CHARACTERIZATION AND VARIABILITY OF BENDING AND FATIGUE PROPERTIES IN REINFORCING STEEL BARS MADE FROM SCRAP

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2015

Characterization and Variability of Bending and Fatigue Properties in Reinforcing Steel Bars Made From Scrap

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

2015

DECLARATION

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

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This thesis has been submitted for examination with our approval as the university supervisors.

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DEDICATION

This work is dedicated to Mzee Francis Wanjogu Wamũgũnda; two inimitable teachers, namely Mrs. Mary Njeri Nahashon Ngigĩ (Gacharũ Primary) and Mrs. Shah (Kabete Technical) as well as my family, namely: Wairiũko, Cirũ, Kĩhooto, Mũrĩithi and Waithĩra.

ACKNOWLEDGEMENTS

I wish to extend my sincere gratitude to my supervisors, Prof. S. M. Maranga and Prof. S. M. Mutuli for their contribution towards the development and conclusion of this study.

I also wish to thank the silent contributors that allowed me hours of free consultation and advice in the laboratories, workshops and industries: Mr. J. Njũe, Mr. Kuria and Mr. Koech of University of Nairobi. At JKUAT I was fortunate to receive the kind assistance of Mr. B. Onyancha, Mr. Dio Mzombo, Mr. Wainaina, Mr. Kagiri and Mrs. Irene Munyerere Fedha.

I would also like to thank my colleagues Mr. James Mutua, Mr. Shem Elahetia Maube, Mr. Bernard Kosgey, Mr. Evan Mũrĩmi, Ms. Esther Wangũi, Ms. Doreen Wanjirũ Irũngũ, Mr. Peter Oketch and Mr. Titus Magicho for actual material contribution, helpful suggestions and moral support, without which this work might never have been written.

This is the high point of my life, getting here. To be alive, to be healthy and happy when everything I have gone through might have turned out entirely different.

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ABBREVIATIONS

ACI	American Concrete Institute
AASHTO	American Association State Highway Transport Officials Standard
AISI	American Iron and Steel Institute
ASTM	American Society of Testing Materials
BCC	Body Centred Cubic
BCT	Body Centred Tetragonal
BOS	Basic Oxygen Steel Making
BS	British Standard
$\mathbf{C_{eq}}$	Carbon Equivalent Value
CoV	Coefficient of Variability
CRSI	Concrete Reinforcing Steel Institute
EAF	Electric Arc Furnace
FCC	Face Centred Cubic
FHWA	Federal Highway Administration
HK CS	Hong Kong Construction Standard
ISO	International Organization for Standardization
K	The ratio between the tensile strength and the 0.2% proof strength
KEBS	Kenya Bureau of Standards
NCHRP	National Cooperative Highway Research Program
NRC	National Research Council of Canada
PCI:	Pre-stressed Concrete Institute
PWD:	Public Works Department, Industrial Area
TFHRC	Turner-Fairbank Highway Research Center
TMT	Thermal Mechanical Treatment
TRRL	Transport and Road Research Laboratory

UON	University of Nairobi
WWF	Welded Wire Fabric

NOMENCLATURE

A	Effective cross-sectional area
A_{CM}	Upper critical temperature: below this martensite is ejected from austenite
A_{gt}	Elongation at maximum force [mm/mm]
A_o	Nominal cross-sectional area of the bar
A_1	Lower critical temperature: point of austenite to pearlite transformation
A_3	Upper critical temperature: below this ferrite is ejected from austenite
A_5	Elongation at fracture [mm/mm]
d	Effective Diameter of the bar
e	acceptable error: the precision
E_b	Energy expended in tensile test in Joules
L	Length of the bar (m)
L_o	Gauge Length
M	Mass of the bar per metre (kg)
N	Size of population
R_e	Upper yield strength [MPa]
R_m	Ultimate tensile strength [MPa]
$R_{p0.2}$	Proof stress or Yield strength at 0.2% strain [MPa]
S	Standard deviation of a sample
$\bar{X}$	Mean of a sample
x_i	population parameter x at the count i=1,2,3,4, 5....
Y_s	Yield Strength [MPa]
z	Standard normal variate at a given confidence level

α	Ferrite phase
γ	Austenite phase
μ	Mean of a population
σ	Standard deviation of a population
σ_{max}	Maximum stress, applied to a bar in axial load fatigue test
σ_{min}	Minimum stress, experienced by a bar in axial load fatigue test

ABSTRACT

The variability of mechanical properties of reinforcing steel bars manufactured from scrap metals by local manufacturers in Kenya was investigated in this research. The key properties were bending and fatigue. Information available on Kenyan rebar behaviour so far has been scant and inadequate. Such information could be used for optimizing concrete structural design and possibly avoiding the frequent collapse of structures in Kenya.

The bars tested were purchased from two local rolling mills. Laboratory tensile tests, bend/rebend test, chemical composition analyses, microstructure examination and hardness tests were carried out on a set of bar specimens.

The results were compared with the existing set standards for specified class of reinforcing steel bars and non-conforming variability discussed. Bars from one rolling mill were seen to fail outright in the tensile test. All bars passed the bend/rebend test, with 0% CoV. Toughness was established by finding the area under the tensile test curve. Most of the tested properties had a coefficient of variation under 10% except for percentage elongation and toughness whose CoV rose to over 30%.

In view of the source A bars that failed the tensile strength test, it is recommended for the rolling mills to add the grain refining alloying elements vanadium and nickel.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

The ever increasing Kenyan population triggers a housing need which in turn indicates high rise buildings especially in urban areas, together with the required infrastructure. Proper and good quality concrete reinforcement can address the issues of:

1. Collapsed structures in Kenya.
2. The experience of earth tremors (few and weak but worrisome).
3. The need for an improved knowledge base (research).
4. The developmental needs of vision 2030.
5. Construction for grandstanding.

Reinforcing bars in the form of concrete reinforcement, are used for the construction of all types of structures such as buildings, piers and hydraulic jibs. Various quality tests are stipulated in BS 4449:2005 [1]. Substandard reinforcing bars in the construction industry could lead to the collapse of structures [2]. This study is an investigation of how well local manufacturers of bars from local scrap have conformed to the standards and obtaining a measure of the inevitable variability of the mechanical properties thus scrutinized.

The quality of the reinforced concrete member is guided by BS8110 [3]. Failure of concrete structures in Kenya, can be attributed to several factors number of factors in the metal bar such as; method of manufacturing the steel, chemical composition, heat treatment, bending, construction [3] and service conditions (aseismatic/ high temperatures). These factors give rise to variation in mechanical properties of the reinforcement steel bar.

Bending is a strain-ageing procedure that can adversely affect the mechanical properties of the bar. The application of bending [4] in practice requires meticulous detail which most construction personnel ignore, often improvising, much to the detriment of the upcoming structure. Bending is done for various reasons: cranking a bar to manage shear effects and transfer main reinforcement from soffit to upper part of beam, hooks to minimize the possibility of pullout, end of bar to reduce pullout tendencies, stirrups, etc. There is apprehension that poor bending practices can lead to weakening of the bar, the cast beam and eventual structural collapse [4–6].

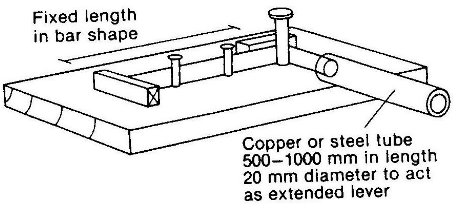


Figure 1.1: Manual bending.

The manufacturer is required to subject the bar to the bend/rebend test according to BS 4449:2005 [1]. On construction sites, common bending practice makes use of nails hammered onto a piece of wood [5], Figure 1.1. However, nowadays, there is a variety of rebar bending machines on the market [5].

Fatigue test for reinforcement bars is carried out on the axial load testing machine, to a specified stress range [1]. Fatigue properties are important especially for countries prone to earthquakes, strong winds and other causes of irregular, active cyclic loads. Most standards on reinforcement bars regard fatigue test as optional [7, 8].

For this study, sample bars obtained from two rolling mills were subjected to the bend/rebend test, tensile test, hardness test, chemical composition analysis and grain size measurement.

1.2 Problem Statement

A lot of construction activity is now evident in Kenya. In most high rise buildings, steel reinforcement is usually used. It is therefore important that proper quality steel reinforcement is employed. The collapse of buildings during construction, which is a fairly regular occurrence in Kenya, is regrettable and depressing. The quality of the reinforcing bars and hence their mechanical properties, can often be attributed to the quality and type of iron-ore, scrap metal, steel making procedure, chemical composition, rolling method, subsequent heat treatment, cold work (twisting and bending) and service conditions (aseismatic/high temperatures). The reinforced concrete member often requires that the bar be bent when forming stirrups, hooks and cranked bars among other shapes.

Such operations can adversely affect the mechanical properties of the rebar. When casting reinforced concrete, the following factors must be got right to obtain a durable structure.

1. Working atmosphere (e.g. corrosive and wet).
2. Design and workmanship.
3. Placing the bars in formwork with adequate clearance resulting in adequate bar cover.
4. Proper quality sand.

5. Ballast.

6. Cement and water mix.

Thus, a wide and varied field awaits any investigator trying to pinpoint the reason for failure of a reinforced concrete member.

Necessary bending activity affects the mechanical properties of the reinforcement bar. The factors that give rise to variation in mechanical properties of the bar, even before the reinforced concrete is cast must be known.

Bars are manufactured as per the standards. However, the actual values for some of the bars may fall off the anticipated specifications. In Kenya, data on such variation, for example mechanical properties of steel bars remain scant and informal. Investigation on reinforcement bars has established information on the yield stress, tensile strength and percentage elongation which showed variation [2].

1.3 Objectives of the Study

1.3.1 Main Objective

The main objective of the study was to determine the variability of bending and fatigue properties in reinforcing steel bars made from local scrap and to identify the possible causes of the variation.

1.3.2 Specific Objectives

In order to achieve the primary objective, the research was subdivided into the following goals:

1. To determine bend / rebend properties of reinforcement bars as received.
2. To determine the microstructure of reinforcement bars as received and establish how this affects the mechanical properties.
3. To determine the fatigue properties of reinforcement bars as received.
4. To determine tensile strength properties of reinforcement bars as received.

1.4 Scope of the Research

The research was carried out on hot rolled deformed (ribbed) reinforcing steel bars made from local scrap. Several bars of different nominal diameters were examined.

1.5 Justification of the Study

The significance of this study is to provide information to the rolling mills, statutory bodies and end users of reinforcing steel bars on the possible causes of variation of mechanical properties of reinforcing steel bars where the bar is subjected to bending and cyclic loading. In Kenya, the data on variation of mechanical properties of reinforcement bars remain scanty and informal. Also, in the recent past, several high rise buildings have been seen to collapse during construction. This study can be considered as a tentative step towards supplying information about the quality of reinforcing steel bars in the Kenyan market. (See Appendix B - Figure B.1).

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Overview

In this chapter we are dealing with aspects of rebars such as standards, chemical composition and weldability. Various methods of producing rebars are discussed. In addition, several tests such as EDX Spectrometry, microstructure (grain size analysis), tensile strength test, bend/rebend and fatigue are laid out. The report by Munyazikwiye [2] recommended the following areas for further research: investigation on fatigue behavior, that manufacturers can micro alloy to improve mechanical properties, further microstructure examination, questioning the quality control practices by manufacturers of reinforcing bars.

The aim of design is the achievement of an acceptable probability that structures being designed will perform satisfactorily during their intended life. With an appropriate degree of safety, they should sustain all the loads and deformations of normal construction and use and have adequate durability and resistance to the effects of misuse and fire. It is assumed that the quality of the concrete, steel and other materials and of the workmanship adopted is adequate for safety, serviceability and durability.

Steel has the same high strength in tension and compression and it is ductile. Ductility is the ability to undergo large plastic deformation before failure. Steel that has yielded sustains cracked concrete and helps reduce the risk of sudden collapse as there is an ample warning before failure. The main issues that affect the performance of reinforcing steel bars are the characteristic strengths, concrete cement bond and the condition of exposure which is the sole determinant of the durability of reinforced concrete structures. Based on the conditions of exposure and environment, the amount of cover concrete over steel reinforcement influences the durability of reinforced concrete.

The rates at which oxygen, carbon dioxide, chloride ions and other potentially deleterious substances penetrate the concrete, and the concrete's ability to bind these substances. Cracks causes pumping in offshore structures or underwater structure for bridges. This can reduce fatigue life.
Rebending the embedded rebar is hazardous at best, especially if ambient temperatures are low. Bending can be done cold or with pre-heat. Can field bent bars be worked as successfully as machine bent bars? The ACI Building code does not specifically refer to straightening or correting embedded rebar, but indicates that the engineer may determine if embedded rebar may be bent.
The results of a bending investigation can provide guidance to field engineers who are confronted with the need to approve a procedure for field bending of reinforcing steel.

2.2 Steel Reinforcing Bars

2.2.1 Standards

Reinforcement bars come in two forms: twisted bars and ribbed bars. The twisted bars are cold formed while the ribbed bars are hot rolled. The specifications and classifications of the bars are detailed in the Kenyan and international standards, [1,3, 4,7–9].

2.2.1.1 Chemical Composition

The chemical composition of steel samples taken preferrably during melting but before pouring of the charge is specified in the standards. The percentages of carbon, manganese, phosphorus, sulphur, silicon, copper, nickel, chromium, molybdenum and vanadium are determined by the manufacturer. The phosphorus content should not exceed 0.06%. For example, in Table 2.1, BS 4449:2005 [1] stipulates that the chemical composition thus determined is subject to a maximum.

Table 2.1: Chemical composition (max) of steel in BS 4449:2005 [1]

	Carbon	Sulphur	Phosphorus	Nitrogen	Copper	C_{eq}
Cast (heat) analysis	0.220	0.050	0.050	0.012	0.800	0.500
Product analysis	0.240	0.055	0.055	0.014	0.850	0.520

Control of the chemical composition produces steel of the required grade and characteristics. The variation of the values of the product and cast analysis is due to heterogeneity arising during casting and solidification.

The X-rays knock off the inner shell electrons of an element. An outer shell high energy electron moves in to replace it. The energy dispersed as the electron shifts between shells, which is characteristic for each element, is sensed by the machine to determine the identity of the element. By scanning the material and comparing with a software database, the machine prints out the results of the elements present.

Figure 2.1: Energy Dispersve X-Ray (EDX) Spectrometer, (at PWD, Industrial Area)

The characteristic X-ray lines are named according to the shell in which the initial vacancy occurs and the shell from which an electron drops to fill that vacancy. For instance, if the initial vacancy occurs in the K shell and the vacancy filling electron drops from the adjacent (L) shell, a Kα x-ray is emitted. If the electron drops from the M shell (two shells away), the emitted x-ray is a Kβ x-ray. Similarly, if an L-shell electron is ejected and an electron from the M-shell fills the vacancy, Lα radiation will be emitted, [10].

Within a given shell, there may be electrons in orbitals differing in energy due to bonding effects. Thus the Kα peak actually comprises the Kα1 and Kα2 X-rays. These are very close together and unresolved in an EDS system so that a Kα1,2 doublet is seen as the Kα peak at an energy between the two individual components and an intensity corresponding to a weighted average, [10].

The most probable transition when a K-shell vacancy is created is the L to K transition, because these are adjacent energy shells. Therefore Kα radiation will always be more intense than Kβ radiation. It also follows that Kβ radiation will be of higher energy than Kα radiation, in as much as the energy difference between the M and K shells (Kβ radiation) is greater than the energy difference between the L and K shells (Kα radiation). Figure 2.2 shows the electron jump from shell to shell and the associated radiation, Hafner, [10].

2.2.2 Weldability

All grade 250 steels can be welded BS 5135 [11]. Steels of grade 460 to 425 are considered weldable if the cast analysis gives a maximum carbon equivalent of 0.51% when

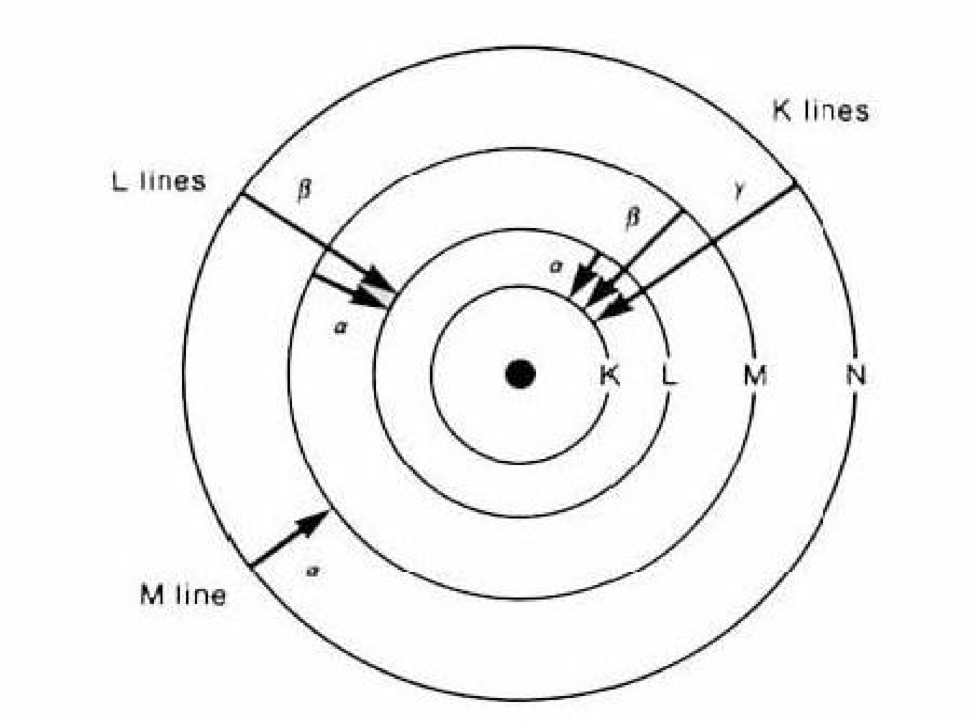


Figure 2.2: K, L, M and N energy shells, the electron jump with associated radiation [10]

derived from the following formula 2.1, [1, 5].

$$\text{Carbon equivalent,} \quad C_{eq} = C + \frac{Mn}{6} + \frac{Cr + V + Mo}{5} + \frac{Cu + Ni}{15} \tag{2.1}$$

where C is % Carbon content, Mn is % manganese content, Cr is % chromium content, V is % vanadium content, Mo is % molybdenum content, Cu is % copper content, Ni is % nickel content and C_{eq} is % carbon equivalent content.

Ordinarily, bars are joined by binding and splicing. Splices of reinforcement shall be made only as required or permitted on the design drawings, in the specifications, or as authorized by the engineer. The traditional lap splice, when it will satisfy all requirements, is generally the most economical splice. Certain instances make the lap splice impractical. Examples are congestion at the splice locations, the location of construction joints, provision for future construction, and the particular method of construction. In addition, the ACI Building Code does not permit lap splices in "tension tie members", or in No.14 and No.18 bars except for compression only, when spliced to smaller size footing dowels. In column design, consideration must also be given to the fact that lapped offset bars may have to come inside of the bars above and therefore reduce the moment arm in bending.

In such cases, the alternative splicing methods of mechanical connections or welding are considered.

Where weld splicing method is selected, there may be need to specify ASTM 706 [12] reinforcement intended for applications where restrictive mechanical properties and chemical composition are required for compatibility with controlled tensile property applications or to enhance weldability.

The C_{eq} as specified in Equation 2.2 as given in [12] must be below 0.55%.

$$\text{Carbon equivalent,} \quad C_{eq} = C + \frac{Mn}{6} + \frac{Cu}{40} + \frac{Ni}{20} + \frac{Cr}{10} - \frac{Mo}{50} - \frac{V}{10} \tag{2.2}$$

Welded Wire Fabric (WWF) saw increased use post World war (II) in the reconstruction of Germany which was short on manpower. Figure 2.3 shows typical WWF.

Figure 2.3: Typical Welded Wire Fabric [13]

2.3 Production of Reinforcing Steel Bars

2.3.1 Manufacture of Steels

Steel can be produced by various methods:

1. from iron ore and coke in a blast furnace,
2. from iron ore and scrap steel in an induction furnace, and
3. from scrap steel.

2.3.1.1 Iron Ore and Coke in a Blast Furnace

The blast furnace is a shaft type some 60 m high [14]. The refractory lining of such a furnace is designed to last for several years since it is uneconomical to shut down for relining. Production takes place every day. The main ores are haematite (Fe_2O_3), magnetite (Fe_3O_4), limonite or bog iron (hydrated haematite) and siderite ($FeCO_3$). They are widely deposited, often in large surface deposits sometimes very rich in iron (e.g. 60% Fe). The better deposits require little or no treatment before smelting.

The iron ore, coke and suitable catalyst (limestone) are fed into the blast furnace to produce pig iron. They are charged to the furnace through the double bell-and-cone gas-trap system, whilst a pre-heated air blast is blown in through the tuyeres near the base of the furnace. The iron oxide is easily reducible, the temperature at which carbon can reduce FeO being about 750^{o}C. At regular intervals of several hours both tap hole and slag hole are opened in order to run off, first the slag and then the molten pig iron. The holes are then replugged with clay.

It is thus not surprising, in view of the abundance, richness and reducibility of iron ores and of the great strength of the metal and the variety of useful properties developable by alloying - that iron far outstrips all other metals in cheapness, production and general engineering use [14].

The smelting operation involves the following chemical reactions:

1. Coke in the region of the tuyeres (bottom zone of furnace) burns completely– $(C + O_2 \rightarrow CO_2 + Heat(Exothermic))$

   Just above the the tuyeres the carbon dioxide is reduced by the white hot coke to carbon monoxide– $(CO_2 + C \rightarrow 2CO - Heat(Endothermic))$

   On balance the overall reaction is strongly exothermic, so that the temperature remains high.

2. As the carbon monoxide, which is a powerful reducing agent, rises through the charge it reduces the iron(III) oxide (in the ore) - $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$. This reaction takes place in the upper part of the furnace where the temperature is too low for the iron so formed to melt.

3. At the same time as this reduction is taking place, the earth waste or 'gangue' associated with the ore combines with lime (formed by the decomposition of limestone added with the charge) to produce a fluid slag:

   $CaCO_3 \rightarrow CaO + CO_2$

   $2CaO + SiO_2 \rightarrow 2CaO.SiO_2$

   The function of the lime here is to liquify the gangue. The latter, being composed largely of silica, would not melt at the blast furnace temperature and must therefore be attacked chemically to form a low melting point slag which will run from the furnace.

The furnace is tapped at regular intervals, the iron generally being stored in the molten state in a 'mixer' prior to transfer to the steel making plant. Some may be cast as ‘pigs’ for subsequent re-melting, [14].

In the Bessemer process air is blown through a charge of molten pig iron contained in a pear-shaped ‘converter’ [14]. Due to the high rate of chemical reactions involved in the oxidation of impurities such as carbon, silicon and manganese in the pig iron, the temperature runs so high that the final product remains molten in the converter and has to be cast. The result is low carbon steel suitable for construction purposes.

2.3.1.2 Iron Ore and Steel Scrap in an Induction Furnace

In the High Frequency Induction Furnace the heat is generated in the metal itself by eddy currents induced by a magnetic field set up by an alternating current, which passes round water cooled coils surrounding the crucible. Metallic iron is first obtained from iron ore (even low grade ore) by the use of solid reductant (carbonaceous material) in a completely enclosed system wherein the heat for reduction originates from induction coils surrounding a vertical retort, the said retort posseses compartments made of steel walls, which are heated by induction. In descending down the retort the iron ore is reduced into molten iron of “blast furnace quality”, (known in some quarters as Direct Reduced Iron) and is suitable for charging directly into a steel making furnace. In the steel making furnace (converter) the molten iron, together with scrap, is blown with oxygen to produce steel. India is second only to Venezuela in DRI capacity, [15, 16].

2.3.1.3 Recent Trends and Challenges in Steel Making

Coke is produced by baking coal in the absence of oxygen to remove the volatile hydrocarbons contained in coal. The resulting coke is mechanically strong, porous, and chemically reactive, which are all critical properties for stable blast furnace operation.

In addition to supplying carbon for heat and the reduction of iron ore, coke must also physically support the burden in the blast furnace shaft and remain permeable to the hot air blast entering from the bottom. Coke-making is extremely problematic from an environmental perspective, as many of the hydrocarbons driven off during the coking process are hazardous. Aging coking facilities and tightening environmental control have made coke-making an economic liability.

Worldwide, direct-reduction capacity via existing gas-based technologies is likely to increase in order to support the expansion of EAF steelmaking to new, high-quality products. However, the blast furnace is likely to remain the backbone of worldwide iron production for several decades. To support the ever increasing steel demands, the industry has several options:

1. Stretch remaining hot metal supply with increased scrap melting in new steelmaking processes,

2. Increase the productivity of remaining large capacity furnaces, and

3. Adopt or develop an entirely new process(es) for the production of hot metal or steel to complement or replace the blast furnace [17].

Depending on scrap has its drawbacks; frequently the scrap is of unknown history and source, undesirable chemical content segregates at the grain boundaries and weakens the new steel. The attempt to sort and categorise the scrap is expensive.

2.3.2 Manufacture of Reinforcement Bars

2.3.2.1 Steel Scrap

Modern reinforcement bars are largely made of steel scrap, which is a cheaper way of obtaining raw materials [17]. Steel scrap, of assorted composition, is charged into an arc furnace: the scrap melts at 1250^{o}C. The target steel usually has about 0.24%C, 1.25%Mn, 0.475%Si and 0.18%V. After all the scrap has melted, samples are drawn out and tested for chemical content. Measured quantities of additives are then added with a view to getting the desired chemical composition. The molten metal is tapped into a ladle which is used to pour the metal into a water cooled mould of 100 or 125 mm square; of length 12 m. The billet is ready for the rolling process [5].
Making steel from scrap is cheap and convenient. However, demand for scrap in Kenya has created a rogue sector that uproots road signposts and guardrails. The choice of rebar making method is the prerogative of the steel maker [1].

2.3.2.2 The Rolling Mill

This consists basically of a reheating furnace (soaking pit) and a series of roll stands. A selected billet is fed into the reheating furnace, and slowly heated to between 1150^{o}C and 1200^{o}C. At the rolling temperature, the material is discharged from the furnace and rolled in different stands. For ribbed bar, longitudinal fins and short ribs are accommodated into the rolls in the last of the stands, before the bar has cooled but after attaining correct diameter. Figure B.2, in the Appendix, shows a typical, finishing roller pair for ribbed bar. Figure 2.4 shows rollers for plain round bar; Figure 2.5 shows a typical hot rolling mill while Figure 2.6 shows typical finishing rolls.

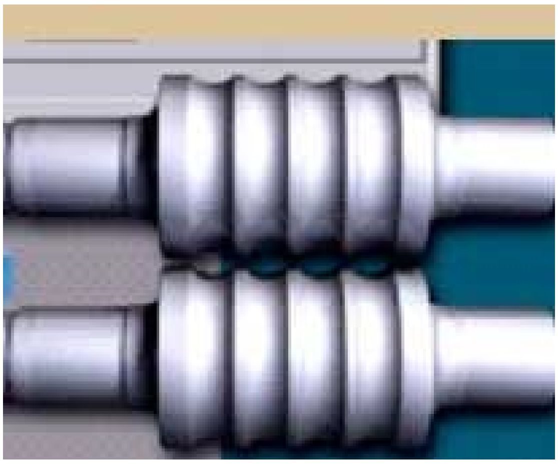


Figure 2.4: Rollers for plain round bar [18].

