FAILURE ANALYSIS OF BUCKET ELEVATOR 
CONVEYOR CHAIN LINKS 

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(Mechanical Engineering) 

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Failure Analysis of Bucket Elevator Conveyor Chain Links

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A thesis submitted in partial fulfillment for the degree of Master of Science in Mechanical Engineering in the Jomo Kenyatta University of Agriculture and Technology

2017
DECLARATION

This thesis is my original work and has not been presented for a degree or any other purpose in this or any other university.

Signature.......................... Date.................................

Edward Yin

This thesis has been submitted for examination with our approval as the University Supervisors:

Signature.......................... Date.................................

Dr. Onesmus M. Muvengei, PhD
JKUAT, Kenya

Signature.......................... Date.................................

Eng. Prof. John M. Kihiu, PhD
JKUAT, Kenya
DEDICATION

I dedicate this thesis to my family who have been by my side throughout my study period.
ACKNOWLEDGEMENTS

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# TABLE OF CONTENTS

**COVER PAGE** ......................................................... i  
**DECLARATION** ....................................................... ii  
**DEDICATION** ........................................................ iii  
**ACKNOWLEDGEMENT** ............................................... iv  
**TABLE OF CONTENTS** ............................................. v  
**LIST OF FIGURES** ................................................ viii  
**LIST OF PLATES** .................................................. xi  
**LIST OF TABLES** .................................................. xiii  
**LIST OF ABBREVIATIONS** ...................................... xiv  
**LIST OF SYMBOLS** ................................................ xv  
**ABSTRACT** .......................................................... xvi  
**CHAPTER ONE** ..................................................... 1  
**INTRODUCTION** .................................................... 1  
1.1 Background ...................................................... 1  
1.2 Bucket Elevators ............................................... 2
1.3 Conveyor Chains and their Failure ........................................... 4
1.4 Problem Statement ................................................................. 10
1.5 Objectives ............................................................................. 13
   1.5.1 Specific Objectives .......................................................... 13
1.6 Scope of Work ....................................................................... 13
1.7 Organization of the Thesis ....................................................... 13

CHAPTER TWO ............................................................................. 15

LITERATURE REVIEW ................................................................. 15
   2.1 Failure Analysis of Conveyor Chain ......................................... 15
   2.2 Types of Failure .................................................................. 27
   2.3 Modeling and Simulation ....................................................... 28
   2.4 Scanning Electron Microscope ............................................... 29
   2.5 Energy Dispersive Analysis by X-Ray ...................................... 31
   2.6 Summary ............................................................................ 32

CHAPTER THREE .......................................................................... 33

METHODOLOGY .......................................................................... 33
   3.1 Visual Examination .............................................................. 33
   3.2 Chemical Analysis ............................................................... 35
   3.3 Metallography ...................................................................... 39
      3.3.1 Polishing of Samples ....................................................... 41
# LIST OF FIGURES

| Figure 1.1 | Central chain bucket elevator | 2 |
| Figure 1.2 | Central chain and belt bucket elevators | 3 |
| Figure 1.3 | Graph of Year versus frequency of failure | 6 |
| Figure 1.4 | Basic structure of roller conveyor chain | 7 |
| Figure 1.5 | General approach to failure analysis investigations | 9 |
| Figure 1.6 | Typical chain link assembly | 12 |
| Figure 2.1 | Progressive marks and striations during fatigue crack propagation | 17 |
| Figure 2.2 | Stress zone in the chain link | 19 |
| Figure 2.3 | Cracking zone at chain bracket | 20 |
| Figure 2.4 | Visual appearance and Optical micrograph | 21 |
| Figure 2.5 | Relation between fatigue life and oxygen content of bearing steels | 29 |
| Figure 2.6 | Striking of high energy electrons on sample | 30 |
| Figure 2.7 | Interaction volume in an SEM sample | 31 |
| Figure 3.1 | Block diagram for mass spectrometer | 37 |
| Figure 3.2 | High energy beam source | 38 |
| Figure 3.3 | Modes of crack propagation | 41 |
| Figure 3.4 | Flowchart for metallographical analysis | 45 |
Figure 3.5 Comparing CAD models for existing and designed chain links .......................... 46

Figure 3.6 CAD model showing distance X ................................................................. 47

Figure 3.7 CAD models for designed chain links ....................................................... 49

Figure 3.8 Meshing of designed chain link ............................................................... 50

Figure 3.9 Crack introduction into the designed chain link ...................................... 52

Figure 3.10 Modeled crack ...................................................................................... 52

Figure 4.1 Simulation results for chain link without a modeled crack
with neck radius 0 mm ......................................................................................... 71

Figure 4.2 Simulation results for chain link without a modeled crack
with neck radius 500 mm .................................................................................. 72

Figure 4.3 Simulation results for chain link without a modeled crack
with neck radius 621.5 mm .............................................................................. 73

Figure 4.4 Simulation results for chain link without a modeled crack
with neck radius 831.9 mm .............................................................................. 74

Figure 4.5 Simulation results for chain link without a modeled crack
with neck radius 1245.5 mm ........................................................................... 75

Figure 4.6 Simulation results for chain link without a modeled crack
with neck radius 2488.4 mm ........................................................................... 76

Figure 4.7 A graph of results for designs with different neck radii
without modeled crack ...................................................................................... 78
Figure 4.8  Simulation results for chain link with a modeled crack with
neck radius 0 mm  . . . . . . . . . . . . . . . . . . . . . . . . . 79

Figure 4.9  Simulation results for chain link with a modeled crack with
neck radius 500 mm  . . . . . . . . . . . . . . . . . . . . . . . . . 80

Figure 4.10 Simulation results for chain link with a modeled crack with
neck radius 621.5 mm  . . . . . . . . . . . . . . . . . . . . . . . . . 81

Figure 4.11 Simulation results for chain link with a modeled crack with
neck radius 831.9 mm  . . . . . . . . . . . . . . . . . . . . . . . . . 82

Figure 4.12 Simulation results for chain link with a modeled crack with
neck radius 1245.5 mm  . . . . . . . . . . . . . . . . . . . . . . . . . 83

Figure 4.13 Simulation results for chain link with a modeled crack with
neck radius 2488.4 mm  . . . . . . . . . . . . . . . . . . . . . . . . . 84

Figure 4.14 A graph of results for designs with different neck radii with
modeled crack  . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 86
LIST OF PLATES

Figure 1.1 Failed chain links ........................................... 5

Figure 3.1 Sectioning of failed sample ............................. 35

Figure 3.2 Chemical analysis using mass spectrometer ............. 39

Figure 3.3 Grinding on silicon carbide papers .......................... 42

Figure 3.4 Drying of specimen .......................................... 43

Figure 3.5 Polished sample ............................................. 44

Figure 4.1 Indentations on the chain link ............................. 55

Figure 4.2 Cracks initiation from inclusions from failed samples ... 56

Figure 4.3 Fracture mechanism .......................................... 57

Figure 4.4 Fracture initiating from the boundary ....................... 58

Figure 4.5 Defects on the un-failed Samples ......................... 61

Figure 4.6 Micro-structure for un-failed chain link sample showing inclusions for samples 1 to 4 ................................. 63

Figure 4.7 Microstructure for un-failed chain link sample showing inclusions for samples 5 to 8 .............................................. 64

Figure 4.8 Microstructure for failed chain link sample showing inclusions for samples 1 to 4 ...................................................... 65

Figure 4.9 Microstructure for failed chain link sample showing inclusions for samples 5 to 8 ...................................................... 66
Figure 4.10 Cracks within material .................................................. 67
Figure 4.11 Cracks initiation from inclusions from failed samples ... 68
Figure 4.12 Cracks initiation from boundary .................................... 69
### LIST OF TABLES

**Table 1.1** Historic Failure Data on Conveyor Chains Obtained from East African Portland Cement  

| Table 1.1 | Historic Failure Data on Conveyor Chains Obtained from East African Portland Cement | 6 |

**Table 1.2** General Information on Bucket Elevator  

| Table 1.2 | General Information on Bucket Elevator | 12 |

**Table 3.1** Corresponding radii for distance X  

| Table 3.1 | Corresponding radii for distance X | 47 |

**Table 4.1** Results of Chemical Analysis for Failed Sample  

| Table 4.1 | Results of Chemical Analysis for Failed Sample | 59 |

**Table 4.2** Simulation Results for Different Neck Radii without a modeled Crack  

| Table 4.2 | Simulation Results for Different Neck Radii without a modeled Crack | 77 |

**Table 4.3** Simulation Results for Different Neck Radii with a modeled Crack  

| Table 4.3 | Simulation Results for Different Neck Radii with a modeled Crack | 85 |
**LIST OF ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANSYS</td>
<td>Analysis System</td>
</tr>
<tr>
<td>EDX</td>
<td>Energy Dispersive X-Ray</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>IC</td>
<td>Internal Combustion</td>
</tr>
<tr>
<td>HAZ</td>
<td>Heat Affected Zone</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>EN</td>
<td>European Standard</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

\( P \) \hspace{1cm} \text{Power rating \([W]\)}

\( F \) \hspace{1cm} \text{Force \([N]\)}

\( v \) \hspace{1cm} \text{Linear velocity \([ms^{-1}]\)}
ABSTRACT

Although designers and manufacturers continue to strengthen the links between design, manufacturing and performance, failures still occur and will continue to occur for one reason or another. In view of this, the cause or reason for failure is paramount for future designs. Chain bucket elevator drives are among the primary systems used in the cement industry to convey powdered cement vertically. Conveyor chain components that suffer premature failure need to be replaced on a frequent basis, negatively impacting on productivity and increasing the cost of the operation.

The main objective of this research is to determine the cause of failure of the chain links of a bucket elevator by carrying out failure analysis on both failed and un-failed chain link samples. The specific objectives of this research are to determine the point of initiation of the fracture, analyse the mechanism of failure and design new component to minimize future failure and test its performance through modeling and simulation.

