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EFFECT OF CYCLIC LOADING ON THE MECHANICAL BEHAVIOUR OF STRUCTURAL STEELS AT VARIOUS TEMPERATURES

by

MUHSIN M. HAMDOON

A Dissertation
Submitted to the Faculty of Graduate Studies
Through the Department of Mechanical, Automotive and Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada
2012

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Effect of Cyclic Loading on the Mechanical Behaviour of Structural Steels at Various Temperatures

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DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION

I. Co-Authorship Declaration

I hereby declare that this dissertation incorporates the outcome of a joint research undertaken in collaboration with Dr Sreekanta Das, Dr Nader Zamani, and Daniel Grenier under the supervision of both Dr S. Das and Dr N. Zamani. The collaboration is covered in Chapters 3 and 4 of the dissertation. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of co-authors.

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ABSTRACT

It was found that the cyclic loading has a considerable effect on the mechanical behaviour of materials. This effect may lead to an early failure which results in human and economical losses. This study was developed to investigate changes in mechanical behaviour of structural steels. Two steels were considered and these are: G40.21 350WT which is used in ship hull structures and AISI 1022 HR which is used in general structural applications. The study was carried out in three parts: experimental, statistical, and numerical. The experimental tests were conducted using strain-controlled axial loading in room, zero, and sub-zero temperatures. In the statistical part, empirical formulae were derived to predict changes in mechanical properties as well as assessment of the experimental strain-life relationship. In the numerical part, a numerical model was developed to determine the strain-life relationship.

The experimental results exhibited an increase in tensile, yield, and fracture strengths. However, reduction in ductility and toughness was observed. The strain-life plots showed higher fatigue life for AISI 1022 HR steel in the high strain region if compared with G40.21 350WT steel. However, the fatigue strain limit was similar in both steels. The fatigue life of G40.21 350WT steel increased significantly at zero and sub-zero temperatures. The numerical model is able to accurately determine the strain-life plot.
DEDICATION

To the memory of my father and mother;

To my siblings, wife, and children (Abdulrahman, Luqman, and Issra);

To my friends who have always shown support and encouragement.
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This study was carried out under the supervision and guidance of Dr. Sreekanta Das and Dr. Nader Zamani to whom I am profoundly grateful for their kindness, endless constructive commentaries, valuable suggestions, and continuous support and encouragement throughout my study. They devoted their time and sincere efforts to provide all necessary research facilities for this work.

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CHAPTER 1: INTRODUCTION

The mechanical behaviour of fatigue-damaged material is expected to differ from that of damage-free material. This change in mechanical behaviour during service of engineering structures and components may lead to unforeseen premature failure. The change in materials behaviour in terms of tensile properties of metals and alloys was reported by a few earlier studies. However, there is no data for many materials which are widely used in the engineering applications. Furthermore, the trend of change (increase or decrease) in tensile properties is dependent on the material type, data of previous materials might not be useful in assessing the behaviour of other materials. The objectives of this study were set after completion of a detailed literature review. Accordingly, equipments, materials required, and other requirements were decided. Two steels were chosen in this study and these are: G40.21 350WT which is used in ship hull structures and AISI 1022 HR which is used in general structural applications.

1.1 SCOPE OF THE WORK

Any study should have reasonable causes to let researchers take decision to carry it out. The outcome should be in the stream of the public needs which is represented in this study by the industry of structural steels and the related applications. The following are the scope of work of this dissertation.

a) The importance of mechanical properties and their changes due to application of cyclic loads. These changes should be studied and recorded to aid the design process for reducing or avoiding the possibility of fatigue damages. This study intended to achieve this through experimental tests.

b) The scope of work also included derivation of empirical formulae for prediction of the changes in mechanical properties of fatigue-damaged structural steels. These formulae could be a tool to reduce the cost of experimentally investigating these changes.

c) The fatigue-life relationship is one of most important experimental information required for design against fatigue failure and for estimating fatigue life. This study targeted to obtain this information for both steels.
d) The strain-life theories were used by researchers to predict fatigue life numerically. These theories are dependent on parameters called the strain-life fatigue parameters. Several methods are available for the calculation of these parameters. The current study intended to assess the methods for calculating strain-life fatigue parameters and recommend usage of the most accurate method(s).

e) There is a little information available on fatigue behaviour of materials at low temperatures. This study decided to take a bold step to understand how zero and sub-zero temperatures influence mechanical properties and fatigue life of steels.

1.2 OBJECTIVES OF THE STUDY

The current study was carried out to investigate the influence of strain-controlled cyclic loading on the mechanical behaviour and fatigue life of structural steels in room and low temperatures. A large number of material tests were undertaken to examine these effects and to achieve the following objectives.

1) Study the mechanical behaviour of two steels under strain-controlled cyclic loading in room and low temperatures.
2) Compare the mechanical behaviour of the two fatigue-damaged steels and determine the effect of various parameters of cyclic loading.
3) Determine the experimental strain-life relationships for both steels.
4) Study the effect of temperature on fatigue life experimentally.
5) Derive empirical formulae for predicting the mechanical behaviour of both steels.
6) Study the appropriate method(s) for calculation the strain-life fatigue parameters that used in the numerical model of estimating fatigue life.
7) Analyse the strain-life relationships statistically to determine if the experimental data falls within desired confidence bands and also determine the validity of fatigue-life linear model.

1.3 PREVIOUS STUDIES

Literature review shows that very limited studies were carried out on metals and alloys to determine the mechanical behaviour of the fatigue-damaged materials. These
studies are conducted by: López et al. (2011) on Titanium alloy, Sánchez-Santana et al. (2008) on 6061-T6 aluminum alloy and AISI 4140T steel, Grenier et al. (2007) on AISI 1018 steel, Ghosh (2001) on En 17 steel, and Rudenko and Splvakov (1975) on 16GNMA steel. More details are provided in section 2.2.5. There are other studies conducted to show the low temperature effect on the monotonic and fatigue behaviour of materials. These studies are detailed in section 2.4.1.

**1.4 METHODOLOGY**

The current study was completed using experimental, statistical, and numerical analyses. The objectives of this study were achieved through the following procedure.

a) Manufacturing test specimens using AISI 1022 HR and G40.21 350WT steels according to ASTM standards E8, A370 and E606.

b) Grouping the specimens in compliance with the experimental design principles.

c) Performing quasi-static tensile tests in room and low temperatures to determine the mechanical properties of the *monotonic* (damage-free) steels.

d) Applying strain-controlled axial cyclic loading tests to a pre-determined cycle count, followed by the application of quasi-static tensile tests to determine the mechanical properties of *post-cyclic* (fatigue-damaged) steels.

e) Analysing the experimental results to determine the changes in mechanical properties of the *post-cyclic* steels.

f) Deriving empirical formulae to predict the mechanical behaviour of both steels using relevant parameters.

g) Conducting fatigue life tests to plot the experimental strain-life relationship of both steels.

h) Conducting fatigue life tests of G40.21 350WT steel at low temperatures to determine the effect of low temperatures on the fatigue life.

i) Analysing the strain-life relationship statistically to determine the validity of the linear model, examining the experimental data with confidence levels, and estimating the scatter factor.

j) Analysing the strain-life relationship numerically using different methods of calculation for the strain-life fatigue parameters and choosing the best method(s).
CHAPTER 2: LITERATURE REVIEW

In this chapter, a detailed review of the effect of cyclic loading on the materials behaviour was presented. First, crystallography including materials atomism, lattice structure, defects, deformations and response to external loads was discussed. This preview will assist in understanding the changes in materials properties. Then fatigue concept including crack initiation, propagation, and fracture mechanism was discussed. Subsequently, fatigue-life theories were presented focusing on strain-life theories. Finally, environmental effects including low and elevated temperatures effects on materials subjected to static and cyclic loads was discussed.

2.1 MATERIAL RESPONSE

For better understanding the effect of cyclic loading on mechanical properties of material, it is essential first to understand crystallographic changes due to applying load, statically and cyclically.

2.1.1 Crystallography

Crystallography is the experimental science of determining the arrangement of atoms in solids. It represents a tool that is often employed by materials scientists. When performing any process on a material, it may be desired to find out what compounds and what phases are present in the material. Crystallography is useful in phase identification. Each phase has a characteristic arrangement of atoms. Techniques such as X-ray diffraction can be used to identify which patterns are present in the material, and thus which compounds are present [Snigirev, 2007].

2.1.1.1 Atomism

An atom is the smallest unit quantity of an element that is capable of existence whether alone or in chemical combination with other atoms of the same or other elements.

The weight of atoms describes the density and specific heat of the material, while it has a very little influence on its engineering properties. The electrons in the outermost shell or sub-shell (which are called valence electrons) affect significantly the chemical properties,
electrical conductivity, some mechanical properties, the nature of interatomic bonding, atom size, and optical characteristics [DeGarmo et al., 2003].

The atoms vary in volume from element to another, for example in the periodic table the calculated radius of the Helium atom is 31 pm (picometres, where pm=10^{-12} m) and the one of Cesium atom is 298 pm, while Iron atom has a calculated radius of 156 pm.

**Atoms Arrangements in Materials:** Atoms usually bond to other atoms in some manner as a result of interatomic forces. As atoms bond together to form aggregates, it was found that the particular arrangement of atoms has a significant effect on the material properties. Depending on the manner of atomic grouping, materials are classified as having molecular structures, crystal (crystalline) structures, or amorphous (glassy or non-crystalline) structures.

Solid metals (such as steel) and most minerals have a crystalline structure. Here the atoms are arranged in a three-dimensional geometric array known as a lattice. Lattices are describable through a unit building block, or unit cell, that is essentially repeated throughout space [Black and Kosher, 2008].

If materials are compared according to their atomic structures, body-centered cubic (bcc) metals offer high engineering strength. Face-centered cubic (fcc) structure is the preferred structure for many engineering metals and tends to provide exceptionally high ductility (the ability to be plastically deformed without fracture). The metals having the hexagonal close-packed (hcp) structure tend to have poor ductility, fail in a brittle manner, and often require special processing procedures [Black and Kosher, 2008].

For more information regarding atomism see the following references: [Leigh, 1990, DeGarmo et al., 2003, Kamrani et al., 2006, and Snigirev, 2007].

### 2.1.1.2 Crystallite

A crystallite is a domain of solid-state matter that has the same structure as a single crystal. Metallurgists often refer to crystallites as "grains". Most materials are polycrystalline; they are made of a large number of single crystals-crystallites-held together by thin layers of amorphous solid. The crystallite size can vary from a few nanometers to several millimetres [David, 1998 and Allen et al., 1999].
The number and size of the grains in a metal vary with the rate of nucleation and the rate of growth. The greater the nucleation rate, the smaller the resulting grains. Because the resulting grain size will influence certain mechanical and physical properties (such as yield strength, refer to Hull-Petch relationship), that rate should be controlled properly. One means of specification is through the **ASTM grain size number**, defined as: \( N = 2^{n-1} \) where \( N \) is the number of grains per square inch visible in a prepared specimen at 100X magnification, and \( n \) is the ASTM grain-size number. Low ASTM numbers (\( n \)) mean a few massive grains, while high numbers refer to materials with many small grains [Black and Kosher, 2008].

### 2.1.2 Crystallographic Defects

Most crystalline materials are not perfect: the regular pattern of atomic arrangement is interrupted by crystallographic defects. These defects may be point, line, planar or bulk defects as explained below. Crystallographic defects play a significant role in mechanical properties changes (i.e. dislocations, or barriers for dislocations movement) as well as sites for fatigue crack initiation and micro crack barriers.

#### 2.1.2.1 Point Defects

are defects which are not extended in space in any direction. There is no strict limit for how small a "point" defect should be, but typically the term is used to describe defects which involve at most a few extra or missing atoms without an ordered structure of the defective positions. Larger defects in an ordered structure are usually considered dislocation loops. For historical reasons, many point defects especially in ionic crystals are called “centers”: for example the vacancy in many ionic solids is called an F-center. Types of point defects are mentioned below:

- **Vacancies** are sites which are usually occupied by an atom but which are unoccupied. If a neighbouring atom moves to occupy the vacant site, the vacancy moves in the opposite direction to the site which used to be occupied by the moving atom. The stability of the surrounding crystal structure guarantees that the neighbouring atoms will not simply collapse around the vacancy. In some materials, neighbouring atoms actually move away from a vacancy, because they
can form better bonds with atoms in the other directions. A vacancy (or pair of vacancies in an ionic solid) is sometimes called a Schottky defect.

- **Interstitials** are atoms which occupy a site in the crystal structure at which there is usually not an atom. They are generally high energy configurations. Small atoms in some crystals can occupy interstices without high energy, such as hydrogen in palladium.

- A nearby pair of a vacancy and an interstitial is often called a Frenkel defect or Frenkel pair. This is caused when an ion moves into an interstitial site and creates a vacancy.

![Figure (2.1) Schematic illustration of some simple point defect types in a monatomic solid](https://en.wikipedia.org/wiki/Point_defect) [permission released into the public domain by the author in 3-3-2007]

- **Impurities** occur because materials are never 100% pure. In case of an impurity, the atom is often incorporated at a regular atomic site in the crystal structure. This is neither a vacant site nor is the atom on an interstitial site and it is called a substitutional defect. The atom is not supposed to be anywhere in the crystal, and is thus an impurity.

- **Antisite defects** occur in an ordered alloy or compound. For example, some alloys have a regular structure in which every other atom is a different species; for
illustration assume that type A atoms sit on the corners of a cubic lattice, and type B atoms sit in the center of the cubes. If one cube has an A atom at its center, the atom is on a site usually occupied by an atom, but it is not the correct type. This is neither a vacancy nor an interstitial, nor an impurity [Mattila and Nieminen, 1995 and Hausmann et al., 1996].

2.1.2.2 Line Defects: Dislocations are linear defects around which some of the atoms of the crystal lattice are misaligned [Hirth and Lothe, 1992]. The presence of dislocations strongly influences many of the properties of materials. The theory was originally developed by Vito Volterra in 1905 [Reed-Hill, 1994]. There are two basic types of dislocations, edge dislocation and screw dislocation. However, third type called mixed dislocation may form as a combination of the first two types.

a) Edge dislocations are caused by the termination of a plane of atoms in the middle of a crystal, as shown in Figure (2.3). In such a case, the adjacent planes are not straight, but instead bend around the edge of the terminating plane so that the crystal structure is
perfectly ordered on either side. The analogy with a stack of paper is apt: if a half a piece of paper is inserted in a stack of paper, the defect in the stack is only noticeable at the edge of the half sheet.

![Figure (2.3) The edge dislocation. The dislocation line is presented in blue, the Burgers vector $b$ in black](wikityke at en.wikipedia) permission: CC-BY-SA-2.5; Released under the GNU Free Documentation License

**b) Screw dislocation** is a partial tearing of the crystal plane [Black and Kosher, 2008]. It is more difficult to visualise, but basically comprises a structure in which a helical path is traced around the linear defect (dislocation line) by the atomic planes of atoms in the crystal lattice (see Figure 2.4).

![Figure (2.4) Schematic diagram (lattice planes) showing a screw dislocation](Javier B. Vlčhez) permission released into the public domain by the author in 27-1-2007

The presence of dislocation results in lattice strain (distortion). The direction and magnitude of such distortion is expressed in terms of a Burger’s vector $b$. For an edge type, $b$ is perpendicular to the dislocation line, while in case of the screw type it is
parallel. In metallic materials, $b$ is aligned with close-packed crystallographic directions and its magnitude is equivalent to one inter-atomic spacing.

c) In many materials, dislocations are found where the line direction and Burger’s vector are neither perpendicular nor parallel and these dislocations are called mixed dislocations, consisting of both screw and edge character, as shown in Figure (2.5). The mixed dislocation is the most popular type in the metallic materials. The theory and mechanism of dislocation are explained in section 2.1.3.3. Dislocations can be observed experimentally using transmission electron microscopy (TEM), field ion microscopy and atom probe techniques.

![Figure (2.5) The mixed dislocation](www.courses.eas.ualberta.ca)

Figure (2.6a–c) show TEM images of 316L steel after cyclic loading with strain amplitudes of 0.25%, 0.75% and 1.0%, respectively. The larger strain amplitudes result in a more distinct dislocation cell structure. To discuss the effect of accumulated plastic strain, dislocation images after 10 cycles are shown in Figure (2.6d). In this figure, there is no distinct dislocation cell structure evident, and the accumulation of dislocations is much more significant than in Figure (2.6a). After the 10 cycles with strain amplitude 1.0% shown in Figure (2.6d) the accumulated plastic strain is 32.83%, smaller than the 48.84% of accumulated plastic strain after 100 cycles with strain amplitude 0.25% shown in Figure (2.6a). This allows the conclusion to be drawn that dislocation structures due to cyclic plasticity depend on both the accumulated plastic strain and the strain amplitude.
Looking at the appearance of variation in the observed grains, in Figure (2.6a) the dislocation structures of grains vary greatly among grains, while in Figure (2.6c) all grains have relatively uniform dislocation cell structures. These observations suggest that cyclic loading with larger strain amplitudes lead to a qualitatively more uniform dislocation cell structure, and similar results have been reported elsewhere [Mayama et al., 2008].

Mayama et al. study prove that cyclic loading leads to dislocation movement from grain interior to the boundaries (which plays a barrier to the dislocation transferring to adjacent grain); subsequently higher driving force will be required to perform a particular strain.

Figure (2.6) Dislocation structures after cyclic loading observed by TEM: (a) strain amplitude = 0.25% after 100 cycles; (b) strain amplitude = 0.75% after 100 cycles; (c) strain amplitude = 1.0% after 100 cycles; and (d) strain amplitude = 1.0% after 10 cycles [Mayama et al., 2008]
2.1.2.3 Planar Defects

- **Grain boundaries** occur where the crystallographic direction of the lattice abruptly changes. This usually occurs when two crystals begin growing separately and then meet.

- **Anti-phase boundaries** occur in ordered alloys: in this case, the crystallographic direction remains the same, but each side of the boundary has an opposite phase: For example if the ordering is usually ABABABAB, an anti phase boundary takes the form of ABABBABA.

- **Stacking faults** occur in a number of crystal structures, but the common example is in close-packed structures. Face-centered cubic (fcc) structures differ from hexagonal close packed (hcp) structures only in stacking order: both structures have close packed atomic planes with six fold symmetry, the atoms form equilateral triangles. When stacking one of these layers on top of another, the atoms are not directly on top of one another, the first two layers are identical for hcp and fcc, and labelled AB. If the third layer is placed so that its atoms are directly above those of the first layer, the stacking will be ABA-this is the hcp structure, and it continues ABABABAB (see Figure 2.7). However there is another location for the third layer, such that its atoms are not above the first layer. Instead, the fourth layer is placed so that its atoms are directly above the first layer. This produces the stacking ABCABCABC, and is actually a cubic arrangement of the atoms. A stacking fault is a one or two layer interruption in the stacking sequence, for example if the sequence ABCABABCAB were found in an fcc structure [Hirth and Lothe, 1992].

![Figure (2.7) hcp lattice (left) and fcc lattice (right)](Twisp) permission released into the public domain by the author in 2-5-2008
2.1.2.4 Bulk Defects

- **voids** are small regions where there are no atoms, and can be thought of as clusters of vacancies.

- **Impurities** can cluster together to form small regions of a different phase. These are often called *precipitates*.

**Porosity:** Pores are holes or cavities in the metal. A major cause is the decrease in volume, typically of the order of 10% when liquid transforms to solid. Holes are formed when pockets of liquid are isolated inside the solid, for example, in the interdendritic spaces. The size of pores, or shrinkage cavities, is proportional to that of the original liquid pocket. Small pores, less than about a micron in size, are generally harmless. Larger ones may subsequently be closed during hot working of the cast product.

2.1.3 Deformation:

2.1.3.1 Elastic Deformation:

An understanding of mechanical behaviour begins with understanding the way crystals react to mechanical loads. Most studies start with carefully prepared single crystals. Through these studies we learn that the mechanical behaviour is dependent on:

1. the type of lattice,
2. the interatomic forces (i.e., bond strength),
3. the spacing between adjacent planes of atoms,
4. the density of atoms on the various planes.

If the applied loads are relatively low, the crystals respond by simply stretching or compressing the distance between atoms as shown in Figure (2.8). The basic lattice unit does not change, and all of the atoms remain in their original positions relative to one another. The applied load serves only to alter the force balance of the atomic bonds, and the atoms assume new equilibrium positions with the applied load as an additional component of force. If the load is removed, the atoms return to their original positions and the crystal resumes its original size and shape. The mechanical response is *elastic* in nature, and the amount of stretch or compression is directly proportional to the applied load or stress.

Elongation or compression in the direction of loading results in an opposite change of dimensions at right angles to that direction. The ratio of lateral contraction to axial tensile
strain is known as *Poisson's ratio*. This value is always less than 0.5 and is usually about 0.3 for steels [Black and Kosher, 2008].

![Figure (2.8) Distortion of a crystal lattice in response to various elastic loadings](http://example.com/figure2.8)

**Figure (2.8) Distortion of a crystal lattice in response to various elastic loadings**

[Black and Kosher, 2008]

### 2.1.3.2 Plastic Deformation

As the magnitude of applied load becomes greater, distortion (or elastic strain) continues to increase, and a point is reached where the atoms either (1) break bonds to produce a fracture, or (2) slide over one another in a way that would reduce the load. For metallic materials, the second phenomenon generally requires lower loads and occurs preferentially. The atomic planes shear over one another to produce a net displacement or permanent shift of atom positions, known as *plastic deformation*. Conceptually, this is similar to the distortion of a deck of playing cards when one card slides over another. The actual mechanism, however, is really a progressive one rather than one in which all of the atoms in a plane shift simultaneously. More significantly, however, the result is a permanent change in shape that occurs without a concurrent deterioration in properties.

Recalling that a crystal structure is a regular and periodic arrangement of atoms, in space it becomes possible to link the atoms into flat planes in an almost infinite number of ways. Planes having different orientations with respect to the surfaces of the unit cell will have different atomic densities and different spacing between adjacent, parallel planes. Given the choice of all possibilities, plastic deformation tends to occur along planes
having the highest atomic density and greatest separation. The rationale for this can be seen in the simplified two-dimensional array of Figure 2.9. Planes A and A' have higher density and greater separation than planes B and B'. In visualizing relative motion, we see that the atoms of B and B' would interfere significantly with one another, whereas planes A and A' do not experience this difficulty.

Figure (2.9) Simple schematic illustrating the lower deformation resistance of planes with higher atomic densities and larger inter-planar spacing [Black and Kosher, 2008]

Although Figure 2.9 represents the planes of sliding as lines, crystal structures are actually three-dimensional. Within the preferred planes are also preferred directions. If sliding occurs in a direction that corresponds to one of the close-packed directions (shown as dark lines in Figure 2.10), atoms can simply follow one another rather than each having to negotiate its own path. Plastic deformation therefore, tends to occur by the preferential sliding of maximum-density planes (close-packed planes if present) in directions of closest packing. The specific combination of plane and direction is called a slip system, and the resulting shear deformation or sliding is known as slip.

Figure (2.10) Close-packed atomic plane showing three directions of atoms touching or close packing [Black and Kosher, 2008]
The ability to deform a given metal depends on the ease of shearing one atomic plane over an adjacent one and the orientation of the plane with respect to the applied load. Consider, for example, the deck of playing cards. The deck will not "deform" when laid flat on the table and pressed from the top or when stacked on edge and pressed uniformly. The cards will slide over one another, however, if the deck is skewed with respect to the applied load so as to induce a shear stress along the plane of sliding. With this understanding, consider the deformation properties of the three most common crystal structures: BCC, FCC, and HCP.

a) **Body-centered cubic**: In the bcc structure, there are no close-packed planes. Slip occurs on the most favorable alternatives, which are those planes with the greatest interplanar spacing (six of which are illustrated in Figure 2.11). Within these planes, slip occurs along the directions of closest packing, which are the cube diagonals. If each specific combination of plane and direction is considered as a separate slip system, we find that the bcc materials contain 48 attractive ways to slip (plastically deform). The probability that one or more of these systems will be oriented in a favorable manner is great, but the force required to produce deformation is extremely large since there are no close-packed planes. Materials with this structure generally possess high strength with moderate ductility (refer to the typical bcc metals in Figure 2.11).
Table 2.1: Crystal Structures and Their Properties

<table>
<thead>
<tr>
<th>Lattice Structure</th>
<th>Unit Cell Schematic</th>
<th>Ping-Pong Ball Model</th>
<th>Number of Nearest Neighbors</th>
<th>Packing Efficiency</th>
<th>Typical Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple cubic</td>
<td><img src="image" alt="Simple Cubic" /></td>
<td><img src="image" alt="Simple Cubic Model" /></td>
<td>6</td>
<td>52%</td>
<td>None</td>
</tr>
<tr>
<td>Body-centered cubic</td>
<td><img src="image" alt="Body-centered Cubic" /></td>
<td><img src="image" alt="Body-centered Cubic Model" /></td>
<td>8</td>
<td>68%</td>
<td>Fe, Cr, Mn, Cb, W, Ta, Ti, V, Na, K</td>
</tr>
<tr>
<td>Face-centered cubic</td>
<td><img src="image" alt="Face-centered Cubic" /></td>
<td><img src="image" alt="Face-centered Cubic Model" /></td>
<td>12</td>
<td>74%</td>
<td>Fe, Al, Cu, Ni, Ca, Au, Ag, Pb, Pt</td>
</tr>
<tr>
<td>Hexagonal close-packed</td>
<td><img src="image" alt="Hexagonal Close-packed" /></td>
<td><img src="image" alt="Hexagonal Close-packed Model" /></td>
<td>12</td>
<td>74%</td>
<td>Be, Cd, Mg, Zn, Zr</td>
</tr>
</tbody>
</table>

1 The diagonal of a cube is equal to \( \sqrt{3} \) times the length of the cube edge, and the cube edge is here equal to two atomic radii or one atomic diameter. Thus the diagonal is equal to 1.732 times the atom diameter and is made up of an atomic radius, open space, and another atomic radius. Since two radii equal one diameter, the open space must be equal in size to 0.732 times the atomic diameter.

**Figure (2.11) Comparison of the crystal structures: simple cubic, body-centre cubic, face-centre cubic and hexagonal close-packed** [Black and Kosher, 2008]

**b) Face-centered cubic:** In the fcc structure, each unit cell contains four close-packed planes, as illustrated in Figure (2.12). Each of those planes contains three close-packed directions, or face diagonals, giving 12 possible means of slip. Again, the probability that one or more of these will be favorably oriented is great, and this time, the force required to induce slip is quite low. Metals with the fcc structure are relatively weak and possess excellent ductility, as can be confirmed by a check of the metals listed in Figure (2.11).
c) **Hexagonal close-packed**: The hexagonal lattice also contains close-packed planes, but only one such plane exists within the lattice. Although this plane contains three close-packed directions and *the force required to produce slips again rather low*, the probability of favorable orientation to the applied load is small (especially if one considers a polycrystalline aggregate). As a result, metals with the hcp structure tend to have *low ductility* and are often classified as *brittle* [Black and Kosher, 2008].

**2.1.3.3 Dislocation Theory of Slippage**

The plastic deformation does not occur by all of the atoms in one plane slipping simultaneously over all the atoms of an adjacent plane. Instead, deformation is the result of the progressive slippage of a localized disruption (known as *dislocation*). These dislocations can be moved about with a rather low applied force. *The ease of plastic deformation therefore, depends on the ease of inducing dislocation movement in the*
certain engineering metal. Barriers to dislocation motion tend to increase the overall strength of a metal. These barriers take the form of other crystal imperfections and may be of point type, line, or surface type (see sec 2.1.2 crystallographic defects) [Black and Kosher, 2008].

One should note that the slip lines do not cross from one grain to another. The grain boundaries act as barriers to the dislocation motion. Therefore, metals with a finer grain structure more grains per unit area tend to exhibit greater strength and hardness, coupled with increased impact resistance. This near-universal enhancement of properties is an attractive motivation for grain size control during processing [Black and Kosher, 2008].

Dislocations can move if the atoms from one of the surrounding planes break their bonds and re-bond with the atoms at the terminating edge as shown in Figure (2.14) below. It is the presence of dislocations and their ability to readily move (and interact) under the influence of stresses induced by external loads that leads to the characteristic malleability of metallic materials.

---

**Figure (2.14) The movement of edge dislocation through the crystal** [www.ic.arizona.edu]
2.1.3.4 Stress-strain Curve: Ductile Materials

Steel generally exhibits a very linear stress–strain relationship up to a well defined yield point (Figure 2.15). The linear portion of the curve is the elastic region and the slope is the modulus of elasticity or Young's Modulus. After yield point, the curve typically decreases slightly because of dislocations escaping from Cottrell atmospheres (see the explanation of Cottrell atmospheres on the next page). As deformation continues, the stress increases on account of strain hardening until it reaches the ultimate strength. Until this point, the cross-sectional area decreases uniformly because of Poisson contractions. The actual rupture point is in the same vertical line as the visual rupture point.

