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PREDICTING THE ANALYSIS OF FRETTING DAMAGE FOR ADDIS ABABA LIGHT RAIL TRAIN WHEEL SET

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfilment of the Requirements for the Degree of

Masters of Science in Mechanical Engineering (Railway stream)

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Abstract

Fretting in railway transportation results usually on the contact areas (fitting zones) of wheels and axles due to repeated relative oscillatory movement of small amplitude which leads to the formulation of cracks. The wheel seat of the axle is the weak zone for fatigue with the impact of fretting; hence to minimize this, this research deals on the analysis of fretting damages on rail vehicle axles and wheels (wheel set) with respect to the Addis Ababa light train (LRT). The main objective of this research deals with the evaluation of fretting fatigue life of wheel set by using CATIA software for the modelling purpose and finite element analysis (FEA) ANSYS workbench for fatigue life and damage analysis. The results are computed by varying the main causes of fretting that is the influence of the coefficient of friction, slip amplitude, and frequency is observed. Calculation of The main causes for the formation of fretting such as bending stress, tangential force and frequency is done. Based on these results fretting fatigue life of wheel set is observed to decrease at friction coefficients ranging from 0.1 to 0.3.in addition to this it is observed that the fretting life of the axle and wheel assembly decreases with an increase of frequency and slip amplitude ranging from 8.84 Hz up to 200Hz and 5 µm up to 25µm respectively. Finally fretting damage is observed to increase with an increment of coefficient of friction, slip amplitude and frequency by the analysis made mathematically and using ANSYS software; hence this thesis would be applicable and will contribute detail information in our country railway system by reducing failures that arise due to fretting.

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Nomenclature

ASTM	American Society for Testing and Materials
COF	Coefficient of friction
ESIS	European Structural Integrity Society
ERC	Ethiopian rail way corporation
HCF	High cycle fatigue
LCF	Low cycle fatigue
MRFM	Material response fretting map
FEA	Finite element analysis
RH	Relative humidity
RCFM	Running condition fretting map
SWT	Smith Watson topper
TLA	Thin layer activation
UIC	International union of railways
a'	The diameter of the central un slipped region
a	The contact diameter
a	The radius of the contact area
a	Distance between journal center & the end of the wheel seat
a	Semi-width of the contact area
2b	Width of contact strip for a cylindrical pad in contact with a plane.
d	Axle diameter
d	Diameter of wheel seat
f	Frequency

g	Wheel tread distance
G	Center of gravity
h	Height from axle to gravity center
H	Material hardness
j	Distance between journal centers
j & g	Axle dimensions
K	Constant
K	Wear coefficient
L	The fretting amplitude
l	Thickness of wheel
k_1 & *m*	Constants
P	Contact pressure
P	The coefficient of friction;
P	Horizontal force
P	Contact load
P	Maximum contact pressure at the interference
P_o	Maximum contact pressure
q_x	Tangential stress along the ‘x' axis
Q	The superimposed tangential force
q	Notch sensitivity factor
r_w	Wheel radius
r_1	Internal radius of wheel
r_2	External radius of wheel
R_o	Re action force
S	Total sliding distance

S_{fr}	The fretting fatigue strength
S_o	Fatigue strength in the absence of fretting
S	Amplitude of slip
u	Displacement amplitude
V	Wear volume
W	The normal load acting on the contact
x	Distance from the outside wheel hub to the contact load
y	Distance from the inside wheel hub to the contact load
v	Radial interference
ω	Rotational velocity of wheel
α	Wear coefficient
σ_{wf1}	Reduced fatigue limit
σ_{w1}	Initial fatigue limit
σ	Axial bulk stress
τ	Interfacial shear stress
δ	Diametral interference
σ_{wo}	The plain specimen fatigue limit,
$\Delta\sigma_L$	Function of local maximum bulk stress
E_1	Young's modulus of the bulk body
α_v	Vertical acceleration coefficient
α_L	Lateral acceleration
μ	Friction coefficient

Chapter One

1. Introduction

1.1 Background of the study

Fretting is caused by the relative oscillatory movement of small amplitude which may occur between two contact surfaces subjected to mechanical vibration, cyclic loads, stresses, electromagnetic shock etc.it leads to fretting wear or catastrophic fretting fatigue(FF) crack with the presence of cyclic bulk fatigue loading under one of the contacting surfaces.

It is a surface damage phenomenon that occurs in a wide range of industries such as offshore oil and gas, biomedical and aerospace. In numerous engineering applications, this damage occurs at size scales competitive with the material microstructure, e.g. 5 to 100μm three main sliding regimes are commonly associated with fretting, namely, partial, gross and mixed slip, Primarily dependent on normal load, displacement amplitude and coefficient of friction (COF) . Fretting is a phenomenon that occurs in a wide range of mechanical assemblies such as osteosynthesis plates and screws bolted and riveted joints, steel wires, blade-disc dovetail connections and splined couplings in gas turbine engines. [1]

Fretting occurs wherever short amplitude reciprocating sliding between contacting surfaces is sustained for a large number of cycles.it results in two forms of damage: surface wear and deterioration of fatigue life. The extent of wear and surface damage is much greater than suggested by the magnitude of sliding distance.

Small sliding amplitude encourages wear particles to remain in the immediate contact region which the characteristic difference between fretting and large amplitude or one way is sliding. The upper limit of amplitude for characteristic fretting has not been found, though the wear rate may increase at amplitudes above 70μm, and the nature and colour of wear debris seem to change at amplitude above about 100μm. the actual limit may be connected with diameter of the microscopic areas of contact.

Fretting also is a contact damage process due to oscillatory micro-slip that occurs between machine components subjected to a clamping pressure and vibratory excitation or an oscillatory tangential force. Fretting damage can be classified into fretting fatigue, fretting wear and fretting corrosion. Fretting fatigue is associated with partial slip contact conditions, where the contact area between the components in contact consists of a stick region in between slip regions.[2,12]

But most importantly my focus will be on fretting fatigue and fretting wear such that:

1. Fretting induced wear (FIW), this kind of wear involves small cyclic displacements as a result of contact alone. The associated production of debris leads to a loss of fit between contacting surfaces.

2. Fretting induced fatigue (FIF), rapid crack nucleation and propagation to shorten the service life of components greatly. This happens in the presence of bulk fatigue load.

Fretting wear modes can be

- Tangential fretting wear
- Rotational fretting wear
- Radial fretting wear
- Torsional fretting wear

There are also various phases of fretting wears .the figure given below shows the different phases.

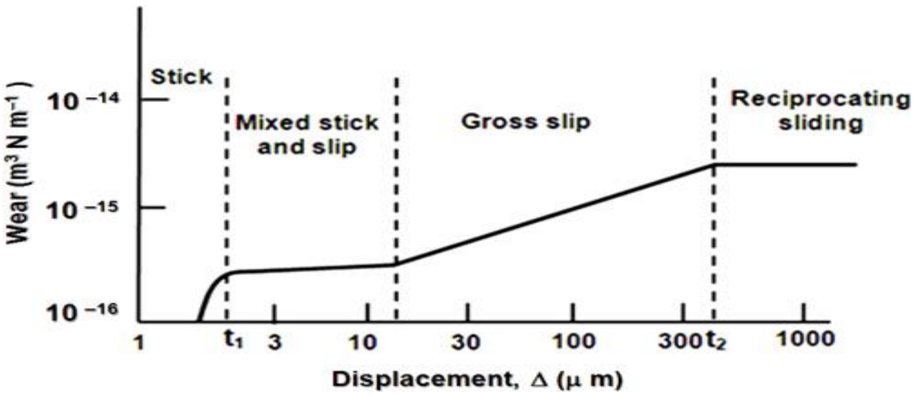


Figure 1.1 process in fretting wear [13]

Surveys reveal that, unlike other forms of wear ,the incidence of fretting problems in machinery has not declined over the past decade .fretting fatigue remains an important but largely unknown factor in the fracture of load bearing components at very low levels of stress.

The fundamental characteristic of fretting is the very small amplitude of sliding which dictates the unique features of this wear mechanism. Under certain conditions of normal and tangential load applied to the contact a microscopic movement within the contact takes place even without gross sliding.one of the characteristic features of fretting is that the wear debris produced are often retained within the contact due to small amplitude sliding. The accumulating wear debris gradually separates both surfaces and, in some cases, may contribute to the acceleration of the wear process by abrasion. The process of fretting wear can be further accelerated by corrosion, temperature and other effects.

Fretting fatigue as well is described as the progressive damage to a solid surface that arises from fretting. Fretting may produce several forms of damage on the faying (contacting) surface. The cause of fretting damage production has been investigated and explained by a number of investigators. A commonly accepted view is that the first stage of fretting is adhesive contact of the asperities on opposing contact surfaces (this is supported by an increase in the coefficient of friction).These adhesive contacts are important as they are often thought to be the mechanism by which the majority of the cracks are nucleated. After this stage several things might occur: breakage of the asperities which causes production of fretting debris, oxidation/corrosion of "fresh surface" (which might cause pits on the contacting surfaces) and/or debris. These damages then accelerate the crack nucleation stage of fatigue. Cracks that nucleate may propagate at various rates and angels to the contacting surfaces and cause premature fatigue failure. The aforementioned stages are dependent on many different variables such as material, stress state, and environment, relative slip amplitude, and contact pressure. In general, fretting may result in the following forms of damage.[3]

- Pits
- Oxide and debris(third body)
- Scratches
- Material transfer
- Surface plasticity
- Subsurface cracking and/or voids
- Fretting craters
- Cracks at various angles to the surface

- **Fretting damage in case of wheel & axle interference fit**

An axle is one of the most important components of rail vehicle which transmits the weight of the vehicle to the wheels, meets the vertical and horizontal loads formed during static and dynamic moving, and carries driving moment and braking moment.

Each axle is used with a wheel press fitted to each of the two wheel sets, the larger diameter portions near both ends of the axle (the axle press fitted with wheels is called a wheel set).unless otherwise specified by the client, the interference for wheel press -fitting (i.e. difference between wheel seat diameter and hub bore diameter) is so controlled that the press-fitting ratio(i.e,ratio of press-fitting interference to axle diameter)becomes1.4/1,000 for standard and 1.5/1,000 for maximum.as a result, the nominal contact pressure between the axle and wheel is 50-70Mpa .when fretting continues for a long period of time ,a brown powder called cocoa gradually accumulates at the contact surfaces, from which the powder is then partly discharged. The phenomenon is called fretting corrosion. Since fretting causes the wear to progress and the fatigue strength to decline, the damage induced by fretting is called fretting damage.[4]

1.2 Statement of the problem

Now a days rail way transportation system is becoming popular in terms of cost and long life operation all over the world including Ethiopia; hence the transportation system should be free of risks that arise due to component failures such as wheel sets.one of the major problems that lead to axle-wheel assembly (wheel set) failures is fretting damage; which leads to rapid crack nucleation and propagation.

Due to this damage axles and wheels may become susceptible to cracks and this become a hole disaster leading the rail vehicles to derailment and destruction as a hole.so before this kind of damage happens detail researches must be done especially in Ethiopia since our country is introducing this technology. So the main questions that may be raised are:

- What are the main sources of fretting damage?
- What kinds of forces lead to the formation of fretting?
- The consequences of fretting damage?
- How is fretting damage minimized?
- Its benefit to Ethiopian Rail way system?

Therefore; to answer such kinds of questions this research is conducted especially with the Ethiopian railway system context.

1.3 The objective of the study

1.3.1 General objective

The general objective of the study is to analyze fretting damages on the axle -wheel assembly (wheel set) of rail way light trains so that the fatigue life is evaluated by varying the coefficient of friction ,frequency and slip amplitude especially for Addis Ababa city tram, making simulation by using CATIA, and ANSYS software's so as to see the effect of the bending stress on the contacting surfaces of axle-wheel fits, and evaluate the fretting fatigue life by varying these parameters and hence set a mechanism on how to minimize their effects with respect to Addis Ababa light vehicle tram.

1.3.2 Specific objective

- 3-D Modeling of rail, axle & wheel by using CATIA, and simulating the results by using ANSYS software.
- Analyzing the effects of loading condition (tangential force and bending stress), amplitude, frequency & friction on the fretting fatigue strength of the wheel set.
- Evaluation of fatigue life, fatigue sensitivity, and damage of wheel set
- Comparing the effects of friction coefficient, slip amplitude and frequency on the fretting fatigue strength of wheel set mathematically and using ANSYS as well Mat lab software's.

1.4 Significance of the study

Failure of axles leads the train to derail, this is due to the cracks formed at the wheel-axle interference fits which are caused by fretting damages.so minimizing fretting would be the most valuable solution to such kind of failures, hence this study will help to minimize fretting damages especially in Addis Ababa light trains and further to Ethiopian future railway system being as a guide for further researches.

1.5 Scope of the study

Fretting damage in railway wheel set does not only occur in the interference fits of axle-wheel assembly; however it also exists in gear seat ,disc brakes, journals and other contacting points having similar mechanism of occurrence as that of axle and wheel interference fits.in this thesis fretting damage in axle and wheel interference fits is covered. Similarly fretting wear and fretting corrosion occur to some extent in this fitting zone, so due to shortage of appropriate software, these two forms of fretting are dealt only theoretically as they are mentioned to be done in the future works.in addition to this due to shortage of experimental equipment's laboratory work is not done.

1.6 Organization of the study

This thesis is organized in to six chapters. In the first chapter, background and justification of this thesis work and the objectives to be achieved are discussed. In chapter two, a review of literature relevant to this thesis work, which has been investigated by different researchers, is given. Chapter three deals with the general concepts of fretting damage in railway wheel set and the methodologies used for conducting this thesis. In chapter four, mathematical models are used to predict the fretting fatigue strength of wheel set and CATIA software is used to develop the model, as well finite element analysis is done in ANSYS workbench. This chapter also presents detailed information about the analysis of fretting damage in wheel sets under different working conditions. In chapter five results of the analysis are summarized and discussions are made based on the outputs of mathematical, mat lab and FEM analysis. Finally, chapter six gives conclusion, recommendation, and propose future work with respect to this field of study.

Chapter Two

2. Literature review

Fretting is a phenomenon which is caused by the relative oscillatory movement of small amplitude which may occur between two contact surfaces subjected to mechanical vibration, cyclic loads, stresses, electromagnetic shock etc.it leads to fretting wear or catastrophic fretting fatigue(FF) crack with the presence of cyclic bulk fatigue loading under one of the contacting surfaces.

All failures induced by fretting can be generally called fretting damage. As one type of important in-service generated structure failure, fretting damage has been discovered and disclosed in many industries since the beginning of the 20th century. Today, it is well known that fretting can lead to severe material surface wear, which is frequently accompanied by corrosion, thus further speeding up the wear process. On the other hand, it is also widely accepted that fretting can significantly degrade local fatigue strength, resulting in an important reduction in high-cycle fatigue (HCF) life. As a matter of fact, the extensive presence of fretting damage in a variety of mechanical and structural components has become one of the major root causes of these structural failures, especially to those critical components in high-tech applications, such as aerospace, energy, and bio-medical engineering, and thus fretting damage is regarded as a “plague” in these industries (Zhou, 2002). Due to the growing concern about such problems, investigations on fretting damage have been carried out widely in industry and there has been a large amount of research into related areas over the past decades.

The early history of fretting studies can be traced back to 1911 (Eden et al., 1911) [5] followed by the first systematic experimental investigation of the fretting wear process conducted by Tomlinson (1927). However, it was not until 1969 that the first review appeared (Campbell, 1969). Thereafter, several review papers (Hurricks, 1970; Waterhouse et al., 1969, 1984, 1992) were published in the open literature, which provide summaries of the state of knowledge at various periods. Up to now, there are mainly two monographs in the English literature, exclusively addressing the fretting subject (Waterhouse, 1972; Hills and Nowell, 1994). In addition, several international symposia were organized over the past 30 years by ESIS (European Structural Integrity Society) and ASTM (American Society for Testing and Materials) to summarize the advances in fretting research (Waterhouse et al., 1981, 1992, 1994; Hoeppner et al., 2000, 2003). Overall, the substantial progress of fretting studies was quite slow before the 1980s, mainly due to the limitations of experimental facilities and computational methods. Indeed, the majority of the research papers on fretting was published in the last 20 years, and fretting has become a very active research area in recent years.[7]

Ekberg (2004) [6] provided an overview of different types of numerical models available to predict fretting fatigue and outlined a numerical model for analysis of fretting fatigue in a finite element simulation of the assembly. Vinder and Leidich in 2009 introduced new energy-based approach for predicting fretting fatigue and applied it for key shaft hub connections. Alfredsson (2009) simulated the fretting fatigue phenomena in a shrink-fit pin subjected to rotating bending using finite element method, and studied the risk of fretting fatigue by the means of two fretting fatigue criteria. In 2011 Lanoue et al. Calculated fretting fatigue strength reduction factor for interference fits based on a comparison between experimental data and finite element analysis for many configurations of interference fits in rotating bending and alternated torsion.

In 1927 Tomlinson determined fretting to be the cause of rusting of steel surfaces in relative motion at their common points of contact. He suggested that the damage was a result of molecular cohesion between the surfaces and noted that it could be observed even when the relative displacement was as small as 2nm.later Tomlinson, Thorpe, and Gough investigated the fretting corrosion of closely fitting surfaces and suggested that the corrosion was mechanical rather than chemical in character. They decided that some surface slip, alternating in direction, was a necessary condition to cause damage [7].

(Swalla and Neu, 2003) [8] Stated that the friction coefficient has a large impact to fretting damage prediction. They performed fretting fatigue experiments and elastic/plastic finite element analysis. With a model of their fretting fatigue test rig, a material behaviour model of stainless steel and multiracial fatigue parameters they correlated experiments and computations changing the friction coefficient between 0.75 and 1.5. For them a value of 1.5 for the slip zone friction coefficient, which is 2.5 times higher than the measured mean value, gave the best results in fatigue prediction.

Fretting in railway axles was reported by Maxwell et al. In 1967, yet remains a cause for concern over thirty years later. For obvious reasons, fretting fatigue is particularly important in safety-critical industries such as aerospace or nuclear power generation. The recent High Cycle Fatigue (HCF) initiative in the USA has provided a focus for fretting research in the aerospace sector, particularly in aircraft engine applications. Here there are a number of important contact features which may suffer fretting fatigue. These include the ‘dovetail’ roots of compressor blades (Nowell,), where failure may have serious consequences for engine integrity (Xi *et al*.)[9].

Szolwinski & Farris examined fretting fatigue experimentally and analytically using a ‘factorial design’ procedure. The parameters varied were the normal (contact) load, the radius of the contact pad, the bulk stress and the ratio of applied tangential force to bulk axial load. Due to the Hertzian contact conditions, the (‘quasi–uniaxial’) tangential stress in the surface at the edge of the contact between the cylinder and the plane could be evaluated by an analytical procedure [10]. This stress and pertinent strains evaluated under the assumption of elastic conditions were then introduced in the Smith–Watson–Topper criterion, equation*)*. Material parameters where taken from the literature. The criterion provided a reasonable accuracy up to the yield limit.

Churchman and Hills (2006) considered in detail the problem of a square block on an elastically similar half-plane and subjected to fretting loading. They developed a general interfacial characteristics map for the case of a monotonically increasing shear load and then an oscillatory shear load. They also employed wedge asymptotes extensively to complement finite element analysis in order to add detail at the edge of a complete contact. This problem was also considered independently by Bohorquez and Dominguez (2005) with more emphasis on the finite element analysis to determine the behaviour of the contact [11].

In a study of a 0.7% carbon steel Waterhose and Taylor [7] concluded that the origin of fatigue cracks in fretting fatigue is the boundary between the slip and non-slip areas in the contact region. They arise at this boundary because of the high stress concentration. When a crack is formed it relives the stress concentration at this point and the boundary between the slip and non–slip areas moves inwards resulting in the initiation of another crack which propagates more rapidly than the first crack because of the higher stress concentration. They suggest that crack formation can be prevented or retarded by insuring that slip occurs over the entire contact region.

Cortez et al [12], performed an investigation on the impact of high frequency vs low frequency fretting load. This was mainly evident for long fatigue lives. The shorter fatigue life for the high frequency load case was attributed to a higher degree of surface damage which was contributed to the high-frequency rubbing. Further, localized heating was suggested as an additional reason for the different fatigue lives. Fatigue lives at varying frequencies and load amplitudes were stated to correlate reasonable well to predictions of Palmgren-Miner’s law although it is not fully clear how damage has been evaluated for the different load cycles.

A number of different terminologies have been used widely in this literature, including fretting, fretting wear, fretting fatigue, fretting corrosion, rubbing fretting, impact fretting, impact-slide fretting, to name the most common. In view of this situation, it has been suggested to use the term “fretting” only as a general term to cover all aspects of the related phenomena (Smith, 1998). Despite the multiformity of the definition, the fundamental characteristics of fretting are consistent: Fretting phenomena are induced by the minute relative movement between two contacting interfaces. They occur most frequently among tightly fitting contact surfaces that undergo minute relative movement produced by oscillating forces. The amplitudes of fretting slip are usually as small as the order of µm (even with sliding amplitudes of less than 1µm).

In some cases, fretting could also be the consequence of the contacted members subjected to an external cyclic force or a static tensile stress while being under heavy transverse loads (pressure).fretting phenomena in real situations are very complicated and difficult to analyse. However, according to the types of relative movements, there are four types of fundamental fretting movement modes (Zhou, 2002)[13], as shown schematically in Figure 2.1: (a) tangential, (b) radial, (c) rotational, and (d) torsional fretting. It should be noted that, although the last three modes also often occur in reality, most of the studies have been focused on the first mode so that the term “fretting” usually just refers to tangential fretting in this literature. In addition, little attention has been paid to more complex situations, such as two or more fretting movement modes mixed together, or fretting movement combined with other movements.[5]

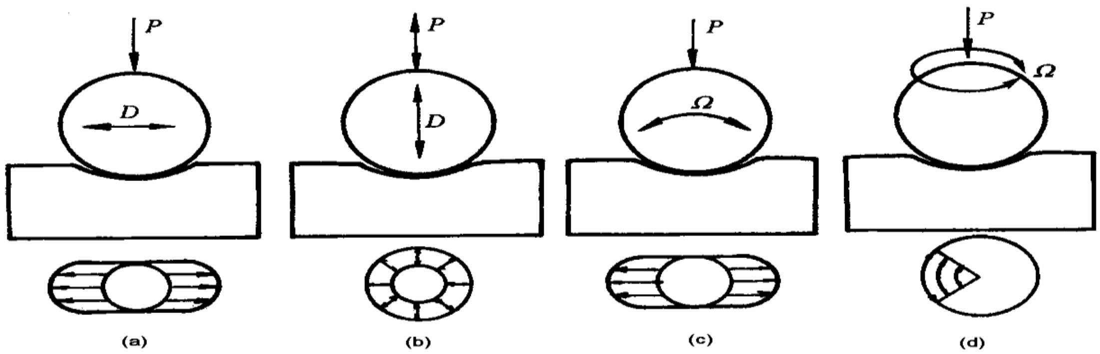


Figure 2.1 fretting movement modes (Zhou, 2002) [5]

A mechanism of fretting based on the mechanism of wear was suggested by Freng and Rightmire according to this proposal, when contacting asperities carry a normal load great enough to cause plastic deformation, the interface of asperities will be roughened by the deformation. This roughening of the interface produces a mechanical interlocking effect and application of a tangential force would shear off the peak of a high spot, which would then become a loose wear particle.