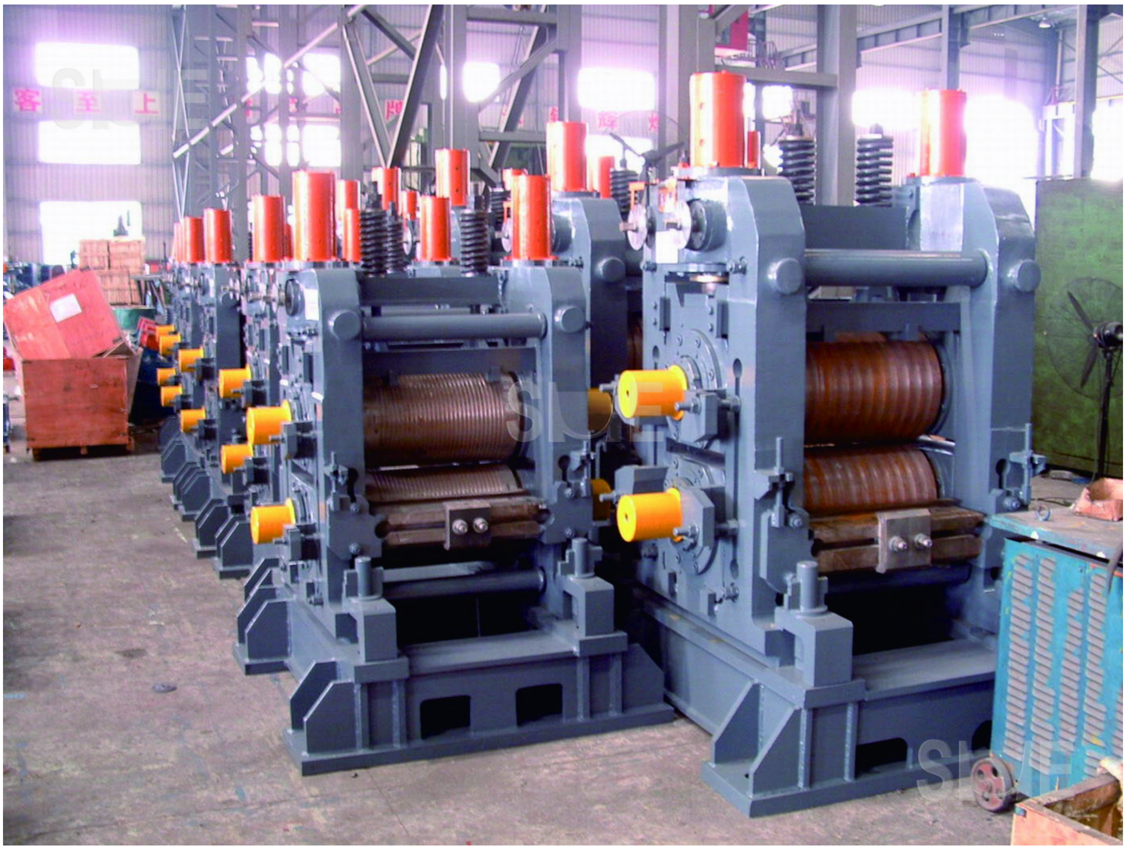


Figure 2.5: Hot rolling mill, made of several stands [18].

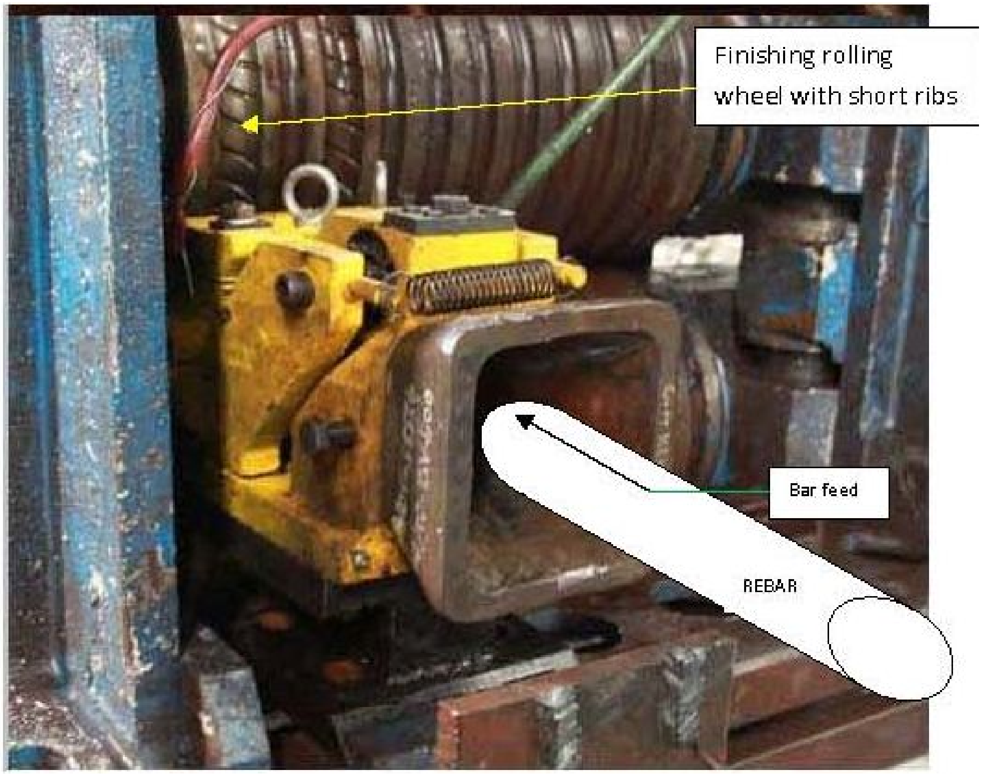


Figure 2.6: Hot rolling mill finishing rollers [19].

2.3.2.3 Categories of Reinforcement Bars

The methods of producing high quality reinforcing steel bars can be classified generally into three distinct categories: cold twisted, micro alloy addition and thermo mechanical treatment.

Cold Deformation (Twisted) The cold twisting process can also be referred to as work-hardening or cold-working. The rebar, usually of square cross section, is plastically deformed, by twisting, after it has cooled. Cold twisting achieves high strength by distortion of the lattice structure. The permanent strain means reduced ductility, which is a drawback. Another drawback is that because this process is performed off-line from the rolling mill, additional equipment and labour is required. The combination of poor mechanical properties and increased manufacturing costs, make this alternative an unpopular process, [20].

Micro-alloying Technique for Ribbed Bars In the microalloying process, small amounts of elements such as Vanadium, Niobium and/or Titanium are added to a carbon-manganese steel to promote strength by precipitation strengthening and grain refinement. Despite the additional cost of microalloying, micro-alloyed rebars possess certain advantages making them an appropriate choice for many high strength applications. Micro-alloyed rebars, unlike the Thermo-Mechanical Treatment (TMT) rebars, have a homogeneous cross section in terms of microstructure, strength and ductility. This characteristic allows machining of threads, which is important for mechanical couplers, and can also contribute to better resistance against atmospheric corrosion [6]. Micro-alloyed rebar can be welded without loss of strength and possess higher fire resistance than TMT rebars, [21].

Thermo-Mechanical Treatment (TMT) for Ribbed Bars This production method is used to increase the strength of the rebar, while limiting the level of carbon and carbon equivalent. In this process, after the bar exits the final rolling stand in the mill it travels through a series of quenching devices. The particular design of the quenching device is unique to the equipment manufacturer,

but in general, high pressure water is applied against the surface of the bar in order to cool it. In a very short time, this rigorous quenching reduces the surface temperature of the bar to a point where martensite develops as shown in Figure 2.7.

After exiting the quenching area, the remaining heat from the core of the bar conducts outwards and tempers the martensitic surface layer, which helps to increase its ductility. This is shown in Figure 2.8. TMT rebar achieves its beneficial qualities from the pearlite/ferrite core. In Appendix B, Figure B.3 shows TMT cooling curves while

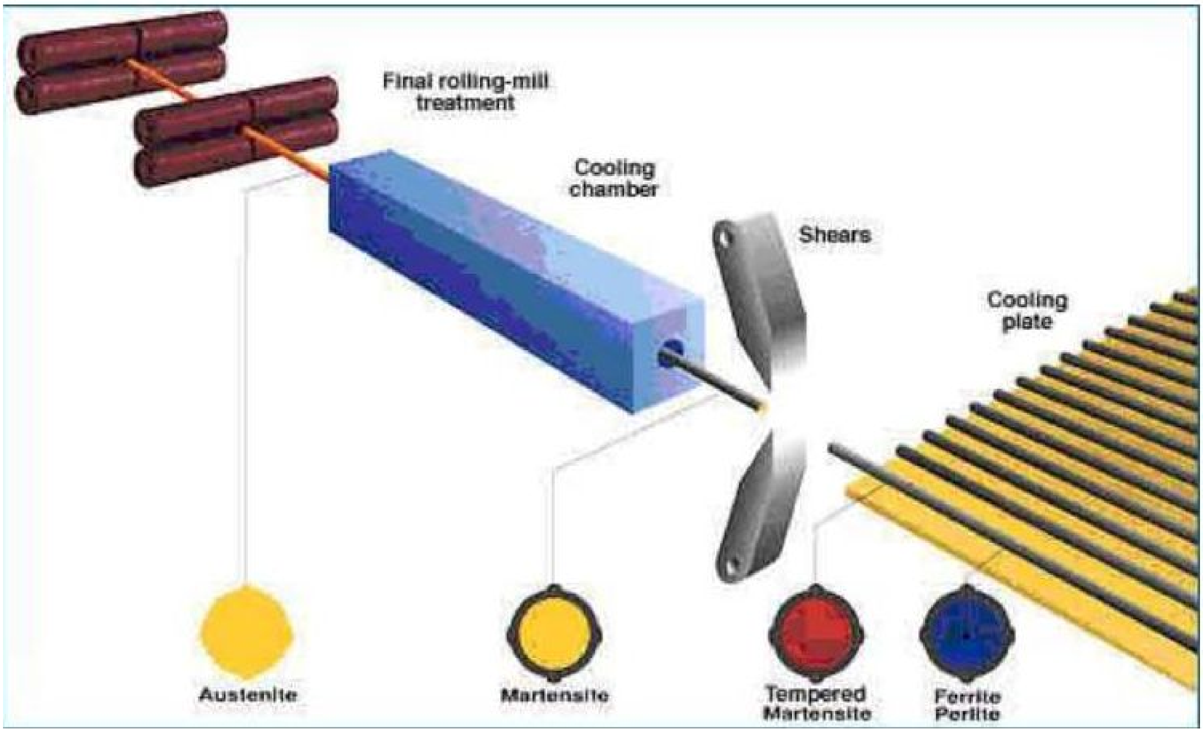


Figure 2.7: Schematic diagram for rolling, quenching unit, shearing and air cooling bench for TMT bars [22].

Figure B.4 illustrates continuous casting.

Of the three methods for forming reinforcing bars described above, TMT is the most cost effective. It requires a moderate investment in new equipment; and avoids the expensive alloy additions in the micro alloying process. Although this process improves many of the mechanical properties of the rebar, it unfortunately has a negative effect on the strain-hardening ratio [20].

2.4 Micro-Structure of Steels

The micro structure depends on the phases present and their proportions. This in turn is governed by the chemical composition and the heat treatment procedure adopted during manufacturing. Figure 2.9 shows some typical phases. Some possible phases

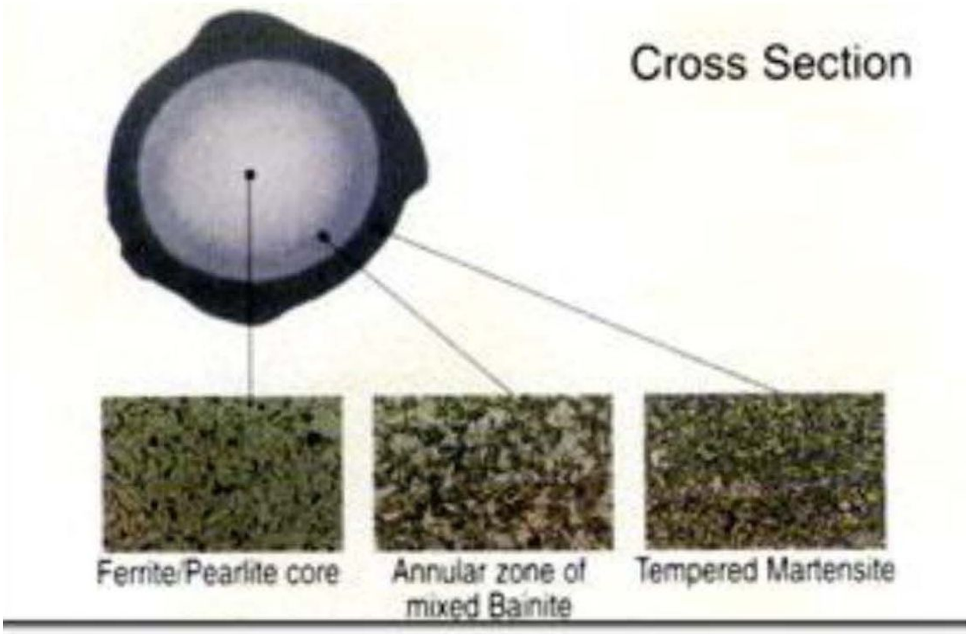


Figure 2.8: TMT bar microstructure showing ferrite/pearlite core, intermediate annular zone of mixed bainite, and the outer tempered martensite [22].

that can occur as the steel cools are Austenite, Face Centred Cubic

(FCC-γ), Ferrite, Body Centred Cubic (BCC-α), Cementite, Pearlite and Martensite, Body Centred Tetragonal (BCT). The phases present, and the amounts, are governed by diffusional transformation: the decomposition of austenite into ferrite, pearlite and bainite; itself depndent on the original chemical composition and rate of cooling. Alloying elements can refine the grain (thermal mechanical hot form), lower the austenite to ferrite transition temperature (reduce grain growth), and precipitation harden (impede dislocation movement) [20]. The microstructure of a material can strongly influence physical properties such as strength, toughness, ductility, hardness, corrosion resistance, high/low temperature behavior and wear resistance. These properties, in turn govern the application of the material in industrial practice.

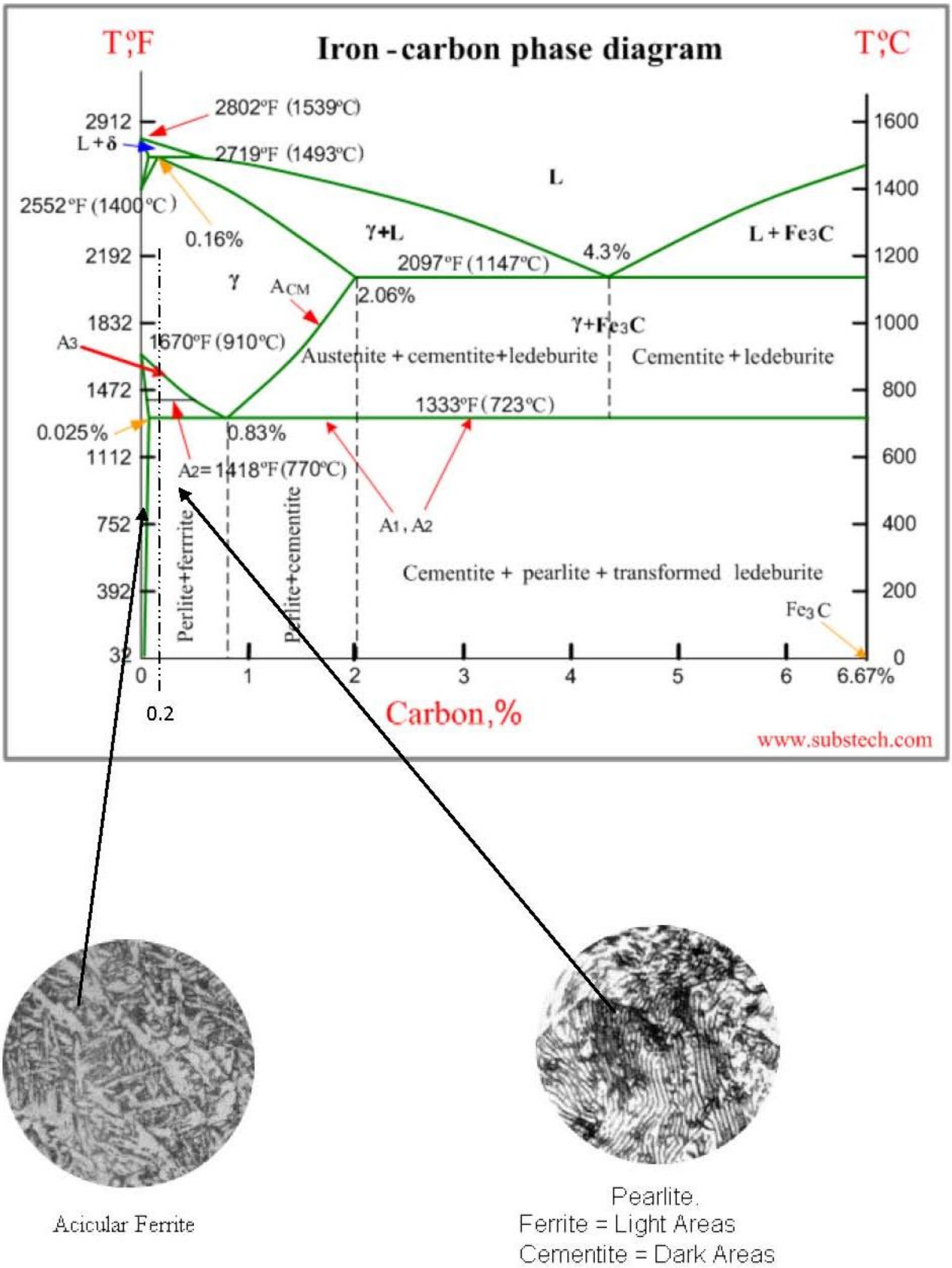


Figure 2.9: The Iron-Carbon phase diagram

2.5 Heat-Treatment

The cooling path for a steel is always significant. Ordinarily, ribbed bars are air cooled, with a ferrite-pearlite phase as the result. However, for cold twisted bar, the ferrite-pearlite phase exists, but is distorted and strained by the cold work. With TMT bars, controlled heat treatment involves careful quenching of the case, followed by self tempering whereby heat from the core reheats the case, then slow air cooling. A tempered martensite case and a ferrite-pearlite core results.

Critical temperatures-Figure 2.9-relevant to heat-treatment of reinforcement bars are:

- Upper critical temperature (point) A_3 is the temperature, below which ferrite starts to form as a result of ejection from austenite in the hypoeutectoid alloys.
- Upper critical temperature (point) A_{CM} is the temperature, below which cementite starts to form as a result of ejection from austenite in the hypereutectoid alloys.
- Lower critical temperature (point) A_1 is the temperature of the austenite-to-pearlite eutectoid transformation. Below this temperature austenite does not exist.

2.6 Grain Size

2.6.1 Grain Size in Steel

Grain size (except in special circumstances) is always associated with increased toughness and strength [23, 24]. In steel the final grain size is affected by the temperature of the steel before cooling started. The higher the temperature above the A_3 point in

Figure 2.9 the larger will be the grain size. When large, coarse or irregular steel grains are heated above the A_3 point, the grains will subdivide to give small ones of the best possible size.

2.6.2 Determination of Average Grain Size

Some of the methods used in determining average grain size, abridged below, are discussed in ASTM E 112 [25].

2.6.2.1 Comparison Procedure

The comparison procedure does not require counting of either grains, intercepts, or intersections but, as the name suggests, involves comparison of the grain structure to a series of graded images, either in the form of a wall chart, clear plastic overlays, or an eyepiece reticle. There appears to be a general bias in that comparison grain size ratings claim that the grain size is somewhat coarser ($\frac{1}{2}$ to 1 G number lower) than it actually is. Repeatability and reproducibility of comparison chart ratings are generally ± 1 grain size number [25].

2.6.2.2 Planimetric Procedure

The planimetric method involves an actual count of the number of grains within a known area. The number of grains per unit area, N_A, is used to determine the ASTM grain size number, G. The precision of the method is a function of the number of grains counted. A precision of ± 0.25 grain size units can be attained with a reasonable amount of effort. Results are free of bias and repeatability and reproducibility are less than ±0.5 grain size units. An accurate count does require marking off of the grains as they are counted [25].

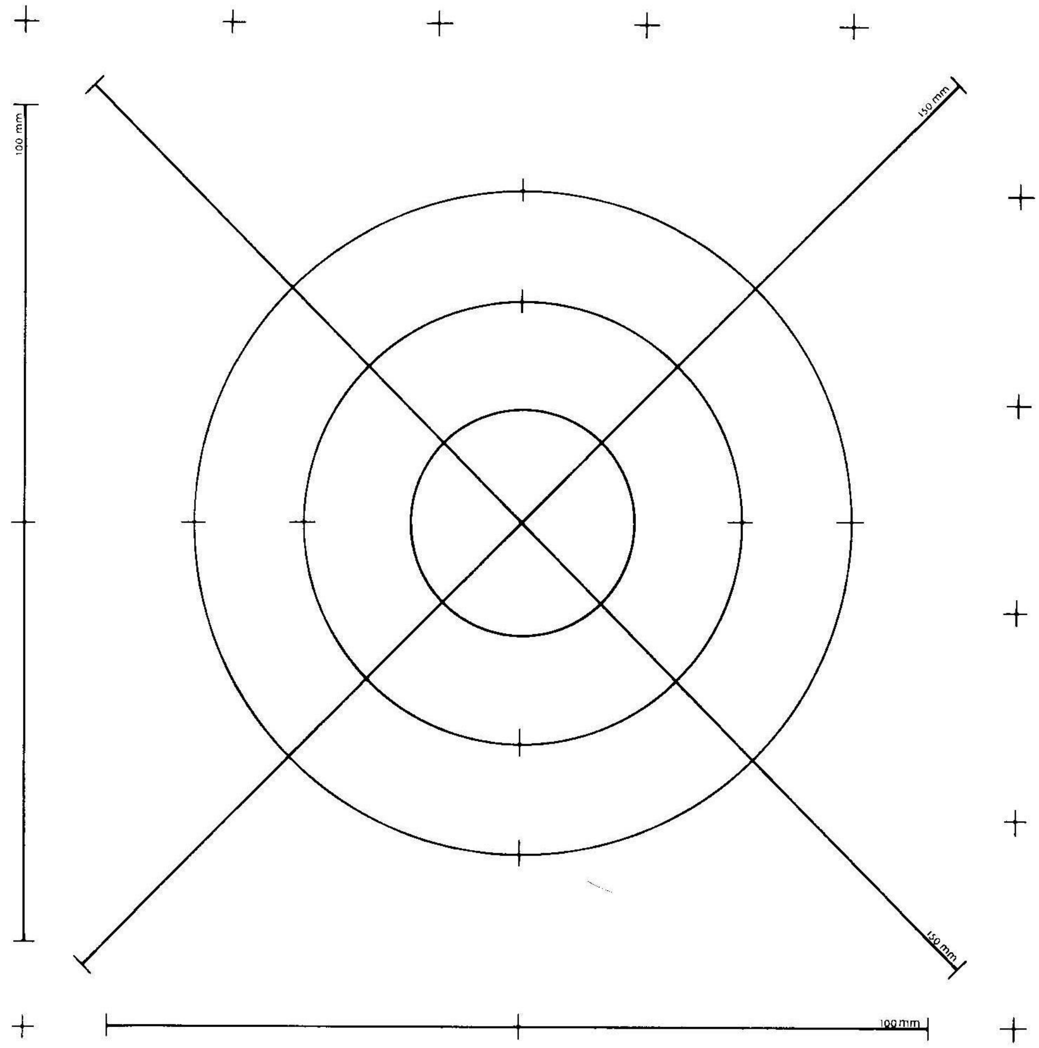
2.6.2.3 Heyn (4) Lineal Intercept Procedure

The intercept method involves an actual count of the number of grains intercepted by a test line or the number of grain boundary intersections with a test line, per unit length of test line, used to calculate the mean lineal intercept length, $\bar{l}$. $\bar{l}$ is used to determine the ASTM grain size number, G. The precision of the method is a function of the number of intercepts or intersections counted. A precision of better than ±0.25 grain size units can be attained with a reasonable amount of effort. Results are free of bias; repeatability and reproducibility are less than ±0.5 grain size units. Because an accurate count can be made without need of marking off intercepts or intersections, the intercept method is faster than the planimetric method for the same level of precision [25].

2.6.2.4 Circular Intercept Procedures

Circular test arrays automatically compensate for departures from equiaxed grain shapes, without overweighting any local portion of the field. Ambiguous intersections at ends of test lines are eliminated. Circular intercept procedures are most suitable for use as fixed routine manual procedures for grain size estimation in quality control.

Abrams Three-Circle Procedure Based on an experimental finding that a total of 500 counts per specimen normally yields acceptable precision, Abrams developed a specific procedure for routine average grain size rating of commercial steels. Use of the chi-square test on real data demonstrated that the variation of intercept counts



NOTE 1—If reproduced to make straight lines marked length:
Straight lines total: 500 mm

Circles are:	Circumference, mm,	Diameter, mm
	250.0	79.58
	166.7	53.05
	83.3	26.53
	Total 500.0	

Figure 2.10: Test Pattern for Intercept Counting [25]

is close to normal, allowing the observations to be treated by the statistics of normal distributions. Thus both a measure of variability and the confidence limit of the result are computed for each average grain size determination.

The test pattern consists of three concentric and equally spaced circles having a total

Table 2.2: Deformed Bar Designation Number, Diameter, Area and Mass [8].

Bar no. ($\frac{1}{8}$in, "mm")	Diameter (mm)	Area (mm^2)	Mass per metre run (kg/m)
4 "13"	12.7	129	0.994
5 "16"	15.9	199	1.552
6 "19"	19.1	284	2.235
7 "22"	22.2	387	3.042
8 "25"	25.4	510	3.973
9 "29"	28.7	645	5.060

circumference of 500 mm, as shown in Figure 2.10. Successively apply this pattern to at least five blindly selected and widely spaced fields, separately recording the count of intersections per pattern for each of the tests. Then, determine the mean lineal intercept, its standard deviation, 95 % confidence limit, and percent relative accuracy. For most work, a relative accuracy of 10 % or less represents an acceptable degree of precision [25].

2.7 Tensile Strength of Reinforcement Bars

Test specimens shall be either at least 600 mm long or 20 times the nominal size, whichever is greater [1]. The deviation of any cross sectional dimension from its nominal size (other than those of ribs) shall not exceed 8%. The tolerance on mass per metre run is ±4.5% [1]. The tensile properties of reinforcement bars are determined from the stress-strain curve, Figure 2.11. Scrutiny of the stress-strain curve can reveal significant information on the mechanical properties. For ribbed bar, the stress-strain curve is linear up to the yield point and the curve has a yield plateau. For the twisted bar, the resulting stress-strain curve has no yield plateau. The yield stress is calculated based on 0.2% proof stress ($R_{p0.2}$) [1]. The yield strength R_e, stress ratio R_m/R_e, and elongation at fracture, A_5, of steel specimens selected, prepared and tested according to BS 4449:2005 [1] are specified as in Table 2.3 where R_m is the tensile strength.

Table 2.3: Tensile properties [1].

Grade	Yield strength R_e N/mm^2	Stress ratio R_m/R_e (min)	Elongation at fracture A_5 (min.) %	Total elongation at maximum force A_{gt} (min.) %
250	250	1.15	22	-
460A	460	1.05	12	2.5
460B	460	1.08	14	5

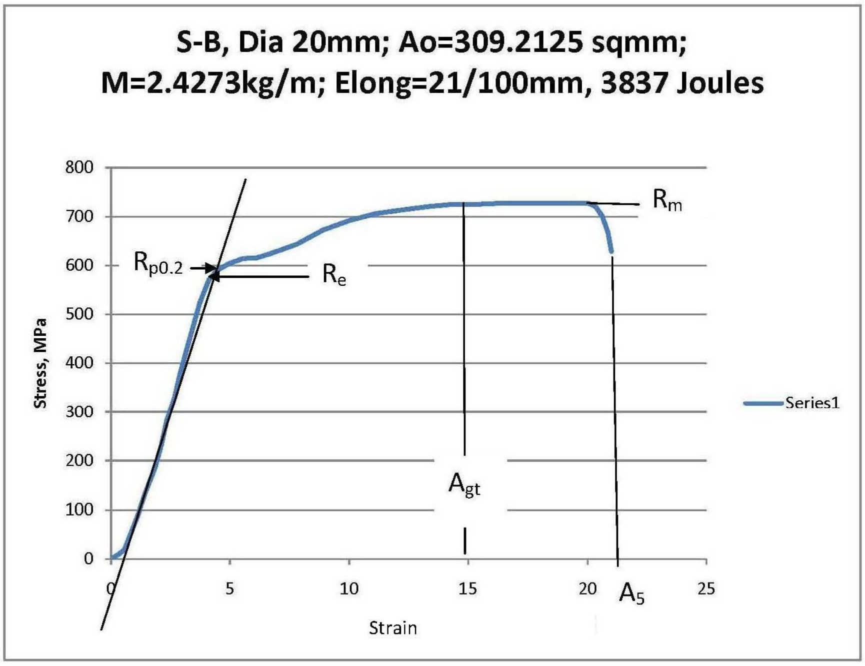


Figure 2.11: Typical stress/strain curve for deformed bars

2.8 Bending and Rebending of Reinforcement Bars

2.8.1 Bending Standards and Practice

BS 8666:2005 [4] specifies the bending practice of rebars. Various basic shapes, known as preferred shapes, are given specific code numbers. For a given bar size, the dimensions of required minimum former radii, bend and hook allowance are indicated. This enables the user to get the cut length. The standards for bend/rebend tests are specified in BS 4449:2005 [1], ASTM 615 [8], KS-02-106-1983 [9] and HK CS2 1995 [26]. Figure B.5 gives examples of Shape codes with a formula to calculate the overall length of the bar. The importance of adhering to standard practice in bending is mainly because it is a strain ageing procedure, with potential embrittlement that alters the bar properties.