Failure analysis was performed on failed and un-failed chain link samples obtained from East African Portland Cement. The methodology adopted included preliminary examination, metallurgical analysis and chemical analysis.

Preliminary examination done on ten failed samples of chain links using stereo microscope revealed a brittle fracture and chevron marks showed that the fracture began either from the core or boundary of the fractured surface and progressed
through the material until eventual fracture occurred. The point of fracture initia-
tion was dependent on where the inclusion was located either at the boundary or
the core. Metallurgical analysis done on both failed and un-failed chain link sam-
pies revealed that the micro-structure for both was that of a tempered martensite.
The un-failed chain link sample has a lot of blow holes and inclusions which are
as a result of a manufacturing defect within it but showed no crack within it.
The failed chain link samples observed under an optical microscope revealed a
lot of cracks on the fractured surface which propagated during loading. Chemical
analysis revealed that the carbon content for sample 1, 2, 3, 4 and 5 were 0.131%,
0.133 %, 0.135 %, 0.202 % and 0.129 % respectively, which was below the required
range of 0.27-0.34 % according to European standard EN 10293. Carbon increases
the hardness of steels. The reduced carbon content improved the ductility of the
steel. The cause of failure was deduced to be as a result of inclusions from which
the cracks had initiated from. The existing chain link design was improved by
re-designing to eliminate the neck. The chain link was tested through modeling
and simulated using analysis system simulation software. The results obtained
from the modeling and simulation show that the new design is an improvement on
the existing design as it had better fatigue life, deformation, safety factor and von
Mises stress than the existing design. The fatigue life increased from $8.25 \times 10^{10}$
cycles to $1.08 \times 10^{11}$ cycles which was 23.61% improvement on the existing design
whilst the equivalent stress in the existing design reduced from 142 MPa to 133
MPa. The safety factor also increased from 3.77 to 4.26 where as the deformation
of 0.05644 mm in the new design was less compared to the existing design i.e. 0.06101 mm.

These results obtained are beneficial to the manufacturer of the bucket elevator conveyor chains in that during the manufacturing process of the conveyor chain links, due diligence will be accorded not only to the carbon content but also all other constituent elements so that they meet the required standards. As a result of improved manufacturing process and design of the conveyor chain links, the user (East African Portland Cement) will be supplied with improved conveyor chain links. The improved conveyor chain link will minimize down-time thereby increasing productivity.
CHAPTER ONE

INTRODUCTION

1.1 Background

Failure of chain links of a bucket elevator is inevitable and for this reason, analysis of failure is very crucial to the continuous improvement of the chain links. As a result of continuous improvement of the chain links, down-time can also be minimized therefore increasing productivity.

Analyzing failure of machine components is a critical process in determining the root causes of failure. The process is complex, draws upon many different technical disciplines, and uses a variety of observations, inspection, and laboratory techniques [1]. Failure of engineering structures in industry can cause loss of life, unscheduled shutdowns, increased maintenance and repair costs, and damaging litigation disputes.

To prevent future recurrence of the problem, it is essential to carry out an investigation aimed at determining the root cause of failure. The results of the investigation can also be used as the basis for insurance claims, marketing purposes, and to develop new materials or improve the properties of existing ones.

When parts or assemblies fail, it can affect the delivery of goods, result in costly repairs, down time, and jeopardize the safety of people near the parts [2]. Failure analysis is therefore important in order to develop preventive measures thereby
minimizing the incidence of failure and reducing their associated costs to indus-
try.

1.2 Bucket Elevators

Central bucket elevators are basically designed to move granular materials ver-
tically through a height. The elevators use an endless chain/belt with a series of
buckets attached to it. The bulk material is spread into an inlet hopper where
the buckets dig into the material and convey it up and over the head sprocket.
Thereafter, the buckets throw the material out via a discharge spout [3] as shown
in Figure 1.1

![Figure 1.1: Central chain bucket elevator](image)

The buckets are then returned to the tail sprocket at the bottom. The bucket
elevator consists of [4]: buckets to contain the material, chain or belt drive to carry
the buckets and transmit the pull, means to drive the chain or belt, accessories for loading the buckets or picking up the material and for receiving the discharged material and accessories for maintaining the chain tension and for enclosing and protecting the elevator.

There are mainly two types of bucket elevators, namely; the belt and chain bucket elevator. The main difference between the two is that the former uses an endless belt with pulleys whilst the later uses an endless chain with sprockets as shown in Figure 1.2.

![Figure 1.2: Central chain and belt bucket elevators](image)

The buckets are designed to stay upright after scooping material to prevent spillage. The head is one of the major structural elements of the overall elevator. It supports the weight of buckets and chain, and also accommodates the drive and anti-run back device [5].
Elevators can be made using different types of materials. Structure and bracket materials can also be different. The materials used to construct the head structure vary depending on conveyed material, cost and appearance, which are specified by the customer. These materials can range from galvanized mild steel to stainless steel sheet. Mild steel is used when a painted finish is required and stainless steel when high moisture or corrosive materials are being conveyed \([5]\). This study will deal with chain bucket elevator where failure analysis will focus on the failure of the chain link.

1.3 Conveyor Chains and their Failure

From a theoretical viewpoint, the chain is a continuous flexible rack engaging the teeth on a pair of sprockets. A sprocket is a form of gear whose teeth are shaped to mesh with a chain. Based on its history and development, the chain is a mechanical belt running over sprockets that can be used to transmit power or convey materials. Chain strips are machine elements that are subjected to extreme service conditions, such as high tensile loads, friction, and sometimes aggressive operating environment which includes presence of humidity, seawater and chemicals, among others. Apart from tensile overload fracture, double shear is also a common failure mechanism which occurs under lower applied loads \([6]\). As these chains operate under various forces, failure of chain assembly is the major problem. The causes of these failures may include improper material selection, uncertainties in manufacturing and faulty manufacturing processes. Plate
1.1 shows failed chain link samples. From the data obtained from East African Portland Cement (EAPC). The chain links of the bucket elevator are the most vulnerable to failure compared to other machine components such as shaft, bearings, buckets, sprocket and the electric motor.

Plate 1.1: Failed chain links

It is important to study the material used, manufacturing process and service conditions which governs the failure modes of the chain [6].

It is often stated that history repeats itself but designers, manufacturers, and users do not want a repeat of history when it comes to the failure of components and equipment. The consequences and costs of fractured, cracked, corroded, and malfunctioned equipment are unwanted, dangerous and expensive. Through the years at East African Portland Cement history has demonstrated that failure of conveyor chain link do occur. Data compiled for the last five (5) years from 2012 to 2016 is as shown in Table 1.1 and Figure 1.3.

Figure 1.3 shows that for the five (5) year interval between 2012 and 2016, the
Table 1.1: Historic Failure Data on Conveyor Chains Obtained from East African Portland Cement

<table>
<thead>
<tr>
<th>Year</th>
<th>Frequency of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>33</td>
</tr>
<tr>
<td>2013</td>
<td>38</td>
</tr>
<tr>
<td>2014</td>
<td>41</td>
</tr>
<tr>
<td>2015</td>
<td>47</td>
</tr>
<tr>
<td>2016</td>
<td>50</td>
</tr>
</tbody>
</table>

The frequency of conveyor chain link failure has had a 34% increment from 33 to 50. Therefore a study into the reasons behind the failure will go a long way towards either eliminating these failures or reducing the frequency of failure.

Figure 1.3: Graph of Year versus frequency of failure

Failure of conveyor chains is a major problem for cement industrial sector. Histor-
ical data shows that the chain link is the major cause for conveyor chain assembly failure \[7\]. As conveyor assembly failure results in huge losses for the user, it is of paramount importance to have a detailed analysis for the causes of failure.

Figure 1.4 shows the basic structure and components of a roller conveyor chain and the different types of fit assembled under its working conditions. The main components of the roller conveyor chain are the pin, link plate or strip, bushing and roller. The press fit between pin and the pin link plate prevents the pin from rotating. Usually there is a cyclic loading, sometimes accompanied by shock. The pin is subjected to shearing and bending forces transmitted by the plate. There is a slip fit between bushing and pin. The bushing is subjected to shearing and bending stresses transmitted by the plate and roller, and also gets shock loads when the chain engages the sprocket \[6\].

Figure 1.4: Basic structure of roller conveyor chain \[6\]
In addition, when the chain articulates, the inner surface of the link forms a load-bearing part together with the pin. The outer surface of the link also forms a load-bearing part with the roller’s inner surface when the roller rotates on the rail or engages the sprocket. There is slip fit between the bushing and the roller [6].

The roller is subjected to impact load as it strikes the sprocket teeth during the chain engagement with the sprocket. After engagement, the roller changes its point of contact and balance. It is held between the sprocket teeth and bushing, and moves on the tooth face getting compressed in the process. A major advantage of the roller chain is that the rollers rotate when contacting the teeth of the sprocket hence reduce abrasive action [6].

During operation, the chain is subjected to cyclic loading, hence premature failure may occur if the geometry of the parts is not properly designed for fatigue. This can occur even if the parts are made of a material known for its best resistance to fatigue.

Due to the effect of failure of the chain, it is important that the user considers the critical design parameters, e.g., service temperature, operating loads, and recommendations regarding start-up and shutdown procedures and maintenance schedule. Therefore premature failure of the chain can result from poor engineering design, weakening of any of the links during manufacturing and performance [8].
Failure analysis can be carried out on a failed conveyor chain to determine the causes of failure or identify the mistakes made in the process of engineering design, manufacturing and performance in order to prevent its recurrence in the future. The function of failure analysis is to trace back the history of the product from design to manufacturing and operation in order to identify the weakest link \[1\]. Figure 1.5 shows the general approach to any failure investigation which requires the analyst to have a broad understanding of engineering design process, materials engineering and the operating condition of the part \[8\].