However, beyond this point a neck forms where the local cross-sectional area decreases more quickly than the rest of the sample resulting in an increase in the true stress. On an engineering stress-strain curve this is seen as a decrease in the stress (curve A in Figure 2.15). Conversely, if the curve is plotted in terms of true stress and true strain the stress will continue to rise until failure (curve B in Figure 2.15). Eventually the neck becomes unstable and the specimen ruptures (fractures). In Figure (2.15) the numbers: 1. Ultimate strength, 2. Yield strength, 3. Rupture, 4. Strain hardening region, 5. Necking region, A: Engineering (apparent) stress, (F/A₀), B: True (actual) stress (F/A)

Less ductile materials such as aluminum and medium to high carbon steels do not have a well-defined yield point. For these materials the yield strength is typically determined by the "offset yield method", by which a line is drawn parallel to the linear elastic portion of the curve and intersecting the abscissa at some arbitrary value (most commonly 0.2%). The intersection of this line and the stress–strain curve is reported as the yield point.
Figure (2.15) A stress–strain curve typical of structural steel [David Richfield, 2009]

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*Cottrell atmospheres:

The concept of the Cottrell atmosphere was introduced by Cottrell and Bilby in 1949 to explain how dislocations are pinned in some metals by carbon or nitrogen interstitials. Cottrell atmospheres occur in body-centered cubic (bcc) materials, such as iron or nickel, with small impurity atoms, such as carbon or nitrogen. As these interstitial atoms distort the lattice slightly, there will be an associated residual stress field surrounding the interstitial. This stress field can be relaxed by the interstitial atom diffusing towards a dislocation, which contains a small gap at its core (as it is a more open structure), see Figure 2.16. Once the atom has diffused into the dislocation core the atom will stay. Typically only one interstitial atom is required per lattice plane of the dislocation.

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Once a dislocation has become pinned, a small extra force is required to unpin the dislocation prior the yielding, producing an observed upper yield point in a stress-strain curve. After unpinning, dislocations are free to move in the crystal, which results in a subsequent lower yield point, and the material will deform in a more plastic manner. Leaving the sample to age, by holding it at room temperature for a few hours, enables the carbon atoms to re-diffuse back to dislocation cores, resulting in a return of the upper yield point.

Cottrell atmospheres lead to formation of Luder’s Bands and large forces for deep drawing and forming large sheets, making them a hindrance to manufacture. Some steels are designed to remove the Cottrell atmosphere effect by removing all the interstitial atoms. Steels such as Interstitial Free Steel are decarburized and small quantities of titanium are added to remove nitrogen [Cottrell and Bilby, 1949].

2.1.3.5 Stress-strain Curve: Brittle Materials

Brittle materials such as concrete and carbon fiber do not have a yield point, and do not strain-harden. Therefore the ultimate strength and breaking strength are the same. A most unusual stress-strain curve is shown in Figure (2.17). Typical brittle materials like glass do not show any plastic deformation but fail while the deformation is elastic. One of the characteristics of a brittle failure is that the two broken parts can be reassembled to produce the same shape as the original component as there will not be a neck formation like in the case of ductile materials. A typical stress-strain curve for a brittle material will be linear. Testing of several identical specimen such as cast iron, or soil, the tensile
strength is negligible compared to the compressive strength and it is assumed zero for many engineering applications.

Figure (2.17) Stress-strain curve for brittle materials. Permission is granted to copy, distribute and/or modify this document under the terms of the GNU Free Documentation License

2.1.3.6 Cyclic Stress-strain Curves

The changes in mechanical properties of a material due to cycle-dependent responses are observed by producing a cyclic stress-strain curve. Cyclic stress-strain curves often refers to the stress-strain relationship obtained by the material once cycle-dependent stabilization has occurred, that is, once plastic shakedown has occurred [Bannantine et al., 1990]. There are various methods of determining the cyclic stress-strain curve, and there are small differences in the results from different methods. In reality, there exist multiple cyclic stress-strain curves at various levels of fatigue damage [Sandor, 1972]. However, the quasi-static tensile tests method was found to be the most efficient at determining the cyclic stress-strain curves at various levels of fatigue damage. From here on, cyclic stress-strain curves refer to the stress-strain relationship obtained at any arbitrary amount of fatigue damage within the material’s fatigue life, and not only once a cycle-dependent stabilization has occurred.

It is expected that the mechanical properties of structural steel change due to cyclic loads. Therefore, the mechanical properties of the material at various levels of fatigue damage need to be understood. Figure 2.18 provides examples of cyclic stress-strain curves that illustrate these possible changes. Line A represents the stress-strain curve of a virgin specimen obtained by a quasi-static tensile test. Line B represents a cyclic stress-strain
curve of a material with the same composition, size, shape, and initial conditions as that of the virgin specimen. Line B is above line A indicating that the material hardened from one cycle to the next and is more resistant to deformation. Therefore, a higher stress level than that of the virgin specimen is required to generate a given strain. On the other hand, line C represents a cyclic stress-strain curve of a material that softened from one cycle to the next and is more susceptible to deformation. Therefore, a lower stress level is required to generate a given strain.

![Stress-Strain Diagram](image)

**Figure (2.18) Cycle-dependent changes in stress-strain response** [Sandor, 1972]

The cyclic stress-strain expression of **Ramberg–Osgood** is usually used to fit the strain-life curve. The stress amplitudes, $\sigma_a$, and plastic strain amplitudes, $\varepsilon_{pa}$, from the stable stress-strain hysteresis loops (plastic shakedown) are being employed along with the corresponding cyclic fatigue life $N_f$ for each test [Dowling 2009].

For cyclic stress-strain curve

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{k}\right)^{1/\hat{n}}$$

(2.1)

For hysteresis loop

$$\Delta \varepsilon = \frac{\Delta \sigma_a}{E} + 2 \left(\frac{\Delta \sigma_a}{2k}\right)^{1/\hat{n}}$$

(2.2)

Where $\hat{k}$: cyclic strain hardening coefficient

$\hat{n}$: cyclic strain hardening exponent (varies from 0.05 to 0.3) [Meggialaro, 2004]

$$k = \frac{\sigma_f}{(\hat{\varepsilon}_f)^{b/c}} \quad \text{and} \quad \hat{n} = \frac{b}{c}$$

[Dowling, 2009]
\( \sigma_f \): fatigue strength coefficient (MPa);
\( \varepsilon_f \): fatigue ductility coefficient, which is the plastic strain amplitude at \( 2n_f = 1 \);
\( b \): fatigue strength exponent (Basquin’s exponent);
\( c \): fatigue ductility exponent (Coffin-Manson exponent);

2.1.4 Cycle-dependent Material Response

The term ‘cycle-dependent’ refers to the behaviour observed by the material from one cycle to the next. When subjected to cyclic loads, materials respond in different ways depending on the specific loading conditions. Cycle-dependent hardening and cycle-dependent softening are two extreme changing responses demonstrating that these responses are not always constant from one cycle to the next. The materials’ responses (such as stress range or strain range) due to both cycle-dependent hardening and softening depend on whether the conditions are stress-controlled or are strain-controlled.

2.1.4.1 Cyclic Stress-strain Response

For many years, and especially since the work of Coffin and Manson, it has been known and well accepted that fatigue failure has to be attributed to the repeated cyclic plastic straining. The stress amplitudes leading to fatigue failure are in most cases too small to cause "macro-yielding" but they are at least large enough to give rise to cyclic "microplastic" strains that are measurable and of the order of \( 10^{-5} \) to \( 10^{-4} \) at the fatigue limit. Consequently, fatigue fracture has to be considered as a result of repeated plastic straining, where the plastic-strain amplitude rather than the stress amplitude represents the decisive loading parameter. Thus, fundamental studies on the nature of fatigue damage must be based on well-designed cyclic deformation experiments in combination with a detailed evaluation of the microstructural changes that occur during cyclic deformation. The dislocations, their interaction among themselves and with second-phase particles, grain boundaries, and so on, and their behaviour in cyclic strain localization play an important role. Even localized events during fatigue, such as crack initiation and crack propagation, which lead to what is commonly referred to as fatigue damage, can be considered a consequence of bulk microstructural changes that normally occur relatively early in fatigue life [ASM HDBK vol. 19, 1996].
2.1.4.2 Stress-controlled Test

In a stress-controlled test, the stress limits remain constant from one cycle to the next while the strain is dependent on the applied stress. Cycle-dependent hardening occurs when the material is gradually increasing its resistance to deformation. Therefore, a decrease in the strain range occurs from cycle to cycle, indicating that the material has been work-hardened. Cycle-dependent softening occurs when the material’s resistance to deformation gradually decreases from one cycle to the next. Therefore, the strain range increases from cycle to cycle during the application of a constant stress range. Figure 2.20 shows the cycle-dependent material responses occurring under a stress-controlled environment. As one of the three common fatigue-life methods (stress-life method, the strain-life method, and the linear-elastic fracture mechanics method), the stress-life method, based on stress levels only, is the least accurate approach, especially for low-cycle applications [Shigley, 2006].

It can be seen from Figure (2.20) that the cycle-dependent responses occur in an exponential envelope with the bulk of the change occurring early in the cycle count. Thus, the material’s resistance to deformation becomes more consistent from cycle to cycle as time progresses. As mentioned early, this phenomenon is known as plastic shakedown. Plastic shakedown can be stated as a condition where there is no net accumulation of plastic deformation from one cycle to the next. At this point, it can be seen that the strain range remains constant from one cycle to the next.
2.1.4.3 Strain-controlled Test

In a strain-controlled test, the strain limits remain constant from cycle to cycle and the stress depends on the applied strain. As mentioned in the stress-controlled environment, a cycle-dependent hardening response refers to a gradually increasing resistance to deformation. Thus, in a strain-controlled environment, cycle-dependent hardening refers to a gradual increase in stress range required to accommodate for the constant strain range applied from cycle to cycle. Also, a gradual decrease in the stress range is a material response due to cycle-dependent softening. Figure (2.21) illustrates examples of cycle-dependent material response under a strain-controlled environment. The strain-life method involves more detailed analysis of the plastic deformation at

Figure (2.20) Stress-controlled cycle-dependent response [Sandor, 1972]
localized regions where the stresses and strains are considered for life estimates. This method is especially good for low-cycle fatigue applications [Shigley, 2006].

Figure (2.21) Strain controlled cycle-dependent response: (a) stress hardening, (b) stress softening, (c) mean stress relaxation [ASM HDBK v19, 1996].

Similar to Figure (2.20) the cycle-dependent responses in Figure (2.21) also proceed in an exponential manner where the bulk of the change occurs early in the cycle count. Therefore, the material’s resistance to deformation becomes more consistent as the stress range stabilizes and plastic shakedown occurs.
2.2 FATIGUE CONCEPT

Fatigue failure from the crystallographic point of view may consist of three stages: crack initiation, crack propagation or growth, and failure or rapture. Below are detailed explanations of these stages.

2.2.1 Crack Initiation

Because of operating cyclic stresses, a microcrack will nucleate within a grain of material. Crack initiation occurs from the material’s surface in most cases, so surface roughness plays a significant role in the crack initiation process. It is believed that the crystallography of a material has some influence on the mechanical behaviour during the crack initiation period. The crystallographic properties vary from one material to another, so the initial microcracking depends on the material type.

Fatigue crack initiation and crack growth are attributed to cyclic slip in slip bands. It implies cyclic plastic deformation as a result of moving dislocations. Fatigue occurs at stress amplitudes below the yield stress. At such a low stress level, plastic deformation is limited to a small number of grains of the material. This micro-plasticity can occur more easily in grains at the material surface because the surrounding material is present on one side only. The other side is the environment, usually a gaseous environment (e.g. air) or a liquid (e.g. sea water). As a consequence, plastic deformation in surface grains is less constrained than in subsurface grains; so it can occur at a lower stress level.

If slip occurs in a surface grain, a slip step will be created at the material surface, see Figure 2.22a. A slip step implies that a rim of new material is exposed to the environment. The fresh surface material will be immediately covered by an oxide layer in most environments, at least for most structural materials. Such very thin layers strongly adhere to the material surface and are not easily removed. Another significant aspect is that slip during the increase of the load also implies some strain hardening in the slip band. As a consequence, upon unloading (Figure 2.22b) a larger shear stress will be present on the same slip band, but now in the reversed direction. Reversed slip will thus preferably occur in the same slip band. However, two reasons have already been mentioned why cyclic slip cannot be fully reversible. First, the thin oxide layer cannot
simply be removed from the slip step. Secondly, strain hardening in the slip band is also not fully reversible. As a consequence, reversed slip, although occurring in the same slip band, will occur on adjacent parallel slip planes. This is schematically indicated in Figure (2.22b). The same sequence of events can occur in the second cycle, see Figure (2.22) c and d.

![Diagram of cyclic slip](image)

**Figure (2.22) Cyclic slip leads to crack nucleation** [Schijve, 2004]

Figure (2.22) offers a simplified picture, but there are some points to be observed:

(i) A single cycle is sufficient to create a microscopic intrusion into the material, which in fact is a microcrack.

(ii) The mechanism occurring in the first cycle can be repeated in the second cycle, and in subsequent cycles and cause crack extension in each cycle.

(iii) The first initiation of a microcrack may well be expected to occur along a slip band.

This has been confirmed by several microscopic investigations, see Figure (2.23). A slip band seen in Figure (2.23a) is actually a microcrack as confirmed in Figure (2.23b) after the band is opened by applying a 5% plastic strain to the material. A part of this slip band was already visible after no more than 0.5% of the fatigue life.
(iv) The small shift of the slip planes during loading and unloading is leading to an intrusion (Figure 2.22b). However, if the reversed slip would occur at the lower side of the slip band, an extrusion is obtained, see Figure (2.22e). From a potential strain energy point of view, the intrusion is the more probable consequence of cyclic slip in a slip band.

(v) The simple intrusion mechanism of Figure (2.22b), even if it would be different or more complicated, implies disruption of bonds between atoms, i.e. decohesion occurs, either by tensile decohesion, shear decohesion, or both. It occurs if a slip step penetrates through a free surface. It can also occur at the tip of a growing fatigue crack. The disruption of bonds at the crack tip might also be caused by generating dislocations from the crack tip. It should be expected that decohesion can be accelerated by an aggressive environment. The lower restraint on cyclic slip at the material surface has been mentioned as a favourable condition for crack initiation at the free surface. However, more arguments for crack initiation at the material surface are present. A very practical reason is the inhomogeneous stress distribution due to a notch effect of a hole or some other geometric discontinuity. Because of an inhomogeneous stress distribution, a peak stress occurs at the surface (stress concentration). Furthermore, surface roughness also promotes crack initiation at the material surface. Other surface conditions with a similar effect are corrosion pits and fretting fatigue damage both occurring at the material surface. Figure (2.24) illustrate most of these effects. In the crack initiation period of this
figure, the beneficial effects to the fatigue life are shown in **bold**, while the detrimental effects are shown in *italics* [Schijve, 2004].

*Effects on:*

**Crack initiation**
- Surface effects: 
  - Surface roughness (production)
  - Surface damage ...
    - scratches
    - dents
    - fretting
  - Surface treatments
    - anodizing
    - nitriding
    - shot peening
  - Soft layers ............
    - cladding
    - decarburizing
- Environmental effects: e.g. *pitting*

**Crack growth**
- Material bulk properties
- Environment

*Figure (2.24) Effects on crack initiation and crack growth period* [Schijve, 2004]

The most detrimental consequence of an unfavourable surface effect is the large reduction of the fatigue limit. This is especially important for structural components designed for an infinite life, i.e. with all amplitudes in service below the fatigue limit, $S_f$. Unintentional surface damage, such as nicks and dents, can then be very harmful. The same is true for damage due to fretting. The large reduction of fatigue limit indicates that there is a range of stress amplitudes between the original $S_f$ and the reduced $S_f$ which can be harmful if surface damage is present. Due to the relatively low stress amplitude, the crack growth life will be large. As a consequence, the inflection point of the S-N curve to the horizontal part (the so-called knee of the S-N curve) occurs at a higher fatigue life as for the original S-N curve, see the shift of the knee in Figure (2.25) [Schijve, 2004].
Figure (2.25) Surface effect on S-N curve, both Sa and N are plotted on logarithmic scale [Schijve, 2004]

If a design is made for a finite life, detrimental surface effects may be less important, specifically if the design life is short. Although surface damage can accelerate crack initiation, the high stress amplitude cycles can generate cracks early in the fatigue life. However, if the design life is large in numbers of cycles, the significance of adverse surface effects should be recognized. The high sensitivity to surface effects at low stress amplitudes and the relatively low sensitivity to surface effects at high stress amplitudes can lead to more scatter of the fatigue life at low amplitudes and less scatter at high amplitudes. This trend is generally observed in fatigue experiments. The most important conclusion to be drawn here is: in the crack initiation period fatigue is a material surface phenomenon [Schijve, 2004].

2.2.2 Crack Propagation

As long as the size of the microcrack is still in the order of magnitude of a single grain, the microcrack is obviously present in an elastically anisotropic material with a crystalline structure and a number of different slip systems. The microcrack contributes to an inhomogeneous stress distribution on a micro level, with a stress concentration at the tip of the microcrack. As a result, more than one slip system may be activated. Moreover, if the crack is growing into some adjacent grains, the constraint on slip
displacements will increase due to the presence of the neighbouring grains. Similarly, it will become increasingly difficult to accommodate the slip displacements by a single slip system only, i.e. on parallel crystallographic planes. It should occur on slip planes in different directions. The microcrack growth direction will then deviate from the initial slip band orientation. In general, there is a tendency to grow perpendicular to the loading direction, see the propagating crack in Figure (2.26).

A microcrack will grow to a size equivalent to that of a grain until a grain boundary barrier impedes its growth. If the grain barrier is very strong, the microcrack will be arrested and become a non-propagating crack. Otherwise, the microcrack will eventually propagate into a macrocrack. The size of the microcrack at the transition from the initiation period to the crack growth period will be significantly different for different types of materials. The transition depends on micro-structural barriers to be overcome by a growing microcrack, and these barriers are not the same in all materials [Schijve, 2004]. When the crack penetrates into the material depends on the bulk properties of the material, it is no longer a surface phenomenon. The minimum stress amplitude to overcome the crack growth barrier for further crack propagation is referred to as the fatigue limit [McGreevy and Socie, 1999; Murakami et al., 2002]. The fatigue limit is the cyclic stress level below which a fatigue failure does not occur. The fatigue limit might be negatively influenced by other factors such as periodic overloads, elevated temperatures, or corrosion. It is believed that the increase in crack driving force due to the periodic overloads will overcome the original grain barrier and help the crack propagate until failure [Lee et al., 2005]. Figure (2.26) show the three stages of fatigue failure.
Because microcrack growth depends on cyclic plasticity, barriers to slip can imply a threshold for crack growth. This has actually been observed. Illustrative results are presented in Figure 2.27. The crack growth rate measured as the crack length increment per cycle decreased when the crack tip approached the first grain boundary. After penetrating through the grain boundary the crack growth rate increased during growth into the next grain, but it decreased again when approaching the second grain boundary. After passing that grain boundary, the microcrack continued to grow with a steadily increasing rate [Schijve, 2004].

Figure (2.27) Grain boundary effect on crack growth in an Aluminum alloy. The crack length was measured along the material surface [Schijve, 2004]
In the literature, several observations are reported on initially inhomogeneous microcrack growth, which starts with a relatively high crack growth rate and then slows down or even stops due to material structural barriers. However, the picture becomes different if the crack front after some crack growth passes through a substantial number of grains, as schematically indicated in Figure (2.28). Because the crack front must remain a coherent crack front, the crack cannot grow in each grain in an arbitrary direction and at any growth rate independent of crack growth in the adjacent grains. This continuity prevents large gradients of the crack growth rate along the crack front. As soon as the number of grains along the crack front becomes sufficiently large, crack growth occurs as a more or less continuous process along the entire crack front. The crack front can be approximated by a continuous line, which could have a semi-elliptical shape. How fast the crack will grow depends on the crack growth resistance of the material. Two important surface aspects are no longer relevant. The lower restraint on cyclic slip at the surface is not applicable at the interior of the material. Secondly, surface roughness and other surface conditions do not affect crack growth. This leads to the second important conclusion: *When the crack penetrates into the material, depends on the bulk properties of material, it is no longer a surface phenomenon.*

![Figure (2.28) Top view of crack with crack front passing through many grains](Schijve, 2004)

In spite of early crack nucleation, microcracks remain invisible for a considerable part of the total fatigue life. Once cracks become visible, the remaining fatigue life of a laboratory specimen is usually a small percentage of the total life. The latter percentage may be much larger for real structures such as ships, aircraft, etc. Corrosive environments
can affect the initiation and propagation periods, but in a different way for the two periods [Schijve, 2004]. Figure (2.29) shows the different stages of fatigue life.

![Diagram showing the different stages of fatigue life](image)

**Figure (2.29) Different stages of fatigue life and relevant factors** [Schijve, 2004]

Figure (2.30) schematically shows the crack growth development as a function of percentage of fatigue life consumed, n/N, where n is the number of fatigue cycles and N is the fatigue life until failure. Complete failure corresponds to n/N = 1 = 100%. There are three curves, all of them in agreement with crack initiation in the beginning of fatigue life, however, with different values of the initial crack length. The lower curve corresponds to microcrack initiation at a “perfect” surface of the material. Here, the mechanism of Figure (2.22) could be applicable. The middle curve represents crack initiation from an inclusion, which is briefly discussed later. The upper curve is associated with a crack starting from a material defect which should not have been present, such as defects in a welded joint.

Figure (2.30) illustrates some interesting aspects:

(i) The vertical crack length scale is a logarithmic scale, ranging from 0.1 nanometer (nm) to 1 meter. Microcracks starting from a perfect free surface can have a sub-micron crack length (<1µm). However, cracks nucleated at an inclusion will start with a size similar to the size of the inclusion. The size can still be in the sub-millimeter range. Only cracks starting from macro-defects can have a detectable macrocrack length immediately.

(ii) The two lower crack growth curves illustrate that the major part of the fatigue life is spent with a crack size below 1 mm, i.e. with a practically invisible crack size.
(iii) Dotted lines in Figure (2.30) indicate the possibility that cracks do not always grow until failure. It implies that there must have been barriers in the material which stopped crack growth.

![Figure (2.30) Different scenarios of fatigue crack growth](image)

The elastic and plastic behaviour of a material depends on its crystal structure, but even for the same crystal lattice large differences can occur. The elastic anisotropy can vary considerably as illustrated by the Elastic moduli in Table (2.1).

**Table (2.1) Some data on elastic anisotropy**

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{\text{max}}$ (MPa)</th>
<th>$E_{\text{min}}$ (MPa)</th>
<th>Ratio (max/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrite, $\alpha$-Fe</td>
<td>284500</td>
<td>132400</td>
<td>2.15</td>
</tr>
<tr>
<td>Aluminum</td>
<td>75500</td>
<td>62800</td>
<td>1.2</td>
</tr>
<tr>
<td>Copper</td>
<td>190300</td>
<td>66700</td>
<td>2.85</td>
</tr>
</tbody>
</table>

The anisotropy is large for copper and fairly small for Aluminum, with ferrite, $\alpha$-Fe at an intermediate position. Fatigue generally occurs at low stress levels without macroplastic
deformation. As a result of the elastic anisotropy, the stress distribution from grain to grain is inhomogeneous as schematically indicated in Figure 2.31 where the homogeneous stress in each single grain is an approximation. The inhomogeneity of stress distribution from grain to grain is small for Aluminum and its alloys, but much larger for steel and copper.

![Figure (2.31) Inhomogeneous stress distribution from grain to grain due to elastic anisotropy](Schijve, 2004)

Most grains in Al-alloys are subjected to a similar stress level, whereas for steel and other more anisotropic materials the stress level varies significantly from grain to grain.

### 2.2.3 Fracture Behaviour

#### 2.2.3.1 Toughness

Toughness may be defined as: a measure of the amount of energy absorbed by a material as it fractures. Toughness is indicated by the total area under materials stress-strain curve [Callister 2001]. It may be defined also as the tendency of a material to fail in a more-or-less ductile or brittle manner. An indication is given by the reduction in area at failure in a tensile test, but it is usually measured under conditions where cleavage fracture is promoted by the presence of a machined notch or fatigue crack. The most common test is the Charpy V-notch impact test, in which the standard specimen is struck opposite the notch by a heavy falling pendulum, and it’s expressed here in terms of kinetic energy absorbed by the fracture (Joule). A more rigorous technique is fracture
toughness testing, in which a sharp crack is produced in fatigue or machining and then extended under monotonic loading until the appearance of an instability in the load-displacement curve [Madeleine, 2003]. Both impact and fracture toughness determines the fracture properties of a material. Fracture toughness is quantitative while impact toughness is qualitative and of little use for design purposes [Callister, 2001]. Fracture toughness depends on the material, strain rate, environment (i.e., temperature), thickness, and, to a lesser extent, crack length [Stephens et al. 2001]. The fracture toughness is generally inversely proportional to the yield strength and the higher its value, the larger the specimen required for a valid measurement [Madeleine, 2003]. Plane strain fracture toughness (for thick plate, $K_{IC}$) decreases with temperature drop, Sulfur content increasing or tensile strength increasing [ASM HDBK vol. 19, 1996]. An example of sulfur content effect on toughness is the tragedy of Titanic sinking. The chemical composition test of rivets kept by a successor of one of the ship construction workers, reveals that the sulfur content was relatively high, which lead to a low toughness of the ship hull when it was impacted by an iceberg at 2 °C [Madeleine, 2003].

Nisha and Fatemi have discussed experimental results on the effect of sulfur content and sulfide inclusions on fatigue behaviour of steels with different sulfur and hardness levels under different loading directions. Ductility and toughness of the transverse samples were found to reduce considerably by the increase in sulfur content, while the differences in the yield and ultimate tensile strengths were not significant. [Nisha and Fatemi, 2009].

The strength of mild steel can be improved by adding small amounts (not exceeding 0.1 %) of niobium, which permits the manufacture of semikilled steels with yield points up to 280 MPa (Low-carbon plate and sheet are made in three qualities: fully killed with silicon and aluminum, semikilled “or balanced”, and rimmed steel). Fully killed steels are used for pressure vessels. Most general-purpose structural mild steels are semikilled steels. Rimming steels have minimum amounts of deoxidation and are used mainly as thin sheet for consumer applications. By increasing the manganese content to about 1.5% the yield point can be increased up to 400 MPa. This provides better retention of strength at elevated temperatures and better toughness at low temperatures [Cheremisinoff, 1996].
2.2.4 Fatigue Damage with Mean Values

Fatigue cycles are characterised by the stress and strain limits of each cycle. In simple fatigue problems, as shown in Figures (2.20) and (2.21a and b) the mean stress and strain are always zero. However, rarely are fatigue problems that simple. Some mean stress or strain is usually present. Figure (2.32) provides an example of a hysteresis loop with no mean stress or strain and one where a mean stress and strain are present. It is important to understand that the material response can also cause these mean stresses or strains to change in a cycle-dependent fashion. Cyclic ratcheting, also known as cyclic creep, and mean-stress relaxation are the two main responses present when a material is subjected to fatigue conditions where a mean stress or strain is present.

![Hysteresis loops with and without mean stress and strain](image)

Figure (2.32) Hysteresis loops with and without mean stress and strain

2.2.4.1 Cyclic Ratcheting

Under stress-controlled conditions, an increase in the mean strain in tension or compression is called cyclic ratcheting. Figure (2.33) provides examples of hysteresis loops creeping in tension (a) and compression (b). This effect can be potentially dangerous as the strain is progressing towards the material’s fracture ductility. In the case
of Figure (2.33a), it can be seen that the strain limits are cyclically increasing in tension at a constant rate (point 5 has larger strain range than point 1). This effect occurs because the stress range in tension is more prominent due to a mean stress ($\sigma_m$) in tension, thus causing greater plastic deformation in tension. Comparatively, Figure (2.33b) shows a test with a mean stress in compression where the strain limits of the hysteresis loops are cyclically increasing in compression.

During the ratcheting process, the mean stress remains constant while the mean strain is cyclically increased or decreased depending on the initial loading conditions. However, the phenomenon of Figure (2.33) does not exist in the current study, as all cyclic tests were conducted in strain control mode.

Figure (2.33) Cyclic ratcheting-stress controlled (a) tension mean stress causes an increase in tensile strain, and (b) compression mean stress causes an increase in compressive strain [Sandor, 1972]
2.2.4.2 Mean-stress Relaxation

The effects of cyclic ratcheting can also be seen in tests under strain-controlled conditions. In these cases, the plastic deformation caused by strain cycles decreases the magnitude of the mean stress present early in the test. This behaviour is called mean-stress relaxation, which is the counterpart of cyclic ratcheting. During this process, the mean strain remains constant (since the strain is controlled) while the mean stress gradually reduces in magnitude in an exponential manner towards zero, as shown in Figure (2.21c). It is important to note that cyclic ratcheting and mean-stress relaxation do not contribute to cycle-dependent changes in energy absorption (area of a hysteresis loop) of the material. However, along with cycle-dependent hardening or softening, its plastic deformation can induce small nucleated fatigue cracks and ultimately lead to the rupture of the material.

2.2.5 Cycle-dependent Changes in Mechanical Properties-Previous Studies

An experimental study carried out by López et al. on Titanium alloy Ti-6Al-4V which is widely used in industry as a result of its combination of low weight, good mechanical properties, and high resistance to hostile service conditions. The results of this study showed that there is a slight difference in mechanical behaviour of this alloy after applying uniaxial cyclic load on sheet samples [López et al., 2011].

