# DAMAGE-BASED FRETTING WEAR MODEL FOR LIFE PREDICTION OF STEEL WIRE ROPES

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# DEDICATION

This thesis is dedicated to my old *me* who was constantly in a dark tunnel. Look where hard work has led *you* now. This work is also dedicated to my husband, Fahmin and my parents, who have always love and pray for me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

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# ABSTRACT

Steel wire ropes are designed with different configurations and arrangements to suit various applications. In most manufacturing industries, fatigue test is often conducted to assess the reliability of new wire ropes. The fatigue test is time-consuming and requires a large collection of stress-life data to suit various wire rope designs and stress ratios. Furthermore, during the reliability test, the sample wire rope is subjected to tension-tension fatigue loading and this would induce fatigue damage by fluctuating stresses in the wire material. The current fatigue life prediction method does not take into account the combined bulk fatigue due to tensile stress fluctuations and fretting wear due to relative sliding and contact stress between the stranded wires, which is the dominant damage mechanism in a wire rope. Therefore, the objective of this study is to develop a validated methodology for fatigue life prediction of newly-designed steel wire ropes that incorporates both bulk fatigue and fretting wear conditions. The interaction between wires is explicitly addressed through the friction and fretting wear damage coefficient. Drawn, bare (non-galvanized), as-received high carbon steel wires and steel rods (undrawn) are used as the reference materials. A series of metallurgical and mechanical testing including microstructure analysis, tensile, interrupted fatigue, hardness and sliding wear tests are conducted on the reference materials to obtain the required properties of the wire materials as the model parameters. The model is then integrated into the user material subroutine (UMAT) of the Abaqus finite element analysis (FEA) software to predict the fretting wear and fatigue life of the drawn steel wires. The load cycle block method with each block representing 10,000 cycles is employed for computational efficiency. The associated coefficient of fretting wear damage, $c_f$ was determined through calibration with reported experimental data and it was found that when $c_f$ = 0.10, the simulated wear depth showed a good agreement with the measured data. The criteria for material removal due to wear and fatigue fracture were established. The material is removed due to wear once the element reaches the terminal value of $D_c$ = 0.90. A new fatigue fracture criterion is proposed based on the total dissipated energy, $E_d$ when the wear depth is 1/3 of the initial wire diameter. Once the energy reaches the critical value of $E_{dc}$ = 32-34 J, fatigue fracture is expected to occur. The number of cycles associated with $E_{dc}$ is taken as the fatigue life of the wire. The calibrated fretting wear damage model was then examined for the reliability of 1×7 steel wire rope samples and the simulated fatigue life showed a good agreement with the measured data by Kiswire. This indicates that the fretting wear damage model is able to quantify the fatigue response of the newly-designed steel wire ropes with various configurations prior to the production of samples for the reliability test. In addition, the design, size, arrangement, and configurations of the wire rope could be improved at an earlier stage based on the reliability requirements. This will increase production productivity and significantly reduce the cost involved in the production and disposal of the steel wire rope that did not achieve the reliability criteria.