2.8.2 Bending Machines

Reinforcement bars are bent to a variety of shapes depending on applications. The bending is either manual or using bending machines. For less complicated shapes, manual bendin is utilised whereby pins are spaced appropriately and a pipe used for leverage (for ease of applying torque). A variety of machines are also available. The drive can be hydraulic or mechanical. Figure B.6 shows a simple bending machine; while Figure B.7 shows typical stirrups formed using the bender.

2.8.3 Bend/Rebend Test

2.8.3.1 Bending

Bending tests are carried out in such a way as to produce a continuous and uniform deformation (curvature) at every section of the bend. There are basically two types of bending test: (a) three point bending and (b) bending with rotating rollers [1, 6]. These are shown in Figure 2.12 and Figure 2.13 respectively.

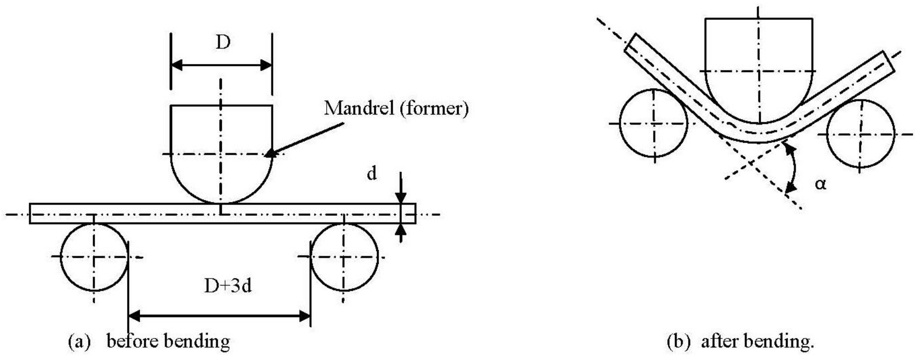


Figure 2.12: Three point bending machine

For 3-point bending, the bar could be bent to a U shape or 180^o bend [1, 8, 26]. The mandrel diameter is specified in the standards. BS4449 [1] requires, on the bending machine, that the work be supported by plain smooth surfaces or rolls that do not resist longitudinal movement of the test piece. The distance between the support rollers is specified in the standards [6]. The test specimens shall withstand being bent through 180^o round a former of the diameter (D) specified in Table A.1 (in Appendix A); showing no signs of fracture on visual examination. Figure 2.13 illustrates the operation of a simple, typical, power bender. Figure 2.14 shows a 50mm GW50 rebar bending machine. The wheel (rotary table) is driven by an electric motor. The wheel rotates together with a former. The wheel also carries a mandrel with changeable washer. The adjustable bars, with regular holes machined on them, are moved on

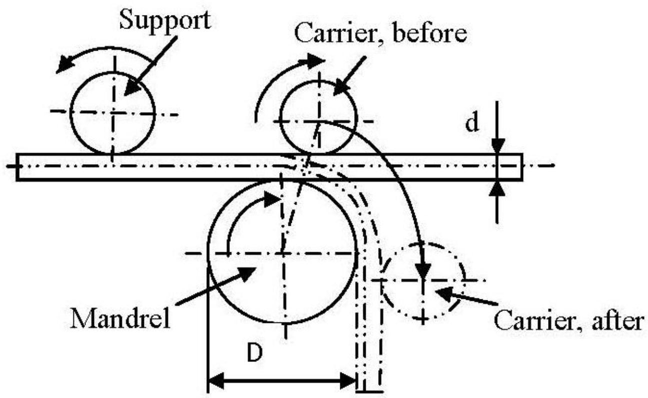


Figure 2.13: Bending with rotating rollers

Figure 2.14: Rebar Bending Machine, Rebar Bender 50mm GW50

small worm threads by handles. They provide the positions for the stop bars and backplate.

2.8.3.2 Rebending

Rebending involves subjecting the bar to load in the reverse direction to wholly or partially restraighten it. The reasons for bending or re-bending rebar on-site are many and varied. Unforeseen circumstances, such as having rebar accidentally run over by a vehicle, are impossible to avoid. Bending is also done in cranking a bar to manage shear effects and transfer main reinforcement from soffit to upper part of beam, in forming hooks to minimize the possibility of pullout, when making stirrups etc. Likewise, last minute corrections and adjustments to building specifications are also a common occurrence in the fast-paced environment of modern building construction.

The purpose of re-bend test is to measure the effect of strain ageing on steel. Strain ageing has an embrittlement effect which takes place after cold deformation by diffusion of nitrogen in steel [6]. Hence, there is limitation stated in some design codes to restrict the nitrogen content of steel to 0.012% maximum [1, 26].

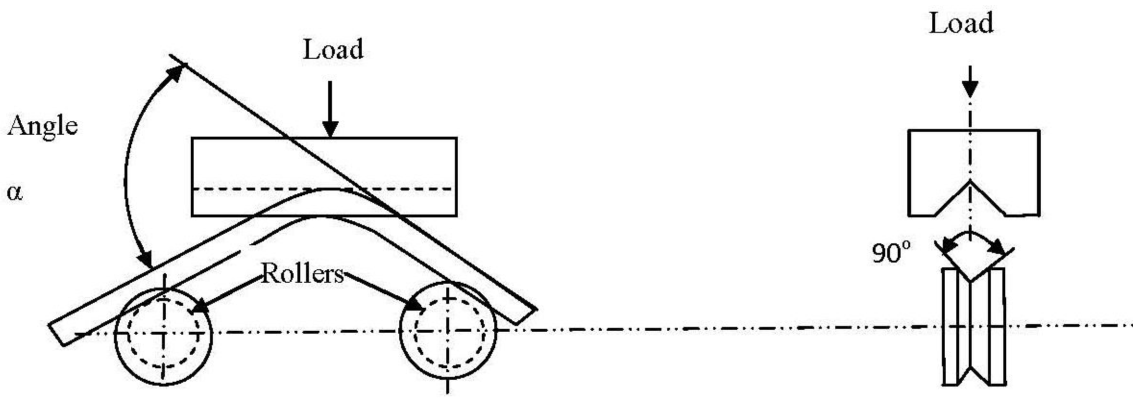


Figure 2.15: Rebending facility

On a 3-point bending test rig, the sample is placed on the lower support rollers, then bent to an included angle of 135^o using a mandrel of appropriate diameter. The bent piece shall be aged by any of the methods described in section (2.7.4). The test piece is then free air cooled to under 30^oC. The test piece shall then be bent back to have an included angle of 157.5^o. The specimen shall be considered to have passed the test if there is no fracture in the bent portion [1, 6, 7]. In the manufacturer's certificate, they specify the mandrel and angle of bend/rebend testing the bar. In Figure 2.15, the angle α is 45^o after bending and 22.5^o after partial restraightening. A typical company certificate is shown in TableA.1.

There is apprehension that poor bending practices can lead to weakening of the bar, the cast beam and structural collapse [4–6]. Does the bending process damage or weaken the bars?

Babael and Hawkins [27] conducted a carefully monitored study on rebars. They used Grade 60, No.4 and No.6 (3/4" diameter) rebar in five different cold bending tests, and Grade 60, No.7 (7/8" diameter) -Table 2.2 - and No.9 ($1\frac{1}{8}$" diameter) in seven different hot bending tests.

These researchers began their study after first completing an extensive literature survey. Their concern stemmed from reports (infrequent but worrisome) of cracking when rebar was bent and straightened and from engineering concerns about the strength of bent/straightened rebar.

They observed that, for example in cold conditions, bar sizes No.10 and No.13 showed no reduction in either yield or tensile strength and a 20% reduction in elongation. In hot conditions, all bar sizes showed a 10% reduction in both yield and tensile strength and a 20% reduction in elongation. The latter behaviour is probably normal -as in hot working- the former could be ductile/brittle transition effects. However, the effect has no basis for discriminating No.10 and No.13 bar sizes.

The best course of action for dealing with uncertainties surrounding the bending of rebar is to always involve an architect or engineer in decision-making. Also, builders would do well to follow the guidelines outlined in the ACI 318-02 Building Code, specifically in Section 7.3.2. Lastly, consultation with a qualified rebar supplier regarding the optimal conditions for bending rebar [28]. Babael [27] found that none of the test specimens broke during the bending or straightening operations, although some micro-cracking was discovered.

Restrepo, Crisafulli and Park, [29] conducted a study in New Zealand where concrete construction standards discourage bending and straightening rebar thats partially embedded in concrete if the procedure is not pre-approved by the design engineer or supervisor. In America, ACI 318-95 building code allows cold bending (bending rebar without first applying heat) and straightening if authorized in the design drawings or by the site engineer. Consequently, the researchers were anxious to learn the effects of this somewhat unusual practice.

They conducted 56 tensile or stress tests, on rebar manufactured in New Zealand (grades 300 and 420) that compares favorably with American rebar in steel grades of 40 and 60. In a significant number of these tests, they cold bent 20.5 inch lengths (520 mm) of No.3 (3/8" diameter) and No.4 (1/2" diameter) rebar. The authors found that cold bending and straightening of rebar embedded in concrete does not weaken the bars if they are not bent through an angle greater than 90^o and the procedure is used only once. On tensile testing restraightened bars, often the bar yield tended to occur in regions remote from the cold worked zone for under No. 11 bars [29, 30].
Based on these and other studies [31–34], the Concrete Reinforcing Steel Institute concluded that: reworking bars entails some risk; No.8 or smaller bars can be successfully field bent/straightened at temperatures above 0^oC; rebars No.9, No.10 and No.11 have a better chance of being successfully bent/straightened when preheated to 760^oC or 815^oC and carefully manipulated; these conclusions do not apply to No.14 or larger rebar.

To avoid rebar breakage and excessive pressure on the concrete inside a bend, ACI

318-89, "Building Code Requirements for Reinforced Concrete," recommends minimum internal bend diameters (measured on the inside of the bar) for various bar sizes [35].

Table 2.4: Bar diameter (d) and bend diameter (D); ACI 318-89 [35].

Bar No. and Nominal size (d)	Bend diameter (D)
No.3 ($\frac{3}{8}$inch) through No.8 (1 inch)	6d
No.9,10,11 ($1\frac{1}{8}$, $1\frac{1}{4}$, $1\frac{3}{8}$ inch)	8d
No.14, 18 ($1\frac{3}{4}$, $2\frac{1}{4}$ inch)	10d

The diameter of the completed bend is expressed as a multiple of the nominal diameter of the bar (d). The ratio of bend diameter (D) to bar diameter is not a constant; the ratio becomes larger as the bar size increases. Factory bending of rebar is typically performed on computer-controlled equipment programmed to produce bends according to these minimum internal diameters. When rebar is bent on the jobsite, it is important to use the proper equipment and procedures to avoid damaging the bars. Bending a bar to an internal diameter less than the recommended minimum can produce stresses in the bend zone that can result in bar weakening or failure. Here are a few precautions to take when bending bars in the field [35].

1. Do not use makeshift devices, such as pipes to bend rebar. It is difficult to control the internal bend diameter, and a pipe's sharp edges can notch the bar, weakening it in the bend area.

2. When using bending equipment, follow ACI 318 recommendations for minimum internal bend diameters for various bar sizes. Do not try to bend bar sizes or grades that the tool or machine is not designed to handle.

3. Avoid using impact blows to assist bending. Use of a sledge hammer, for example, can result in overbending of the bar and damage to the rebar surface.

4. Bending of galvanized rebar can cause flaking of the galvanized coating in the bend area. Repair any damaged coating by applying a zinc-rich paint.

5. Special precautions are required when bending epoxy-coated bar to prevent coating damage. Bending should only be performed around a smooth, non abrasive die to avoid damage to the epoxy coating. If the coating rubs off in spots, these areas must be repaired. Get approval from the project engineer before attempting to bend epoxy-coated bars.

2.8.4 Ageing

The test piece is heated to 100^{o}C, maintained at this temperature ± 10^{o}C for a period of 60^{+15}_{-0} minutes, and then cooled in still air to room temperature. The method of heating is left to the discretion of the manufacturer [1]. An alternative is to age at 100^{o}C for two hours in still air furnace or half an hour in boiling water followed by free cooling in air to ambient temperature. Another option is to age at 250^{o}C for half an hour [6]. Bending, which is a strain ageing process, reveals through mechanical testing an embrittling effect of free (unbound) nitrogen. For example, the high nitrogen content of Bessemer steel is a disadvantage for certain cold forming applications. As such, nowadays, mainland European steel works attempt to limit the maximum nitrogen content to under 0.012% N [6, 7, 36].

2.9 Fatigue

2.9.1 Fatigue Performance for High Strength Rebars

The introduction of high strength rebars has raised the need for fatigue testing such bars so as to optimise in limit state design, use fewer bars and avoid rebar congestion at joinnts, understand bar performance at the elevated stresses especially for bridge deck work as well as crack initiation owing to rib geometry. Fatigue strength specification is largely the province of professional bodies e.g AASHTO, ACI, NCHRP, PCI, TRRL etc. In some countries, the specification of fatigue for reinforcement bars is not required [7], [8]. The fatigue test for rebar as specified is not a suitable model of the bar working conditions for either concrete column or concrete beam, not to mention the variegated vibratory motions obtaining during an earthquake.

Fatigue strength is by no means the dominating requirement of reinforcement and the rib patterns are designed to give good pull-out strength and crack control. Material is supplied against a minimum characteristic strength i.e. 02% proof stress. Past developments in reinforcement have involved the introduction of deformed high strength steels and commercially available bars commonly have minimum characteristic yield strengths of about 410N/mm^2 with values of 460N/mm^2 for sizes of up to 16mm diameter. Very high strength bars having yield strengths of up to 875N/mm^2 can be obtained for special applications [37].

There has been attempts to limit the strength of high yield bars after noting that fatigue strength does not improve much beyond 420 N/mm^2 and that high yield bars have strain at yield stress much beyond the 0.003 associated with concrete at characteristic strength.

Fatigue is not a major consideration in the design of most reinforced concrete structures. To date, there have been no fatigue fractures reported for concrete structures under normal service loading. However, reinforced concrete is widely used in bridges, offshore structures and machine foundations. These structures are subjected to time-dependent oscillatory loads that result from vehicles, strong wave and wind action, and dynanmic loading from machines. The stresses due to these loads may cause fatigue in the structures and result in premature failure [38].

Damage due to corrosion can be a serious problem in highway bridges particularly for concrete decks subjected to application of salt for de-icing. There have been numerous cases where salt has reached the reinforcement, resulting in corrosion of the steel and spalling of the concrete. Such damage has been reported for a large number of concrete bridge decks [37]. The combination of corrosion and fatigue on embedded rebar can be serious.

2.9.2 Testing Machine

BS 4449:2005 [1] recommends the axial load fatigue test for reinforcement bars, of which several machine models are available. Typical examples are the brute force axial load and the hydraulically actuated axial load testing machine. Others include the electro-hydraulic, servo-hydraulic, electro-mechanical, and the mechanical types. Figure 2.16 shows a brute force axial fatigue testing machine in which the test specimen is exposed to axial tensile load or axial compressive load [39].

2.9.3 Tests

The test is performed by exposing a test specimen either to an axial tensile or an axial compressive load to a prescribed mean value (σ_m) and then alternate between a maximum and a minimum peak value. The wave shape is normally sinusoidal. The axial load fatigue testing is used to determine the effect of component geometry, surface conditions, stress, etc., on the fatigue resistance of reinforcing and prestressing steel bars and wires subjected to cyclic stress for a relatively large number of cycles. The test is carried out at ambient temperature. Bar specimens of 300 mm approximate length are held on the brute force axial load fatigue testing machine. Of special consideration is the gripping. The applied stress range is 150-200 MPa, with a stress ratio ($\sigma_{min}/\sigma_{max}$) of 0.2. The test sample shall survive 5 million stress cycles. Table 2.5 shows the applicable stress ranges.

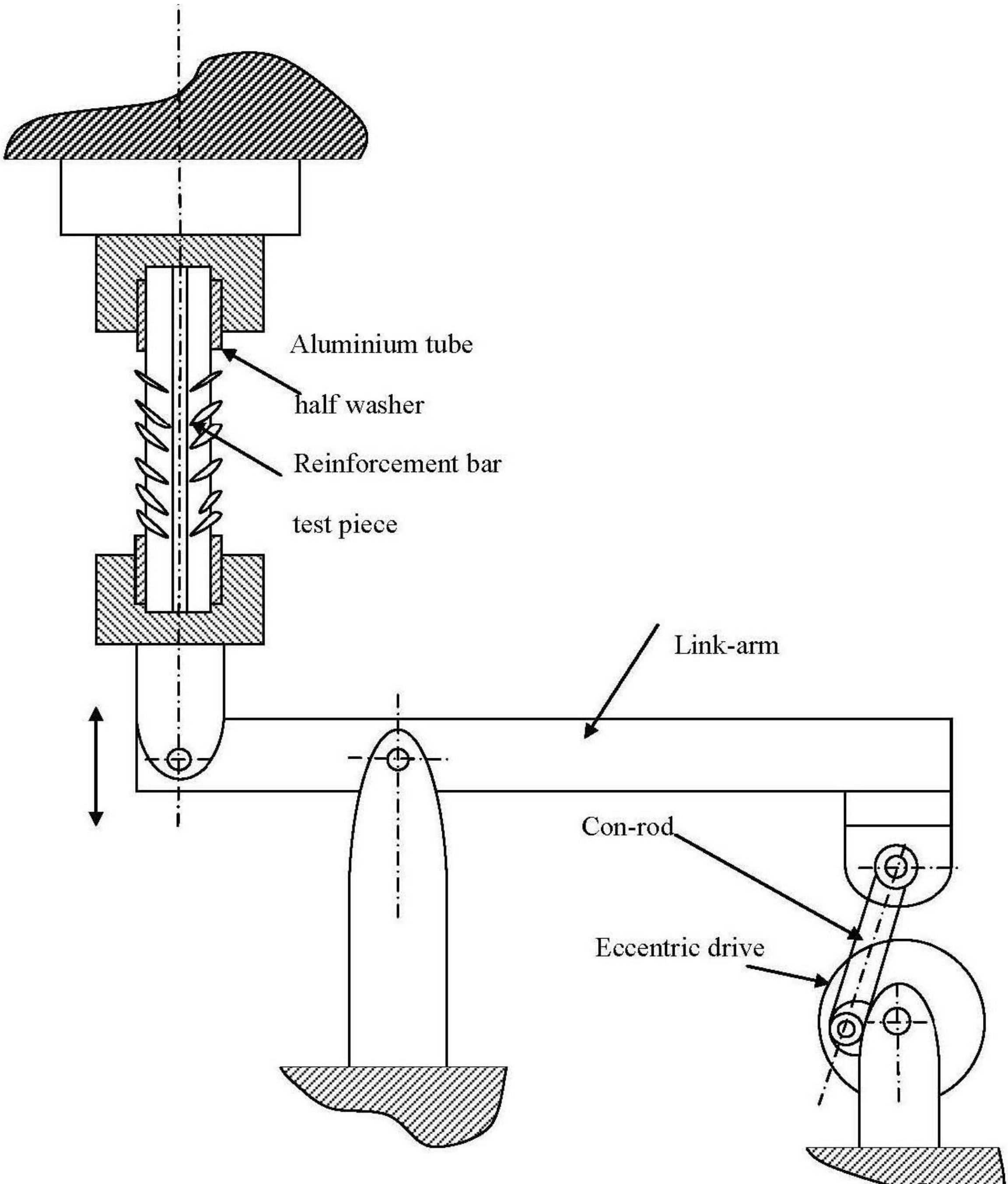


Figure 2.16: Brute force axial load fatigue testing machine

Table 2.5: Fatigue test stress range [1]

Bar size (mm)	Stress range (MPa)
≤ 16	200
$> 16, \leq 20$	185
$> 20, \leq 25$	170
$> 25, \leq 32$	160
> 32	150

The maximum permitted stress range (f_f) in straight reinforcement resulting from the fatigue load combination is given as:

$$f_f \quad \leq 145 - 0.33 f_{min} + 55(\frac{r}{h}) \quad (MPa) \tag{2.3}$$

where:

f_{min} = algebraic minimum stress level (compression is negative); and

$(\frac{r}{h})$ = ratio of base radius to height of rolled-on transverse deformations; 0.3 may be used in the absence of actual values. The fatigue design stress range (endurance limit) has been established at 161.5 MPa [38, 40]. Questions remain whether a bar has the same the fatigue strngth when tested in air as when embedded in concrete. Until 1999, no test had been standardized in the United States for fatigue testing deformed bars. Ruhl and Walker [41] measured stresses produced by the passage of a test truck and reported values of up to 103 N/mm^2 and 144 N/mm^2 for transverse reinforcement in two separate bridge decks. For the types of bar used in such bridges the stress range to give an endurance of $5x10^6$ cycles is quoted as being from 159 to 197 N/mm^2. This apparently gives a safe situation but the margin is actually less because fatigue strengths at 10^4 cycles can be as much as 25% lower than at $5x10^6$ cycles. Furthermore corrosion can decrease the fatigue strength whilst the dynamic interaction between the superstructure and vehicle can increase the applied stresses. There has been much research into fatigue of reinforcement. This has been intensified in recent years by the introduction of higher strength materials, the development of advanced applications such as offshore structures and the adoption of new design codes [37]. There may be need to test Kenyan bars intended for bridges and offshore structures for conformity with best practice elsewhere interms of yield stress σ_y and the ratio R_m/R_e.

2.9.4 Gripping Methods

The methods for gripping the specimen on an axial loading machine are discussed in [1, 38, 39, 42, 43]. The preparation of the test specimen depends on the objective of the test programme, type of testing machine and the form in which the material is available. There are various methods for gripping the specimen in a fatigue test. Four methods A, B, C, D are discussed in Nord Test Method [39].

- Method A

  Reduce the diameter over the gripping length of the test specimen by about 1 mm and with a transition radius to the test section between 1 and 5 mm. This method is limited to relatively low value of σ_{max}.

- Method B

  This glass fibre lamination method is employed for gripping devices that distribute the clamping forces evenly. On a lathe, with the test portion protected with a strip of polypropylene, centre drill either end. The lamination is made on a specially designed apparatus which continuously feed the glass fibre strip through the bath and around the rotating test specimen. The lamination shall be made over a length of at least 120 mm at each end with glass fibre strip and epoxy resin. Immediately after the lamination the ends of the test specimen is winded with a 50 mm wide strip of polypropylene in order to compress them during the hardening process of the epoxy. Later, the laminated ends are machined to fit the hydraulic grips. The protecting strips of polypropylene are removed after the test specimen has been mounted in the testing machine.

- Method C

  This method can only be used for gripping devices which distributes the clamping force evenly. The procedure is as follows: In a lathe, reduce the diameter over the gripping length of the test specimen by about 1 mm. An aluminium tube with an inside diameter equal to the turned part diameter, and a wall thickness of 1 to 2 mm is cut to a length equal to the turned part length and then halved longitudinally. Both the turned parts and the inside of the tube halves are sand-blasted. The tube halves are glued on the turned parts. After the prescribed time of hardening a radius is turned between the aluminium tube and the test section as shown in Figure 2.17. The specimen thus prepared should fit into the designed adaptor for the UON axial load fatigue testing machine, as in Appendix B, Figure B.8.

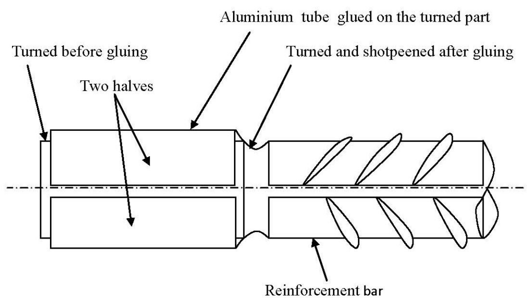


Figure 2.17: Fatigue test specimen preparation for reinforcement bars

- Method D

  This method is normally used for pre-stressing steel. The method consists of using two different sets of jaw faces in order to distribute the forces over a longer distance than normal. It is also advisable to use some sort of inlay in the first set of gripping devices on the longer jaw faces. A typical anchor for pretensioned strand is shown in Figure 2.19. Normally referred to as "strand chuck," the device consists of a hardened steel barrel with a machined conical core. This barrel receives the jaw or wedge assembly. Wedges are used in sets of 2 or 3 pieces. They are held in alignment by a rubber "O - ring" and are tapered to match the conical shape of the barrel. The wedges have machined serrations or "teeth" that bite into and grip the strand, distributing the radial load. The cap is spring loaded to keep the wedges in place during jacking or tensioning.

Most anchors for post tensioned strand are proprietary, but generally use wedges similar to pretensioning anchors. These anchorages are embedded in the concrete prior to stressing, and are reinforced to resist the bursting stresses associated with high localized concentrated loads. In many cases, the wedges are hydraulically pressed into conical holes in the anchor head to reduce sitting losses after jacking. Post tensioning tendons vary from single strand tendons to multiple strand tendons which occupy the same duct and anchorage device [44].

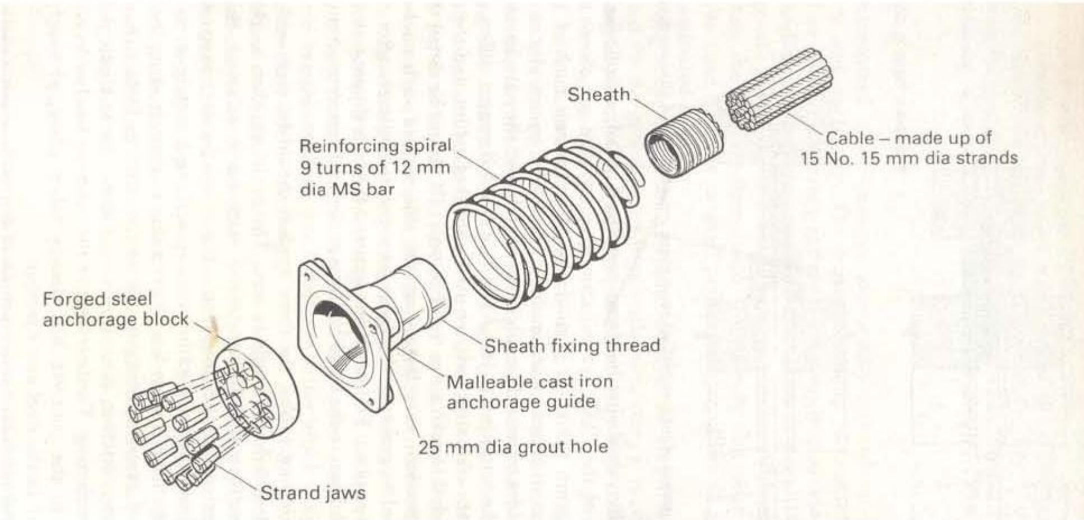


Figure 2.18: Multistrand anchorage of wire rope - with wedges - for pre-stressed concrete [45].

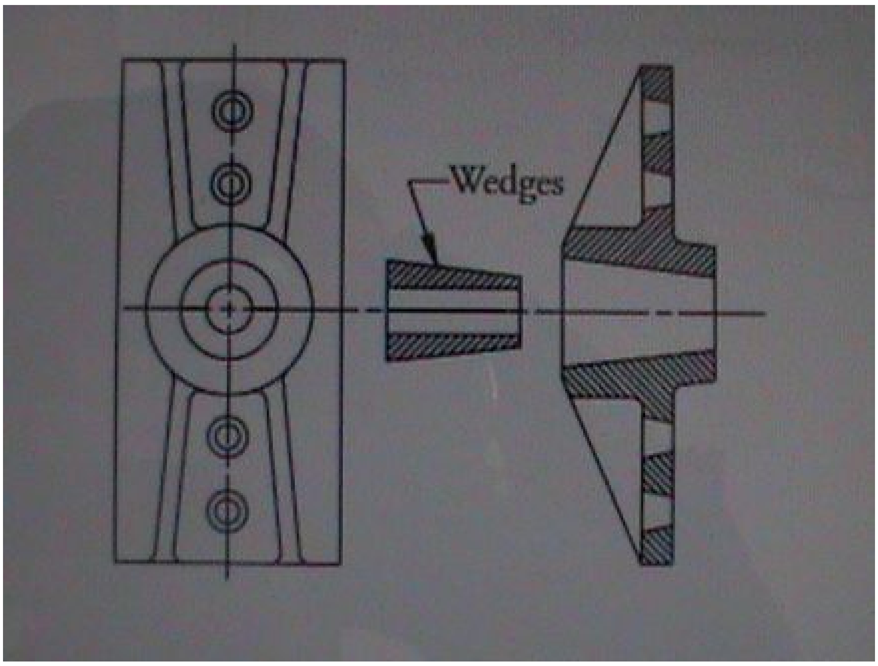


Figure 2.19: Monostrand anchorage of wire rope-with wedges- for pre-stressed concrete [44].