Failure analysis can serve the following purposes \[1\]:

1. Failure analysis provides information that is extremely useful to designers of the same or similar products which can be useful in developing products of improved reliability and durability. Frequently, however, such information never reaches the designer for one reason or another.

2. In view of the legal aspects of failures, the results of failure analysis in-
vestigations can be used as the basis for litigation and insurance claims. Manufacturers can also use the results of failure analysis investigations for marketing purposes to promote a new product with better performance capabilities.

3. By identifying the deficiencies of certain structural materials through failure analysis investigations, it is possible to develop new materials or improve the properties of existing materials.

### 1.4 Problem Statement

The conveyor chain is an important element in the cement industry for conveying of materials. As these chains operate under various forces, failure of chain assembly is the major problem.

A central chain bucket elevator is needed to lift the cement from the outlet of the mill through a height into a centrifugal separator, where the finer cement particles are separated from the coarse ones. The finer ones are then pumped into the silos to be stored via a screw pump. This makes the bucket elevator a very important machinery in the cement production process; without it production ceases.

Whenever the chain link of a central bucket elevator fails, the technicians take a minimum of three days to fix it depending on the severity of damage. This is because when one of the chain links fails, the entire chain together with the buckets drop to the bottom of the bucket elevator. A chain block is then used to pull the chain link up through a height of between 20 m to 25 m depending
on where it failed in order to join it. In addition to this, some of the links and buckets get damaged and they need to be replaced with new ones.

This results in increased down-time and goes a long way to affect production time and also increases maintenance cost. This study seeks to carry out failure analysis on a failed chain links in order to analyse the mode of failure and propose corrective measures to minimize future failures.

Bucket elevators are very important to the extent that the whole production process cease whenever the elevator is not in operation condition and this is mainly caused by failure of chain links. Although other parts such as bearing, shaft, and gears can also fail, they do not fail as frequently as chain links. Failure of chain links does not only reduce productivity but also increases cost of maintenance, which in turn affect cost of production because of damaged buckets and links associated with the failure.

The bucket elevator on which the study is being carried out has the following specifications as shown in Table 1.

The data was obtained from East African Portland Cement Company (EAPC), Kenya. On the average the down-time during failure (the number of hours for which the bucket elevator is not in operation) is three (3) days (72 hrs) because the conveyor runs 24 hrs a day. Therefore, the amount of cement lost during the down-time is 5760 tons (5,760,000 kg) which is equivalent to 115,200 bags.

It is therefore imperative to analyze the causes of failure so as to improve on
Table 1.2: General Information on Bucket Elevator

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Capacity of the Bucket Elevator</td>
<td>80 tons/hr</td>
</tr>
<tr>
<td>2</td>
<td>Power Rating</td>
<td>75 KW</td>
</tr>
<tr>
<td>3</td>
<td>Speed of Bucket Elevator</td>
<td>1.62 m/s</td>
</tr>
<tr>
<td>4</td>
<td>Weight of Chain link per Unit Length</td>
<td>57 kg/m</td>
</tr>
<tr>
<td>5</td>
<td>Height of Bucket Elevator</td>
<td>30 m</td>
</tr>
<tr>
<td>6</td>
<td>Width of Bucket Elevator</td>
<td>2.35 m</td>
</tr>
</tbody>
</table>

the quality of chain links produced, which in turn will reduce down-time thereby improving productivity.

Figure 1.6 shows a typical assembly of the chain link at East African Portland Cement Company (EAPC)

(a) Assembled chain link
(b) Parts of the assembled chain link

Figure 1.6: Typical chain link assembly
The chain link is made up of an inner and an outer link which are press fitted to form a continuous chain.

1.5 Objectives

The principal objective of this study is to analyse and provide solution to the frequent failure of the chain links of the bucket elevator by carrying out laboratory tests on failed conveyor chain sample of a central bucket elevator.

1.5.1 Specific Objectives

The specific objectives of this research will be to:

1. Determine the point of initiation of the fracture of the chain link.

2. Analyse the mechanism(s) of the failure of the chain links and deduce the type of failure.

3. Improve the design of the existing chain link based on findings to minimize failure and test its performance.

1.6 Scope of Work

The scope of this research is limited to analysing the failure of the bucket elevator chain link and designing a new chain link to minimise future failure.

1.7 Organization of the Thesis

This thesis is fractionated into five chapters. Chapter one gives a background to bucket elevators, conveyor chains and their failure, types of failure and the
problem statement. Chapter two is a review of literature on past studies that has been carried out on bucket elevator conveyor chains and their failure.

Chapter three encompasses the methodology used to obtain the data for the research where as in chapter four, the results from preliminary examination, chemical analysis, micro-structural analysis and FEA simulation are presented and discussed. Chapter five includes the conclusions deduced from the research, and the recommendations given for further research.
CHAPTER TWO

LITERATURE REVIEW

2.1 Failure Analysis of Conveyor Chain

All machine/component failures, without exception, occur at the weakest link in the design, fabrication and performance chain of a product. The ability to identify this weakest link and propose remedial measures is the key for a successful failure analysis investigation and this requires a multidisciplinary approach [8].

Clearly, through the analysis of failures and the implementation of preventive measures, significant improvements have been realized in the quality of products and systems. This requires not only an understanding of the role of failure analysis, but also an appreciation of quality assurance and user expectations [1].

Haris [2] in his investigation of a failed chain conveyor at dewatering system used four techniques of failure analysis to determine the causes of the chain failure. He used visual examination, hardness testing, chemical analysis by using Scanning Electron Microscopy Energy Dispersive Analysis by X-Ray (EDAX) and microstructure examination. These four techniques are normally used by researchers to collect and analyse the data in the failure field. His analysis by metallographic examination revealed shrinkage cavities, high density of gas porosity and cracks in the cast chain link. He inferred that the large cavities and high porosity were formed during solidification in casting. The spherical area was due to bubbles of gas that were ejected as the metal solidified and then trapped before it could leave...
the liquid. Based on this investigation, he concluded that these manufacturing
defects are the dominant cause responsible for the failure. He further concluded
that a comprehensive quality control system in the manufacturing process could
reduce the cause of material defects.

Haris et. al. [2] investigated failure of Grade-80 alloy steel towing chain links.
By using optical metallography and SEM analysis, the fatigue failure was found
to result from the generated cracks at the outer circumference of the weld. The
fatigue crack propagation was evident through progressive marks and striations
as shown in Figure 2.1 Points 1, 2, 3 and 4 on the figure represent fatigue origin,
fatigue progressive marks and final rupture, void formation and step-like brittle
rupture respectively. The authors concluded that, the evidence of lack of some
key alloying elements, welding defects and improper post weld heat treatments
of the chain links led to the failures.
Haris [2] investigated the causes of failure of a chain system through characterization of the failed component. The analysis revealed that the weld defects such as craters lead to crack propagation and a cyclic loading causes the fatigue failure. The fatigue failure occurred due to this inherited crack at the outer circumference of the weld within chain attachment and outer chain link plate. This type of defect can also be categorized as designing-in defect. Fatigue crack propagation was evident by progressive beach marks and the scanning electron microscopy (SEM) analysis revealed the types of microstructure that resulted at the heat affected zone (HAZ). Hardness testing by using Rockwell Tester found the different hardness profiles at the three areas, i.e., weld metal, base metal and heat affected zone. The maximum hardness values were found at the heat affected zone and
the weld metal. Cracks within the material led to fatigue failure and therefore the failed chain link sample will be examined for cracks.

Jagtap et. al. [6] studied analytically, experimentally and numerically the behavior of a roller conveyor chain strip under tensile loading. Comparison was made between the three methods and the results showed that they are within +/- 10 percent of the calculated working stress. The fatigue cracks initially nucleated at the external cracks of the link, and later propagated to the inside of the links until sudden fracture occurred. It was concluded that a roller chain drive may be subjected to tensile loads, thus it must have high tensile strength to withstand the wide range of tensile loads that may be imposed on it.

Bošnjak et. al. [9] carried out failure analysis on a Stacker Crawler Chain Link. The goal of the study was to diagnose the cause of chain link breakdown. Working stresses in the chain link were calculated by applying FEM. Experimental investigations were also carried out including; chemical composition analysis, tensile properties, impact toughness and macro and microhardness. Metallographic examinations were conducted additionally. Based on the results of the numerical-experimental analysis, it was concluded that chain link breakdown is predominantly caused by (a) substantial deviation of the mechanical properties of the material with respect to those prescribed by the standard and (b) the existence of macro and microcracks in the material structure. It was therefore concluded that the failure of the chain link was caused by ‘manufacturing-in’
defects. The findings of this study is in agreement with the results obtained in this work as the macro and microcracks had initiated from inclusions within the material.

![Stress zone in the chain link](image)

Momcilovic et al. [10] investigated a failed bracket of a conveyor using Scanning Electron Microscopy analysis and established the presence of oxide on the crack surface. The authors observed that the contact zone between chain link and bracket as shown in Figure 2.3 is one of the most stressed zones and fracture always occurred in that zone. Based on their research, they concluded that the origin of cracks in chain brackets in this case was due to the production process, because the wrinkling of the material appeared during hot bending. The implications of the oxide found on the crack surface were not stated and also the relationship between the wrinkling of the material and the crack were not established. The forming of the chain link studied by Momcilovic and the one
studied in this work are different but both chain links are used in the cement industry.

Sujata et al. [11] in their study using visual examination found a shallow crack on the surface of the chain link as shown in Figure 2.4. Under stereo-binocular microscope, the authors found that the fracture surface showed coarse crystalline features. The sample containing the crack was cut, mounted, metallographically prepared and observed under an optical microscope. Visual examination revealed a crack-like surface defect and the optical micrograph showed oxide entrapment in the material near the surface. It can be seen in Figure 2.4 that the crack-like defect is not perpendicular to the surface. In between the crack surfaces, the authors used Energy Dispersive X-Ray (EDX) analysis in SEM for investigation and found that the non-metallic inclusions were mainly iron oxide.
The authors concluded that the conveyor chain links had failed due to presence of manufacturing-in defects. The defects were identified as forging laps or folds and can be summarized as inherent defects. The investigation also showed that surface defects were present in the billet itself. They then recommended that the billet be properly dressed and the surface defects be removed prior to the forging operations. The significance of the coarse crystalline features and the iron oxide inclusions were not stated in this paper.