# ABSTRAK

Tali dawai keluli direka bentuk dengan konfigurasi dan susunan yang berbeza untuk disesuaikan dengan pelbagai aplikasi. Dalam kebanyakan industri pembuatan, ujian lesu sering dijalankan untuk menilai kebolehharapan tali dawai yang baru dihasilkan. Ujian lesu memakan masa dan memerlukan sejumlah besar data tegasan-hayat untuk disesuaikan dengan pelbagai reka bentuk tali dawai dan nisbah tegasan. Tambahan pula, semasa ujian kebolehharapan, sampel tali dawai terdedah kepada bebanan lesu tegangan-tegangan dan ini akan menyebabkan kerosakan lesu melalui tegasan turun naik di dalam dawai. Kaedah ramalan hayat lesu semasa tidak mengambil kira gabungan lesu pukal akibat turun naik tegasan tegangan dan penggeselsuaian haus akibat gelangsar relatif dan tegasan sentuhan antara dawai, yang merupakan mekanisme kerosakan yang dominan dalam sesebuah tali dawai. Oleh itu, objektif kajian ini adalah untuk membangunkan metodologi yang disahkan untuk ramalan hayat lesu bagi tali dawai keluli baharu yang menggabungkan kedua-dua lesu pukal dan keadaan penggeselsuaian haus. Interaksi antara dawai diambil kira secara eksplisit melalui pekali geseran dan pekali penggeselsuaian haus. Dawai keluli tinggi karbon tidak bersadur yang melalui proses penarikan dan rod keluli (tidak melalui proses penarikan) digunakan sebagai bahan rujukan. Siri-siri ujian metalurgi dan mekanikal yang merangkumi analisis struktur mikro, tegasan, lesu, kekerasan dan ujian gelangsar haus dijalankan ke atas bahan rujukan untuk mendapatkan sifat-sifat bahan dawai yang diperlukan untuk digunakan sebagai parameter-parameter model. Model itu kemudiannya disepadukan ke dalam subrutin bahan pengguna (UMAT) melalui analisis unsur terhingga perisian Abaqus untuk meramalkan penggeselsuaian haus dan hayat lesu dawai keluli. Kaedah blok kitaran beban dengan setiap blok mewakili 10,000 kitaran digunakan untuk kecekapan pengiraan. Pekali kerosakan penggeselsuaian haus, $c_f$ ditentukan melalui penentukuran dengan data yang diperoleh melalui eksperimen yang telah diterbitkan dan didapati bahawa apabila $c_f$ = 0.10, kedalaman permukaan yang haus menunjukkan persetujuan yang baik di antara data simulasi dan data eksperimen. Kriteria penyingkiran bahan akibat haus dan lesu patah telah ditetapkan. Bahan dikira haus sebaik sahaja mana-mana elemen mencapai nilai kritikal $D_c$ = 0.90. Kriteria patah lesu yang baharu dicadangkan berdasarkan jumlah tenaga terlesap, $E_d$ apabila kedalaman haus ialah 1/3 daripada diameter asal dawai. Sebaik sahaja tenaga mencapai nilai kritikal $E_{dc}$ = 32-34 J, dawai dijangka akan patah akibat lesu. Bilangan kitaran pada waktu $E_{dc}$ tercapai diambil sebagai hayat lesu dawai. Model kerosakan penggeselsuaian haus yang ditentukur kemudiannya diperiksa untuk kebolehharapan sampel tali dawai keluli 1×7 dan hayat lesu yang disimulasikan menunjukkan persetujuan yang baik dengan data yang diukur oleh Kiswire. Ini menunjukkan bahawa model kerosakan penggeselsuaian haus dapat mengukur tindak balas lesu tali dawai keluli yang baharu dengan pelbagai konfigurasi sebelum pengeluaran sampel untuk ujian kebolehharapan. Disamping itu, reka bentuk, saiz, susunan dan konfigurasi tali dawai boleh ditambahbaik pada peringkat awal berdasarkan keperluan kebolehharapan. Ini akan meningkatkan produktiviti pengeluaran dan mengurangkan kos yang terlibat dalam pengeluaran dan pelupusan tali dawai keluli yang tidak mencapai kriteria kebolehharapan.

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| | | |
|---|---|---|
| AE | - | Acoustic Emission |
| CDM | - | Continuum Damage Mechanics |
| COF | - | Coefficient of Friction |
| CP | - | Critical Plane |
| DOE | - | Design of Experiment |
| EPFM | - | Elastic Plastic Fracture Mechanics |
| FPSO | - | Floating Production Storage and Offloading |
| FC | - | Fibre Core |
| FE | - | Finite Element |
| FESEM | - | Field Emission Scanning Electron Microscope |
| FRP | - | Fibre Reinforced Polymer |
| FW | - | Filler Wire |
| GDS | - | Glow Discharge Spectrometer |
| IWRS | - | Independent Wire Rope Core |
| LEFM | - | Liner Elastic Fracture Mechanics |
| MBL | - | Minimum Breaking Load |
| MPM | - | Material Point Method |
| OM | - | Optical Microscope |
| RVE | - | Representative Volume Element |
| R&D | - | Research and Development |
| S | - | Seale |
| SDV | - | Solution Dependent State Variable |
| SPD | - | Severe Plastic Deformation |
| SWT | - | Smith-Watson-Topper |
| SWV | - | Specific Wear Volume |
| UMAT | - | User Material |
| WSC | - | Wire Strand Core |
| W | - | Warrington |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| A | - | Energy ratio |
| B | - | Aperture ratio |
| C | - | System free ratio |
| $A_c$ | - | Contact area |
| $A_D$ | - | Damage area |
| $A_w$ | - | Wear area |
| $D$ | - | Damage parameter |
| $D_c$ | - | Critical damage |
| $E$ | - | Young's modulus |
| $E_d$ | - | Energy dissipation |
| $E_{dc}$ | - | Critical energy dissipation |
| $E(N)$ | - | Residual Young's modulus |
| $F_c$ | - | Load reading |
| $F_f$ | - | Friction force |
| $F_k$ | - | Dead weight |
| $F_n$ | - | Normal load |
| $F_p$ | - | Ploughing force |
| $F_s$ | - | Shear force |
| $H$ | - | Hardness |
| $K_t$ | - | Stress concentration factor |
| $N$ | - | Number of cycles |
| $N_f$ | - | Fatigue life |
| $P$ | - | Load |
| $QF$ | - | Friction power intensity |
| $R$ | - | Minimum to maximum stress ratio |
| $R^2$ | - | Coefficient of determination |
| $R_a$ | - | Average roughness |
| $R_z$ | - | Average of five total roughness |
| $S$ | - | Strength |