The process then continues through a period during which the accumulation of wear particles shift the wear action to abrasive action.

There were various studies conducted with regard to the mechanisms of fretting fatigue some of them are:

Based on an analysis of experimental results,Liu,Corten, and Sinclair suggested that the primary mechanism responsible for damage was the repeated frictional shear stress on the asperities or surface 'high spots' which were in contact. Based on prevention of fatigue crack initiation by this mechanism, a mathematical expression was proposed which relates the fretting fatigue strength to the fatigue limit of the specimen, the hardness of the gripping material, and the coefficient of friction.

Yamamoto et al, conclude that, for induction hardened press-fitted wheel–axle assemblies, fatigue initiation (defined as a 30 μm crack) occurred at an accumulated Palmgren Miner damage of less than one. The minimum value of accumulated damage for which fretting fatigue occurred was 0.03 to 0.05mm. The decrease was unaffected by the order of loading (i.e. low–high or high–low).[13]

Szolwinski & Farris, studied the crack morphology. From theoretical evaluations of the stress field below the contact it was concluded that the contact stress will only influence crack growth to a depth of **a** to **2a** below the surface. Here **a** is the semi-axis of the contact between a cylinder and a plane. Based on this finding, initiation was, under current conditions, defined as the formation of a 1 mm crack. Below that length, propagation was assumed to be driven by the bulk stress stemming from the global tension and was evaluated theoretically using Paris law. The estimated propagation life was found to be some 10–15% of the experimentally found (total) fatigue life.

More recent studies have indicated an increase in fretting life for smaller radii in rounded flat specimens. Ciavarella & Demelio, further analysed this phenomenon by analytical modelling. It was demonstrated that for an "almost flat" geometry, the surface damage parameters (in terms of micro displacements) decreases whereas the tensile stress increases and becomes more localized. The analysis was carried out for cases of elastically similar half-planes (an exact definition of this concept is presented in textbook on classic Hertzian theory, such as Johnson,). The localization of the tensile stresses indicates high likelihood for self-arrest of small cracks initiated in the vicinity of the contact.in their study they raised the following points to be the main causes of fretting.[13]

- Contact pressure (normal load),
- Coefficient of friction (COF),
- Slip amplitude.

2.1 Limitations

Although fretting damage in railway axle-wheel assembly is rarely investigated by most researchers until now; in some of the literatures and journals that are reviewed it was not clearly identified on how to minimize fretting damages and the methodology used for the prediction of the fatigue life varies accordingly. In addition to this almost all journals used experimental fretting damage measurement, this is so coasty and time consuming. Similarly some researchers used very complex mathematical Modell that is so difficult for other interested person (researcher) to understand. Hence in this exploratory type thesis ;even though this is a new technology and concept for our country all the mechanisms that minimize the occurrence of fretting damage are mentioned and analytical model is developed and the fatigue life is evaluated by using ANSYS software considering friction coefficient, slip amplitude and frequency as the major varying parameters.

2.2 Summary

Life prediction of engineering components subjected to fretting damage appears to have advanced, but certain aspects of the mechanism of fretting are still not thoroughly understood.in a study about different practical cases where fretting fatigue arise (e.g. propeller hub/drive,axle-wheel assembly ,shaft flange assembly of aircraft engine, gas turbine disc/shaft connection, etc.) it is shown that even much progress has been done in the last years in both understanding and design for fretting damage, prevention and control, “much remains to be done”.

Generally fretting damage in railway wheel set is rarely investigated by most researchers however, based on these related researches this study focuses on the current Ethiopian railway corporation system so that prediction of wheel set fretting damage analysis is done such that the main technical specifications are done specifically with regard to the current Addis Ababa light rail train.

Chapter Three

3. Basic concepts and methodology for modelling fretting damage in railway wheel set

3.1 Introduction

Fretting is the small-amplitude oscillatory movement that may occur between contacting surfaces, which are usually nominally at rest. One of the immediate consequences of the process in normal atmospheric conditions is the production of oxide debris; hence the term "fretting wear" or "fretting corrosion" is applied to the phenomenon. The movement is usually the result of external vibration, but in many cases it is the consequence of one of the members of the contact being subjected to a cyclic stress (that is, fatigue), which gives rise to another and usually more damaging aspect of fretting, namely the early initiation of fatigue cracks. This is termed "fretting fatigue" or "contact fatigue." Fatigue cracks may also be initiated where the contacting surfaces are under a very heavy normal load or where there is a static tensile stress in one of the surfaces. There are cases where the movement is not simply tangential, but is complicated by the normal force also oscillating to the extent that the surfaces lose contact in each cycle. This leads to a hammering effect, which is termed “impact fatigue." In this case, the phase relationship between the two motions can be an important factor.[5]

3.2 Methodology of the study

There are three basic forms of models: word, pictorial, and mathematical. Word models are descriptions of phenomena or behaviour of materials. Pictorial models are sketches and/or a series of sketches describing the functioning of some device or phenomenon. Mathematical models are equations that simulate, or describe the response of, some entity of unknown internal composition to some input variable.so in this thesis all the modelling aspects are used interchangeably and generally the following methods are used for the study.

- Literature review.
- Data collection.
- Mathematical modeling

- Data analysis
- Result and discussion
- Recommendation , conclusion and future works

3.2.1 Data collection

The following data's are collected from the ERC of the Addis Ababa tram for the purpose of the numerical modelling.

3.2.1.1 Bogie type (7SKD870006)

Bogies under the vehicle have two versions: 2x edge and 2x central. Edge bogies are loaded by forces of max. 9,660 kg per bogie whereas central bogie are loaded by 13,730 kg per bogie (at fully occupied vehicle). These two versions of bogie differ from each other by the rigidity of their springs of the secondary spring loading design.[14]

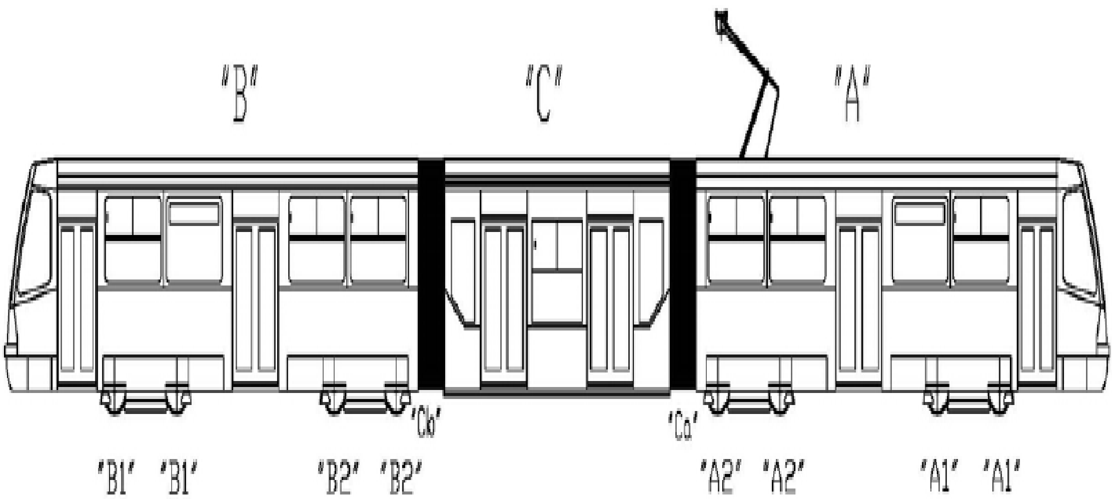


Figure 3.1 Addis Ababa tram bogie arrangement [14]

Table 3.1: ERC specification of the Addis Ababa tram [14]

	"B1"	"B2"	"A2"	"A1"
Axle-load unladen tram[KN]	47.276	51.228	49.785	50.115
Axle- load by 8 standees/m^2[KN]	74.431	89.097	90.006	70.060
Axle- load by 5 standees/m^2[KN]	65.697	77.631	77.497	64.432
Total weight of the tram unladen[t]	40.4			
Total weight of the tram 8 standees/m^2 [t]	66.0			
Total weight of the tram 5 standees/m^2 [t]	58.2			

Table 3.2: values of vertical and lateral acceleration coefficients at different speeds [15]

s.no	Speed(km/hr)	Comfort index Wz	
		Vertical (α_v)	Lateral(α_L)
1	40	1.09	1.37
2	50	1.24	1.74
3	60	1.31	2.15
4	70	1.31	2.04
5	80	1.36	1.96
6	90	1.37	1.83
7	100	1.36	1.56

As we can see from **table 3.2** various comfort indexes are given for different speeds for a meter gauge bogie. But the comfort index is most importantly dependent on the frequency not on the gauge so the operating frequency of calculated for this type of bogie is from 0.1 to 10Hz.Due to this similar assumption is made since the working frequency for the case of this thesis work i.e (1435) type bogie is 8.84 Hz this is applicable as the human beings are most sensitive in the frequency range 4 to 12.5 Hz [38].

3.2.1.2 Technical specification of the tram

Table 3.3: specifications of the light train of Addis Ababa tram [14]

Guage (mm)	**Maximum speed (km/hr)**	**Minimum radius(18m in depot with out load(m)**	**Length of vehicle With couplers(mm)**	**Width of vehicle(mm)**	**Heihgt of vehicle(mm)**	**Height of the coupler(mm)**	**Axle formula**	**Diameter of wheels(mm)**	**Maximum axle load (8 passangers /m^2 load) (KN)**	**Number of passangers (5 passangers /m^2 load)**
1435	70	20	34470	2200	3742	500	Bo'Bo'Bo'Bo'	700 / 610	90	236

3.2.2 Mathematical modelling

In this portion various equations are formulated for the purpose of data analysis so as the results obtained are used as the main inputs for the purpose of software correlations such as ANSYS.However due to scarcity of laboratory equipment's, this thesis lacks verification of results practically as that of laboratory works.

3.3 General Concepts of Fretting Damage in Railway Wheel set

3.3.1 Categories of Fretting Damage

Although there are many nuances in the definitions of fretting phenomena, and no matter how they are labelled and whatever specific investigations were conducted, most fretting damage studies fall into three categories: **fretting fatigue**, **fretting wear**, and **fretting corrosion**. In addition, it should be mentioned that, due to the close association between fretting wear and fretting corrosion, studies of fretting wear have traditionally been called "fretting corrosion" especially in the early days of fretting studies. Many fretting fatigue studies have also been frequently addressed using this terminology.

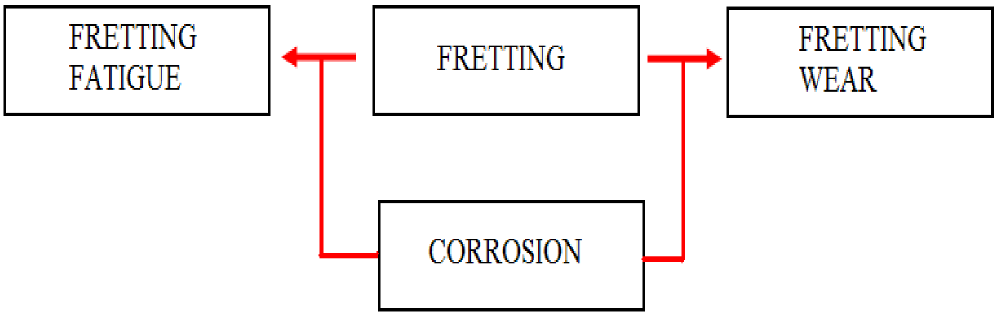


Figure 3.2: types of fretting damage [28]

3.3.2 Fretting fatigue

Another and usually more damaging aspect of fretting is fretting fatigue. Numerous field experiences and experimental reports have disclosed that the initiation of fretting cracks and their rapid propagation could significantly degrade local fatigue strength, resulting in a severe reduction in high-cycle fatigue (HCF) life. Therefore, from the perspective of structural durability, the danger and detrimental effects of fretting fatigue are much beyond the other two types of fretting damage.

Fretting is an insidious type of damage that is the result of the interactions between wear and corrosion. This phenomenon is most commonly witnessed between contacting surfaces that experience small amplitude oscillatory loads. These loads can be induced via vibrations or nearly any variety of mechanical force(s).The strain associated with cyclic fatigue forces creates ideal circumstances in which fretting can occur. Fretting fatigue is a particularly vexing issue as the damage caused by fretting is often responsible for the early nucleation of Fatigue cracks.[20]

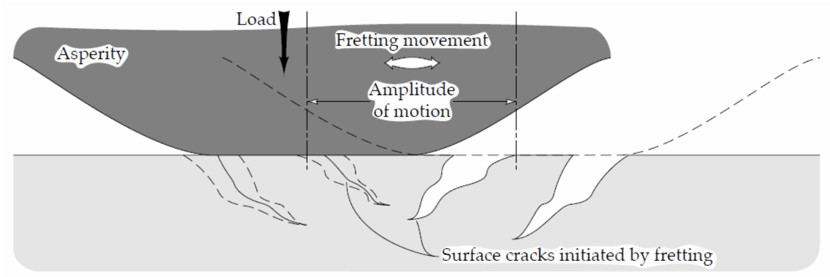


Figure 3.3: physical modelling of fretting fatigue [20]

Compared with other types of fatigue, the most distinctive feature of fretting fatigue is the involvement of complicated tribological phenomena so that fretting fatigue sometimes is also called contact fatigue. From the viewpoint of contact mechanics, fretting friction is much more complex than common sliding and rolling frictions due to the occurrences of “partial slip contact” status, accompanied by local plasticity at the edge-of-contact area, and the third body layer (wear debris) between contacting surfaces. From the viewpoint of fatigue, as opposed to conventional low-cycle fatigue (LCF) failures (less than 10^5 cycles), fretting fatigue is generally associated with high-cycle fatigue (HCF) failure (greater than 10^6 cycles), as well as LCF-HCF interactions (Gallagher et al., 2001).

In addition, different from fretting wear investigations, fretting fatigue research typically uses the approaches of applied mechanics to study the initiation and propagation of fretting cracks, estimate fretting fatigue life reduction, and develop means to mitigate fretting fatigue. In the literature in this field, there are more “parametric studies” than “modelling studies”. That is to say, the majority of this literature addresses the effects of various factors on fretting fatigue, such as fretting slip amplitude, normal load, shear load, plasticity, pre-stress, external tangential force frequency, tangential contact stiffness, contact mode, contact surface quality, material properties, coefficient of friction, elevated temperature, oxidation, wear debris, stress field effects, geometry effects, and so on. Relatively much less research has focused on the development of methodologies to model fretting fatigue damage.[15]

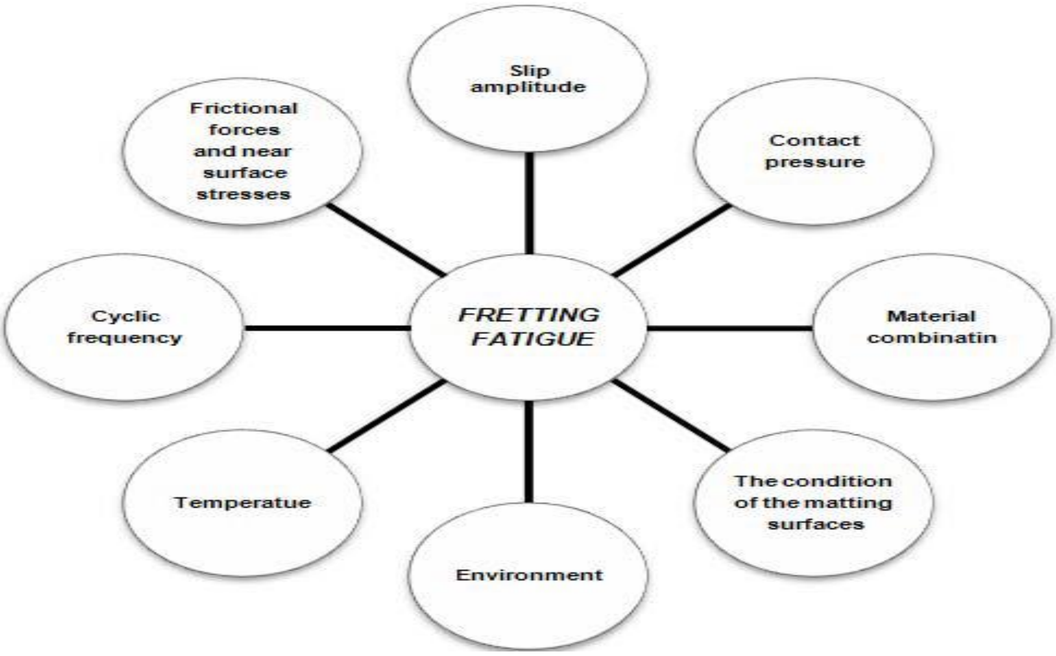


Figure 3.4: interrelated factors that influence fretting fatigue phenomena [28]

Fretting fatigue is a common form of fretting damage as the majority of contact problems experience a variety of complex loading situations and are at some point subjected to fatigue loading. The term fretting fatigue is used to describe a situation where a reduction in the plain fatigue life of a material is explained by the relative slip between two or more contacting bodies. Fretting fatigue is present in a wide number of industries and is a major concern in critical engineering situations such as cable transportation, aerospace and railway. Extensive modelling has been carried out by several groups in an attempt to (i) characterise the controlling parameters in fretting fatigue, as well as (ii) investigate the reduction in life compared to plain fatigue testing, (iii) implement life prediction methodologies and (iv) investigate the effect of microstructural modelling. [13]

Since fatigue is closely related to fretting fatigue, many fatigue methodologies have been implemented within the context of fretting fatigue prediction. Lykins et al.investigated a number of fatigue methodologies and compared the predictions against experimentally obtained data. The main parameters evaluated within the context of this work were SWT, and the Ruiz parameter, as the formulas will be discussed in detail in chapter (4).

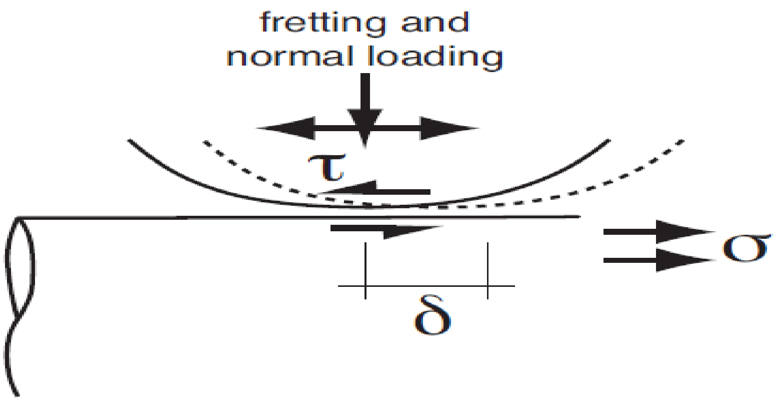


Figure 3.5: Parameters involved in fretting fatigue [6]

It was concluded that (**τδ**) was ineffective at predicting the numbers of cycles to crack initiation but did predict crack locations that were reasonably consistent with experimental results. Other fatigue parameters such as SWT have been found to be more effective at predicting initiation lives. For example, Araujo and Nowell [16] evaluated two critical plane implementations of SWT under a variety of contact pad radii to investigate contact size effects.This parameter predicted accurate results for the large pad radii but overly conservative lives for the smaller pad radius.

A limitation of this fatigue parameter however is its inability to capture the stress gradient effects. For that reason two averaging methods were implemented, namely critical depth and critical volume. Averaging methods hypothesise that a critical volume or depth of highly stressed material must be achieved before fatigue cracks initiate.

Fatigue parameters are used to determine the location of initiation sites and subsequent averaging methods are thus applied at this region. The analytically determined location, at the trailing edge, correlates well with the experimental observations. Within the work of Araujo and Nowell both averaging methods resulted in more accurate life predictions. Similar work is presented by Naboulsi and Mall [16] which corroborates the use of these fatigue parameters within fretting fatigue situations for crack location and life prediction. As it is mentioned above, most fretting fatigue situations occur under complex loading scenarios, it is difficult to apply methodologies evaluated on simple geometries or simplified test rigs to real-life service components.

Houghton et al. [17] used the back calculated SWT parameter to locate and quantify crack nucleation in a representative fretting fatigue test, designed to mimic the complex fretting condition between aero engine spline teeth under combined torque and rotating bending moment. The El Haddad correction with the Paris crack growth equation, incorporating mixed mode fracture via a weight function method, was subsequently employed to simulate crack propagation through the substrate. The predicted and experimental fretting fatigue results correlated with each other.