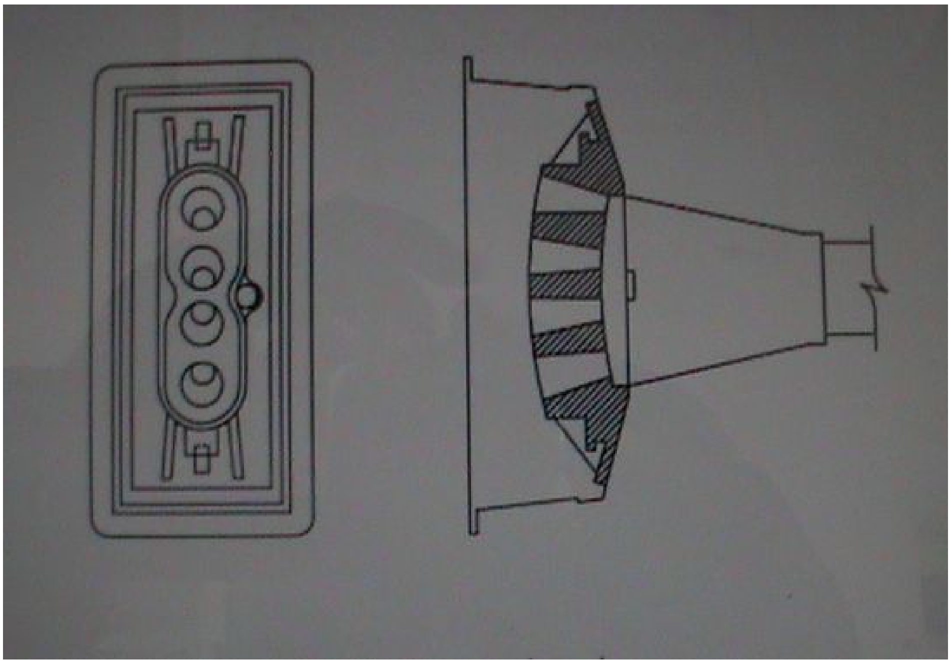


Figure 2.20: Multistrand anchorage for pre-tensioning concrete [44].

Figure 2.21: Gripping jaws come tapered and split at 120^o [44].

2.10 Summary

To satisfy design requirements, we may have to employ high-yield bars. These will need to possess specific mechanical and chemical properties. There are opportunities in securing good quality raw materials, obtaining modern and efficient steel making equipment and optimizing and properly controlling the production process. Once the bar has been made, it must be taken through various tests. These tests are described in various standards and give information on certain aspects of the bar specimen e.g tensile strength, hardness, ductility, grain size, fatigue strength, bendability e.t.c. Here there is room for improving the machinery (new equipment) or devicing a new method. So the steel making process seems headed to electric arc furnace methods. Optimizing various factors and proper process control could yield dividends.

The tensile test is a brutal method of assessing the strength of a specimen, hardness test can be used for material evaluation and selection, metallurgical examination can explain atomic arrangement, physical chacteristics and application, fatigue test needed to adopt prestressing grippers while bending test can offer the field engineer an orthodox method of bending bars in the field.

It may be that fatigue needs can be met indirectly: proper grade concrete, adequate bar cover and avoiding or controlling conditions of corrosion and general wetness.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Introduction

The methodology adopted in this research comprised of a survey, sampling of bars, tests for bending/rebending, fatigue and tensile strength tests. The bending tests were done for bars as received. During the rebend test the bars were aged. Chemical composition tests were carried out on the sampled bars to determine the composition. Microstructural examinations were carried out to reveal the structure of the sampled bars as well as the grain size.

3.2 Survey

A survey was carried out in hardwares, construction sites and rolling mills to determine the methods of controlling the quality of reinforcement bars against the set standard. The survey was done through questionnaires, site visits or both. The industries and hardwares sampled were mainly in Nairobi and Mombasa and their environs. A sample questionnaire is presented in Appendix D, Figure D.1.

3.3 Sampling

Sampling is the process of obtaining information of an entire population by only examining a part of it. The sample should, where possible, be truly representative of the population without any bias so that it results in valid and viable conclusions.

Statistical sampling techniques enable the inspector to take controlled random samples of components, which are then checked by measurement or gauging. The quality of the whole batch of work produced is then judged by the results of the sample.

The alternative would be to carry out 100% inspection, such that every component leaving the production line is checked. This is expensive, and seems to imply more certainity in the results; but there is contrary evidence that 100% inspection does not guarantee that all unacceptable work would be found out and rejected. There is always the chance that under repetitive and monotonous circumstances, the inspector will commit an error. Again, in certain classes of work where the part must be destroyed in order to check its quality, statistical sampling techniques must be used [46].

Industry must tolerate variabilities of size within certain limits during manufacture. No two parts can be produced with identical measurements. There will be variation in the measured sizes of parts due in part to the inherent inaccuracies of the manufacturing process, and also partly due to inaccuracies of the measuring equipment and its application.

Variability refers to the spread or scatter of x values about the mean and is most commonly measured by the *range*, or the *standard deviation*.

Range(w) is a simple but rather crude measure of spread, being equal to the difference between the largest and smallest x values. [46].

$$w = x_{max} - x_{min} \tag{3.1}$$

There are many sampling methods to choose from, for example random sampling, systematic sampling, stratified sampling, quota sampling, cluster sampling, multi stage and sequential sampling [47]. The distribution can be modelled on, for example, normal, t, beta, chi-squared, F, binomial or Poisson [48].

The coefficient of Variability is the ratio of sample standard deviation (S) to the mean of the sample ($\bar{X}$).

$$CoV = \frac{S}{\bar{X}} \tag{3.2}$$

Table 3.1 illustrates the method of evaluating the CoV for data for No.4 bars, column 5 on Table 4.7 .

Table 3.1: Calculating CoV from given data (example)

	x_i	$(x_i - \bar{X})$	$(x_i - \bar{X})^2$	CoV
Item	487	43.4	1883.56	$CoV = \sigma/\bar{X}$
	487	43.4	1883.56	
	414	-29.6	876.16	
	460	16.4	268.96	
	401	-42.6	1814.76	
	442	-1.6	2.56	
	414	-29.6	876.16	
	Sum=3105	-	SUM=7605	=32.962/443.57
	$\bar{X}$=443.57	-	$\sigma = 32.962$	=7.4%

The CoV is the measure of variability of mechanical properties of different bars tested. In order to estimate the number of bars to be tested from a population of N bars, the following formulae [49] can be used.

$$\text{Mean of the population,} \quad \mu = \frac{\sum x_i}{N} \tag{3.3}$$

and the standard deviation (σ) of the population is given by

$$\sigma = \sqrt{\left(\frac{\sum_{i=1}^{n}(x_i - \bar{X})^2}{N}\right)} \tag{3.4}$$

The number of samples [50] will be given by Equation 3.5.

$$\text{Sample size,} \quad n = \frac{z^2 N \sigma^2}{(N-1)e^2 + z^2\sigma^2} \tag{3.5}$$

where; e is the acceptable error (the precision); N is the size of population; z is the standard normal variate at a given confidence level (to be read from normal tables giving the area under the normal curve). As an example, at 97.5% confidence level, if the acceptable error (e) is 3% i.e. ±3; z = 2.24. σ is the standard deviation of the population (to be estimated from past experience). For N=500 bars, equation 2.7 gives n=50.24 bars; if σ=10 MPa.

3.3.1 Meaning of Standard Deviation

The population standard deviation is an important index of variability that conveys a great deal of information. It is a fundamental parameter of the mathematical function describing the normal curve that fits the frequency distribution of so many populations. But σ is useful in describing many other frequency distributions as well. The coefficient of variation (CoV) is a direct function of standard deviation [51].

In the factory, bars can be categorised according to the heat. At the hardware, bars can be sourced from various rolling mills which in turn will have obtained the bars from different heats. At the construction site, bars could be sourced from different hardware stores and factories.

Random sampling is to be preferred. After establishing the sample size and the distribution, the reinforcing steel bars were purchased [47,48,52]. On considering the various alternative sampling methods, accidental sampling was, for all its deficiencies, settled upon [53]. Essentially, one goes to a rebar store, conducts the purchasing transaction, picks any bar that comes to hand and takes it for testing. Because of limited resources, there was need for prudent management of finances. The recommended method of selecting a bar periodically from each heat, or after every 30 tonnes of production, would have required the authors to be present at every heat, or to engage the services of a completely honest assistant who would select the bars from the factory as directed. Such activity would require goodwill and co-operation from rolling mill management, without which one is quickly disillusioned. Again, should one sample bars cast at the start, in the middle, or at the end of pouring a heat? The issues raised here show that sampling can be both financially expensive and time consuming; even here the resulting sample is certainly not random, [53, 54]. The pragmatic methods discussed in section 7 of ASTM E 105 [53] were much appreciated.

3.4 Tensile Test

Bar samples were obtained from two manufacturers, A and B. These were cut to a length of 1000 mm, weighed and measured for length. The specimens were then marked for gauge length, evaluated as in Equation 3.6. The cross-sectional area, by use of Equation 3.8 and mass per metre run were then computed. The specimen was then loaded in tension on the Universal Testing Machine (UTM) with a capacity of 30 tonne-force at a rate of 8 mm/minute until final fracture occurred. The stress/ extension curve was plotted and the yield strength, tensile strength and elongation read off. The results are shown in Table 4.4 and 4.5. The gauge length (L_0) was calculated using the standard formula:

$$L_0 = 5.65\sqrt{A_0} \tag{3.6}$$

Where A_0 is the nominal cross-sectional area of the bar given by:

$$A_0 = \frac{M}{(0.00785L)} \tag{3.7}$$

Rebars are assumed to have a mass of 0.00785 kg/mm^2 per metre run [1, 8]. The effective cross-sectional area and mass (Table 2.2, 3.2) are related by the following Equations 3.8,3.9 [5].

$$\text{Effective cross-sectional area, A } mm^2 = \frac{M}{(0.00785L)} \tag{3.8}$$

where M = the mass of the bar per metre (kg)

L = the length of the bar (m)

$$\text{Effective diameter, d, is given by:} \quad d \quad mm = \sqrt{\frac{4A}{\pi}} \tag{3.9}$$

Table 3.2: Cross sectional area and mass [1]

Nominal size mm	Cross sectional area, (A) mm^2	Mass per metre run, (M) kg/m
12	113.1	0.888
16	201.1	1.579
20	314.2	2.466
25	490.9	3.854

3.5 Micro Structural Analysis

The purpose of the microstructural analysis was to assist in explaining the mechanical properties. Specimens roughly 20 mm long, were cut longitudinally with a hacksaw, filed flat, then mounted in resin as shown in Figure 3.1. Grinding using various grades of emery paper (grade 200 to grade 600) followed to finally achieve a fine polish. They were then etched in nital - (2% nitric acid in 98% alcohol). Alternative etchants might have been picral or alkaline sodium picrate. During etching the mounted specimen, held with tongs, was simply immersed in the etchant contained in a shallow bath, agitated for several seconds [14], rinsed in water and dried in a stream of warm air.
They were then scrutinized on the optical microscope at 200 % magnification as shown

in Figure 3.2. The OPTIKA microscope at UON which is from LECO, a US manufacturer, was used for this purpose. By use of specialized software it analyses by a combined lineal intercept and three circle method and outputs the ASTM average grain size number. A typical output from this machine is shown in Figure 4.9.

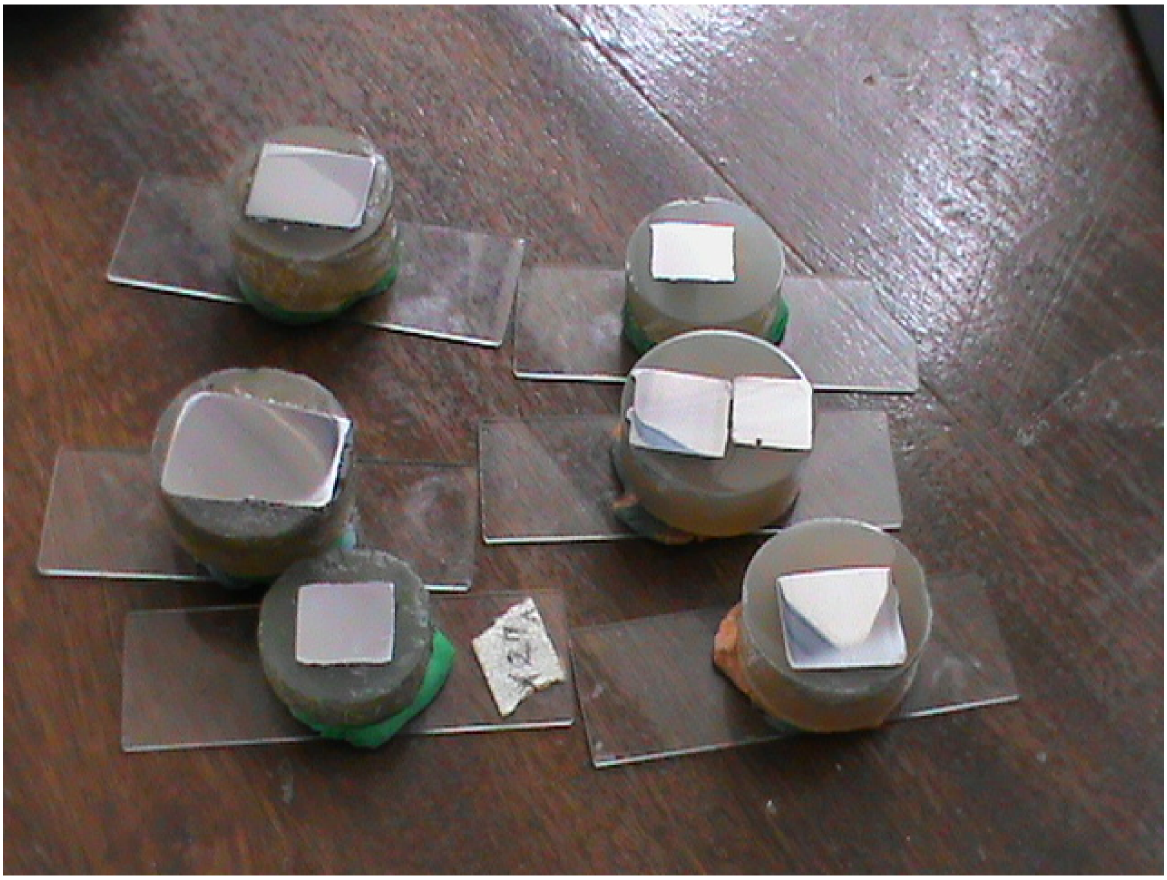


Figure 3.1: Polished and etched specimens for microstructure examination

3.6 Chemical Composition Analysis

A chemical analyses on the rebars were carried out using an Energy Dispersve X-Ray (EDX) Spectrometer, which is shown in Figure 2.1 located at the Public Works Department, Directorate of Urban Development, Ministry of Lands, Housing and Urban Development, Industrial Area, Nairobi. The specimens approximately 80 mm long,

Figure 3.2: Scrutinising a specimen mounted on photomicrograph

were filed flat at one end. This flat surface was then exposed to an X-ray stream in the machine.

3.7 Bending/Rebending Test of Reinforcement Bars

3.7.1 Bending Test

The operation was carried out in such a way as to produce a continuous and uniform bending deformation (curvature) at every section of the bend. The presence of any mill scale was ignored. The maximum bending rate was 3 revolutions per minute or equivalent. The test was conducted on a 3-point hydraulic bending machine. This was achieved on the Universal Tensile Testing Machine at JKUAT materials testing laboratory after attaching the milled mandrel, of external diameter 62 mm shown in Figure 3.3. The complete set up is shown in Figure 3.4. To pass, the test specimens needed to withstand being bent through 180^o round a former of the prescribed diameter specified in Table A.1; without showing signs of fracture on visual examination.

Figure 3.3: Milled modifier mandrel

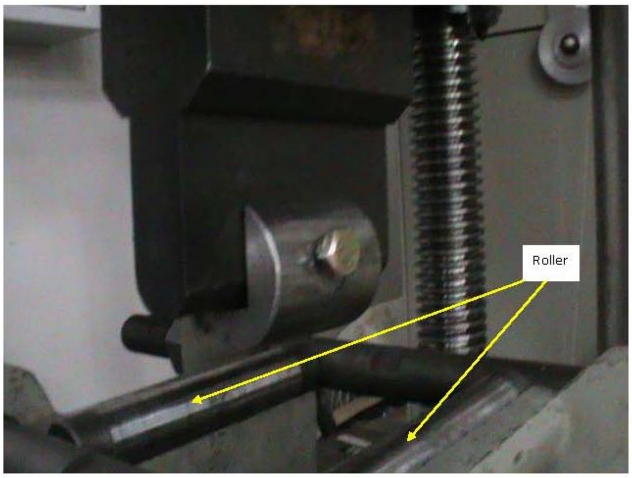


Figure 3.4: 3-point bending set up with modifier mandrel

3.7.2 Rebend Test

The test specimen was bent through 45^o using the 3-point bending method round a former of diameter as specified in Table A.1. The Universal Tensile Testing Machine at Technical University of Mombasa was employed in bending mode, Figure 3.6. For the No.4 specimen, mandrel diameter was 62.5 mm. Length of the specimen was 400 mm, see Figure 3.5.

The bent test piece was then artificially aged at 100^oC for two hours in still air electric muffle furnace (Figure 3.7) followed by free cooling in air, to ambient temperature, (this was 32^oC). The bar was further bent back towards its original shape (partially restraightening) by a steadily applied force through at least 23^o on the same setting on the same bending machine used to obtain the 45^o angle (Figure 3.8). Scrutiny of the test piece for any fracture, transverse or oblique cracks followed.

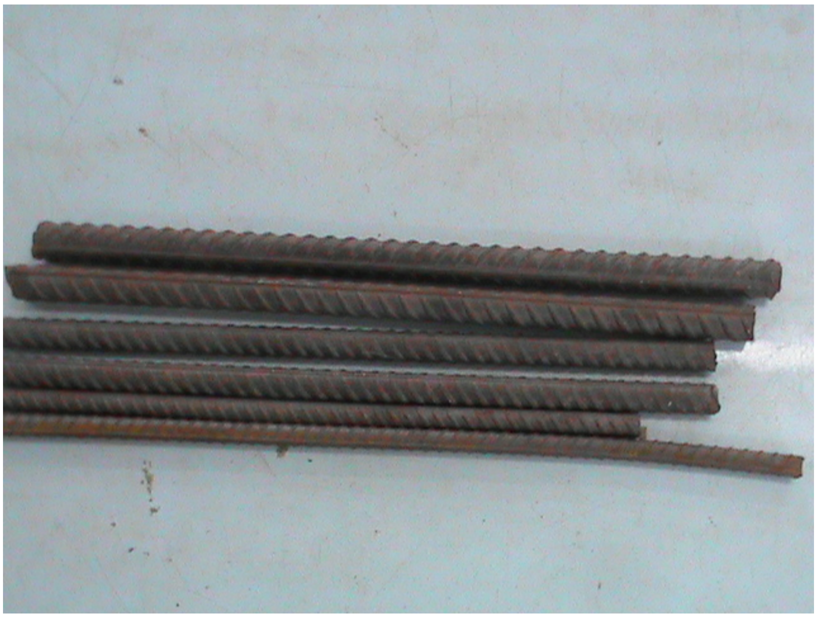


Figure 3.5: Straight Source A rebend specimens

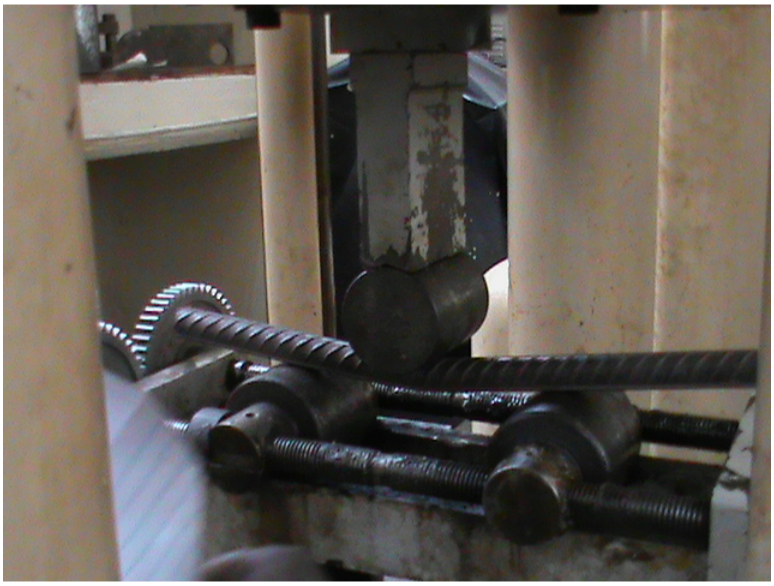


Figure 3.6: Bending a rebend specimen to 45^o

Figure 3.7: Bars packed in electric muffle furnace ready for ageing

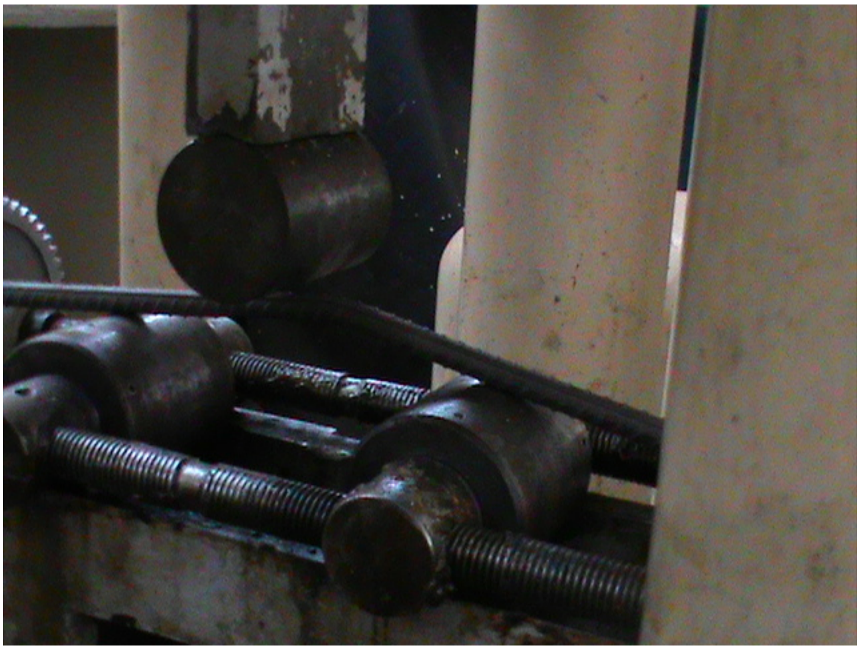


Figure 3.8: Rebending - Restraightening the bar by 23^o

3.8 Fatigue Test on Reinforcement Bars

3.8.1 Test Specimen and Gripper Design

Bars normally must not be machined, but tested as received. The argument is that machining the ribs and lugs or otherwise takes away an important component of the reinforcement bar. For example, TMT produced rebars have a hard martensitic surface layer different from the ductile, and softer, pearlite/ferrite core. See Figure 2.17.

The diameter 63 mm shaft was drilled axially at one end. The other end was machined to produce a flat and given a bore normal to the bar axis, Figure 3.9. The attempt

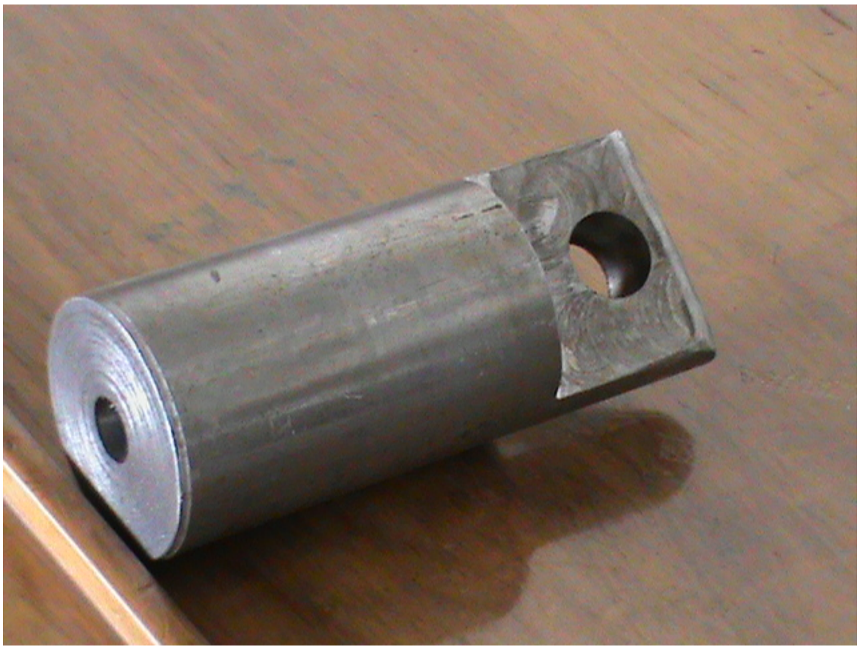


Figure 3.9: Gripper design for axial load fatigue test

to bond the bar with grout failed: the set grout proved to be too brittle. Grout is a high quality, fine, water-resistant, polymer modified, cement based powder designed for grouting glazed tiles mosaics, vitrified and fully vitrified tiles, ceramic tiles, industrial tiles etc.

The alternative was epoxy steel. This contained epoxy and polyamine resins. This epoxy resin and atomized steel in putty form reputedly chemically welds, fills, seals and bonds most metals including brass, steel, copper and iron. The 4 minute KWIK-SET facility was a bonus in saving time. The gripper elements shown in Figure 3.10 were made of a 63 mm diameter shaft. The flats were made by the shaping machine and the pin hole drilled. The axial hole that takes the test bar was drilled on the lathe

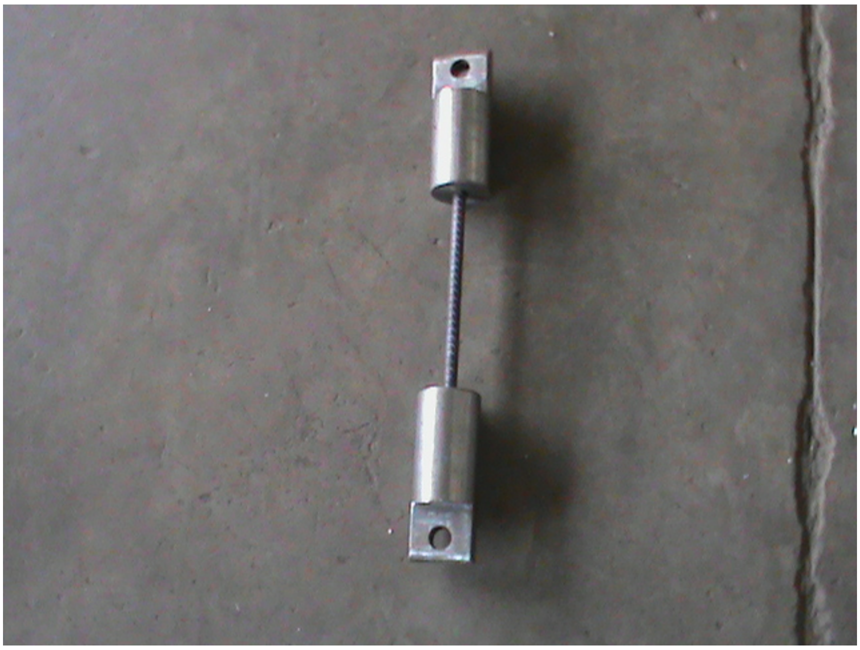


Figure 3.10: Machined gripper design elements for axial load fatigue test

machine. The deformed test bar was assembled by application of a bond of epoxy-steel.

The test would be carried out at ambient temperature. Bar specimens, of 300 mm approximate length, would be held on the brute force axial load fatigue testing machine as in Figure 3.10. The applied stress range is 150-200 MPa, with a stress ratio ($\sigma_{min}/\sigma_{max}$) of 0.2. To pass, the test sample should survive 5 million stress cycles.

3.8.2 Fatigue Test

The intention was to use the UON fatigue test machine, Figure 3.11. After preparation of the specimen mounted on the grippers, as in Figure3.10; it was to be loaded as in Figure 3.12, swapping the plate specimen for the bar specimen. It was then that the author was informed that the fatigue testing machine needed repairs: a ball bearing needed to be changed to reduce noise, the con-rod needed to be severed and rewelded for better alignment; machine footage, floating as it were on planks of timber, ought

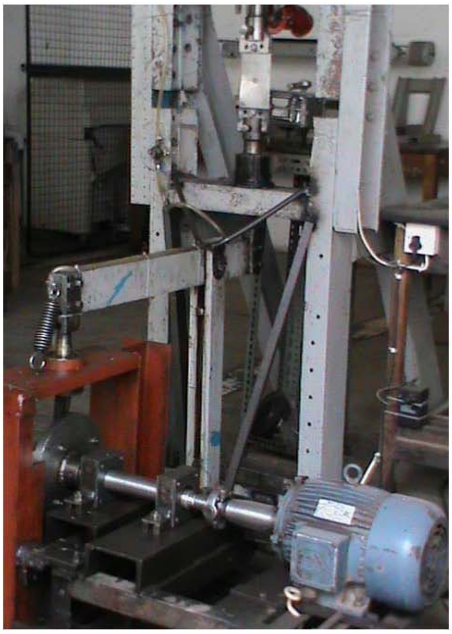


Figure 3.11: Brute force axial-load fatigue testing machine (UON)

to be secured to the floor with rag bolts. Concerted exertions in the repair exercise are reported in Appendix C. For the reasons cited in the report, it was not possible for the author to carry out the fatigue test.