| | | |
|---|---|---|
| $S_e$ | - | Fatigue limit |
| $S_{us}$ | - | Adhesive shear strength |
| $S_{ut}$ | - | Ultimate tensile strength |
| $V_w$ | - | Wear volume |
| $V_{wr}$ | - | Wear rate |
| $a$ | - | Contact radius |
| $c$ | - | Surface constant / calibration coefficient |
| $c_f$ | - | Coefficient of fretting wear damage |
| $c_t$ | - | Coefficient of tribological wear damage |
| $e$ | - | Specific energy wear resistance |
| $h_w$ | - | Wear depth |
| $k$ | - | Wear coefficient |
| $k_a$ | - | Surface finish reduction factor |
| $p_c$ | - | Contact pressure |
| $s$ | - | Sliding distance |
| wt.% | - | Weight percent |
| $\alpha$ | - | Cross angle/lay angle |
| $\gamma$ | - | Life parameter fitting constant |
| $\Delta\sigma$ | - | Axial stress range |
| $\Delta\tau$ | - | Shear stress range |
| $\delta$ | - | Displacement |
| $\varepsilon_f$ | - | Fracture strain |
| μ | - | Coefficient of friction |
| $\{\tilde{\sigma}\}$ | - | Effective stress tensor |
| $\{\sigma\}$ | - | Cauchy stress tensor |
| $\sigma_o$ | - | Static stress |
| $\sigma_1, \sigma_2, \sigma_3$ | - | Principal stresses |
| $\sigma_a$ | - | Stress amplitude |
| $\sigma_m$ | - | Mean stress |
| $\sigma_{max}$ | - | Maximum stress |
| $\sigma_{min}$ | - | Minimum stress |
| $\sigma_Y$ | - | Yield strength |
| $\tau_{abs.max}$ | - | Absolute maximum shear stress |

| | | |
|---|---|---|
| ν | - | Poisson's ratio |
| $\chi$ | - | Life parameter |
| λ, μ | - | Lame's constants |

**LIST OF APPENDICES**

CHAPTER 1

# INTRODUCTION

## 1.1 Research Background

Steel wire ropes are often used for hoisting and hauling operations with typical applications ranging from the hoisting cables for cranes, elevators and mines, to the mooring lines for floating production storage and offloading (FPSO) and offshore installations as depicted in Figure 1.1. These applications, as well as the combined environmental effects of corrosions, induce complex loading on the wire rope.

