Development of Fatigue Reliability Model Using Spreadsheet (Steel Structures)

By

Amir Fahmi bin Jalilluddin

Dissertation submitted in partial fulfilment of
the requirment for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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(MECHANICAL ENGINEERING)

Approved by,

____

(Dr. Ainul Akmar binti Mokhtar)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
September 2013

CERTICIFATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or person.

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AMIR FAHMI BIN JALILLUDDIN

ABSTRACT

Accurate predictions of failure probability is very useful in manufacturing and building sector when aiming at the most cost effective maintenance strategy which can be determine by predicting the time need to do inspection and maintenance on steel equipments, machines and steel structures so loss of profit can be minimize and control. In this study, we will **focus more on steel structures, rather than steel equipments and machines**.

In this study, the **statistical probability** using Fatigue Reliability Model (FRM) approach **to determine the reliability of the steel bridges**, which is one of the **common steel structures**, will mainly used. This will be included developing a useful spreadsheet-based using Microsoft Office Excel software that not only user-friendly but also practical to be used in practical field work. This study will use the useful lifetime, which defined as the number of stress cycles before failure, N, of the steel structures and the time which the structures need to be inspected in order to come up **reliability index** which then been use as bench marks for the maintenance schedules.

There are several softwares that exist in the market that can assess the fatigue reliability of structures. Some of these softwares are Weibull++, RCM++, RGA, and BlockSim. There are also web-based softwares like eFatigue. However this software is expensive, Ranging from $1000 to $9000 for single user license and not suitable for education purpose. Developing the FRM by using spreadsheet software, Microsoft Office Excel will lower the cost and user-friendly to be used especially for education purpose.

The spreadsheet is been develop by first defining the limit state function of the FRM bu using Miner's critical damage accumulation index for metallic materials. After that we will identify the random variables that must be included in this study which are mean stress range, $\bar{S}$, and number of design stress cycles in service, N_s. By using this random variables as input, the reliability index can be obtained after using the following set of formulas in Chapter 3.

The data used in this study obtained from past research paper as to obtain a new set of data will requires huge expenses. After the FRM and the spreadsheet are been develop, we will use another researches paper to validate the spreadsheet and eventually prove that this spreadsheet-based FRM is suitable to be used in practical field works and for education purpose.

ACKNOWLEDGEMENT

All praise to Allah S.W. for blessing me with good physical and mental health to complete this final year project report.

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Their contributions are highly appreciated. May God bless everyone involve.

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AMIR FAHMI BIN JALILLUDDIN

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CHAPTER 1
INTRODUCTION

1.1 Background of the Study

Fatigue is a form of failure that occurs when an object is subjected or experienced fluctuating load. This repeating load will causes cracks on the surface of an object starting at the most force-concentrated area. This will be discussed more in Chapter 2.

There are several failures cases that occur because of fatigue present in **steel structures, like steel bridges** of railroads and highways. Most of the cases involving the welded parts of the steel structures which always subjected repeating pressure constantly.

The **first case** is Ashtabula River Railroad Disaster. This disaster causes by failure of the bridge when two locomotives hauling 11 railcars which carrying 159 passengers pass over the bridge on 29 December 1876 [4]. As seen in **Figure 1**, those 11 railcars plunged into the river when the bridge gave away beneath them [4]. This tragedy **killed 92 people and injured another 64 peoples**. It was the worst rail accident in United States of America (USA) until 1918. The investigation report on this disaster stated that the railroad was improperly designed and inadequately inspected. It was believed that the collapsed of the bridge is due to the fatigue of the cast iron lug pieces which were used as anchor the wrought iron bars of the truss together [4]. The investigators claim that the lug pieces are poorly made and needed shims of metal inserted to hold the bars in place [4].

The **second case** is a recent accident that happens on 23 May 2013. This tragedy happen at 97 km long, I-5 Skagit River Bridge, Washington State, when it was been struck by over-weight truck [5]. As result, the bridge collapsed and **three vehicles including the over-weight truck fell into the river**, like been shown in **Figure 2**, and luckily, there are only three peoples with minor injuries from the fell [5]. After investigation, it shows that this steel trough-truss bridge had an initial failure, perhaps a crack, of a single essential part that overload other parts and make them fails, which then trigger a chain reaction of even more failures and causes the entire bridge to collapse [5]. This slow cracking of single undersized and over-stressed gusset plate believed to take years to grow large enough to initiate failure in the bridge design [5]. This cracking may have been overlooked since the last inspection been done on it is on August and November 2012 with only minor inspection [5].

Figure 1: Collapse of Ashtabula River Railroad [4]

Figure 2: Collapse of Skagit River Bridge [5]

From the two cases, it is seems that steel structures like steel bridges and boilers of power plant always subjected to fatigue, thermal fatigue and corrosion fatigue that need to be inspects and monitors continuously.

There are many ways to assess the fatigue reliability of a subjects which some of them are:

- S-N Curve approach
- First Order Reliability Model (FORM)
- Second Order Reliability Model (SORM)
- Paris's Law relationship
- Miner's Rule

In this study, fatigue reliability model is developed by using Miner's critical damage accumulation index for metallic materials to formulate limit state function for assessing the fatigue failures of steel structures and the failure probability is estimated by using Fatigue Reliability Model (FRM) in form of reliability index.

Furthermore, in this study, we use **American Association of State Highway and Transportation Officials (AASHTO) S-N Curve approach** and **Miner's Rule** in order to develop the FRM.

The reason development of FRM is using spreadsheet is because:

- No or less complex coding.
- Cheap.
- User-friendly.
- Can be altered in order to make the FRM more flexible.

1.2 Problem Statement

There are several softwares that exist in the market that can assess the fatigue reliability of structures. Some of these softwares are Weibull++, RCM++, RGA, and BlockSim. There are also a web-based software like eFatigue. However this software is expensive and not suitable for education purpose.

This study is to develop the FRM by using spreadsheet software, Microsoft Office Excel. This is because the existing software in the market is range at $1000 to $9000 for single user license and even the web-based software also needs at least $500 a year to use. Therefore, there is need to develop FRM using spreadsheet which is low cost and user-friendly to be used especially for education purpose.