Sánchez-Santana et al. studied the influence of previous fatigue damage on the quasi-static and dynamic tensile behaviour of 6061-T6 aluminum alloy and AISI 4140T. From the quasi-static tension tests of aluminum, a small decrease in yield strength (around 5%) and ultimate tensile strength (around 6%) result when increasing the damage level (number of loading cycles). The damage rule proposed was the Palmgren-Miner model expressed mathematically as: \( D = \sum \left( \frac{n_i}{N_i} \right) \). The stability of quasi-static mechanical properties at different damage levels enhances the behaviour of this structural aluminum alloy. On the other hand, the steel exhibited a different response. In general, the yield and tensile strengths are significantly lower for fatigue-damaged specimens than those for damage-free specimens. The yield stress is not affected by damage level at high strain rates; however, at low strain rates the influence of damage on the yield stress is important, it decreases about 40% when increasing the damage level. There is a decrease
in percentage elongation and in percentage reduction in area when the damage level is increase. Previous fatigue damage has a detrimental effect on ductility of 4140T steel, principally under dynamic loading. The modulus of elasticity did not change [Sánchez-Santana et al., 2008].

The study by Grenier et al. on steel AISI 1018 steel specimens showed an increase in tensile and yield strengths and a reduction in ductility for post-cyclic specimens. The tests were undertaken under strain control axial load [Grenier et al., 2007].

Ghosh and Maity (2001) studied the effect of cyclic loading on the mechanical properties of En 17 steel which has been use in crankshaft manufacturing. This study shows that changes occur in tensile strength, yield strength, percentage elongation, and percentage reduction in area for the post-fatigue specimens. Furthermore, the effect of heat treatments such as normalising, and hardening and tempering was investigated. This study showed that the reductions in cross-sectional area and elongation in length at fracture occur in the post-fatigue tested specimens as compared to those in virgin specimens. The tensile strength either increased or decreased depending on the number of load cycles applied. The latter observation was the same for both heat treatments which were used. The yield strength also increased or decreased for the hardened and tempered specimens while it always decreased in normalised specimens [Ghosh, 2001].

Rudenko and Splvakov (1975) studied the effect of load cycles and level of stresses on mechanical properties of 16GNMA steel which is widely used in boiler construction. The fatigue tests were conducted for both as-received (Sy=450MPa) and heat treated (normalized at 925ºC and tempered at 660ºC, Sy=389MPa) steels to a certain number of cycles. The applied stress exceeded the yield strength by 10% and the frequency was 20 cycles/min (0.333Hz). Subsequently, the quasi-static tensile tests were carried out on the post-fatigued specimens until rupture. The results show an increase in tensile and yield strengths for the post-fatigued steel if compared with the monotonic tested steel for both as-received and heat treated specimens. For the as-received steel, the tensile strength increased by 7%, while the yield strength increased by 32%. For the heat treated steel the tensile and yield strengths increased by 5% and 20%, respectively. The ductility in terms
of percentage elongation reduced as a result of applying stress cycles. Up to 2000-3000 cycles, the percentage elongation for the as-received and the heat treated steels drops sharply and then stabilizes [Rudenko and Splvakov, 1975].

The forging studies show that the mechanical behaviour of fatigue-damaged steels depends on the steel type. Therefore, an individual study relevant to specific steel is recommended to predict its behaviour due to cyclic loading.

2.3 FATIGUE LIFE PREDICTION

2.3.1 Linear Damage Rule

In 1945, the first mathematical model representing fatigue damage was proposed by Miner [Miner, 1945]. He became the first to represent the Palmgren linear damage concept (Palmgren, 1924) in mathematical format which is also known today as the Linear Damage Rule (LDR) as shown in Equation 2.3.

\[
D = \sum r_i = \sum \frac{n_i}{N_{f_i}}
\]  

(2.3)

Where:

\[
\sum \frac{n_i}{N_{f_i}} = \sum_{i=0}^{n} \frac{n_i}{N_{f_i}} = \frac{n_1}{N_{f_1}} + \frac{n_2}{N_{f_2}} + ... + \frac{n_n}{N_{f_n}}
\]  

(2.4)

The damage index \(D\) is a measure of the accumulated damage. It is calculated from the summation of cycle ratios \(r_i\) and it is assumed that fatigue failure occurs when \(\sum r_i = 1\). The cycle ratio of \(n_i/N_{f_i}\) represents the number of counted reversals for a given load case \(i\) divided by the number reversals to failure for the same given load case. The summation \(\Sigma\) indicates that the damage index is calculated using the sum of all cycle ratios (1 to n) applied to the material in question (see Equation 2.4). This model proposes a linear representation of fatigue damage throughout the fatigue life of the material. In fact, due to the simplicity of the LDR, it is the most used model when designing for fatigue damage.

2.3.2 Nonlinear Damage Theories

It has since been shown that the fatigue damage may not necessarily occur in a linear fashion. Therefore, since the introduction of LDR, well over fifty mathematical
models were established to account for the various parameters that affect the rate of the fatigue damage. To remedy the deficiencies associated with the linear damage assumption, many nonlinear cumulative fatigue damage rules have been proposed. Fatemi and Yang have reviewed and classified most of these rules into several categories in a review paper [Fatemi and Yang, 1998]. These theories account for the nonlinear nature of fatigue damage accumulation by using nonlinear relations such as \( D = \sum (n_i/N_{f_i})^{\alpha_i} \), where the power \( \alpha_i \) depends on the load level, proposed by Marco and Starkey [Marco and Starkey, 1954] rather than the linear relation in Equation 2.4. Though many nonlinear damage models have been developed, unfortunately none can encompass many of the factors encountered during complex variable amplitude loading. However, no mathematical model currently has universal acceptance. Consequently, the Palmgren-Miner linear damage rule is still dominantly used in fatigue analysis or design in spite of its many shortcomings [Stephens et al., 2001].

2.3.3 Strain-life Theories

As mentioned earlier, the three known fatigue-life methods are: stress-life method, the strain-life method, and the linear-elastic fracture mechanics method. Because all fatigue tests in this study were conducted under strain control, the focus in this section is on strain-life theories. The fatigue life of a material is a function of various parameters such as: (i) stress or strain amplitude, (ii) material composition and properties (ranging from mechanical, to thermal, and even molecular), (iii) loading history, (iv) environmental factors, (v) structural composition, (vi) corrosion, and (vii) time. The experimental studies proved that fatigue tests with a tensile mean stress produced shorter lives than tests with the same amplitude at zero mean stress. The effect of different mean stresses on the stress-strain hysteresis loops is shown in Figure (2.34).
The Coffin-Manson expression (1954) can govern the relation between strain and life for loading cases with zero mean stress:

\[
\left( \frac{\Delta \varepsilon}{2} \right) = \left( \frac{\Delta \varepsilon_e}{2} \right) + \left( \frac{\Delta \varepsilon_p}{2} \right) = \frac{\sigma_f}{E} \left( 2N_f \right)^b + \dot{\varepsilon}_f \left( 2N_f \right)^c
\]

(2.5)

A number of methods for allowing the effects of mean stress have been proposed. The most important methods were suggested by Morrow, Walker and Smith-Watson-Topper.

**Morrow:**

\[
\varepsilon_a = \frac{\sigma_f}{E} \left( 2N_f \right)^b + \dot{\varepsilon}_f \left( 1 - \frac{\sigma_m}{\sigma_f} \right)^{c/b} \left( 2N_f \right)^c
\]

(2.6)

**Walker:**

\[
\varepsilon_a = \frac{\sigma_f}{E} \left( 2N_f \right)^b + \dot{\varepsilon}_f \left( 1 - \frac{\sigma_m}{\sigma_f} \right)^{c(1-\gamma)/b} \left( 2N_f \right)^c
\]

(2.7)

**SWT:**

\[
\varepsilon_a = \left( \frac{1-R}{2} \right)^{1/2} \left[ \frac{\sigma_f}{E} \left( 2N_f \right)^b + \dot{\varepsilon}_f \left( 2N_f \right)^c \right]
\]

(2.8)

**Or SWT:**

\[
\left( \frac{\Delta \varepsilon}{2} \right) \sigma_{max} = \left( \frac{\sigma_f}{E} \right)^2 \left( 2N_f \right)^{2b} + \dot{\sigma}_f \dot{\varepsilon}_f \left( 2N_f \right)^{b+c}
\]

(2.9)

Where: 

\( \Delta \varepsilon/2 \): total strain amplitude  

\( \Delta \varepsilon_e/2 \): elastic strain amplitude  

\( \Delta \varepsilon_p/2 \): plastic strain amplitude  

\( \sigma_f \): fatigue strength coefficient (MPa)  

\( \dot{\varepsilon}_f \): fatigue ductility coefficient  

\( b \): fatigue strength exponent (Basquin’s exponent)
c: fatigue ductility exponent (Coffin-Manson exponent)

$N_f$: number of load cycles (life)

$\gamma$: material constant (for steels: 0.4 for high $S_{ut}$, and 0.8 for low $S_{ut}$)

The latter equation (SWT) was selected by analysts more than other methods to govern the non-zero mean stress tests due to its simplicity and accurate results. Smith, Watson and Topper in 1970 suggested that fatigue life was a function not of strain amplitude alone but of the product of strain amplitude and the maximum stress in the cycle [fe-safe, 2002, and Dowling, 2009].

While certainly most accurate, experiment-based determination of required Coffin-Manson fatigue parameters ($\dot{\sigma}_f, \dot{\varepsilon}_f, b$ and $c$) quickly becomes prohibitive due to the complexity and high costs of cyclic experiments, especially if many different materials are to be taken into consideration. Since monotonic tensile tests are simple and inexpensive, and their results usually readily available, one of the methods for estimation of strain based fatigue parameters from monotonic material properties is usually implemented in such circumstances. Figure (2.35) shows a typical strain-life curve.

![Figure (2.35) Total strain-life curve [Lee et al., 2005]](image-url)
2.3.3.1. Existing Methods for Estimation of Strain-life Fatigue Parameters

In the **Universal slopes method**, Manson proposed $\sigma_f$ to be estimated from the ultimate strength $S_u$, and $\varepsilon_f$ from true fracture ductility $\varepsilon_t$, while for the exponents $b$ and $c$, constant values of -0.12 and -0.6 were assumed, respectively.

Same author in his **Four-point correlation method** proposed more intricate expressions, which are based on estimates of elastic $\Delta\varepsilon_e/2$ and plastic $\Delta\varepsilon_p/2$ strain amplitudes at four different numbers of loading cycles ($N = 1/4, 10, 10^4, 10^5$).

According to **Mitchell’s method** developed for steels, both $\sigma_f$ and $b$ can be estimated from $S_u$, whereas $\varepsilon_f$ represents the basis for the calculation of $\varepsilon_t$. Exponent $c$ is to be assigned a constant value: -0.6 for ductile and -0.5 for ‘strong’ materials.

**Muralidharan and Manson** proposed somewhat modified **universal slopes method**, in which $\sigma_f$ is estimated from newly introduced parameter $S_u/E$, while $\varepsilon_f$ from $S_u/E$ and $\varepsilon_t$, however, constant values of $b$ and $c$ were changed to -0.09 and -0.56, respectively.

**Bäumel and Seeger** were the first to consider steels separately from aluminum and titanium alloys. Coefficient $\sigma_f$ was related to the ultimate strength $S_u$ in both cases. Value of $\varepsilon_f$ was made dependent on the parameter $S_u/E$ for steels, while for Al and Ti alloys it was assigned a constant value of 0.35. Exponents $b$ and $c$ were given different constant values for each group of alloys.

In his **Modified four-point correlation method**, Ong made some modifications to the original method and proposed very similar expressions for the calculation of fatigue parameters.

**Roessle and Fatemi** proposed both coefficients $\sigma_f$, and $\varepsilon_f$ to be functions of Brinell hardness $H_B$ alone, and $H_B$ and $E$, respectively. The exponents $b$ and $c$ were assigned same values as in Modified universal slopes method (-0.09 and -0.56).

In their **Medians method**, Meggiolaro and Castro also approached the problem selectively, thus proposing different (although in case of $\varepsilon_f$, $b$, and $c$ constant) values for fatigue parameters of steel and aluminum alloys.

For all methods mentioned above, the main parameters on which estimations of individual fatigue parameters are based, and constant values assigned to the fatigue parameters, are summarized in Table (2.2) [Basan et al., 2010].
<table>
<thead>
<tr>
<th>Estimation method</th>
<th>$\dot{\sigma}_f$</th>
<th>$b$</th>
<th>$\dot{\varepsilon}_f$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morrow (1964)</td>
<td>---</td>
<td>$\frac{-\dot{n}}{1+5\dot{n}}$</td>
<td>---</td>
<td>$\frac{-1}{1+5\dot{n}}$</td>
</tr>
<tr>
<td>Manson’s Original universal slopes (1965)</td>
<td>1.9 ($Su$)</td>
<td>- 0.12</td>
<td>$0.76 \left[ \ln \left( \frac{1}{1-R_A} \right) \right]^{0.6}$</td>
<td>- 0.6</td>
</tr>
<tr>
<td>Manson’s Four-point correlation (1965)</td>
<td>1.25[$Su(1\epsilon_f)$]2b</td>
<td>$\log \left( \frac{0.36SU/\sigma_f}{5.6} \right)$</td>
<td>$\frac{0.125}{20^{c}} \left[ \ln \left( \frac{1}{1-R_A} \right) \right]^{3/4}$</td>
<td>$\frac{1}{3} \log \left[ 0.0066 - \frac{\dot{\sigma}_f (2 \times 10^{4})^b}{E} \right]$</td>
</tr>
<tr>
<td>Raske - Morrow (1969)</td>
<td>---</td>
<td>---</td>
<td>$0.002 (\frac{\dot{\sigma}_f}{S_A})^{1/6}$</td>
<td>---</td>
</tr>
<tr>
<td>Mitchell (1977) - Steels</td>
<td>$Su+ 345$ MPa</td>
<td>$\frac{1}{6} \log \frac{0.5 S_u}{S_u + 345}$</td>
<td>$\varepsilon_f$</td>
<td>- 0.6 (ductile) or - 0.5(strong)</td>
</tr>
<tr>
<td>Modified univ. slopes (1988)</td>
<td>0.623$E \left( \frac{S_u}{E} \right)^{0.832}$</td>
<td>- 0.09</td>
<td>$0.0196 \left( \frac{S_u}{E} \right)^{-0.53}$</td>
<td>- 0.56</td>
</tr>
<tr>
<td>Bäumel – Seeger steels (1990)</td>
<td>1.5($Su$)</td>
<td>- 0.087</td>
<td>$0.59$ if $Su/E \leq 0.003$or $0.812$ if $Su/E &gt; 0.003$</td>
<td>- 0.58</td>
</tr>
<tr>
<td>Bäumel - Seeger Al and Ti (1990)</td>
<td>1.67($Su$)</td>
<td>- 0.095</td>
<td>0.35</td>
<td>- 0.69</td>
</tr>
<tr>
<td>Ong (1993)</td>
<td>$Su (1 + \varepsilon_f)$</td>
<td>$\frac{1}{6} \log \frac{(S_u/E)^{0.81}}{6.25 \sigma_f/E}$</td>
<td>$\varepsilon_f$</td>
<td>$\frac{1}{4} \log \frac{0.0074 - \frac{\dot{\sigma}_f (10^{4})^b}{E}}{2.074 \varepsilon_f}$</td>
</tr>
<tr>
<td>Roessle–Fatemi steels (2000)</td>
<td>4.25HB +225MPa</td>
<td>- 0.09</td>
<td>$[0.32$ HB$^2 - 487$ HB$+ 191,000]$ MPa] / E</td>
<td>- 0.56</td>
</tr>
<tr>
<td>Medians steels (2002)</td>
<td>1.5 ($Su$)</td>
<td>- 0.09</td>
<td>0.45</td>
<td>- 0.59</td>
</tr>
<tr>
<td>Medians Al alloys (2002)</td>
<td>1.9 ($Su$)</td>
<td>- 0.11</td>
<td>0.28</td>
<td>- 0.66</td>
</tr>
</tbody>
</table>
2.4 ENVIRONMENTAL EFFECTS

2.4.1 Low-temperature Effects

Low temperatures can change the material fatigue behaviour for two reasons. First, the mechanical response of the material is different; in general, the yield strength and tensile strength are higher than those at room temperature. This trend is associated with an increasing resistance against plastic deformation (lower mobility of dislocations). Second, environmental effects on fatigue are reduced at a low temperature because reaction rates of chemical processes and diffusion are lower [Schijve, 2004].

Many fatigue designs in diverse fields of engineering must operate at temperatures below room temperature. These operating temperatures may be climatic temperatures as low as -54°C (-65°F) for ground vehicles, civil structures, pipelines, and aircraft or cryogenic temperatures of -163°C (110K) for natural gas storage and transport, -196°C (77K) for liquid nitrogen storage and transport, -253°C (20K) for aerospace structures, and -269°C (4K) for superconducting electrical machinery. Fatigue behaviour at these low temperatures has received much less attention than that at room and elevated temperatures.

Most reports of low-temperature fatigue behaviour have been based on constant amplitude tests, and little verification of real-life fatigue results and predictions have been published for low temperatures. Low temperature fatigue behaviour will be considered first by reviewing the effect of low temperatures on monotonic material properties and then by considering $S-N$, $\varepsilon-N$, $da/dN-\Delta K$, variable amplitude loading, and life predictions [Stephens et al., 2001].

2.4.1.1 Monotonic Behaviour at Low Temperatures

In general, un-notched ultimate tensile strength and yield strength increase at lower temperatures for metals, with the ratio of the ultimate strength to the yield strength tending toward a value of 1 at lower temperatures. Ductility, as measured by the percent elongation or reduction in area at fracture, usually decreases with lower temperatures, while the modulus of elasticity usually increases slightly. Total strain energy or
toughness at fracture usually decreases at lower temperatures, as measured by the area under the stress-strain curve.

Under notched conditions, toughness and ductility can decrease even further. This is true for both low and high strain rates. Impact energy absorbed, as measured from the Charpy V-notch (CVN) impact test, the pre-cracked Charpy ($K_{td}$) test, or the dynamic tear (DT) test, shows substantial decreases. An upper and a lower shelf, characterized by a significant difference in energy absorbing capacity and ductility, and a transition region usually exist for low and medium-strength steels. Both plane stress fracture toughness ($K_C$), and plane strain fracture toughness ($K_{IC}$), often decrease with lower temperatures. The nil-ductility temperature (NDT), as measured from the drop weight test using a brittle weld bead with a machined notch has varied from above room temperature to almost absolute zero Kelvin for steels. Thus, it is well known that the impact energy-absorbing capabilities of notched or cracked components can be drastically reduced at lower temperatures, depending on their composition, microstructure, and alloy system. This implies that greater notch and crack sensitivity exists at lower temperatures. Final fatigue crack lengths at fracture can then be drastically reduced at lower temperature. The lower fracture toughness, lower ductility, and higher un-notched tensile strength do not, however, provide sufficient information indicating how cracks will nucleate and grow in components under real-life fatigue loadings at low temperatures [Stephens et al., 2001].

2.4.1.2 Stress-life (S-N) Behaviour

Comprehensive summaries of $S$-$N$ fatigue behaviour at low temperatures were provided by Teed (1950), Forrest (1962), and by Stephens et al. (1979). A tabular summary by Forrest for carbon steels, alloy steels, and cast steels is shown in Figure (2.36). Here the averages of long-life, fully reversed fatigue strengths at low temperature divided by the fully reversed fatigue strengths at room temperature are shown for un-notched and notched specimens. No effort was made to correlate strength levels or stress concentration factors. The goal was to provide a general trend for long-life fatigue strengths at low temperatures compared to room temperature. The number of materials is given at the bottom of each column in Figure (2.36). The average ratios for specimens ranged from essentially 1.0 to 2.5 with the higher ratios occurring at lower temperatures.
For the notched specimens, the average ratios ranged from essentially 1 to 1.5, again with the higher ratios at lower temperatures. From a design standpoint, the most important aspect of Figure (2.36) is the substantially smaller increases in fatigue strength in the notched specimens.

Spretnak et al. (1951) determined the complete $S$-$N$ behaviour of un-notched and notched specimens between $10^3$ and $10^7$ cycles at low temperatures for many materials. Their results and others can be summarized as follows: at short and long lives, low temperatures are usually beneficial for constant amplitude, un-notched fatigue [Stephens et al., 2001].

Figure 2.36 Average ratio of fully reversed ($R = -1$) long-life fatigue strengths at room and low temperatures for un-notched and notched steels [Forrest, 1962]
At short lives (but more than $10^3$ cycles) low temperatures do little or harm to constant amplitude, notched S-N fatigue behaviour. At long lives, notched fatigue strengths are usually slightly better than or similar to those at room temperature. However, repeated impact loadings, and thus high rates at low temperatures can show quite different behaviour from this cases.

2.4.1.3 Strain-life ($\varepsilon$-N) Behaviour

Very little $\varepsilon$-N fatigue data at low temperatures exist. Under strain-controlled testing at low temperatures, metals can cyclically strain harden and/or soften, and their fatigue behaviour generally fits the strain-life model of Equation (2.5) (Coffin-Manson, 1954). Nachtigall (1974) determined the $\varepsilon$-N behaviour of 10 different materials using un-notched, smooth axial specimens at room temperature 27°C (300 K) and at two cryogenic temperatures: -195°C (78 K) liquid nitrogen, and -269°C (4 K) liquid helium. Comparative strain-life curves for three of the materials at three different temperatures from Nachtigall's report are shown in Figure (2.37). In all 10 cases investigated by Nachtigall, at high cyclic fatigue lives, where the elastic strain range component is dominant, fatigue resistance increased at the cryogenic temperatures. Conversely, at low cyclic lives, where the plastic strain range component is dominant, fatigue resistance generally decreased with decreasing temperature. Only one nickel base alloy, Inconel 718, showed increased fatigue resistance over the entire life range at the cryogenic temperatures.
A substantial decrease in fatigue resistance at short lives occurred for the 18Ni maraging steel at -269°C (4 K). This was accompanied by a drastic reduction in ductility, as measured by the percent reduction in area. This great loss in ductility explains the substantial decrease in fatigue resistance at short lives, where the plastic strain range should be predominant. All 10 materials had an increase in ultimate tensile strength and a decrease in ductility at the cryogenic temperatures. Nachtigall used the Manson method of universal slopes to predict the strain-life fatigue behaviour of the 10 materials at cryogenic temperatures with a degree of accuracy similar to that obtained for room temperature results. He concluded that low-cycle fatigue behaviour of these materials at cryogenic temperatures can be predicted by using material tensile properties obtained at the same temperatures.
Stephens et al. (1985) reported $\varepsilon$-$N$ fatigue behaviour of five different cast steels using un-notched smooth axial specimens at room temperature and -45°C (-50°F). For all five cast steels, the -45°C (-50°F) fatigue resistance at longer lives was either similar to or slightly better than that at room temperature. However, at shorter lives, the -45°C (-50°F) fatigue resistance was either similar to or slightly lower than that at room temperature. Both monotonic and cyclic stress-strain curves at -45°C (-50°F) were higher than at room temperature for all five cast steels.

Polak and Klesnil (1976) obtained strain-life curves for mild steel at room temperature, -60°C (213 K) and -125°C (148 K). Their data were obtained between about 200 and $10^5$ cycles to failure. They found lower fatigue resistance at the lower temperatures for the shorter lives, which they attributed to very short fatigue cracks at fracture, along with brittle fracture.

Kikukawa et al. (1970) showed that the plastic strain range-life curves between about 5 and $10^3$ cycles tend to be lower at lower temperatures. They showed this detrimental effect at low temperatures for both low- and medium-strength steels.

A summary of low-temperature strain-life fatigue behaviour indicates that un-notched long-life fatigue resistance is unchanged or increased at lower temperatures, while short-life fatigue resistance may be decreased as a result of lower ductility and lower fracture toughness. At short lives, ductility is a controlling factor in strain-control behaviour, while at longer lives strength is a more important controlling factor [Stephens et al., 2001].

### 2.4.1.4 Fatigue Crack Growth (da/dn-$\Delta k$) Behaviour

In general, fatigue crack growth occurs more slowly at low temperatures if small to moderate $\Delta K$-values are applicable, whereas faster crack growth has been observed for larger $\Delta K$-values with $K_{max}$ close to $K_C$ or $K_{IC}$. The increased crack growth rate for large $\Delta K$-values can be understood because of the reduced ductility at lower temperatures.

Further details in regarding fatigue crack growth behaviour are available in the following references: [Schijve, 2004, Stephens et al., 2001, Yarema 1977, and Gerberich 1979]
2.4.1.5 Transition from Ductile Failures to Brittle Failures

In general, less plastic deformation occurs during static failures at low temperatures. The material ductility is reduced and this is manifest during fatigue crack growth under severe load cycles with high $K_{\text{max}}$. Fractographic observations have shown that ductile striations may disappear at low temperatures, while indications of crack extension by a cleavage mechanism have been found depending on the type of material. However, an exceptional transition from ductile to brittle failure is exhibited by low carbon steels (mild steel). This phenomenon is usually studied by impact tests on Charpy V-notch specimens.

The tests are carried out at different temperatures and the impact energy for breaking the specimen is measured. If the temperature is decreased, the impact energy suddenly drops to a substantially lower level within a fairly narrow temperature range, see Figure (2.38).

![Figure 2.38 The transition temperature revealed by impact tests on Charpy V-notch specimens of low carbon steel. A higher transition temperature for fatigue cracks [Schijve, 2004]](image)

The range is characterized by the transition temperature $T_{\text{trans}}$. For $T > T_{\text{trans}}$ the failure of the Charpy specimen is a ductile failure with much plastic deformation and without separating the specimen in two pieces, see Figure (2.39). However, for $T < T_{\text{trans}}$ a brittle failure occurs without apparent plastic deformation also shown in Figure (2.39).
Microscopic investigation have revealed that the failure for $T > T_{\text{trans}}$ occurs as a quasi-static type of failure by void formation and coalescence. For $T < T_{\text{trans}}$ a cleavage type of failure occurs. Although the Charpy test is useful to indicate whether a material is sensitive to cold-brittleness, it should be understood that the transition temperature is not a material constant. In general, $T_{\text{trans}}$ will move to a higher temperature if plastic deformation at the tip of the notch of the Charpy specimen is more restrained. A smaller plastic zone and a higher peak stress in this zone are then obtained. This will promote the brittle type of fracture.

Figure 2.39 Two Charpy V-notched specimens, thickness 10 mm. Brittle failure in the front specimen tested below the transition temperature, and ductile failure in the rear specimen tested above the transition temperature [Schijve, 2004]

Because of the restraint on plastic deformation, the transition temperature is also increased by a higher yield stress, which implies that the risk of brittle failures in structures of mild steel is larger if the hardness of the material is higher. The increased hardness can be due to higher carbon content or the heat treatment of the steel. A most dramatic example of brittle failures occurred during World War II and also afterwards, when welded Liberty ships in cold water broke in two parts by brittle failures in welded joints [Schijve, 2004].

Tobler and Reed (1977) showed that Fe-Ni alloys provided similar or better fatigue crack growth resistance as long as the temperature remained in the "upper shelf" range, which was defined as the region where dimpled rupture or fibrous fractures occur during static
fracture toughness tests. Cleavage cracking led to drastic acceleration of fatigue crack
growth rates at temperatures below the transition region. Kawasaki et al. (1977) and
Stephens et al. (1985) however, found that the fatigue crack growth transition
temperature was substantially below the nil-ductility temperature, NDT, or Charpy V-
notch, CVN, temperature transitions. Stonesifer (1978) also indicated that CVN ductile-
brITTLE transition temperature mechanisms can be completely different from ductile-brittle
transition temperature fatigue crack growth mechanisms. When large decreases in
fracture toughness occur at low temperatures, crack nucleation and short crack growth
may constitute almost the entire low-temperature fatigue life [Stephens et al., 2001].
CHAPTER 3: MATERIALS AND TEST PROCEDURE*

In this chapter, a variety of issues are discussed. These issues include material selection, test specimen and test procedure.

3.1 MATERIALS SELECTION

Steels can be classified by several ways depending on (1) the compositions, such as carbon, low-alloy, alloy, or stainless steels; (2) the manufacturing methods, such as basic and acid open hearth, or electric furnace methods; (3) the finishing methods, such as hot rolling or cold rolling; (4) the product shape, such as bar, plate, strip, tubing, or structural shape; (5) the application, such as structural, spring, and high tensile steels; (6) the deoxidation practice, such as killed, semikilled, capped, and rimmed steels; (7) the microstructure, such as ferritic, pearlitic, and martensitic; (8) the required strength level, (9) heat treatment, such as annealing, quenching and tempering, and thermo-mechanical processing; and (10) quality descriptors/classifications, such as forging quality and commercial quality.

Critical structural components must be fabricated from steels that exhibit adequate low temperature fracture toughness because of the serious consequences of failure due to brittle fracture. The need for steels with higher fracture toughness and better weldability, as well as lower cost, has prompted major advancements in structural steel technology. These advancements are highlighted by the development of controlled-rolled and accelerated-cooled steels [ASM Metals HDBK vol. 1, 2005].

As this study focused on ship hull steels, the steels recommended for ship hull construction by American Bureau of Shipping (ABS), American Society for Testing and Materials (ASTM), Canadian Standards Association (CSA), DET NORSKE VERITAS (DNV) a Norwegian ship classifier, and International Association of Classification Societies (IACS) were considered.