Conwell and Johnson [12] investigated experimentally, the dynamic behavior of roller chain drives. A strain gauge mounted on a link side plate was used to determine chain tension during normal operation over a wide range of linear chain speeds and preloads. The test machine also included specially instrumented idler sprocket that allowed the measurement of the horizontal and vertical components of the bearing reaction force. The roller-sprocket impact force was then computed by an experimental transfer function approach facilitated by a Brue Kjaer 2032
dual channel spectrum analyzer. It was observed that the tension in a chain link increases rapidly as the link exited the driven sprocket. The increase in tension occurred over less than two sprocket teeth from loose side to tight side. The tension in the chain link then decreased very rapidly as the link entered the drive sprocket. The decrease from tight side to average loose side tension occurred over less than two sprocket teeth. The impact force tended to increase as chain tension and speed increased. In this research, it confirms the observation that chain links are subject to high levels of fatigue loading in the findings of this study and therefore the new chain link has to be designed taking into consideration fatigue loading.

Sadagopan et. al. [13] studied the wear reduction of existing chain used in 100cc motorcycles. Elongation of chain was calculated and compared with the experimental results. In an alternate design developed, theoretical evaluation for elongation was made by applying the same conditions used for evaluating the existing chain. Fatigue properties of existing standard chain components were evaluated using mathematical modeling as well as by using ANSYS software. This research intends to use ANSYS software to evaluate the fatigue properties of the chain links.

Kerremans et. al. [14] focused on the wear of conveyor chain with polymer rollers. In his research the different components of conveyor chains and the loading conditions were described. In addition, the applications and disadvantages of chains
with polymer rollers were discussed. From the contact mechanics of the chain and pressure-velocity limit of the roller materials, the design constraints for the laboratory test-rig were derived. He observed that experiments performed on this test-rig gave better correspondence with the wear mechanisms occurring in conveyor chain applications. The capabilities and working principles of the developed test-rig are explained in this thesis. He concluded that for conveyor chains with polymer rollers, the expected wear mechanisms are adhesive wear, abrasive wear, impact with sprocket and softening of the polymer due to heat generation.

Singh et. al. [15] studied the failure of bridle chain used for hoisting in the mines. Laboratory examination proved that the defect is a mechanically induced one. Visual and stereo-binocular observations revealed surface defects in samples. It was observed that it was not safe to strain the chain to beyond the elastic limit of the material. It was concluded that the cause of failure was as a result of inherited defects in the material and that the chain can fail mechanically by overloading, fatigue and wear.

Bosnjaka and Arsic [16] investigated the cause of the chain link breakdown on a hydraulic excavator. Its superstructure leans on three crawlers of the same length, width and the height. During the stackers travel from the erection site to the open pit mine, three crawler chain links fractured. The working stresses in the chain link were evaluated by finite element analysis (FEM). Experimental techniques were used to investigate the chemical composition, tensile properties, impact
toughness, and macro and micro hardness. Based on the numerical-experimental analysis, the authors concluded that substantial deviation of the mechanical properties of the material with respect to those prescribed by the standard occured and the presented failure of the chain link was caused by ‘manufacturing-in’ defects.

Han et. al. [17] investigated failure analysis on the fracture of a S135 drill pipe. The fracture of the drill pipe was mainly controlled by the material of the drill pipe and environment of operation. A fractured 3 1/2 S135 drill pipe was analyzed through physical and chemical properties, Scanning Electron Microscope (SEM) and Energy Dispersive Spectrometer (EDS) method. Additionally, a series research about sulfur resistance of S135 was also estimated by sulfide stress cracking test [17] and hydrogen-induced cracking test [17]. The results showed that the failure of the drill pipe was due to sulfide stress corrosion cracking. High hydrogen sulphide content condition and the material with high strength led to the final rupture of the drill pipe. The application of drill pipe with high strength was also proposed on the basis of results obtained.

Kumar et. al. [18] studied crankpin failure in Internal Combustion engine. Under analysis the crankpin was identified as tempered. Chemical composition, micro-hardness and microstructure were studied and compared with the specified properties of the crankpin material. Reason for failure was identified as wear due to lower hardness, improper lubrication and high operating oil temperature. Me-
ch analytical and metallurgical properties of the crankshaft including chemical composition, micro-hardness, microstructure and tensile properties were studied and compared with the specified properties of the crankshaft material. As a result of the analysis, the main reason of failure was determined as lower surface hardness followed by rapid wear due to the contact of crankpin and bearing surface. The contact between the crankpin and bearing surface was due to the absence of oil and improper lubrication.

Bošnjak et. al. [19] carried out a failure investigation of the bucket wheel excavator crawler chain link to diagnose the cause of the damage. In order to identify the reasons behind chain link failures, stress state calculations were performed as well as experimental investigations which included visual and metallographic examinations, chemical composition analysis and tests of mechanical properties. Based on the results of the numerical–experimental analyses, it was concluded that the chain link breakdowns are caused by ‘manufacturing-in’ defects.

Zambrano et. al [20] carried out failure analysis on a shaft used in a bridge crane. The shaft fractured in the keyway with evidence of fatigue. Chemical analysis, micro-structural characterization, fractography, hardness measurements, and finite element simulation were used for the analysis. The microstructure was predominantly tempered martensite; large amounts of oxides, micropores, and manganese sulfide inclusions were found. The geometry of the keyway also promoted the initiation crack because the width and height were erroneously designed. It
was concluded that all these factors produced fatigue failure. It was recommended to first guarantee the chemical composition and microstructure of the material. Secondly, magnesium or calcium should be added in the steel casting process to obtain better shape control of inclusions and, finally, accomplish the geometric parameters recommended by the standard to avoid high stress concentration factors.

Sudhakar [21] carried out a metallurgical investigation on a failed cast iron component. A fractured nutcracker was examined to determine the root cause for premature failure. This is one of the common tools used typically for cracking hard nuts. In this study, metallurgical failure analysis techniques namely, visual inspection, optical microscopy, SEM, and hardness tests were used in investigating the broken product. From the metallurgical analysis, it was determined that the combined effect of low carbon equivalent and presence of inclusions contributed to the sudden fracture of the nut cracking tool.

Christie [22] carried out a review of the science and art of visual examination in failure analysis. In his paper, techniques of visual examination and documentation using digital photography were discussed. The use of different types of lighting to reveal characteristics of manufactured and fracture surfaces was explored. Practical examples of lighting setups and photographs obtained using these setups were presented. This techniques of visual examination will be employed in this study.
2.2 Types of Failure

The physical failure of materials can be placed in one of many categories depending on the classification system. The four categories which form a convenient way to descriptively categorize and discuss failures [23] are distortion or undesired deformation, fracture, corrosion and abrasion.

These four categories represent the general forms of failure, and each form of failure may have a variety of different underlying mechanisms (e.g., fatigue crack propagation in the case of fracture or galvanic effects in metal corrosion). It is important to point out that two or more mechanisms can occur simultaneously in some failures. For any of these failure types, materials performance plays a critical role. Just as the performance of a component or system is dependent on the behavior of the materials of construction under the service conditions, the manner in which a component or system sustains a physical failure is strongly affected by materials performance. For example, corrosion failures of dissimilar metals in physical contact in an aggressive environment are associated with the differences in the electrochemical behavior as a result of the chemical compositions of the two metals [23]. This illustrates that one of the most basic tenets in materials science and engineering applies to failures; the interaction of the composition, processing, structure, and properties defines materials performance whether satisfactory or unsatisfactory.

Gagg [24] and Bošnjak S. et. al. [9] pointed out in their case studies that failures
can be caused by designing-in defects, manufacturing-in defects, operating-in defects and environment-in defects.

Reddy [25] described in his investigation that there are two types of defects that are generally observed in materials. These are inherited defects where the origin is in the ingot; and generated defects that are introduced in the material during various metal working operations and thermal treatments.

2.3 Modeling and Simulation

At the end of the Converter or Electric Arc Furnace process, the steel has high dissolved oxygen content (greater than 500 ppm) and it must be decreased to 2-4 ppm dissolved oxygen to be able to cast as the final product [26]. In the process of decreasing the content of the dissolved oxygen from 500 ppm to 2-4 ppm, micro inclusions are produced from the reaction between the deoxidant and oxygen. Oxygen reduces both strength and toughness by forming oxygen rich microscopic inclusions and blow holes [27]. Strength and toughness are important mechanical properties of steel and therefore the oxygen content has to be reduced to an acceptable level through deoxidation [28]. The purpose of deoxidation is to reduce the level of oxygen to acceptable level for casting purposes. As the oxygen content increases, the number of dissolved microscopic inclusions also increase [28] thereby decreasing the fatigue life as shown in Figure 2.5.
The deoxidation process therefore cannot be excluded from the steel manufacturing process as the presence of oxygen beyond the acceptable level means drastic reduction in strength, toughness and more importantly fatigue life. Inclusions therefore will always exist since producing a clean steel (steel without inclusions) is impossible. Inclusions tend to reduce the fatigue life of steels and therefore it is important to have a design which has a better fatigue life than the existing chain link with the inclusions present.

2.4 Scanning Electron Microscope

The scanning electron microscope (SEM) has been a tool for imaging and chemical analysis in research for several decades. The combination of a resolution down to around 1 nm and a large depth of focus enables a detailed study of the typically rough surfaces of samples that may be difficult to study in the optical microscope.
In addition, if an energy dispersive X-ray (EDX) spectroscopy analysis system is attached to the scanning electron microscope, chemical analysis can be carried out. SEM is commonly used for imaging of the micro-structure of materials grain sizes, distribution of phases and surface topography as well as chemical analysis of specific oxides \[30\]. The resolution can be as low as 10 nm or better.