1.3 Objective

To create a spreadsheet-based model using Microsoft Office Excel software that can be used to predict the estimation useful lifetime of steel structures in order to predict the suitable time for inspection and maintenance checks on the structures.

1.4 Scope of Study

This study focus more on development of reliability model by developing FRM by using spreadsheet software for predicting the useful lifetime of steel structures where the useful lifetime of the structures is defined as the number of stress cycles that cause failure to the steel structures.

1.5 Relevancy and Feasibility of the Project

This study is relevant to the Mechanical Engineering undergraduate course under Manufacturing Major, MBB4333 Reliability and Maintenance. This study thus can assist the lecturers in teaching the students in assessing fatigue reliability.

The objective of this study, as stated previously, can be achieved within the timeframe that been provided by the Final Year Project coordinator.

CHAPTER 2
LITERATURE REVIEW

2.1 Fatigue

Fatigue is a form of failure that occurs in structures subjected to dynamic and fluctuating stress [3]. Which means that fatigue can occurs on material when the material is subjected to lengthy period of constant and repeated stress especially to cyclic stress [6]. Under this conditions it is possible for failure to occur at stress level that lower than ultimate tensile stress (UTS) limit and in some cases is lower than yield stress limit of the material itself compare when subjected to static load [3].

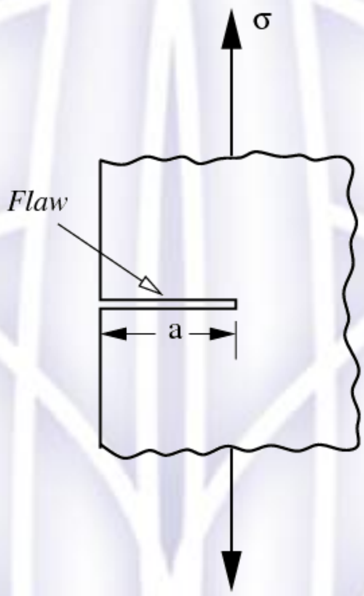

Figure 3: Crack Propagation

When the material subjected to certain constant stress at repeating interval, it will experience cracks which begin to form at the most stress-concentrated surface and grain boundary [6]. This failure begin at the discontinuity or imperfections on the surface of the material which known as crack initiation like been shown in **Figure 3**. This crack then will eventually reach critical size without any clear signs or evidences and the material will experience sudden fracture.

This crack cause by fatigue can be developed in materials in four stages:

- Crack nucleation [6].
- Stage I crack growth [6].
- Stage II crack growth [6].
- Ultimate ductile failure [6].

There are many factors that affect the fatigue life of material, mainly are:

- Geometry of the structure [6].
- Finished surface quality of the structure [6].
- Type of material [6].
- Average grain size of the material [6].
- Surrounding temperature and environment condition [6].

Even though fatigue occurs when the material subjected to fluctuating external mechanical stress, there are two types of environment-assisted fatigue which mechanical stress from external forces needs not to present [3]. These fatigues are:

- Thermal fatigue [3].
- Corrosion fatigue [3].

Thermal fatigue is a type of fatigue that induced at elevated temperatures by fluctuating thermal stress [3]. This is because of the restraint of dimensional expansion and contraction that occurs on material within extreme temperature changes [3]. Its behavior can be observed by:

$$\sigma = \alpha_1 E \Delta T \text{ [3]}$$

where σ = thermal stress

α_1 = coefficient of thermal expansion

E = modulus of elasticity

ΔT = changes in temperature

Corrosion fatigue is a type of fatigue due to the simultaneous action of fluctuating stress and chemical attack on the material [3]. Small pits may form as result of chemical reactions between the environment and material which these small pits serve as stress concentrated area and further developed as crack nucleation area by fluctuating stress [3].

Fatigue stress limit is an important characteristic of material as it been estimated that approximately 90% of material failure is due to fatigue [3]. This is because there is no visible warning prior to failure.

2.2 Corrective Maintenance VS Preventive Maintenance VS Predictive Maintenance

There are several steps that need to be done in order to inspect the steel structures like steel bridges.

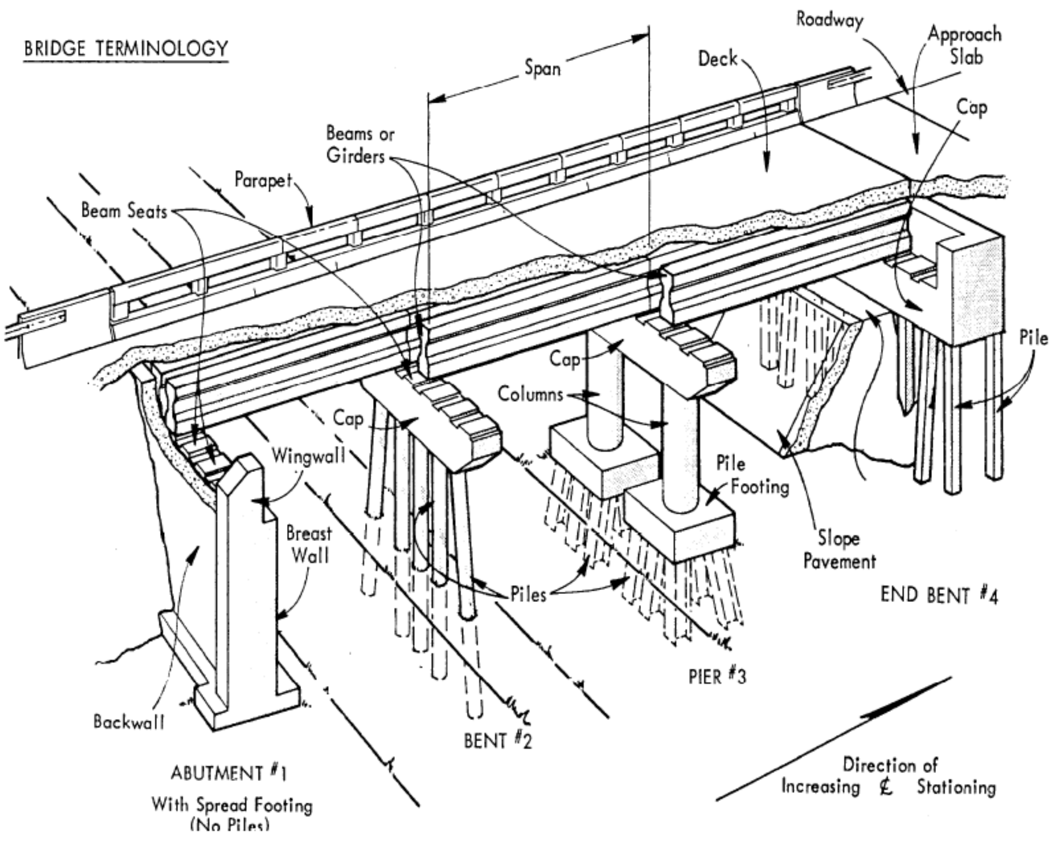

Figure 4: Bridge Terminologies [7]