3.1.1 Offshore Applications

The essential characteristics of steels for these applications include the following.

- Yield strength in the region of 350 to 415 MPa (50 to 60 ksi)
- Good weldability

*This chapter is an outcome of joint research*
• High resistance to lamellar tearing
• Tend composition to minimize preheating requirements
• High toughness in the weld heat-affected zone
• Good fracture toughness at the designated operating temperatures

Some of these goals have been realized through a reduction in impurities such as sulfur, nitrogen, and phosphorus in the steelmaking process for conventional steels. A major challenge, however, was to reduce carbon equivalents to improve weldability while still maintaining strength. This trend toward lower carbon equivalents and adequate strengths is shown in Table (3.1). Controlled rolling and accelerated cooling of niobium steels has also allowed reductions in carbon contents, which can be further reduced when accelerated cooling is employed.

Table (3.1) Comparison of typical 1972 and 1986 chemical composition of offshore structural steel [ASM Metals HDBK vol. 1, 2005]

<table>
<thead>
<tr>
<th>Element</th>
<th>Typical, 1972 (a)</th>
<th>Typical, 1986 (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U.S. mill</td>
<td>Foreign mill</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.17</td>
<td>0.15</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.30</td>
<td>1.34</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.025</td>
<td>0.015</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.02</td>
<td>0.006</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.40</td>
<td>0.30</td>
</tr>
<tr>
<td>Niobium</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Aluminum, total</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Nickel</td>
<td>…</td>
<td>0.17</td>
</tr>
<tr>
<td>Chromium</td>
<td>…</td>
<td>0.08</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>…</td>
<td>0.056</td>
</tr>
<tr>
<td>Vanadium</td>
<td>…</td>
<td>0.002</td>
</tr>
<tr>
<td>Copper</td>
<td>…</td>
<td>0.032</td>
</tr>
<tr>
<td>Arsenic</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>Tin</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>Antimony</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>Carbon equivalent, max (c)</td>
<td>0.41</td>
<td>0.40</td>
</tr>
</tbody>
</table>

(a) Minimum yield strength of 290 MPa (42 ksi).
(b) Minimum yield strength of 345 MPa (50 ksi).
(c) Carbon equivalent (CE) = C + (Mn/6) + [(Cr + Mo + V)/5] + [(Ni + Cu)/15]
Most offshore structures were built using normalized carbon-manganese-niobium steel. Advances in computer control and rolling capability have led to the development of thermo-mechanically controlled processes that produce steels with higher strength, high fracture toughness, improved weldability, and lower cost. Thermo-mechanically controlled processes combine controlled rolling and accelerated cooling (with controlled water sprays) or direct quenching to room temperature. Very fine-grain steel (ASTM grain size numbers 10 to 12) is produced. These steels are characterized by low-carbon content (usually less than 0.10% C), which makes them less susceptible to increases in hardness caused by rapid cooling rates between 425 to 260 °C (800 to 500 °F) during welding. Potentially, these steels can be welded with little or no preheat.

Two approaches were taken to eliminate lamellar tearing. One is to reduce sulfur to levels below 0.008%, while the other involves modification of the sulfide shape. The latter relies on the addition of calcium or rare-earth (Cerium, Lanthanum, and Praseodymium) metals to form spheroidal calcium or rare-earth sulfides. This approach usually results in both the elimination of lamellar tearing and an improvement in transverse impact properties. Both sulfur reduction and sulfide shape control are often used to eliminate lamellar tearing. Calcium treatment is preferred for sulfide inclusion shape control [ASM Metals HDBK vol. 1, 2005].

3.1.2 American Bureau of Shipping (ABS)

The American Bureau of Shipping classified steels used in ship building to three categories:

3.1.2.1 Ordinary-Strength Hull Structural Steel

The chemical and mechanical properties of this steel are listed in Appendix (Ai) [ABS, 2008].

3.1.2.2 Higher-Strength Hull Structural Steel

The chemical and mechanical properties of this steel are listed in Appendix (Aii) [ABS, 2008].
3.1.2.3 Low Temperature Materials

The classification approved by ABS depends on the low temperature range (0 ºC and above, -55 to 0 ºC, -196 to -55 ºC, and below -196 ºC). The most popular temperature range in Canadian weather is (-55 to 0 ºC). Hence, this was considered in this study. Steels intended for this temperature range are normally carbon manganese steels furnished with fully killed fine grain normalized. The chemical and mechanical properties of this steel are listed in Appendix (Aiii) [ABS, 2008].

3.1.3 American Society for Testing and Materials ASTM A945.709-1 (2006e1)

This standard recommends using HSLA Grade 50 and HSLA Grade 65 for welded construction of Naval ships where saving in weight (mass) is important. The chemical properties, tensile strength and impact requirements of these steels are listed in Appendix (B) [ASTM A945.709-1 2006e1]

3.1.4 Canadian Standards Association (CSA)

The Canadian Defence uses CSA/G40.21 350WT steel in ship hull construction. The notation WT stands for Weldable notch-Tough steel. It is considered for this purpose due to its resistance to brittle fracture (exhibits a certain level of notch toughness). The chemical composition and mechanical properties of this steel are presented in Appendix (C) [CSA, 2002]. This steel was also considered in this study.

3.1.5 Advanced Materials and Process Technology Information Analysis Centre (AMPTIAC)

AMPTIAC is a USA Department of Defence (DOD)’s information analysis centre administered by the Defence Information System Agency, Defence Technical Information Centre (USA). This centre conducted an extensive study to evaluate the history of steels used in shipping construction. The study is summarized below.

- HSLA steels provide high strength, less weight, improved weldability, improved low temperature toughness.
- HSLA-80 steel (yield strength = 80 ksi or 550 MPa) is an optimized version of ASTM A710 steel and was certified for use in ship construction in 1984 after an extensive evaluation of plate properties, welding, and fabrication characteristics,
including the construction and destructive test of structural models. Cost savings from US$2,000 to $3,000 per ton of fabricated structure was estimated for using HSLA-80 in place of high yield steel, HY-80. The cost saving includes reduced material, labor, energy, and inspection costs.

- **HSLA-100 steel** (yield strength =100 ksi or 690 MPa), is a replacement for HY-100 steel to further reduce the fabrication cost. It has a very low carbon content, copper-precipitation-strengthened steel, but with higher alloy content than HSLA-80 steel. It is weldable and does not need preheating, which is required for HY-100 steel.

- Most ship structure, including the hull shell plating, uses plate with thickness of 6-30 mm (0.25-1.25 inches). Thinner plate and less weld metal are required for structures made of HY/HSLA-80 steel as compared to HSS (ABS/DH-36) steel with yield strength of 50 ksi (345 MPa). Hence the structure becomes lighter and that is one of the advantages of HSLA steels.

- **HSLA-80 steel plate** is used in US Navy surface combatant construction, including cruisers, destroyers, and aircraft carriers.

- Buckling limits required additional stiffening of the steel plates and this may prevent optimum use of HSLA/HY-80 for weight reduction. Furthermore, plate cost per ton weight of HSLA and HY are more than double of HSS, and fabrication cost for HSLA and HY steels is higher as well.

- In early 1990’s, it was shown that HSLA-65 steel (yield strength = 65ksi or 450MPa), was able to achieve similar weight savings as HSLA-80. Moreover, HSLA-65 steel has a lower fabrication cost. Hence, it enabled weight reduction in new aircraft carrier design.

- In year 2002, HSLA-65 steel was certified for using in primary hull structure in combatant ships [AMPTIAC, 2003].
3.1.6 Det Norske Veritas (DNV)

DNV is one of the well known international ship classification societies located in Norway. DNV’s current classification guidelines [DNV, 2008] are comparable with those adopted by the International Association for Classification Societies, IACS [IACS, 2006]. Table (D1) in Appendix D presents the mechanical properties of the ordinary and high strength steels recommended by DNV for the use in ship hull. The first row lists the ordinary strength steels, while the second, third and fourth rows are associated with the high strength steels. The material factor $k$ of normal and higher strength steel for scantling purposes is to be understood as defined in Table (D2), as a function of the minimum yield stress ($R_{yH}$). Table (D3) illustrates the material grade requirement for the three classes (I, II, and III) of steel according to the thickness used. Table (D4) presents the applications of materials classes and grades classifications such as primary, secondary and special, and sorted in terms of within or outside 0.4 of the amidship length. Table (D5) illustrates application of material classes and grades for structures exposed to low temperatures, and are presented in the same manner of Table (D4). Tables (D6, D7, and D8) show the material grade requirement for the three classes (I, II, and III) respectively, according to the thickness used, in low temperatures [DNV and ISCS].

3.1.7 Steels Chosen

The steels of the current study were chosen taking into account requirements of the foregoing standards and studies. CSA/G40.21 350WT steel was chosen because it is used in Canadian Defence ships building. The considerable notch toughness of this steel is an advantage over other types especially in cold weather. Figure (3.1) illustrates the microstructure of G40.21 350WT steel (as received) using Scanning Electron Microscope, SEM. The ferrite-pearlite regions are shown in the etched samples (Etchant is 2% Nital). Tests were carried out in the University of Windsor labs.
AISI 1022 HR steel was chosen in this study as a general purpose structural steel, to increase the data pool. This type of steel has excellent formability, good machinability, and weldability. Tables (3.2) and (3.3) show the chemical compositions and mechanical properties of these steels.

Table (3.2) Chemical composition of the steels used in this study

<table>
<thead>
<tr>
<th>Steel</th>
<th>C %</th>
<th>Mn %</th>
<th>S %</th>
<th>P %</th>
<th>Si %</th>
<th>Cr %</th>
<th>Ni %</th>
<th>Cu %</th>
<th>Mo %</th>
<th>Al %</th>
<th>V %</th>
<th>N %</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 1022 (^a)</td>
<td>0.19</td>
<td>0.71</td>
<td>0.039</td>
<td>0.01</td>
<td>0.20</td>
<td>0.15</td>
<td>0.25</td>
<td>0.28</td>
<td>0.11</td>
<td>--</td>
<td>0.01</td>
<td>--</td>
</tr>
<tr>
<td>G40.21 350WT (^b)</td>
<td>0.17</td>
<td>1.36</td>
<td>0.007</td>
<td>0.01</td>
<td>0.32</td>
<td>0.20</td>
<td>0.02</td>
<td>0.18</td>
<td>0.00</td>
<td>0.05</td>
<td>0.057</td>
<td>0.01</td>
</tr>
</tbody>
</table>

\(^a\) Tests were carried out by Schmolz+Bichenbach Co., Windsor ON, Canada

\(^b\) Data was retrieved from mill test of ALGOMA STEEL INC.
Table (3.3) Mechanical properties of the steels used in this study

<table>
<thead>
<tr>
<th>Steel</th>
<th>Element</th>
<th>Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Young’s Modulus (GPa)</th>
<th>Hardness (BHN)</th>
<th>% Elong.</th>
<th>% Red. in Area</th>
<th>Average CVN Impact Energy (J) in -22 °F (-30 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 1022</td>
<td>a</td>
<td>564</td>
<td>350</td>
<td>203</td>
<td>154</td>
<td>34</td>
<td>60</td>
<td>---</td>
</tr>
<tr>
<td>G40.21350WT</td>
<td>b</td>
<td>524</td>
<td>350</td>
<td>205</td>
<td>125</td>
<td>40</td>
<td>76</td>
<td>46d</td>
</tr>
</tbody>
</table>

a, b Tests were carried out in the University of Windsor Laboratories  
c These tests were conducted using Rockwell “B” tester, and converted to Brinell using ASTM standard E140-07, table 2.  
d Result extracted from the mill test certificate of ALGOMA STEEL INC.

3.2 TEST PROCEDURE

There are three test procedures conducted in this study.

1) Cyclic loading tests: strain history for specific number of cycles was applied on specimens that denoted as post-cyclic (fatigue-damaged) specimens.

2) Fatigue test: strain cycles were only applied on specimens that denoted as fatigue specimens. This procedure is required to find the strain-life relationship.

3) Quasi-static tensile test: Applying tensile load monotonically until rapture on the monotonic (damage–free) and post-cyclic specimens in order to determine their mechanical properties.

3.2.1 Tensile Tests

The quasi-static tensile tests were conducted in order to determine the mechanical properties of materials used in this study. The properties which were determined from these tests are: tensile strength, yield strength, fracture strength, modulus of elasticity, elongation, and reduction in area [ASTM A370, 2009].

The ASTM E606 standard which followed for cyclic and fatigue test in this study allows for doubling the diameter of 6.35mm within the gauge length region [ASTM E606, 2004]. ASTM E8/E8M standard specimen has a diameter of 12.7mm which satisfies the geometry requirements of ASTM E606 standard. Thus all quasi-static tension, cyclic loading, and fatigue specimens were manufactured in compliance with ASTM E8/E8M standard geometry. The geometry and mounting are shown in Figure (3.2).
To ensure a proper distribution of the load throughout the cross-section, and to minimize stress concentration, a large fillet radius (represented by ‘R62.34’ in Figure 3.2a) is preferred. It is also important to ensure that no undercut is present at the base of shoulder or anywhere else in the reduced section. This undercut can create a weak link in the specimen and cause premature failure. The diameter of specimen in the gauge length region was measured using an instrument with an accuracy of +/- 0.0005 inch (0.0127 mm). Three positions of measurements along the gauge length were considered. The smallest measurement was used for stress calculations.

Figure (3.2) The geometry, assembly and mounting of test specimen

The tension specimens were prepared in compliance with the E8/E8M-08 and ASTM A370-09 standards. The same preparation method was used for all test specimens and identical test conditions were maintained as well in order to ensure similarity of test parameters. These parameters included, but were not limited to: cutting, machining, surface finish, air humidity, temperature, and test setup procedure. Surface roughness is a very important parameter in cyclic loading and fatigue tests, especially in high cycle...
fatigue tests. Therefore, the recommended value of the average roughness, \( Ra \), did not exceed the value of 0.2 \( \mu m \) according to the ASTM E606 [ASTM E606, 2004]. Hence, the surface of all cyclic loading and fatigue specimens were finished with a value of average roughness lower than the recommended value. Figure (3.3) illustrates sand paper and roughness measurement equipment used.

![Sand paper](image1.jpg) ![TR200 portable surface roughness tester](image2.jpg)

(a) Sand paper used  
(b) TR200 portable surface roughness tester

**Figure (3.3) Surface preparation of specimens**

An infrared thermometer capable of operating in a temperature range of -50°C to 320°C was used in monitoring the specimen temperature at various locations during fatigue tests. Figure (3.4) illustrates the infrared thermometer during the measurement process. The benefit of usage the infrared thermometer is the ability of detection crack initiation (and subsequently fatigue failure) as a possible prediction of any temperature difference along the specimen gauge length region.
A servo-hydraulic MTS system along with “Instron 1332” fatigue test frame of ±100kN capacity was used for all the fatigue and tension tests. This fatigue actuator is run by MTS hydraulic system and controlled by a computerized MTS controller. In this particular MTS controller system, the test procedure was set as a multipurpose testware in order to perform sequential processes as shown in Figure (3.5). These processes included tensile and data acquisition processes, as well as load extension plot and process termination (failure). The termination process was set to run when the load dropped down to 5% of the maximum load applied on the specimen, i.e. when the specimen fails. All tension tests were conducted under displacement rate of 3.0 mm/min as recommended by ASTM E8/E8M.
The limits (or detectors) were set to perform safe tests for operator and/or system equipments. Figure (3.6) illustrates these limits which were set for categories such as displacement, force, and extension. Furthermore, for low temperature tests, the temperature limits were also set. Each category has a rule of action that activated when one or more of these limits were trimmed. The rules include: disabled, indicate, station power off, interlock, program interlock, program stop, and program hold. The limits and rules of the quasi-static tensile tests are shown in Figure (3.6a). The limits and rules of the cyclic loading or fatigue tests are different from those of quasi-static tensile test, as shown in Figure (3.6b). The rules of all limits in fatigue test were “station power off”. Any trim to one or more of these limits would thereby cause system shut down. These rules were chosen to insure safety of operator, whereas the strain controlled test is relatively dangerous. Meanwhile, system components were more protected using the “station power off” setting, as fatigue test are time consuming and operator might be away from the test area for periods of time.
Some quasi-static tensile tests were carried out at room temperature (≈25°C) while other tests were conducted at low temperatures (+10, 0, -5, -15, and -30°C). Some of the virgin specimens were tested monotonically in order to determine the mechanical properties of the as-received steels, and these specimens are called monotonic (damage-free) specimens. Others were tested in tension after application of the strain history for a specific number of cycles, and these specimens are called post-cyclic (fatigue-damaged) specimens. The third set of specimens were tested in strain-controlled fatigue load only and they are called fatigue specimens. More details are presented in section 3.2.2.2.
The *yield strength* was determined from the stress-strain plot using the 0.2% offset strain method. The *elongation* is the increase in length of the gauge length, expressed as a percentage of the original gauge length, and it was determined using either traditional or automated method. The traditional method was performed by attaching the two ends of the fractured specimen together carefully and measuring the distance between the gauge marks to the nearest 0.01 inch (0.25 mm) for gauge lengths of 2 inch. The automated method was able to read the extension through the extensometer at failure. The difference in elongations measured from these two methods was negligible. The American gauge length standard was considered in percentage elongation measurements, i.e. the gauge length is four times the diameter [Dowling 1999]. The *Reduction in Area* was estimated by fitting the ends of the fractured specimen together and measuring the diameter at the smallest cross section to the same accuracy as the original dimensions. The difference between the original area and the area at failure, expressed as a percentage of the original area, is the reduction in area [ASTM A370, 2009].

### 3.2.2 Fatigue Tests

The cyclic loading and fatigue tests were carried out under strain control mode as recommended in ASTM Standard E606. The strain ranges applied to these specimens were large enough to produce low cycle fatigue life. Therefore, it was decided to use strain-controlled fatigue test method [ASTM E606, 2004].

Selection of either the uniform-gage section or hourglass profile is commonly based upon the magnitude of strain range to be imposed (Figure 3.7). The recommended uniform gage specimen is usually suitable for strain ranges up to about 2%. However, for strain ranges above 2%, the hourglass specimens may be necessary [ASTM E606, 2004]. As the strain ranges applied in this study is relatively low (0.3% for *post-cyclic* specimens, and 0.48% for *fatigue* specimens), all tests were conducted using uniform-gage section specimens.
3.2.2.1 Fatigue Tests Setup

It is important to keep all parameters constant throughout the test, due to the elevated plastic flow when preparing a test setup using strain feedback. However, there are no such restrictions necessary regarding environmental parameters. Generally speaking, it is important to ensure that the tests are performed under the same conditions to avoid the influence of dissimilar initial conditions on the test data. The alignment of the specimens was such that the maximum bending stress did not exceed 5% of the total axial stress.

It is recommended that the maximum and minimum strains be repeatable throughout the tests to an accuracy of 1%. Hence, the peak-valley compensator was preset in the cyclic loading process to minimize error in strain limits between command and actual signals. Although the strain limits applied on steel structures are rarely constant, such consistency in laboratory tests can provide a better understanding of the effect of fatigue damage at a specific strain range and can be further compared with other studies.
When conducting the test, a fatigue rated extensometer suitable for dynamic measurements over long periods of times was employed. As the knife edge of extensometers can sometimes slip on the surface of the specimen causing undesirable strain, several layers of transparent tape were used. This plastic tape assisted in minimizing the occurrence of slippage, protected the specimen from the extensometer edges, and cushioned the attachment.

Certain tests may require a gradual increase in the strain amplitude in order to prevent overshooting the strain on the first cycle. Therefore, it is advisable to increase the strain amplitude gradually to its maximum value, within the lesser of 20 cycles or 2% of its fatigue life. If no waveform is specified, a triangular waveform is preferred. For the current study, the waveform was of the sinusoidal type.

3.2.2.2 Test Matrix

Tables (3.4) and (3.5) show the test matrix of the specimens tested at room temperature and made of AISI 1022 HR steel and G40.21 350WT steel, respectively. Three different types of specimens were tested: post-cyclic, monotonic, and fatigue specimens as discussed in section 3.2.1. For post-cyclic specimens, a pre-selected number of strain controlled push-pull cycles were first applied. Then, hardness tests were conducted in the gauge length of the specimen. Finally, a quasi-static tensile test was undertaken to determine various mechanical properties of the specimens. Measurements of diameter and length after the tensile test were performed to estimate the percentage reduction in area and percentage elongation, respectively. However, for the monotonic specimens (not shown in Tables 3.4 and 3.5) only quasi-static tensions test were conducted in accordance with ASTM standards E8/E8M and A370. Thus, no cyclic loading was applied to these specimens. On the other hand, specimens designated as fatigue specimens in Tables (3.4) and (3.5) were subjected to cyclic loading only until fatigue failure in accordance with ASTM standard E606. These specimens were used to determine the fatigue life at various strain amplitudes.
Table (3.4) Test matrix for AISI 1022 HR steel

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Specimen name</th>
<th>Strain (mean, amplitude) µε</th>
<th>No. of cycles (×1000) for post-cyclic specimens</th>
<th>Fatigue life (×1000) for fatigue specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td></td>
<td>1000, 1500</td>
<td>5, 25, 50, 75, 100</td>
<td>227, 262</td>
</tr>
<tr>
<td>A2</td>
<td>post-cyclic or fatigue</td>
<td>5500, 1500</td>
<td>5, 25, 50, 75, 100</td>
<td>119, 131</td>
</tr>
<tr>
<td>A3</td>
<td></td>
<td>10500, 1500</td>
<td>5, 25, 50, 75, 100</td>
<td>106, 110</td>
</tr>
<tr>
<td>A4</td>
<td>fatigue</td>
<td>variable, 1500</td>
<td>N/A</td>
<td>variable</td>
</tr>
</tbody>
</table>

Table (3.5) Test matrix for G40.21 350WT steel in room temperature

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Specimen name</th>
<th>Strain (mean, amplitude) µε</th>
<th>No. of cycles (×1000) for post-cyclic specimens</th>
<th>No. of cycles (×1000) for fatigue specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td></td>
<td>1000, 1500</td>
<td>5, 25, 50, 75</td>
<td>60, 96</td>
</tr>
<tr>
<td>G2</td>
<td>post-cyclic or fatigue</td>
<td>5500, 1500</td>
<td>5, 25, 50, 75</td>
<td>59, 138</td>
</tr>
<tr>
<td>G3</td>
<td></td>
<td>10500, 1500</td>
<td>5, 25, 50, 75</td>
<td>80, 87</td>
</tr>
<tr>
<td>G4</td>
<td></td>
<td>1000, 1000</td>
<td>5, 25, 50, 75, 100</td>
<td>762, 720</td>
</tr>
<tr>
<td>G5</td>
<td>fatigue</td>
<td>0, variable</td>
<td>N/A</td>
<td>variable</td>
</tr>
</tbody>
</table>

Figure 3.8 presents a screen shot of the controller used in fatigue test. The first item “Ramp to mean strain” represents a monotonic process which applies strain equal to the mean strain value. The next item “Cyclic loading” represents a process of applying strain amplitude cyclically. This process window enables user to specify the tests frequency as well as the number of cycles to be applied. In the post-cyclic specimens the number of cycles was specified as listed in Tables (3.4) and (3.5). In the fatigue specimens the number of cycles was not specified whereas the check box of the number of cycles was left unchecked to run the process until fatigue failure. The peak-valley compensator is essential for this process to compensate the error in maximum and minimum strain limits.
which often occurs between actual and command signals. The third item “Ramp to zero load” follows the “Cyclic loading” process in case of pre-specified number of cycles tests to bring the force applied on the specimen to zero before terminating the entire test. However this process was ignored in the fatigue specimens as failure occurred in the “Cyclic loading” process.

Three ‘Data’ processes were prepared to record the four parameters of data (time, force, extension, and number of cycles) to a single text file. Each data process was prepared in its own form for better data recording, whereas the time interval were changed to ensure full data scanning with lower size of the output file. The first data process was designed to record data of the first few cycles with a very small time interval to acquire detailed force-extension data. The second data process was designed to acquire force-extension data for two cycles in an interval of 100 cycles. Finally, the third data process was prepared to catch data for two cycles in an interval of 2000 cycles. The last item “Force plot” is included to display a graph illustrating the relationship between force and time simultaneously. The last process was useful for acquiring the values of tensile and compressive force in the first few cycles.

Figure (3.8) The fatigue test processes sequence
Figure (3.9) shows a screen shot of real time updates on various fatigue test control and input parameters with its most important windows. The number of cycles, recent active process (indicated by 0 or 1 in “Sequence Counters”) and other commands can be shown in the “Station Manager” window. This window allows user to start, pause, or stop the test. In the “Meters” window, the displacement (lower grip position), force (load cell reading), and extension (extensometer reading) are displayed. The “Scope” window displays the actual and command signals which allow the user to tune the actual signal (shown in blue) thereby providing a better match with the command signal (shown in red).

![Image of疲劳测试控制系统](image)

**Figure (3.9)** The fatigue test as set in the MTS controller system
3.2.2.3 Strain Rate Calculation

Either strain rate or frequency of cycling need to be held constant for the duration of the test. However, this phenomenon is invalid if the test objective is to determine either the effect of strain rate or frequency specifically. While constant strain rate testing is often preferred, constant frequency testing may be of greater practical significance to the fatigue analysis of certain machine components. On the other hand, constant strain rate testing may be experimentally more tractable than constant frequency testing since long-life, small-strain tests in the former mode may be completed in shorter periods of time than tests conducted in the latter mode. In using a servo-controlled testing machine, a comparison of the program and feedback signals should be carried out to ensure that the selected rates or frequencies are and remain within system capabilities and accuracy requirements [ASTM E606, 2004].

For the post-cyclic specimens in the current study (investigation of mechanical properties changes) the frequency was maintained at 4.0 Hz, i.e. strain rate was 0.024 s\(^{-1}\). The strain amplitude of 1500 µε was maintained for test series A1, A2, A3, A4, G1, G2, and G3. For test series G4, a frequency of 6.0 Hz was used to produce a strain rate of 0.024 s\(^{-1}\) whereas the strain amplitude was 1000 µε. However, for the fatigue specimens (strain amplitude-life relation) the strain rate was maintain at level of 0.048 s\(^{-1}\) for test series G5. In the last series G5 the strain amplitude was variable, and hence, the frequency was varied to produce a constant strain rate (see Table 3.6).

Using Figure (3.10), the strain rate can be estimated as:

\[
\text{Strain rate} = \frac{\text{strain amplitude}}{\text{Quarter cycle time}} = \frac{\text{strain amplitude}}{\left[(1/4) \times (1/\text{frequency})\right]}
\]

**Strain rate = 4 × strain amplitude × frequency**

For frequency of 4.0 Hz and the strain amplitude of 1500 µε the strain rate is as follows:

\[
\text{Strain rate} = (1500\times10^{-6}) \times 4(\text{4Hz}) = 0.024 \text{ (s}^{-1}\text{)}
\]

The same result of the strain rate can be obtained using the expression of ASTM E606:

**Strain rate = 2 × strain range × frequency** [ASTM E606, 2004]
Figure (3.10) Strain rate estimation for frequency of 4.0 Hz

Table (3.6) Strain amplitude-frequency setting for the strain-life curve

<table>
<thead>
<tr>
<th>Strain amplitude (µε)</th>
<th>Frequency (Hz)</th>
<th>Strain rate (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>12.00</td>
<td>0.048</td>
</tr>
<tr>
<td>1100</td>
<td>10.91</td>
<td>0.048</td>
</tr>
<tr>
<td>1200</td>
<td>10.00</td>
<td>0.048</td>
</tr>
<tr>
<td>1300</td>
<td>9.230</td>
<td>0.048</td>
</tr>
<tr>
<td>1400</td>
<td>8.571</td>
<td>0.048</td>
</tr>
<tr>
<td>1500</td>
<td>8.000</td>
<td>0.048</td>
</tr>
<tr>
<td>1600</td>
<td>7.500</td>
<td>0.048</td>
</tr>
<tr>
<td>1700</td>
<td>7.059</td>
<td>0.048</td>
</tr>
<tr>
<td>1800</td>
<td>6.667</td>
<td>0.048</td>
</tr>
<tr>
<td>1900</td>
<td>6.315</td>
<td>0.048</td>
</tr>
<tr>
<td>2000</td>
<td>6.000</td>
<td>0.048</td>
</tr>
<tr>
<td>2100</td>
<td>5.714</td>
<td>0.048</td>
</tr>
<tr>
<td>2200</td>
<td>5.454</td>
<td>0.048</td>
</tr>
<tr>
<td>2300</td>
<td>5.217</td>
<td>0.048</td>
</tr>
<tr>
<td>2400</td>
<td>5.000</td>
<td>0.048</td>
</tr>
</tbody>
</table>
3.2.2.4 Low Temperature Fatigue Test

The fatigue tests at low temperatures (+10°C, 0°C, -5°C, -15°C, and -30°C) were conducted using the same fatigue Instron frame along with MTS (651.06E-03) model environmental chamber. The apparatus is shown in Figure (3.11). The liquid Nitrogen was used in the cooling process to maintain temperature within a tolerance of ±1°C. Fatigue, cyclic loading, and tension tests were carried out at low temperatures.
Two extensions rods made of AISI 4340 steel were used to adapt the specimen inside the environmental chamber, while keeping the upper and lower grips outside the chamber. The AISI 4340 steel was selected due to its Nickel content (more than 1%), low sulphur content (less than 0.04%) and relatively high Manganese content. These elements provided the AISI 4340 steel adequate low-temperature fracture toughness [ASM Metals HDBK vol.1, 2005]. These two extensions ran for millions of cycles without fatigue crack and/or failure. A steadily-decreasing time, of approximately one hour under low temperature was applied on every test specimen. This sinking time was important in order to reach a stable, stress-free status before starting the cyclic loading test.