The principle of the SEM is as follows; an electron beam produced in the electron gun is passed through a series of magnetic lenses and apertures, which provides a focused electron beam. As the beam strikes the sample, the beam electrons interact with the atoms in the sample and a variety of signals is generated as shown in Figure 2.6.

![Figure 2.6: Striking of high energy electrons on sample](30)

The signals originate from different depths and volumes in the sample. The interaction volume in the sample showing the depth from which the different signals are generated is as shown in Figure 2.7.
The X-rays escape from a greater depth than both secondary electrons and back scattered electrons and have the lowest resolution of the signals generated in the SEM, typically around 1μm at an accelerating voltage of 20 kV.

2.5 Energy Dispersive Analysis by X-Ray

Energy dispersive X-ray spectroscopy (EDX) provides chemical information about a material [30]. When an incident beam electron strikes an atom, it may knock out an inner shell electron if the beam electron has sufficient energy. As the excited atom returns to its stable state, the excess energy is released as an X-ray photon or Auger electron. The X-rays emitted have energies characteristic for each specific atom, thus they provide chemical information about the sample. For most of the EDX analysis, an accelerating voltage of 10 kV is used in order to improve spatial resolution. This accelerating voltage is sufficient to generate elemental peaks from all of the elements in the sample [30].
2.6 Summary

From the literature surveyed, the following conclusions were drawn. Various studies have been done on the bucket elevator conveyor chains which never considered the fact that poor design can be a contributing factor if not the main factor for failure. An anomaly in design can also be a cause of failure but none of the studies considered the design aspect.

From the literature survey, it was realized that only the micro-structure of failed samples were studied without studying the original sample (unfailed sample) for comparison. The original sample needs to be studied to reveal the origin of these manufacturing defects (inclusions). By studying an un-failed sample, the origin of the inclusions can be clarified through comparison.

The cause of failure according to the various literature studied was deduced to be as a result of manufacturing defects, i.e. from inclusions which are formed during manufacturing but none of the research provided solutions to these manufacturing defects whether through design or manufacturing to prolong the life of the chain links.

From the previous studies, it can be noted that, even though several patents are filed on roller chains and conveyors, most of the patents are based on metallurgical investigation, improvement of efficiency and performance of chain. Hardly any patents are there on improving life of the chain and minimization of its failure.
CHAPTER THREE

METHODOLOGY

Ten different failed samples and un-failed samples were obtained from East African Portland Cement (EAPC) Kenya for analysis. The un-failed samples are original chain links that had not been in use before where as the failed samples are the samples that failed whilst in use.

Visual examination, chemical and metallurgical analysis were employed in this study to analyse the failure on a failed conveyor chain link of the central bucket elevator. In addition, the micro-structure of an un-failed conveyor chain link of a central bucket elevator was also examined. The methodologies adopted in this study to establish the cause of failure are as follows:

3.1 Visual Examination

Visual examination and documentation is the first and very important step in failure analysis. If performed thoroughly and carefully, some failures can be “solved” by visual examination, and for most failures visual examination will dictate the subsequent steps in the analysis. If performed poorly, key elements may be missed, lost, or destroyed. The result of poor visual examination may be that the investigation tracks down a dead end or the analyst arrives at an incorrect conclusion. It is important to adopt a carefully considered, stepwise approach so that the maximum amount of information may be gathered and recorded before and during subsequent processes that may require physical alteration of the failed
The use of a stereo-microscope enables higher magnification viewing than is generally obtained simply with a digital camera, and magnifications up to a limit of approximately 100 may be used. Visual examination is used to select locations for microscope examination (optical), cross sectioning, chemical analysis, etc.

Both failed and un-failed samples were taken from East African Portland Cement Company (EAPC) for analysis. Visual examination was done on fractured samples with stereo microscope to magnify the fractured surface for analysis. Special attention was paid to anomalies such as scratches, fractures, unusual marks and wear.

Visual examination was then aided by using stereo microscope to see more clearly the fracture surfaces and surface defects. This step was to examine fracture surfaces and to identify whether the fracture is ductile or brittle. Chevron marks always appear at a fractured surface as a result of the fracture process. Chevron marks are very helpful because they can point to the crack origin.

The bucket elevator was studied with special attention paid to the operating conditions such as temperature, speed and capacity. The power rating, weight of chain link, height and width of the bucket elevator was taken.

Before the fractured samples was examined by mounting under the stereo microscope, it was first sectioned 12mm from the fractured surface as shown in Plate 3.1 with hacksaw (low speed cutter) so as not to alter the micro-structure.
The sectioned samples were then mounted on a stereo microscope to observe the grains on the surface so as to deduce the type of fracture. Also the mechanism of failure was deduced by tracing the chevron mark on the surface as the it shows the path for the failure.

3.2 Chemical Analysis

Chemical analysis should be conducted on the original material to determine if the material was of proper type and grade, whether it met appropriate standards,
and whether deviation from the specifications contributed to the fracture, wear, breaks, corrosion and failure.

Chemical analysis of samples from the component provides information regarding any deviation from the standard specifications, compositional inhomogeneities, impurities, inclusions, segregations, etc. It also helps in identifying the nature of corrosion products, coatings, external debris, etc. Analysis at microscopic levels provides information about the nature of inclusions, phases, and surface layers. Several cases of service failures are known to have been caused by the presence of deleterious inclusions from which cracks start in the component and propagate, leading to fracture [31]. Certain impurities are known to cause embrittlement in metals [31]. Segregation of constituent elements sometimes provides an easy path for crack propagation. Hence, identification of these harmful constituents is very important in failure analysis. A variety of instruments are available for bulk chemical analysis and micro-chemical analysis [31].

Chemical analysis provides information regarding any deviation from the standard specifications, compositional inhomogeneities, impurities, inclusions and segregations. Identification of these harmful constituents is very important in failure analysis because impurities are known to cause embrittlement in metals and segregation of constituent elements sometimes provides an easy path for crack propagation.

The chemical analysis at the fractured surface was done to determine the chem-
ical composition. Five (5) samples were taken for chemical Analysis with mass spectrometer of model Maxx LMF06 at Numerical Machining Complex limited in Nairobi. Plate 3.2 shows the mass spectrometer used for the chemical analysis with a sample mounted on it.

Mass spectrometry is essentially a technique for "weighing" molecules. Mass spectrometry is based upon the motion of a charged particle, called an ion, in an electric or magnetic field.

Figure 3.1: Block diagram for mass spectrometer

Figure 3.1 is the block diagram that shows the basic parts of a mass spectrometer. The inlet transfers the sample into the vacuum of the mass spectrometer. Firstly the sample was ionized using electrons i.e. electron ionization by passing current through the filament. An electric field then accelerates these electrons across the source region to produce a beam of high energy electrons as shown in Figure 3.2.
After ions are formed in the source region, they are accelerated into the mass analyzer by an electric field. The mass analyzer is the heart of the mass spectrometer. This section separated the ions according to their mass to charge ratio value i.e. m/z. After the ions were separated, they were then detected and the signal was transferred to a data system for analysis (detector). The mass spectrometer had a vacuum system to maintain the low pressure, which is also called high vacuum, required for operation. High vacuum minimizes ion-molecule reactions, scattering, and neutralization of the ions. The pumping system is an important part of any mass spectrometer as it is used to keep the spectrometer in vacuum condition.

The data was then displayed on a display unit and printed out. Plate 3.2 shows the sample mounted on a mass spectrometer for chemical analysis. In all, five
(5) different samples from different failed chain link samples were tested. The original sample was not tested because there already exist standards to compare results with.

3.3 Metallography

The metallurgical microscope is yet another instrument very useful to the failure analyst. After collecting all the information through fractography of the failed component, a section of the component can be cut transverse to the fracture surface. The section is then polished and examined in the metallurgical microscope, both before and after etching [31]. The microscope used was Optika of model
Inclusions present in the material are observed on the as-polished surface. The polished specimen is then etched with suitable etchants to reveal the microstructure of the material. Abnormalities in the microstructure that may have been responsible for the failure can be identified at this stage. The path of a crack, whether it is intergranular or transgranular, and branched or not branched, will be clear in the microstructure \[31\].

Cracks due to stress corrosion, hydrogen embrittlement, and liquid metal embrittlement are generally intergranular with some exceptional situations. Fatigue cracks are transgranular. If a stress-corrosion crack propagates by fatigue, the transition from intergranular to transgranular mode can be seen in the microstructure. Stress-corrosion cracks in certain stainless steels are transgranular with extensive branching. Plastic deformation of the component prior to fracture can be recognized in the microstructure by the elongated grains. Abnormal grain growth, segregation of brittle or weak phases at the grain boundaries, and recrystallization are some of the other features that can be identified by metallography. Figure \[3.3\] (a) and (b) shows the intergranular and transgranular modes of crack propagation, revealed by metallography \[31\] respectively.
3.3.1 Polishing of Samples

Before metallography was done using optical microscope, the samples needed to be firstly prepared by polishing. An unpolished sample when observed under an optical microscope does not reveal informative image of the micro-structure because roughness and scratches at the surface reflects the incident light randomly thereby making it impossible to observe the micro-structure. The equipments and the reagents used are listed below;

3.3.2 Metallographical Specimen Preparation Procedures

The following procedure was followed in polishing of the samples;

1. The already sectioned samples (failed and un-failed) during visual examination were ground on four (4) silicon carbide papers of grade 220, 320, 400
and 600. Plate 3.3 shows a polishing deck with the silicon carbide grades mounted on it.

2. After grinding was completed, the specimen was washed with water flushed with methanol and dried with a drier before polishing was done on a polishing machine. Plate 3.4 shows the drying procedure.