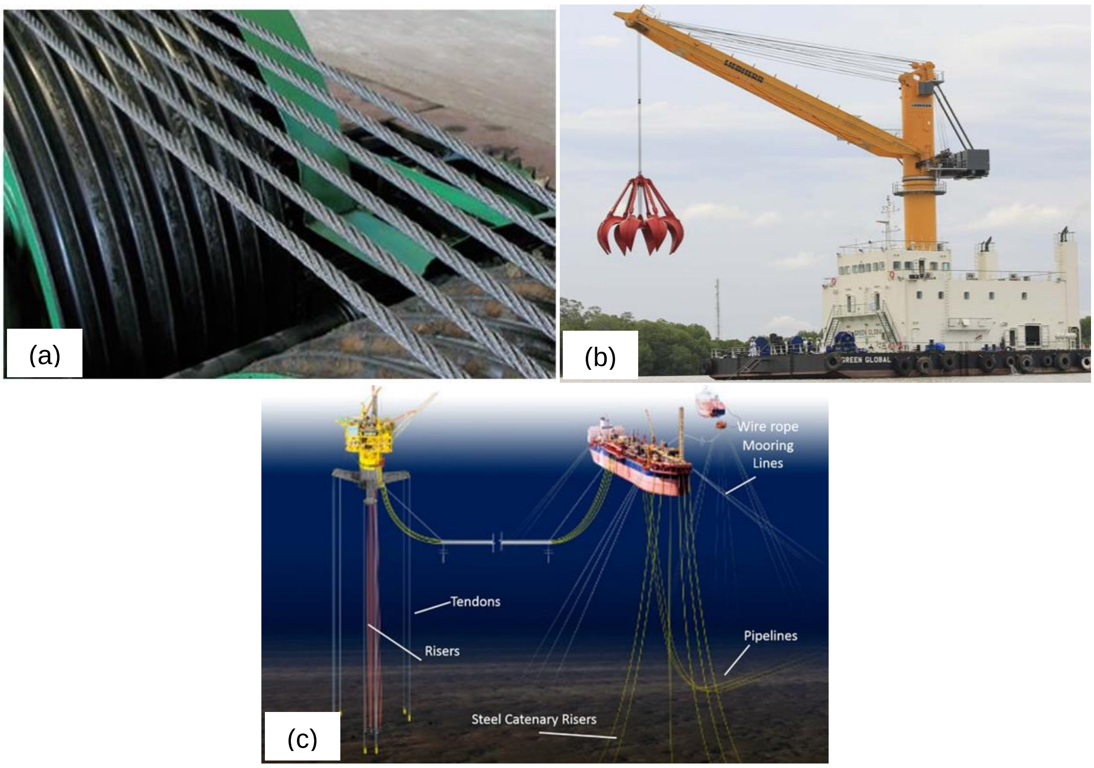


Figure 1.1 Typical applications of wire rope (a) elevator rope, (b) ship crane and (c) mooring system for FPSO [1–3]

This study focused on the preproduction activities and requirements of the newly-designed steel wire ropes which include the selections of steel and multi-step drawing processes to produce the required size of drawn steel wires. The winding process formed the desired pre-production wire ropes. These wire rope samples are then tensile tested to determine the breaking load and fatigue tested to establish their reliability. However, there are cases where the desired properties or reliability level are not achieved, thus the whole process needs to be repeated.

Therefore, this study provides a means to predict whether the wire rope samples would pass the reliability test, before actually sending them for the test. To do this, a computationally driven approach to optimize the properties of the drawn wire material prior to winding or testing the preproduction wire rope samples is proposed. The drawn steel wires are tensile tested for properties to complete the constitutive models of the material. Mechanism-based damage model that incorporated the fretting wear phenomenon is developed. Once validated, this model could be implemented in finite element (FE) analysis to predict the reliability of the wire ropes. The schematic diagram of the proposed preproduction activities of steel wire ropes is shown in Figure 1.2.