Table (3.7) Chemical composition of AISI 4340 steel

<table>
<thead>
<tr>
<th>Element</th>
<th>C%</th>
<th>Mn%</th>
<th>S%</th>
<th>P%</th>
<th>Si%</th>
<th>Cr%</th>
<th>Ni%</th>
<th>Cu%</th>
<th>Mo%</th>
</tr>
</thead>
<tbody>
<tr>
<td>4340 Steel *</td>
<td>0.40</td>
<td>0.72</td>
<td>.022</td>
<td>.008</td>
<td>0.25</td>
<td>0.82</td>
<td>1.74</td>
<td>0.15</td>
<td>0.23</td>
</tr>
</tbody>
</table>

* Data was retrieved from mill test of GERDAU MACSTEEL (through Essex Metals)

Table (3.8) Mechanical properties of AISI 4340 steel

<table>
<thead>
<tr>
<th>Element</th>
<th>Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Young’s Modulus (GPa)</th>
<th>Hardness (BHN)</th>
<th>% Elong.</th>
<th>% Red. in Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>4340 Steel a</td>
<td>1089</td>
<td>1020</td>
<td>200</td>
<td>247 b</td>
<td>16</td>
<td>61</td>
</tr>
</tbody>
</table>

a Data was retrieved from mill test of GERDAU MACSTEEL (through Essex Metals)
b This test was conducted using Rockwell “C” scale, and converted to Brinell using ASTM standard E140-07, table 1.

The test matrix of the low temperature tests is shown in Table (3.9). Only post-cyclic and fatigue specimens are included in this table. However, a group of monotonic specimens (not shown in Table 3.9) were tested at low temperatures as well. Each test series was denoted by C which stands for “Cold” followed by a number which represents the test temperature. All of the low temperature test specimens were subjected to a mean strain of 1000 $\mu$ε and a strain amplitude of 1500 $\mu$ε. This strain history allows for the low temperature test series to be compared with series G1 which was tested at room
temperature. The post-cyclic specimens of the low temperature test series were tested cyclically for a similar number of cycles as those of series G1. However, the fatigue specimens of the low temperature series exhibited longer life than those of series G1. This difference in fatigue life is discussed in Chapter 4 (Experimental results and discussion).

Table (3.9) Test matrix for G40.21 350WT steel in low temperatures

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Temp. (°C)</th>
<th>Specimen Name</th>
<th>Strain (mean, amplitude) (µε)</th>
<th>No. of cycles (×1000) for post-cyclic specimens</th>
<th>Fatigue life (×1000) cycles, for fatigue specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>C10</td>
<td>+10</td>
<td>Post-cyclic</td>
<td>1000, 1500</td>
<td>5, 25, 50, 75, 100</td>
<td>318, 288</td>
</tr>
<tr>
<td>C0</td>
<td>0</td>
<td>1000, 1500</td>
<td>5, 25, 50, 75, 100</td>
<td>351, 366</td>
<td></td>
</tr>
<tr>
<td>C-5</td>
<td>-5</td>
<td>1000, 1500</td>
<td>5, 25, 50, 75, 100</td>
<td>375, 421</td>
<td></td>
</tr>
<tr>
<td>C-15</td>
<td>-15</td>
<td>1000, 1500</td>
<td>5, 25, 50, 75, 100</td>
<td>555, 664</td>
<td></td>
</tr>
<tr>
<td>C-30</td>
<td>-30</td>
<td>1000, 1500</td>
<td>5, 25, 50, 75, 100</td>
<td>765, 722</td>
<td></td>
</tr>
</tbody>
</table>

3.2.2.5 Laboratory Testing and Full-Scale Testing

The results derived from laboratory tests are often included in the design of structures. However, some structures such as ship hulls are subjected to more complex loads. It is difficult to rely on laboratory S-N or ε-N curves in order to determine the fatigue life of the structure. Therefore, further testing is required at a full-scale level to determine the fatigue life of the structure. These tests are either conducted on the structure itself or a critical section is sampled and tested in a laboratory facility. Unlike the usual laboratory tests, full-scale test parameters fluctuate greatly and, thus, those results can generally only be used for that specific structure. In the current study no full scale tests were conducted.

3.3 SUMMARY

In this chapter, selection of steels and test procedures used to achieve the objectives of the current study are discussed. A detailed study on these steels was carried
out using the codes and standards such as ABS, ASTM, CSA, AMPTIAC and DNV. The decision was made to use G40.21 350WT steel as a ship hull steel as well as AISI 1022 HR steel as a general purposes structural steel.

The steel specimens were manufactured, sorted in groups (series), and prepared for tensile and cyclic loading tests. The ASTM standards A370, E8/E8M and E606 were utilized in the preparation processes.

The Instron apparatus which was utilized to conduct the tensile and cyclic loading tests was powered by a servo-hydraulic power unit. The cyclic loading tests were carried out using strain controlled push-pull mode in compliance with ASTM standard E606.

Two main approaches were followed in this study. The first one is the investigation of mechanical behaviour of both fatigue-damaged steels at room temperature. In addition, the mechanical behaviour of G40.21 350WT steel in zero and subzero temperatures was studied. To achieve this goal the steel specimens were tested first with axial cyclic loading followed by a quasi-static tensile test in order to determine changes in their mechanical properties. The second approach is the determination of strain-life relationship for both steels at room temperature. Furthermore, the effect of temperature on the fatigue life for G40.21 350WT steel was studied. The study of low temperature effects was limited to G40.21 350WT steel because these tests are extremely expensive in terms of monetary and time required.
CHAPTER 4: EXPERIMENTAL RESULTS AND DISCUSSIONS*

In this chapter, the experimental results of AISI 1022 HR and CSA G40.21 350WT steels are discussed and compared. Several important behaviours are included such as stress-strain relationship, tensile strength, yield strength, fracture strength, ductility, toughness, stress softening, mean stress relaxation, hysteresis loop, and strain life relationship.

4.1 STRESS-STRAIN RELATIONSHIP

Figure (4.1) shows typical engineering stress-strain curves for monotonic (damage-free) specimens and post-cyclic (fatigue-damaged) specimens from test series A1 of AISI 1022 HR steel (see Table 3.4 for the test matrix of AISI 1022 steel). These specimens were subjected to mean strain of 1000 µε and strain amplitude of 1500 µε. The chemical composition and mechanical properties of AISI 1022 HR and G40.21 350WT steels were discussed in section 3.1.7. The stress-strain relationships of post-cyclic specimens indicate a general trend of strain hardening as compared to the behaviour of monotonic specimens until the strain reached a value of 0.19. Strain hardening, is the strengthening of a metal by plastic deformation. It is believed that strengthening occurs because of dislocation movements within the crystal structure of the material [Degarmo et al., 2003]. For post-cyclic specimens, the strain hardening increases as the number of applied strain cycles increases. Similar behaviour was observed in the other two test series A2 and A3. The yield points and yield plateau of the stress-strain curve are obvious in the monotonic specimens. However, yield points and yield plateau do not appear in the post-cyclic specimens because they experienced strain hardening. Necking results from an instability during tensile deformation. Necking occurs when the materials cross-sectional area decreases by a greater proportion than the material strain hardens. The necking location is specified by heterogeneities such as flaws or local variations in dimensions or composition that cause local fluctuations in stresses and strains. In Figure (4.1), necking occurred at strain of 0.19. It was found that the modulus of elasticity did not change. This observation regarding modulus of elasticity agrees with the findings of Sánchez-Santana et al. (2008). Their study was conducted using AISI 4140T steel in stress-controlled mode.

*This chapter is an outcome of joint research
Figure (4.1) Stress-strain plots of AISI 1022 HR steel

Figure (4.2) shows the complete stress-strain curves of the monotonic and post-cyclic specimens for series G1 of G40.21 350WT steel. These specimens were subjected to mean strain of 1000 µε and strain amplitude of 1500 µε. For G1 series specimens (see Table 3.5) necking results from instability during tensile deformation at strain of 0.20. The comparison between stress-strain curves of AISI 1022 HR and G40.21 350WT steels show that necking in both steels occurred at almost the same strain. This indicates the fact that the tensile strength of these two steels was very similar. The tensile strength of the two steels was found to be 564 MPa and 524 MPa, respectively.
Figure (4.2) Stress-strain plots of G40.21 350WT steel in room temperature

The *monotonic* tensile tests of G40.21 350WT steel that were conducted in room and low temperatures (25°C to -30°C) exhibited a small difference in the tensile strengths as shown in Figure (4.3). The tensile strength in room temperature was 524 MPa, while it reached 532 MPa in both sub-zero temperatures of -15°C and -30°C. This change in tensile strength of G40.21 350WT steel in low temperatures is less than 1.5%. However, low temperature tests specimens introduced a relatively higher difference in yield strength as compared to room temperature tests. The 0.2% offset strain method was used in determination of yield strength. The yield strength was 350 MPa at room temperature while it reached 400 MPa at zero and subzero temperatures (0°C to -30°C). Hence, the increase in yield strength in G40.21 350WT steel in zero and sub-zero temperature was 14%. These observations regarding increasing of tensile strength and yield strength in low temperatures agree with those reported by Stephens et al., (2001).
4.2 TENSILE STRENGTH

4.2.1 Effect of Mean Strain

Figures (4.4) and (4.5) present the effect of mean strain on the tensile strength of AISI 1022 HR and G40.21 350WT steels, respectively. Each figure shows data of three loading histories and these are test series A1 to A3 for AISI 1022 HR steel and G1 to G3 for G40.21 350WT steel. In general, it can be observed that the tensile strength increased in all loading histories as strain cycles increased. The maximum increase is 5% for AISI 1022 HR steel, while the maximum increase is 3% for G40.21 350WT steel. The percentage change is calculated as follows.

\[
\text{Percentage Change} = \left( \frac{\text{Property of damaged material} - \text{Property of damage free material}}{\text{Property of damage free material}} \right) \times 100
\]

The maximum increases in tensile strength in both steels are recorded in specimens tested at lowest mean strain (1000 µε). This increase in tensile strength was due to the strain...
hardening. The dislocation accumulation in the grains borders implies higher value of force required to perform specific plastic deformation during monotonic tensile test. This resistance to plastic deformation led to higher tensile strength in the post-cyclic steel specimens [Mayama et al., 2008]. For both steels, the increase in tensile strength was found to be similar in the three levels of mean strain used. The value of increase in tensile strength was 2.9%, 1.5%, and 1.2% for mean strains of 1000 µε, 1000 µε, and 10500 µε, respectively. The lower mean strain (1000 µε) produced higher increase in tensile strength than that of the higher mean strain (10500 µε). Hence, it was found that the effect of the mean strain on the tensile strength was insignificant.

Figure (4.4) Effect of mean strain on tensile strength of AISI 1022 HR steel
4.2.2 Effect of Strain Amplitude

The effect of strain amplitude on tensile strength of G40.21 350WT steel is illustrated in Figure (4.6). It is obvious from this figure that the specimens tested with strain amplitude of 1500 με exhibited higher tensile strength. The maximum increase in tensile strength is 3% for specimen tested at strain amplitude of 1500 με, while the maximum increase was 1.5% in strain amplitude of 1000 με. Thus, it can be concluded that for G40.21 350WT steel, the higher strain amplitude led to larger increase in tensile strength.
4.2.3 Effect of Temperature

The effect of temperature on the tensile strength of G40.21 350WT steel is shown in Figure (4.7). The tensile strength increased in zero and sub-zero temperatures for the post-cyclic specimens by almost the same amount as those of the room temperature specimens for G40.21 350WT steel. The maximum increase in tensile strength in room temperature specimens was 3%, while it reached 2.5% in the low temperature specimens for the same strain history. Nevertheless, the effect of temperature on tensile strength was found to be insignificant as well. It should be noted that for AISI 1022 HR steel no test was conducted to study the effect of temperature because these tests are very expensive and time consuming.
4.3 YIELD STRENGTH

4.3.1 Effect of Mean Strain

Application of strain cycles affected the yield strength of both steels as shown in Figures (4.8) and (4.9). It can be found that in general, the yield strength increased as strain cycles increased and this is true for all three loading histories (the three levels of mean strain). However, a lower mean strain caused smaller increase in yield strength for both steels. The maximum increase in the yield strength for AISI 1022 HR steel is 19% and recorded from specimen tested at mean strain of 5500 \( \mu \varepsilon \). The maximum increase in yield strength for G40.21 350WT steel is 16% and recorded from specimens tested at mean strain of 5500 \( \mu \varepsilon \) and 10500 \( \mu \varepsilon \). However, the increase in yield strength stabilized, or reduced slightly after cycle count of 50 kcycles. The rationale for this increase in yield strength with the increase of cycle count is the same as that explained for the increase in tensile strength (see section 4.2.1).
Figure (4.8) Effect of mean strain on yield strength for AISI 1022 HR steel

Figure (4.9) Effect of mean strain on yield strength of G40.21 350WT steel
4.3.2 Effect of Strain Amplitude

Figure (4.10) illustrates the effect of strain amplitude on yield strength of G40.21 350WT steel. Similar to the tensile strength the yield strength increased in specimens tested with strain amplitude of 1500 $\mu$e exhibited the largest increase in yield strength, especially in high cycles count. The maximum increase is 13% in specimens tested with a strain amplitude of 1500 $\mu$e, while it is 9% in specimens tested with a strain amplitude of 1000 $\mu$e. Therefore, the higher strain amplitude produced higher increase in yield strength for G40.21 350WT steel.

![Figure (4.10) Effect of strain amplitude on yield strength of G40.21 350WT steel](image)

4.3.3 Effect of Temperature

The yield strength increased at zero and sub-zero temperatures for G40.21 350WT steel due to application of strain cycles. This effect is shown in Figure (4.11). The increase in yield strength was found to be higher in room temperature test specimens. The maximum increase is 13% in room temperature specimens, while its maximum increase in low temperatures specimens is 9% which was recorded in temperature of -30°C for the same loading history (see Table 4.3). Similar to tensile strength higher values of yield strengths were found in specimens tested at very low temperature (-30°C). It should be
noted that the *monotonic* yield strength in low temperature was high as compared to the room temperature *monotonic* yield strength. The *monotonic* yield strength was found to be 350 MPa and 400 MPa, in room temperature and -30°C, respectively.

**Figure (4.11) Effect of temperature on yield strength of G40.21 350WT steel**

### 4.4 FRACTURE STRENGTH

#### 4.4.1 Effect of Mean Strain

Figures (4.12) and (4.13) illustrate the effect of mean strain on fracture strength (strength at failure in the quasi-static tensile test) of AISI 1022 HR and G40.21 350WT steels, respectively. The fracture strength increased in both steels due to application of strain cycles. In general, the fracture strength of AISI 1022 HR steel gradually increased as the cycle count increased. The higher increase in fracture strength of AISI 1022 HR steel was found in specimens tested at higher mean strains (5500 µε and 10500 µε) as shown in Figure (4.12). The maximum increase in fracture strength for this steel is 5%. However, Figure (4.13) shows that the higher increase in fracture strength of G40.21 350WT steel were found in specimens tested at the lowest mean strain (1000 µε). For all three mean strain levels, the fracture strength of G40.21 350WT steel increased until
about cycle count of 25 kcycles, and then the strength reduced as the cycle count increased. The maximum increase in fracture strength for this steel is 16%. It may therefore be concluded that the effect of mean strain on increase in fracture strength is dependent on the type of steel.

The comparison between AISI 1022 HR and G40.21 350WT steels for specimens tested with the minimum mean strain (1000 µε) indicates that the higher increase occurs in G40.21 350WT steels (see Table 4.1). The maximum increase is 16% which was recorded from data of specimen made of G40.21 350WT steel and loaded to 25 kcycles.

![Figure (4.12) Effect of mean strain on fracture strength for AISI 1022 HR steel](image-url)
4.4.2 Effect of Strain Amplitude

Figure (4.14) presents the effect of strain amplitude on fracture strength of G40.21 350WT steel. Similar to the tensile strength and yield strength, specimens tested to the higher strain amplitude (1500 µε) exhibited higher fracture strength. The maximum increase in specimens tested with strain amplitude of 1500 µε is 16%, while it is only 6% in the specimens tested with 1000 µε.
4.4.3 Effect of Temperature

Figure (4.15) illustrates the effect of temperature on fracture strength of G40.21 350WT steel. The changes in fracture strength for specimens tested in low temperatures were different of those tested in room temperature. In general, specimens tested at lower temperatures (-15°C and -30°C) exhibited increase in fracture strength. However, specimens tested in temperatures of 0°C and -5°C exhibited no pattern (increase or decrease) in fracture strength as the number of cycles count increased. The maximum increase in fracture strength in room temperature specimens is 16%, while in the low temperature specimens this value was 9% and recorded from specimen tested at -15°C.
4.5 DUCTILITY

The ductility of AISI 1022 HR and G40.21 350WT steels reduced as a result of application of strain cycles. The ductility was calculated as a percentage elongation and also as a percentage reduction in cross-sectional area. The tests were conducted at room temperature for AISI 1022 HR, and at room and low temperatures for G40.21 350WT steel.

4.5.1 Effect of Mean Strain-Percentage Elongation

For both steels, the maximum reduction in percentage elongation was found in post-cyclic specimens tested to higher mean strains (5500 με and 10500 με). The maximum reduction is 18% for AISI 1022 HR steel and it is 20% for G40.21 350WT steel. This observation in percentage elongation is illustrated in Figures (4.16) and (4.17) for AISI 1022 HR and G40.21 350WT steels, respectively.

Crystallographic analysis of material imputes decrease in percentage elongation to dislocations movement inside grains towards boundaries. This movement leads to dislocations accumulation in grain boundaries. Different dislocation orientations of the
adjacent grains cause dislocations restriction at grains boundaries. Application of a particular applied strain will need more force to be performed. This led to lower ductility values for post-cyclic specimens [Mayama et al., 2008].

Figure (4.16) Effect of mean strain on percentage elongation of AISI 1022 HR steel
Figure (4.17) Effect of mean strain on percentage elongation of G40.21 350WT steel

4.5.2 Effect of Strain Amplitude-Percentage Elongation

Figure (4.18) illustrates the effect of strain amplitude on percentage elongation. This figure is plotted using experimental data of post-cyclic specimens made of G40.21 350WT steel. The higher reduction in percentage elongation were found in specimens tested at higher strain amplitude (1500 µε) as shown in Figure (4.18). This observation agrees with that found in the tensile strength for this steel. Figure (4.6) shows that the higher increase in tensile strength was found in specimens tested with the higher strain amplitude (1500 µε). It can be concluded that for the fatigue-damaged steels the ductility reduced while the tensile strength increased. This observation agrees with the previous studies [Rudenko and Splvakov 1975, and Grenier et al., 2007].
The specimens made of G40.21 350WT steel and tested in zero and subzero temperatures exhibited higher reduction in percentage elongation as compared to those tested in room temperature. The temperature played a significant role in the change of percentage elongation. The highest reductions in percentage elongation were found in specimens tested at lower temperatures (-15°C and -30°C). The maximum reduction in ductility in terms of percentage elongation is 22% which was recorded from specimen tested in -30°C. Thus, the lower temperature produced smaller value of percentage elongation. Figure (4.19) shows the effect of temperature on percentage elongation of G40.21 350WT steel.
4.5.4 Effect of Main Strain-Percentage Reduction in Area

There are insignificant changes in percentage reduction in area for both steels in all the three mean strains in room temperature. This observation is shown in Figures (4.20) and (4.21) for AISI 1022 HR and G40.21 350WT steels, respectively. The maximum reduction is 7% found in AISI 1022 HR steel while it is 14% in G40.21 350WT steel.
Figure (4.20) Effect of mean strain on percentage reduction in area of AISI 1022 HR steel

Figure (4.21) Effect of mean strain on percentage reduction in area of G40.21 steel
4.5.5 Effect of Strain Amplitude-Percentage Reduction in Area

Figure (4.22) shows the relationship between percentage reduction in area and number of strain cycles as a function of strain amplitude. This figure exhibits insignificant change in the percentage reduction in area, for specimens made of G40.21 350WT steel and tested at strain amplitudes of 1000 µε and 1500 µε. The maximum reduction is 1.9% and recorded from specimen tested at strain amplitude of 1500 µε.

![Graph showing effect of strain amplitude on percentage reduction in area of G40.21 steel](image)

**Figure (4.22) Effect of strain amplitude on percentage reduction in area of G40.21 steel**

4.5.6 Effect of Temperature-Percentage Reduction in Area

Similar to specimens tested in room temperature no significant change in percentage reduction in area for specimens tested in low temperatures was observed. The maximum reduction is 5.8% which was recorded in specimen tested in -15°C. Figure (4.23) shows the effect of temperature on percentage reduction in area of G40.21 350WT steel.
4.6 TOUGHNESS

The toughness indicated in this study is the ability to absorb energy as it fractures. It can be estimated as the area under the stress-strain curve and it has the unit of energy per unit volume. This area is divided into two parts. The first one is the elastic part which lies under the linear region of stress-strain curve (strain energy recovered upon fracture). The second part lies under the nonlinear region of stress-strain curve. Thus, a tough material is the one which has a large area under the plastic part of the curve [Sandor, 1972 and Callister, 2001]. In this study, the toughness was estimated as the area under the plastic part of the stress-strain curve for both post-cyclic and monotonic specimens. Figures (4.24) and (4.25) illustrate the relationships between toughness and the number of strain cycles for AISI 1022 HR and G40.21350WT steels, respectively.

4.6.1 Effect of Mean Strain

In general, toughness decreased as the strain cycle count increased for both steels. It is found that major reduction in toughness occurred in the first 25,000 load cycles, and then no considerable change in toughness was found. The maximum reduction in toughness was recorded from specimens tested with the higher mean strains (5500 με and
10500 με), and it is true for both steels. The maximum reduction in toughness in AISI 1022 HR steel is 14% which was found in specimen tested with mean strain of 5500 με, while the reduction was 24% in G40.21 350WT steel for specimen tested with mean strain of 10500 με.

![Figure (4.24) Effect of mean strain on toughness for AISI 1022 HR steel](image)

Figure (4.24) Effect of mean strain on toughness for AISI 1022 HR steel
4.6.2 Effect of Strain Amplitude

Figure (4.26) presents the effect of strain amplitude on the toughness of G40.21 35WT steel. In general, the toughness reduced in specimens tested with both strain amplitudes due to cyclic loading. The specimens tested at 1500 με strain amplitude shows much lower toughness as compared to those tested at 1000 με strain amplitude. However, the maximum reduction in toughness for both strain amplitudes is 12%.
4.6.3 Effect of Temperature

Figure (4.27) illustrates the effect of temperature on toughness of post-cyclic specimens made of G40.21 350WT steel. The toughness reduced at room and low temperatures due to application of strain cycles. The maximum reduction of 12% was recorded in specimens tested in room temperature, as compared to the average reduction of 8% for the specimens tested in low temperatures. In general, application of strain cycles led to a smaller area under stress-strain curve for the post-cyclic specimens as compared to monotonic specimens. As a result, the crack propagation rate increased and caused lower fatigue life of the steel. This observation complement the fact that fatigue lives found in specimens tested at room temperature were lower than those of specimens tested at low temperatures (see Figure 4.36). This study therefore, found that the temperature has a significant effect on the toughness of G40.21 350WT steel of both monotonic and post-cyclic specimens. The lower test temperatures resulted in lower reduction in toughness, which led to longer fatigue lives in very low temperatures.
4.7 STRESS SOFTENING AND MEAN STRESS RELAXATION

In strain-controlled mode, cycle-dependent softening refers to a gradual decrease in stress range required to accommodate the constant strain range applied [Shigley, 2006]. Usually, cycle-dependent responses occur in an exponential envelope with the bulk of change occurring early in the cycle count of up to 5 kcycles. Thus, the materials resistance to deformation becomes weaker as the load cycle count increases and the stress range stabilizes. This phenomenon is known as plastic shakedown.

Figure (4.28) shows the stress softening of AISI 1022 HR and G40.21 350WT steels for test series A1 and G1, respectively. In this figure the vertical axis represents stress and the horizontal axis represents the number of strain cycles. The first cycle of loading is similar in both steels in terms of stress required to perform the applied strain. However, after a few thousands of cyclic loading (i.e. in stress stability period) the stress required for sustaining the applied strain in G40.21 350WT steel is less than that of AISI 1022 HR steel. In other words, the resistance to strain cycles of AISI 1022 HR steel is higher than G40.21 350WT steel. The mean stress relaxed in a similar manner for both steels.
However, a slightly higher mean stress in AISI 1022 HR steel was found. Similar behaviour was observed from other test series A2, A3, G2 and G3. These observations in terms of stress-strain curve are consistent with those obtained by Landgraf (1969) on SAE 4142 steel. Landgraf’s study also proved that steel of BHN less than 500 is cyclically softens under cyclic loading [Landgraf, 1969].

![Stress softening and mean stress relaxation of AISI 1022 HR and G40.21 350WT steels](image)

Figure (4.28) Stress softening and mean stress relaxation of AISI 1022 HR and G40.21 350WT steels

Figure (4.29) shows the effect of temperature on stress softening and mean stress relaxation of post-cyclic specimens made of G40.21 350WT steel. In the first cycle, stress required to perform the applied strains (mean strain of 1000 $\mu$ε and strain amplitude of 1500 $\mu$ε) is higher for specimens tested in low temperatures. After plastic shake down occurred the stress range in low temperatures specimens is higher than that of room temperature specimens. This is another affect of temperature which attribute to the higher resistance of structural steel to cyclic loading in low temperatures. This resistance is a result of strengthening interatomic bonds in the steel lattice structure due to cooling effect [DeGarmo, 2003]. The mean stress relaxed in low temperatures specimens with higher plateau as compared to that of room temperature specimens.
Figure (4.29) Effect of temperature on stress softening and mean stress relaxation of G40.21 350WT steel

The hysteresis loops of the three test series A1 to A3 for AISI 1022 HR steel are shown in Figure (4.30). All series were tested in strain amplitude of 1500 µε while the mean strain varied from 1000 µε to 10500 µε. Each series consists of two loops: first loop corresponds to the 1st cycle and the second corresponds to the 100,000th cycle. The cyclic loading history (i.e., strain limits) was increased gradually to ensure no overloading occurs in the commencement of the test. Therefore, the 1st cycle here is the cycle where the full loading history was applied. The stress relaxation is obvious at the 100,000th cycle loop if compared with the 1st cycle loop. The maximum stress relaxation of 18% occurred in series A1 (tested in the lower mean strain of 1000 µε). The amount of stress relaxation reduced as the mean strain level increased. The minimum stress relaxation of 14% was recorded in series A3 which was tested with mean strain of 10500 µε.
Figure (4.31) shows the hysteresis loops of G40.21 350WT steel for the first three series G1, G2 and G3. Those three series were tested in the same loading histories as those of series A1, A2, and A3, respectively. The trend of stress relaxation is similar as that of AISI 1022 HR steel. However, the stress relaxation is almost doubled in G40.21 350WT steel (series G1 of 37%) as compared with that found in AISI 1022 HR steel (series A1 of 18%). The other two series G2 and G3 of G4021 350WT steel exhibited a stress relaxation of 31% and 30%, respectively. Simple comparison between stress relaxation of G40.21 350WT steel and those found for AISI 1022 HR steel indicates that the latter steel has higher resistance to cyclic loading. The last observation regarding stress relaxation agrees with the behaviour of G40.21 350WT and AISI 1022 HR steels found in Figure (4.28). This figure also shows that AISI 1022 HR steel has higher resistance to cyclic loading than G40.21 350WT steel in room temperature.
Figure (4.32) shows the effect of strain amplitude on hysteresis loops of G40.21 350WT steel in room temperature. Each series was represented by two loops, the first loop is for the 1\textsuperscript{st} cycle and the second one is for the 100,000\textsuperscript{th} cycle. Examination of the stress relaxations of the two series of specimens shows a very small difference. The reduction in stress was 37\% and 38\% for specimens tested in strain amplitudes of 1500 $\mu$\varepsilon and 1000 $\mu$\varepsilon, respectively. Therefore, it was found that the strain amplitude has no effect on stress relaxation of G40.21 350WT steel in room temperature.
Figure (4.32) Effect of strain amplitude on hysteresis loops of G40.21 steel at RT

The effect of temperature on hysteresis loops of G40.21 350WT steel is illustrated in Figure (4.33). Two specimens were compared in this figure. The first one was tested at room temperature (~25°C) and the second specimen was tested at -30°C. Both specimens were subjected to the same loading history (mean strain of 1000 µε and strain amplitude of 1500 µε). As in the last three figures, each series in Figure (4.33) is represented by two loops: the first loop is for the 1st cycle and the second is for the 100,000th cycle. The specimen tested in temperature of -30°C exhibited higher stress relaxation than the specimen tested in room temperature. The stress relaxation was 46% in specimen tested at -30°C, while it was 37% for specimen tested in room temperature. Hence, Figure (4.33) shows that the stress of the 1st cycle is much higher in the -30°C specimen than that of the room temperature specimen, which caused higher difference between stress limits of the first and the 100,000th cycle. This difference led to a higher relaxation in the -30°C specimen as compared to that of the room temperature specimen. Furthermore, Figure (4.33) also reveals that the maximum stress of the 100,000th cycle in specimen tested in -30°C loop is higher than that of the room temperature specimen. It can be
concluded that resistance of G40.21 steel to cyclic loading at low temperatures is higher than that at room temperature.