Plate 3.3: Grinding on silicon carbide papers
3. Polishing was done using 6 and 4 micron diamond paste. The diamond paste was put on the polishing cloth. Lapping fluid was put on the polishing cloth with the diamond paste.

4. After polishing the sample with 4 micron diamond paste, it was then washed with water, flashed with methanol and then dried with a drier to obtain the final polished sample as shown in Plate 3.5. The procedure was repeated for the other un-polished samples.
Plate 3.5: Polished sample

Figure 3.4 shows the schematics for the metallographical analysis.
3.4 Design Modification on the Existing Chain Link

The shape of the newly designed chain link differs from the existing chain link as shown in Figure 3.5. In design, stress concentration points (circular holes, grooves, necks and notches) are undesirable and so they must be as minimal as possible and that was the motivation for the new design. Therefore new designs of the chain link with minimal discontinuities was modeled and simulated to see...
if an improvement was made on the existing design. The existing design has two
necks on each side whilst in the new design it is eliminated as shown in Figure
3.5 Different neck radii were used to predict its effect on the chain link. Various
designs were produced and tested numerically with ANSYS for comparison.

![Comparison of CAD models](image)

(a) Existing design   (b) New design

Figure 3.5: Comparing CAD models for existing and designed chain links

The designs were simulated for the equivalent (von Mises) stress, deformation,
fatigue life and factor of safety with a crack and without a crack; then comparison
of the results were made between the existing and new design. The existing chain
link was modeled using autodesk inventor as well as the newly designed chain
links. The neck radius was gradually reduced from 5 mm to radius 0 mm by
reducing the distance X as shown in Figure 3.6 so as to predict the effect of the
neck radius on the chain link.
The existing chain link had the largest $X$ of 5 mm and therefore the largest neck radius. The distance $X$ was reduced gradually by 1 mm from 5 mm to 0 mm to obtain six (6) models with different neck radii. The neck radii corresponding to $X$ values are as tabulated in Table 3.1.

<table>
<thead>
<tr>
<th>Distance $X$/mm</th>
<th>Corresponding Neck Radius/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>621.5</td>
</tr>
<tr>
<td>3</td>
<td>831.9</td>
</tr>
<tr>
<td>4</td>
<td>1245.5</td>
</tr>
<tr>
<td>5</td>
<td>2488.4</td>
</tr>
</tbody>
</table>

Figure 3.7 shows the CAD models for the chain links with different neck radii. Six (6) models were designed with different neck radii and simulated to obtain results for comparison. These models were then simulated using ANSYS simulation.
software to obtain the von Mises stress, deformation, safety factors and fatigue life for comparison to deduce which design is best so as to minimize failure.

3.4.1 Modeling and Simulation Procedure for Chain Links

1. First and foremost the chain links were modeled to scale with accurate dimensions using autodesk inventor software as shown in Figure 3.7.

2. Static structural analysis tool was used to perform the simulation on the chain link.
Figure 3.7: CAD models for designed chain links

The following were performed using the Static structural analysis tool:
3. The modeled chain links were firstly imported into ANSYS simulation software for simulation.

4. The coordinates of the chain link were then set.

5. The models were fine meshed as shown in Figure 3.8 so as to obtain accurate results. The number of elements used was 2199 with an element size of 5mm. The number of nodes were 12099

![Meshing of designed chain link](image)

**Figure 3.8: Meshing of designed chain link**

6. After meshing, static structural analysis was performed by applying the loads and boundary conditions on the chain link. The applied force was calculated using equation 3.1

\[ P = Fv \]  

(3.1)

where,


\( P \) is the power rating
\( F \) is the force
\( v \) is the linear velocity

From Table 1.2 on page 20, \( P = 75 \text{ kW} \) and \( v = 1.62 \text{ m/s} \)

Therefore, from (3.1) the force was calculated as:

\[
F = 46.296 \text{ kN}
\]

7. The properties of the materials i.e. Poison ratio (0.3), Young’s Modulus (210 GPa), Density (7850 kgm\(^{-3}\)) and Tensile Strength (600kN) were then imputed. This data was obtained from the manufacturer of the bucket elevator conveyor chain links at East African Portland Cement [32].

8. von Mises stress and deformation were then inserted into the solution tree and then simulated to obtain the results.

9. Fatigue tool was then inserted in the solution tree and used to obtain the fatigue life and safety factor by running the simulation. The failure theory that was used was the Goodman theory of failure because its a better predictor of failure than the other theories [33].

10. The same procedure was again repeated for the six (6) different chain links but this time after meshing, a semi-elliptical crack was modeled into the chain link as shown in Figure 3.9. The semi-elliptical crack was introduced as a model for the inclusion which from the experimental results was known
to be the cause of failure. The major radius, minor radius and contour radius are 2, 1 and 3 mm respectively.

11. The modeled crack is as shown in Figure 3.10

Figure 3.9: Crack introduction into the designed chain link

Figure 3.10: Modeled crack
CHAPTER FOUR

RESULTS AND DISCUSSION

This section analyzes and discusses the results obtained from the experiment and simulation.

4.1 Visual Examination

The preliminary examination was done in two sections, namely; on the factory site and on the fractured surface for analysis.

The preliminary examination done at the factory site revealed indentations on the chain links which is as a result of the sprocket impacting on the chain link as shown in Plate 4.1. This indicates misalignment and vibrations within the bucket elevator system. This impact force aided in the progression of the cracks within the chain link. Misalignment and vibrations are undesirable in bucket elevator system as it affects the performance of other component parts of the elevator such as bearing, chains and shaft by causing pre-mature fracture. The vibrations result in unsteady chain speeds which affect the engagement process as well as the impact levels. The impact force is one of the main sources of vibration and noise existing in the bucket elevator. It may also result in the stretch and fatigue of the chain links. The impacting of the sprocket on the chain link also increases the noise generated during the operation of the chain drive. The noise is generated from the intensive impacts due to relative velocity between the chain links and sprocket teeth during their meshing process. The transient peaks of the impact
force are present as the chain starts to mesh with the sprocket. The impact force is one of the main sources of vibration and noise existing in the bucket elevator. It may also result in the stretch and fatigue of chain drives.

Accurately alignment of sprockets is very important to the life of both the chain links and sprockets as the life of a properly aligned sprocket can be maximized and in so doing also ensures that the bucket elevator operates at maximum efficiency. Chain and sprockets misalignment directly affects the drive system performance (electric motor) and therefore proper alignment is required to minimize the life reduction of the drive. It was observed that the sprockets were not in alignment as there was an offset between the two shafts and the sprockets. Due to this, the chain forces were not evenly distributed to each tooth of the sprockets, thereby increasing the tension in the chain. Accurate alignment of shafts and sprocket tooth faces provides a uniform distribution of load across the entire chain width and contributes substantially to maximum drive life and also reduces the wear and the damage of the sprockets and chain.
Also, observing fractured surface using stereo microscope revealed that the type of fracture was brittle fracture as smooth grains appeared on the fractured surface. Brittle fracture also occurs as a result of induced inclusions at grain boundaries [34].
Plate 4.2: Cracks initiation from inclusions from failed samples

Plate 4.3 shows that the crack had initiated from an inclusion which points to the fact that the fracture is of brittle type. Another observation that emphasize that the fracture was of the brittle type was that the fractured surface was without any necking.

Also the mechanism of failure was obtained by tracing the chevron mark on the
fractured surface. The chevron mark showed that the fracture initiated from the core of the fractured surface of the chain link and progressed outward until it snapped i.e., A → B → C → D → E as shown in the Plate 4.3.

Plate 4.3: Fracture mechanism

Plate 4.3 (a) shows that the crack began at point A and progressed gradually to the surface at point B. Since the chain link is under tensile loading and the crack had already been initiated at A and grown to B, it then progressed from C to D and finally fractured at E. The initiation and growth of the crack from A to B is as shown in Plate 4.3 (b). The point of fracture initiation was dependent on where the inclusion which was the cause of failure was located; whether at the surface or the core. Plate 4.4 shows a sample where the crack had initiated from...
near the surface and progressed until eventual fracture occurred. Plate 4.4 (a) shows the crack initiation where as (b) shows the crack growth. The point at which the crack initiated was therefore dependent on the location of the inclusion from which the crack had initiated from.

Plate 4.4: Fracture initiating from the boundary

4.2 Chemical Analysis

The chemical analysis was done on five (5) different failed chain link samples and yielded the following results as shown in Table 4.1

The two elements that are detrimental to steel are Sulphur and phosphorus. Sulphur promotes internal segregation in the steel matrix. Both Sulphur and phosphorus act to reduce the ductility and weldability of the material. They
<table>
<thead>
<tr>
<th>Sample</th>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Content(%)</td>
<td>0.131</td>
<td>0.345</td>
<td>0.0002</td>
<td>0.000510</td>
<td>1.49</td>
<td>1.47</td>
<td>0.174</td>
</tr>
<tr>
<td>2</td>
<td>Content(%)</td>
<td>0.133</td>
<td>0.3610</td>
<td>0.0003</td>
<td>0.000581</td>
<td>1.51</td>
<td>1.50</td>
<td>0.183</td>
</tr>
<tr>
<td>3</td>
<td>Content(%)</td>
<td>0.135</td>
<td>0.372</td>
<td>0.00042</td>
<td>0.000652</td>
<td>1.518</td>
<td>1.54</td>
<td>0.180</td>
</tr>
<tr>
<td>4</td>
<td>Content(%)</td>
<td>0.202</td>
<td>0.420</td>
<td>0.00015</td>
<td>0.000552</td>
<td>1.48</td>
<td>1.60</td>
<td>0.179</td>
</tr>
<tr>
<td>5</td>
<td>Content(%)</td>
<td>0.129</td>
<td>0.331</td>
<td>0.00035</td>
<td>0.000592</td>
<td>1.5</td>
<td>1.61</td>
<td>0.175</td>
</tr>
<tr>
<td></td>
<td>Standard(%)</td>
<td>0.27-0.34</td>
<td>Max 0.6</td>
<td>Max 0.02</td>
<td>Max 0.025</td>
<td>Max0.5-1.7</td>
<td>Max 1.3-1.7</td>
<td>Max 0.15-0.5</td>
</tr>
</tbody>
</table>

must therefore be held to less than 0.020 max for sulphur and 0.025 max. for phosphorus. From the chemical analysis they are all within range.