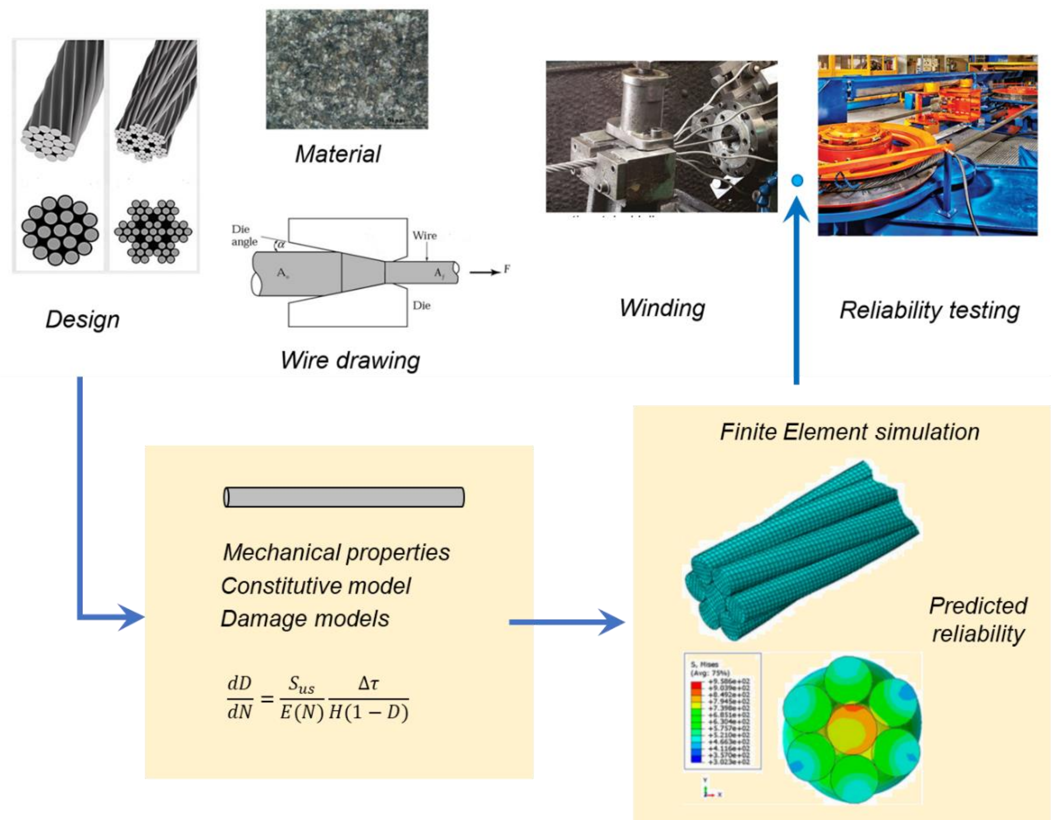


Figure 1.2 Preproduction activities of steel wire ropes

The task is to describe the fretting wear damage model for life prediction of pre-production steel wire ropes during the reliability (fatigue) test. Different tests are conducted to establish the required properties, model parameters and the criterion for fracture using the drawn steel wires. The model is calibrated through a coefficient to match the measured data. The validated model is then examined using a case study on 1×7 steel wire ropes.

During the reliability test, the sample wire rope is subjected to tension-tension fatigue loading and this would induce fatigue damage by fluctuating stresses in the wire material. In addition, the winding of the wires induces contact stress and relative sliding between the wires. In the proposed fretting wear damage model, the bulk fatigue damage by stress fluctuation is addressed through the degradation of the residual Young's modulus, $E(N)$ while the contact stress and relative sliding that will cause fretting wear is adopted through the range of shear stress, $\Delta\tau$ experience by the wire. In high cycle fatigue, the fretting wear is more dominant in causing damage to the interwire, thus it is of outmost importance to take into account the contact between the wires in the reliability prediction.

## 1.2 Statement of the Research Problem

In most manufacturing industries, fatigue test is often conducted to assess the reliability of the produced wire ropes which utilized the S-N curve to estimate the fatigue life of the material. The effect of mean stress on fatigue life is taken into consideration by incorporating the Goodman, Gerber, Morrow and/or Soderberg diagrams. These conventional methods used a phenomenological approach that is based on the mean load over the net section area of the wire ropes, without taking into consideration the failure of individual wires in the strand under fatigue stress. Furthermore, establishing and interpolating constant life diagram data using these methods is a tedious task, since they are time-consuming and require a large collection of stress-life data to suit various wire rope designs and stress ratios. To date, the computational approach to predicting the fatigue life of materials had been vastly studied. Most of the approaches predicted the fatigue life by calculating the cycles to cause crack initiation and propagation until the final fracture. However, this is not the case for the fretting wear phenomenon because instead of producing cracks, the surface material is scraped until a sudden fatigue fracture occur. In addition, to the best of the author's knowledge, the current fatigue life prediction methods do not take into account the combined bulk fatigue due to tensile stress fluctuations and fretting wear due to relative sliding and contact stress between the stranded wires, which is the dominant damage mechanism in a wire rope. Therefore, in this study, a damage-based model that incorporates both bulk fatigue and fretting wear is proposed. The interaction between wires is explicitly addressed through the friction and fretting wear damage coefficient. New criteria for material removal and fatigue fracture are also implied. The validated model is able to predict the fatigue life of the newly-designed wire ropes with various configurations and assess their reliability requirements for design improvement before mass production.

## 1.3 Objectives

The aim of the research is to develop a validated methodology for fatigue life prediction of the newly-designed steel wire ropes under fretting wear condition. Specific objectives are:

(a) To establish residual modulus and fatigue life model of drawn steel wires

(b) To develop a validated damage-based fretting wear model for stranded wires in a wire rope

(c) To quantify the mechanics of the fretting wear damage phenomenon and reliability in the steel wire rope

## 1.4 Scope of Study

The present study covers the following scope:

1. Drawn, bare (non-galvanized), as-received high carbon steel wires and high carbon steel rods (undrawn) are used as the reference materials.

2. A series of metallurgical studies which involved microstructure analysis, chemical composition analysis, surface roughness test and fractographic analysis are conducted to establish the required properties.