![Hysteresis loops of G40.21 350WT steel in +25 °C and -30 °C](image)

**Figure (4.33) Hysteresis loops of G40.21 350WT steel in +25 °C and -30 °C**

Tables (4.1) to (4.3) present comparisons of percentage changes in mechanical properties. The ductility in these three tables was represented by the percentage elongation. The change in ductility in terms of percentage reduction in area was not presented in these tables because changes in percentage reduction in area were insignificant. All of the specimens listed in these three tables are tested with mean strain of 1000 µε. Specimens in Tables (4.1) and (4.3) were subjected to mean strain of 1000 µε and strain amplitude of 1500 µε. Specimens in Table (4.2) were subjected to mean strain of 1000 µε and two strain amplitudes of 1000 µε and 1500 µε.

Table (4.1) shows the changes in properties of G40.21 350WT and AISI 1022 HR steels tested in room temperature. The increases in tensile strength in both steels were similar. The maximum percentage of increase was 5% which was recorded from specimen made of AISI 1022 HR steel and loaded to 75 kcycles. The yield strength increased in both steels as well. However, AISI 1022 HR steel exhibited slightly higher increase. The
maximum increase in yield strength was 16%. This increase was recorded from of specimen made of AISI 1022 HR steel and loaded to 100 kcycles. The fracture strength also increased in both steels. However, G40.21 350WT steel showed slightly higher increase in fracture strength. The maximum increase is 16% in specimen made of G40.21 350WT steel and loaded to 25 kcycles.

However, the ductility reduced in both steels. The reduction of AISI 1022 HR steel was relatively higher than G40.21 350WT steel. The maximum reduction was 12% in specimens made of AISI 1022 HR steel and tested to 5 kcycles and 100 kcycles. The toughness reduced in both steels as well. The higher reduction was found in specimens made of G40.21 350WT steel. The maximum reduction of 12% was recorded in specimen tested to 75 kcycles. The stress softened in both steels. The higher softening found in G40.21 350WT steel. The maximum softening is 37% which was recorded in specimen made of G40.21 350WT steel and loaded to 100 kcycles.

It can be concluded that the tensile strength and yield strength increased in AISI 1022 HR steel with higher percentages than those of G40.21 350WT steel. Generally, the fracture strength increased in G40.21 steel with higher percentages than those of AISI 1022 steel. However, ductility decreased in AISI 1022 HR steel more than that of G40.21 350WT steel. On the contrary, the reduction in toughness and stress softening of G40.21 350WT steel are higher than those of AISI 1022 HR steel.
Table (4.1) Comparison of changes in properties of G40.21 and AISI 1022 HR steels

<table>
<thead>
<tr>
<th>Property</th>
<th>G40.21 350WT steel</th>
<th>AISI 1022 HR steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of strain cycles (kcycles)</td>
<td>No. of strain cycles (kcycles)</td>
</tr>
<tr>
<td></td>
<td>5 25 50 75 100</td>
<td>5 25 50 75 100</td>
</tr>
<tr>
<td>Tensile St.</td>
<td>2% 2% 3% 3% --</td>
<td>2% 3% 4% 5% 4%</td>
</tr>
<tr>
<td>Yield St.</td>
<td>5% 13% 13% 13% --</td>
<td>9% 14% 14% 14% 16%</td>
</tr>
<tr>
<td>Fracture St.</td>
<td>3% 16% 11% 14% --</td>
<td>4% 5% 4% 4% 5%</td>
</tr>
<tr>
<td>Elongation</td>
<td>5% 5% 3% 11% --</td>
<td>12% 9% 9% 9% 12%</td>
</tr>
<tr>
<td>Toughness</td>
<td>3% 10% 11% 12% --</td>
<td>4% 6% 7% 7% 8%</td>
</tr>
<tr>
<td>Softening</td>
<td>35% 35% 35% 35% 37%</td>
<td>18% 18% 18% 18% 18%</td>
</tr>
</tbody>
</table>

Note: The specimens of this table were subjected to mean strain of 1000 µε and strain amplitude of 1500 µε, and test were conducted at room temperature.

Table (4.2) shows a comparison of test carried out with two different strain amplitudes at room temperature. The strain amplitudes are: 1500 µε and 1000 µε. These tests were conducted on G40.21 350WT steel in room temperature. This table presents percentage changes to illustrate the difference in mechanical properties. In general, the tensile strength increased in specimens tested with both strain amplitudes. The higher increase was recorded in specimens tested with strain amplitude of 1500 µε. The maximum increase was 3% which was occurred in specimens loaded to 50 kcycles and 75 kcycles. Similarly, the yield strength increased in specimens tested in both strain amplitudes. The higher increase was recorded in specimens tested with strain amplitude of 1500 µε. The maximum increase in yield strength was 13% which occurred in specimens loaded to 25 kcycles, 50 kcycles, and 75 kcycles. The fracture strength also increased in specimens tested with both strain amplitudes. The higher increase was recorded in specimens subjected to 1500 µε. The maximum increase is 16% and recorded from specimen tested to 25 kcycles.

The ductility reduced in specimens tested in both strain amplitudes. The higher reduction was recorded in specimens loaded with strain amplitude of 1500 µε. The maximum
reduction is 11% which occurred in specimens tested to 75 kcycles. The toughness reduced in specimens tested in both strain amplitudes as well. The higher reduction was recorded in specimens tested in strain amplitude of 1500 µε and the value was 12% which occurred in specimen loaded to 75 kcycles. The stress softened in both steels; however a higher reduction was found in specimens tested with strain amplitude of 1500 µε. The maximum reduction is 37% which occurred in specimen loaded to 100 kcycles.

It can be concluded that the maximum increase or reduction in any mechanical property was found in specimens tested at strain amplitude of 1500 µε. In other words, the higher strain amplitude leads to the higher change in the mechanical property.

Table (4.2) Summary of changes in properties of G40.21 steel in different strain amplitudes

<table>
<thead>
<tr>
<th>Property</th>
<th>Strain amplitude = 1500 µε</th>
<th>Strain amplitude = 1000 µε</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of strain cycles (kcycles)</td>
<td>No. of strain cycles (kcycles)</td>
</tr>
<tr>
<td>Tensile St.</td>
<td>5  25  50  75  100</td>
<td>5  25  50  75  100</td>
</tr>
<tr>
<td></td>
<td>2%  2%  3%  3%  --</td>
<td>1%  .75%  2%  1.5%  1.5%</td>
</tr>
<tr>
<td>Yield St.</td>
<td>5%  13%  13%  13%  --</td>
<td>9%  9%  7%  5%  3%</td>
</tr>
<tr>
<td>Fracture St.</td>
<td>3%  16%  11%  14%  --</td>
<td>5%  6%  4%  5%  3%</td>
</tr>
<tr>
<td>Elongation</td>
<td>5%  5%  3%  11%  --</td>
<td>0.5%  7%  1%  5%  3%</td>
</tr>
<tr>
<td>Toughness</td>
<td>3%  10%  11%  12%  --</td>
<td>2%  5%  6%  6%  9%</td>
</tr>
<tr>
<td>Softening</td>
<td>35%  35%  35%  35%  37%</td>
<td>10%  21%  21%  21%  21%</td>
</tr>
</tbody>
</table>

Note: The specimens of this table were subjected to mean strain of 1000 µε, and tests were conducted in room temperature (~25°C).

Table (4.3) presents the effect of temperature on mechanical properties of G40.21 350WT steel. All specimens in this table were subjected to mean strain of 1000 µε and strain amplitude of 1500 µε. The comparison in this table is made between specimens tested in room temperature and in -30°C. The temperature (-30°C) was selected in this comparison because it was the lowest testing temperature chosen in this study and shows the effect of extreme temperature.
Similar to specimens tested at room temperature (+25°C), the tensile strength increased in specimens tested at -30°C. The increase in tensile strength was similar in both temperatures. The maximum increase was 3% which occurred in specimens tested to 50 kcycles and 100 kcycles in room temperature, and those tested to 100 kcycles in -30°C. The yield strength of specimens tested at room temperature and -30°C also increased. The higher increase was recorded in specimens tested in room temperature. The maximum increase in yield strength was 13% and occurred in specimens loaded to 25 kcycles, 50 kcycles, and 75 kcycles. The fracture strength increased as well in specimens tested in room and low temperatures. The higher increase was recorded in specimens tested in room temperature. The maximum increase was 16% in specimen tested to 25 kcycles.

However, the ductility reduced in both temperatures. The higher reduction was recorded in specimens tested in -30°C. The maximum reduction was 22% which occurred in specimens tested to 75 kcycles in -30°C. Moreover, the toughness reduced in -30°C similar to its reduction in room temperature tests. The maximum reduction of 12% was recorded in specimen tested to 75 kcycles in room temperature. The stress softened in temperature of -30°C as it was in specimens tested in the room temperature. The maximum reduction was 48%. This softening was recorded in specimens loaded to 25 kcycles, 50 kcycles, 75 kcycles, and 100 kcycles and tested in -30°C.

It can be concluded that the higher increase of most mechanical properties (tensile, yield and fracture strengths) was recorded in specimens tested in room temperature. However, the higher reduction of other mechanical properties (ductility and stress softening) was recorded in specimens tested in -30°C. Furthermore, the higher reduction in toughness was recorded in specimens tested in room temperature.
Table (4.3) Summary of changes in properties of G40.21 steel in different temperatures

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Temperature= +25°C</th>
<th>Test Temperature= -30°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of strain cycles (kcycles)</td>
<td>No. of strain cycles (kcycles)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Tensile St.</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Yield St.</td>
<td>5%</td>
<td>13%</td>
</tr>
<tr>
<td>Fracture St.</td>
<td>3%</td>
<td>16%</td>
</tr>
<tr>
<td>Elongation</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Toughness</td>
<td>3%</td>
<td>10%</td>
</tr>
<tr>
<td>Softening</td>
<td>35%</td>
<td>35%</td>
</tr>
</tbody>
</table>

Note: The specimens of this table were subjected to mean strain of 1000 µε and strain amplitude of 1500µε.

4.8 STRAIN-LIFE DIAGRAM

As mentioned in Chapter 2, fatigue-life can be presented in three different ways and these are: the stress-life, the strain-life, and the linear-elastic fracture mechanics. The stress-life method based on stress levels only and this is the least accurate approach, especially for low-cycle applications. The strain-life method involves more detailed analysis of the plastic deformation at localized regions where the stresses and strains are considered for life estimates. This method is especially suitable for low-cycle fatigue applications [Shigley, 2006]. Therefore, the strain-life method was used in this study to determine the fatigue limit in terms of strain.

Three approaches are presented in this section. The first approach is the strain-life relationship considering the mean strain for AISI 1022 HR and G40.21 350WT steels. The second approach is also strain-life relationship but considering strain amplitude for G40.21 350WT steel. Finally, the third approach considers the effect of temperature on strain-life relationship of G40.21 350WT steel.
4.8.1 Mean Strain Approach

In Figure (4.34) the mean strain is considered in determining the strain-life relationship of AISI 1022 HR and G40.21 350WT steels. The strain amplitude was 1500 $\mu \varepsilon$ while the mean strain was varied from 1000 $\mu \varepsilon$ to 10500 $\mu \varepsilon$. Figure (4.34) shows that the fatigue life of G40.21 350WT steel in the region of high mean strains was slightly less than that of AISI 1022 HR steel. This may have attributed to the higher reduction in toughness of G40.21 350WT steel due to application of strain cycles as compared to that of AISI 1022 HR steel. However, the fatigue strain limit was found to be almost the same for both steels.

![Mean strain-life diagram of AISI 1022 HR and G40.21 350WT steels](image)

Figure (4.34) Mean strain-life diagram of AISI 1022 HR and G40.21 350WT steels

4.8.2 Strain Amplitude Approach

Figure (4.35) shows the effect of strain amplitude on fatigue life of G40.21 350WT steel in room temperature. The mean strain was zero while strain amplitude was varied. The specimens were tested with fifteen different levels of strain amplitudes ranging from 1000 $\mu \varepsilon$ to 2400 $\mu \varepsilon$. The maximum life of 2.017 million cycles was recorded in specimen subjected to strain amplitude of 1000 $\mu \varepsilon$. However, the minimum life of 14,000 cycles was found in specimen subjected to strain amplitude of 2400 $\mu \varepsilon$. 
Figure (4.35) shows that the fatigue limit in terms of strain amplitude would be less than 1000 $\mu\varepsilon$. The strain fatigue limit is defined as the stress generates from applying strain amplitude to overcome the crack growth barrier for further crack propagation [McGreevy and Socie, 1999, and Murakami et al., 2002].

The scatter in fatigue life was higher in tests conducted under lower strain amplitudes. The rationale of this scatter is the high sensitivity for surface effects at low stress amplitudes. This observation agrees with the findings mentioned in Schijve (2004): “The high sensitivity for surface effects at low stress amplitudes and the relatively low sensitivity for surface effects at high stress amplitudes can lead to more scatter of the fatigue life at low amplitudes and less scatter at high amplitudes”.

![Figure (4.35) Strain-life diagram of G40.21 350WT steel](image)

**4.8.3 Temperature Effect**

One of the most significant observations found in this study is the effect of temperature on fatigue life of G40.21 350WT steel. Figure (4.36) presents the data obtained from specimens tested in temperatures of +25°C, +10°C, 0°C, -5°C, -15°C, and -30°C. The mean strain was maintained at the level of 1000 $\mu\varepsilon$ and the strain amplitude was kept at 1500 $\mu\varepsilon$. Surface roughness was prepared to be less than 0.2 $\mu$m as recommended by ASTM standard E606. Strain rate, $\dot{\varepsilon}$, was maintained at 0.024 (s$^{-1}$). In
order to keep the strain rate unchanged, the testing frequency was changed accordingly as strain amplitude changed (see Table 3.2 in Chapter 3). The experimental results show a substantial increase in fatigue life as the temperature decreased. For each temperature two repeat specimens were tested. The fatigue life varied from 60 kcycles to 96 kcycles for specimens tested at room temperature (≈25°C), while the life varied from 722 kcycles to 765 kcycles in specimens tested at -30°C. The fatigue life increased by a factor of 7 to 12 as the test temperature changed from +25°C to -30°C. This observation can be justified by the strengthening of inter-atomic bonds in the steel microstructure as temperature decreased. In the crack propagation period, the crack propagates through breaking bonds between atoms toward final rupture of steel specimen [Schijve, 2004]. It was found that, for tests carried out at low temperatures, the binding forces become stronger [DeGarmo, 2003]. Hence, the crack propagation rate decreased and led to longer fatigue life. The observation found from Figure (4.36) agrees with that found by Forrest (1962) on carbon steels, cast steels, and alloy steels. From the findings of Forrest the fatigue life of carbon steels increased by a factor of 4 when tested at temperature of -40°C. Moreover, Spretnak et al. (1951) concluded that, low temperatures are usually beneficial to fatigue life for un-notched specimens tested under constant amplitude load [Stephens et al., 2001].

![Figure (4.36) Life-temperature relationship of G40.21 350WT steel](image)

Mean=1000με, Amplitude=1500με, \( \dot{\varepsilon} = 0.024 \) 1/s, Ra<0.2 μm
Quick rise in temperature at a specific location along gauge length usually indicates initiation of cracks at that location. The infrared thermometer was utilized to measure temperatures along the gauge length as shown in Figure (4.37). The temperature increased up to 50ºC from point to another along gauge length of the specimen tested at room temperature. This temperature difference is related to the strain amplitude applied. The higher the strain amplitude, the higher the temperature difference among the points was found. On the other hand, the temperature difference is related inversely to fatigue life.

![Infrared Thermometer](image)

**Figure (4.37) Temperature difference detection using infrared thermometer**

### 4.9 SUMMARY

This chapter discussed the experimental results from the current study. Two main sections of this chapter are the mechanical behaviour of the fatigue-damaged steels and the strain-life relationship. The experimental results can be summarized in the following points.

**Stress-strain Curve**

The monotonic tensile strength and yield strength of G40.21 350WT steel increased at low temperatures. The monotonic tensile strength increased at temperatures of -15°C to -30°C by 1.5%. However, the yield strength increased in temperatures of 0°C to -30°C by 14%.

Both AISI 1022 HR and G40.21 350WT steels were strain hardened until necking began (around strain of 0.20). Then both steels softened until rapture.
The modulus of elasticity did not change as a result of application of strain cycles for both steels.

**Tensile Strength**

The tensile strength increased as a result of applying strain cycles on both steels. However, the effect of the mean strain on the tensile strength was negligible. The maximum increase is 5% for AISI 1022 HR steel, while the maximum increase is 3% for G40.21 350WT steel. Both maximum values were recorded in specimens tested with mean strain of 1000 $\mu\varepsilon$. Therefore, the lower mean strain produced higher increase in tensile strength of both steels.

The strain amplitude affected the tensile strength more than that of the mean strain for G40.21 350WT steel. The maximum increase was 3% for strain amplitude of 1500 $\mu\varepsilon$, while it was 1.5% for strain amplitude of 1000 $\mu\varepsilon$. Hence, the higher strain amplitude led to higher increase in tensile strength.

The tensile strength increased for the *post-cyclic* specimens made of G40.21 350WT steel in low temperatures by similar amount as that of the room temperatures specimens. The maximum increase at room temperature was 3%, while it was 2.5% at low temperature.

**Yield Strength**

The yield strength increased for the *post-cyclic* specimens if compared with the monotonic specimens in both steels. Both mean strain and strain amplitude showed large effect on the yield strength. The maximum increase was 19% in AISI 1022 HR steel while it was 16% in G40.21 350WT steel.

The strain amplitude of G40.21 350WT steel affected the yield strength as well. The maximum increase was 13% in specimen tested in 1500 $\mu\varepsilon$ while it was 9% in specimen tested in 1000 $\mu\varepsilon$.

The yield strength of G40.21 350WT steel was influenced by temperature. It increased in all temperatures considered in this study. The maximum increase was 13% at room temperature while its maximum increase was 9% and recorded at -30°C for the same loading history.
**Fracture Strength**

The fractures strength increased in both steels as a result of application of strain cycles. For AISI 1022 HR steel the maximum increase is 5% while it was 16% for G40.21 350WT steel, for the same loading history in room temperature. The maximum increase for AISI 1022 HR steel was recorded in the higher mean strain while it was recorded in lower mean strain tests in G40.21 350WT steel.

The effect of strain amplitude on the fracture strength was investigated using G40.21 350WT steel. The higher strain amplitude (1500 µε) produced higher increase of 16% while the maximum increase was 6% in the lower strain amplitude tests (1000 µε).

The temperature effect on the fracture strength for G40.21 350WT steel was studied as well. The low temperature produced lower increase than that of the room temperature tests. The maximum increase was 9% and recorded at temperature of -15°C while it was 16% at room temperature tests, for the same loading history.

**Ductility**

The ductility was studied for both steels in terms of percentage elongation and percentage reduction in area. In general, the percentage elongation decreased more than that of percentage reduction in area, due to application of strain cycles. The maximum reduction was 18% for AISI 1022 HR steel and it was 20% for G40.21 350WT steel. These maximum reductions occurred in specimens tested to the higher mean strains (5500 µε and 10500 µε).

The strain amplitude affected the percentage elongation of G40.21 350WT steel. The higher reductions were found in specimens tested at higher strain amplitude (1500 µε) as compared to the 1000 µε strain amplitude specimens.

The test temperature affected the changes in percentage elongation. The highest reduction in percentage elongation was found in specimens tested at lower temperatures (-15°C and -30°C) as compared to the room temperature specimens for the same loading history. The maximum reduction recorded is 22% at -30°C.
**Toughness**

The toughness decreased as the strain cycle count increased for both steels. The maximum reduction in toughness for AISI 1022 HR steel is 14% in specimen tested with mean strain of 5500 µε, while the reduction is 24% for G40.21350WT steel tested to mean strain of 10500 µε.

The strain amplitude affected the reduction of toughness in G40.21 350WT steel. The toughness plateau of the 1500 µε strain amplitude was shifted down as compared to those of the 1000 µε strain amplitude. However, the same maximum reduction of 12% was found in specimens tested in both strain amplitudes (1000 µε and 1500 µε).

The temperature influenced the reduction in toughness as a result of application strain cycles. The average of maximum reduction of 8% was recorded in specimens tested in low temperatures as compared to the 12% for those tested in room temperatures, for the same loading history. As a result, lower temperatures produced higher toughness if compared with room temperature.

**Stress Softening and Mean Stress Relaxation**

The stress softened in both steels as a result of application strain cycles. The first cycle of loading was similar for both steels in terms of stress required to perform the applied strain. However, after a few thousands of cycles (i.e. in the stress stability period) the stress required to perform the applied strain in G40.21 350WT steel was less than that of AISI 1022 HR steel. Therefore, the stress wave of G40.21 350WT steel has lower range. The maximum softening in AISI 1022 HR steel was 18%, while it was 37% in G40.21 350WT steel. The maximum softening occurred in tests conducted with a mean strain of 1000 µε, in both steels.

The strain amplitude did not affect the softening of G40.21 350WT steel. The softening was 37% in strain amplitude of 1500 µε while it was 38% in strain amplitude of 1000 µε.

The temperature affected stress softening and mean stress relaxation of G40.21 350WT steel significantly. In the first cycle, stress required to perform the applied strain is higher for specimens tested in low temperatures. Likewise, after plastic shake down occurred the
stress range in low temperatures tests is higher than that of room temperatures tests. However, less difference in the stress ranges of the room temperature and -30°C specimens was observed after shakedown occurrence. The maximum softening was 46% in tests conducted in -30°C, while it was 37% in room temperature specimens for the same loading history. The mean stress relaxed in room temperatures with lower plateau than that of low temperature tests.

Strain-Life relationship

There are three approaches considered in studying the strain-life relationship experimentally. In the first approach, the mean strain was considered in studying fatigue-life relationship of AISI 1022 HR and G40.21 350WT steels. AISI 1022 HR steel revealed higher fatigue life than that of G40.21 350WT steel in the high strains region. However, the fatigue strain limit was almost similar for both steels.

In the second approach, the strain amplitude was considered in studying strain-life relationship of G40.21 350WT steel. This approach is the most familiar approach in studying strain-life relationship. The mean strain was maintained on zero magnitude while strain amplitude varies from 1000 µε to 2400 µε. The maximum life was 2.017 million cycles, while the minimum one was 14 thousand cycles. The fatigue limit in terms of strain amplitude was less than 1000 µε.

In the third approach, the effect of temperature on strain-life relationship of G40.21 350WT steel was studied. The mean strain was maintained on magnitude of 1000 µε and strain amplitude was 1500 µε. The testing temperatures considered were +25°C, +10°C, 0°C, -5°C, -15°C, and -30°C. The fatigue life varied from 60 kcycles to 96 kcycles for specimens tested in +25°C while it varied from 722 kcycles to 765 kcycles in specimens tested in -30°C. The fatigue life multiplied by a factor varies from 7 to 12 as the test temperature reduced from +25°C to -30°C.
CHAPTER 5: EMPIRICAL FORMULATION AND STATISTICAL ANALYSIS

Scatter in fatigue life test data is expected in fatigue testing and analysis. A variety of factors contribute to this scatter. This includes inherent variability of the material (i.e., variations in chemical composition, impurity levels, and discontinuities), variations in heat treatment and manufacturing (i.e., surface finish and hardness), variations in specimen or component geometry (i.e., differences in notch radii and weld geometry), and variability from differences in the test conditions (i.e., environmental and test machine alignment variations). In addition, there are sources of uncertainty arising from variations in the history of measured or applied load as well as from the analytical methods used. These variations and uncertainties can result in significant variability in the fatigue life of the specimen, component, or machine.

A fatigue analysis conducted by Sinclair and Dolan (1953) on 7075-T6 Aluminum alloy revealed that higher scatter occurred at lower stress levels, as indicated by steeper slopes in the results. At the highest stress level the fatigue life varied from about $1.5 \times 10^4$ to $2 \times 10^4$ cycles (i.e., by a factor of less than 2). At the lowest stress level, the fatigue life varied from about $2 \times 10^6$ to $7 \times 10^7$ cycles, (i.e., a factor of about 35). The scatter factor was estimated as the difference between highest and lowest lives of group of identical tests divided by the lowest life. Variation in fatigue life to a scatter factor of 100 is not uncommon for very low stress levels in fatigue tests. Scatter is usually greater in unnotched polished specimens than notched or cracked specimens. The greater scatter at low stress levels in these smooth unnotched specimens can be attributed to the greater proportion of the fatigue life needed to nucleate small microcracks and then macrocracks. At higher stress levels a greater percentage of the fatigue life involves the growth of macrocracks. Tests involving only fatigue crack growth under constant amplitude conditions usually show more consistent scatter factors of 2 or 3 or less for identical tests. Thus, the greatest variability in fatigue life results involves with the nucleation of microcracks and small macrocracks. In notched specimens and components cracks form more quickly, and subsequently, a greater proportion of the total fatigue life involves with crack growth and hence, it results in more consistent and less scattered test data.
Statistical analyses are used to describe and analyze fatigue properties as well as to estimate the probability of fatigue failure or fatigue life. This type of analysis allows quantitative evaluation of component or product reliability and prediction of service performance for a given margin of safety.

Statistical analyses are also used for experimental design in order to avoid confounding of the sources of variability and to determine the minimum number of specimen or component tests required for a given reliability and confidence level [Stephens et al., 2001].

5.1 TEST PLANNING

Group selection (and order of testing) was made to ensure that key variables are either randomized or balanced across the test groups are essential features of a well-planned test program. In particular, good test methodology requires the use of planned group selection and test order to achieve the following.

(i) to balance potentially spurious effects of nuisance variables (e.g., laboratory humidity) across all test groups, and

(ii) to reduce the impact of potential data collection difficulties (e.g., equipment malfunction during testing) so that the disruptive effects are spread across all groups [ASTM E739-10].

In the current study, the specimens were selected and classified in groups using specific order (see section 3.2.2.2, Test Matrix).

5.2 SAMPLING

It is vital that sampling procedures have to be adopted to ensure a random sample of material being tested. Random sampling is required so that the test specimens are representative to the conceptual framework upon which both statistical and engineering inferences are drawn. The random sampling procedure allows each specimen to has an equal opportunity of actually being selected at each stage of the sampling process. Thus, it is poor practice to use specimens obtained from a single source (e.g., plate, heat, supplier) when seeking a random sampling of the material being tested unless that particular source is of specific interest. The minimum number of specimens required in S-
$N$ (and $\varepsilon$-$N$) testing depends on the type of test program to be conducted and it can be calculated using statistical power analysis [ASTM E739, 2010]. In the current study, the number of strain amplitudes for developing the $\varepsilon$-$N$ diagram was 15 to ensure smooth curve fitting (see italicized second line in Table 5.1). Table (5.1) specifies the minimum number of stress or strain amplitudes recommended for fatigue tests.

**Table (5.1) Minimum number of stress or strain amplitudes recommended for fatigue tests**

[ASTM E739, 2010]

<table>
<thead>
<tr>
<th>Type of Test</th>
<th>Minimum Number of Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary and exploratory (exploratory research and development tests)</td>
<td>6 to 12</td>
</tr>
<tr>
<td><em>Research and development testing of components and specimens</em></td>
<td>6 to 12</td>
</tr>
<tr>
<td>Design allowable data</td>
<td>12 to 24</td>
</tr>
<tr>
<td>Reliability data</td>
<td>12 to 24</td>
</tr>
</tbody>
</table>

### 5.3 REPLICATION

As mentioned at the beginning of this chapter, scatter is quite common in fatigue life test results. Conclusions based on a single case or test result cannot be considered reliable and adoptable. Therefore, each particular test must be repeated at least once to assess the correctness of the results. The accuracy and consistency of experimental test results of fatigue life is in doubt if the technique used did not include replication. Replication is needed to assess variation or scatter. The degree of variation affects the reliability (i.e., consistency of findings obtained under the specified experimental conditions) and validity (i.e., whether or not the findings can be generalized to similar materials) of the experimental findings.

The ASTM E739-10 guidelines governing replication in fatigue testing include the following definition for percent replication.

Percent replication = \[1 - \left(\frac{\text{total number of different stress or strain levels used in testing}}{\text{total number of specimens tested}}\right)\] ×100
In the current study, the total number of strain amplitudes used for the $\varepsilon$-N curve was 15. Therefore, the total number of specimens used was 30 as the number of replicates was 2. Using the above equation the percent replication is 50%. This replication percentage falls within the [ASTM E739-10] recommended levels for research and development fatigue testing of components and specimens (see italicized second line in Table 5.2).