According to Florida Department of Transportation: Bridge Inspection Process, these steps can be simplified as shown in **Figure 5** below:

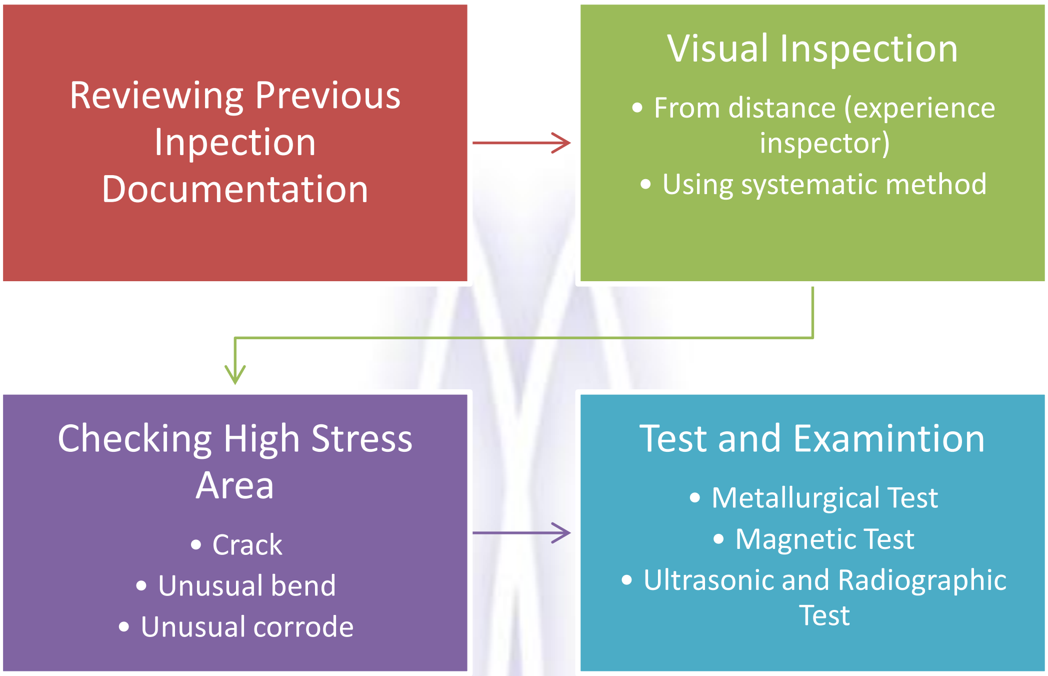

Figure 5: Steps to Inspect Steel Bridges According To Florida Department of Transportation [7]

This practice however can only adopt corrective maintenance in order to repair the steel bridges. There are three type of maintenance, including corrective maintenance, which can be used in order to repair the failure boiler. The three types of maintenance which can be used:

- Corrective maintenance, where the maintenance is been done after the failures occurs on system [8].
- Preventive maintenance, where the maintenance is been done before the failures occurs on system [8].
- Predictive maintenance, cost saving preventive maintenance [9].

Corrective maintenance is undesirable as it is the most expensive and dangerous maintenance because waiting the bridges to fail due to the failures occurs in steel bridges may cause fatalities [8].

The difference between preventive maintenance and predictive maintenance is that predictive maintenance is a method where the failures is been predicted beforehand and the maintenance is been done at the most cost-efficient time while preventive maintenance is time-based maintenance where the system is been repair whether it need it or not [9].

For steel bridges, the most suitable type of maintenance is predictive maintenance in order to reduce the maintenance checks schedule, reduce maintenance costs and increase maintenance efficiency [9]. Since predictive maintenance needs to predict the future failures, it can rely on failure reliability analysis to make the prediction by predicting the reliability index within certain period.

2.3 Reliability

Reliability is the probability that an item will perform a required function without failure under stated conditions for stated period of time [2].

Therefore, manufacturer needs for time-based concept of quality [2]. Reliability is usually concerned with failures in the time domain. This time mainly divided into three stages, as shown in **Figure 6**:

- Burn in period, the failure rate is decreasing [2].
- Useful lifetime period, the failure rate is approximately constant [2].
- Wear out period, the failure rate is increasing [2].

Therefore it is need to predict the failure of the steel structures before the wear out period so that the maintenance checks that been done onto the structures will prolong the useful lifetime of the structures themselves.

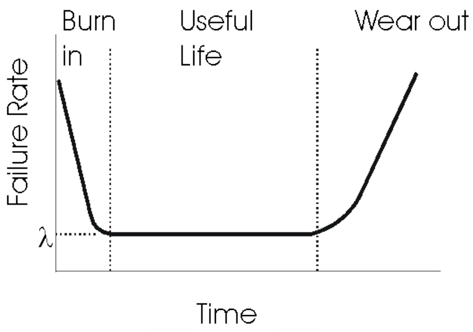

Figure 6: Bathtub Curve

Reliability is therefore an aspect of engineering uncertainty as it is used to predict the useful lifetime of a structure which not certain yet in future [2]. This marks the differences between the traditional quality control and reliability engineering.

Reliability also can be expressed as the number of failures over certain period of time.

The objective of reliability engineering, therefore:

- To apply specialist engineering knowledge to reduce the likelihood of frequent failures [2].
- To identify and correct the causes of failures [2].
- To determine the ways to coping with failures if the causes is unknown [2].

The concept of reliability as a probability means an attempt to quantify which involve the uses of statistical method. Mathematical and statistical method can be used for quantifying reliability and for analyzing reliability data [2].