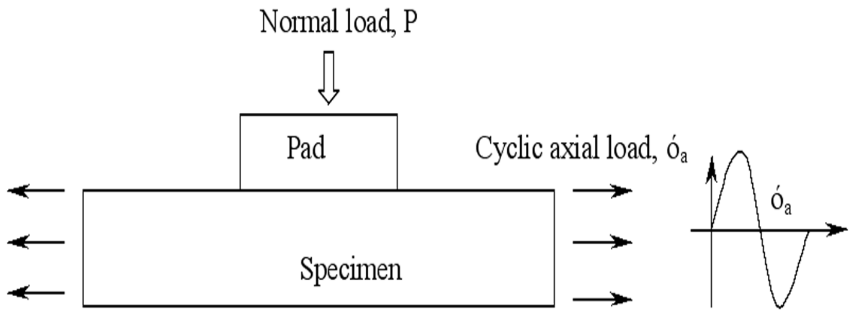


Figure 3.6: Schematic illustration of fretting fatigue loading [19]

3.3.2.1 Critical areas for fretting fatigue initiation

In a wheel–axle assembly there are four critical positions for fatigue initiation:

- ✓ At the notch root,
- ✓ Subsurface,
- ✓ At the contact edge,
- ✓ In the vicinity of the stick–slip interface

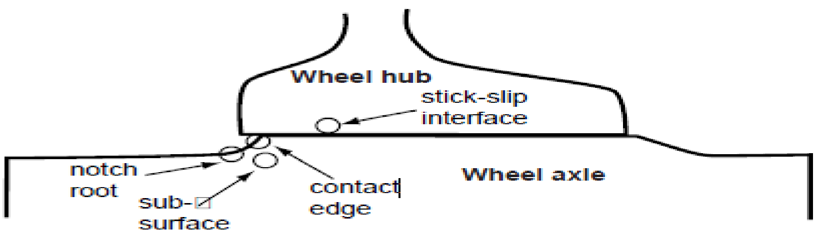


Figure 3.7: Possible locations for fretting fatigue crack initiation in a wheel–axle assembly. [20]

3.3.2.2 Experimental measurement of fretting fatigue in rail way wheel set

3.3.2.2.1 Rotatory bending fretting fatigue test rig

A rotatory bending fretting fatigue test system, is shown in Fig. 3.8, structure of press-fitted wheel-axle assemble was used for this test rig. The axle specimen was mounted on the rig by a pinchcock to realise the rotatory motion. The rotary speed range was 0–5000 rpm, and the rotary speed of the motor was controlled by an AC converter with control accuracy of 1 rpm. A driven wheel was assembled on the base to support the press-fitted wheel-axle and rotate with it during the experimental process. The location of the support wheel can be modified according to the experimental request. During the test process, the driven wheel was fastened on the base through eight bolts. A high-speed bearing was used to supply a bending load on the half wheel seat specimen. The distance from the bearing centre to the press-fitted contact rim was proportional to the distance on the real axle. The bending load was generated by a dead weight through a lever system which is not shown in Fig.3.8 [18]

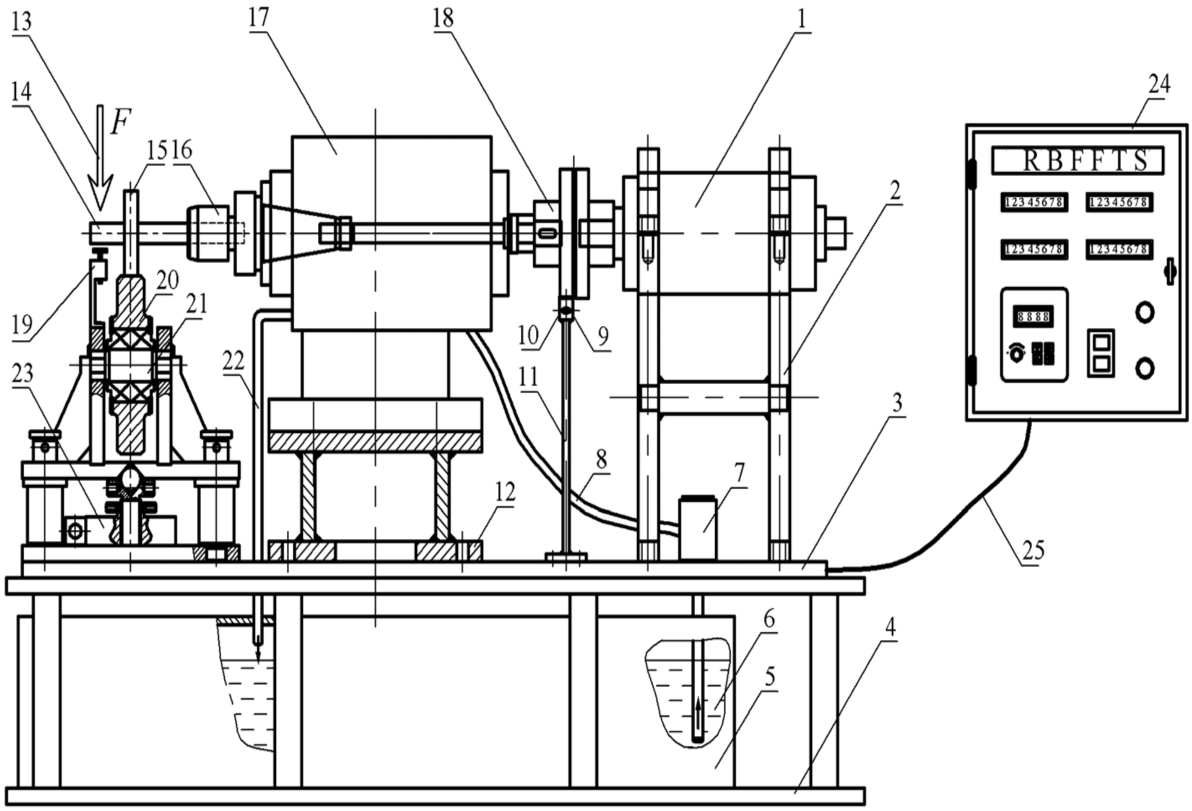


Figure 3.8: rotary bending fretting fatigue test rig apparatus [18]

1-motor, 2-bracket for motor, 3-surface plate, 4-base, 5-oil box, 6-cooling oil, 7-oil pump,8-oil pipe, 9-tachometer, 10-revolution counter, 11-bracket for sensor, 12-bracket for axle, 13-

loading force, 14-axle specimen, 15-halfwheel set specimen, 16-pinchcock, 17-headstock, 18-principal axle, 19-coupling, 20-driven wheel, 21-driven shaft, 22-oil pipe, 23-pressure sensor, 24-control chamber and 25-cable.

3.3.3 Fretting wear

The most significant difference between fretting wear and other types of wear is that fretting wear always occurs on contacting (mating) surfaces that are intended to be fixed in relation to one another but actually undergo minute relative movement. Historically, the largest body of fretting related research was focused on fretting wear. Almost all fretting wear investigations were conducted from the material and metallurgy science perspectives, mainly using experimental approaches Hurricks (1970) summarized the early studies on this topic, and proposed a theory that explains a fretting wear process in three stages: the adhesion and transfer of contact surfaces in the early stage of fretting; the formation of debris and its oxidation; and the steady state of fretting wear. Waterhouse (1977), the leading investigator on fretting wear (known as “the father of fretting research”), further extended Hurricks’ findings, and demonstrated that the delamination theory of wear is also applicable to fretting. This classical “three-stage theory” has had a far-reaching influence on the subsequent studies.[7]

Hoeppner (2002) [19] considered metal fretting wear mechanisms from five aspects: influence of surface films; adhesion of contacting surfaces; plastic deformation and smearing; material transfer from one surface to another; and oxide build up. It is noted that, although there were many other different explanations on the mechanisms of fretting wear process (besides the above mentioned), the role of material oxidation was long regarded as essential during the early development of fretting wear theories. However, this opinion has been gradually discarded due to the fact that fretting wear could also occur in some materials (e.g. diamond) without oxidizing environments.

An important contribution by Berthier,Vincent and Godet(1988) is a velocity accommodation mechanism of fretting contact interfaces is proposed to address the friction properties and relative movement process. Furthermore, by examining the formation and evolution of wear debris, they proposed the notable “third-body” theory of fretting, with a focus on the load-carrying capacity of wear debris (the so-called “third-body”) and its positive effects on reducing fretting wear and fretting fatigue (Berthier et al., 1984, 1989, 1990). According to this theory, the formation and escape (removal) of wear debris is a dynamic process, during which both occur continuously and simultaneously. This theory also explains the fretting wear process in three stages: **(a)** Two-body contact stage; **(b)** Transition stage (transition from two-body contact to three-body contact); and **(c)** Three-body contact stage.

By this theory, the variation of the frictional coefficient with fretting cycles during fretting wear of metallic materials can be explained (Figure 3.9)**:** At the beginning of fretting wear, the frictional coefficient remains low due to the influence (protection and removal) of contacting surface films; thereafter, it starts to increase rapidly with fretting cycles due to the increase of contact interaction, adhesion, local plastic deformation, as well as smearing. Gradually, wear debris is generated between the two contact surfaces. Wear debris is regarded as the “third-body”. Hence, the two-body contact is gradually transformed into three-body contact. Like the effects of solid lubricant, wear debris protects contact surfaces and restrains the contact adhesion, leading to the decrease of the frictional coefficient and frictional force during this second stage. When the third stage begins, the “third-body layer” has been established, which means the continuous formation and escape of wear debris reach a dynamical balance. The friction coefficient and frictional force thus become stable (constant), indicating that fretting wear is reaching a steady state.[20]

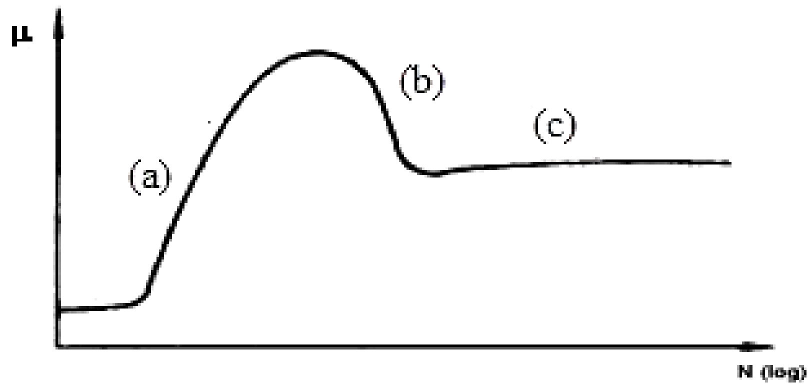


Figure 3.9: Variation of frictional coefficient with fretting cycles during fretting wear of metallic materials (Zhou et al., 2002) [5]

Fretting wear is associated with the removal of material from the contacting bodies. The importance of wear in terms of fatigue cracking is evident, where a significant increase in wear rate is seen to occur concomitantly with an increase in component life on transition from partial slip to gross sliding. The significance of wear-induced material removal on fretting fatigue life has been simulated by Madge et al. [21], where SWT life predictions were presented incorporating the effects of wear using a (FE) methodology. Within the partial slip regime, minimal material removal leads to only a comparatively small effect on fatigue life.

The key conclusion was the successful prediction of the pickup in life in the gross sliding regime, as validated by comparison with experimental fretting tests. Consequently, the development of fundamental methods for simulating and predicting the interaction of wear and fatigue, particularly for crack nucleation, is critical. Micro-plasticity is argued here to be the key tool for unification of wear and fatigue crack nucleation via micro-cracking prediction in contact.

Archard's equation is the most commonly used wear law. It is a relativity simple expression which has been shown to successfully predict sliding wear across a wide range of materials and loading conditions. The equation is presented as follows:

$$\frac{\mathbf{V}}{\mathbf{S}} = \mathbf{K}\frac{\mathbf{P}}{\mathbf{H}} \quad [22] \qquad \textbf{(3.1)}$$

Where

- V=wear volume (m^3/Nm)
- S=total sliding distance (µm)
- K=wear coefficient
- P= contact pressure (Mpa)
- H=material hardness (HV)

However there are some limitations to the equation. It has been shown that the Archard equation only works for a constant COF value which is not always the case in fretting. McColl etal [23] applied a modified version of the Archard equation to gross slip fretting wear of a high strength CrMoV aero-engine site alloy, with a reasonable degree of success in predicting wear-scar dimensions across a range of normal loads. As previously mentioned, the limitation of the Archard equation means it is successful within the gross slip regime, but, is less accurate within the partial slip regime when $q(x) < \mu p(x)$. Fouvry and co-workers [23] have developed an alternative wear equation based on fretting energy dissipation. This integrates COF into the wear analysis and is argued to be independent of load and stroke. This is achieved through an energy based wear volume calculation as follows:

$$\mathbf{V} = \boldsymbol{\alpha} \sum_{i=1} \boldsymbol{E}(\boldsymbol{x}, \boldsymbol{t}) \quad [23] \qquad \textbf{(3.2)}$$

Where

- α=wear coefficient
- Σ E=accumulated dissipated (frictional) energy, summed over the total number of fretting cycles.

$$\mathbf{E(x,t)} = \int_{\mathbf{t=0}}^{\mathbf{t}} \mathbf{q(x,t)\,ds(x,t)} \quad [23] \qquad \mathbf{(3.3)}$$

Where

- q(x,t)=instantaneous shear stress
- ds(x,t)=relative slip at a time ***t***,and position ***x***

Hence, wear volume from sliding (gross slip) or partial slip experiments are calibrated against energy (measured) dissipated over the complete number of cycles, via a wear coefficient **k**. This energy equation calculates the shear traction times the sliding distance. Since the shear force in sliding is equal to the instantaneous COF (coefficient of friction) value times the normal load, the shear force changes accordingly and is dependent on the COF.

A typical assumption in the modelling of wear is that the removed material simply disappears. This is clearly not realistic, as seen previously with abrasive wear; it is quite common for a third body layer to be created. It is hypothesised that this third body layer has two effects;

1. The first is a positive effect where the third body debris forms an oxide layer that acts as a protective barrier from further first body contact.

2. The second is a detrimental abrasive effect that accelerates the rate of wear.

Ding et al.used the idea of third body flow to model the effects of debris in fretting wear, a continuous thin layer of "debris" elements that formed on the top surface of the substrate debris formation but elimination of wear particles that define a real wear process. The detached particles are transported outside of the contact region via third body flow. [22]

3.3.3.1 Fretting wear in mechanical components

Because vibration is one of the main causes of the fretting movement, it follows that the most likely area for it to occur is in machinery. The contacts between hubs, shrink and press-fits, and bearing housings on loaded rotating shafts or axles are particularly prone to fretting damage, but because the movement arises from alternating stresses in the shaft surface, the problem is more one of fatigue than wear. However, wear rather than fatigue can be a problem in bearing housings. Thin-shell bearings are universally used in diesel engines, and such bearings involve an interference fit between the bearing and the housing. If the contact pressure is not high enough, movement can occur, giving rise to the fretting damage.[23]

3.3.3.2 Experimental measurement of fretting wear

3.3.3.2.1 Profilometry. The very small amount of material that is removed in most fretting experiments renders the traditional method of measuring wear by weight loss impracticable. The recently developed method of surveying the surface by profilometry, where the instrument can plot out an isometric projection of the surface and the computer can produce a figure for the volume of the scar below the original surface and also the volume above the original surface, gives one of the best quantitative and descriptive assessments of the damage. When this method was checked with weight loss measurements, good agreement was found.

3.3.3.2.2 Holographic interferometry. Another method that gives a visual impression of the damage is holographic interferometry. This enables a contour map of the surface to be generated prior to the wear process in order to compare it with a similar map generated after the wear has occurred. By using holographic image subtraction, very small changes in surface topography can be detected.

3.3.3.2.3 Thin-layer activation. A quantitative method applied to measuring fretting wear is "thin-layer activation" (TLA). A thin layer of radioactive atoms is produced on the surface by bombardment with a high-energy ion beam from an accelerator. After wear has taken place, debris is removed and the residual radioactivity is measured. A sensitivity of at least 0.2 m (8 in.) is claimed.

3.3.3.2.4 Measurement of axial distance. A less-sophisticated method for the case of crossed cylinders is the determination of wear from the decrease in distance between their axes. The advantage of this method is that it allows measurements to be made without dismantling or disturbing the contact.[23]

3.3.4 Fretting corrosion

The concept of fretting corrosion here in has some different connotation from the conventional one in that a more rigorous explanation is endued. Fretting corrosion is frequently associated with fretting wear. However, among the three major categories of fretting damage studies, there are relatively fewer publications about “genuine” fretting corrosion because most investigations and reported case studies of fretting wear occur under strictly "clean" conditions while fretting corrosion must involve some corrosive agents, such as sea water, acid rain, corrosive gas, and so on. The environmental effects on fretting are the most significant features of fretting corrosion research, with the objectives to reduce the action of corrosive media on the surface of fretting components and to develop corrosion-resistant materials. Therefore, environmental, chemical, and electrochemical knowledge and approaches become crucial to study fretting corrosion. [7]

3.4 Factors influencing fretting damage

Several researchers stated that there are around 50 factors that might cause considerable variation in the fretting behaviour/life. Few notable among them are: normal load, tangential load, relative displacement amplitude, applied bulk load, contact geometry, temperature, frequency, hardness, coefficient of friction, surface conditions etc. as it will be discussed below we can see that there are strong synergy links between many of those variables.

Technical literature reports vary, sometimes significantly, in the assessment of the influence of these variables. The difference can be explained by the use of testing procedures of the fretting process that have not been standardized yet. This causes a large scatter on the results, making it sometimes difficult to draw quantitative conclusions regarding the changes and influence of the various factors involved. All these facts create extreme difficulties in obtaining experimental data on the influence of a single variable on the fretting process. Generally the following are some of the influencing factors.

3.4.1 Normal contact load

Normal contact load is a significant variable on fretting fatigue, being important to look at its effect on fretting fatigue life. In general, if normal contact load increases the fretting fatigue life should decrease because of the monotonous increase in frictional stress amplitude with contact pressure. The reports in some technical literature regarding its influence on fretting fatigue life lead to contradictory conclusions. Some researches state that normal contact loads have a significant influence on fretting fatigue life while others consider that its influence is insignificant. In order to assess the effect of normal load on fretting fatigue life it is important to look at its variation with the number of cycles, and also at its interaction with different factors and variables.

The relation between normal load and relative displacement amplitude was also studied. It has been stated that the slip zone size is dependent upon the magnitude of the normal load.

Jin and Mall examined the effect of normal load on the slip zone, having observed that by increasing the normal load the slip zone decreased.[24,28]

3.4.2 Tangential contact load

The tangential load is a consequence of the contact friction between pads and specimen and it is another parameter that affects the fretting fatigue life of a component or specimen. In a fretting fatigue situation the tangential load is typically cycled with the bulk load cycles.

Jin and Mall showed that the maximum tangential load in some situations continuously increased, or increased and suddenly dropped. The sudden drop in tangential load was explained by the decrease in the applied normal contact load, resulting from material removal of both specimen and pad. Jin [25] in another investigation, showed the typical evolution of tangential load under both partial slip and gross slip fretting conditions: in partial slip the tangential load quickly stabilized and remained constant throughout the test; in gross slip conditions the tangential load monotonically increased and then decreased at some points during fretting cycles. Wittkowsky observed with his particular apparatus that the maximum tangential load decreased in the beginning (few hundred of cycles) then stabilized with the increasing number of cycles.

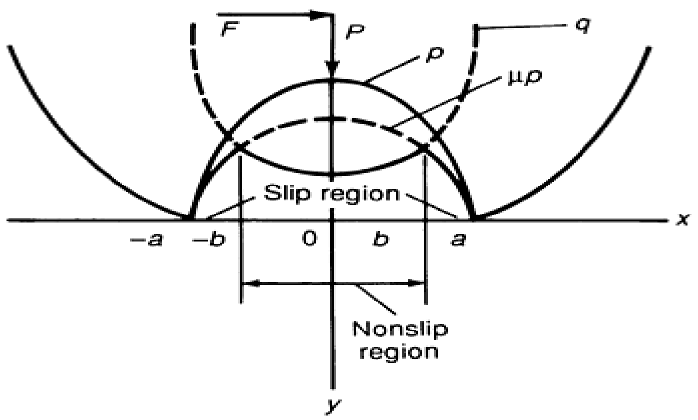


Figure 3.10: Mindlin analysis of partial slip for a ball in contact with a flat and subjected to a tangential force [23]

Any small change in the tangential load leads to a big change in the relative displacement amplitude. Zhou, in another investigation observed that as the tangential load increases the slip region also increases and the stick zone decreases, until full slip occurs within the contact.

3.4.3 Relative displacement amplitude

Relative displacement amplitude has been recognized as one of the most important parameters in fretting fatigue behaviour which control crack initiation and propagation processes .The influence of relative displacement amplitude has been known for many years. One of the first comprehensive investigations of the effects of slip was carried out by Nishioka and Hirakawa (1969). Their investigations were concentrated mainly on the partial slip regime but other works extended the study to the regime of fully-sliding contact (Spink, 1990) [28].

In order to highlight the effects of the relative displacement amplitude in fretting fatigue life first we will see how it changed with the number of cycles (for different equipment and test conditions), and also which are the interactions of this with different factors and variables.

The effect of the relative displacement amplitude on fretting fatigue life (fig 3.11) has been reported by Vingsbo and Soderberg.It has been summarized the effect of slip amplitude on wear rate and fretting fatigue life. At low slip amplitude fretting is mild and long fatigue lives were recorded. The wear rate is correspondingly low.

As the slip amplitude is increased, the fatigue life falls and the wear rate increases as a result of the increased fretting. A minimum in fatigue life is eventually reached, often around the transition from partial slip to full sliding. The wear rate continues to increase if slip amplitude is increased beyond this value, but the fretting fatigue life increases again. This phenomenon of increased life is often interpreted as being the result of the rapid increase on in wear rate. Although fretting is quite severe and cracks are readily initiated, the enhanced wear rate means that embryo cracks are worn away before they have chance to grow, and hence wear becomes the dominant manifestation of fretting.

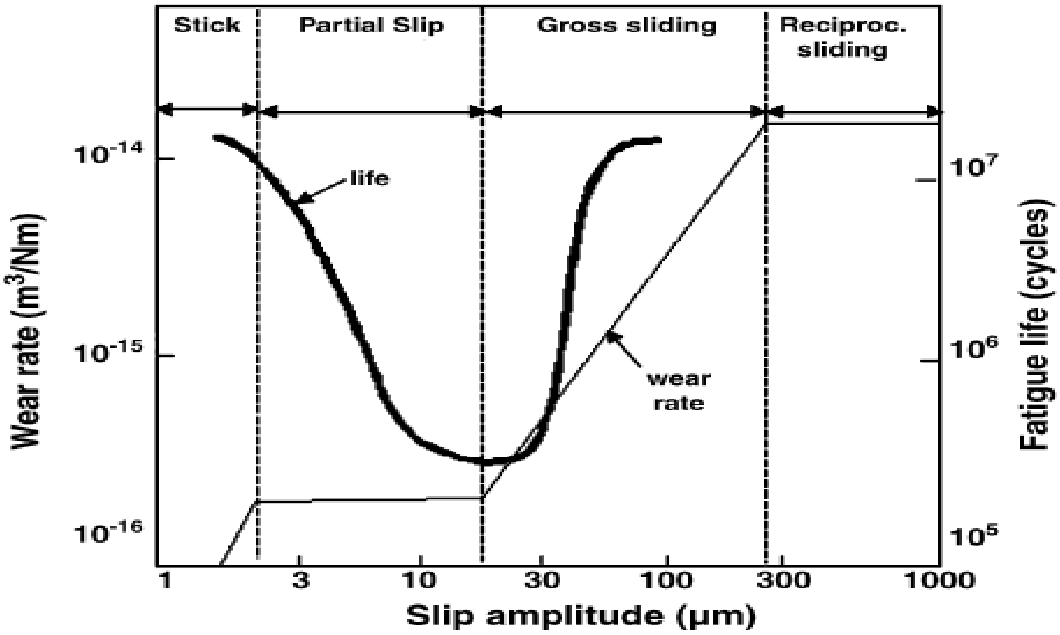


Figure 3.11: Fretting fatigue life vs. relative displacement amplitude [28]

3.4.4 Surface roughness

Surface roughness affects the mechanism of fretting fatigue, as this phenomenon arises as result of surface interaction between contacting bodies. Some efforts have been made to understand the effect of surface roughness on fretting resistance, and different results were obtained.