**Table (5.2) Percent replication recommended for fatigue tests [ASTM E739, 2010]**

<table>
<thead>
<tr>
<th>Type of Test</th>
<th>Percent Replication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary and exploratory (exploratory research and development tests)</td>
<td>17 to 33 min</td>
</tr>
<tr>
<td><em>Research and development testing of components and specimens</em></td>
<td>33 to 50 min</td>
</tr>
<tr>
<td>Design allowable data</td>
<td>50 to 75 min</td>
</tr>
<tr>
<td>Reliability data</td>
<td>75 to 88 min</td>
</tr>
</tbody>
</table>

**5.3.1 Replication Quality (examples)**

*Example of proper replication:* Suppose that ten specimen samples are used for the purpose of research and development for the fatigue testing of a component. If two specimens are tested at each of five stress or strain amplitudes (repeated measures design), the test program involves a replication percentage of 50%. This Percent Replication level is considered adequate for most research and development applications [ASTM E739, 2010].

*Example of inadequate replication:* Suppose that eight different stress or strain amplitudes are used in testing, with two replicates at each of two stress or strain amplitudes (and no replication at the other six stress or strain amplitudes, which are tested using independent specimens). This test design involves a replication percentage of only 20%, which is not generally considered adequate [ASTM E739, 2010].

**5.4 DEVELOPING EMPIRICAL FORMULAE**

It is well known that cyclic load tests are expensive in terms of both time and cost. Consequently, in design processes, empirical formulae that can predict changes in mechanical properties due to cyclic loading are very useful. In the current study,
experimental data were analysed and used to derive empirical relationships that can predict the properties of post-cyclic steels using their monotonic properties and other parameters. The properties considered for the derived relations (subsequent to cyclic loading) were: the tensile strength, yield strength, fracture strength, toughness, and ductility. In addition to the monotonic properties, the parameters considered are: the number of strain cycles, mean strain, strain amplitude, and temperature. For example, Table (5.3) shows the observed and monotonic tensile strength of G40.21 350WT steel along with parameters affecting its tensile strength. The observed (experimental) tensile strength ($S_{\text{t,obs-cyc}}$) was obtained from the quasi-static tensile test after loading for a specific number of cycles and the monotonic tensile strength ($S_{\text{t,mon}}$) is for virgin steel. The normal numeric values in Table (5.3) refer to independent variables that do not change or change repeatedly within a group of populations. The bold numeric values refer to the independent variables that change in a group of populations. Finally, the italic numeric values refer to independent variables for the low temperature tests.
Table (5.3) Variables of tensile strength for G40.21 350WT steel

<table>
<thead>
<tr>
<th>Observation</th>
<th>Sut obs cyc (MPa)</th>
<th>Sut mon cyc (MPa)</th>
<th>No. of Cycles</th>
<th>Mean strain (με)</th>
<th>Strain Amp (με)</th>
<th>Temperature (°C)</th>
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</tbody>
</table>
5.4.1 Regression Analysis

Regression is usually used to find and/or analyse the relationship between a dependant variable, the response, and independent variable(s), predictor variable(s). The relationship between these variables is characterized by a mathematical model called a regression model. The regression model may be linear (such as \( y = \beta_0 + \beta_1 x \)) or nonlinear (such as \( y = \beta_1 x^p \)), where \( y \) is the response, \( x \) is the predictor, \( \beta_0 \) is the intercept, \( \beta_1 \) is the regression coefficient, and \( p \) is the power. Moreover, the model may be a single regression model (with one predictor variable, \( x \)), or a multiple regression model (with more than one predictor variable, such as \( y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_q x_q + \epsilon \)). The parameters \( \beta_j \), \( j = 0, 1, \ldots, q \), are the regression coefficients, \( q \) is the number of independent/predictor variables, and \( \epsilon \) is the error. This model describes a hyper-plane in the \( q \)-dimensional space of the predictor variables \( x_j \). The parameter \( \beta_j \) represents the expected change in the response \( y \) per unit change in \( x_j \) when all of the remaining independent variables \( x_i \) (\( i \neq j \)) are held constant [Montgomery, 2001].

5.4.1.1 The Traditional Method for Deriving a Nonlinear Multiple Regression Model

Commercially available software such as SPSS, Minitab, and Microsoft Excel can derive the functional relationship between the response variable and predictor variable(s). However, the capabilities of these software applications are limited to single or multiple linear relationships or to a single nonlinear relationship. Currently, multiple nonlinear relationships are not derivable using the commercial software mentioned above, although these software packages can perform a multiple nonlinear regression analysis if the appropriate multiple regression model is provided. The following section (5.4.1.2 Eureqa Software Method) discusses the characteristics of the Eureqa software application, which is able to derive multiple nonlinear regression models.

In the current study, the relationships between the response and predictor variables are nonlinear in nature as shown by curves fitted to experimental observations (i.e., the post-cyclic mechanical properties of steel such as tensile strength, yield strength, fracture strength, toughness, elongation, or reduction in area). The independent/predictor variables are the monotonic mechanical properties of virgin steel and the variables that were varied during experimentation (i.e., number of strain cycles, mean strain, strain...
amplitude, and temperature). Figure (5.1) illustrates an attempt to define the relationship between the response variable, post-cyclic tensile strength ($S_{tpc}$), and the predictor variables mentioned above using Microsoft Excel and Minitab software. These software can derive a linear multiple regression model (e.g. $S_{tpc} = 529 -2.09N\cdot0.003 \varepsilon_m + 0.0045 \varepsilon_a -0.147 T$). Furthermore, Excel and Minitab software can also derive a nonlinear single regression model (e.g. the tensile strength $S_{tpc} = 523.21 N^{0.0023}$ for G40.21 350WT steel, and $S_{tpc} = 561.27 N^{0.0034}$ for AISI 1022 HR steel). However, it is evident from Figure (5.1) that these derived regression models do not provide a very accurate fit with the experimental observations of the relationship between the number of loading cycles ($x$) on tensile strength ($y$), though only one predictor variable is involved in the model. In general, graphical illustrations such as Figure (5.1) show a high degree of error between the curves fitted to the observed (experimental) data and predicted data (calculated from the regression models derived with this software).

![Figure (5.1) Comparison of the regression models derived by Microsoft Excel](image)

Figure (5.1) Comparison of the regression models derived by Microsoft Excel

The traditional method for deriving multiple non-linear regression models can be summarized in the following steps [Wesolowsky, 1976].
a) Identifying correlations between the response variable and each of the predictor variable in order to evaluate the strength and nature of the relationship between predictor and response; the correlation coefficient \((r)\) indicates the nature and strength of the relationship between two variables. Subsequently, correlations between predictor variables must also be considered in order to eliminate overlapping or confounding relationships between predictors. For example, the response or the influence of two predictors on the response may be diminished if one predictor is negatively correlated and the other positively correlated with the response variable. A strong correlation between two predictors might even indicate that a single factor underlies the relationship between these predictors. In any case, accurate multiple regression models need to incorporate correlations between the predictors as well as between the predictor and the response. The higher the correlation factors, the stronger the association between variables. The maximum value of the correlation factor is unity.

b) Deriving individual relationships (i.e., defining the function between the response variable (e.g., \(S_{tp}\)), and each predictor variable \((x_i)\).

c) Integrating the individual functions and revising the regression equation, so that the response term is on the left side and the predictor terms are on the right side. Multiply all of the predictor terms on the right in order to integrate the correlation between predictors and between predictor(s) and response to obtain the nonlinear multiple regression model. It should be noted that the polarity of the predictor terms should be taken into account (so that positive terms are placed in the numerator and the negative terms in the denominator).

d) The final step is to perform the regression analysis and determine the accuracy of the model by comparing its predictions to experimental outcomes. If the coefficient of determination \((R^2)\) is equal to 1.0, this means that all of the observed data points coincide exactly with the curve predicted by the regression model [Wesolowsky, 1976]. If the coefficient of determination \((R^2)\) is too low and the amount of error is too high, then the proposed model will not fit the experimental data well. An analysis of variance (ANOVA) is used to determine the accuracy of the regression model (i.e., test statistical significance; in general,
$P \geq 0.05$ indicates that the apparent fit between experimental data and predicted response is due to chance rather than because the model accurately describes the functional relationship between the predictor variables and the response). When the fit between the regression model and the experimental data is poor, then an iteration process needs to be conducted to revise the parameters of the regression equation and improve the accuracy of the predictions of the regression model to the required level of confidence (i.e., $P < 0.05$).

The above steps were implemented in the current study to derive a non-linear multiple regression model. The modeling of tensile strength is presented as an example to explain and illustrate the traditional procedure used in this type of analysis.

**Case study: Tensile strength**

**a) Correlation between parameters**

The tests for correlation between predictor and response parameters were carried out using Microsoft Excel. In the case of G40.21 350WT steel, there were strong direct correlations between the response variable, *post-cyclic* tensile strength, ($St_{pc}$) and each of the following predictor variables: monotonic tensile strength ($St_{mon}$) and number of strain cycles ($N$). Meanwhile, there were also inverse correlations noted between the *post-cyclic* tensile strength ($St_{pc}$) and each of the following predictor variables: mean strain ($E_m$), strain amplitude ($E_a$), and temperature ($T$). For example, Table (5.4) presents the correlation between the response ($St_{pc}$, observed *post-cyclic* tensile strength) and the predictor ($St_{mon}$, *monotonic* tensile strength). The correlation coefficient ($r$) of 0.515685751 in Table (5.4) indicates that there is a marked positive relationship between *monotonic* tensile strength and the observed *post-cyclic* tensile strength, suggesting that the parameter $St_{mon}$ can be used in a regression model to make predictions about *post-cyclic* tensile strength.

<table>
<thead>
<tr>
<th>$St_{(p-cyc)}$</th>
<th>$St_{(mon)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Column 1</strong></td>
<td><strong>Column 2</strong></td>
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<tr>
<td>Column 1</td>
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</tr>
<tr>
<td>Column 2</td>
<td><strong>0.515685751</strong></td>
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</tbody>
</table>

Table (5.4) Sample of correlation analysis output
Conclusions drawn from the analysis may be summarized by this statement: the higher the correlation factor, the greater the effect of the predictor variable on the response. A positive value for the correlation factor means that the response increases when the predictor increases in magnitude. Hence, the relevant predictor variable should be placed in the numerator of the right side of the empirical formula that relates response with predictor variables. Meanwhile, the negative value for the correlation factor means that the response decreases when the predictor increases in magnitude and hence, the relevant predictor should be placed in the denominator of the right side of the regression equation.

Using Microsoft Excel, the overall correlation characteristics of the parameters that affected the observed mechanical properties of G40.21 350WT steel were determined and are listed in Table (5.5). This table shows the correlation factors between the response $St_{pc}$ and each of the predictor variables. The values obtained for the correlation coefficients varied from -0.686 to +0.682. The italic numbers indicate positive correlation factors (i.e., a direct relationship between predictor and response) while the normal numbers indicate negative correlation factors (i.e., an inverse relationship between predictor and response). The strongest correlations were indicated by bold numbers in the table; the strongest positive relationship was found between the post-cyclic tensile strength and monotonic tensile strength, $x_1$. However, the strongest negative relationship was found between the post-cyclic yield strength and temperature, $x_5$.

**Table (5.5) Correlation factors between responses and predictor variables of G40.21 steel**

<table>
<thead>
<tr>
<th>Post-cyclic property</th>
<th>Monotonic property ($x_1$)</th>
<th>Number of cycles ($x_2$)</th>
<th>Mean strain ($x_3$)</th>
<th>Strain amplitude ($x_4$)</th>
<th>Temperature ($x_5$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>0.682</td>
<td>0.484</td>
<td>-0.439</td>
<td>0.402</td>
<td>-0.661</td>
</tr>
<tr>
<td>Yield strength</td>
<td>0.652</td>
<td>0.196</td>
<td>-0.163</td>
<td>0.564</td>
<td>-0.686</td>
</tr>
<tr>
<td>Fracture strength</td>
<td>-0.013</td>
<td>0.166</td>
<td>-0.034</td>
<td>0.138</td>
<td>-0.070</td>
</tr>
<tr>
<td>Toughness</td>
<td>0.515</td>
<td>-0.389</td>
<td>-0.553</td>
<td>0.015</td>
<td>-0.0578</td>
</tr>
<tr>
<td>% Elongation</td>
<td>-0.226</td>
<td>-0.537</td>
<td>-0.254</td>
<td>-0.329</td>
<td>0.238</td>
</tr>
<tr>
<td>% Reduction in area</td>
<td>0.321</td>
<td>-0.090</td>
<td>-0.269</td>
<td>-0.174</td>
<td>-0.041</td>
</tr>
</tbody>
</table>
Each row of Table (5.5) should be checked to determine the presence of correlation factors with the same values, but opposite valence for two or more predictors. The presence of the same values with opposite signs suggests that there is also a strong correlation between these predictors and that the contributions of these predictors to the response overlap. Subsequently, the correlated predictors can be integrated and replaced by a single combined variable \( x_{1c} \) in the ongoing analysis. In this example, however, simple review of Table (5.5) revealed that none of the correlation factors in a particular row had the same values with opposite signs. Hence, there are no obvious overlapping correlations between predictors of the mechanical properties of G40.21 350WT steel, so all of the predictors should be retained in the regression model.

The next step graphically illustrates the relationship between the response \textit{post-cyclic} tensile strength, \( S_{tpc} \), and each of the five predictor variables \( x_1 \) through \( x_5 \). These five predictor variables will then be integrated as parameters in the regression model describing the overall relationship between the predictors correlated with this response.

\begin{itemize}
  \item[b)] \textbf{Deriving individual relationships}
  
  The relationship between the response \textit{post-cyclic} tensile strength, \( S_{tpc} \), and individual predictors was illustrated using the ‘chart’ features in Microsoft Excel; a trend line was added. Figures (5.2) to (5.6) show these individual relationships. Figure (5.2) shows the observed (experimental) relationship between the \textit{post-cyclic} tensile strength, \( S_{tpc} \), and the \textit{monotonic} tensile strength, \( S_{tmon} \), for G40.21 350WT steel. The series considered here are G1 and C-30 which were tested with the same loading history, while the temperatures were +25°C and -30°C, respectively. Test data from two series are shown (dotted lines) indicates that temperature interacts with both of these variables. The derived relationships in both temperatures are linear. MS Excel cannot show the derived linear relationships. The derived relationships between \( S_{tpc} \) and \( S_{tmon} \) are linear for both temperatures. However, Microsoft Excel cannot show the derived linear relationships and hence, the trend lines are not depicted in Figure (5.2).

  The relationship between the \textit{post-cyclic} tensile strength, \( S_{tpc} \), of G40.21 350WT steel and the number of strain cycles, \( N \), was non-linear, as shown in Figure (5.3). The dotted
lines in this figure show the experimental data collected for series G1, G2, and G3 which were tested with mean strains of 1000 µε, 5500 µε, and 10500 µε, respectively, and with a common strain amplitude of 1500 µε.

Figure (5.3) also shows the data for series G4 which was tested with a mean strain of 1000 µε and strain amplitude of 1000 µε. Polynomial trend lines (solid lines) were added to illustrate the functional relationship between the observed response (St_{pc}) and the predictor (N) under each of these four test conditions. The most accurate of the derived functional relationships between N and St_{pc} depicted in Figure (5.3) is the polynomial trend line for series G3 [tested with the highest mean strain (10500µε) and strain amplitude (1500µε)]; the strongest correlation between derived trend line and experimental observations was found for series G3 (R^2 = 0.9156).

Figure (5.4) depicts the relationships between the post-cyclic tensile strength and the mean strain for the three series: G1, G2, and G3. Similarly, Figure (5.5) illustrates the relationships between the post-cyclic tensile strength, St_{pc}, and the strain amplitude for series G1 and G4. All of the regression models of Figures (5.4) and (5.5) are linear. Likewise, Figure (5.6) illustrates the relationships between the post-cyclic tensile strength, St_{pc}, and temperature for series G1 and C-30. The relationship between St_{pc} and the temperature is also linear.

**Figure (5.2) Relationship between post-cyclic and monotonic tensile strength**
Figure (5.3) Relationship between *post-cyclic* tensile strength and number of cycles

**Equations and R² Values for Figure (5.3):**

1. \( y = -4E-09x^2 + 0.0005x + 524.87 \)  
   \( R^2 = 0.8737 \)
2. \( y = -3E-09x^2 + 0.0003x + 524.54 \)  
   \( R^2 = 0.769 \)
3. \( y = 8E-14x^3 - 1E-08x^2 + 0.0006x + 522.96 \)  
   \( R^2 = 0.9156 \)
4. \( y = -9E-10x^2 + 0.0001x + 523.96 \)  
   \( R^2 = 0.7192 \)

Figure (5.4) Relationship between *post-cyclic* tensile strength and mean strain

**Equations and R² Values for Figure (5.4):**

**G40.21 350WT steel**

- \( \epsilon_m = 1000 \mu \epsilon, \epsilon_a = 1500 \mu \epsilon \)
- \( \epsilon_m = 5500 \mu \epsilon, \epsilon_a = 1500 \mu \epsilon \)
- \( \epsilon_m = 10500 \mu \epsilon, \epsilon_a = 1500 \mu \epsilon \)
- \( \epsilon_m = 1000 \mu \epsilon, \epsilon_a = 1000 \mu \epsilon \)

**Equations for Figure (5.4):**

1. \( y = -3E-09x^2 + 0.0003x + 524.54 \)  
   \( R^2 = 0.769 \)
2. \( y = -9E-10x^2 + 0.0001x + 523.96 \)  
   \( R^2 = 0.7192 \)
3. \( y = 8E-14x^3 - 1E-08x^2 + 0.0006x + 522.96 \)  
   \( R^2 = 0.9156 \)

**Notes:**

- Poly. (\( \epsilon_m = 1000 \mu \epsilon, \epsilon_a = 1500 \mu \epsilon \))
- Poly. (\( \epsilon_m = 5500 \mu \epsilon, \epsilon_a = 1500 \mu \epsilon \))
- Poly. (\( \epsilon_m = 10500 \mu \epsilon, \epsilon_a = 1500 \mu \epsilon \))
- Poly. (\( \epsilon_m = 1000 \mu \epsilon, \epsilon_a = 1000 \mu \epsilon \))
c) Developing the regression model

In this step, the predictor variables illustrated in the previous step are incorporated into the regression model. The correlation coefficients representing the nature and strength of each predictor-response relationships are treated as described previously. Predictors with inverse (or negative) correlations to the response variable are placed in
the denominator and those with direct (or positive correlations to the response variable) are placed in the numerator of the regression equation.

It can be concluded that it would be difficult to develop a single reliable regression model that will accurately predict material properties such as post-cyclic tensile strength using the simple procedures outlined above for the traditional method. In any case, a validation test must be carried out to determine whether the accuracy of a regression model is acceptable (i.e., meets the required level of confidence). The following section describes the inferential statistical analysis used to evaluate the accuracy of regression models; models that predict outcomes that differ significantly from experimental findings are rejected.

d) The regression analysis and analysis of variance (ANOVA):

The inferential statistical methods described in this step are used to evaluate the proposed regression model and to determine if the procedures used need to be refined (e.g., use of more sophisticated software or optimization of the model’s parameters through an iteration process). Essentially, the observed variance for a particular variable (response variable) is partitioned into components attributable to different sources of variation (predictor variables) when deriving a regression model; in modelling, the validation test (ANOVA or F-test) involves comparison of the variance in experimental data to the predictions of the regression model. The F-test name was coined by George W. Snedecor in honour of Sir Ronald A. Fisher. Fisher initially developed the statistic as the variance ratio in the 1920s [Lomax, 2007]. The calculated value for F is related to the probability that differences between the experimental and predicted findings are either due to chance or to fundamental differences between the model parameters and ‘real world’ influences on the response variable. The objective in modelling is to derive a regression model that accurately predicts real world outcomes so that any differences between prediction and reality are due solely to chance. Consequently, models with predictions that differ significantly from test data will be rejected.

Table (5.6) shows the regression analysis and analysis of variance of the post-cyclic tensile strength, \( S_{tpc} \), which was carried out using Microsoft Excel; df is the degrees of
freedom, SS is the sum of squares, MS is the mean square, and F is the calculated value of the F-test statistics. There is another value of F called the tabulated (or critical) value of F test statistics which is taken from the F-distribution that can be found in Table (E2) in Appendix E.

Table (5.6) The regression analysis and ANOVA for post-cyclic tensile strength

<table>
<thead>
<tr>
<th>Regression Statistics</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple R</td>
<td>0.884</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R Square</td>
<td>0.781</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted R Square</td>
<td>0.754</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Error</td>
<td>3.298</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>5</td>
<td>1558.77</td>
<td>311.75</td>
<td>28.64</td>
<td>0.000</td>
</tr>
<tr>
<td>Residual</td>
<td>40</td>
<td>435.33</td>
<td>10.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>45</td>
<td>1994.10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
<th>Lower 95.0%</th>
<th>Upper 95.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>370.36</td>
<td>87.88</td>
<td>4.21</td>
<td>0.0001</td>
<td>192.74</td>
<td>547.98</td>
<td>547.98</td>
</tr>
<tr>
<td>X Variable 1</td>
<td>0.2669</td>
<td>0.1680</td>
<td>1.58</td>
<td>0.1199</td>
<td>-0.0725</td>
<td>-0.0725</td>
<td>0.6064</td>
</tr>
<tr>
<td>X Variable 2</td>
<td>0.0001</td>
<td>0.0000</td>
<td>6.70</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>X Variable 3</td>
<td>-0.0005</td>
<td>0.0002</td>
<td>-2.60</td>
<td>0.0129</td>
<td>-0.0010</td>
<td>-0.0010</td>
<td>-0.0001</td>
</tr>
<tr>
<td>X Variable 4</td>
<td>0.0143</td>
<td>0.0036</td>
<td>3.98</td>
<td>0.0003</td>
<td>0.0070</td>
<td>0.0215</td>
<td>0.0070</td>
</tr>
<tr>
<td>X Variable 5</td>
<td>-0.0457</td>
<td>0.0502</td>
<td>-0.91</td>
<td>0.3679</td>
<td>-0.1471</td>
<td>0.0557</td>
<td>-0.1471</td>
</tr>
</tbody>
</table>

RESIDUAL OUTPUT

<table>
<thead>
<tr>
<th>Observation</th>
<th>Predicted Y</th>
<th>Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>529.40</td>
<td>-7.39</td>
</tr>
<tr>
<td>2</td>
<td>529.84</td>
<td>1.15</td>
</tr>
<tr>
<td>3</td>
<td>531.63</td>
<td>1.37</td>
</tr>
<tr>
<td>4</td>
<td>533.85</td>
<td>5.14</td>
</tr>
<tr>
<td>5</td>
<td>536.08</td>
<td>2.91</td>
</tr>
<tr>
<td>6</td>
<td>526.94</td>
<td>-4.93</td>
</tr>
<tr>
<td>7</td>
<td>527.38</td>
<td>1.61</td>
</tr>
<tr>
<td>8</td>
<td>529.16</td>
<td>1.83</td>
</tr>
<tr>
<td>9</td>
<td>531.39</td>
<td>0.60</td>
</tr>
<tr>
<td>10</td>
<td>533.62</td>
<td>-1.62</td>
</tr>
<tr>
<td>11</td>
<td>524.20</td>
<td>-2.20</td>
</tr>
<tr>
<td>12</td>
<td>524.65</td>
<td>2.35</td>
</tr>
</tbody>
</table>
The regression analysis was based on populations of specimens in series G1, G2, G3, and G4. These specimens were made of G40.21 350WT steel and tested with four different experimental conditions (various mean strains and strain amplitudes). A multiple linear regression model for post-cyclic tensile strength, $S_{tpc}$, was derived using the simple traditional method based on the parameters of monotonic tensile strength, number of cycles, mean strain, strain amplitude, and temperature. The empirical formula for the predicted post-cyclic tensile strength, $S_{tpc}$, is shown in Equation (5.1).

$$S_{tpc} = 370.37 + 0.26 S_{mon} + 0.0001 N - 0.0005 \varepsilon_m + 0.014 \varepsilon_a - 0.045 T$$  \hspace{1cm} (5.1)
where $St_{pc}$ is post-cyclic tensile strength, $St_{mon}$ is monotonic tensile strength, $N$ is number of cycles, $Em$ is mean strain, $Ea$ is strain amplitude, and $T$ is temperature.

The model’s predictions and the experimental responses differed significantly ($R^2=0.781$, $SE=3.299$) as shown in Figure (5.7).

Figure (5.7) shows that the predicted values for post-cyclic tensile strength (response, Y) as a function of number of cycles (predictor, X) [solid lines] do not fit the experimental data [dotted lines] well. The simple analytical procedures described above derived a linear regression model, but the observed data are clearly non-linear in nature.

![Multiple linear regression model of the post-cyclic tensile strength.](image)

**Was the derived model found by chance?**

In theory, any estimated linear relationship may be derived due to chance rather than because it accurately represents the actual relationship. In order to determine whether the derived relationship is due to chance or not, the standard hypothesis testing method is used. In standard hypothesis test, the worst case scenario is assumed with the null hypothesis $H_0$:

$$H_0=\beta_1=\beta_2=\beta_3=......=\beta_q=0$$
The alternative hypothesis is $H_1$.

$$H_1 : \text{not all } \beta_i \text{ are equal to zero, where } i > 0$$

The linear relationship $y_R = \beta_0 + \beta_o x_1 + ... + \beta_q x_q$ (when $q = 1$) is shown in Figure (5.8).

The $F$-test statistics is often used to compare statistical models that have been fit to a data set, in order to identify the model that best fits the population from which the data were sampled [Lomax, 2007]. Similarly, inferential statistics such as ANOVA can be used to compare the responses predicted by a statistical model to actual test data in order to determine whether the model’s predictions are comparable to actual data. In this section, the $F$-test is used to determine if the derived regression model was found by chance or whether it accurately represents ‘real world’ observations.

Table (E2) in Appendix E lists the critical regions of $F$ at 1% and 5% levels of significance [Wesolowsky, 1976]. In general terms, if the 5% level of significance was chosen, it means that there is a probability of 0.05 of incorrectly rejecting the null hypothesis ($H_0 = \beta_1 = \beta_2 = \beta_3 = ... = \beta_q = 0$) when it is true. If a calculated value of $F$ is greater than the critical value found in Table (E2), then the null hypothesis is rejected. Hence, the notion that the regression slopes differ from zero purely by chance is rejected.

$$F_{calculated} = \frac{\text{mean square due to regression}}{\text{mean square about regression}} = \frac{MS (\text{regression})}{MS (\text{residual})}$$ (5.2)
For the $F$ distribution with $\nu_1 = m - 1$ degrees of freedom for the numerator, and $\nu_2 = n-m$ degrees of freedom for the denominator. It should be noted that if one of the regression coefficients equals zero, then $F_{calculated}$ will no longer be equal to $MS$ (regression) /$MS$ (residual) in the regression analysis.

For example, in the tensile strength relationship for the eight test series G1, G2, G3, G4, Co, C-5, C-15 and C-30 there are 46 observations. Therefore, $n=46$ with five independent variables ($m=5$: $S_t$mon, N, $e_m$, $e_a$ and T).

From Table (E2), the tabulated (critical) value for $F_{0.05} = 2.6$ (using interpolation) where $\nu_1 = m-1= 5 - 1 = 4$ (the degrees of freedom for the listed row) and $\nu_2 = n-m = 46-5 =41$ (the degrees of freedom for the listed column). Meanwhile, the $F_{calculated} = 311.75/10.88 = 28.64$ (from the regression analysis in Table 5.6 above). As $F_{calculated} > F_{critical}$, the null hypothesis was rejected. The rejection of the null hypothesis means that the above mentioned model was unlikely (only a 5% probability) to be due to chance. However, the prediction responses generated from the regression model exhibited poor fitness with the observed responses and high error (Figure 5.7). Hence, it cannot consider as a reliable empirical formula.

Thus, the traditional procedure for derivation of a regression model can be summarized as a time-consuming, multi-step, and inaccurate method. These deficiencies in the traditional method inspired the search for more accurate and time-efficient methods. Fortunately, a solution was found using Eureqa software and is described in the following section.

**5.4.1.2 Eureqa Software Method for Deriving a Nonlinear Multiple Regression Model**

As noted in sub-section 5.4.1.1, examination of commonly available statistical software revealed that these applications offer only linear regression modelling (with single and multiple predictor variables) and/or nonlinear regression modelling (with only a single predictor variable). The current study includes several predictor variables. For example, the case study presented in section 5.4.1.1 involved one response variable and five predictor variables. The individual relationships between predictor and response variables were not uniformly linear (see Step b in section 5.4.1.1) and the linear multiple
regression model derived using Excel predicted outcomes that differed significantly from actual test data (see Step e). Hence, a more sophisticated statistical analysis software package capable of deriving nonlinear multiple regression models was used instead. The powerful software “Eureqa” was developed in Cornell University, New York, USA. This software is capable of nonlinear multiple regression modelling and offers a user-friendly interface which was utilized to derive more accurate and reliable empirical formulae than the traditional procedures described in the previous section. The models derived using Eureqa were used to predict changes in post-cyclic mechanical properties. As was the case with the traditional methods described earlier, the post-cyclic property is the dependent variable (y; response), while related parameters are considered as independent variables (x; predictors).