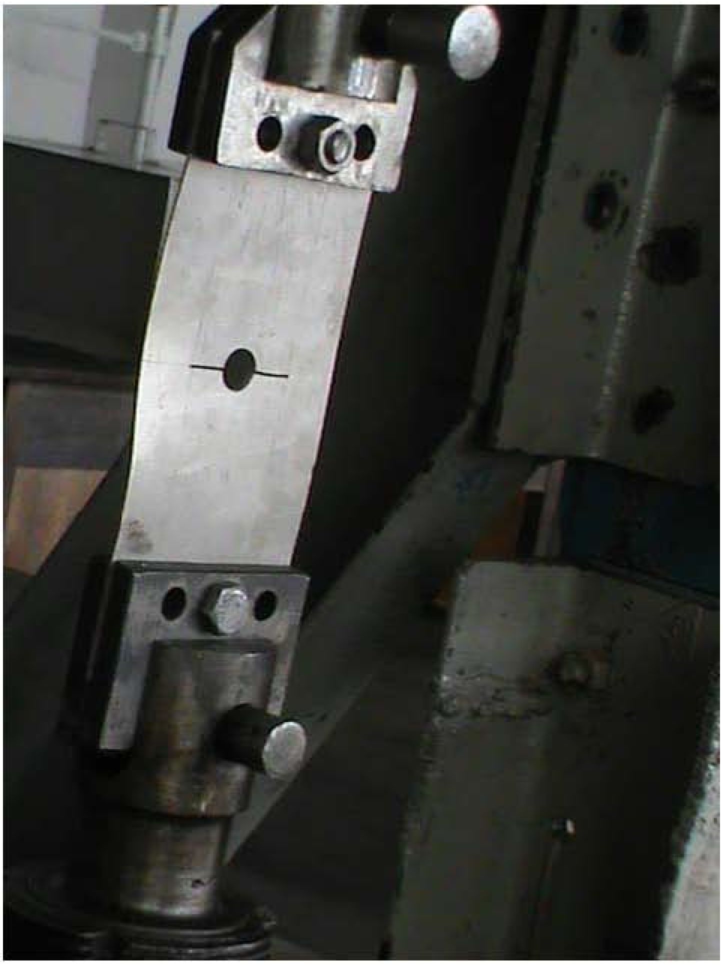


Figure 3.12: Notched plate work on fatigue testing machine (UON)

3.9 Hardness Test

The Rockwell Hardness test was conducted. This test is based on the measurement of the depth of penetration of the indenter. A load of 10kgf is first applied to the indenter, and the depth of penetration then reached is taken as the zero for further measurements. A further load (called the major load) is then applied and removed, leaving only the minor load. The depth, d mm, of the indenter relative to the zero position is recorded on a suitable dial gauge [55], as in Figure 3.13.

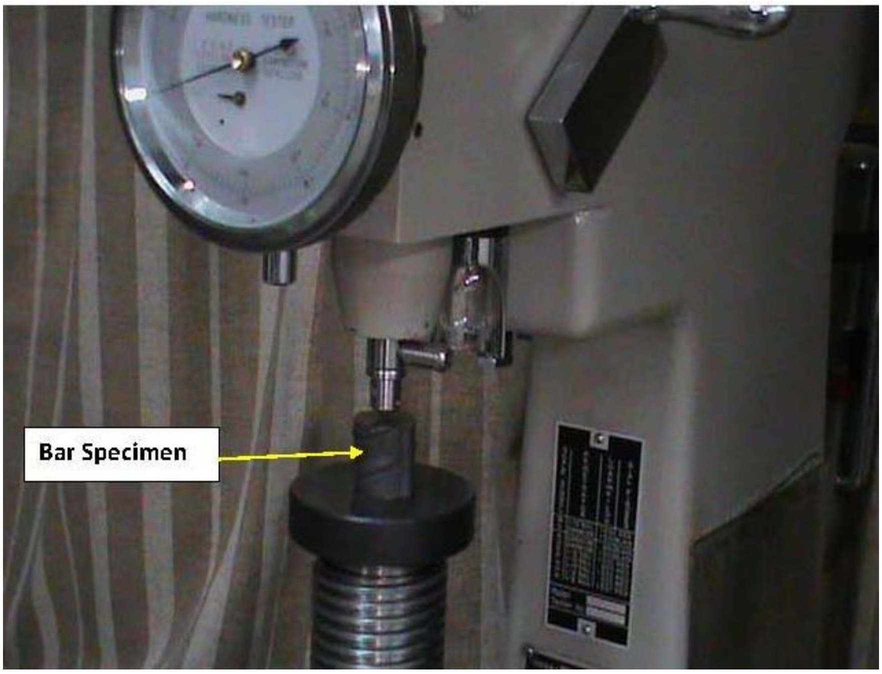


Figure 3.13: Rockwell Hardness testing machine

Test specimens of length 10 - 25 mm were filed flat, ground and polished. For the sake of conversion to BHN, the HRB scale was the best choice on account of the hardness range of the bars. But the requisite ball of $\phi 1.6$ mm was missing. So the tests were conducted on HRA scale, using a diamond cone indenter of included angle 120^o. The full load was 60kgf [56, 57]. Conversion to BHN was effected on consulting ASTM E-140 [58]. The results are presented in Table 4.7.

The Rockwell hardness test is an empirical indentation hardness test. Rockwell hardness tests provide useful information about metallic materials. This information may correlate to tensile strength, wear resistance, ductility, and other physical characteristics of metallic materials, and may be useful in quality control of manufacturing processes and selection of materials.

While Rockwell hardness testing at a specific location on a part may not represent the physical characteristics of the whole part or end product, nevertheless the Rockwell hardness tests are considered satisfactory for acceptance testing of commercial shipments, and have been used extensively in industry for this purpose.

The ultimate strength (σ_{uts}) of a material can be calculated from the hardness (BHN) values by the expression (3.10) [56]. The values so obtained give a useful, quick and rough estimate for the tensile strength of a specimen.

$$\sigma_{uts} = 3.45 \times BHN. \tag{3.10}$$

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Fatigue on Rebars

Equation 4.1 is known to be conservative. It gives stress range values which are low. However, some design manuals do away with fatigue considerations so long as certain loading features are adhered to and not exceeded. Table 4.1 shows the calculated design stress range for fatigue. The values are agreeably low. But caution is important where corrosion and dynamic loads are significant.

Generally fatigue is not taken into account in design. However, fatigue shall be considered by rational evaluation when the stress range in concrete members under a large number of repeated service loads exceeds, for example,

$$f_{cr} = 0.5f_c - (\frac{2}{3})f_{min} \tag{4.1}$$

where:

f_{min} =minimum compressive stress in psi (compressive stress is positive); and

f_c=corresponding static strength

f_{cr}=stress range in concrete under repeated service loading i.e. difference between maximum and nminimum compressive stress in (psi) [59] For rebars that are embedded in concrete, it can be that good construction can indicate durability and hence mitigate many fatigue issues. For example good grade concrete made of good grade materials should not be air or water permeable; hence the bar will have adequate cover, avoiding damage to the bar by oxidation and corrosion.

Table 4.1: Fatigue test stress range for given f_{min}

Bar size (mm)	Stress range (MPa) [1]	Stress range f_{min}=0(MPa)	Stress range f_{min}=90(MPa)
≤ 16	200	165	135
$> 16, \leq 20$	185	165	135
$> 20, \leq 25$	170	165	135
$> 25, \leq 32$	160	165	135
> 32	150	165	135

4.2 Survey

From the summaries of response to the questionnaires used to carry the survey shown in Appendix D, it is noted that 5% of Kenyan steel making plants are not compliant with the set standards [2]. Most construction work in Kenya uses cold twisted, rather than ribbed bars. Kenya, therefore, lags Europe and America who have adopted ribbed bars and purposed not to employ cold twisted bars anymore. Kenya Bureau of Standards (KEBS) uses tensile and bending tests as well as chemical composition analysis as the main quality control methods. Construction companies interviewed reported 80% usage of twisted rebar and 20% ribbed bars. Failure of rebar in construction has been occasionally experienced; largely traced to low yield strength and poor bending characteristics. On a visit to Steel Makers Limited, Athi River, the bar making process was witnessed. This rolling mill imports steel billets from South Africa which together with local scrap, are loaded into the induction furnace. Samples of the melt are taken when furnace is halfway full and analysed for chemical content. Necessary chemicals are added, and the ingots cast. The ingots are later heated and rolled, cut to size and cooled in open air, then cold twisted. Quality control was achieved by carrying out chemical analysis using atomic emission spectrometer as well as the tensile tests on the bars after rolling and twisting.

4.3 Bending/Rebending

4.3.1 Bending

Figures 4.1, 4.2, 4.3, 4.4 show bending results for rebars in the Kenyan market:

Figure 4.1: Bent Rebars Source A

Figure 4.2: Bent rebars Source B

Figure 4.3: Bent sample bars Source A

Figure 4.4: U-bent rebars Source B

Table 4.2: Bending Test Results

Source A			Source B		
Sample	Bar No.	Outcome	Sample	Bar No.	Outcome
No. 4	1	Pass	No. 4	1	Pass
	2	Pass		2	Pass
	3	Pass		3	Pass
	4	Pass		4	Pass
	5	Pass		5	Pass
	6	Pass		6	Pass
$\phi 13mm$	7	Pass		7	Pass
	All bars	Pass		All bars	Pass
	%CoV	0.0		%CoV	0.0
No. 5	1	Pass	No. 5	1	Pass
	2	Pass		2	Pass
	3	Pass		3	Pass
	4	Pass		4	Pass
	5	Pass		5	Pass
$\phi 16mm$	All bars	Pass		All bars	Pass
	%CoV	0.0		%CoV	0.0
No. 6	1	Pass	No. 6	1	Pass
	2	Pass		2	Pass
	3	Pass		3	Pass
	4	Pass		4	Pass
$\phi 19mm$	All bars	Pass		All bars	Pass
	%CoV	0.0		%CoV	0.0

Table 4.2 Full bending test results.

Sample rebars from two local sources were bent to a U-shape successfully. Visual examination [6,7] showed that mill scale and iron oxide cover were seen to peel off. This seems to agree with Restrepo, Crisafulli and Park, [29] that bending and straightening of rebar embedded in concrete does not weaken the bars if they are not bent through an angle greater than 90 degrees.

These and other studies show that care must be taken, that it is hazardous to re-straighten cold rebar. The smaller rebar sizes No.3, No.4, No.5 and No.6 usually can be bent cold as needed. However, care should be taken to make smooth bends, not kinks. Larger bars (larger than No.6) take special handling and may require heating. It is worth noting that bending is in a sense a measure of ductility. Thus the pass result in the bend/rebend test should be seen together with columns 7 and 8 in Tables 4.4 and 4.5. Seismic rebars for use in China need fulfill three basic requirements:

1. σ_y is 400 - 500 MPa

2. Ratio R_m/R_e not less than 1.25

3. A_{gt} not less than 9%

4.3.2 Rebending

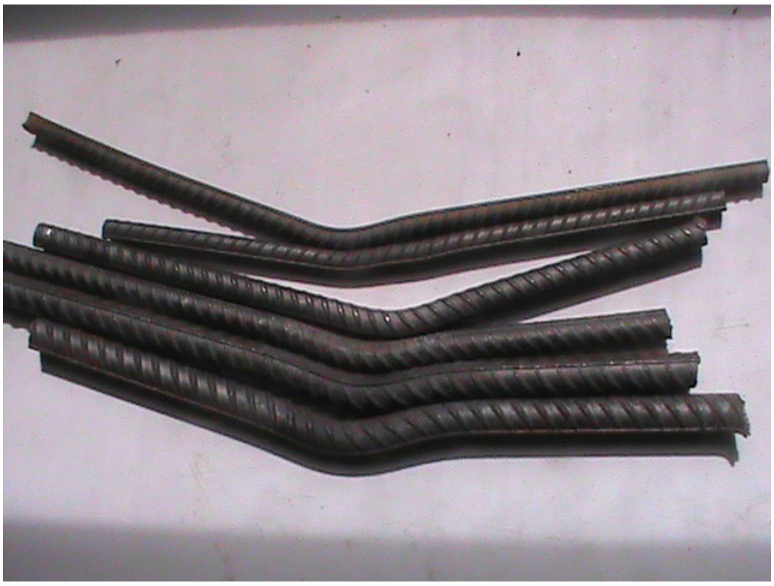


Figure 4.5: Rebent specimens - source A

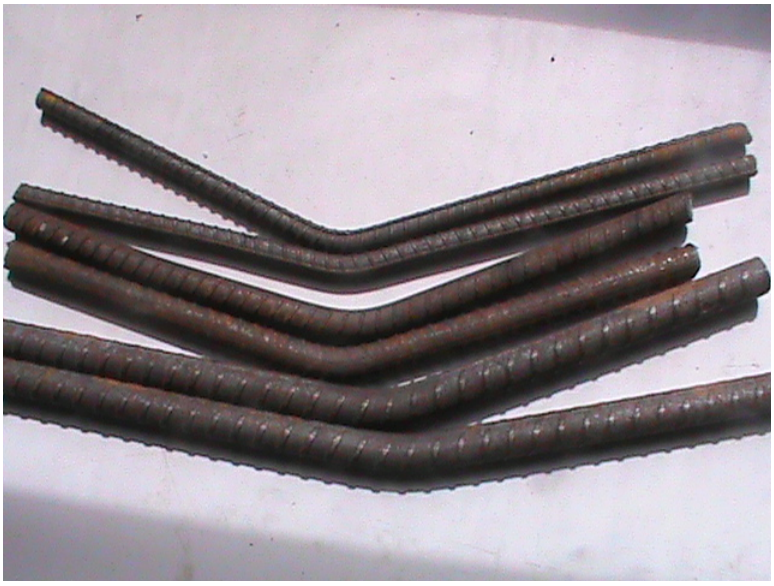


Figure 4.6: Rebent specimens - source B

Figure 4.7: Visual of Rebent outside curve - source A

Figure 4.8: Visual of Rebent outside curve - source B

Table 4.3: Rebending Test Results

Source A			Source B		
Sample	Bar No.	Outcome	Sample	Bar No.	Outcome
No. 4	1	Pass	No. 4	1	Pass
	2	Pass		2	Pass
	3	Pass		3	Pass
	4	Pass		4	Pass
	5	Pass		5	Pass
	6	Pass		6	Pass
$\phi 13mm$	7	Pass		7	Pass
	All bars	Pass		All bars	Pass
	%CoV	0.0		%CoV	0.0
No. 5	1	Pass	No. 5	1	Pass
	2	Pass		2	Pass
	3	Pass		3	Pass
	4	Pass		4	Pass
$\phi 16mm$	5	Pass		5	Pass
	All bars	Pass		All bars	Pass
	%CoV	0.0		%CoV	0.0
No. 6	1	Pass	No. 6	1	Pass
	2	Pass		2	Pass
	3	Pass		3	Pass
$\phi 19mm$	4	Pass		4	Pass
	All bars	Pass		All bars	Pass
	%CoV	0.0		%CoV	0.0

Table 4.3 Full rebending test results.

Sample bars of size No.4, No.5 and No.6 were successfully rebent, Table 4.3. Visual examination of the outer curve of the bent portion revealed no fracture or cracks whatsoever. However, a number of the specimens were observed to have kinks; probably occasioned by asymmetrical loading. See Figures 4.5, 4.6, 4.7 and 4.8.

4.4 Grain Size

On microscopical examination the following plates were observed: the 12 mm diameter bar from source A was seen to have a grain size number 11.843, which is equal to mean lineal intercept grain size $\bar{l}$ of 0.0053 mm or 5.3 μm

It was observed that the lower diameter bars tended to have finer grains than the thicker bar. This was particularly noticeable with Source A steels where the thicker diameter 25 mm bar was seen to have large grains. The thicker bars, in an air-cooled

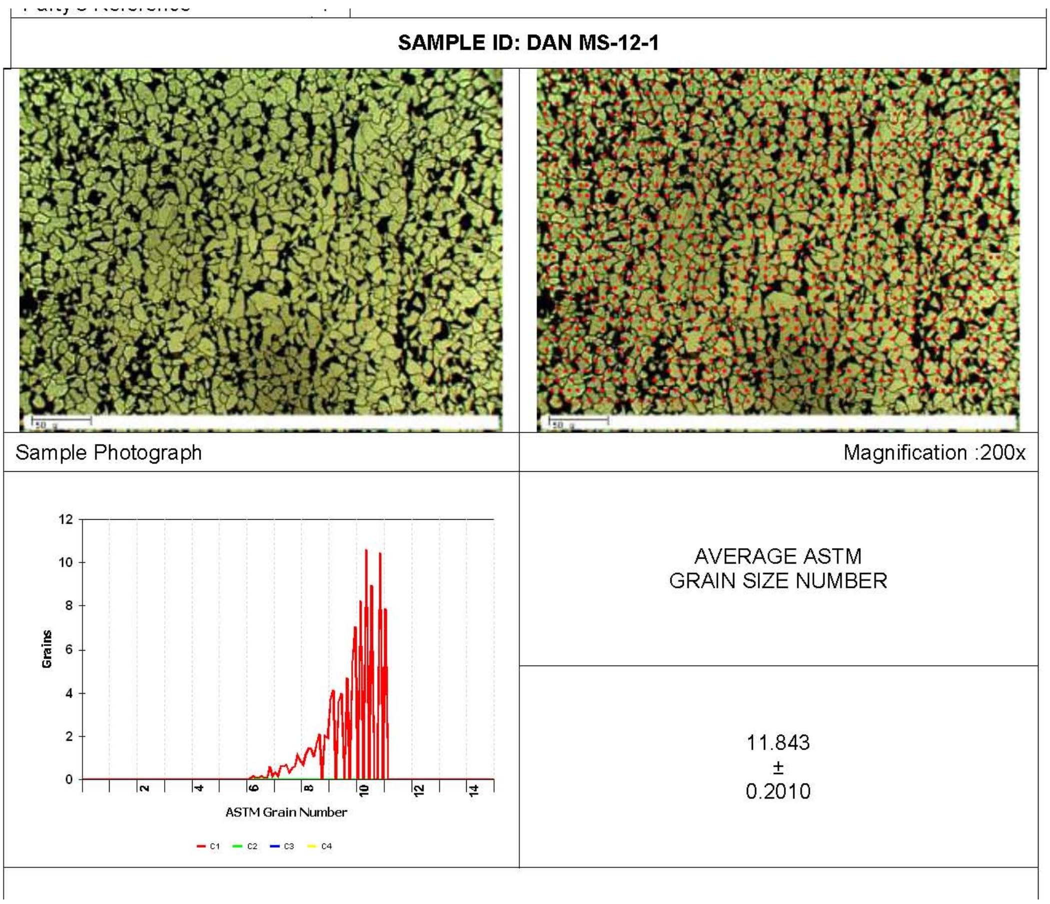


Figure 4.9: Grain field-Source A, diameter 12 mm (x200)

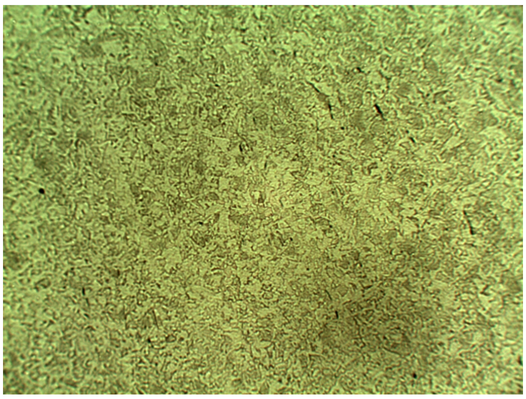


Figure 4.10: Source B, diameter 12mm, core (x200)

procedure, take a longer time to cool when compared to thinner bars. Another reason for large grains is probably the absence of grain refining elements such as vanadium and nickel. In Figure 4.12 can be seen the largely ferrite and pearlite phases. All bars

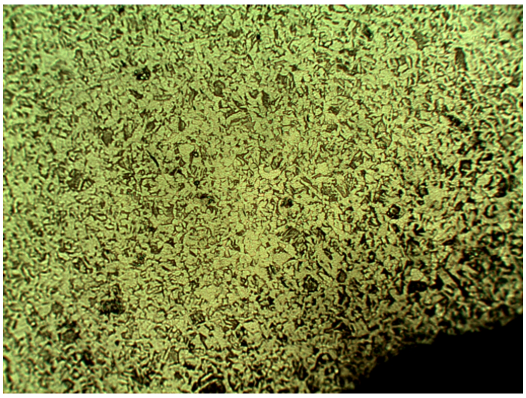


Figure 4.11: Source B, diameter 12mm, Edge (x200)

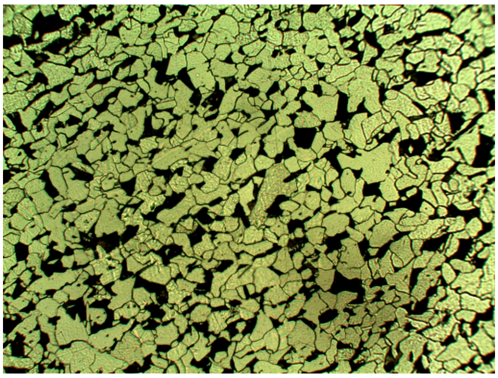


Figure 4.12: Source A, diameter 20 mm, core (x200)

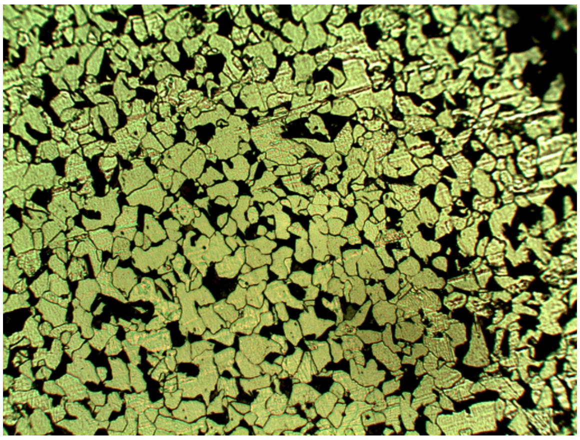


Figure 4.13: Source A, diameter 20 mm, Edge (x200)

compared well with the American Standard ASTM E-112. From equation 2.1 and data

Grain Size No. G	$\bar{N}_A$ Grains/Unit Area		$\bar{A}$ Average Grain Area		$\bar{d}$ Average Diameter		$\bar{\ell}$ Mean Intercept		$\bar{N}_L$
	No./in.^{2} at 100X	No./mm^2 at 1X	mm^2	μm^2	mm	μm	mm	μm	No./mm
00	0.25	3.88	0.2581	258064	0.5080	508.0	0.4525	452.5	2.21
0	0.50	7.75	0.1290	129032	0.3592	359.2	0.3200	320.0	3.12
0.5	0.71	10.96	0.0912	91239	0.3021	302.1	0.2691	269.1	3.72
1.0	1.00	15.50	0.0645	64516	0.2540	254.0	0.2263	226.3	4.42
1.5	1.41	21.92	0.0456	45620	0.2136	213.6	0.1903	190.3	5.26
2.0	2.00	31.00	0.0323	32258	0.1796	179.6	0.1600	160.0	6.25
2.5	2.83	43.84	0.0228	22810	0.1510	151.0	0.1345	134.5	7.43
3.0	4.00	62.00	0.0161	16129	0.1270	127.0	0.1131	113.1	8.84
3.5	5.66	87.68	0.0114	11405	0.1068	106.8	0.0951	95.1	10.51
4.0	8.00	124.00	0.00806	8065	0.0898	89.8	0.0800	80.0	12.50
4.5	11.31	175.36	0.00570	5703	0.0755	75.5	0.0673	67.3	14.87
5.0	16.00	248.00	0.00403	4032	0.0635	63.5	0.0566	56.6	17.68
5.5	22.63	350.73	0.00285	2851	0.0534	53.4	0.0476	47.6	21.02
6.0	32.00	496.00	0.00202	2016	0.0449	44.9	0.0400	40.0	25.00
6.5	45.25	701.45	0.00143	1426	0.0378	37.8	0.0336	33.6	29.73
7.0	64.00	992.00	0.00101	1008	0.0318	31.8	0.0283	28.3	35.36
7.5	90.51	1402.9	0.00071	713	0.0267	26.7	0.0238	23.8	42.04
8.0	128.00	1984.0	0.00050	504	0.0225	22.5	0.0200	20.0	50.00
8.5	181.02	2805.8	0.00036	356	0.0189	18.9	0.0168	16.8	59.46
9.0	256.00	3968.0	0.00025	252	0.0159	15.9	0.0141	14.1	70.71
9.5	362.04	5611.6	0.00018	178	0.0133	13.3	0.0119	11.9	84.09
10.0	512.00	7936.0	0.00013	126	0.0112	11.2	0.0100	10.0	100.0
10.5	724.08	11223.2	0.000089	89.1	0.0094	9.4	0.0084	8.4	118.9
11.0	1024.00	15872.0	0.000063	63.0	0.0079	7.9	0.0071	7.1	141.4
11.5	1448.15	22446.4	0.000045	44.6	0.0067	6.7	0.0060	5.9	168.2
12.0	2048.00	31744.1	0.000032	31.5	0.0056	5.6	0.0050	5.0	200.0
12.5	2896.31	44892.9	0.000022	22.3	0.0047	4.7	0.0042	4.2	237.8
13.0	4096.00	63488.1	0.000016	15.8	0.0040	4.0	0.0035	3.5	282.8
13.5	5792.62	89785.8	0.000011	11.1	0.0033	3.3	0.0030	3.0	336.4
14.0	8192.00	126976.3	0.000008	7.9	0.0028	2.8	0.0025	2.5	400.0

Figure 4.14: Grain size relationships computed for uniform, Randomly Oriented, Equiaxed Grains; ASTM E-112 [25]

in Figure 4.14 [25], the yield strength of the bar is calculated as :

$$
\begin{aligned}
f_y &= f_o + \frac{k}{\sqrt{d}} \\
&= 5N/mm^2 + \frac{38}{\sqrt{0.0053}} \\
&= 527N/mm^2 \qquad (4.2)
\end{aligned}
$$

where:

f_y is yield strength,

f_o is yield strength of very large isolated crystals (for mild steel this is taken as 5N/mm^2),

k is a constant, for mild steel k = 38 N/$mm^{\frac{3}{2}}$ [23],

d is the mean lineal grain size $\bar{l}$.

This compares well with the recommended standard strength 460N/mm^2. There is no evidence on the basis of this microstructural analysis that local rebars are substandard. The structure in Figure 4.9,4.12,4.13 are showing the ferrite-pearlite structure of air cooled bar. Figure 4.13, an edge field view, shows remarkable absence of martensite, just like the core of the same bar 4.12. The structure seems to indicate lack of thermo-mechanical treatment.

4.5 Tensile Test

The following graphs are typical of the results achieved:

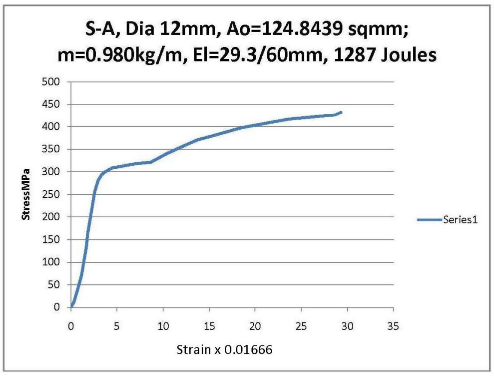


Figure 4.15: Stress/Strain curve; diameter 12mm; Source A

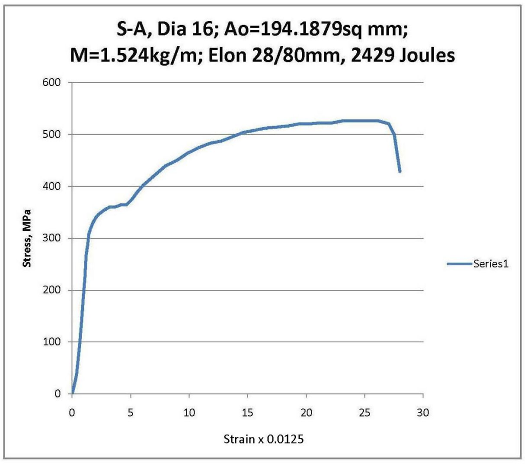


Figure 4.16: Stress/Strain curve; diameter 16mm, Source A.