In order to analysis the steel structures, which in this study is steel bridges, useful lifetime, we will use American Association of State Highway and Transportation Officials (AASHTO) S-N Curve method on the steel bridges.

2.4 Structural Reliability Analysis

Theory and methods for structural reliability have been developed significantly are in fact a useful means to evaluate the safety of complex structures or structures with unusual designs. In structural reliability analysis, the concept of limit state, which is the boundary between desired and undesired performance of a structure, is used to define failure in the context structural reliability analysis. This boundary is often represented mathematically in from of failure function.

For any structure, the failure function represent by g(x), a measure of the ability of the material to resist failure:

$$g(x) = R - S \tag{1}$$

where R = material resistance

S = applied force

However, each structure has different formula for R and S as each structure use different material and design.

It is stated that the failure in any structures will occurs when the limit state function, denoted as g(x), is g(x) < 0 whereas no failure occurs when g(x) > 0. Thus means that, as long as material resistance, R, value is bigger then applied force, S, value, which equal to g(x) > 0 and the structure will not fail.

For structural reliability analysis, the parameters in the equation will be treated as random variables having normal distributions. The mean and standard deviation are assumed to be known for each. The failure behavior depending on basic random variables, such as load and structural resistance parameters, such as dimensions and material properties. The failure probability, P_f, can be calculated as probability content of failure domain, F:

$$P_f = f_n(x_n) \tag{2}$$

where $f_n(x_n)$ = represents the probability densities of the respective basic variables, which for the sake of simplicify are assumed to be stochastically independent

In simplified terms, the failure probability, P_f:

$$P_f = \text{Prob}\ (g(x) < 0) \tag{3}$$

Noted that, failure probability, P_f, is the probability of limit state function, $g(x) < 0$. The more negative the value of g(x) the less reliable the structure is.

CHAPTER 3
METHODOLOGY

3.1 Research Methodology

To start this study, some flow of methodology needed to be executed in order to get full understanding about the study. These steps simplified as shown in **Figure 7**.

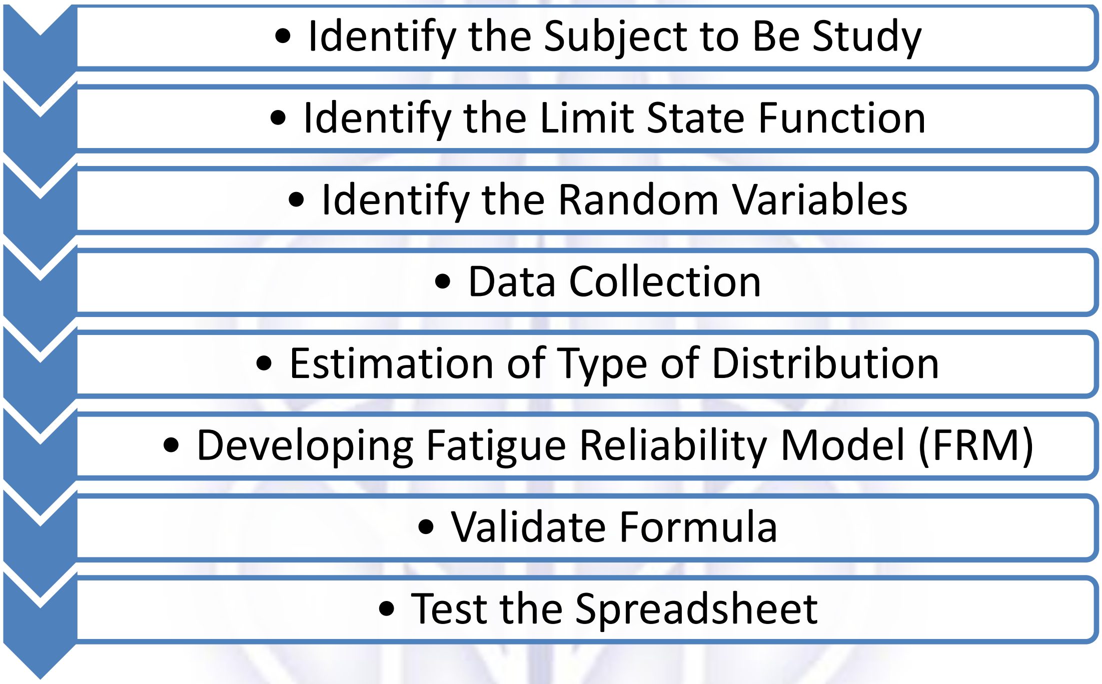

Figure 7: Methodology

Step 1: Identify the Subject to Be Study

In this study, the subject that has been identified to be studied is the steel bridge which is the one of the most common steel structures in the world.

Step 2: Identify the Limit State Function

The limit state function can be defined as following:

$$g(x) = R - S \tag{4}$$

In general, the stress range acts on the steel structures provides the load effect, S, while the American Association of State Highway and Transportation Officials (AASHTO) S-N curve and the Miner's rule provide information associated with R:

$$g(x) = \Delta - e.D \text{ [10, 11, 12]} \tag{5}$$

where Δ = Miner's critical damage accumulation index for resistance of metallic materials with $E(\Delta) = 1.0$ and $COV(\Delta) = 0.3$

e = Measurement error factor

D = Miner's damage accumulation index for load effect

According to Miner's rule, failure due to fatigue occurs when $D \geq 1.0$ which typical values of D failure range is $0.5 \leq D \leq 2.0$ to account this high level of uncertainty [10]:

$$D \geq \Delta \tag{6}$$

Take note that, in designing purposes, assume D = 1.

The limit state function then can be defined as:

$$\mathrm{D} - \Delta = 0 \text{ [10]} \tag{7}$$

$$\frac{\mathrm{N}}{\mathrm{A}}\mathrm{E}(\mathrm{S}^{\mathrm{B}}) - \Delta = 0 \text{ [10]} \tag{8}$$

where N = Number of stress cycles before failure

A = Fatigue –strength coefficient

$E(S^B)$ = Mean stress effect of Rayleigh distribution

Δ = Miner's critical damage accumulation index for resistance of metallic materials with $E(\Delta) = 1.0$ and $COV(\Delta) = 0.3$

Step 3: Identify the Random Variables

There are several random variables that must be identified in this study in order to properly build the suitable formula to get the reliability index. Those random variables are the mean stress range, $\bar{S}$, and number of design stress cycles in service, N_s.