Increased roughness results in smaller discreet areas of real contact so that the critical volume of material per contact to initiate a crack, as proposed by Bramhall, is not achieved. A rough surface has a higher plasticity index than a smooth surface, so some plastic deformation will occur at the tips of the asperities.[28]

3.4.5 Coefficient of friction

In the fretting fatigue case it is important to draw a clear difference between the static coefficient of friction and the dynamic coefficient of friction (or kinetic COF, or normalized frictional force). The static coefficient of friction is defined as the "friction coefficient corresponding to the maximum force that must be overcome to initiate macroscopic relative motion between two bodies. The dynamic coefficient of friction is calculated as the ratio of the tangential to the normal load and it is defined as the “coefficient of friction under conditions of macroscopic relative motion between two bodies". The stick-slip situation occurs when the dynamic coefficient of friction is higher than the static coefficient of friction.

The coefficient of friction depends on the fretting regime. If the two bodies are subjected to fretting in partial slip (as in the case of the present study), there will be surface modification due to relative motion in the slip zones. Figure 3.12 shows the evolution of the friction coefficient during fretting contact in the partial slip regime (Hertzian case). It can be seen in Figure 3.12 (a) that initially the COF is constant in both zones of contact (slip and stick). From figure 3.12 (b) it can be observed that after n cycles, when the central zone will develop (stick zone) the COF increases in the slip zone. This increase was attributed to surface modification.[28]

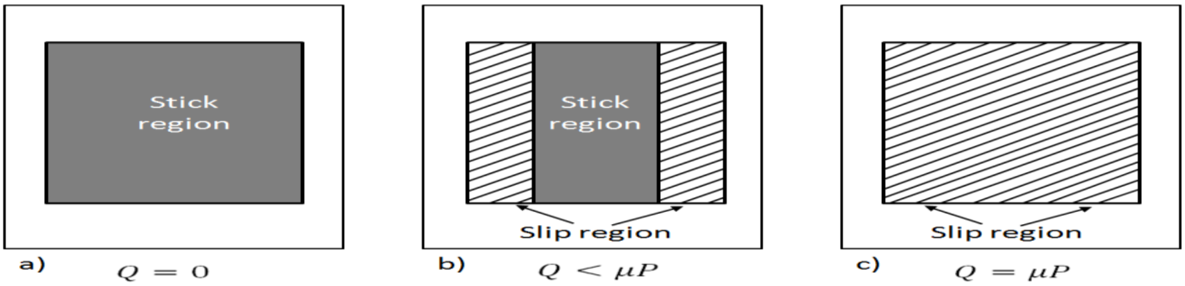


Figure 3.12: Plan view schematics of different slip regimes for cylinder on flat, (a) stick regime, (b) partial slip regime, (c) gross sliding regime.[17]

As reported above the increase of COF modifies the stress level and changes the location of the maximum loading. Less COF should lead to a smaller slip region, and consequently low damaged area. In practice, much effort has been made to reduce the COF. The decrease in COF can also improve the fretting fatigue strength because of the decrease in the alternating tensile tangential stresses. It is these high alternating stresses that result in local high strain fatigue and the rapid initiation of fatigue cracks.

3.4.6 Contact geometry

In a practical application, by designing the appropriate contact geometry, stress concentration and consequently the fatigue cracks can be avoided. For example, in a study [30] about an automotive-formed suspension component it was showed that a significant improvement in fatigue life could be achieved with a small change on the contact geometry (introducing a curvature radius on the head of the original screw). This small change on the geometry reduced locally the stress level and increased the relative displacement amplitude and consequently fatigue life.[26]

3.4.7 Load frequency

Cortez et al [27], performed an investigation on the impact of high frequency versus low frequency fretting load. Generally, longer fatigue lives were obtained for a1 Hz test condition as compared to tests at 200 Hz. The shorter fatigue life for the high frequency load case was attributed to a higher degree of surface damage which was contributed to the high-frequency rubbing.

Further, localized heating was suggested as an additional reason for the different fatigue lives. Fatigue lives at varying frequencies and load amplitudes were stated to correlate reasonable well to predictions of Palmgren-Miner’s law although it is not fully clear how damage has been evaluated for the different load cycles.

3.4.8 Environmental factors

3.4.8.1 Temperature

The contact temperature is a dependent variable, being a function of size and shape of the real contact area, as well as of the thermal properties of the contacting bodies, coefficient of friction, normal load and sliding velocity. Temperature may affect the process of fretting in two ways: firstly, the corrosion and oxidation rates usually increase with temperature; secondly, the mechanical properties of materials change with temperature. There are not many studies giving attention to this subject and the published results vary significantly.[28]

3.4.8.2 Humidity.

After oxygen, water vapour is the most significant environmental factor in fretting wear. In a study of a wide variety of pure metals tested in a hemisphere on flat configuration and at a slip amplitude of 80 μm (0.0030 in.), most metals such as silver, copper, titanium, and iron showed a peak coefficient of friction value between 10 and 15% relative humidity (RH), with a corresponding peak in wear volume. With chromium, the peaks appeared at 5% relative humidity, but with aluminium and nickel the peaks occurred at very low humidity. At normal atmospheric humidity (50% relative humidity), all the metals except nickel showed a gradual decrease in fretting wear.

This corresponds well with earlier observations on steel specimens. Because aluminium alloys are particularly sensitive to the effects of water vapour in fatigue situations due to the reactivity of an exposed aluminium surface and the liberation of hydrogen, further work has been devoted to the aluminium-zinc-magnesium alloy. Fretting wear was found to be the same in dry air as in dry argon, thus discounting oxygen as an active agent; however, in air of 60% relative humidity, the wear rate was much higher because the wear debris was non adherent and thus metal-to-metal contact was increased. In addition, it was found that softening due to averaging of the surface material in the contact region developed in humid air.[28]

3.4.9 Materials

If fretting wear is a possible occurrence in the design of a machine or structure, it may be possible to reduce the effect by choosing materials that are more resistant to such damage. This section deals with bulk materials not coated or surface treated; coated and surface-treated materials are dealt with in the section "Prevention of Fretting Damage" in this last portion of this thesis.

Steels have been most extensively studied, largely because of their ability to change mechanical properties over a wide range by heat treatment without changing their chemical composition. In experiments with a steel ball on a steel flat, in which the hardness was varied from 220 to 850 (HV), there was little difference in the wear loss. In crossed cylinder experiments with three alloys of the same crystal structure, increasing hardness is shown to lead to a decrease in the critical amplitude between partial and total slip. The materials were copper, copper-silicon, and austenitic stainless steel, all materials of low stacking fault energy; as a consequence, work hardening occurred at low frequencies but softening set in at high frequencies because of the temperature rise.

In some investigations, notably those by Dobromirski and Beard [28] the formation of a white etch-resistant layer has been detected in fretting of carbon steels. This material is extremely hard and tends to develop cracks. It is often referred to as martensite, and some authors have regarded this as evidence that high local temperatures can be developed in fretting. For their optimum mechanical properties (for example, most aluminium alloys) are likely to suffer a further type of damage in fretting.

Chapter Four

4. Mathematical modelling and predicting the analysis of fretting damage for railway wheel set

During the last 50 years intense research efforts have been devoted to find out the controlling parameters on fretting fatigue. A number of intends have been made to apply global stress or displacement based parameters to the prediction of initiation life. Ruiz et.al. Proposed criteria based on the density of dissipated energy multiplied by the direct stress component parallel to the surface. Hills et.al [29] tested such parameter on different geometries with good results. However the Ruiz parameter is totally empirical and deriving design lines from it, is a difficult task.

More recently, stress based criteria have been proposed, using multi-axial fatigue initiation parameters have been proposed. Szolwinski and Farris have combined the Smith-Watson Topper approach with the critical plane concept to successfully predict fretting-fatigue experiments assuming an analytical stress situation. Neu et al. have presented a concept to predict fretting fatigue based on fracture mechanics and equivalent crack size to characterize crack initiation. A global approach has been employed by Fouvry et. Al. who have combined a volume averaging method with the Dang Van criterion have shown that this can give more realistic life predictions for cases where the stress field varies very rapidly.

4.1. Formation of fretting in axle-wheel (wheel set) assembly.

In wheel set applications, fretting fatigue may occur in the (press- or shrink) fitting between the wheel and the axle. Further, fretting can occur in the connection between the axle and assembled gear seats, motor and brake disc seats; though this is not a major concern of this thesis. In all of these cases, the relative motion and lateral stress between the axle and the wheel, due to bending of the loaded axle, will cause fretting cracks to form. The bending of the loaded axle will cause a relative motion and lateral stress between the axle and the hub, causing fretting. The location of fatigue initiation is typically towards the inner edge of the band of fretting (presumably close to the stick slip interface), Maxwell et al and Hirakawa et al[18].The bending moment tends to move the edge of contact into the hub–axle interface, thus shifting the location of maximum tensile stress.

4.2 Modelling types of fretting contacts

4.2.1 Elastic model for fretting contacts

Normal stress ‘**p**’ in a stationary non-moving Hertzian contact rises smoothly from zero at the edge of the contact to its maximum value at the centre of the contact as shown in Figure 3.la. Assuming that the coefficient of friction ‘**μ**’across the contact is constant, the frictional stress **‘μp’,** resulting from the normal stress **‘p’** also rises smoothly from zero at the edge of the contact to a maximum value at the centre as shown in Figure 3.lb. If an external tangential force Q **< μW** is subsequently applied to the contact and no slip occurs, then the resulting tangential stress **‘q’** rises from some finite value at the middle of the contact to an infinite value at the edges as shown in Figure below. The distribution of tangential stress **‘q’**across, e.g. a circular contact, can be described by the following expression

$$\mathbf{q_x}=\frac{\mathbf{Q}}{\mathbf{2\Pi a(a^2-x^2)^{0.5}}} \qquad \mathbf{(4.1)}$$

Where:

- $\mathbf{q_x}$ = calculated tangential stress along the **‘x’** axis [Pa]
- **a** = radius of the contact area [m]
- Q = superimposed tangential force [N]

Cattaneo and independently Mindlin [30] realized that the no-slip model could not correspond to real contacts and proposed that slip would occur wherever the calculated tangential stress ‘q’ exceeded the product of normal stress and the coefficient of friction ‘μp’as shown in Figure 4.1 in the region of slip, the real value of tangential stress was reasoned to be no greater than the product of local contact stress and the coefficient of friction. Therefore assuming, for example, that the normal load ‘W’ is constant and the tangential load ‘Q’ increases gradually from zero then micro-slip occurs immediately at the edges of the contact area and spreads inwards until ‘Q’ approaches ‘μW’ and the ‘stick’ region reduces to a line for the line contacts, a point for the point contacts, etc. If ‘Q’ is increased further and exceeds ‘μW’**,** the contact starts to slide.

The contact is characterized by a central no slip region surrounded by an annular slip region. Slip, which reciprocates along with the tangential force, is the source of fretting damage and the edges of the contact are most vulnerable. The existence of a slip and a no-slip region in Hertzian contacts subjected to a tangential load has been confirmed experimentally [31]. In one of these studies a steel ball 5 [mm] in diameter was pressed against a glass plate under a load of 9.8[N] and subjected to reciprocating sliding of varying amplitude. At 1.25[μm] amplitude, a thin ring of damaged glass surface on the edges of the Hertzian contact was evident. At 2.5 [μm] amplitude, the annular damage zone was much larger leaving only a small circular un slipped region. A further increase in amplitude, above 3μm resulted in gross sliding with no central un slipped zone. An example of the effect of increased amplitude of fretting between a hard steel ball and steel surface is shown in Figure below.

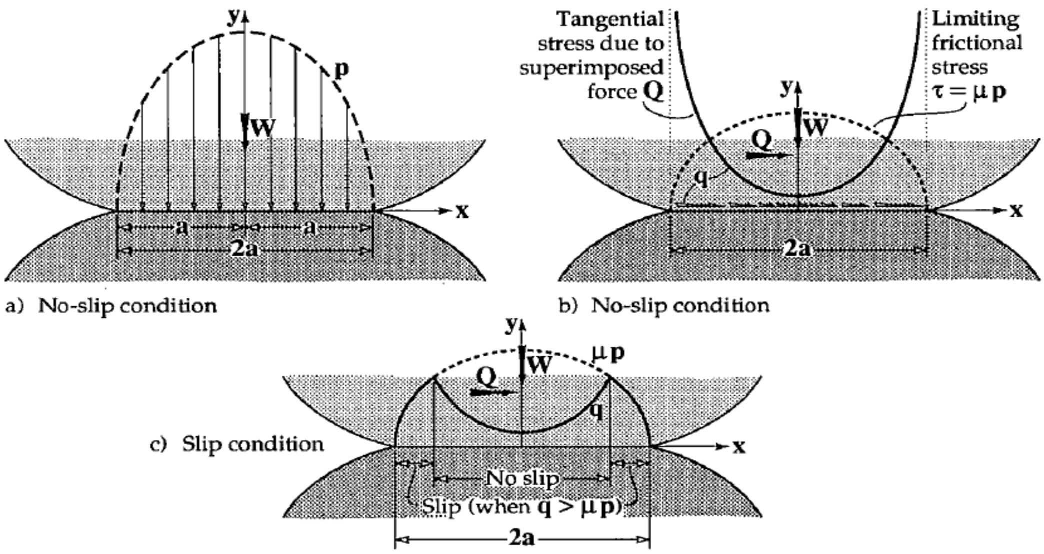


Figure 4.1: Normal and tangential stress fields for Hertzian contact with and without slip (adapted from [30]).

According to the model proposed by Mindlin [30], the ratio of the diameter of the central un slipped region to the diameter of the contact area is given by

$$\mathbf{a'/a = (1 - Q/\mu W)^{1/3}} \qquad \mathbf{(4.2)}$$

Where

- **a'** = diameter of the central un slipped region [m];
- **a** = contact diameter [m];
- ***Q*** = superimposed tangential force [N];
- **P** = coefficient of friction;
- **W** = normal load acting on the contact [N].

The relationship between the ratio a'/a and the ratio of tangential force Q to limiting frictional force 'μW' is shown in Figure 4.1**.** In experiments conducted with a steel ball oscillating on a glass surface a reasonably good agreement between theoretical and experimental results was found. It was assumed in the experiments that the diameter of the central un slipped region was identical to the area of contact remaining un obscured by wear debris.

4.2.2 Elasto-plastic model for fretting contacts

In the 'elastic' model of fretting it is assumed that relative displacement is accommodated by micro slip between the surfaces in contact and elastic deformation of the contacting solids. However, it has been found from fretting experiments conducted on metals of varying hardness and under sufficiently high load to cause plastic yield, that the maximum displacement amplitude which could be sustained without incipient gross slip was higher than predicted by elastic theory. These discrepancies have been explained in terms of elasto-plastic behaviour of the material in the contact zone. The 'elastic' model of fretting is based on the classical theory of friction which assumes that contact between the solids is achieved through contacts between the individual asperities. The theory assumes that the junctions between the asperities are rigid under load, and that when the surface shear stress exceeds a critical value slip will occur. Slip results from the sudden fracture of the asperity junction which takes place without any previous elastic or plastic deformation. This simplified assumption might be the reason for the discrepancy between the 'elastic' model and the experimental results.

The 'elasto-plastic' model of fretting contact has therefore been suggested .According to this model, the asperities under the influence of a superimposed tangential force deform elastically in a central stick zone. This zone is surrounded by a zone in which the asperities have just yielded plastically but not fractured. The plastic deformation zone is in turn surrounded by a slip zone, where the asperities are subjected to fracture in a similar manner as in the 'elastic' model. This is illustrated in Figure 4.2. It can be seen from Figure 4.2 that the transition in surface stresses between the stick and slip regions is rounded as opposed to the sharp transition.[30]

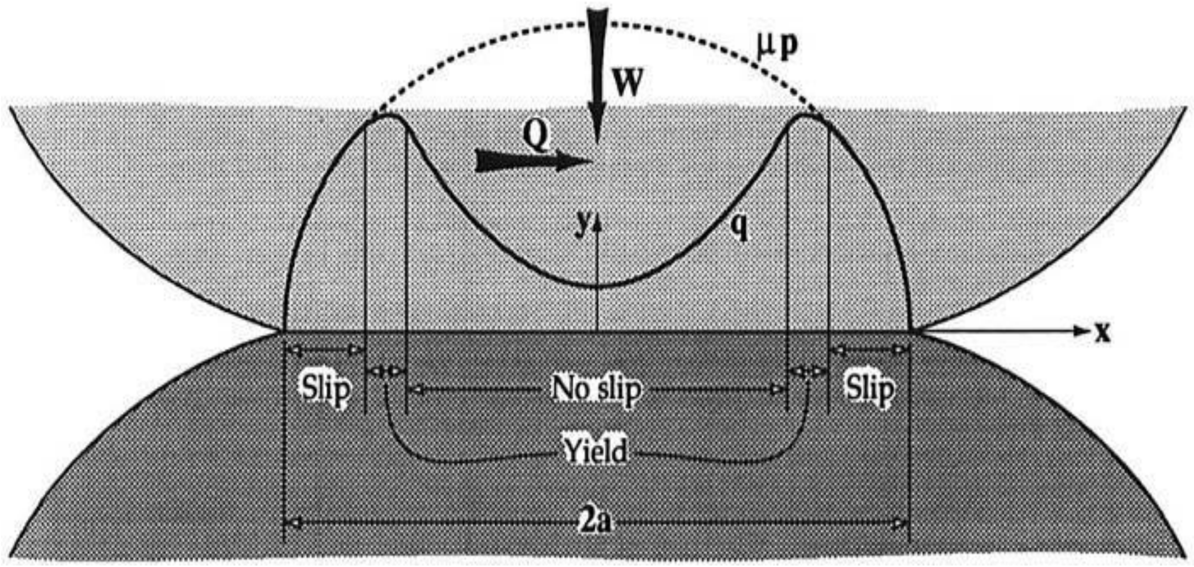


Figure 4.2: Surface stress distribution in an elasto-plastic fretting contact [30]

Observations of a variety of fretted contacts confirm that movement and wear occur at the edges of a load bearing contact at levels of tangential force insufficient to initiate bulk sliding. The centre of the contact may remain stationary while the edges reciprocate with amplitude of the order of 1 [μm] to cause fretting damage. Therefore from a practical standpoint, there is no lower limit to the tangential force required for fretting damage and this fact must be allowed for in the design of mechanical components.

4.3 Material selections for axle, wheel and rail

According to the UIC standard, the suitable material for railway axles is A1N steel grade and the suitable material for the wheel hub is R7T steel grade [2]. Chemical composition and mechanical properties of the steels are shown in Tables 4.1 and 4.2.

N.B.the material composition which is selected for this thesis work may not represent the exact composition which is set for the current (LRT). Due to shortage of appropriate data and is currently being tested by the authorized person, the material compositions are taken to the approximation.

Table 4.1: Chemical compositions of steels (wt %)

Steel Grade	c	si	Mn	p	S	cr	Mo	cu	v	Ni
A1N	0.37	0.46	1.12	0.04	0.04	0.3	0.05	0.3	0.05	0.3
R7T	0.52	0.4	0.8	0.04	0.04	0.3	0.08	0.3	0.05	0.3

Table 4.2: Mechanical properties of A1N and R7T steels

Steel Grade	S_y (MPa)	S_{ut} (MPa)	Elongation (%)	Minimum impact energy at 20°C (J)
A1N	320	550-650	22	25
R7T	560	820-940	14	15

Table 4.3: Technical specifications of the axle

S.N	Gauge (mm)	Axle load (KN)	Poisons ratio	Young's modulus (Gpa)	Length (mm)
1	1435	90	0.3	207	1900

4.3.1 Rail materials

Rails are grouped according to their standards, strength, grade, quality and length. The rail steel qualities can be distinguished in to two categories. So according to ERC the selected rail material is (Chinese 50kg/m) type rail.[26]

- Normal steel quality, with an ultimate tensile strength of 700-900 MPa
- Hard steel quality, used mainly on curves, and crossings etc. with an ultimate tensile strength of 900-1200 MPa

4.3.2 UIC,Chinese and ERC specifications of wheel, axle and rail dimensions

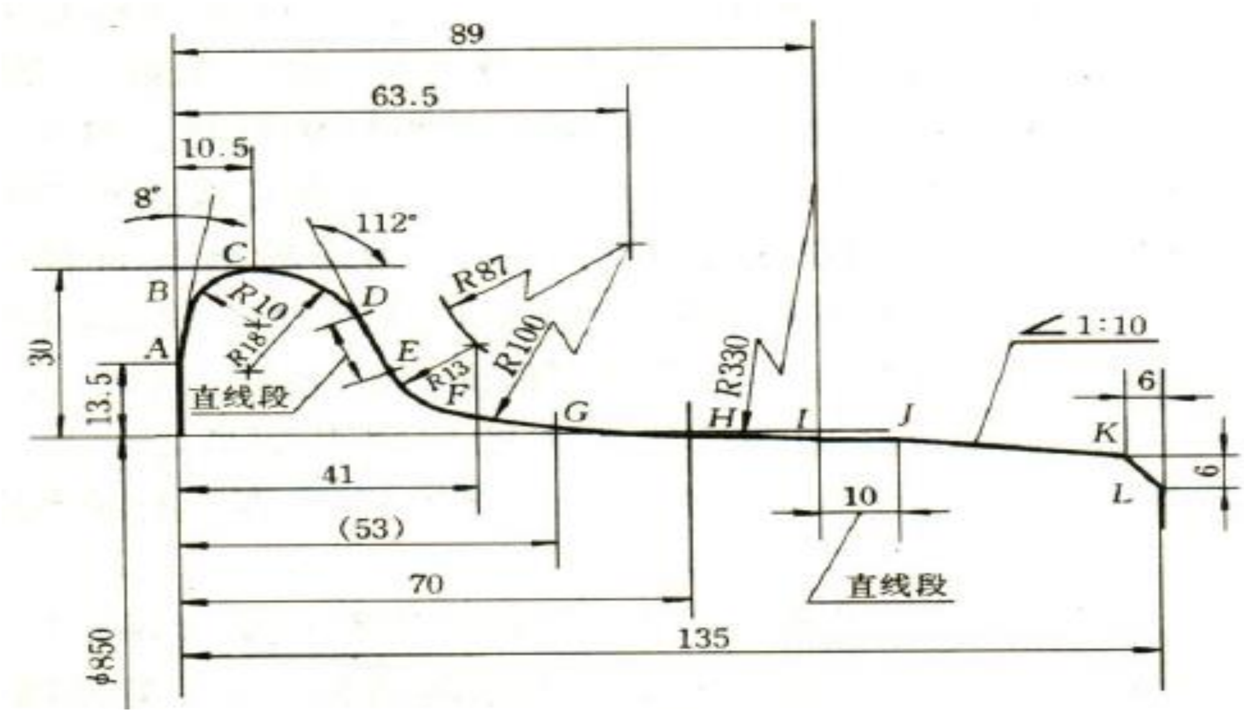


Figure 4.3: wheel dimensions[14,26]