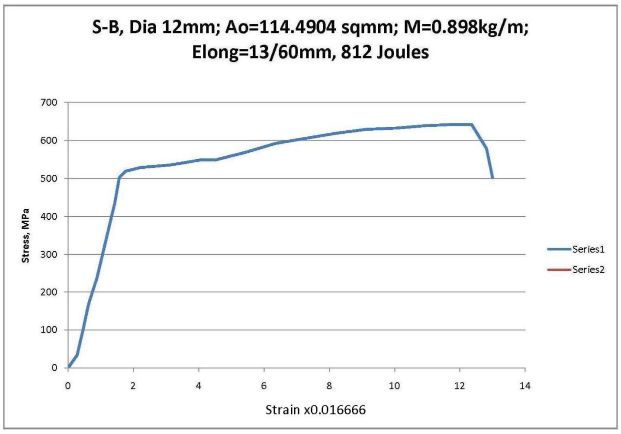


Figure 4.17: Stress/Strain curve; diameter 12mm rebar; Source B

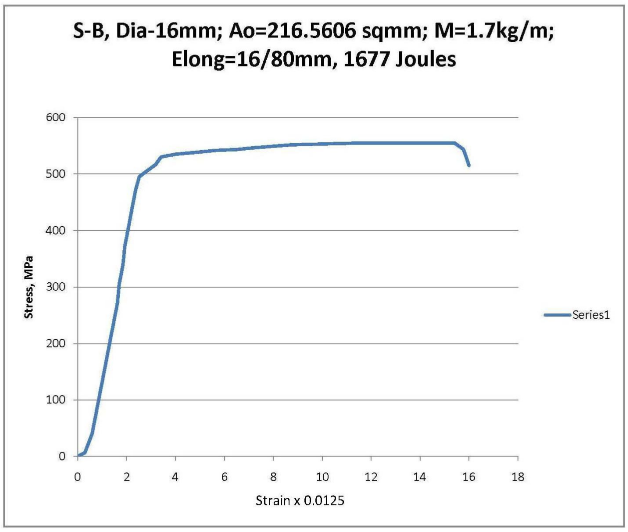


Figure 4.18: Stress/Strain curve; diameter 16mm; Source B

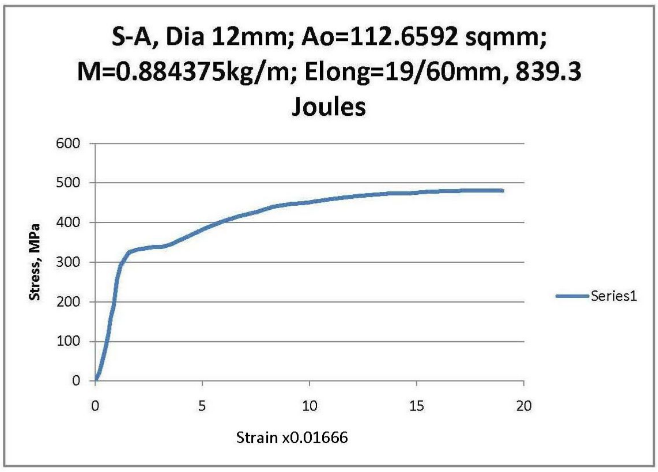


Figure 4.19: S-A ϕ12 mm

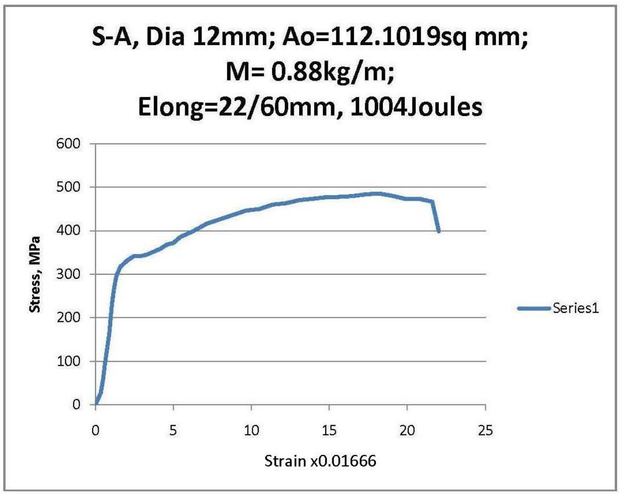


Figure 4.20: S-A $\phi 12$ mm

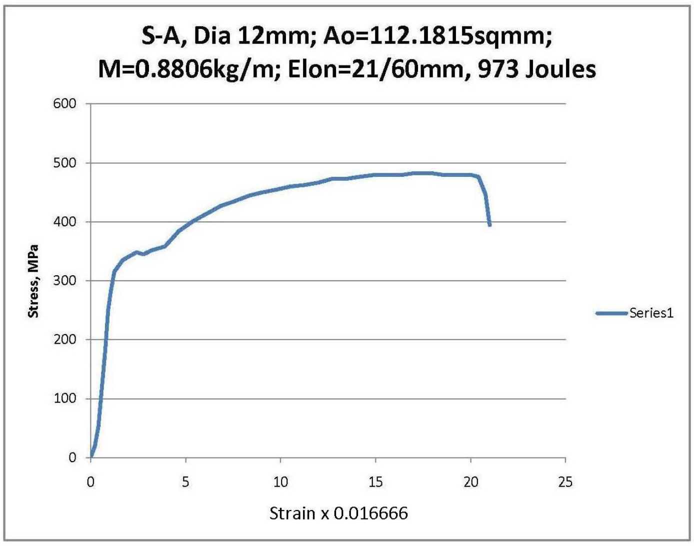


Figure 4.21: S-A ϕ12 mm

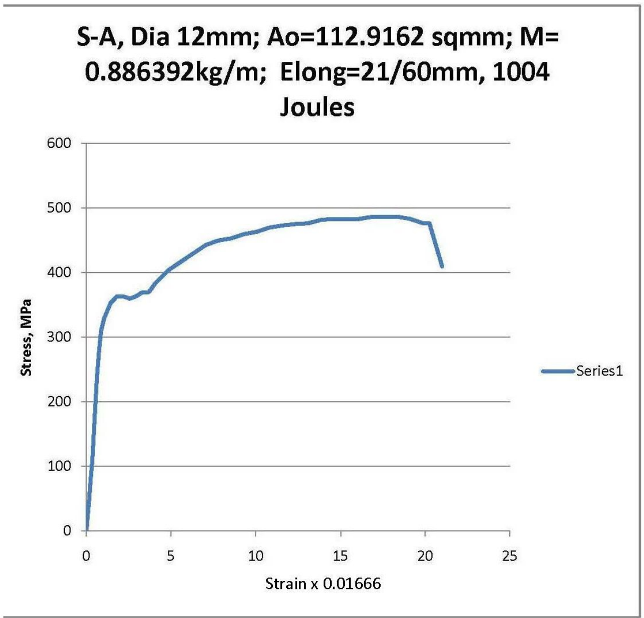


Figure 4.22: S-A ϕ12 mm

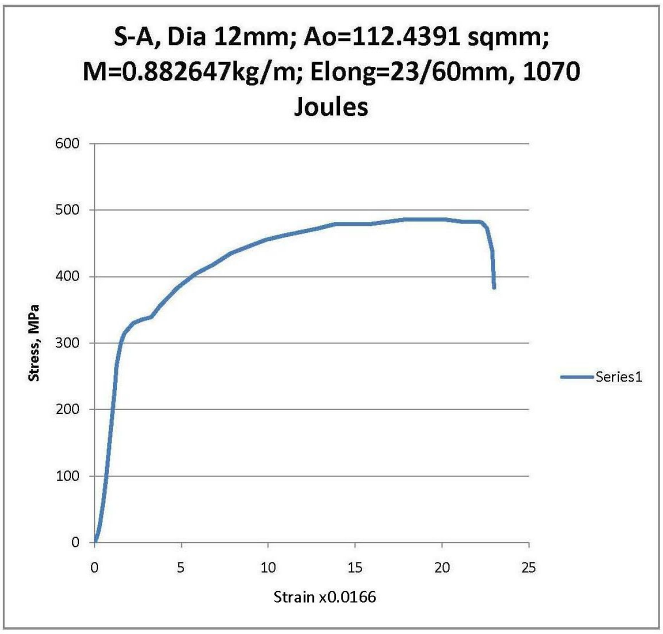


Figure 4.23: S-A ϕ12 mm

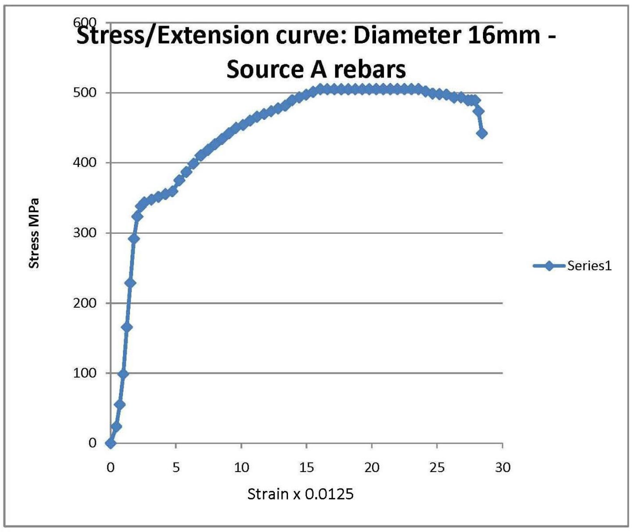


Figure 4.24: S-A ϕ12 mm

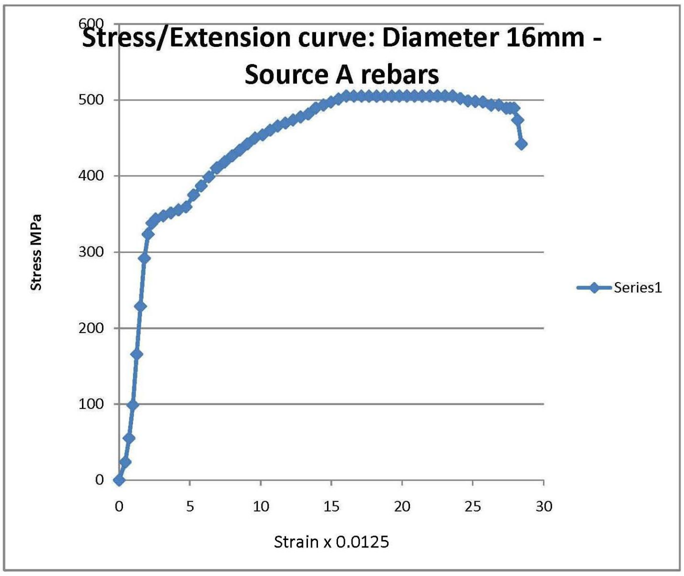


Figure 4.25: S-A ϕ16 mm

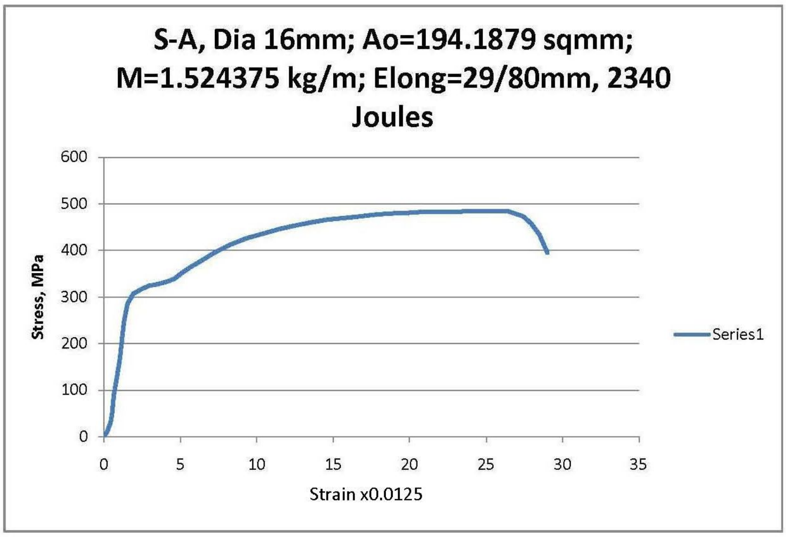


Figure 4.26: S-A ϕ16 mm

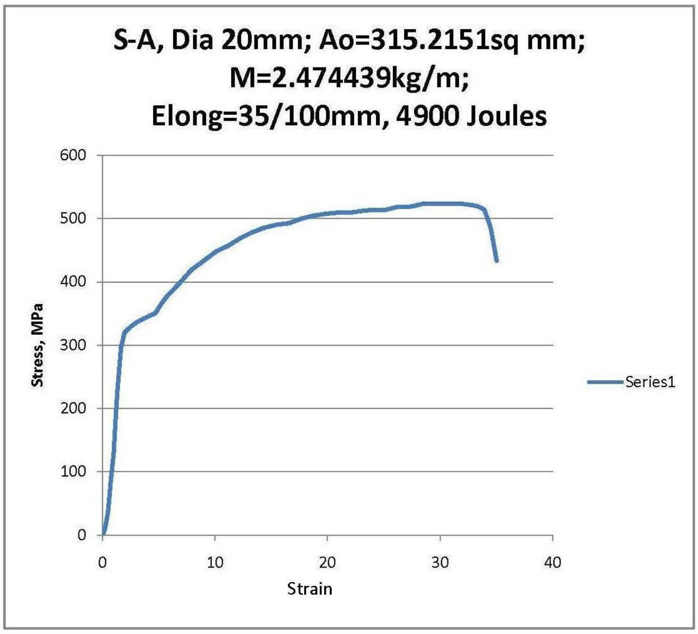


Figure 4.27: S-A ϕ20 mm

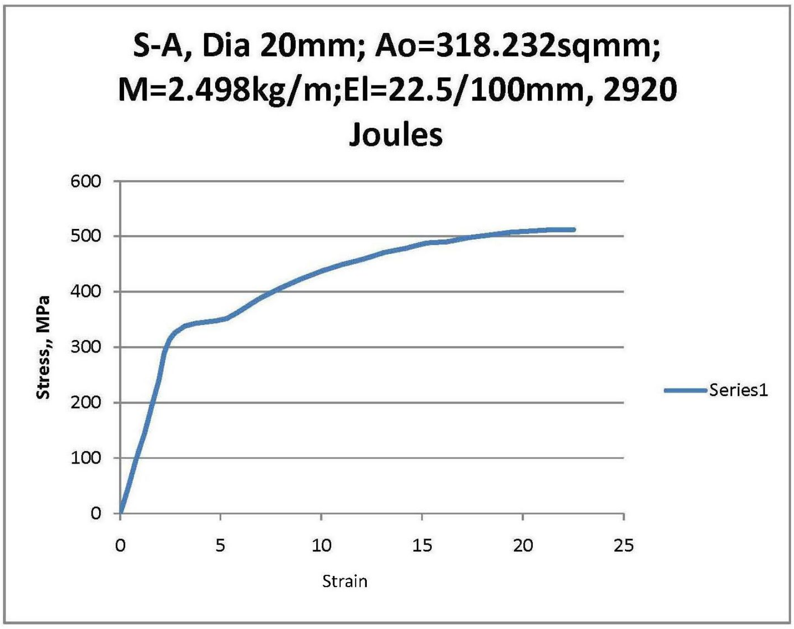


Figure 4.28: S-A ϕ20 mm

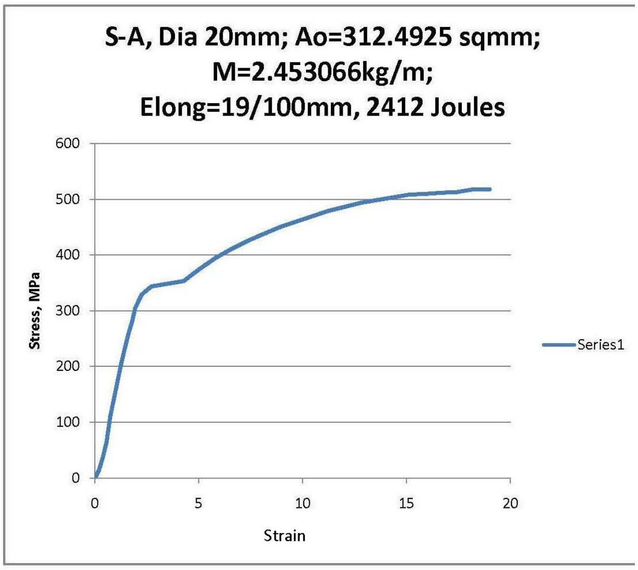


Figure 4.29: S-A ϕ20 mm

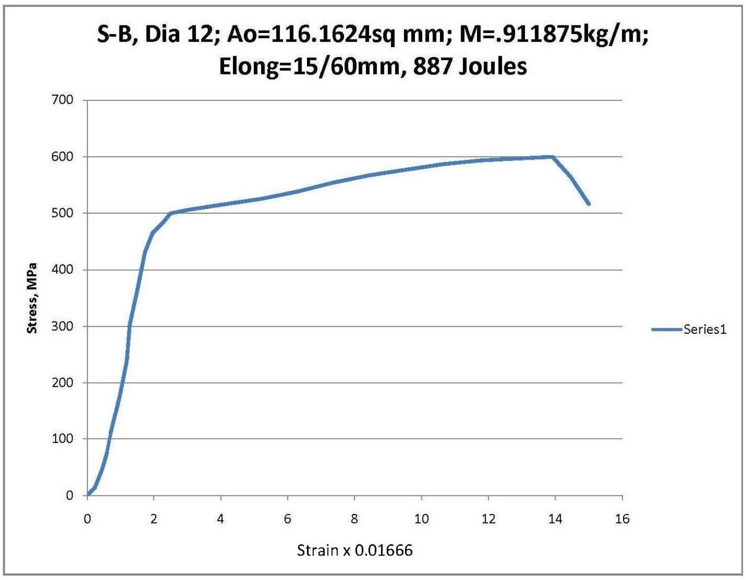


Figure 4.30: S-B ϕ12 mm

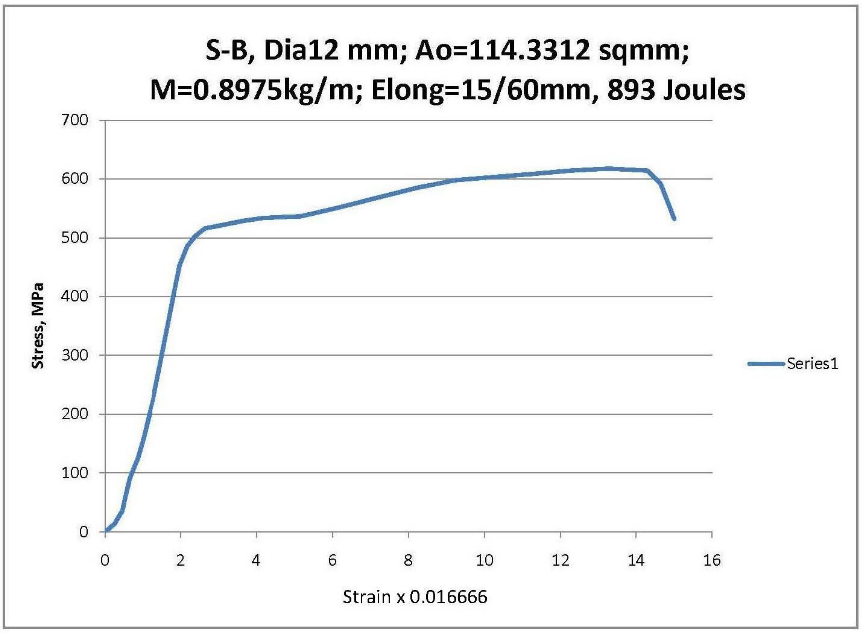


Figure 4.31: S-B ϕ12 mm

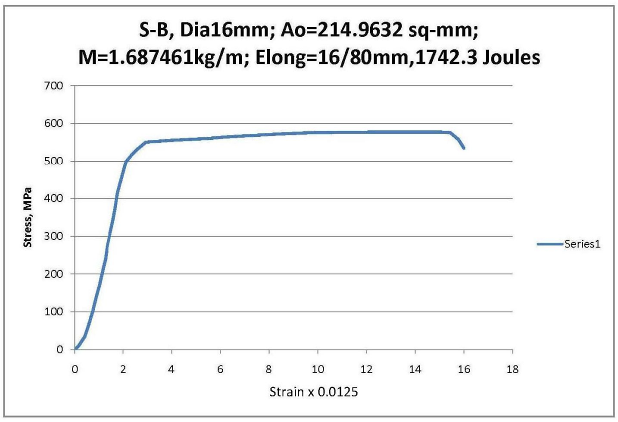


Figure 4.32: S-B ϕ16 mm

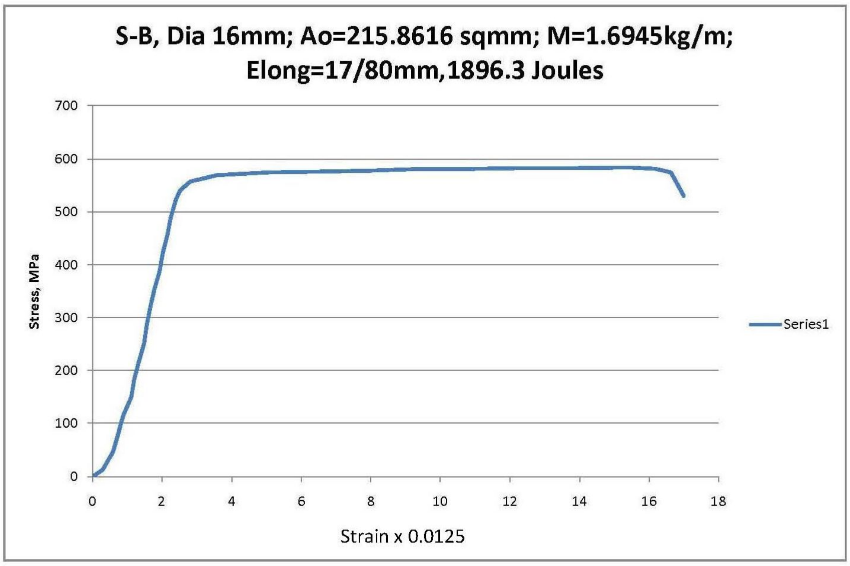


Figure 4.33: S-B $\phi 16$ mm

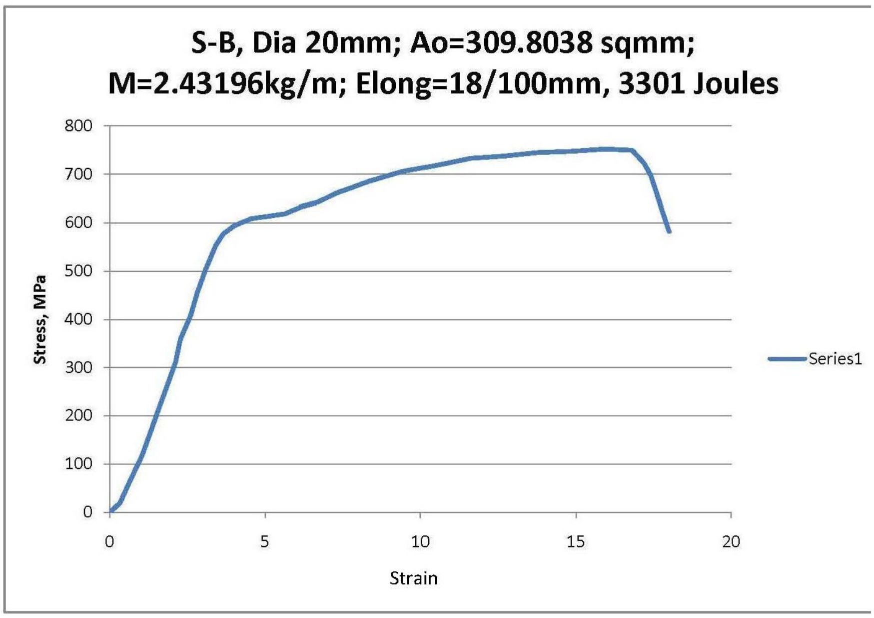


Figure 4.34: S-B $\phi 20$ mm

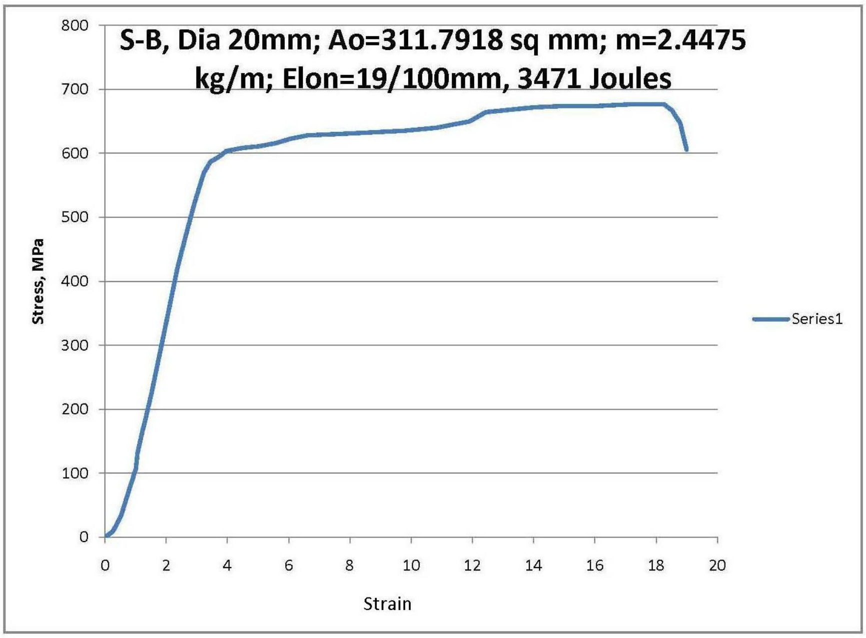


Figure 4.35: S-B ϕ 20 mm

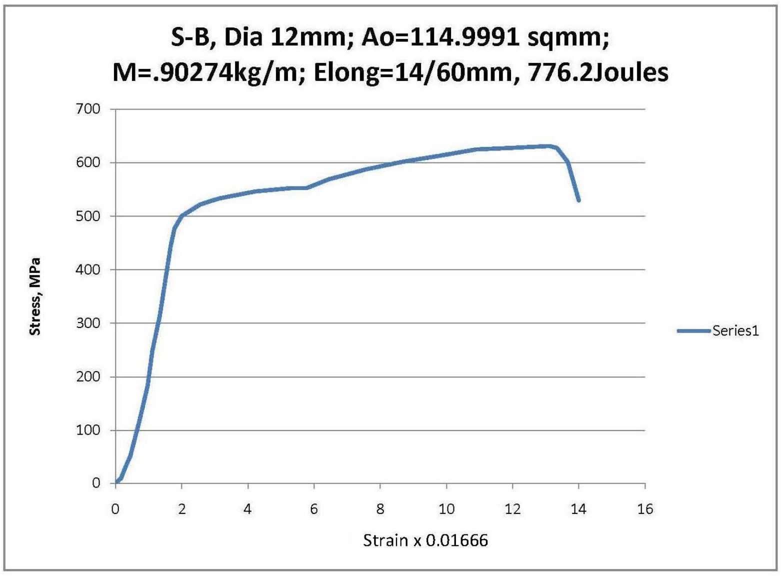


Figure 4.36: S-B ϕ12 mm

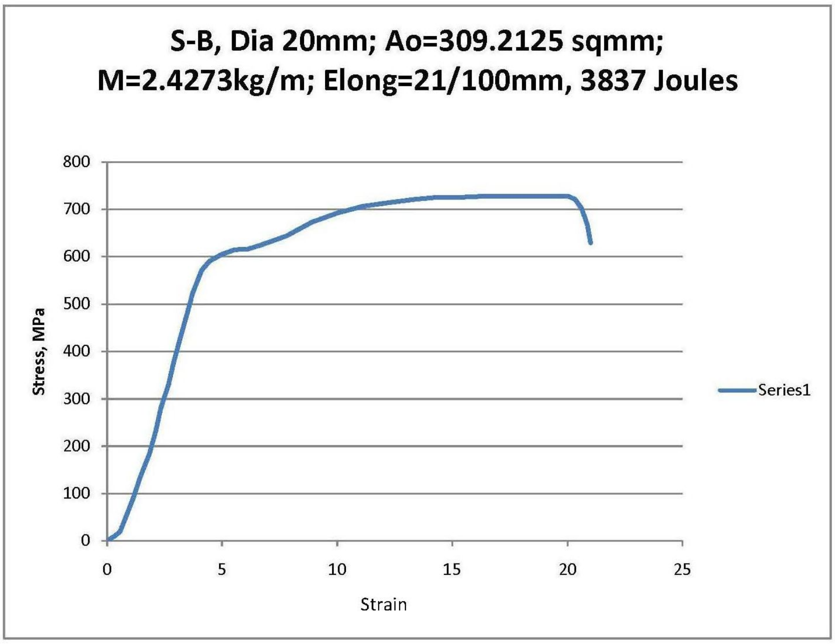


Figure 4.37: S-B ϕ12 mm

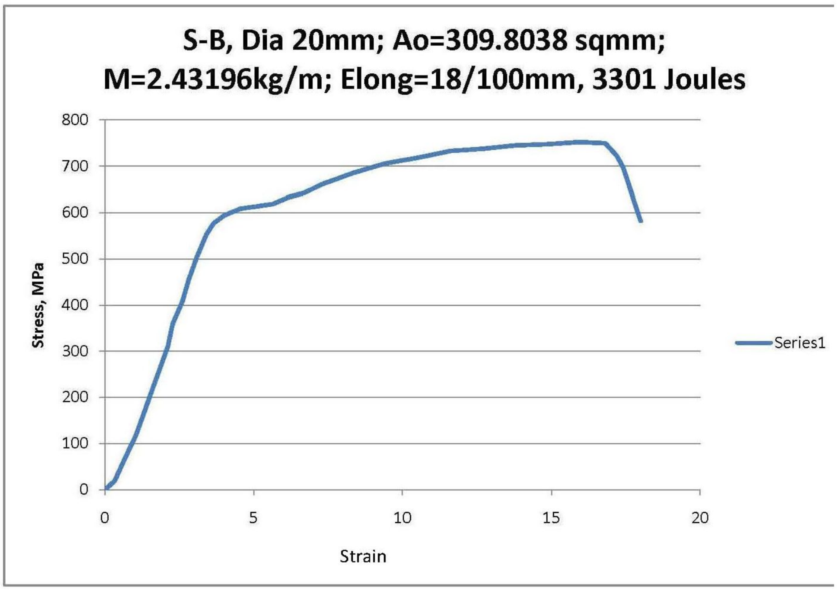


Figure 4.38: S-B ϕ12 mm

From the graphs, Figures 4.15, 4.16, 4.17, 4.18 and Appendix B, it is noted that bars from Source A failed the tensile strength test by not meeting the 460MPa yield strength threshold. Figure 4.15 has yield stress at 300 MPa while Figure 4.16 has a yield stress