These random variables then can be used to define another set of formulas in order to find certain parameter to get certain value:

Statistical parameter:

$$S_0 = \sqrt{\frac{2}{\pi}}\,\bar{S} \text{ [10]} \tag{9}$$

where S_0 = Statistical parameter

$\bar{S}$ = Mean stress range

Mean stress effect of Rayleigh distribution:

$$E(S^B) = \left(\sqrt{2}S_0\right)^m \Gamma\left(\frac{m}{2} + 1\right) [10]$$

(10)

where $E(S^B)$ = Mean stress range

S_0 = Statistical parameter

m = Material constant representing the slope of S-N curves from AASHTO

Γ = Gamma function

This value of mean stress effect then can be used in (8) to get number of cycles before failure, N:

$$\frac{N}{A}E(S^B) - \Delta = 0$$

(11)

$$N = \frac{\Delta . A}{E(S^B)}$$

(12)

where N = Number of stress cycles before failure

Δ = Miner's critical damage accumulation index for resistance of metallic materials with E(Δ) = 1.0 and COV(Δ) = 0.3

A = Fatigue–strength coefficient

$E(S^B)$ = Mean stress range

From the number of stress cycles before failure, N, obtain, we find the reliability index, β given that we have the number of design stress cycles in service, N_s.

But first, the standard deviation of lognormal of number of stress cycles before failure, $\sigma_{\ln N}$, must be obtain by using the coefficients of variation of fatigue-strength coefficient, COV_A and coefficient of variation of Miner's critical damage accumulation index for resistance of metallic materials, COV_Δ.

$$\sigma_{\ln N} = \sqrt{\ln[(1 + COV_A{}^2)(1 + COV_\Delta{}^2)]} \text{ [10]}$$

(13)

By obtaining the value in (13) and (12) along with the number of design stress cycles in service, N_s, the reliability index can be obtained:

$$\beta = \frac{\ln\left(\frac{N}{N_S}\right)}{\sigma_{\ln N}} \text{ [10]}$$

(14)

Step 4: Data Collection

In this study there is no data collection process since it is impossible to do experiment on steel structures without huge expenses. Because of that, the data used in this study is obtained by previous research paper that been done by person that have more experience and professional in this type of study which will be explain later in the chapter.

Another collection that also been done in this study is the AASHTO bridge's category and the mean value of fatigue-strength coefficient each of the category which is shown in **Table 1** below:

Table 1: AASHTO Category and Fatigue-strength Coefficient [13]

AASHTO Category	Fatigue-strength Coefficient, A (ksi)
A	(not available)
B	1.20E+11
B'	(not available)
C	4.40E+10
D	2.20E+10
E	1.07E+10
E'	3.90E+09

Step 5: Estimation of Type of Distribution

Refer to **Step 4**, since there are no data collection, there are no estimation of distribution need to be done since it provided by the previous research.

Table 2 below shown the estimation of type of distribution that been used in this study

Table 2: Data and Its Type of Distribution [10, 11, 12]

Data	Type of Distribution
Δ, Miner's critical damage accumulation index for resistance of metallic materials	Lognormal
S, Stress range	Rayleigh
m, Material constant	Constant
A, Fatigue-strength coefficient	Lognormal

Step 6: Developing Fatigue Reliability Model (FRM)

In order to develop the FRM using spreadsheet, the formula in **Step 1** until **Step 3** is been used. The data obtained in **Step 4** is been used as data input and the result in **Step 4** is been used as data output of the formula, It also must be determined which data input that need to fixed and which data input need to be vary, according to the scenario that been used in this study.

Step 7: Validate Formula

Formula in **Step 6** is validating by using two research papers. The process involves putting the input obtained in the research papers and if the output is the same as the research papers results, the FRM is validated.

Step 8: Test the Spreadsheet

Step 8 is the same process in **Step 7**.

In this study, it must be assume that the initial number of stress cycles experienced on the surface of steel bridges is fixed at the moment the structures is been installed. The method accounts for closure effects by predicting the occurrences of damage only when the stress cycles start acts on the structures.

When the inspection reveals fatigue cracks, field data in the form of strain measurements can be collected in the vicinity of fracture detail to identify the characteristic and fluctuations of the stress. The data then can be analyzed to identify the statistical properties for the parameter.

3.2 Area of Study

The study explores the possibility of using the structural reliability analysis technique to assess the failure probability for steel structures subjected to fatigue and to be further used in establishing the inspection interval for steel structures. First Order Reliability Method (FORM) model which is based on the reliability index will be employed to estimate the failure probability where the model requires data such as material properties and physical geometric of the steel structures.

3.3 Data Collection

The data collection for this study is very hard to find, provided that steel structure, like steel bridges are built to last for centuries. So in order to get the data needed for this study, the data collected from Z. Zhao, A. Haldar and F. L. Breen Jr. (1994) is been used as a current data collected. By using this data collected and the result obtained from Z. Zhao, A. Haldar and F. L. Breen Jr. (1994) we can validate the formula thus validated the spreadsheet that will be develop at the end of the study.

3.4 Data Analysis

By using two different research papers including Z. Zhao, A. Haldar and F. L. Breen Jr. (1994), we use the data and result in the research papers to validate the spreadsheet. By using two different researches papers will allow the spreadsheet to be validated as practical to be used on any steel structures given the material and design parameter needed in the spreadsheet, like material constant, is been provided.