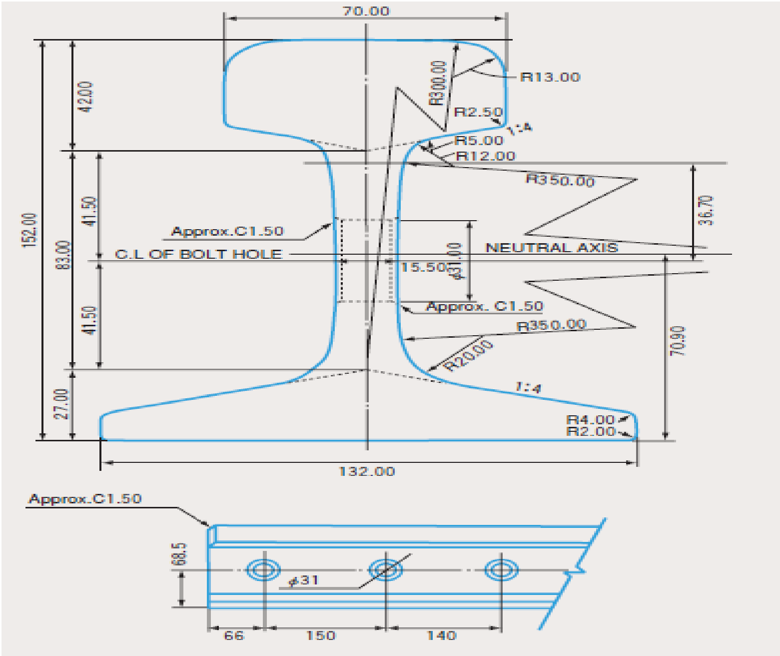


Figure 4.4 ERC 50kg/m type rail dimension [14]

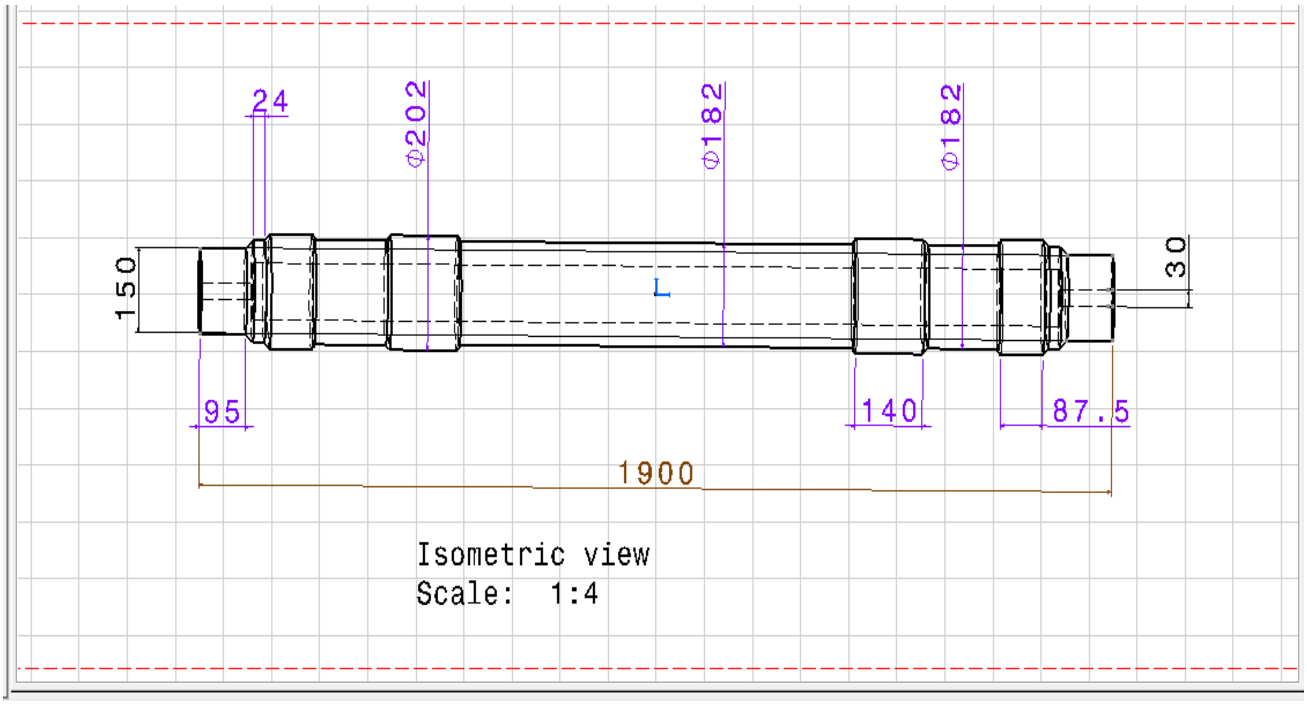


Figure 4.5: axle dimensions [14, 34]

4.4 Methods for the prediction of fretting damages in railway wheel set

4.4.1 Fretting fatigue life prediction-- 'classic approaches'

The predictive models treated in this are 'classic' in the sense that they are not developed to be implemented in numerical e. *g.* finite element (FE) models.

Perhaps the oldest approach to fretting fatigue prediction is to relate the fretting impact to the relative displacement of the contacting surfaces. This slip amplitude can be regarded as proportional to the number of asperity passes per cycle.

An extension of the slip amplitude criterion is the friction energy dissipation parameter

$$\mathbf{F_1 = \tau\delta} \qquad \textbf{(4.3)}$$

This is also referred to as the fretting wear– or D –parameter.

Here $\boldsymbol{\tau}$ is the interfacial shearing stress and again $\boldsymbol{\delta}$ denotes the relative surface displacement. $\mathbf{F_1}$ Represents the surface density of friction work. According to Ambrico & Begley, $\mathbf{F_1}$ has been shown to be fairly accurate in predicting nucleation sites, but not in addressing number of cycles to crack initiation.

Another energy based approach is presented by Ruiz *et al*. It quantifies the fretting impact in terms of the fretting parameter

$$\mathbf{F_2 = \sigma\tau\delta} \qquad \textbf{(4.4)}$$

This criterion is obtained by complementing equation **(6)** with the tension acting parallel to the free surface $\boldsymbol{\sigma}$. This method is further reviewed by Fellows*et al*, and Waterhouse,[31] Lykins *et al*, state that there is no correlation between F_2 and the number of cycles to fatigue initiation.

4.4.2 Reduction of S–N curves and fatigue limits

S-N curves can be constructed to describe the fatigue life of the fretted component, normally fretting fatigue life is here given as a function of the alternating (nominal) stress. However, problems will occur when other conditions (normal stress, residual stresses, lubrication etc) vary from original conditions.

A criterion that addresses the decrease in the fatigue limit due to fretting is given in Wharton *et al*, The criterion expresses the reduced fatigue limit as

$$\sigma_{wf} = \sigma_{wo} - q\left(\frac{8\mu P}{\Pi 2b}\right) \quad [33] \qquad \textbf{(4.5)}$$

Where

- σ_{wo} = plain specimen fatigue limit(cycles)
- **q** =notch sensitivity factor
- **P** =contact load (N)
- **μ** =coefficient of friction
- **2b**=width of contact strip for a cylindrical pad in contact with a plane.(μm)

Increasing contact pressure will be detrimental at low magnitudes. However, after a certain magnitude, an increase will have no effect (or be beneficial). In order to model this, Exponential models for the decrease in fatigue limit due to fretting, such as the model by Nishioka and Hirakawa, is given by

$$\sigma_{wf1} = \sigma_{w1} - 2\mu P_o\,(1 - e^{-S/k}) \quad [33] \qquad \textbf{(4.6)}$$

Where

- σ_{wf1} =reduced fatigue limit (cycles)
- σ_{w1} = initial fatigue limit(cycles)
- **μ**=friction coefficient
- P_o=maximum contact pressure(Mpa)
- **S**=amplitude of slip(μm)
- K=constant

A similar model is presented by Elkholy, [32]. With the same notation as above, this criterion can be written as

$$\sigma_{wf1} = \sigma_{w1} - 2\mu P_o(1 - e^{-(E1u)/(apo)} \quad [33] \qquad \textbf{(4.7)}$$

Where

- E_1=young's modulus of the bulk body (Gpa)
- u =displacement amplitude (μm)
- a=semi-width of the contact area (μm)

The major drawback with the 'classic' approaches is that they are not easily extrapolated to new conditions. In fact, as shown by Lykins *et al* , it may well be that there is no correlation at all between a fretting parameter and the fretting fatigue strength of a component.

Further, it is not straightforward (and sometimes even very complicated), to implement ‘classic’ approaches in a numerical modelling scheme.[32,33]

4.4.3 Mapping concept

Two categories of fretting maps can be stated

(i) Running condition fretting map (RCFM) :involving contact conditions or fretting regimes (stick, partial and gross slip);

(ii) Material response fretting map (MRFM): involving non-degradation, cracking and wear (or debris formation) as a function of normal force and relative displacement for a given experimental condition.

Vingsbo and Söderberg, [33] distinguished between three different regimes of fretting:

- **Stick regime;** with very limited surface damage and no fatigue crack formation.
- **Mixed stick-slip regime***;* with small wear and oxidation damages, but reduced fatigue life due to the influence of the fretting.
- **Gross slip regime;** with severe surface damage due to wear assisted by oxidation, but with limited crack formation.

These three regions were visualized in so-called fretting maps where fatigue life is plotted against **δ**.

The original concepts of fretting maps are employed and further developed by Fouvry*et al* . The fretting conditions are here divided into two regions. In cases of small amplitude sliding fatigue cracks will be the dominating damage mechanisms, whereas under gross sliding conditions, wear will dominate.

In a further refinement, the transition between partial and gross slip was defined through a sliding criterion. The limit of crack nucleation was quantified using a multiaxial fatigue criterion (in this case the Dang Van criterion) and size effects are accounted for by an averaging approach. The transition between low- and high-cycle fatigue is defined by the von- Mises boundary and wear is quantified by an energy approach. The resulting fretting map separates regions of no damage, low- and high-cycle fatigue, competing wear/fatigue and pure wear, as shown in the figure 4.6.

In order to verify the crack nucleation boundary, fretting tests were carried out for several tangential force magnitudes at constant normal force levels. This will give the limiting applied tangential force as a function of applied normal force. Results are analysed and compared to predictions of the Dang Van criterion. Judging from these results, it could be the case that the Dang Van approach runs into problems when low normal forces are employed.

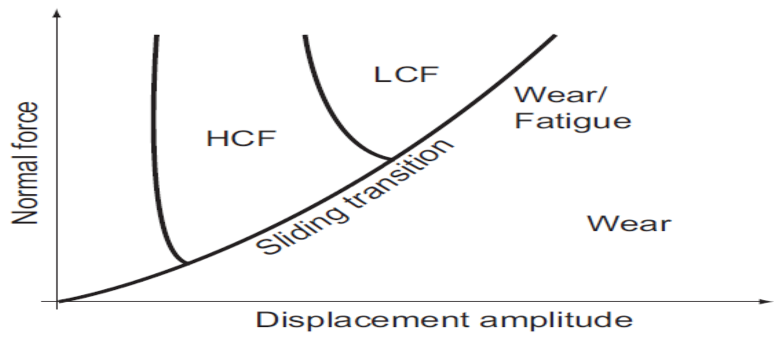


Figure 4. 6: Schematic fretting map [33]

Although, at first, very appealing as an engineering tool for wheel-axle assembly design, there are problems in adopting a mapping concept, some of which are:

- In the maps, displacement amplitude is plotted against the normal force. Judging from the literature, for instance Lykins*et al*, and Waterhouse, the slip amplitude may not be a suitable parameter to predict the fatigue life (although perhaps more suitable for fretting wear life predictions).
- The fretting maps, which are derived to reflect the material response, may not be suited for extrapolation to new operating conditions (altered axle dimensions, altered corrosive protection etc). This is because such changes alter parameters that are not reflected in the maps but still may alter the fretting response.

4.4.4 Plain fatigue approaches

There are several examples in the literature where uniaxial fatigue criteria have been employed to predict fretting fatigue life. A comparison of some criteria is compiled by Lykins*et al*, [33].

The study included a low-cycle fatigue criterion of Coffin–Manson type:

$$\mathbf{\varepsilon max, R_{\varepsilon} = C_1(N_f)^{C2} + C_3(N_f)^{C2}} \quad [33] \qquad \mathbf{(4.8)}$$

Where

- **C**=fitting constant
- $\mathbf{N_f}$**=**fatigue life (cycles)

- ε_{max},R_ε= $\varepsilon_{max}(1- R_\varepsilon)^m$
- ε_{max}=maximum strain amplitude along the contact interface(μm)
- R_ε=strain ratio(N/m^2)
- **m=**fitting parameter

Iyer, [33]. evaluates the influence on fretting fatigue life of peak contact pressure, maximum local cyclic bulk stress range, maximum local cyclic shear stress, maximum local cyclic shear stress range, maximum local slip amplitude and contact semi–width. It was first concluded that all parameters except peak contact pressure and local, maximum bulk stress range were irrelevant. Then, it was stated that the fatigue life could be predicted by the equation

$$N_f = k_1[\Delta\sigma_L, Max]^{-a} . g[\Delta\sigma_L, Max]e^{mpo} \quad [33] \qquad \textbf{(4.9)}$$

Where

- k_1 **& m**=constants
- $\Delta\sigma_L$,**Max**=function of local maximum bulk stress(N/m^2)
- p_o=maximum contact pressure(Mpa)

4.5 Modelling aspects

During the whole thesis work, **CATIA V-19** is used for modelling the axle, rail, and wheel so that each components are assembled to form a wheel set. After the assembly is finished it is converted to an (igs) form and is imported it into **ANSYS-12 (**64 –bit). Hence, the effect of friction coefficient on the fatigue life in static case and evaluation of the effect frequency and displacement in the harmonic case are shown consecutively.

4.5.1 Force distribution in wheel-axle assembly drawing

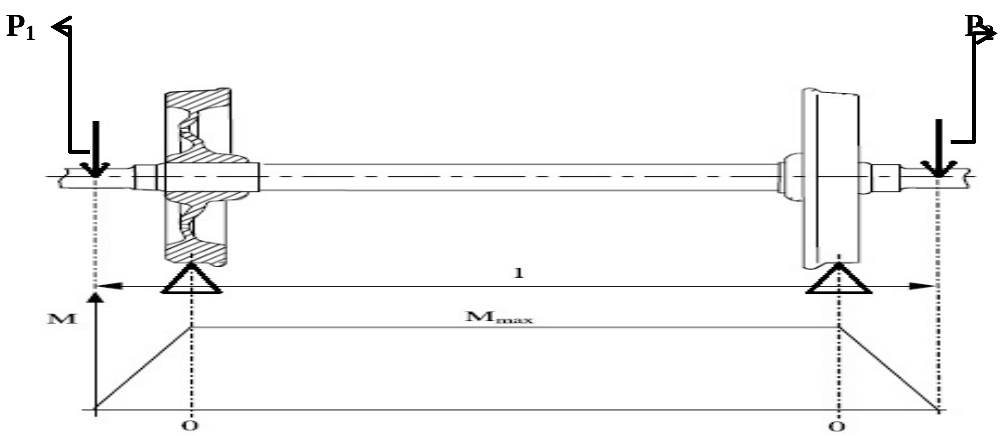


Figure 4.7: loading conditions of wheel set[2]

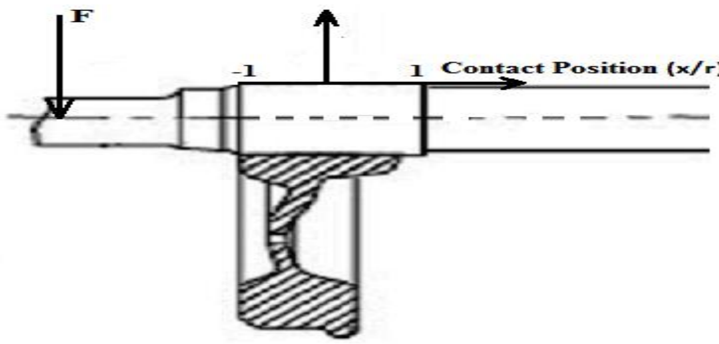


Figure 4.8: local coordinate system on the contact surface [2]

4.6 Determining the interference fit of railway wheel set

Press fitting and shrink fitting are two methods of attaching the wheel hub to the axle. In order to have a right attachment, UIC code sets a restriction for the proportion of the interference [2]. The maximum and minimum allowable values of the radial interference are presented in equations **(4.10)** and **(4.11)**

$$2\nu_{max} = 0.0015D+0.06 \qquad (4.10)$$

$$2\nu_{min} = 0.0009D \qquad (4.11)$$

Where

- ν=radial interference
- D=diameter of wheel seat

So taking this into account the maximum interference fit will be

$$2\nu_{max} = 0.0015(202) +0.06$$

- ❖ ν_{max}=0.1815(mm)

  ≈0.182 (mm)

And the minimum interference is also given by

$$2\nu_{min} = 0.0009(202)$$

- ❖ ν_{min} =0.0909(mm)

After calculating these values the wheel and axle are assembled as well analysed considering the maximum interference fit. Hence [ν] max=0.182 (mm)].hence the diameter of the wheel where the axle fits is ≈ 202.182(mm)

4.7 Acting forces of railway wheel -axle assembly

The following datas are considered in the analysis of bending stress.

Table 4.4: basic Input datas

Wagon dead weight per wheel set at ‘’A’’ (W) (kg)	Lateral acceleration coefficient (α_L)	Vertical acceleration coefficient (α_V)	Speed of tram (V) (km/hr)	Radius of wheel (r_w) (mm)	Wheel thread distance (g) (mm)	Distance Between Journals(j) (mm)
13730	2.04	1.31	70	350	1551	1852.5

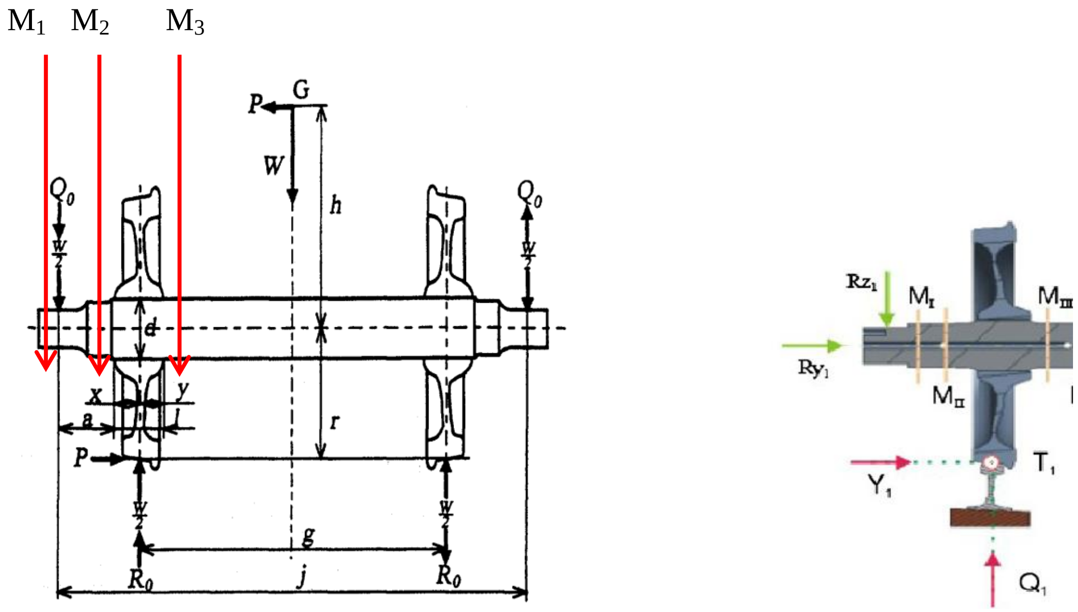


Fig. 4.9: free body diagram and dimensional representations of wheel set[33]

4.7.1 Calculation of the maximum bending stress (σ_b)

$$\sigma_b=\frac{m(M1+M2+M3)}{Z} \quad [33] \qquad \textbf{(4.12)}$$

Where

- $M_1=(j-g)W/4$ **(4.13)**
- $M2=\alpha_v M_1$ **(4.14)**

- M_3**=P.r + Q_o(a + l) –R_o.y** **(4.15)**
- d=axle diameter
- r=wheel radius
- W= wagon dead weight per wheel-set
- j=distance between journal centers
- g=wheel tread distance
- a=distance between journal center & the end of the wheel seat
- h=height from axle to gravity center
- x=distance from the outside wheel hub to the contact load
- y=distance from the inside wheel hub to the contact load
- l=x+y
- G=center of gravity
- α_v=vertical acceleration coefficient
- j & g =axle dimensions
- α_v=vertical acceleration coefficient
- P= horizontal force= α_LW
- $Q_o=\frac{Ph}{j}$
- $R_o=\frac{P(h+r)}{g}$
- α_L=lateral acceleration
- Z=section modulus of axle at the wheel seat.
- m=factor of safety
- α_L=horizontal acceleration coefficent
- Q_o= vertical force of journal by P = P(h/j),
- R_o= vertical force of treads by P = (h+r)P/g,
- The distance between the journals (**j) =**1852.5(mm)=1.853m
- factor of safety(m)=2 for a mesh size of 4mm at the contact interface.[33]
- Accelaration(a)=1470mm/s^2[14]
- Friction coefficient=0.16[14]

Hence;

$$\mathbf{M_1} = \frac{1.853-1.551}{4}*13730*9.8$$

$$\mathbf{M_1} = 10158.9 \text{N.m}$$

To calculate $\mathbf{M_2}$

$\mathbf{M_2=\alpha_v M_1}$

- Taking the vertical acceleration coefficient ($\boldsymbol{\alpha_v}$)=1.31 from table 3.2 at70km/hr

=10158.9*1.31

$\mathbf{M_2}$ = 13308.2N.m

To calculate **M3**

- $\mathbf{M_3=P.r + Q_o(a + l) - R_o.y}$
- P= horizontal force = $\alpha_L w$

Taking the lateral acceleration coefficient (α_L) =2.04(table 3.2) at 70km/hr

P=2.04*13730*9.8

P=274.5KN

- $\mathbf{Q_o} = \frac{Ph}{j}$

h=1024mm =1.024m

j=1852.5mm =1.852m

$Q_o = \frac{274.5*10^3 *1.024}{1.852}$

Q_o =151.8KN

r=350mm=0.035m

- $\mathbf{R_o} = \frac{\boldsymbol{P(h+r)}}{\boldsymbol{g}}$

$=274.5 * 10^3 \ \frac{(1.024+0.35)}{1.551}$

R_o =243.2KN

- **l =**x+y=134mm

=0.134m

- Y =67mm=0.067m
- a=71.5mm=0.0715m

From this

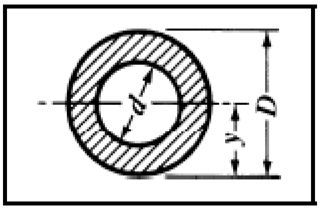
M_3=P.r + Q_o(a + l) –R_o.y

$=274.5 * 10^3 * 0.035 + 151.8 * 10^3 (0.0715+0.134) - 243.2 * 10^3 * 0.067$

=9607.5 +31194.98 -16294.4

=24508.1N.m

To calculate **Z**(section modulus of axle at wheel seat) circular section modulus is considered hence, for circular modulus