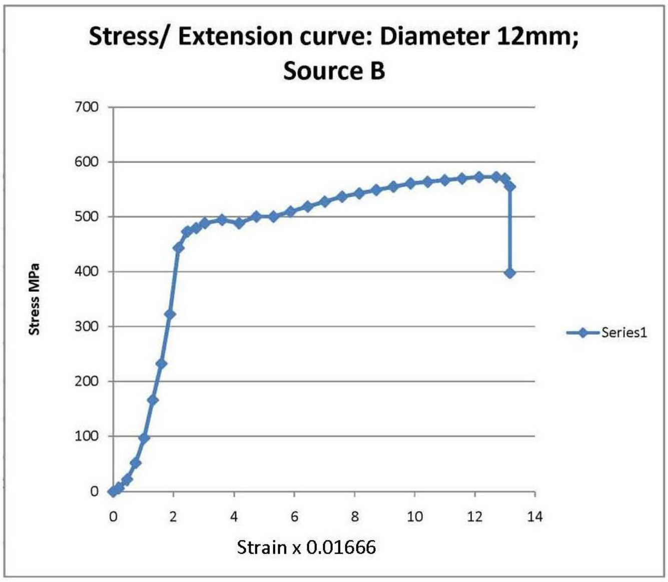


Figure 4.39: S-B ϕ 12 mm

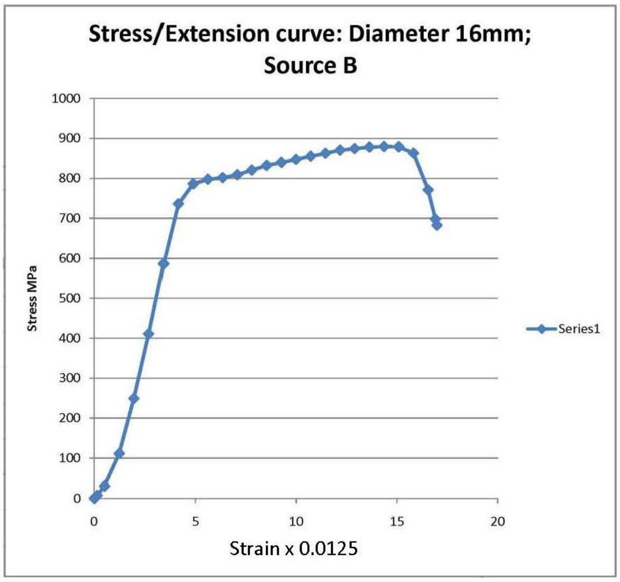


Figure 4.40: S-B ϕ16 mm

of 350 MPa. Source B bars were all seen to pass the tensile strength test. Table 4.4 shows Source-A bar values for (Area/Nominal Area), the yield stress, ultimate tensile strength, mass (kg/m), % Elongation, the ratio (σ_u/σ_y), Elongation at fracture and

Table 4.4: Source A; Physical properties.

Sample	Bar No.	Area/Nom. Area -	$\sigma_y(R_e)$ MN/m^2	$\sigma_{uts}(R_m)$ MN/m^2	M kg/m	% Elong -	σ_u/σ_y -	A_5 -	E_b Joules
No. 4	1	0.9961	320	481	0.8844	31.7	1.5	31.7	839
	2	0.9912	310	485	0.88	36.7	1.57	30	1004
	3	0.9919	320	483	0.8806	35	1.51	28.3	973
	4	0.9984	360	486.5	0.8864	35	1.35	30	1004
	5	0.9942	315	486.4	0.8826	38.3	1.54	36.6	1070
	6	0.9915	290	420	0.8832	38.3	1.45	35	996
$\phi 13mm$	7	0.9912	350	508	0.88	28.3	1.45	26	983
	All bars	0.9935	323.6	479	0.8824	34.76	1.48	31.1	981.3
	%CoV	0.265	6.8	5.3	0.25	9.73	4.5	11.0	6.6
	1	0.9656	340	520	1.5243	35	1.53	32.5	2429
No. 5	2	0.9625	300	486	1.51937	37.5	1.62	35	2450
	3	0.9656	300	485	1.5243	36.2	1.62	31.2	2340
	4	0.9634	320	488	1.5218	35	1.53	32	2365
	5	0.9622	344	505	1.52	35	1.47	33	2428
$\phi 16mm$	All bars	0.96386	320.8	496.8	1.5219	35.74	1.55	32.74	2402
	%CoV	0.15	5.9	2.8	0.14	2.8	3.74	3.9	1.76
No. 6	1	0.9946	330	518	2.4531	19	1.57	18	2412
	2	1.0128	320	512	2.4981	22.5	1.6	22	2920
	3	1.0032	320	524	2.4744	35	1.64	31	4900
	4	1.00636	354	519	2.48	33	1.47	31	2817
$\phi 19mm$	All bars	1.00424	331	518.25	2.4764	27.375	1.57	25.5	3262.2
	%CoV	0.65	4.2	0.8	0.65	24.8	4	22.3	30

Energy expended to cause the frature, obtained by integrating the tensile test curve, as in Equation 4.3. Table 4.5 is similar data for Source-B bars.

$$U = \int_a^b P de \tag{4.3}$$

where P = the tensile load (N)

e = the extension (m)

U = work (Nm)

The coefficient of variation ranged from a low value of 0.15% for (Area/Nominal Area) ratio for Source-A No.5 bars to a high of 24.8% for % Elongation for Source-A No.6 bars. Scrutiny of Chemical composition and method of manufacture may offer clues as to the reasons for these variations.

It must be noted that a low coefficient of variation is not necessarily indicative of a

Table 4.5: Source B; Physical properties.

Sample	Bar No.	Area/Nom. Area -	$\sigma_y(R_e)$ MN/m^2	$\sigma_{uts}(R_m)$ MN/m^2	M kg/m	% Elong -	σ_u/σ_y -	A_5 -	E_b Joules
No. 4	1	1.027	500	600	0.911875	25	1.2	21.6	887
	2	1.0108	515	617	0.8975	25	1.2	23.3	893
	3	1.0167	480	631	0.90274	23.3	1.31	20	776
	4	1.0122	500	643	0.89875	21.6	1.29	20	812
	5	1.018	460	575	0.9028	21.6	1.25	22	779
$\phi 13mm$	6	1.01326	541	638	0.9	20	1.18	18	829
	All bars	1.01633	499.33	617.33	0.9023	22.75	1.24	20.81	829.33
	%CoV	0.529	5.1	3.84	0.52	8.2	3.9	8.2	5.6
No. 5	1	1.0768	490	554	1.7	20	1.13	18.75	1677
	2	1.0689	500	577	1.6874	20	1.15	18.75	1742
	3	1.0734	550	583	1.6945	21.2	1.06	18.75	1896
	4	1.0722	750	880	1.6905	21.5	1.17	17	2360
$\phi 16mm$	5	1.0716	692	778	1.69	16.3	1.12	15	1920
	All bars	1.072	596.4	674.4	1.6925	19.8	1.13	17.65	1919
	%CoV	0.24	17.7	19.4	2.065	9.4	3.3	8.4	12.4
No. 6	1	0.9841	570	728	2.4273	21	1.28	19	3837
	2	0.9860	570	752	2.4319	18	1.32	17	3301
	3	0.9872	470	654	2.435	25	1.39	25	3964
	4	0.9923	586	674	2.4475	19	1.15	18	3471
$\phi 19mm$	5	0.9831	600	720	2.42	20	1.2	18	3643
	All bars	.98654	559.2	706.5	2.43234	20.6	1.26	19.4	3643.2
	%CoV	0.3265	8.22	5.1	0.37	11.7	6.7	14.8	6.6

successful result. For example, column 4 of Table 4.4 gives low CoV, although the bars have failed in the tensile strength test. Essentially, the bars failed uniformly, consistently and invariably. On the contrary, column 4 for No. 5 bars in Table 4.5 posts a CoV of 17.7; here the bars have passed in the tensile strength property.

4.5.1 Area/Nominal Area

The variability in area along any bar is small, the CoV being of the order 0.15 to 0.65 per cent. These results are to be expected owing to the nature of the rolling process, since each heat is rolled at one setting of the rolls. Reducing the cross-sectional area might be informed by economic reasons since tolerance for area is upto 8%, while tolerance on mass per metre run is upto 4.5% [1].

4.5.2 Yield Stress σ_y

The CoV ranges from 4.2% for No.6 Source-A specimens to 17.7% for No.5 Source-B specimens tested. Since the different size bars are likely to have been derived from different heats, the values may be in order. However, the CoV of 17.7% along No.5 Source-B bar is high and inexplicable. We note that in structural design it is the static yield stress that gives the best definition of yield. As such, to correct for rate of loading, one may have to subtract 28MPa to arrive at the static yield stress [47, 52].

4.5.3 Ductility- % Elongation

The CoV for Source-A bars ranges from 2.8% for No. 5 bar to 24.8% for No. 6 bar. CoV for No.4 bar is 9.73. Source-A bars generally showed more elongation than Source-B bars, the 2.8% indicating much less scatter for bar No.5 while the 24.8% indicates much more variation along the No.6 bar.

For Source-B bars, the CoV was 8.2% for No.4 bar, 9.4% for No.5 bar and 11.7% for No.6 bar. While Source-B bars exhibited less ductility, the manufacturing procedure resulted in much less variation in comparison with Source-A bars. All bars met the 14% elongation requirement threshold.

4.5.4 Ratio R_m/R_e

The minimum value for the ratio of ultimate tensile strength to yield strength σ_{uts}/σ_y should be 1.05 for Grade 460A [1]. All Source A bars easily satisfied this condition. In column 8 of Table 4.5 for Source-B bars, No.5 bar is seen to barely meet this requirement.

4.5.5 Toughness - Energy E_b Joules

By integrating the tensile test curve, the work done in extending the bar specimen was estimated. Source-A had higher energy values for No.4 and No.5 bars while Source-B bars had the higher energy value for No.6 bar. Source-A bars had CoV of 1.76% for No.5 bar, 6.6% for No.4 bar and 30% for No.6 bar. Source-B bars had CoV of 5.6% for No.4 bar, 12.4% for No.5 bar and 6.6% for No.6 bar. Noting that impact tests are not always reliable, [14, 55, 56, 60–63], we can state that the method adopted gives an indication of the energies involved and not necessarily an accurate result. Charpy testing some non-standard specimens obtained several instances where there was no fracture: the specimen passed through with a high energy value. This is probably to be expected owing to the high ductility of the rebars.

4.6 Chemical Composition Analysis

Figure 4.41: Bars end filed flat ready for chemical analysis, Source A

All bars are within the weldable range, i.e. the C_{eq} is less than 0.51%. One must

Figure 4.42: Bars end filed flat ready for chemical analysis, Source B

Table 4.6: Analysed by EDX Spectrometer, (at PWD, Industrial Area, Nairobi).

Chemical composition									
Alloy %		Fe	Mn	Cr	C	Cu	Zn	Si	C_{eq}
S-A	ϕ12	99.272	0.728	-	0.21				0.331
	ϕ16	99.109	0.784	0.107	0.2019				0.353
	ϕ20	97.419	0.677	0.262	0.212	0.157	0.047	1.438	0.387
	ϕ25	99.023	0.869	0.108	0.212				0.378
CoV%		0.875	10.75	10.75	0.481	200	231	200	6.988
S-B	ϕ12	99.102	0.815	0.177	0.201	0.112			0.379
	ϕ16	99.004	0.821	0.175	0.197				0.368
	ϕ20	97.860	0.783	0.176	0.199	0.103	0.079	0.998	0.371
CoV%		0.7	2.53	0.56	1.005	86.83	173.2	173.2	1.525

notice the absence of, say, vanadium and nickel, elements well recognised for refining the grain and strengthening the steel. This might be motivated by economic considerations. The most common and convenient way to guarantee a fine grain size is to alloy the steel with certain elements that encourage rapid grain formation during solidification. These elements are called grain refiners, and the most common used are vanadium, columbium, and aluminum.

Examination of Table 4.6 shows that both manufacturers used basically the same alloying elements. The difference is in the amounts and the consistency. To this end, Source-A bars have a CoV of 10.75% for manganese and chromium; the CoV for Cu, Zn and Si is at least 200%. Source-B bars have manganese CoV of 2.53%, chromium CoV of 0.56%, copper CoV of 86.83%, zinc CoV of 173.2% and silicon CoV of 173.2%. This seems to suggest that the manufacturer of Source-B bar has better process control in terms of ingredients used and repeatability. Column 4, for chromium, gives the best contrast of under strength Source-A bars in comparison with Source-B bars. The silicon amount by both manufacturers exceed the maximum 0.5% allowed by ASTM A706 [12].

Carbon is the most important alloying element in steel because it is responsible for the broad range of microstructures, and resulting properties, that can be achieved with varying concentration. It increases the strength of hot-rolled steel but compromises ductility, impact toughness and weldability. Besides improving both the strength and hardenability of steel, manganese also acts as a mild deoxidizer and plays a vital role in preventing the formation of FeS inclusions [64].

Vanadium is the most widely used of the microalloying elements on account of its profound effect on mechanical properties even at low concentrations, metallurgical compatibility with less-sophisticated steelmaking practices, minimal effect on weldability, and reasonable cost (relative to other microalloy options). Vanadium's ability to impart a fine grain size to cast steel is the basis for several ASTM grades, such as A572. Hardenability is mildly improved by vanadium additions, but due to high cost relative to manganese or chromium, it is seldom selected for this benefit. Vanadium is added as ferro-vanadium. Typical composition is V-35% minimum, 0.75-1.00% C, 2-3.5% Si and 1-2% Al. Columbium (also known as niobium outside the U.S.) can provide many of the same benefits as vanadium in terms of grain refinement and strengthening, but comes at a significantly higher cost. However, columbium's potency grants the same improvement at roughly half the concentration as vanadium.

Nickel, like chromium, is a key component of a wide variety of high-performance steel alloys. Nickel is unmatched in its ability to provide fracture resistance (toughness) at extremely low service temperatures, and is commonly employed in arctic pipeline steels for this reason. It also provides a mild boost to hardenability, provides corrosion resistance against acid attack, and stabilizes austenite down to room temperature. This effect allows for the distinctive properties of 300-series stainless steel, which possess a rare combination of high strength, high-temperature stability, corrosion resistance [14].

Steel alloys utilizing chromium are extremely diverse in chemistry and application, including the popular chrome-moly alloy steel family, the entire range of stainless steels, many tool steel grades, and even exotic high-temperature-stable superalloys. Chromium provides improved hardenability, wear resistance, and corrosion resistance to steel alloys. High-chromium alloys are protected from corrosive environments by a thin, highly-adherent oxide layer that acts as a barrier betweenincreases hardness, strength, yield point and elasticity [65].

4.7 Hardness Test

Table 4.7: Hardness Test Results

Source A					Source B				
Sample	Bar No.	HRA	BHN	σ_{uts} MN/m^2	Sample	Bar No.	HRA	BHN	σ_{uts} MN/m^2
	1	48	141.2	487		1	51.5	161	555
No. 4	2	48	141.2	487		2	50.5	156	538
	3	43	120	414		3	51	159	549
	4	46	133.3	460	No. 4	4	49	147.5	509
	5	42	116.5	401		5	51	159	549
	6	45	128.3	442		6	55	184	635
$\phi 13mm$	7	43	120	414		7	58.5	212	731
	All bars	45	128.64	443.6		All bars	52.357	168.35	580.9
	%CoV	5.44	7.4	7.4		%CoV	5.8	12.22	12.22
	1	50	153	528		1	53	170	587
No. 5	2	45	128.3	443		2	52	163.5	564
	3	45.6	131	452	No. 5	3	54.5	180	621
	4	44	124	428		4	55.3	185	638
$\phi 16mm$	5	46	133.3	460		5	51.5	161	555
	All bars	46.12	133.92	462.2		All bars	53.26	171.9	593
	%CoV	4.45	7.5	7.5		%CoV	2.7	5.4	5.4
No. 6	1	48.5	144	497		1	52	163.5	564
	2	47	137.7	475	No. 6	2	55	184	635
	3	46	133.3320	460		3	52	163.5	564
$\phi 19mm$	4	46	133.3	460		4	54	176	607
	All bars	46.9	137.09	473		All bars	53.25	171.7	592.5
	%CoV	2.2	3.2	3.2		%CoV	2.4	5.08	5.09

The hardness was observed to be HRA 45-53 along the bar, converting to BHN 128.6 to 172. By use of equation 3.10, the σ_{uts} given in columns 5 and 10 of Table 4.7 was estimated. The mean value of σ_{uts} came out as 443.6 - 593 MPa, with CoV 3.2 - 7.5 along a bar. These results bear comparison with column 5 of Tables 4.4 and 4.5; the mean values of σ_{uts} there is 479 - 706 MPa. The wide disparity can be explained by means of chemical analysis, nature of the test and method of analysis.

Hardness tests results can be employed for materials evaluation and quality control of manufacturing processes e.g. rolling and heat treatment. The field engineer can also benefit from these results with respect to incidents where the bar is bent or otherwise strained.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

It is not possible, with the presently available technology, to manufacture several items that are perfectly similar. Inevitable variation arises owing to state of machine tool (sturdy or shaky), skill of the operator, perfect tools (compared to improperly profiled, worn out tools), use of coolant, rate of machining etc.

Where reinforcement steel bars are concerned, the mechanical properties are affected by quality of original iron-ore, the steel making procedure adopted, as well as the skills of the attendant manpower, the final chemical composition of the resulting steel, rolling procedure, heat treatment adopted and possible cold working (for cold twisted or bent bars). A coefficient of variation of below 10% is easily explained by the manufacturing process. Larger values of CoV need to be scrutinised. The high CoV values for Toughness and % elongation can possibly be explained by the chemical composition. From the results, it can be stated that:

1. Fatigue is not a main factor in the design of most structures but can become important in limit state design, and structures serving under conditions of wetness, corrosive and/or dynamic load (bridges).

2. The tensile test failure of bar samples invalidates such product which should "not be sold".

3. Uncategorised scrap could be the cause of weakness in reinforcing bars owing to tramp element content

4. Hardness test gave strength values that are not completely reliable

5. Microstructural examination and Grain size measurement can explain the material structure, but the Hall/ Petch relation handled carelessly can give dubious results

6. For the sampled bars, the alloying elements vanadium, molybdenum and nickel are completely absent

7. All bars met the minimum 14% elongation threshold. Taken with the good results in bending, it means the Kenyan bars can be field bent without fear.

8. Kenyan made bars are not weldable judged by ASTM A-706 on silicon content

9. Obtaining a truly random sample is impossible. Accidental sampling is the way to go. Other methods have a capital and time cost tag much out of proportion to the purported improvement in results

10. The Kenyan made bars are not up to mark for seimic grade rebar. However, to be fair, the local rebar manufacturers are not known to have made this claim.

11. The Kenya Bureau of Standards reported that 5% of rolling mills operating in the country are not certified. This could be the reason for failure of bars collected from hardware stores/distributors of reinforcing steel bars reported in this work.

5.2 Recommendations

Where the property has a CoV of under 10%, this can be taken as within limits and no corrective action is deemed necessary. This, for example, was the case with bending/rebend test for all specimens and tensile strength test for Source-B bars.

On the issue of Source-A bars that failed the tensile strength test, one can say that Kenya Bureau of Standards needs to revitalise its inspectorate arm to deal with this and other such cases.

Regarding fatigue test, it is noted that apart from Britain and Hongkong, the rest of the world consider fatigue test only for high-yield reinforcement bars. Suitability of rebars for seismic resistant structures is assessed by altogether different criteria: not fatigue test. Rebar loading in service conditions are at variance with the recommended axial fatigue test loading. In Kenya, we do not even have fatigue testing equipment that is calibrated and standard. Fatigue test is mainly done for high strength bars intended for special applications. Could KEBS (or Kenyan Professionals) legislate a construction standard in the manner of ACI-318 and NCHRP report Nos. 679 and 721?
On sampling, it will serve anybody well to go for accidental sampling; or may be sequential sampling where there may be some spare cash. To attempt to obtain a trully random sample is mission impossible.

With respect to under strength bars, the manufacturer should consider adding a little more chromium, copper, vanadium, molybdenum and nickel. Improvement of the production process control in terms of ingredient amounts and consistency can raise the quality of the bars.

Future research can be conducted on the following topics:

1. Fatigue and corrosion in under water structures, guided by ACI standards.
2. Efficient and economic methods of steel making and
3. Hazards of rebending of rebars partially embedded in concrete, ACI 318.
4. Effect of scrap tramp elements on reinforcing bars.
5. Effect of rebar rib geometry on bonding

REFERENCES

[1] BSI-BS 4449:2005, "Specification for Carbon steel bars for the reinforcement of concrete," *British Standards Institution*, 2005.

[2] Munyazikwiye, B. B., "Investigation on characterization and variability of mechanical properties of reinforcing steel bars made from scrap," *Mechanical Engineering M.Sc. Thesis, JKUAT*, 2010.

[3] BSI-BS 8110:2002, "Structural use of concrete - Part1; Part2; Part3," *British Standards Institution*, 2002.

[4] BSI-BS8666:2005, "Specification for scheduling, dimensioning, bending and cutting of steel reinforcement for concrete," *British Standards Institution*, 2005.

[5] Tony T, "Steel reinforcement," *Construction Press (London and New York)*, 1984.

[6] Nordtest Tekniikantie, "Nordtest method - steels for concrete reinforcement: Rebend testing of bars.," *Nord Test*, 1986.

[7] Indian Standards-IS:1786, "Indian Standard Specification for High Strength Deformed Steel Bars and Wires for Concrete Reinforcement," *Indian Standards*, 1992.

[8] AASHTO ASTM A 615/615M, " Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement," *ASTM*, 2003.

[9] KEBS KS-02-106, "Specification for bending dimensions and scheduling of bars for reinforcement of concrete," *Kenya Bureau of Standards*, 1983.

[10] Bob Hafner, "Energy Dispersive Spectroscopy on the SEM: A Primer," *Characterization Facility, University of Minnesota*, 2011.

[11] BSI-BS 5135:1984, "Specification for arc welding carbon and carbon-manganese steels," *British Standards Institution*, 1984.

[12] ASTM A 706, "Standard Specification for Low-Alloy Steel Deformed and Plain Bar for Concrete Reinforcement," *ASTM*, 2002.

[13] Web Page, "Welded Wire Fabric (Reinforcement)," *www.concrete-mesh.com/images/black-welded-concrete-deformed-mesh*, 2015.

[14] Higgins R.A., "Engineering Metallurgy-Part 1, Applied Physical Metallurgy," *Edward Arnold*, 1989.

[15] Dipl.-Ing. Wolfgang R. Schütze, "Hot Briquetting of Direct Reduced Iron, Technology and Status of Industrial Applications," *Maschinenfabrik KÖPPERN GmbH*, 2013.

[16] Wikipedia, "Direct Reduced Iron," *"https://en.wikipedia.org/w/index.php?title=Direct_reduce*

2015.

[17] Manning C.P. and Fruehan R.J., "Emerging technologies for iron and steel making," *The Minerals, Metals and Materials Society, JOM.*, 2001.

[18] Shanghai Metallurgy Equipment, "Hot Rolling Mill," *Shanghai Metallurgy Equipment*, 2011.

[19] Steel Worldwide Services LTD, "Long Product Hot Rolling Mills Services and Products," *www.steelws.com*, 2007.

[20] Allen Matthew, "An investigation of the Suitability of Using AISI 1117 Carbon Steel in a Quench and Self-Tempering Process to Satisfy ASTM A 706 Standard of Rebar," *University of Toronto*, 2011.

[21] Milbourn D. and Li Yu., "Metallurgical benefits of Vanadium Microalloying in Producing High Strength Seismic Grade Rebar," *Proceedings of International Seminar on Production and Application of High Strength Seismic Grade Rebar Containing Vanadium, Beijing, China*, 2010.

[22] Rajuri steel, "Sail, rajuri steel and evcon," *SAIL, Rajuri steel and Evcon, website*, 2011.

[23] Kumar S.R.S and Kumar A.R.S., "Design of steel structures," *Indian institute of Technology MADRAS.*, 2005.

[24] Panigrahi B.K., "Microstructures and properties of low-alloy fire resistant steel," *R and D Centre for Iron and Steel, Steel Authority of India Limited*, 2005.

[25] ASTM E 112, "Standard Test Methods for Determining Average Grain Size," *American Society for the Testing of Metals*, 2004.

[26] HONG KONG Govt.-CS2:1995, " Construction standard-Carbon steel bars for the reinforcement of concrete," *Hong Kong Government*, 1995.

[27] Babael K., and Hawkins N.M., "Field bending and straightening of reinforcing steel," *Concrete International*, vol. 1, pp. 67–72, January, 1992.

[28] White Cap Construction Supply., "How to bend rebar: Does bending bars in the field weaken them?," *customerservice@whitecap.com*, 2009.

[29] Restrepo J.I., Crisafulli F.J. and Park R., "How harmful is cold bending/straightening of reinforcing bars?," *Concrete International.*, vol. 4, pp. 45–48, April, 1999.

[30] Stecich J.P., Hanson J.M., "Bending and straightening grade 60 reinforcing bars," *Wiss, Janney, Elstner and Associates, Inc, Northbrook, Illinois, CRSI.*, 1982.

[31] Lalik J.R and Cusick R.L., "Cold straightening of partially embedded reinforcing bars," *Concrete International*, July 1979.

[32] William C. Black, "Field corrections to partially embedded reinforcing bars," *ACI Journal*, October 1973.

[33] Erasmus L.A., "Cold straightening of partially embedded reinforcing bars-a different view," *Concrete International*, June 1981.

[34] The Aberdeen Group, "Field bending of reinforcing bars partially embedded in concrete; what the code allows, and supplemental findings by researchers," *Publication: #C830244*, 1983.

[35] Anne Balogh, "Bending rebar on the job," *Publication: # C950684, The Aberdeen Group*, 1995.

[36] KEY TO METALS., "Material Basics, The Basics of Ferrous Metallurgy, Steelmaking processes," *Total Materia article, www.KEY to METALS htm.com*, 2010.

[37] Tilly G.P., "Fatigue of reinforcement bars in concrete, a review," *Fatigue of Engineering Materials and Structures,Pergamon Press.*, vol. 2, pp. 251–268, 1979.

[38] Fei J. and Darwin D., "Fatigue of high relative rib area reinforcing bars," *University of Kansas Centre for Research*, 1999.

[39] Nord Test, "Nord test method-steels for concrete reinforcement-axial load fatigue testing of bars," *Nord Test*, 1989.

[40] Helgason T., Hanson J.M., Somes N.F., Corley W.G., and Hognestad E.,, " Fatigue strength of high -yield reinforcing bars," *NCHRP Report No. 164, Transportation Research Board, Washington, DC.*, 1976.