Carbon plays an important role in the hardness and ductility of steels. The higher the carbon content the harder the steel but the ductility reduces and vice versa. For this reason the carbon content for chain link is limited to 0.27- 0.34 [35]. From the chemical analysis, the carbon content for the five samples were all below the required standard of between 0.27-0.34 and therefore do not meet the requirements according to the British standards for steel manufacturing.

The carbon content is low but the manganese and chromium content are high. Manganese and chromium addition to steel increases the strength and hardness of the steel which compensate for the lower carbon content as stated earlier. The lower carbon content therefore helps in improving the ductility whilst high manganese and chromium content improves the strength and hardness of the steel. Therefore, the lower carbon content is compensated for by higher manganese and chromium content and can not be the cause of failure.
The higher chromium content further causes the steel to be resistant to corrosion and high temperature strength as the bucket elevator conveyor chain operates between temperatures of 70 to 100°C. Molybdenum meanwhile increases the tensile strength as well as helps in the formation of fine grains as fine grains are more desired than course grains in steel manufacturing because they give better strength. From the microstructure it was observed that the grains were fine and this was due to the addition of molybdenum. Silicon serves the purpose of de-oxidization as it has higher affinity for oxygen and therefore reacts readily with oxygen and also improves the castability of the steel by increasing it fluidity. Therefore it was concluded that the steel was of good grade and that the fracture was not caused by any deviation from specifications.

4.3 Metallography Analysis

The microstructural analysis was done in two parts, namely; on the failed and un-failed chain link samples. Ten different samples were examined for both failed and un-failed samples.

4.3.1 Microstructural Analysis on Un-failed Samples

After polishing of the samples was completed, the samples were then observed under optical microscope with magnification 500x un-etched. The un-failed polished samples showed a lot of (a) blow holes which is a casting defect and (b) inclusions within the material as shown in Plate[4.5]. These blow holes and inclusions reduce the fatigue life of the chain links as they cause premature failure.
Most of the inclusions in steel are the product of the deoxidation process. The aim of deoxidation or “killing” is to reduce the dissolved oxygen content of the steel. As the steel solidifies, oxygen dissolved in the liquid cannot be accommodated by the solid crystal structure; it therefore reacts with dissolved carbon forming CO gas which is trapped in the casting as porosity or pinholes. The addition of deoxidizers to molten steel reduces the dissolved oxygen in the system through the formation of liquid or solid oxide phases. When the steel starts to cool, there is a corresponding decrease in oxygen solubility and inclusions precipitate to satisfy the new and constantly changing equilibrium conditions. The inclusions which precipitate early in the cooling process have a greater opportunity to escape through flotation. However, as the metal solidifies and dendrites continue to grow larger, the inclusions precipitated late during solidification become entrapped, and appear as small non-metallic phases in the finished product [36].
The mechanical behavior of steel is controlled to a large degree by the volume fraction, size, distribution, composition and morphology of inclusions and precipitates, which act as stress raisers \cite{29}. The inclusion size distribution is particularly important, because inclusions are the most harmful to mechanical properties. Sometimes a catastrophic defect is caused by just a single inclusion in a whole steel heat. Ductility is appreciably decreased by increasing amounts of inclusions. Fracture toughness decreases when inclusions are present in higher-strength lower-ductility alloys.

Small inclusions are unimportant for crack initiation but contribute to fatigue crack propagation. Inclusion size and volume fraction (occurrence of inclusions) affects fatigue crack propagation properties of steel. Crack growth is enhanced by the presence of a large number of inclusions \cite{37,38}.

The inclusions are detrimental to steel because they serve as crack initiation points during loading. No crack was observed on the surface of the un-failed sample and this means that the cracks were generated during operation.

The polished failed samples were then etched in an etchant made of 98% methanol and 2% nitric acid (Nital) to reveal the micro-structure. The micro-structure observed under an optical microscope with magnification 500x is as shown in Plate 4.6 and Plate 4.7.

The microstructure of the un-failed chain links is that of a tempered martensite. Martensite in its quenched state is very hard and brittle and because of
this brittleness, martensitic steels are usually tempered to restore some ductility and increase toughness [39]. The samples do share the same microstructure but the size and distribution of the inclusions differ as shown in Plate 4.6 and Plate 4.7.

Plate 4.6: Micro-structure for un-failed chain link sample showing inclusions for samples 1 to 4
Plate 4.7: Microstructure for un-failed chain link sample showing inclusions for samples 5 to 8
4.3.2 Microstructural Analysis on Failed Samples

The polished failed samples were then etched in an etchant made of 98% methanol and 2% nitric acid (Nital). The microstructure of the failed sample observed under an optical microscope with magnification 500x is as shown in the Plate 4.8 and Plate 4.9.

Plate 4.8: Microstructure for failed chain link sample showing inclusions for samples 1 to 4
Plate 4.9: Microstructure for failed chain link sample showing inclusions for samples 5 to 8

The microstructure of the failed chain link was also tempered martensitic and it can be deduced that the material has undergone heat treatment, i.e. quenching and tempering as shown in Plate 4.8 and Plate 4.9. The microstructure of the samples studied showed cracks on the fractured polished surface of the chain link.
as a result of the inclusions introduced during the manufacturing of the steel as shown in the Plate 4.10. The inclusions were introduced during manufacturing because they existed in the un-failed chain links samples as already shown in Plate 4.6 and Plate 4.7. Inclusions are known to have low formability and during loading they produce cracks in the steel. Also inclusions produce cracks during heating because of different co-efficient of thermal expansion between steel and inclusion which results in stress development and subsequent cracking. Although the presence of inclusions can never be entirely avoided, the quantity, size, shape, distribution and composition can be modified to achieve better mechanical properties [26]. These cracks then propagated during loading leading to the eventual fracture of the material.

Plate 4.10: Cracks within material

The cracks on the various samples studied were observed to have initiated from
an inclusion as shown in the Plate 4.10 and Plate 4.11.

Plate 4.11: Cracks initiation from inclusions from failed samples

For other samples studied the failure was observed to have initiated from the boundary as shown in Plate 4.12 as a result of the inclusion located at the boundary. The point at which the crack initiated was therefore dependent on the location of the inclusion from which the crack is initiation from.
Inclusions are therefore the cause of failure as shown in Plates 4.11 and 4.12.

Inclusions are produced when the quantity of metal added is greater than necessary to kill steel. The remaining metal combines with oxygen to form inclusions. The metal usually used in killing steels is aluminum. Casting operation and steel quality are greatly affected by both composition and the quantity of inclusions present in steel. Problems of nozzle clogging during casting are often related to micro inclusions that are solid at steel making temperatures promoting nozzle blockage [40,41].

Since inclusions cannot be eliminated completely from steels, it is imperative to modify them with calcium in terms of chemical composition to minimize their harmful effect. Calcium (modifier) addition is therefore the solution to eliminat-
ing these inclusions by chemically reacting them to form calcium aluminate. The calcium aluminate floats at a faster rate and produces cleaner liquid steel [42]. Calcium aluminate improves machinability, toughness and surface quality rather than being a crack initiation point [40].

One of the essential tasks in the steelmaking process is to control non-metallic inclusions; their amount, composition, size, and other properties. The composition of the inclusions can be controlled through the chemistries of the metal and the slag. Deoxidation is an important start for a kind of inclusion path. The practice of adding calcium to steels for the reduction and control of sulphide and oxide inclusions is now used worldwide [43]. It is therefore recommended that further research should be done on modifying the chemical composition of these inclusions by using calcium.

4.4 Modeling and Simulation

The results obtained from the simulation are as follows;

4.4.1 Results for Designed Chain Link without a Modeled Crack

The following results were obtained from the simulation of the designed chain links for the different neck radii. Each designed chain link was simulated for equivalent stresses, deformation, fatigue life and safety factor and comparison was made to establish which design was to be selected.

Figure 4.1 shows the results obtained from the simulation of the chain link without
a modeled crack with neck radius of 0 mm (with no neck). The equivalent stress, deformation, fatigue life and safety factor were obtained as 135 MPa, 0.05645 mm, $1.143 \times 10^{11}$ cycles and 4.33 respectively.

Figure 4.1: Simulation results for chain link without a modeled crack with neck radius 0 mm

The results obtained from the simulation of the chain link without a modeled crack with neck radius of 500 mm are as shown in Figure 4.2. The equivalent...
stress, deformation, fatigue life and safety factor were obtained as 139 MPa, 0.05774 mm, $1.088 \times 10^{11}$ cycles and 4.27 respectively.

Figure 4.2: Simulation results for chain link without a modeled crack with neck radius 500 mm

Figure 4.3 shows the results obtained from the simulation of the chain link without a modeled crack with neck radius of 621.5 mm. The equivalent stress, deformation, fatigue life and safety factor were found to be 141 MPa, 0.05830 mm,
\[1.055 \times 10^{11}\] cycles and 4.23 respectively.

