fatigue knowledge deeper, the study found that running a fatigue test on a concrete specimen is not an easy task. The impediments are in the form of lack of clear global standard used, no detailed procedures to practice, not much of safety measures to conduct the experiment itself, time-consuming and refractory.

Having said that, in this challenging situation, the fatigue study has discovered the Theory of Critical Distances (TCD). TCD is a formulation that capable to perform fatigue assessment not only on steel but also on concrete. TCD has been proven to be accurate in various perspectives of Fracture Mechanics (12). Experts in the field like Luca Susmel and David Taylor have propounded that TCD is suitable for practical interest like industrial engineers and indeed, it is well-proven (13,14). For now, TCD is acting as one of the most practical solution in fatigue assessment. Nevertheless, as far as the development of fatigue in concrete is inadequate, TCD which operates in fatigue condition also is limited when it comes to some applications towards concrete material.

Based on one of the recent findings by Luca Susmel where he applied the TCD formalisation on two batches of concrete specimen – both batches of concrete are made of different water-cement ratio, a batch is 0.4 and another batch of concrete with water-cement ratio 0.5. It was found out that the difference in percentage error between water-cement ratios in both batches are severely high, although the individual errors are low and acceptable (5). Henceforth, it shows instability of TCD towards different concrete mixes specifically on the change of water-cement ratio. Although he has confirmed the accuracy of TCD by controlling every test over minimal allowance of error, however it is wise to know that the accuracy should be accompanied with precision that will do the formulation best. Therefore, TCD must be investigated further so as to identify its consistency and application on different water-cement ratio in concrete composition.

As the research of fatigue in concrete is already in a worrying state with the unavailability of certified fatigue methodology and unsteadiness of TCD towards different water-cement ratio in concrete, the situation is worsened by the absence of steady establishment between static and fatigue behaviour of concrete testing. Realising the difficulties, the study will try to make use of previous researches related to static and cyclic loading on a material, exploits a scientific technique and propose a unified linkage to connect them. Through this study, it will definitely improve the understanding in the TCD and enhance its application in future. This will embark the journey of static and fatigue study in concrete to become more dynamic and practical by easing the formulation to cross from static to fatigue, and enhance its application throughout different concrete mixes.

1.4 Aim and Objectives of Study

The aim of this research is to investigate in detail numerical characterisation of crack in concrete governed by water-cement ratio using an improved linkage between static and fatigue loading. The characterisation is based on the Theory of Critical Distance (TCD) framework and Xiao Zhi Hu's static concrete methodology (15–17). The technique based on the use of local stresses suitable for estimating fatigue damage in notched concrete components subjected to in-service fatigue and static loading. In order to achieve the stated aim, the following are the objectives;

(a) To examine concrete's fracture behaviour respecting the water-cement ratio variation.
(b) To establish relationship between static and cyclic loading on concrete material under fracture mechanics.
(c) To improvise the sensitivity of TCD formulation through the study of accuracy and compatibility on different water-cement ratio of concrete.

1.5 Scope of Study

This section will discuss on the boundaries of the study – based on literature reviews and researches, the formalization suits the study which focusing on concrete under cyclic/repeated loading.

The study is governed by formalization on fatigue and fracture called the TCD. The arguments on how or why TCD, and the concrete beam under static and fatigue loading are chosen are discussed further ahead. The study is expected to investigate the crack and failure of a concrete structure under static and cyclic loading. The concern on crack will cover two loading modes; static and cyclic. It is important to know the fracture mechanics in both phases. Some might suggest that as in civil engineers do not tolerate with any cracks, hence the comprehension must be more on crack initiation compared to the propagation phase – that is perhaps the reason why engineers must not allow any crack to occur in any concrete structure. But in reality, concrete structure is not that ideal. The study examines crack initiation critically and predicts the number of cycle to failure, and post-processes further to study the propagation of cracks and its characteristics.

It is worth to remember, the study is not meant to choose which formalization is better – the explanations on TCD previously is based on its suitability to the case of the study. The case is not simply chosen because there is less study or there are research gaps. The study is hold because of the concern and apprehensive in the development of fatigue especially in concrete which is left behind while it endangers human life by immediate and catastrophic failure without giving any sign of malfunction at any part of structure, as cases stated above. So, the testament is done through experimental scale – applying the static and cyclic loading on the concrete beam.

The research involves laboratory works where concrete beams need to be casted. The outputs in this research are within the concrete mix of water-cement ratio 0.3, 0.4, and 0.5 and the size of beam is about 1 meter in length, 100 mm in depth, and 110 mm in width. In running fatigue testing on concrete, the limit is taken at 10 million cycles based on (18).

1.6 Significance of Study

While engineers are confident on concrete study and its applications and contributions to the world's constructions, some of them overlooked the design and might neglect the consequences from the repeated cyclic loading.

Generally, the study of fatigue in concrete is important to ensure the design of a structure includes an allowable degree of tolerance in deficiency. Thence, it is essential for engineers to understand the phases of fatigue cracks in concrete. Through the study, both engineers and researchers are able to appreciate fatigue in concrete using TCD and apply it in concrete study with confidence and zero-reluctance. The unexpected and sudden failure can be avoided by understanding purely the material's fatigue endurance limit through the first objective. Therefrom, research involving fatigue in concrete can be enhanced if the study successfully comes out with a unified connecting equation between these two modes of loading; static and cyclic as underlined in the second objective. Therewithal, the reason and parameter affecting TCD's precision when bumped into cases of static and fatigue with different water-cement ratio in concrete will be revealed – and TCD will be more sensitive to its application on concrete over the third objective. Besides, despite addressing only stress magnitude in every design calculation, concrete's toughness and endurance limit should not be put aside. Engineers have to realise that static and fracture mechanics are related and should not distinguish them apart as what happened in previous decades – structures will be better in quality in any way.

If TCD can be improved by considering concrete's water-cement ratio in its mathematical expression, it will contribute for betterment in assessing predicting microcracks initiation and life expectancy of railway concrete structures. This is in line with the urge to strengthen infrastructure as in Chapter Seventh of "Eleventh Malaysia Plan (2016-2020)". In the chapter, this research is exactly in the "Focus Area A: Building An Integrated Need-Based Transport System" named "Strengthening infrastructure to support economic expansion", under the focus area A of "Building An Integrated Need-Based Transport System", the second strategy (Strategy A2 – Improving safety, efficiency, and service levels of transport operations) ensuring the effective preventive maintenance and improving road and rail. Thus, the research is in the perfect timing to corporate in Malaysia strategic thrust of Eleventh Malaysia Plan and definitely be worthwhile for our nation's future in construction and maintenance work.

1.7 Thesis Layout

The thesis is divided into six comprehensive chapters where each chapter is connected to one another. Chapter One explained on the significant establishment of the research. Chapter Two focused on the related researches that have been done and the build-up that contribute to the initiation of the research. Chapter Three is typically the methodology of the entire research where it is divided into two parts – general and overall methodology, and specific and detailed methodology to achieve every objective. Chapter Four analysed the information and data that contributes to the first and second objectives. Chapter Five is the ultimate chapter of the research, which to comprehend and adjust TCD formulation by incorporating water-cement ratio element as in line with the third objective. Last but not least, Chapter Six consists of general and objectival conclusion, and the recommendations for future research purpose.

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