Y=D/2

$$I=\frac{\Pi(D^4 - d^4)}{64}$$

- $$\mathbf{Z=\frac{\Pi(D^4 - d^4)}{32D}}$$

Where

D=202mm

d=40mm

$$z=\frac{\Pi(202^4 - 40^4)}{32*202}$$

Z =0.257m^3

Finally the nominal bending stress (σ_b) stress becomes

$$\sigma_b = \frac{m(M1+M2+M3)}{Z}$$

$$=\frac{2(10158.9+13308.2+24508.1).N.m}{0.257m^3}$$

σ_b = 373.35KN/m^2=373.35kpa

σ_b =0.373Mpa

4.7.2 Calculation of the tangential shear force on the axle (F_t)

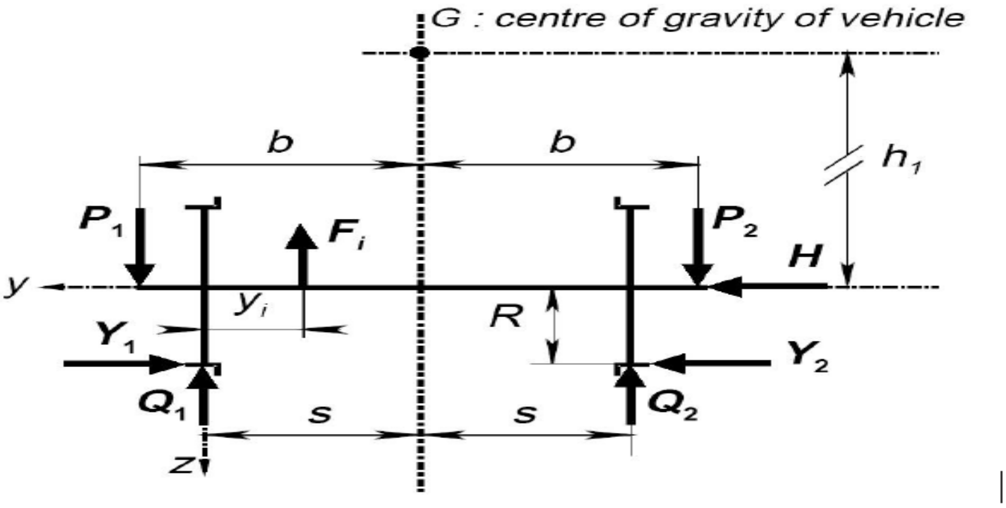


Figure 4.10 forces interacting in wheel set assembly [38]

This force is induced at the tangential interference fits of the axle and wheel, so from the figure above it is calculated by the formula [34]

$$\mathbf{F_t} = H = \boldsymbol{Y_1} - \mathbf{Y_2} = \mathbf{0.175 m_1 g} \qquad \textbf{(4.16)}$$

Where

$\mathbf{y_1}$ =0.35m_1g

$\boldsymbol{y_2}$ =0.175m_1g

m_1 =bogie mass UIC standard=10000kg

$=0.175 * 10000 * 9.8$

$\mathbf{F_t}$ =17150=17.15KN

4.7.3 Calculation of the rotational velocity of the wheel (ω)

$$\boldsymbol{\omega} = \frac{\boldsymbol{v}}{\boldsymbol{r_w}} \qquad \textbf{(4.17)}$$

Where

- ω=rotational velocity of wheel (rad/s)
- r_w=radius of wheel=350mm=0.35m

- v=speed of train =70km/hr=70000m/3600

  = 19.44m/s

From this $\omega=\frac{19.44}{0.35}$=55.54rad/s

4.7.4 Calculation of the Frequency of the axle-wheel assembly (f)

$$\mathbf{f=\frac{\omega}{2\Pi}} \qquad \textbf{(4.18)}$$

Where

- ω=rotational velocity of wheel (rad/s)
- f=vibrational frequency(Hz)

$f=\frac{55.54}{2\Pi}$=8.84Hz

4.8 Calculation of the fretting fatigue strength of axle-wheel contact points

$$\mathbf{S_{fr}=S_o-2\mu P_o[1-e^{-l/k}]} \text{ [30]} \qquad \textbf{(4.19)}$$

Where

- $S_{fr=}$ fretting fatigue strength [Mpa]
- S_o= fatigue strength in the absence of fretting [Mpa]
- μ= coefficient of friction;
- P_o= contact pressure [Mpa]
- l= fretting amplitude [μm]
- k=a constant. Typically k = 3.8 [μm] , which renders the Exponential term negligible for amplitudes of slip greater than 25[μm]

4.8.1 Contact pressure at the axle-wheel interference fits

According to lames equation [35]

$$\mathbf{P=\frac{E\delta(r_2^2 - r_1^2)}{4r_1r_2^2}} \qquad \textbf{(4.20)}$$

Where

- P= maximum contact pressure at the interference (Mpa)
- δ =diametral interference=0.182mm=0.000182m
- r_1=internal radius of wheel=101mm=0.101m
- r_2 =external radius of wheel=350mm=0.35m
- E=Young's modulus =207Gpa

$$\mathbf{P}=\frac{207*10^9*0.000182(0.35^2-0.101^2)}{4*0.101*0.35^2}$$

P **=**84.61Mpa

4.8.2 Effect of amplitude and coefficient of friction on the fretting fatigue strength of axle-wheel assembly

The fretting fatigue strength of the wheel set varies with respect to the coefficient of friction and amplitude.so the table below gives the variation in accordance to these. **Equation (4.19)** is used for evaluating the results.

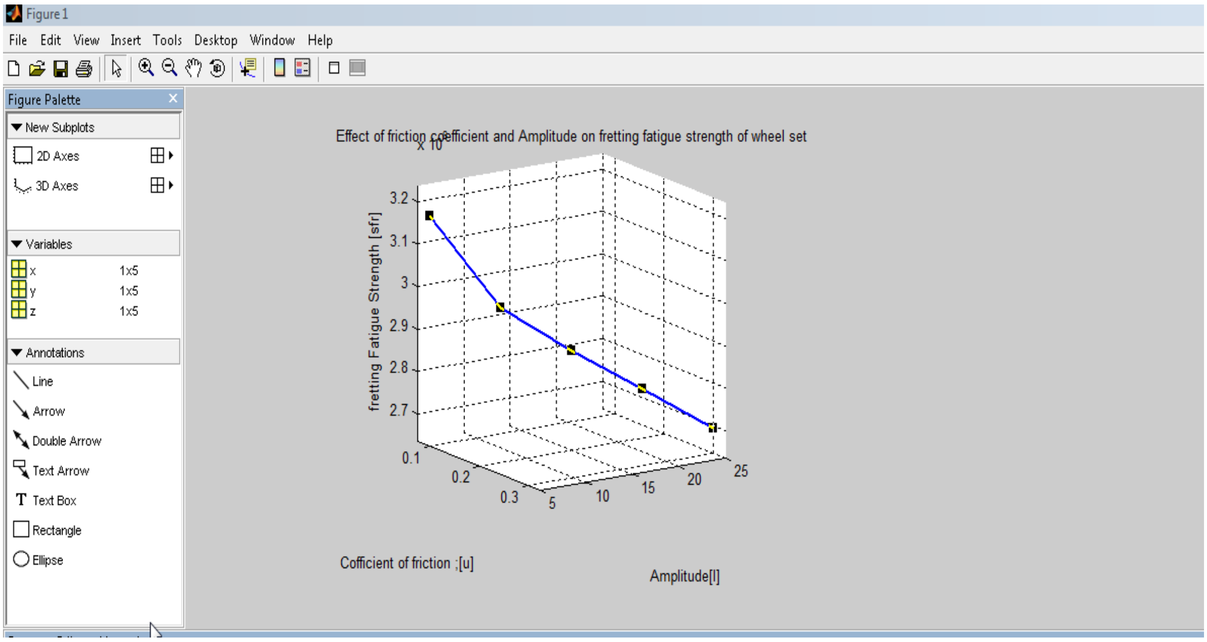
Hence the results are calculated for example for (μ=0.1) and amplitude (l=5μm)

$$S_{fr}=320-2(0.1)(84.61)[1-e^{-5/3.8}]=317.65$$

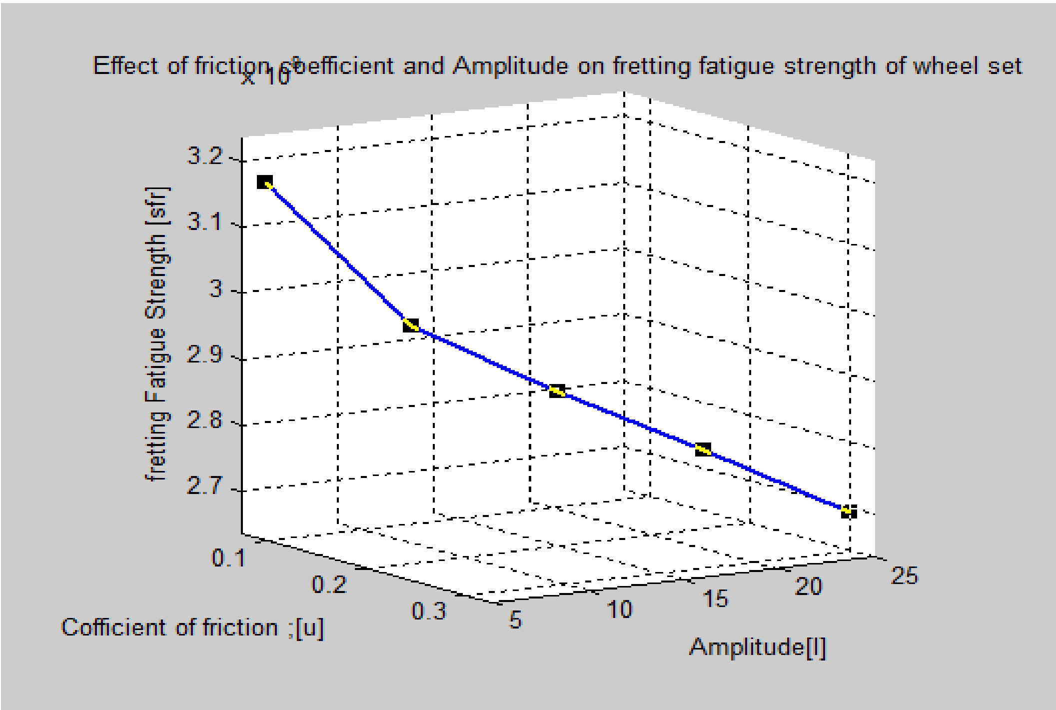
N.B the results which are given in **table 4.5** are calculated accordingly.

Table 4.5: effects of friction coefficient and slip amplitude on the fretting fatigue strength of Wheel set

Coefficient of friction(μ)	Amplitude (l) (μm)	Contact pressure(Mpa)	Yield strength of axle(S_{ult})(Mpa)	Fretting Fatigue strength (s_{fr})(Mpa)
0.1	5	84.61	320	317.65
0.15	10	84.61	320	296.47
0.2	15	84.61	320	286.83
0.25	20	84.61	320	278.22
0.3	25	84.61	320	269.31



(a)



(b)

Figure 4.11: (a) and (b) effects of friction coefficient and amplitude on the fretting fatigue strength of wheel set

4.8.2.1 Discussion of results

The results obtained From **table 4.5** are plotted in **Mat lab** software as shown in **figure 4.11** hence as it is shown in the figure as the amplitude and friction coefficient increase, the fretting fatigue strength of the axle-wheel assembly (wheel set) decrease so that it will have a shorter life and will be very susceptible to the formation of cracks and breakage.

4.9 Axle, wheel, rail & wheel set model by using CATIA software v - (19)

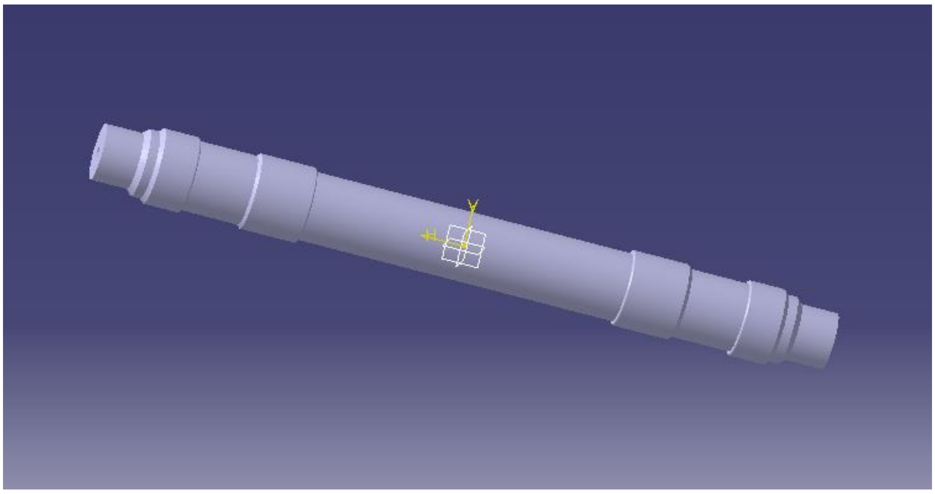
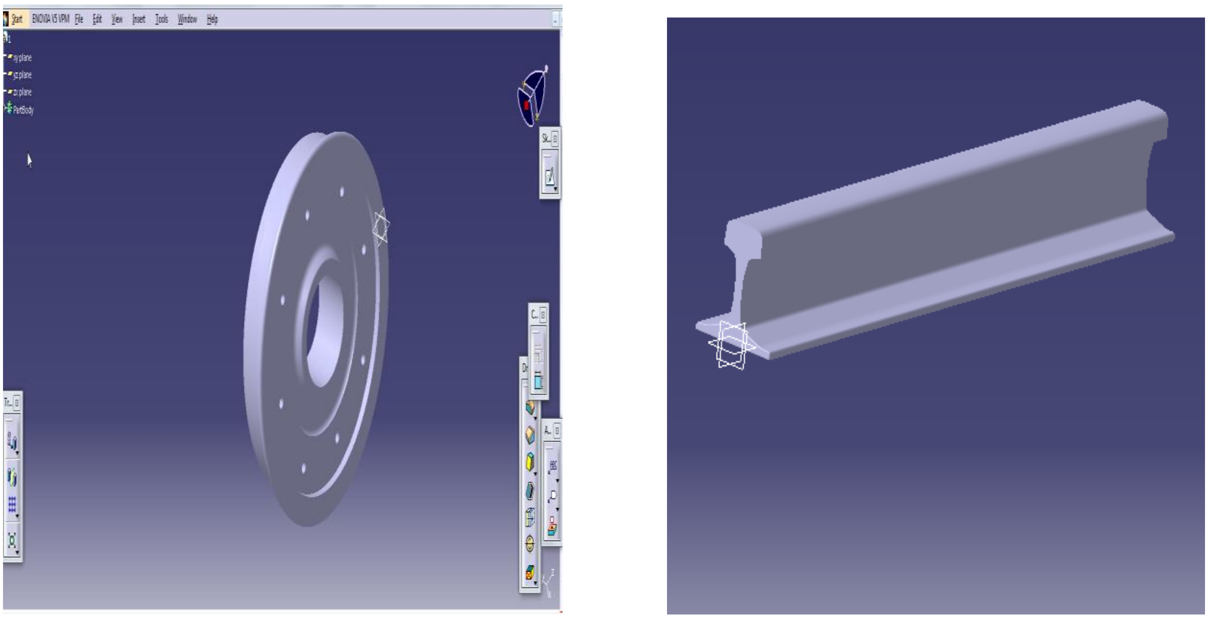


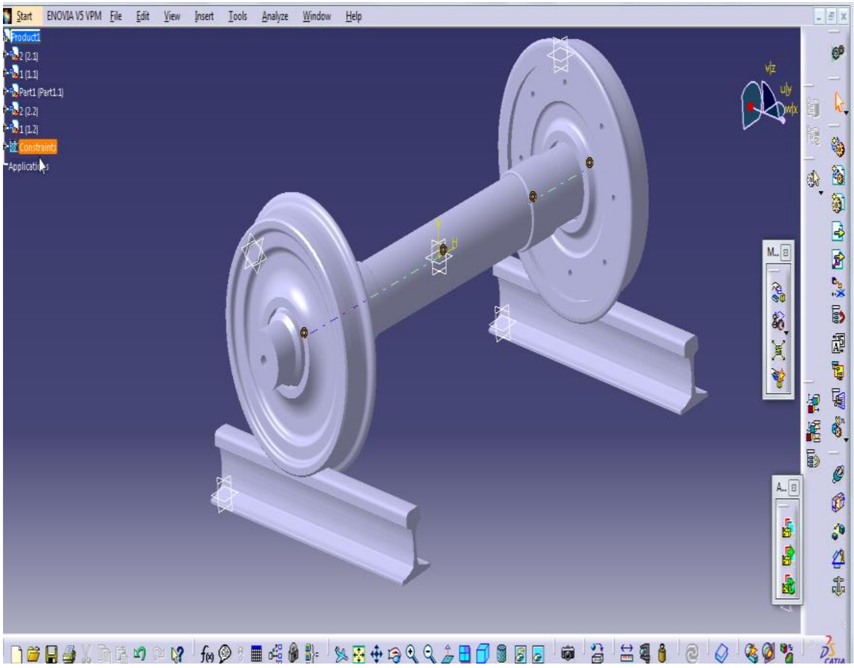
Figure 4.12: axle model



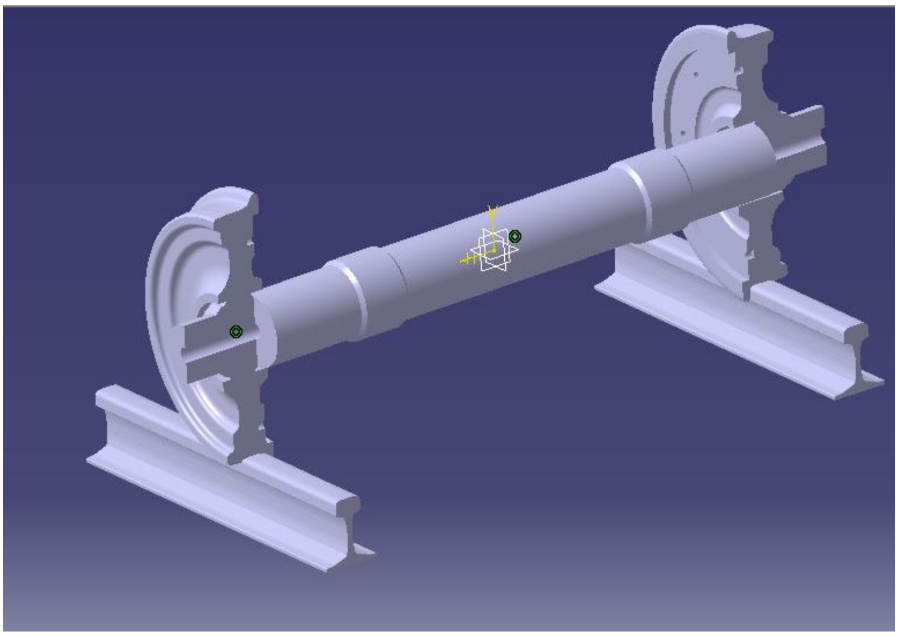
(a) (b)

Figure 4.13: (a) and (b) wheel and Rail model

4.9.1Wheel set assembly modelling



(a)



(b)

Figure 4.14: (a) and (b) wheel set models

Chapter Five

5. Results and discussion

5.1 Reviewing fatigue results

In ANSYS Workbench, there are nine results for evaluating fatigue, some of these are:

1. **Life:-**This result contour plot shows the available life for the given fatigue analysis. If loading is at constant amplitude, this represents the number of cycles until the part will fail due to fatigue. If loading is non-constant, this represents the number of loading blocks until failure. Thus if the given load history represents one month of loading and the life was found to be 120, the expected model life would be 120 months. In a constant amplitude analysis, if the alternating stress is lower than the lowest alternating stress defined in the S-N curve, the life at that point will be used.

2. **Damage:-**Fatigue damage is defined as the design life divided by the available life. The default design life may be set through the options dialog box. A damage of greater than 1indicates the part will fail from fatigue before the design life is reached.

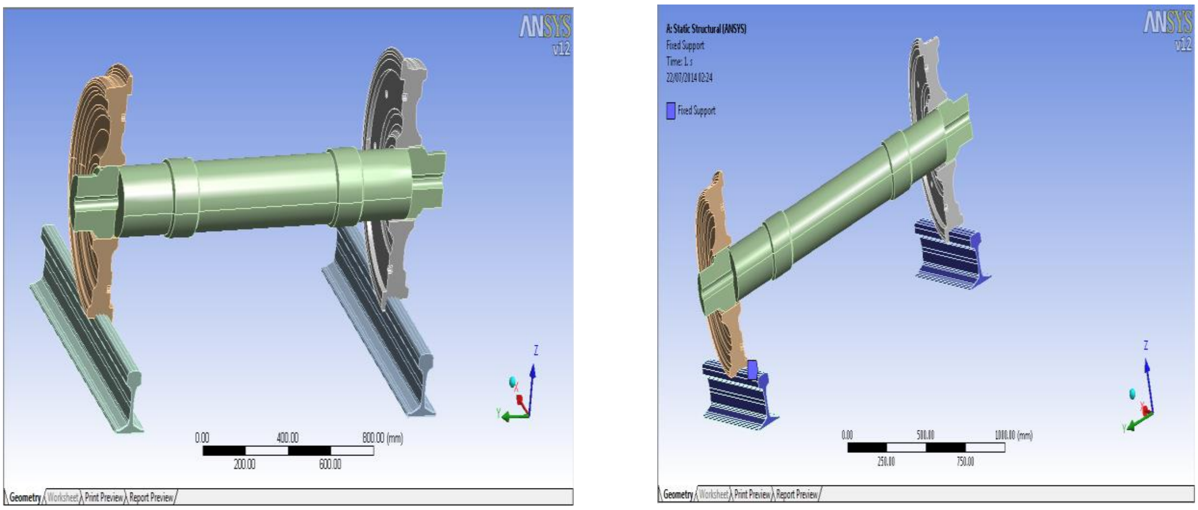
3. Fatigue Sensitivity:-This plot shows how the fatigue results change as a function of the loading at the critical location on the scoped region. Sensitivity may be found for life, damage, or factory of safety. For instance, if you set the lower and upper fatigue sensitivity limits to 50% and 150% respectively, and your scale factor to 3, this result will plot the data points along a scale ranging from a 1.5 to a 4.5 scale factor. You can specify the number of fill points in the curve, as well as choose from several chart viewing options (such as linear or log-log).