3.5 Key Milestones

Table 3: Key Milestone

No.	Activities	Date
1	Title selection and identification of problem statement and objectives of study.	Week 1
2	Completion literature review and research methodology.	Week 6
3	Submission of Proposal Defense Report.	Week 7
4	Proposal Defense (Oral presentation).	Week 9
5	Submission of Interim Report.	Week 14
6	Submission of Progress Report.	Week 21
7	Complete the analysis of bridge pier section.	Week 25
8	Submission of draft of dissertation.	Week 26
9	Submission of dissertation.	Week 27-28

3.6 Gantt Chart

Table 4: Gant Chart

NO	ACTIVITIES	WEEK																											
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	Preliminary Research work	■	■	■	■	■																							
2	Extended proposal Defense						■																						
3	Proposal Defense							■	■	■																			
4	Project Work Continues										■	■	■																
5	Submit Interim Draft Report													■															
6	Interim Report														■														
7	Project Work Continues															■	■	■	■	■	■	■							
8	Submit Progress Report																						■						
9	Project Work Continues																							■	■	■			
10	Pre-SEDEX																									■			
11	Submission of Draft Report																										■		
12	Submission of Dissertation																											■	
13	Submission Technical Paper																											■	
14	Oral Presentation																												■
15	Submission of Hardbound																												■

CHAPTER 4
RESULT AND ANALYSIS

4.1 Data Gathering and Analysis

As been stated in **Step 4** from section 3.1 of Chapter 3, the data collection for this study is obtained from Z. Zhao, A. Haldar and F. L. Breen Jr. (1994) as it is really hard to get the real data from steel bridges without huge expenses. By using this research paper, we can validate the formula of the spreadsheet which will be developed at the end of this study.

To validate the formula in the spreadsheet, we will use another research paper which we will then compare the reliability index from the research paper and from the spreadsheet.

4.2 Development of the Fatigue Reliability Model (FRM)

From using the formula and data obtained from Z. Zhao, A. Haldar and F. L. Breen Jr. (1994), the following spreadsheet is been developed as seen from **Figure 8**.

In the spreadsheet there are some certain value or data input that been fixed, which is vary from one steel structures to another according to its application like material constant, m, and number of design stress cycle in service, N_s.

As can be seen from **Figure 8**, there several white boxes which this white boxes is the input that must be enter in order for the spreadsheet to calculate the reliability index. Those white boxes are:

- Mean Stress Range, $\overline{S}$.
- Number of Design Stress Cycle in Service Range, N_s.
- American Association of State Highway and Transportation Officials (AASHTO) Categories.
- Type of Steel Structure.

The **output of the spreadsheet will be the reliability index, β, at mid-lif**e which highlighted in blue box and the graph which span within the range that been put in the number of design stress cycle in service range, N_s. In additional to the reliability index, β, another output also been added to the spreadsheet which is the **number of cycles when reliability index is equal to zero**.

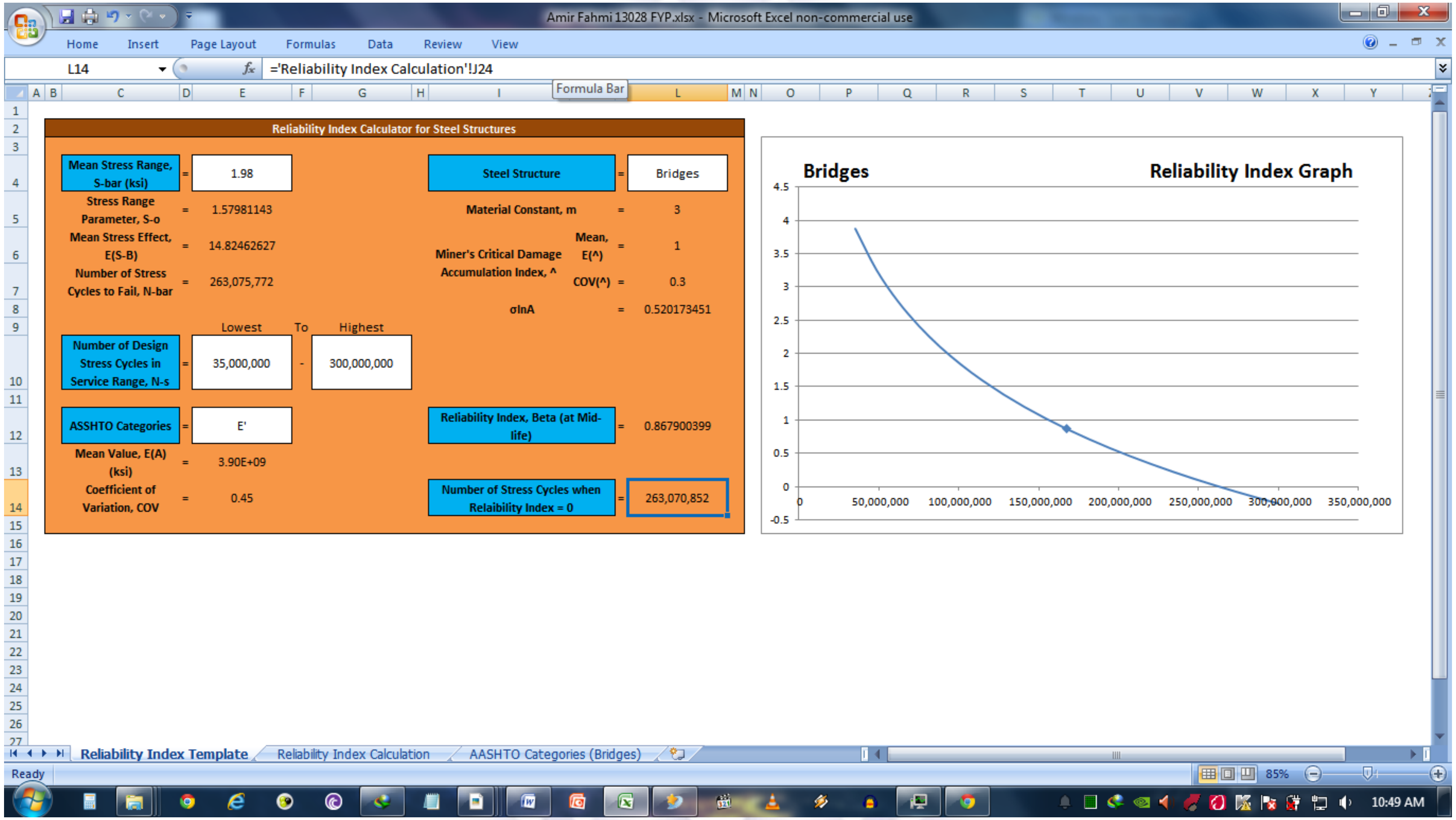

Figure 8: Spreadsheet of the FRM

This is the list of the formula that been used in order to develop the FRM spreadsheet as seen in **Figure 9**:

Table 5: List of Formula in Calculation and in Spreadsheet

Label	Formula in Calculation	Formula as in Spreadsheet
1	$S_0 = \sqrt{\frac{2}{\pi}}\bar{S}$	= (SQRT(2/PI()))*E4
2	$E(S^B) = \left(\sqrt{2}S_0\right)^m \Gamma\left(\frac{m}{2} + 1\right)$	=(((SQRT(2))*E5)^L5)*1.3293
3	$N = \frac{\Delta . A}{E(S^B)}$	=(L6*E13)/E6
4	$\sigma_{\ln N} = \sqrt{\ln\left[\left(1 + COV_A{}^2\right)\left(1 + COV_\Delta{}^2\right)\right]}$	=SQRT(LN((1+(E14^2))*(1+(L7^2))))
5	$\beta = \frac{\ln\left(\frac{N}{N_s}\right)}{\sigma_{\ln N}}$	=((LN(E7/((E10+G10)/2))/L8))

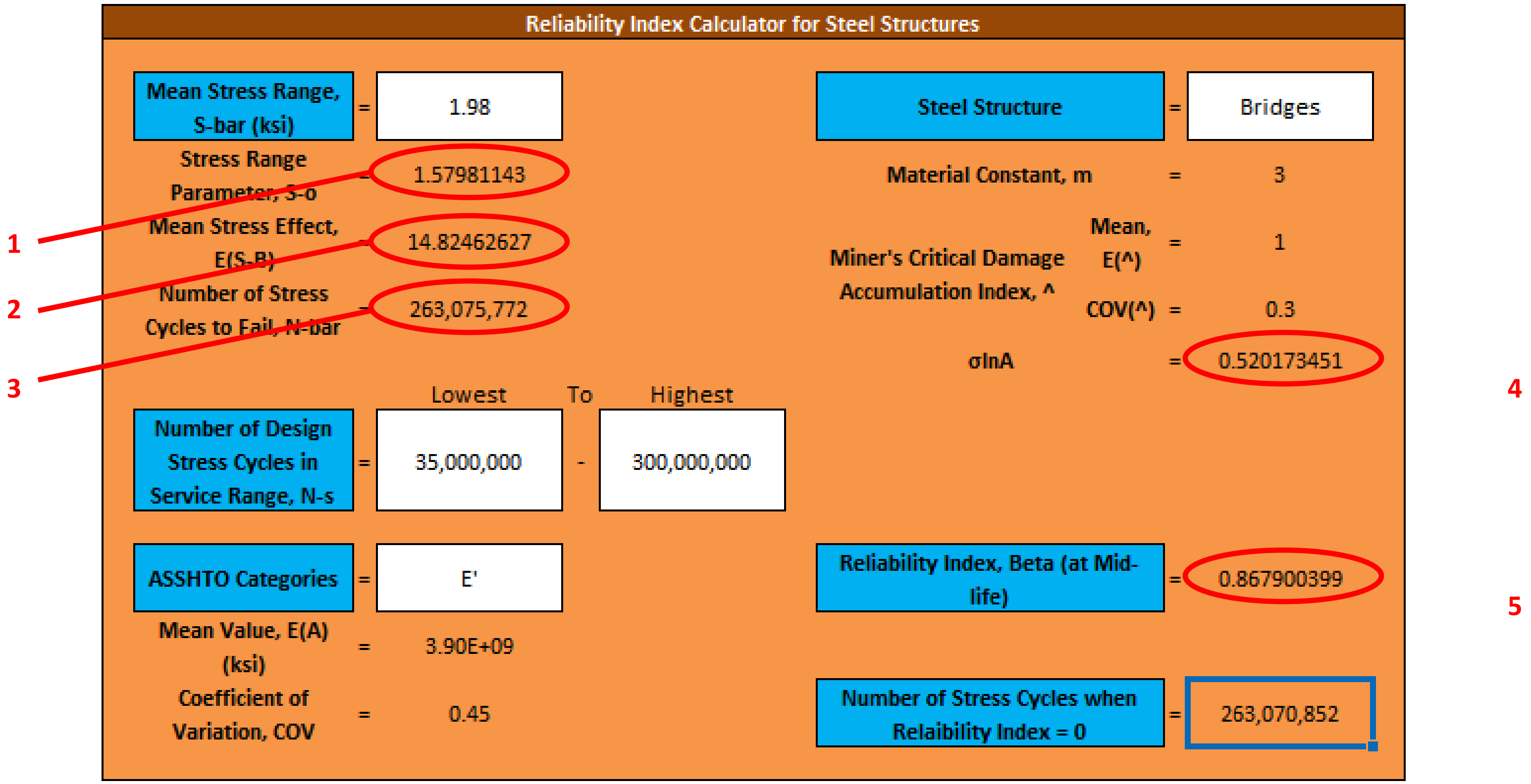

Figure 9: The Reliability Index Calculator with Label

This spreadsheet has been validated using Z. Zhao, A. Haldar and F. L. Breen Jr. (1994) LEFM method. The result from the research paper and the spreadsheet are been compare using graph, as shown in **Figure 10**. The validation proves that the reliability index from the spreadsheet when compare to the reliability index from the research paper have 0%-10% differences in value.

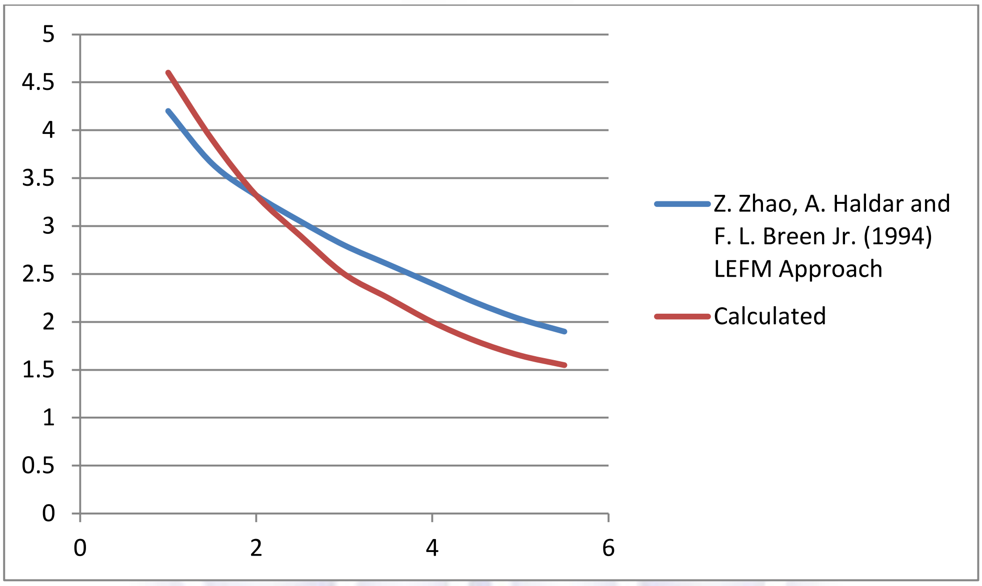

Figure 10: Graph Comparing the Reliability Index from Z. Zhao, A. Haldar and F. L. Breen Jr. (1994) LEFM Method and Reliability Index from the Spreadsheet