[41] Ruhl J.A., Walker W.H., "Stress histories for highway bridges subjected totraffic loading," *Report UILU-ENG-75-2004. Dept. Civil Eng, University of Illinois,Urbana, Illinois.*, 1975.

[42] ASTM E 647, " Standard Test Method for Fatigue Crack Growth Rates," *ASTM*, 2000.

[43] Virmani Y.P., Wright W. and Nelson R.N., *Fatigue Testing for Thermex Reinforcing Bars*. AASHTO, 1991.

[44] PCI, "PCI Bridge Manual," *PCI*, vol. 16, pp. R1–R21, 2007.

[45] Murdock L.J. and Brook K.M., "Concrete materials and practice," *Edward Arnold.*, 1979.

[46] Haslehurst M., "Manufacturing technology," *Edward Arnold, 3rd Edition*, 1993.

[47] Bournonville M., Dahnke J. and Darwin D., "Statistical analysis of the mechanical properties and weight of reinforcing bars," *University of Kansas Report.*, 2004.

[48] Kreyszig E., "Advanced engineering mathematics," *John Wiley and Sons, Inc.,6th Edition*, 1988.

[49] Douglas C.M., "Introduction to statistical quality control," *John Wiley and Sons, 5th Edition*, 2005.

[50] Kothari C.R., "Research methodology," *New Age International Publishers, 2nd Edition*, 2004.

[51] Lapin L.L., "Probability and statistics for modern engineering," *Duxbury Press, An imprint of Wadsworth Publishing Company, 2nd Edition.*, 1990.

[52] Allen, D.E., "Statistical study of the mechanical properties of reinforcing bars," *Division of Building Research, National Research Council of Canada.*, 1972.

[53] ASTM E 105, " Standard Practice for Probability Sampling of Materials," *ASTM*, 1996.

[54] Nyamu D.M., Maranga S.M and Mutuli S.M, "Selecting a Sampling Plan for Reinforcement Bars," *Industrial Engineering Letters, www.iiste.org*, vol. 3-No.4, 2013.

[55] Pascoe K.J., "An introduction to the properties of engineering materials," *Van Nostrand Reinhold, 3rd Edition*, 1985.

[56] Dowling N.E., "Mechanical behaviour of materials-engineering methods for deformation, fracture and fatigue," *Prentice Hall, 3rd Edition*, 2007.

[57] ASTM E 18, "Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials," *ASTM*, 2003.

[58] ASTM E 140, " Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleloscope Hardness," *ASTM*, 2002.

[59] Hawkins N.M., Shah S.P., "American concrete institute considerations for fatigue.," *Fatigue codes and design concepts.*, 1982.

[60] Cottrell A., *An introduction to metallurgy.* Edward Arnold, 2nd Edition., 1985.

[61] ASTM A 673, " Standard Specification for Sampling Procedure for Impact Testing of Structural Steel," *ASTM*, 2004.

[62] Sidney, H. Avner, "Introduction to physical metallurgy," *Tata McGraw Hill, 2nd Edition*, 1997.

[63] Rollason E.C., *Metallurgy for Engineers.* Edward Arnold, 4th Edition., 1986.

[64] NUCOR STEEL CORPORATION, "Quality reference book, bar products," *Bar Mill Group, 2014 Edition*, 2014.

[65] Tupkary R.H., "Introduction to modern steel making," *Khanna Publishers Delhi, 2nd Edition*, 1980.

[66] Arcelormittal, "Reinforcing steel bars-hot rolled plain and deformed steel bars, mild and high strength grades," *Arcelormittal Brochure*, 2009.

APPENDIX A

TYPICAL MANUFACTURER'S CERTIFICATE

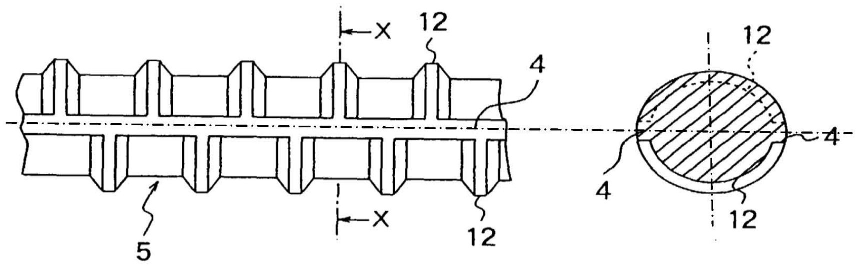
Table A.1: Typical manufacturer's certificate with specified mandrel diameter ranging from 2d to 7d:-Certificate by Arcelormittal. [66]

Specification	Yield Strength (min) [MPa]	Elongation (min) [%]	Mandrel diameter for 180^o bend test	Tensile Strength (min) [MPa]
SANS 920:2005 250 MPa	250-400	22 min	2d	>1.15x Actual yield strength
SANS 920:2005 450MPa	450 min	14 min	3d and re-bend 5d	
BS 4449:1997 250MPa	250 min	22 min	2d	>1.1xActual yield strength; $\frac{UTS}{Y_s} > 1.06$d
BS4449:1997 460B BS4449:2005 GrB500B (only available in 8-20mm)	460 min 500-650	12 min A_{gt}=5 min	3d and re-bend 5d rebend≤16→4d re-bend>16→ 7d	

APPENDIX B

PLATES ON REBARS

Figure B.1: Bent Bars at a section of Thika-Nairobi highway



5: steel bar for reinforcement

12: plurality of protrusions (knots, lugs)

4: two protrusions (longitudinal ribs)

(a) Ribbed bar: FRONT ELEVATION SECTION X-X

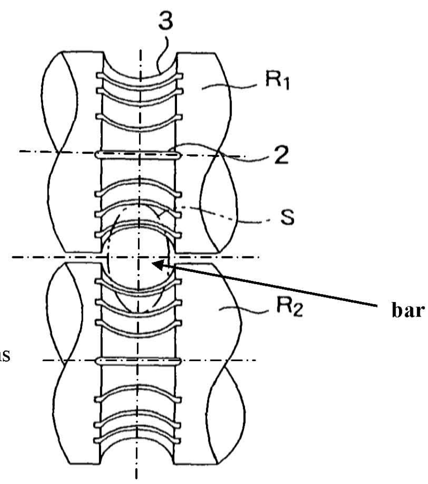
R_1: roll 1(top)

R_2: roll 2 (bottom)

S: speed of rolled bar

3: roll caliber (3 contacts 5)

2: round caliber (part that forms lugs-12)



(b) TYPICAL FINISHING ROLL PAIR FOR RIBS ON REINFORCEMENT BARS

Figure B.2: Ribbed Bar: Features and typical finishing roll pair. (Source: European Patent Application by Takeda, Ryo (et al), Mizushima Iron Works, of Kawasaki, Kurashiki-shi Okayama 712 (JP))

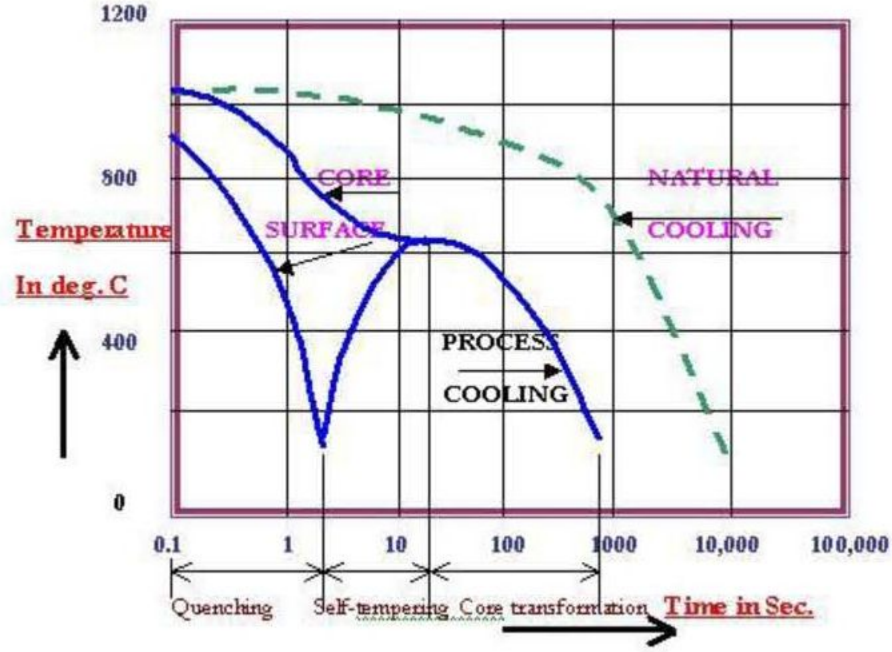


Figure B.3: Time-Temperature transformation curve for TMT bars, [22].

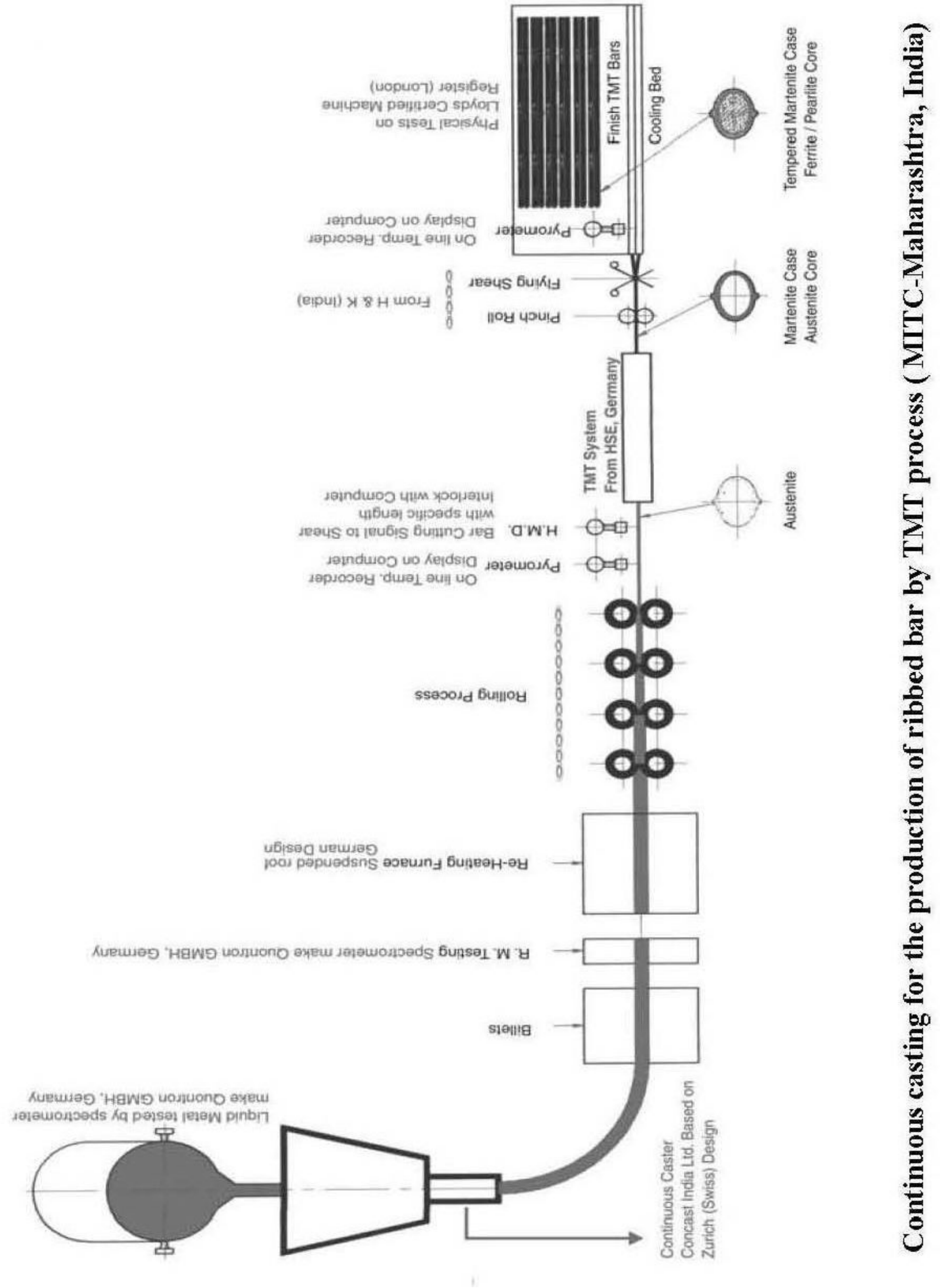
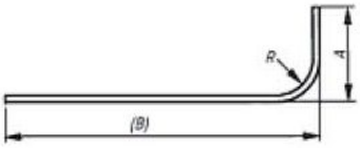


Figure B.4: Continuous casting (MITC-Maharashtra-India)

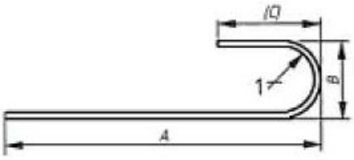
Shape Code 12



A+(B)- 0.43R - 1.2d

Neither A nor B shall be less than P in Table 2 nor less than (R + 6d)

Shape Code 13

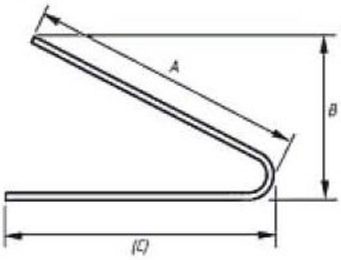


A + 0.57B+(C)- 1.6d

B shall not be less than 2(r + d). Neither A nor C shall be less than P in Table 2 nor less than (B/2 + 5d). See Note 3.

Key
1 Semi-circular

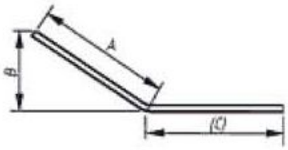
Shape Code 14



A + (C)- 4d

Neither A nor (C) shall be less than P in Table 2. See Note 1.

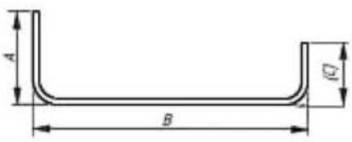
Shape Code 15



A+(C)

Neither A nor (C) shall be less than P in Table 2. See Note 1.

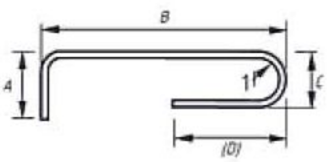
Shape Code 21



A + B + (C)- r - 2d

Neither A nor (C) shall be less than P in Table 2.

Shape Code 22



A +B +C +(D) -1.5r - 3d

C shall not be less than 2(r + d). Neither A nor (D) shall be less than P in Table 2. (D) shall not be less than C/2 + 5d.

Key
1 Semi-circular

Figure B.5: Sample of Shape codes in BS 8666:2005

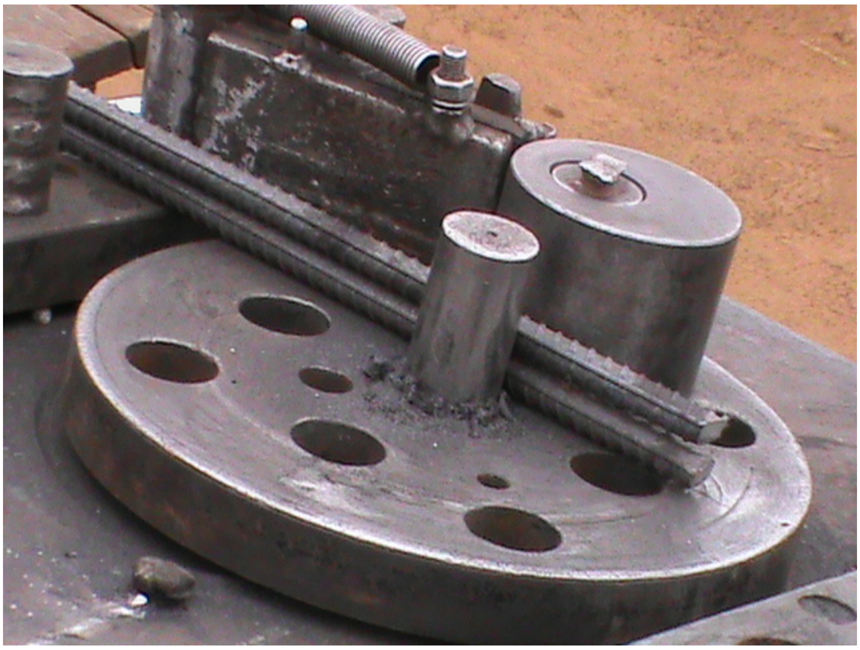


Figure B.6: Simple bending machine for reinforcement bars at Nairobi-Thika highway site: SHENG-LI Co, Mang'u Site.

Figure B.7: Bent stirrups for the Nairobi-Thika highway using the above bender,(SHENG-LI Co., Mang'u site)

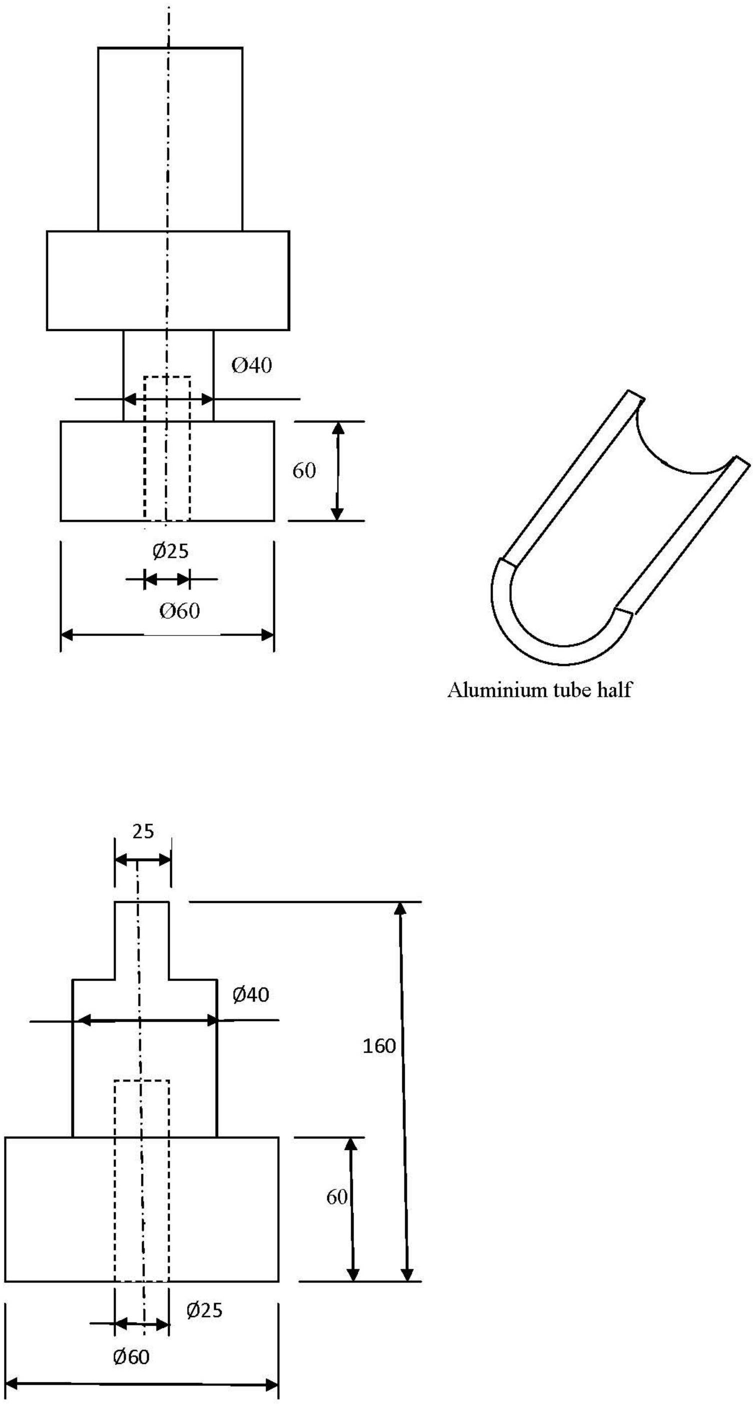


Figure B.8: Fatigue test gripper adaptor for the UoN axial load machine

APPENDIX C

Preparing for fatigue test at UON-REPORT 4-February-2013

C.1 Getting Ready For Fatigue Test

C.1.1 Work Done at UON on Fatigue Testing Equipment.

Bars normally must not be machined, but tested as received. The argument is that machining the ribs and lugs or otherwise takes away an important component of the reinforcement bar. For example, heat treatment may have obtained a hard surface different from the core.

The gripper elements shown in FigureC.1a were made of a 63 mm diameter shaft. The flats were made by the shaping machine and the pin hole drilled. The axial hole that takes the test bar was drilled on the lathe machine. The deformed test bar was assembled by application of a bond of epoxy-steel.

The diameter 63 mm shaft was drilled axially at one end, Figure C.1a. The other end was machined to produce a flat and given a bore normal to the bar axis. The attempt to bond the bar with grout failed: the set grout proved to be too brittle. Grout is a high quality, fine, water-resistant, polymer modified, cement based powder designed for grouting glazed tiles mosaics, vitrified and fully vitrified tiles, ceramic tiles, industrial tiles etc.

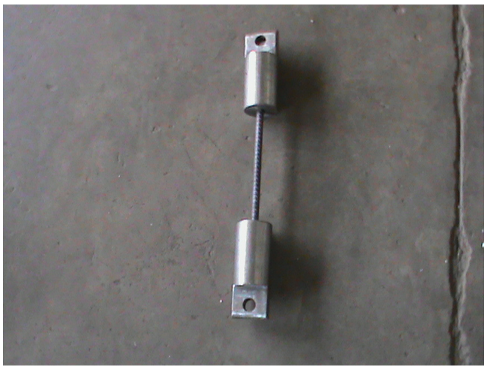
The alternative was epoxy steel. This contained epoxy and polyamine resins. This epoxy resin and atomized steel in putty form reputedly chemically welds, fills, seals and bonds most metals including brass, steel, copper and iron. The 4 minute KWIK-SET facility was a bonus in saving time.

The test is performed by exposing a test specimen either to an axial tensile or an axial compressive load to a prescribed mean value (σ_m) and then alternate between a maximum and a minimum peak value. The wave shape is normally sinusoidal. The axial load fatigue testing is used to determine the effect of component geometry, surface conditions, stress, etc., on the fatigue resistance of reinforcing and prestressing steel bars and wires subjected to cyclic stress for a relatively large number of cycles. The test would be carried out at ambient temperature. Bar specimens, of 300 mm approximate length, would be held on the brute force axial load fatigue testing machine.. The applied stress range is 150-200 MPa, with a stress ratio ($\sigma_{min}/\sigma_{max}$) of 0.2. To pass, the test sample should survive 5 million stress cycles.

Preliminary work done in peparing the specimen was in purchasing the bar and diameter 63 mm shaft, shaping the ends of the diameter 63 mm shaft to produce flats, and drilling axially and laterally, Figure C.1a.

A 300mm long specimen was cut. It was mounted on the grips as shown in Figure C.1b by means epoxy -steel. It was then that the 'discovery' was made that the con-rod was misaligned and that the machine made too much noise. A decision was reached that I needed to change the big end bearing on the con-rod. A replacement bearing was purchased from an auto spare parts dealer. Again, changing the bearing with the con-rod misaligned might not have solved the problem, so the bearing not only required changing, but the bearing housing needed to be cut off, and then welded back to the con-rod in a more aligned position. In view of this, the big end bearing housing was severed by the use of a hand grinder, Figure C.2. At this point it turned out that the machine, as it then stood, had its footage floating on pieces of wood, Figures C.3 and C.4a; completely unsecured. To remedy this it was decided that the footage, and especially on the region where the crank and piston applied, needed to be secured. To this end, it was required to obtain a rubber sheet (obtained second hand, from a

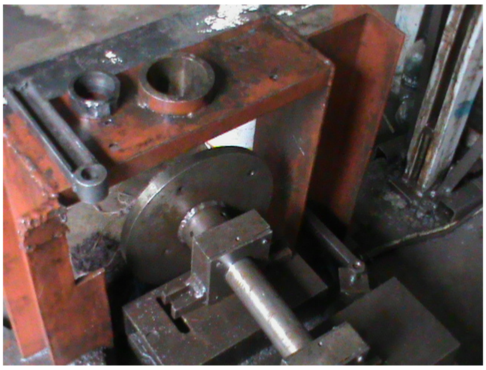
(a) The grip: notice axial hole for bar and lateral hole to interface with machine



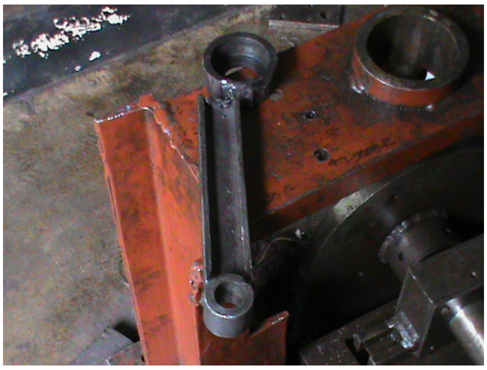
(b) Deformed bar mounted on grips and attached with epoxy steel

Figure C.1: The grip design

discarded conveyor belt), and steel plates and packing for leveling. Rag bolts were also purchased. The main task was to gingerly excavate the holes, on the concrete floor, that were to take the rag bolts. Then templates of the foot were cut off the rubber damper and holes punched appropriately by the application of the sharpened end of a pipe. The steel plate was gas-cut to size, and matching holes marked out and drilled on the radial arm drilling machine. Then the main frame was carried to the radial arm drilling machine and the foot holes enlarged to take the appropriate rag bolts. After this the machine footings could now be secured to the floor, Figures C.5 and C.6a. After this mounting, the piston and cylinder assembly became problematic - the piston, dropping from the main link arm to the cylinder, appeared misaligned. It tended to suggest that while mounting with rubber pads may have solved the issue of noise, it may well have aggravated the alignment problem, Figure C.6b.



(a)



(b)

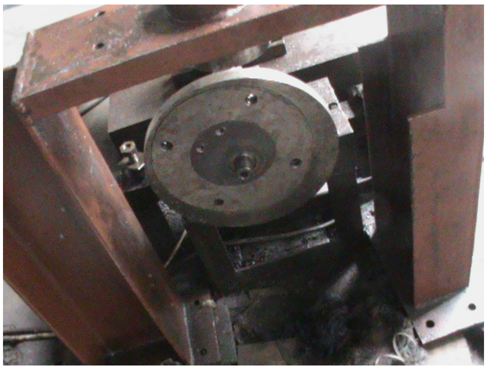
Figure C.2: Cylinder with piston rod removed; notice severed con-rod

(a)

(b)

Figure C.3: Machine footing floating on timber

(a) Machine footing floating on timber



(b) Eccentric facility for adjusting crank 'radius'

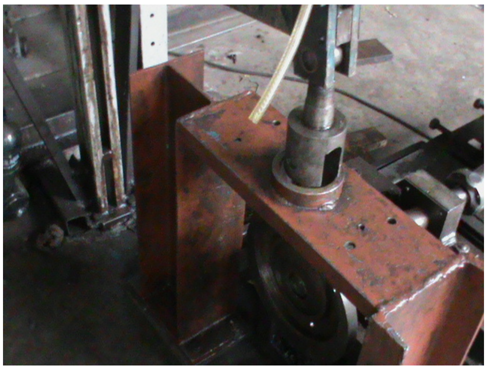
Figure C.4: Unsecured foot (left) and Eccentric crank 'radius' (right)

(a)

(b)

Figure C.5: Foot, on rubber pads, secured to floor by rag bolts

(a) Foot, on rubber pads, secured to floor by rag bolts



(b) Misaligned piston pivoted on link arm can't slide freely in cylinder

Figure C.6: Secured foot (left) and misaligned piston (right)

APPENDIX D

SAMPLE QUESTIONNAIRE

Questionnaire to statutory bodies

Variables		Respondents		
		KEBS	RBS	MRPW
1	Types of tests carried out			
i	Tensile test			
ii	Microstructure examination			
iii	Chemical analysis			
2	Does the company have a data bank of tests carried out? (Yes/No)			
i	Yes			
ii	No			
3	How often does the company carry out routine inspection?			
i	Monthly			
ii	Quarterly			
iii	Yearly			
iv	Randomly			
4	What minimum yield strength of the bar does the company specify?			
i	450 Nmm^{-2}			
ii	460 Nmm^{-2}			
iii	500 Nmm^{-2}			
iv	No specification			
5	What minimum % Elongation of the bar does the company specify?			
i	10			
ii	12			
iii	14			
iv	20			
6	What is the percentage rolling of certified mills in the country?	95%		
7	Who are the main importers of reinforcing steel bar in the country?			
i	Building contractors			
ii	Hardware stores			
iii	Main distributers			
iv	All the above			

Figure D.1: Sample questionnaire