4. Damage matrix (history data only):-this graph depicts how much relative damage each bin has caused. This result can give you information related to the accumulation of the total damage (such as if the damage occurred though many small stress reversals or several large ones).

5. Strain life analysis:−Since the strain-life method is equation based it has no built-in limit, unlike stress-life for which the Fatigue Tool uses a maximum life equal to the last point on the SN curve. Thus to avoid skewed contour plots showing very high lives, you can specify Infinite Life in a strain-life analysis. For example, if you set a value of 1e9 cycles as the Infinite Life, the maximum life reported is 1e9.hence this option is used for the analysis of this thesis work. [36]

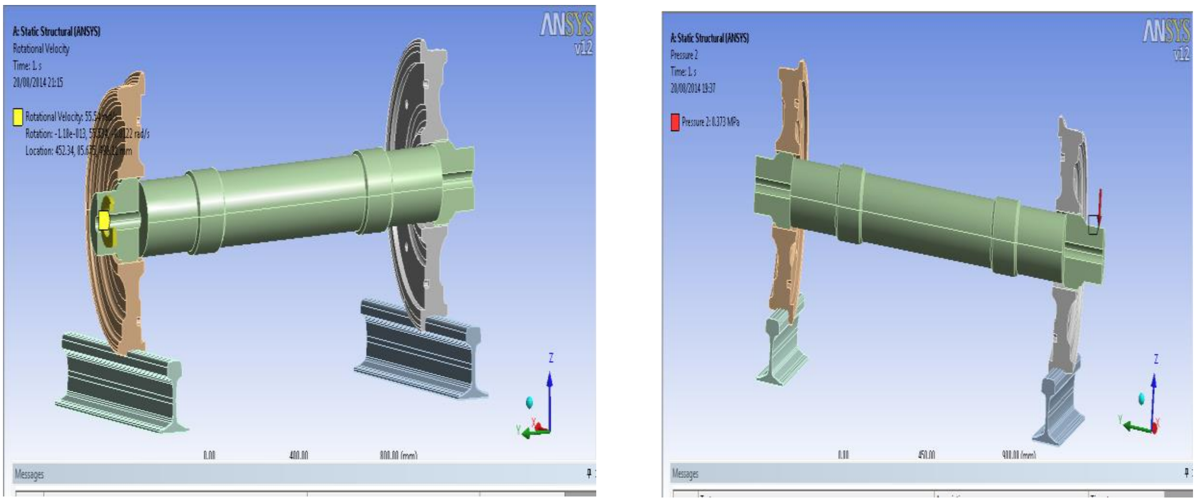
5.2 Static analysis case

In this case the rail is considered to be a fixed support so that the analysis is done to see the effects of coefficient of friction at the interference fittings of the axle and wheel. Here the bending load, contact pressure and tangential force are considered to be constant; though the increment of those decreases the fretting fatigue strength of the wheel set.



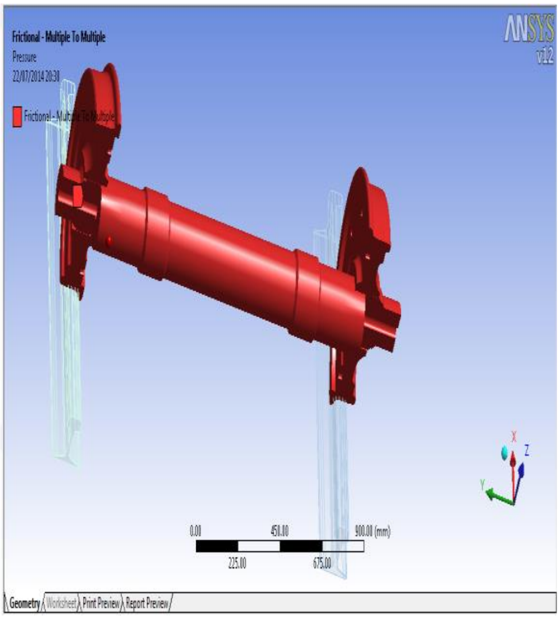
(a) (b)

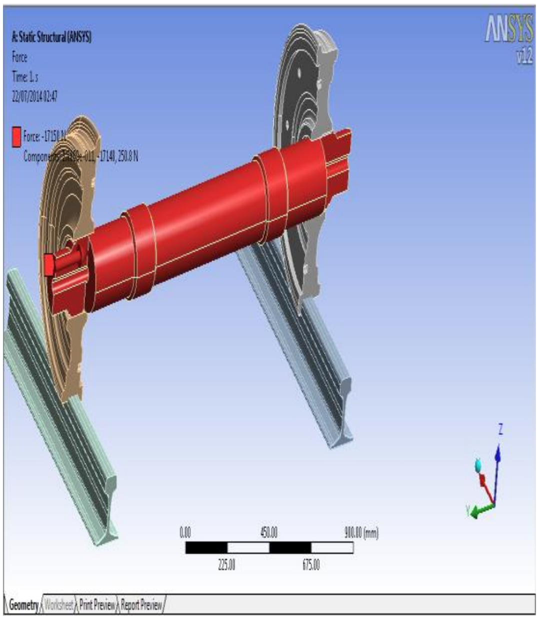
Figure 5.1: (a) and (b) importing into ANSYS and fixed support respectively



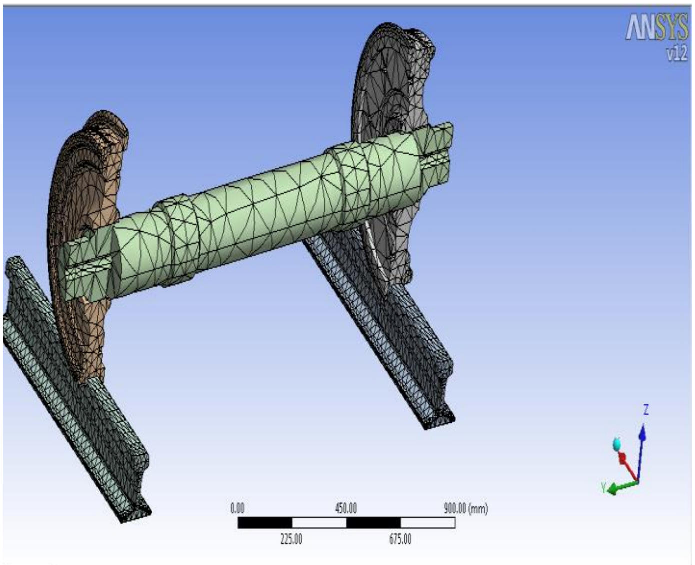
(c) (d)

Figure 5.2: (c) and (d) applying rotational velocity and pressure respectively





(e) (f)



(g)

Figure 5.3: (e), (f) and (g) application of friction force, tangential force and meshing

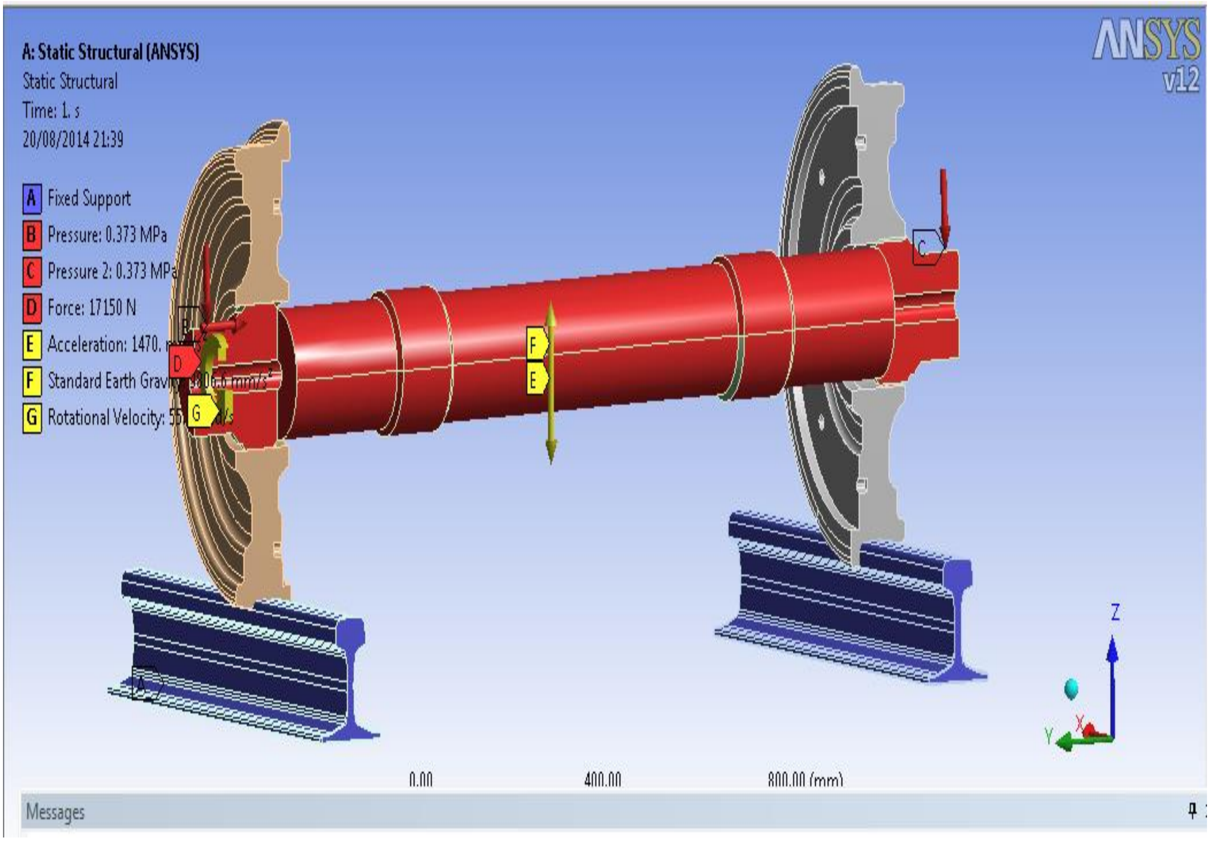
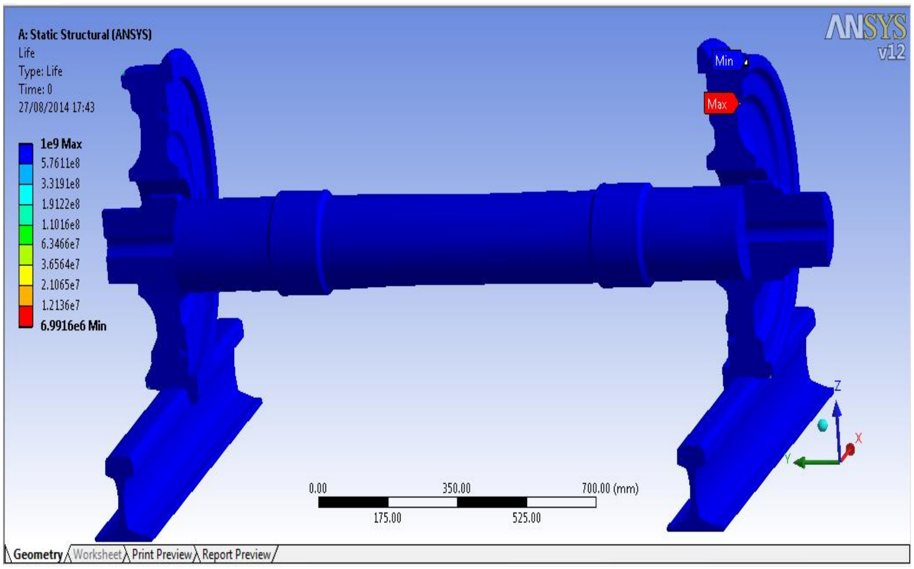
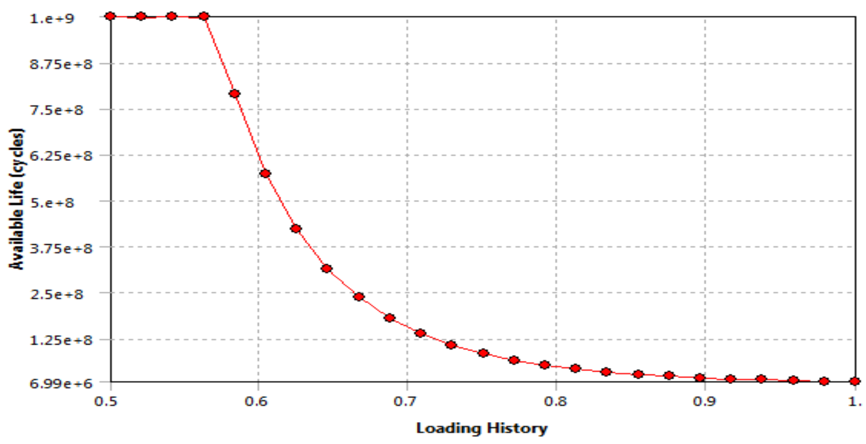


Figure 5.4: Interacting forces for the formation of fretting

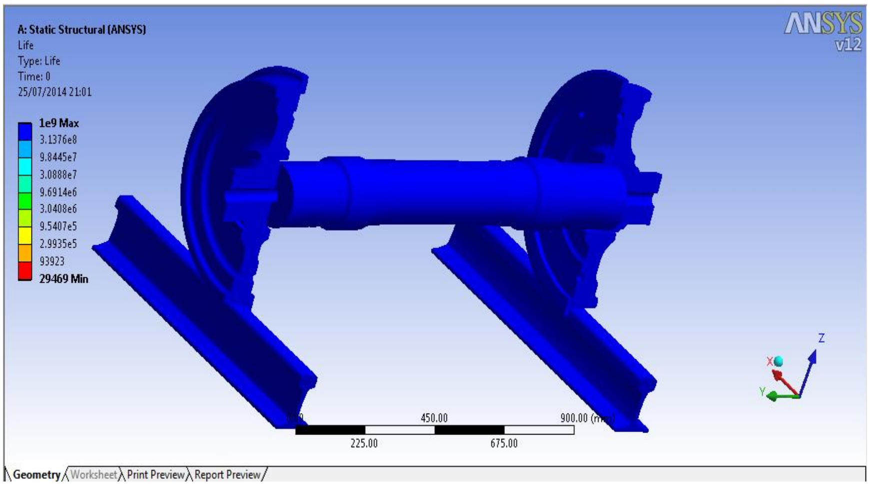


(a)

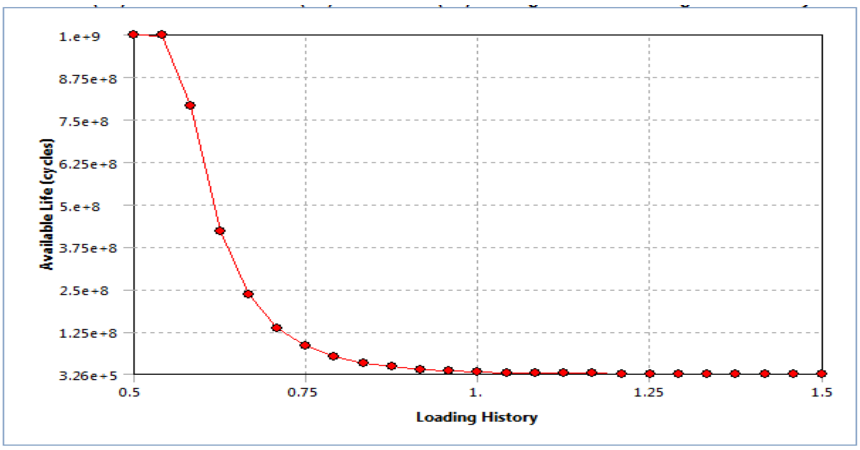


(b)

Figure 5.5: (a) and (b) Fretting fatigue at u=0.1

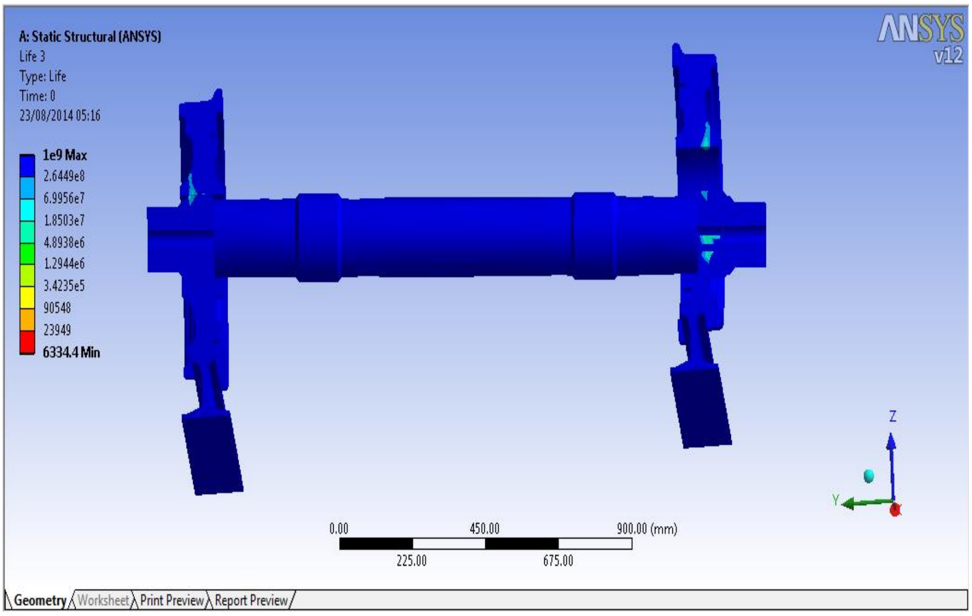


(c)

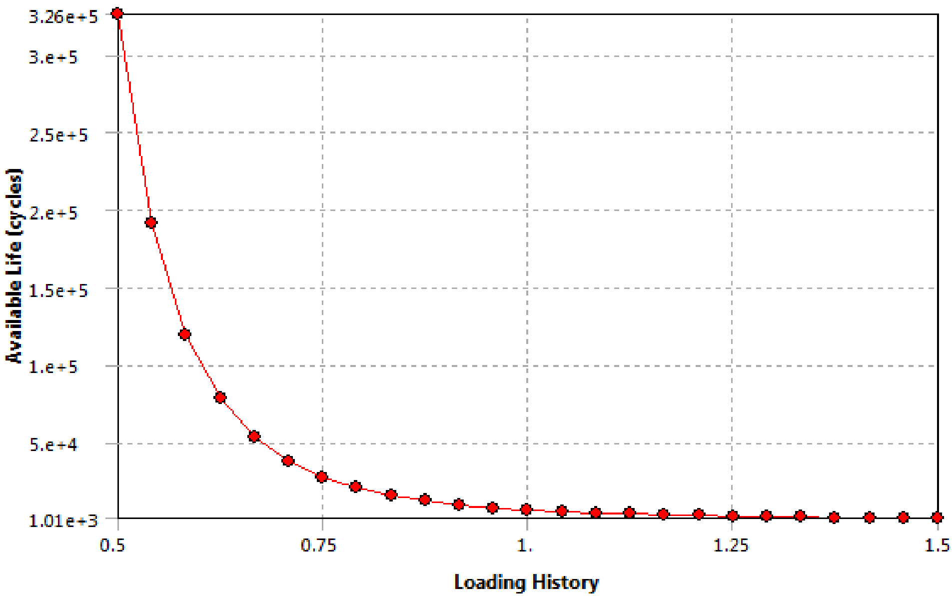


(d)

Figure 5.6: (c) and (d) Fretting fatigue at u=0.2



(e)



(f)

Figure 5.7: (e) and (f) Fretting fatigue at u=0.3

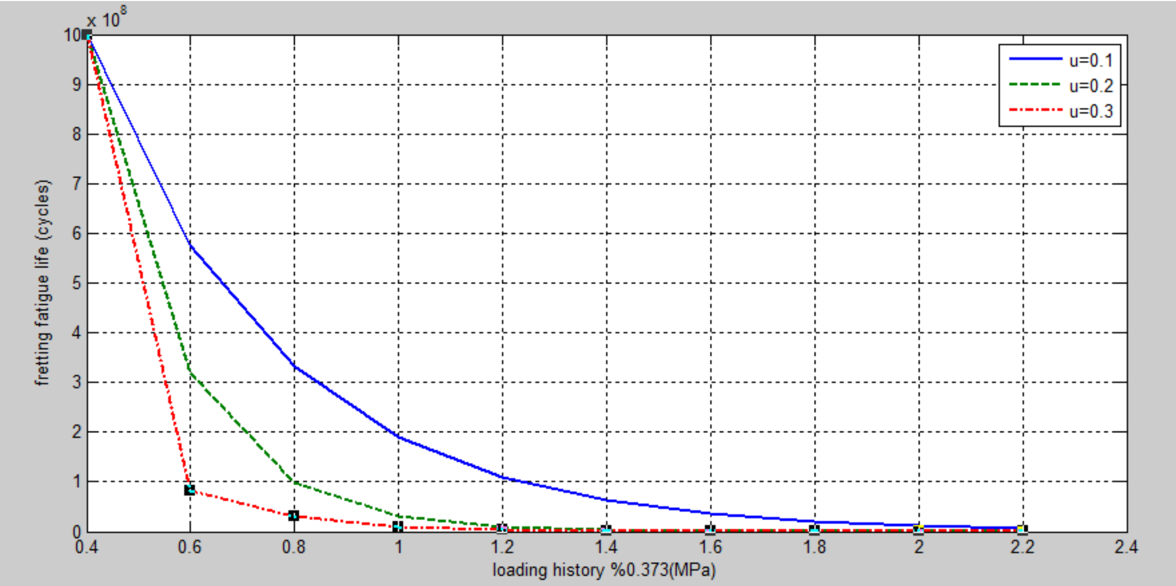


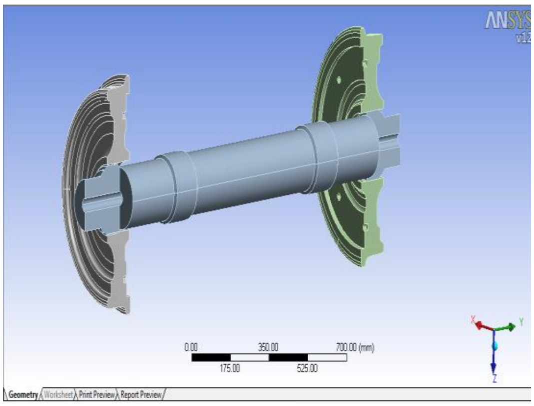
Figure.5.8: effect of friction coefficient on fretting fatigue life

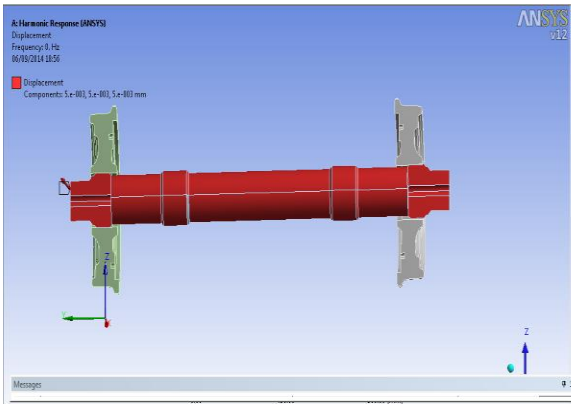
5.2.1 Discussion of results

As we can see from **figures 5.5, 5.6** and **5.7** the analysis is done by using maximum bending stress as 0.373Mpa, maximum tangential force as 17150N and rotational velocity of wheel as 55.54 rad/s. From this, as the friction coefficient is increased from 0.1 to 0.3 the fretting fatigue life of the wheel set is decreased so that it will be very susceptible to form cracks and fail as a hole. Similarly **figure 5.8** shows the inverse relation between friction coefficient and fretting fatigue life which is plotted in **mat lab** software for different loading history.