This spreadsheet also been validated using another research paper, K. Kwon and D. M. Frangopol (2011), in order to make sure that this spreadsheet can be practically used on any steel bridges, provided that this following data input is known:

- Type of structure (in the spreadsheet is strictly for steel bridges).
- Mean stress range, $\bar{S}$ (lognormal distribution).
- Material constant, m (strictly only metallic structure).
- Number of design stress cycle in service, N_s.
- The bridge's type according to AASHTO.

By using graph, we can easily compare the result from the research paper and the spreadsheet, as shown in **Figure 11**.

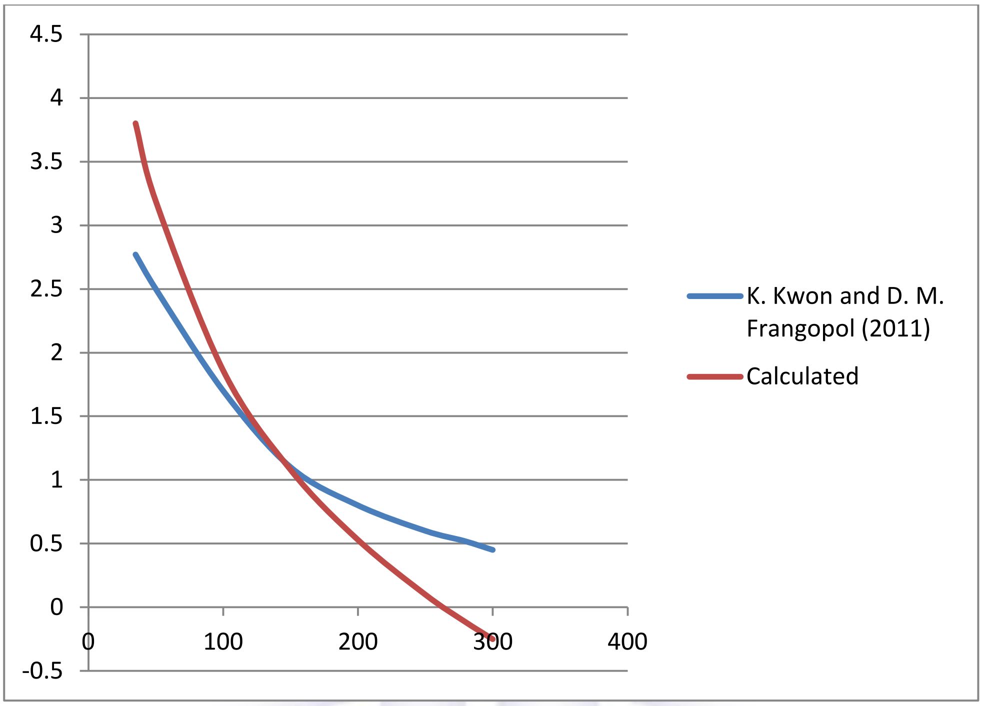

Figure 11: Graph Comparing the Reliability Index from K. Kwon and D. M. Frangopol (2011) and Reliability Index from the Spreadsheet

By using this research paper, the differences between the reliability index of the spreadsheet and the research paper is within 1%-15%.

The significant differences in the reliability index value are due to the spreadsheet **not taking account of the crack growth** within the structures before installment. Due to this crack growth, there are probabilities that the structure will fail first before it reached the useful lifetime as suggested in the spreadsheet or may have longer lifetime than suggested value in the spreadsheet.

CHAPTER 5
RECOMMENDATION AND CONCLUSION

5.1 Relevancy to the Objective

As been stated in section 1.3 of Chapter 1, the objective of this study is to create a Fatigue Reliability Model (FRM) by using spreadsheet-based software via Microsoft Office Excel that can be used to predict the estimation useful lifetime of steel structures in order to predict the suitable time for inspection and maintenance checks on the structures. This objective is been achieved when the FRM is been developed using Microsoft Office Excel software which has been shown in Chapter 4.

The spreadsheet is already been validated using two different research papers which are:

- Z. Zhao, A. Haldar and F. L. Breen Jr. (1994) *Fatigue-Reliability Evaluation of Steel Bridges.*
- K. Kwon and D. M. Frangopol (2011) *Bridge Fatigue Assessment and Management Using Reliability-Based Crack Growth and Probability of Detection Models*.

This validation suggest that the spreadsheet **need to modified** a little bit by adding additional element that is the crack growth model by using **linear-elastic fracture mechanics (LEFM)** so that it can be used in practical inspection and maintenance of any type of American Association of State Highway and Transportation Officials (AASHTO) steel bridges category provided that the data input needed to used the spreadsheet, as per stated in section 4.2 of Chapter 4, is obtained beforehand.

5.2 Recommendation for Future Works

There are several recommendations that can be implementing so that this study can be more practical to be used in field work. Some of the recommendations are:

- Include crack-growth model in the spreadsheet by using LEFM method as per stated in Z. Zhao, A. Haldar and F. L. Breen Jr. (1994).
- Include many material constant and type of structure so that any type of metal structures and application reliability index can be predict thus making the spreadsheet more suitable to be used in practical field works.

5.3 Conclusion

From the developed of the FRM using Microsoft Office Excel software, the study objective is been achieved. The validation using two different research papers make the spreadsheet more reliable to be used in practical field works even though some additional element as per stated in section 5.2 of Chapter 5 need to be implement so that the spreadsheet can be more reliable.

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APPENDIX