3. Tensile test, interrupted fatigue test, hardness test and sliding wear test are conducted as part of the mechanical testing to obtain the mechanical properties of the drawn steel wires and the model parameters.

4. The proposed fretting wear damage model is adapted and adopted from the stress-based damage mechanics model to simulate fretting wear of Hertzian line contact.

5. FE simulations are performed using the commercial SIMULIA Abaqus (ver. 2017) software, linked with Microsoft Visual Studio (ver. 2012) and Intel Parallel Studio XE (ver. 2016). The simulation covers:

   (a) Determination of the model surface constant, $c$

   (b) Determination of material removal due to wear and fatigue fracture criteria

   (c) Validation of fretting wear damage model for cross-wire contact

   (d) Fatigue life prediction of cross-wire contact

   (e) Quantification of the mechanics of fretting wear damage in 1×7 steel wire rope

   (f) Fatigue life prediction of 1×7 steel wire rope under fretting wear condition.

## 1.5 Significance of Study

A new methodology that is employing a validated FE simulation for fatigue life prediction of steel wire ropes will be obtained upon finishing this study. An accurate material model for fretting wear mechanisms can be utilized to take into account the inter-wires interaction in the wire ropes. Ultimately, the model should be able to quantify the fatigue response of the newly-designed steel wire ropes with various configurations prior to the production of samples for the reliability test. Other than that, when failure is dominated by fretting wear, the design, size, arrangement and configurations of the wire rope could be improved at an earlier stage based on the reliability requirements. This will increase the production productivity and significantly reduce the cost involve in the production and disposal of the steel wire rope that did not achieve the reliability criteria.

## 1.6 Thesis Layout

This thesis consists of a total of six chapters. Chapter 1 presents the background and the requirement of the research. The issues with the current reliability test of wire ropes are briefly described. Additionally, the objectives, scope limitations and significance of the research are also defined.

A detailed definition of wire rope that involves materials, geometry, manufacturing process and applications is given in Chapter 2. Other than that, the three main fatigue failure mechanisms in wire rope which are corrosion fatigue, fretting fatigue and fretting wear are clarified. The criteria to discard wire rope in service are also discussed. This chapter also outlines the theoretical reviews of various wear models to provide a base to develop the wear damage model. Finally, the chapter provides comprehensive reviews of previous work done on the prediction of fatigue life of wire rope and fretting wear.

In Chapter 3, the research methodology is described. It includes the details of the research material model, experimental setup and FE simulation models. The input required for FE simulation is clarified in this chapter. The aspects of the FE simulation models are described in depth with a complete flowchart of the User Material (UMAT) subroutine to predict the fatigue life of steel wires in contact.

Chapter 4 and 5 present the results and discussion corresponding to Objective 1, 2 and 3, respectively. The tribological and fretting wear damage models are comprehensively discussed in Chapter 4. The theoretical review and the derivation of the models are shown in this chapter. Other than that, the materials characterization of the wire including chemical composition, microstructure and surface roughness were presented. Besides, the material and mechanical properties that are used as inputs in the wear damage model are thoroughly reported in this chapter. This is followed by the calibration of the tribological and fretting wear damage model and the determination of the wear-induced material removal criterion. Along the way, the result of the FE simulation for two wires in contact is discussed in depth. The validation of the calibrated tribological and fretting wear damage model is also presented. At the end of this chapter, the determination of critical dissipated energy which is the fatigue fracture criterion is reported.

The calibrated and validated fretting wear damage model is then utilized for the reliability prediction of the 1×7 steel wire rope system, which is presented in Chapter 5. Finally, this thesis is ended with the general conclusion of the study and some recommendations for future works, which are outlined in chapter 6.

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# LIST OF PUBLICATIONS

1. **Maslinda Kamarudin**, Mohamed Jefri Jamaluddin and Mohd Nasir Tamin. Fatigue Assessment of Steel Wire Rope. (2019) AIP Conference Proceedings. (Scopus indexed)
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2. **Maslinda Kamarudin**, Zaini Ahmad and Mohd Nasir Tamin. Residual Properties of the Drawn Steel Wires for Damage-based Fretting Fatigue Models of the Wire Ropes. (2020) Materials Science Forum. (Scopus indexed)
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3. **M. Kamarudin**, Z. Ahmad, A.N. Sung, M.N. Tamin. Effects of Different Lay Angles on Characteristic Fatigue Responses of Steel Wire Ropes. (2022) AIP Conference Proceedings. (Scopus Indexed)
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