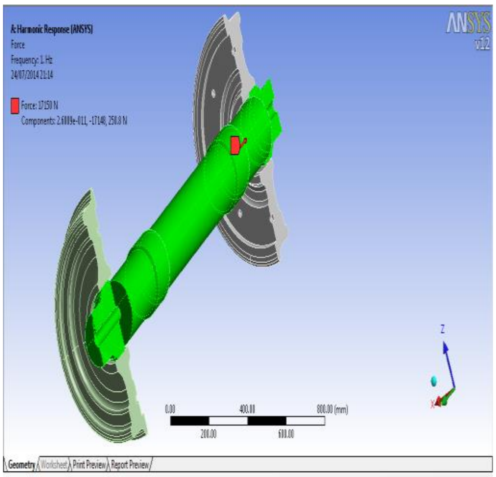
5.3 Harmonic analysis case

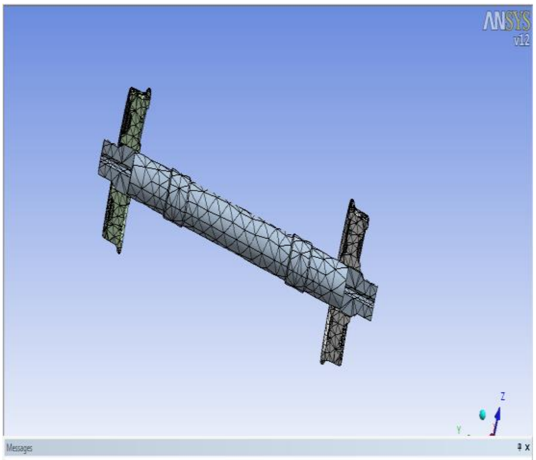
In this case the wheel and axle are considered to have displacements (instead of fixed supports) so that the analysis is done to see the effects of frequency and slip amplitudes. Here also the bending load, contact pressure and tangential force are considered to be constant; though the increment of those decreases the fretting fatigue strength of the wheel set as that of the static analysis case.



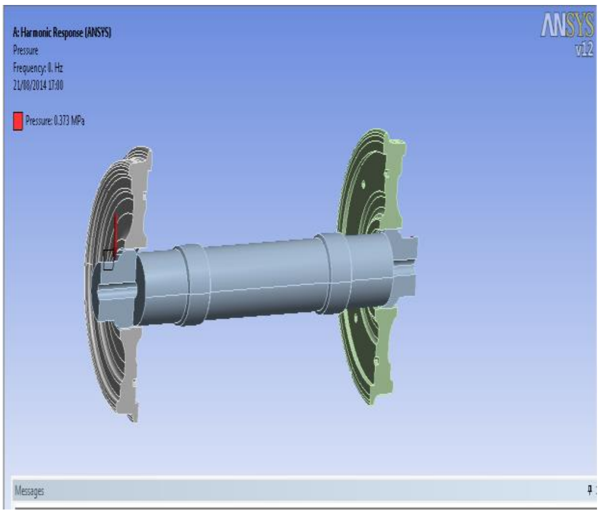


(a) (b)





(c) (d)



(e)

Figure 5.9: importing into ANSYS(a) aplication of slip amplitude(b) ,tangential force (c) meshing (d)and pressure(e) respectively

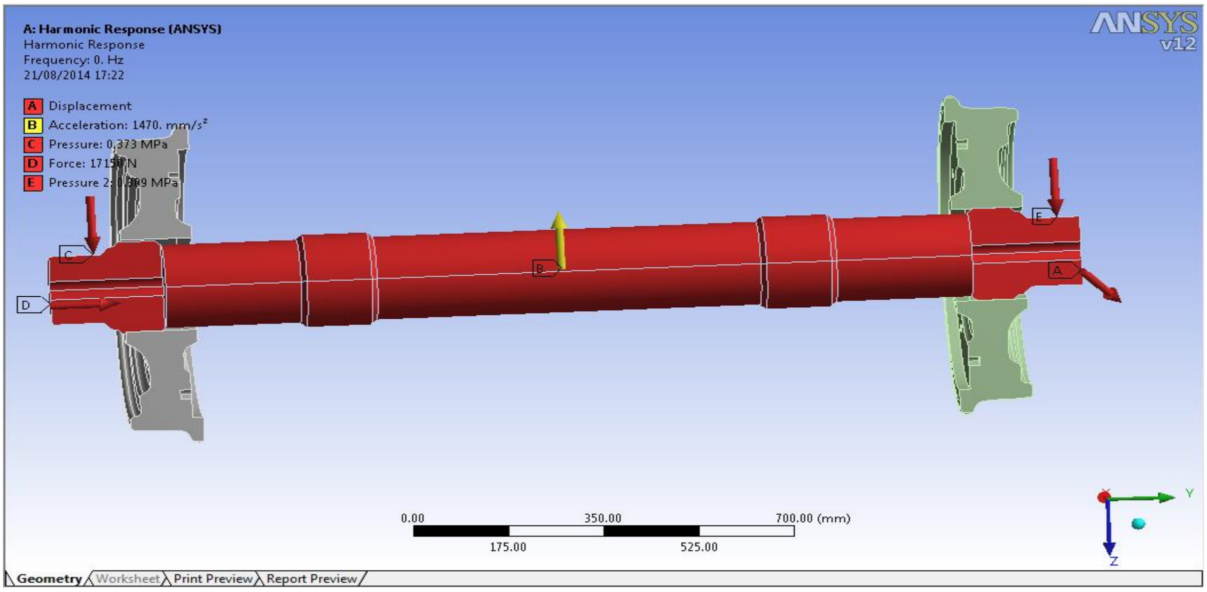
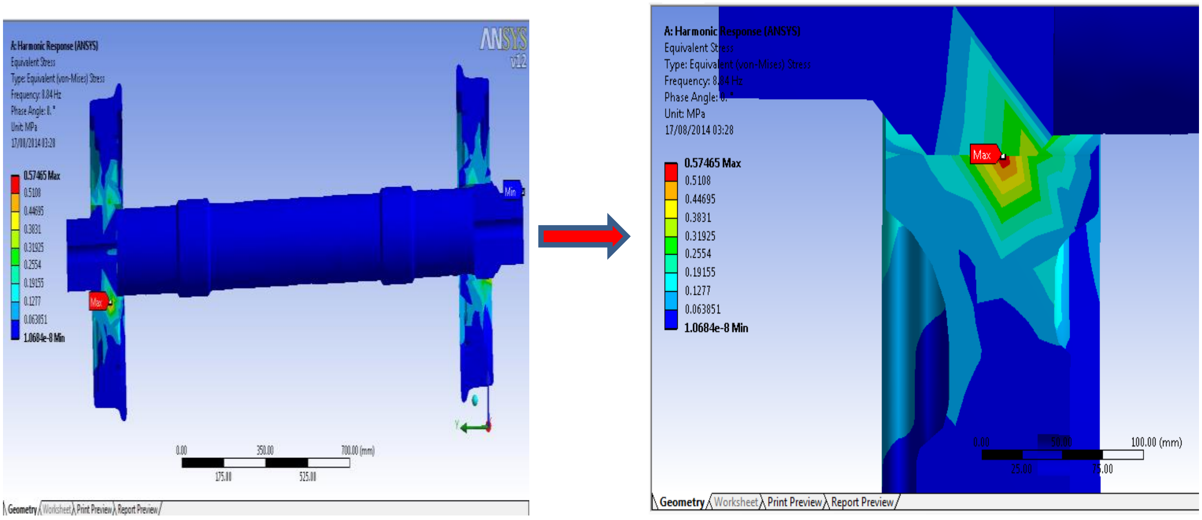
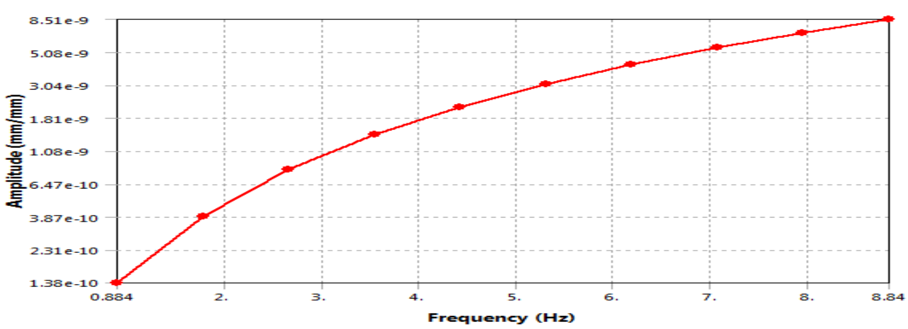


Figure 5.10: interacting forces for harmonic case

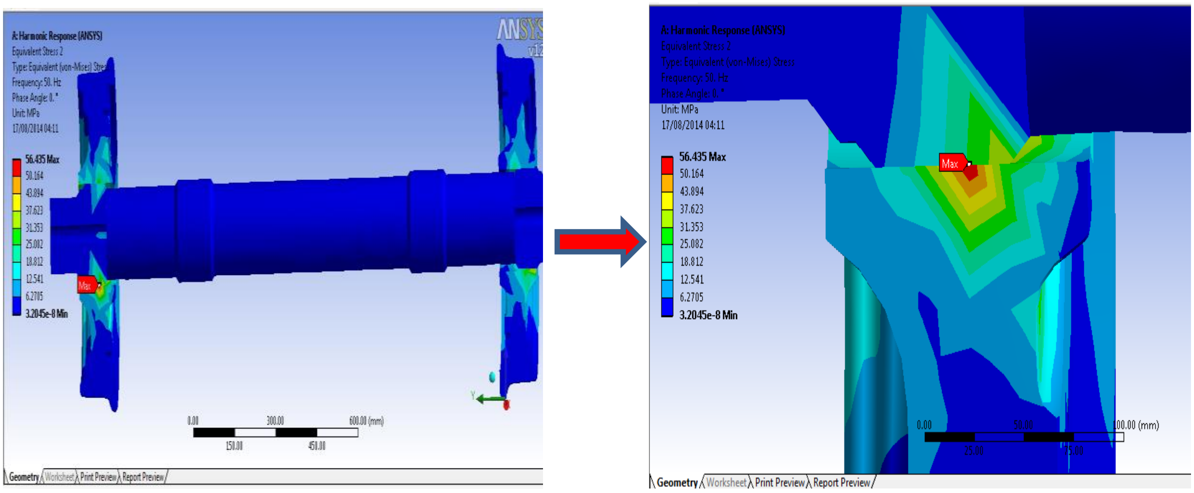


(a)

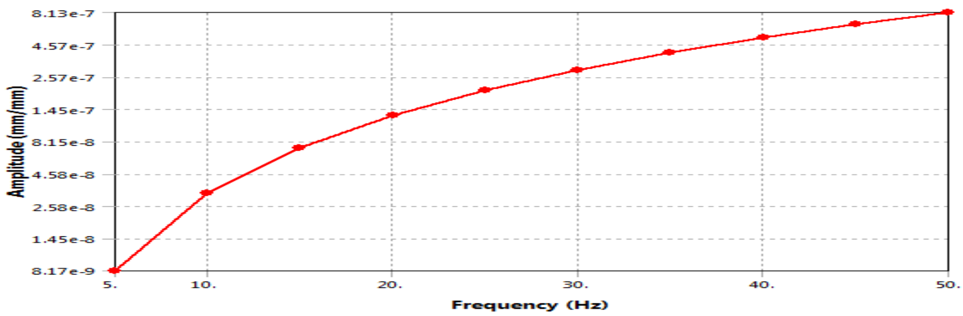


(b)

Figure 5.11: (a) and (b) Frequency response At f=8.84Hz and l =5μm

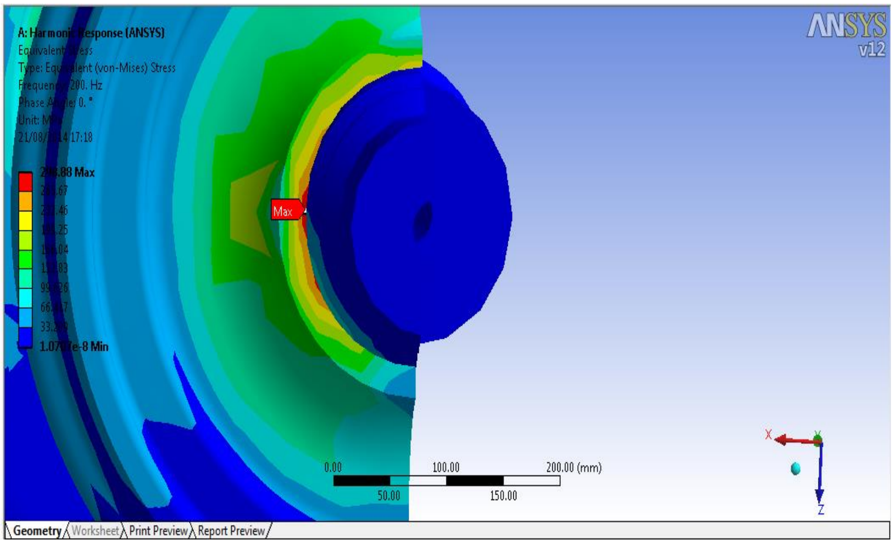


(c)

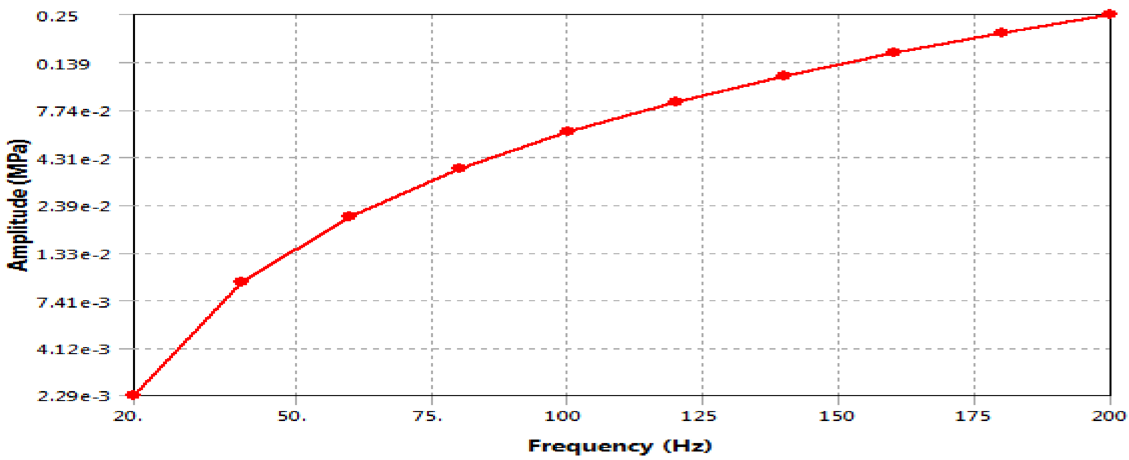


(d)

Figure 5.12: (c) and (d) Frequency response at f=50HZ and l=15μm



(e)



(f)

Figure 5.13: (e) and (f) Frequency response at f=200HZ and l=25μm

5.3.1 Discussion of results

As we can see from **figures 5.12,5.13** and **5.14** the analysis is done with similar manner as that of the static case .hence as the frequency and slip amplitude increase from 8.84 up to 200 (Hz) and 5 upto 25(μm) respectively, we can see that the fretting damage enlarges at the fitting and contact points of the axle-wheel assembly;hence this tends to form craks and increase failure rate.

5.4. summary of static and harmonic analysis cases

In this thesis work ,after having calculated the fretting bending load,tangential contact load freqency and rotational velocity; it is observed that the wheel set which chosen for this analysis is less succeptible to fretting damage for friction coefficient of(μ=0.16) which is the current working friction coefficient of the Addis Ababa city tram. But this does not mean that fretting damage does not exist ;however,fretting is observed to occur starting from amplitudes of 5(μm) and frequency of 8.84(Hz). So in general even if it is difficult to eliminate fretting damages,but it is easy to reduce their effect of forming cracks as well failures by using the following points.

5.5. Prevention of fretting damage

Here are some of the major fretting damage reducing mechanisms in railway wheel set.

5.5.1 Improved design. Because fretting only arises where there is relative movement between two surfaces, the reduction of this movement is a prime objective.

Fretting often arises as a result of a stress concentration. In any case, reducing the stress via improved design in this case; eliminating stress-relieving grooves in wheel-axle assemblies and increasing the fillet zone in the axle is demanded.

5.5.2 Surface finish. Rough surfaces are less prone to fretting damage than highly polished surfaces. Rough surfaces can be obtained by shot peening with glass beads or steel shot. Shot peening has the advantage of work hardening the surface, although the residual compressive stress appears to have little effect on the wear process; however, it has a considerable effect if fatigue crack initiation and propagation is involved. Shot peening is often applied as a surface preparation for the application of coatings.

5.5.3 Coatings. Surface treatments that radically change the chemical composition of the surface can be divided into three categories:

(1): Methods where foreign atoms or ions are introduced into the existing surface by diffusion (for example carburizing, nitriding ,chromizing,sheradizing and aluminizing).

(2): Methods where the surface reacts with a chosen environment to form a compound (for example, oxidation, anodizing, and phosphating).

(3): Methods where an entirely foreign material is applied to the surface (for example, electro deposition, plasma spray, ion plating, physical vapour deposition [PVD], and chemical vapour deposition [CVD]

Most of these coatings are harder and consequently more brittle than the substrate, which, if it is not strong enough, will plastically deform in the fretting contact, where local stresses can be high. This plastic deformation will crack and break up the coating.

Carburizing and nitriding of steels is a well-established treatment for reducing wear and is also effective against fretting. Electrodeposited coatings are extensively used in electrical contacts; gold alloys are the preferred coating because they are not subject to oxide formation, which is disastrous in its effect on conductivity.

The growth of oxide films at high temperatures has been specified above to provide wear-resistant self-repairing coatings. These have been improved by ion implantation, particularly in titanium alloys, to give coatings that have low friction and low wear.

Anodizing is applied to aluminium alloys and the hard coating provides protection against fretting, but it may cause wear of the opposing surface.

5.5.4 Inserts. Separation of the two surfaces by an insert, either a shim of a soft metal or a shim of a polymer with a low elastic modulus, will sometimes be effective. The intention is to take up the movement by either plastic deformation or elastic deformation of the material. A combination of metal and polymer can be more effective because it combines the advantages of both materials the low elasticity of the polymer and the good conductivity of the metal. Bronze-filled polytetrafluorethylene (PTFE) when fretted against steel has a very low friction coefficient and undetectable wear.

5.5.5 Lubricants. Lubricants are usually difficult to apply in fretting contacts because of the difficulty of maintaining the lubricant in the contact, but lubricants are included in the construction of steel ropes (for example, locked coil ropes).In a survey of the effect of additives to a base mineral on the fretting wear of steel surfaces, zinc di*n*octyldithiophosphate was found to be most effective. Solid lubricants applied to the surfaces such as molybdenum disulphide (MoS2) reduce the coefficient of friction initially, but eventually tend to wear away.[23, 37]

Chapter six

6.Conclusion,recommendation and future works

6.1 Conclusion

In this thesis work,the effects of friction coefficient,slip amplitude and frequency on fretting fatigue strength of wheel set is observed using finite element analysis (FEA) work bench.CATIA software is also used for modelling the various wheel set parts and then the final assembly.In additin to this bending loads ,tangential force,material properties ,contact pressures do have a tremendous decrement in the fretting faigue strength of the wheel set; although they are taken to be constant for the analaysis of this thesis work.similarly the mathematical model developed supports this.generally the following points may be raised.

- The friction coefficient which is available now for the Addis Ababa Light Rail train is about (μ=0.16) ;hence this seems to be safe in the analysis made from μ=0.1 to 0.3
- Increament in Friction coefficient does have an effect of reducing the life of wheel set
- Slip amplitude and frequency also play a greater role in the reduction of fretting fatigue strength of wheel sets
- The fretting fatigue strength developed mathematicaly is comparable to that of ANSYS software with regard to the effects of friction,amplitude and frequency.
- it can be predicted that usage of inserts ,lubricants ,coatings etc can decrease the fretting damages that arise at the fitting zones of wheel set.

6.2 Recommendation

Due to shortage of time, experimental equipments and labaratories this thesis is restricted for some instances;however it is also possible to predict the fretting damage analysis mathematicaly and using(FEA)as the results domenstrate this.finally since fatigue is a progrssive process in nature;it is difficult to set the exact friction coefficient,amplitude and frequency which leads to the formation of fretting.but it is recommended to use lubricants,coatings,shot peening ,desighn modification and inserts for the minimization of fretting damage during the periodic maintainance and operation as well.having done this

,the(LRT) vehicle will be free of risks and the cost which will be used for the maintainance of wheel set will be minimized.

6.3 Future works

In this thesis work effects of friction coefficient, slip amplitude, bending load, tangential contact force, slip amplitude and frequency is observed on the fretting fatigue strength of axle-wheel assembly. Even if fretting fatigue is the dominant factor that is formed in the fitting zones of wheel set the following points may be studied further in the fretting damage analysis.

- Effect of fretting wear in wheel set using software's
- Effect of fretting corrosion
- Experimental measurement of fretting fatigue and fretting wear cracks in wheel set
- Fretting damage in motor, gear seat and disc brakes of the wheel set.
- Effect of surface roughness in fretting damage etc.

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