Figure 4.3: Simulation results for chain link without a modeled crack with neck radius 621.5 mm

The results obtained from the simulation of the chain link without a modeled crack with neck radius of 831.9 mm are as shown in Figure 4.4. The equivalent stress, deformation, fatigue life and safety factor were obtained to be 142 MPa, 0.05930 mm, \[1.022 \times 10^{11}\] cycles and 4.19 respectively.
Figure 4.4 shows the results obtained from the simulation of the chain link without a modeled crack with neck radius of 1245.5 mm. The equivalent stress, deformation, fatigue life and safety factor were found to be 144 MPa, 0.06035 mm, $9.6565 \times 10^{10}$ cycles and 4.13 respectively.
Figure 4.5: Simulation results for chain link without a modeled crack with neck radius 1245.5 mm

The results obtained from the simulation of the chain link without a modeled crack with neck radii of 2488.4 mm are as shown in Figure 4.6. The equivalent stress, deformation, fatigue life and safety factor were obtained as 145 MPa, 0.06101 mm, $9.25 \times 10^{10}$ cycles and 4.08.
Figure 4.6: Simulation results for chain link without a modeled crack with neck radius 2488.4 mm

The results obtained from simulation for the different designs with different neck radii without a modeled crack are tabulated as shown in Table 4.2. As the neck radius increase from 0 mm to 2488.4 mm, the equivalent stress also increased from 135 to 145 MPa because the neck act as a stress raiser. The deformation also increased from 0.05644 mm to 0.06101 mm because of the increase in equivalent stress. However, the fatigue life and the safety factor decreased from $1.14 \times 10^{11}$
to $9.25 \times 10^{10}$ and 4.32 to 4.08 respectively. This observation was also as a result of the equivalent stress increasing.

Table 4.2: Simulation Results for Different Neck Radii without a modeled Crack

<table>
<thead>
<tr>
<th>Neck Radius/mm</th>
<th>Equivalent Stress/MPa</th>
<th>Deformation/mm</th>
<th>Fatigue Life/cycles</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>135</td>
<td>0.05644</td>
<td>$1.14 \times 10^{11}$</td>
<td>4.32</td>
</tr>
<tr>
<td>500</td>
<td>139</td>
<td>0.05744</td>
<td>$1.09 \times 10^{11}$</td>
<td>4.27</td>
</tr>
<tr>
<td>621.5</td>
<td>141</td>
<td>0.05830</td>
<td>$1.05 \times 10^{11}$</td>
<td>4.23</td>
</tr>
<tr>
<td>831.9</td>
<td>142</td>
<td>0.05930</td>
<td>$1.02 \times 10^{11}$</td>
<td>4.19</td>
</tr>
<tr>
<td>1245.5</td>
<td>144</td>
<td>0.06036</td>
<td>$9.66 \times 10^{10}$</td>
<td>4.13</td>
</tr>
<tr>
<td>2488.4</td>
<td>145</td>
<td>0.06101</td>
<td>$9.25 \times 10^{10}$</td>
<td>4.08</td>
</tr>
</tbody>
</table>

Figure 4.7 shows graphs comparing the equivalent stress, deformation, life and safety factor for the designs with different neck radius without a modeled crack. From the graphs it can be seen that as the neck radius increases, the equivalent stress and deformation also increase but the fatigue life and safety factor decrease. It was observed that the higher the equivalent stress the lower the fatigue life and safety factor but the higher the deformation. It can therefore be concluded that the design with no neck i.e. 0 mm neck radius is the most effective.
4.4.2 Results for Designed Chain Link with a Modeled Crack

The following results were obtained from the simulation of designed chain links with a modeled crack. The modeled crack was located around the neck region. The equivalent stress, deformation, fatigue life and safety factor were obtained.
using ANSYS simulation software. The crack was introduced as a model for the inclusions so as to predict the effects of inclusions on the chain link.

Figure 4.8 shows the results obtained from the simulation of the chain link with a modeled crack with neck radius of 0 mm. The equivalent stress, deformation, fatigue life and safety factor were obtained as 133 MPa, 0.05852 mm, $1.008 \times 10^{11}$ cycles and 4.17 respectively.

![Simulation results for chain link with a modeled crack with neck radius 0 mm](image)

(a) Equivalent Stress  (b) Deformation

(c) Fatigue Life  (d) Safety Factor

Figure 4.8: Simulation results for chain link with a modeled crack with neck radius 0 mm
The results obtained from the simulation of the chain link with a modeled crack with neck radius of 500 mm are as shown in Figure 4.9. The equivalent stress, deformation, fatigue life and safety factor were obtained as 135 MPa, 0.05947 mm, $9.774 \times 10^{10}$ cycles and 4.145 respectively.

Figure 4.9: Simulation results for chain link with a modeled crack with neck radius 500 mm

Figure 4.10 shows the results obtained from the simulation of the chain link with a modeled crack with neck radius of 621.5 mm. The equivalent stress, deformation,
fatigue life and safety factor were obtained as 136 MPa, 0.06045 mm, $9.241 \times 10^{10}$ cycles and 4.08 respectively.

The results obtained from the simulation of the chain link with a modeled crack with neck radius of 831.9 mm are as shown in Figure 4.11. The equivalent stress, deformation, fatigue life and safety factor were obtained as 137 MPa, 0.06148 mm, $8.959 \times 10^{10}$ cycles and 4.19 respectively.
Figure 4.11: Simulation results for chain link with a modeled crack with neck radius 831.9 mm

Figure 4.12 shows the results obtained from the simulation of the chain link with a modeled crack with neck radius of 1245.5 mm. The equivalent stress, deformation, fatigue life and safety factor were obtained as 139 MPa, 0.06245 mm, $8.522 \times 10^{10}$ cycles and 3.99 respectively.
Figure 4.12: Simulation results for chain link with a modeled crack with neck radius 1245.5 mm.

The results obtained from the simulation of the chain link with a modeled crack with neck radii of 2488.4 mm is as shown in Figure 4.13: The equivalent stress, deformation, fatigue life and safety factor were obtained as 142 MPa, 0.06293 mm, $8.249 \times 10^{10}$ cycles and 3.767 respectively.
Figure 4.13: Simulation results for chain link with a modeled crack with neck radius 2488.4 mm

The results obtained from simulation for the different designs with different neck radii with a modeled crack are tabulated as shown in Table 4.3. As the neck radius increased from 0 mm to 2488.4, the equivalent stress increased from 133 to 142 MPa because the neck radius act as stress raiser. The increase in equivalent stress resulted in increase in deformation from 0.05731 mm to 0.06301, a reduction in fatigue life from $1.01 \times 10^{11}$ to $8.25 \times 10^{10}$ as well as reduction in safety factor.
from 4.26 to 3.77.

Table 4.3: Simulation Results for Different Neck Radii with a Modeled Crack

<table>
<thead>
<tr>
<th>Neck Radius/mm</th>
<th>Equivalent Stress/MPa</th>
<th>Deformation/mm</th>
<th>Fatigue Life/cycles</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>133</td>
<td>0.05731</td>
<td>$1.01 \times 10^{11}$</td>
<td>4.26</td>
</tr>
<tr>
<td>500</td>
<td>135</td>
<td>0.05947</td>
<td>$9.77 \times 10^{10}$</td>
<td>4.15</td>
</tr>
<tr>
<td>621.5</td>
<td>136</td>
<td>0.06045</td>
<td>$9.24 \times 10^{10}$</td>
<td>4.08</td>
</tr>
<tr>
<td>831.9</td>
<td>137</td>
<td>0.06148</td>
<td>$8.96 \times 10^{10}$</td>
<td>4.04</td>
</tr>
<tr>
<td>1245.5</td>
<td>139</td>
<td>0.06293</td>
<td>$8.52 \times 10^{10}$</td>
<td>3.99</td>
</tr>
<tr>
<td>2488.4</td>
<td>142</td>
<td>0.06301</td>
<td>$8.25 \times 10^{10}$</td>
<td>3.77</td>
</tr>
</tbody>
</table>

Figure 4.14 shows graphs comparing the equivalent stress, deformation, fatigue life and safety factor for the designs with different neck radii without a modeled crack. From the graphs it can be seen that as the neck radius increases the equivalent stress and deformation also increase but the fatigue life and safety factor decreases. The observation made was that, the higher the equivalent stress the lower the fatigue life and safety factor but the higher the deformation. It can therefore be concluded that the design with no neck i.e. 0 mm neck radius is a better option compared to the others. The new design shows an improvement on equivalent stress, deformation, fatigue life as well as safety factor in comparison with the existing design.
This proves that the fewer the number of discontinuities in designs the better the design. The results obtained from the simulation tend to support the experimental results in that the life of the existing chain link reduced when the inclusion which was modeled as a crack was introduced. From the experimental results,
the cause of failure was found to be from inclusions as already shown in Figures 4.11 and 4.12. Juvonen [44] in his study on effects of non-metallic inclusions on fatigue properties of calcium treated steels concluded that the fatigue properties of steels are decreased by inclusions. From the simulation results, the life of the chain link reduced when modeled with the inclusion existing within the chain link.
CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Both Failed and un-failed samples of bucket elevator chain link were collected from east African Portland Cement (EAPC) for analysis. Preliminary examination, chemical analysis and micro-structural analysis was performed on the samples and the following conclusions were drawn;

1. The point of initiation of the fracture was found to be from inclusions within the chain link. These inclusions generated micro cracks within the material which progressed during loading and impact forces as a result of the sprocket teeth impacting on the chain links. These inclusions were either located at the surface or the core and therefore the fracture had initiated either at the surface or the core depending on the location of the inclusions.

2. The type of failure was deduced to be brittle as the grains on the fracture surface were fine grains. Brittle fractures initiate from inclusions at grain boundaries and as the fracture had initiated from inclusions at the grain boundaries, it confirms that the type of failure is of the brittle type.

3. Based on the findings, an improvement was made on the chain link from the design point of view as nothing can be done from the manufacturing process aspect because producing a clean steel is impossible. The results showed
that the newly designed chain link had a better fatigue life $1.08 \times 10^{11}$ cycles compared to $8.25 \times 10^{10}$ cycles of the existing chain link. This is a 23.61% improvement on the existing chain link.

5.2 Recommendation

The following is recommended;

1. It is recommended that further research should be done on these inclusions on how to make it useful in improving on the fatigue life of the chain link instead of it being detrimental to the fatigue life of the chain link by modifying its chemical composition.
REFERENCES


struction and Design, 2011.