Eureqa (pronounced "eureka") is a software tool for detecting and formulating mathematical relationships hidden in specific sets of data. The primary goal of the software is to identify the simplest mathematical formulae, which describe the underlying mechanisms that produced the data. Eureqa is a free application that is downloadable from the Cornell University website [www.Cornell.edu]. Two beta versions of Eureqa (Eureqa formulize) have been issued: Eureqa I (0.85 beta) and Eureqa II (0.93 beta). The most up-to-date version, Eureqa II offers more features and performs tasks faster than its predecessor. Therefore, Eureqa II was chosen for use in this study. Table (E1) in Appendix E presents a comparison between the two versions of Eureqa.

This program starts by searching within the dataset for numbers that seem to be connected to each other and then proposes a series of simple equations to describe the relationships. These initial equations invariably fail to fit the dataset. However, some equations provide slightly better fit than others. The optimal formulae are selected, adjusted, and tested again against the test data. Eureqa repeats this optimization cycle over and over, until it derives equations that fit the data well [www.wired.com].

Figures (5.9) to (5.12) show screen shots of Eureqa II software captured while deriving a solution to predict change in tensile strength for G40.21 350WT and AISI 1022 HR steels. The data from nine test series (G1, G2, G3, G4, C0, C-5, C-15, C-30, and A1)
were included in the development of this model. Figure (5.9) presents the first window which looks like a spread sheet. The 1st and 2nd rows allow for data description and notation, respectively, while the following rows represent data numeric values. Data can be copied and pasted from a document in another format such as MS Excel. Figure (5.10) is another screenshot (displayed by clicking the ‘Set Target’ tab) showing the ‘Target Expression’ \( S_{tpc} = f (S_{mon}, N, E_m, E_a, T) \), which includes the response variable with the five predictor variables. The arithmetic options used to build the formula are listed with check boxes that allow the user to select which of these functions are to be used to develop the target formula.

Figure (5.9) Data entry in Eureqa II software
Figure (5.10) Selection of arithmetic functions in Eureqa II software

Selection of parameters and modeling options with Eureqa II

The screen shot shown in Figure (5.11) includes details about the search for an optimal solution that would predict the observed data with minimal error (e.g. time cost, number of CPU cores, performance, and confidence). The solutions that were derived and assessed in order to determine the optimal solution are listed in Figure (5.12), as well as the coefficient of determination ($R^2$), error, complexity, and other statistical information relevant to the optimal solution on the left side of the screen shot. The optimal solution here is the one that produces the best fit between observed and predicted results. It should be noted that the best solution has the highest value for $R^2$ with a lower level of error than the other solutions that were derived and assessed by Eureqa. Charts showing the fit between the plots for observed versus predicted data as well as the degree of error vs. complexity are located on the right side of the screen shot. Each of the assessed solutions is represented by a blue dot in the error-complexity plot while the optimal solution is represented by a red dot. The solution with the highest complexity represents the most accurate model and the least amount of error which are evident in the ‘Solution Details’ table in the lower left corner of the screen shot of Figure (5.12). The ‘Solution Details’
The table presents information for the solution selected in the ‘Best Solution of Different Sizes’ table (upper left corner; selected solution is highlighted in blue).

**Figure (5.11) Start search for solution in Eureqa II software**

**Figure (5.12) View results in Eureqa II software**
Eureqa II was used to derive universal nonlinear regression models for a) tensile strength; b) yield strength, c) fracture strength, d) toughness, e) percentage elongation, and f) percentage reduction in area. These models are presented in the following sections and the accuracy of their predictions is considered by comparing the data with the experimental observations.

a) Tensile strength

While considering the observations for a single test series (e.g., G1 series only), four of the predictors (monotonic tensile strength, mean strain, strain amplitude, and temperature) listed in Table (5.3) are held constant. Consequently, only the changeable predictor variable, number of cycles \(N\), is related to the predicted response, post-cyclic tensile strength, \(S_{tpc}\). Therefore, the data predicted by a single nonlinear regression model (Equation 5.3; derived using Eureqa II) appear to fit perfectly with the observed data, as shown in Figure (5.13). The value of \(R^2\) is unit.

\[
S_{tpc} = 522 + 0.002446 N -1.44 \times 10^{-7} N^2 + 3.061 \times 10^{-12} N^3 -2.048 \times 10^{-17} N^4
\]  
(5.3)

Figures (5.13) to (5.36) illustrate the formula derived using Eureqa fit well to the observed data for the responses modelled in this study. The observed data are represented by dashed lines, while the predicted data are represented by solid lines. There is almost no error \((1.477 \times 10^{-11}\%)\) for model (5.1) and the coefficient of determination \((R^2)\) of unit indicates that the model’s predictions are almost perfectly correlated with the observed test results. The error was estimated as the difference in tensile strengths between the predicted and observed data divided by the observed tensile strength as shown below.

\[
Error = \left[\frac{\Delta S_{tpc} / S_{tpc(\text{observed})}}{100}ight] 
\]  
(5.4)
Similarly, the single nonlinear regression models derived for test series G2 and G3 produced similar curve fitting, error, and coefficient of determination values as were found for the regression model for test series G1. The error values are $1.102 \times 10^{-11}\%$ and $7.275 \times 10^{-12}\%$ for test series G2 and G3, respectively while the coefficient of determination was 1.0 for both series. The formulae derived for test series G2 and G3 are provided in Equations (5.5) and (5.6), respectively. The fit between the predicted and observed data for test series G2 and G3 are illustrated in Figures (5.14) and (5.15), respectively.

\[
St_{pc} = 522 + 0.002446 N - 1.44 \times 10^{-7} N^2 + 3.061 \times 10^{-12} N^3 - 2.048 \times 10^{-17} N^4 \quad (5.5)
\]

\[
St_{pc} = 522 + 0.001297 N - 6.542 \times 10^{-8} N^2 + 1.254 \times 10^{-12} N^3 - 8.003 \times 10^{-18} N^4 \quad (5.6)
\]
The inclusion of the two steels (G40.21350WT and AISI 1022 HR) into one regression model converted the single nonlinear regression models described in the

Figure (5.14) Predicted and observed post-cyclic tensile strength of G40.21 steel-G2

\[ S_{tpc} = 522 + 0.001871 N - 1.042 \times 10^{-7} N^2 + 2.087 \times 10^{-12} N^3 - 1.341 \times 10^{-17} N^4 \]

\[ R^2 = 1, \text{ error } = 1.102 \times 10^{-11} \% \]

Figure (5.15) Predicted and observed post-cyclic tensile strength of G40.21 steel-G3

\[ S_{tpc} = 522 + 0.001297 N - 6.542 \times 10^{-8} N^2 + 1.254 \times 10^{-12} N^3 - 8.003 \times 10^{-18} N^4 \]

\[ R^2 = 1, \text{ error } = 7.275 \times 10^{-12} \% \]
previous paragraphs to a multiple nonlinear type of regression model. The response is still the predicted post-cyclic tensile strength, $S_{p_c}$, but there are now two changeable predictor variables: the monotonic tensile strength for each type of steel, $S_{mon}$, and the number of cycles, $N$. The remaining three predictors (mean strain, strain amplitude, and temperature) are held constant for the series used to develop the regression model, so these variables are excluded from the formula derived by Eureqa (Equation 5.7).

$$S_{p_c} = 21 + S_{mon} + \tan (N - 2.528) + \tan (53.51 - 2.833 N) - 3.409 \cos (39.33 N - S_{mon})$$
- $0.3609 \tan (N - 2.528) \cos (39.33 N - S_{mon})$

(5.7)

The observed and predicted results are illustrated in Figure (5.16). It should be noted that the optimal multiple nonlinear regression model is less accurate than the single nonlinear regression models developed for one type of steel. Hence, for the nonlinear regression models, the fit between the predicted and observed post-cyclic tensile strengths is weaker and the amount of error is higher than that of the single nonlinear models for series G1, G2, and G3 shown in Figures (5.13), (5.14), and (5.15). The coefficient of determination ($R^2$) of 0.978 which is smaller than that of the previous single nonlinear models ($R^2=1.0$ in the three cases based on one type of steel). Likewise, the maximum error between observed results and the multiple nonlinear regression model’s predictions is higher than that of the single nonlinear models. The value of error in multiple regression model reached 1.2% for series G1 (i.e., data from G40.21 350WT steel) at 5 kcycles (Figure 5.16). Thus, it may be concluded that increasing the number of changeable parameters (i.e., predictor variables) in the regression function increases the error and reduces the coefficient of determination which was used to determine whether the model meets the required level of confidence.
After examining the impact of assuming only one or two changeable predictors (as discussed in the previous paragraphs), now all five predictors will be considered in order to develop a ‘Universal Regression Model’. The universal regression model for post-cyclic tensile strength, $St_{pc}$, was derived using data from nine test series G1, G2, G3, G4, C0, C-5, C-15, C-30, and A1. As the number of changeable variables was relatively high (i.e., five predictors: $St_{mon}$, $N$, $E_m$, $E_a$, and $T$) the coefficient of determination, $R^2$, was relatively low ($R^2 = 0.634$). In order to avoid figures filled with dense curves and to clearly show the degree of variability graphically, the predicted data (by the universal regression model) and observed data are shown in a set of three figures. Figures (5.17), (5.18), and (5.19) plot $St_{pc}$ in relation to the number of cycles $N$ for several test series under different experimental conditions. The derived universal regression formula of tensile strength is shown in Equation (5.8); this equation as well as the specific experimental condition (e.g. temperature) and series plotted are included in each figure.

$$St_{pc} = 8636 + 0.007347 \varepsilon_a + 1.467 \sin (T) + 0.02964 St_{mon}^2 + 1.484 \times 10^{-7} N (\varepsilon_a)$$

$$- 31.03 St_{mon} - 7.641 \times 10^{-10} (N)^2 - 1.682 \times 10^{-8} N (\varepsilon_m)$$  (5.8)
The time required to derive the optimal universal regression model for post-cyclic tensile strength $S_{tpc}$ was only 37 minutes which is lower than the time required to derive the universal regression models for other properties. The time required to derive the universal regression models with Eureqa II is depends on the performance of a computer. In this study a pc with the following configuration (Intel (R), core (TM) 2Duo CPU, T6570 @ 2.10 GHz, and RAM of 4.0 GB) was used.

Figure (5.17) illustrates the outcomes for post-cyclic tensile strength predicted by the universal regression model fits well with the experimental observations. Both AISI 1022 HR steel (Series A1) and G40.21 350WT steel (series G1) are considered at room temperature (25°C). In this figure, the number of strain cycles ($N$) changed. However, the mean strain and strain amplitude remain unchanged ($\varepsilon_m$=1000 $\mu$e and $\varepsilon_a$=1500 $\mu$e). It should be noted that the curves for the predicted and the observed results do not perfectly overlay each other which indicates the presence of small error. The maximum error between the predicted and observed data depicted in Figure (5.17) is 1.4% obtained from series A1 of AISI 1022 HR steel. This error is relatively low considering the number of changeable predictors in the universal regression model. The fit between the predictions of the model and the experimental data is considered to be high in this case. Hence, the derived universal regression model is accurate enough while considering different types of steel tested under similar experimental conditions.
Figure (5.17) Universal regression model of the tensile strength for both steels

Figure (5.18) illustrates the fit between observed and predicted data for the post-cyclic tensile strength of G40.21 35WT steel after the application of different numbers of strain cycles \((N)\) using the same universal regression model. In this case, the results for one type of steel are displayed under four different strain conditions (series G1, G2, G3, and G4) tested under different mean strains and strain amplitudes. However, the temperature was held constant (25°C). The maximum amount of error found for these series of tests was only 0.98% (for series G1; mean strain=1000 \(\mu\epsilon\); strain amplitude=1500 \(\mu\epsilon\)). Hence, these findings indicate that the predictions of the derived universal regression model are accurate under different strain conditions.
Figure (5.18) Universal regression model of the tensile strength for G40.21 350WT steel at different strain histories

The curves fit well to the predicted (universal regression model) and observed post-cyclic tensile strengths for G40.21 350WT steel at various low temperatures (0°C to -30°C) are shown in Figure (5.19). Figure (5.19) illustrates the good fit between the predicted and observed outcomes for all temperatures tested. The maximum error is 1.15% for series C-30 which was tested at -30°C. The findings depicted in Figure (5.19) indicate that the predictions of the derived universal regression model for post-cyclic tensile strength are also accurate enough in low temperature condition.
Similarly, the predictions of the universal regression models (derived using Eureqa II software) for the other response properties were also compared to experimental observations under various experimental conditions. The response properties include yield strength ($S_y$), fracture strength ($S_f$), toughness ($Tgh$), percentage elongation ($El$), and percentage reduction in area ($R$). As was the case for post-cyclic tensile strength ($St_{pc}$), the accuracy of each universal model is illustrated with sets of three figures. These figures compare the fit between observed and predicted data under different experimental conditions in order to show the effect of varying the predictor variables on the models’ accuracy. Each of the three figures shows the response variable on the vertical axis and the predictor variable (the number of strain cycles, $N$) on the horizontal axis. The first figure in the set depicts the influence of varying monotonic tensile strength for each steel. The second figure shows the effect of strain (mean and amplitude). The third figure in the set describes the effect of temperature on the amount of error between prediction and observation.

\[
St_{pc} = 8636 + 0.007347 \varepsilon_a + 1.467 \sin T + 0.02964 S_{mon}^2 + 1.484 \times 10^{-7} N \varepsilon_a - 31.03 S_{mon} - 7.641 \times 10^{-10} N^2 - 1.682 \times 10^{-8} N \varepsilon_m
\]
b) Yield strength

Figures (5.20), (5.21), and (5.22) illustrate the accuracy of the predicted values for yield strength based on the universal regression model [Equation (5.9) derived with Eureqa II] for this response variable ($S_{y_{pc}}$).

$$S_{y_{pc}} = 359 + \tan (\varepsilon_a) \log (S_{y_{mon}} + 0.001459 N - 349.1) + \tan (0.1023 + T) - 6.486 \sin (N) - 6.233 \sin [0.001459 N - 13.17 \tan (0.1023 + T)]$$

(5.9)

It can be noted that the change in the observed post-cyclic yield strength ($S_{y_{pc}}$) due to various mean strains ($\varepsilon_m$) is relatively small. Hence, Eureqa II considered the impact of this predictor variable to be negligible, and excluded this parameter from the derived empirical regression equation (5.9). Consequently, there are only four predictor variables ($S_{y_{mon}}$, $N$, $\varepsilon_a$ and $T$) included in the universal regression model for post-cyclic yield strength. The amount of error between the predicted and observed values for yield strength is higher than that for tensile strength (compare Figures 5.17-5.19 to Figures 5.20-5.22). The maximum error estimated for yield strength is 8.3% (calculated for the specimen tested to 100 kcycles at the temperature of -30°C, see Figure 5.22). However, several conditions produced error levels that were greater than those seen for post-cyclic tensile strength. The time required to derive the universal regression model for post-cyclic yield strength with Eureqa II was 2 hours and 17 minutes.

Figure (5.20) shows the effect of monotonic tensile strength on the accuracy of the fit between the predicted and observed results for post-cyclic yield strength ($S_{y_{pc}}$). The error between the predicted and observed data is almost identical for both steels (AISI 1022 HR and G40.21 350WT). The solid line of the curve predicted for data from AISI 1022 HR steel overlaps the curve predicted for data from G40.21 350WT steel completely. Hence, the latter curve cannot be distinguished in the figure.
Figure (5.20) Universal regression model of the yield strength for both steels

Figure (5.21) illustrates the accuracy of the universal regression model if compared curves for the predicted responses and experimental observations. In this figure the strain history changes. The data for series G4 (tested with mean strain of 1000 µε and strain amplitude of 1000 µε) shows a better fit between the predicted and observed response than that for the other series.

Temperature does not affect the accuracy of the universal regression model for post-cyclic yield strength. The fit between the curves for the predicted and observed post-cyclic yield strength of G40.21 350WT steel is similar at different temperatures. The error is almost the same for all series tested at various low temperatures as shown in Figure (5.22).
Figure (5.21) Universal regression model of the yield strength for G40.21 350WT steel at different strain histories

\[ Sy_{pc} = 359 + \tan(\varepsilon_a) \log(Sy_{mon} + 0.001459 N - 349.1) + \tan(0.1023 + T) - 6.486 \sin(N) - 6.233 \sin[0.001459 N - 13.17 \tan(0.1023 + T)] \]

Figure (5.22) Universal regression model of the yield strength for G40.21 350WT steel at low temperatures

\[ Sy_{pc} = 359 + \tan(\varepsilon_a) \log(Sy_{mon} + 0.001459 N - 349.1) + \tan(0.1023 + T) - 6.486 \sin(N) - 6.233 \sin[0.001459 N - 13.17 \tan(0.1023 + T)] \]
c) Fracture strength:

The accuracy of the universal regression model derived for fracture strength is illustrated in Figures (5.23), (5.24), and (5.25). These figures show the fit of curves between the predicted and the observed fracture strength. The universal empirical formula was derived using Eureqa II software and it is shown in Equation (5.10).

\[
S_f^{pc} = 2.336 + S_f^{mon} + \tan (0.3797 N + 0.3797 \varepsilon_m) - \tan (N - S_f^{mon} - \varepsilon_a) - N^{0.2568} \sin(3.467 \times 10^4 T) - \tan (\varepsilon_a) \cos (S_f^{mon} + 12.02 N)
\]

All five of the predictor variables (\(S_y^{mon}\), \(N\), \(\varepsilon_m\), \(\varepsilon_a\), and \(T\)) were found to have a marked relationship with the response variable (post-cyclic fracture strength, \(S_f^{pc}\)) during the optimization process. Hence, all of these terms are included in the model developed by Eureqa II. Nevertheless, the amount of error between the curves fit of the predicted and the observed fracture strength data is greater than the error levels found for the universal regression models for post-cyclic tensile strength and yield strength (Equations 5.6 and 5.7). The maximum amount of error noted is 14.4% (for the 75 kcycles sample from test series G1 that was tested at room temperature; see Figure 5.23). Review of Figures (5.23) to (5.25) indicates that some of the changeable predictors were associated with less accurate predictions by the derived model. For example, the predictions for G40.21 steel depicted in Figure 5.23 were less accurate than those for AISI 1021 steel (differing monotonic tensile strengths, \(S_t^{mon}\)). The time required to derive the universal regression model for fracture strength with Eureqa II was 3 hours and 23 minutes.
Figure (5.23) Universal regression model of the fracture strength for both steels

\[ \varepsilon_m = 1000 \mu \varepsilon, \ \varepsilon_a = 1500 \mu \varepsilon \]

\[ S_{f_{pc}} = 2.336 + S_{f_{mon}} + \tan (0.3797 N + 0.3797 \varepsilon_m) - \tan (N - S_{f_{mon}} - \varepsilon_a) - N^{0.2568} \sin(3.467 \times 10^4 T) - \tan (\varepsilon_a) \cos (S_{f_{mon}} + 12.02 N) \]

Figure (5.24) Universal regression model of the fracture strength for G40.21 350WT steel at different strain histories

\[ S_{f_{pc}} = 2.336 + S_{f_{mon}} + \tan (0.3797 N + 0.3797 \varepsilon_m) - \tan (N - S_{f_{mon}} - \varepsilon_a) - N^{0.2568} \sin(3.467 \times 10^4 T) - \tan (\varepsilon_a) \cos (S_{f_{mon}} + 12.02 N) \]
d) Toughness

Figures (5.26), (5.27), and (5.28) show the curve fitting of the predicted and observed results for the post-cyclic toughness of steel in relation to the number of cycles \( N \). The derived universal formula for this property is shown in Equation (5.11).

\[
T_{ghpc} = 175.3 + 3.706 \tan \left( \epsilon_m/ N \right) - \sqrt{\log N} \cos \left( T + 1.815 \times 10^{-8} N \frac{\epsilon_m}{T} \right) - 0.171 T \\
- 1.815 \times 10^{-8} N \epsilon_m - 1.546 \log (N) 
\]  

(5.11)

Three of the predictor variables \( N, \epsilon_m, \) and \( T \) are included in the universal model derived for toughness. Eureqa II found that the observations for post-cyclic toughness \( (T_{ghpc}) \) showed weak relationship with the properties of monotonic toughness \( (T_{gh_{mon}}) \) and strain amplitude \( (\epsilon_a) \). Hence, these parameters are excluded from the universal regression model for toughness. The error between the predicted outcomes and observations for toughness is the highest of all the universal regression models derived by Eureqa II. The maximum error is 16.3% (see Figure 5.27 for the 75 kcycles specimen for test series G3 tested at room temperature). The time required to derive the universal regression model for
toughness (6 hours and 43 minutes) was also higher than the time required for derivation of the other universal models. The predicted toughness of G40.21 steel (the solid curve) is not visible in Figure (5.26) because it coincides with the predicted toughness of AISI 1022 steel.

![Universal regression model for toughness](image)

**Universal regression model - Toughness**

\[
\varepsilon_m = 1000 \ \mu \varepsilon, \ \varepsilon_a = 1500 \ \mu \varepsilon
\]

- Obs-G40.21
- Pred-G40.21
- Obs-AISI 1022
- Pred-AISI 1022

\[
T_{gh_{pc}} = 175.3 + 3.706 \tan (\varepsilon_m - \varepsilon_m/N) - \sqrt{\log (N)} \cos (T + 1.815 \times 10^{-8} N \varepsilon_m T) - 0.171 T - 1.815 \times 10^{-8} N (\varepsilon_m) - 1.546 \log (N)
\]

**Figure (5.26) Universal regression model of the toughness for both steels**
Figure (5.27) Universal regression model of the toughness for G40.21 350WT steel at different strain histories

Figure (5.28) Universal regression model of the toughness for G40.21 350WT steel at low temperatures

Universal regression model - **Toughness**

\[ T_{gh} = 175.3 + 3.706 \tan \left( \varepsilon_m - \varepsilon_m/N \right) - \sqrt{\log(N)} \cos (T + 1.815 \times 10^{-8} N \varepsilon_m T) - 0.171 T - 1.815 \times 10^{-8} N (\varepsilon_m) - 1.546 \log(N) \]
e) Percentage Elongation

The curve fitting of the predicted outcomes and observed results for ductility measured as the percent elongation in relation to the number of cycles \((N)\) are illustrated in Figures (5.29), (5.30), and (5.31). The universal regression model (Equation 5.12) derived for percent elongation using Eureqa II is as follows.

\[
El_{pc} = El_{mon} + 0.05509 \cdot T + 3.169 \times 10^{-10} (N)^2 + \cos (0.1954 N) - 1.086 \cdot (0.982)^{El_{mon}} -0.0004022 \varepsilon_m - 4.9 \times 10^{-8} N (\varepsilon_a)
\]

(5.12)

All five of the predictor variables \((El_{mon}, N, \varepsilon_m, \varepsilon_a, T)\) are included in the model since their relationship to post-cyclic percentage elongation \((El_{pc})\) is strong. Nevertheless, the error between the predicted and the observed percentage elongation results is relatively high. The maximum error estimate is 14.4% (for the 150 kcycles sample from test series G4 tested under mean strain of 1000 \(\mu\varepsilon\) and strain amplitude of 1000 \(\mu\varepsilon\) at room temperature as shown in Figure 5.30). The time required to derive this universal regression model is longer than that of the other universal models in this study. The total time required for this model is 4 hours and 10 minutes.

![Universal regression model- % Elongation](image)

Figure (5.29) Universal regression model of the percentage elongation for both steels
Figure (5.30) Universal regression model of the percentage elongation for G40.21 350WT steel at different strain histories

Figure (5.31) Universal regression model of the percentage elongation for G40.21 350WT steel at low temperatures
f) Percentage Reduction in Area

The curve fitting of the predicted outcomes and test data for percentage reduction in area are shown in Figures (5.32), (5.33), and (5.34). The derived universal regression model that was used to generate the predicted outcomes is defined in Equation (5.13).

\[
R_{pc} = R_{mon} + \frac{1.526}{N} + \sin (\varepsilon_a) + \sin (6.099 + R_{mon} + N + \varepsilon_m) - 0.534 - \sin (6.099 + R_{mon} + N + \varepsilon_m) \sin (R_{mon} + 1.526 \varepsilon_a - R_{mon} N)
\]

(5.13)

It should be noted that only four of the predictors \((R_{mon}, N, \varepsilon_m, \text{ and } \varepsilon_a)\) are included in the formula derived by Eureqa II. In particular, the effect of test temperature was found to be unrelated to the observed responses. Therefore, the predictor variable \((T)\) was excluded from this universal regression model. The maximum error between the predicted and observed percentage reduction in area reached 13.8\% (for a specimen from series G2 tested to 25 kcycles at room temperature as shown if Figure 5.34). The time required to derive this regression model was relatively low (1 hour and 22 minutes).

![Universal regression model- % Reduction in Area](image)

**Figure (5.32) Universal regression model of the reduction in area for both steels**
Figure (5.33) Universal regression model of the percentage reduction in area for G40.21 350WT steel at different strain histories

\[
R_{pc} = R_{mon} + \frac{1.526}{N} + \sin(\varepsilon_a) + \sin(6.099 + R_{mon} + N + \varepsilon_m) \\
- 0.534 - \sin(6.099 + R_{mon} + N + \varepsilon_m) \sin(R_{mon} + 1.526 \varepsilon_a - R_{mon} N)
\]

Figure (5.34) Universal regression model of the percentage reduction in area for G40.21 350WT steel at low temperatures

\[
R_{pc} = R_{mon} + \frac{1.526}{N} + \sin(\varepsilon_a) + \sin(6.099 + R_{mon} + N + \varepsilon_m) \\
- 0.534 - \sin(6.099 + R_{mon} + N + \varepsilon_m) \sin(R_{mon} + 1.526 \varepsilon_a - R_{mon} N)
\]
The statistical data resulting from the validation tests (regression analysis and ANOVA) of the foregoing regression models are summarized in Table (5.7). All models presented in this table passed F-test. Hence, their resemblance to experimental observations is unlikely to be due to chance (probability is less than 5%).

For tensile strength, five potential models were included in this chapter to illustrate the development of regression models and conversion from single to multiple nonlinear models (Equations 5.3 and 5.5 to 5.8). The maximum error found for these tensile strength models is 1.4% which was found for the universal regression model of the tensile strength. The increase in error observed for the universal regression models is expected as the number of predictors contributing to the response is relatively high (five predictors and each can be a possible source of error).

Simple comparison of the universal models of the various properties examined in this study shows that the most accurate universal model for predicting a post-cyclic property is the tensile strength universal model, the model with the smallest error value of 1.4%. However, the maximum error value of 16.3% was found from the toughness universal model. Moreover, the universal models of fracture strength, percentage elongation, and percentage reduction in area exhibited almost the same maximum error values as that of the toughness model.

In terms of the amount of time elapsed during derivation of the universal models included in Table (5.7) when using Eureqa II, the toughness universal model required the longest time (6 hours and 43 minutes), while the tensile strength universal model required the least time (37 minutes). Therefore, the tensile strength universal model is the most accurate of the derived universal regression models and also required the least time to derive.
Table (5.7) Summary of regression analysis of the proposed regression models

<table>
<thead>
<tr>
<th>Post-cyclic property</th>
<th>Equ. No.</th>
<th>Changeable Predictors</th>
<th>Max. Error (%)$^1$</th>
<th>F-test</th>
<th>Time elapsed</th>
<th>Relevant to series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>5.3</td>
<td>1</td>
<td>1.477×10$^{-11}$</td>
<td>Pass</td>
<td>34 sec</td>
<td>G1</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>1</td>
<td>1.102×10$^{-11}$</td>
<td>Pass</td>
<td>1min 41 sec</td>
<td>G2</td>
</tr>
<tr>
<td></td>
<td>5.6</td>
<td>1</td>
<td>7.275×10$^{-12}$</td>
<td>Pass</td>
<td>39 sec</td>
<td>G3</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>2</td>
<td>1.2</td>
<td>Pass</td>
<td>23min</td>
<td>A1&amp;G1</td>
</tr>
<tr>
<td></td>
<td>5.8</td>
<td>5</td>
<td>1.4</td>
<td>Pass$^2$</td>
<td>37min</td>
<td>Universal</td>
</tr>
<tr>
<td>Yield strength</td>
<td>5.9</td>
<td>4</td>
<td>8.3</td>
<td>Pass</td>
<td>2hr 17min</td>
<td>Universal</td>
</tr>
<tr>
<td>Fracture Strength</td>
<td>5.10</td>
<td>5</td>
<td>14.4</td>
<td>Pass</td>
<td>3hr 23min</td>
<td>Universal</td>
</tr>
<tr>
<td>Toughness</td>
<td>5.11</td>
<td>3</td>
<td>16.3</td>
<td>Pass</td>
<td>6hr 43min</td>
<td>Universal</td>
</tr>
<tr>
<td>% Elongation</td>
<td>5.12</td>
<td>5</td>
<td>14.4</td>
<td>Pass</td>
<td>4hr 10min</td>
<td>Universal</td>
</tr>
<tr>
<td>% Red. in area</td>
<td>5.13</td>
<td>4</td>
<td>13.8</td>
<td>Pass</td>
<td>1hr 22min</td>
<td>Universal</td>
</tr>
</tbody>
</table>

$^1$ The error here is the difference in post-cyclic property between the predicted and observed data, divided by the observed post-cyclic property. The result is multiplied by 100.

$^2$ m=5, n=53 (observations of both steels), $\nu_1=m-1=4$, $\nu_2=n-m=48$, $F_{0.05}=2.56<F_{cal}=222$, so the null hypothesis is rejected, which means this model was not derived by chance.

5.5 FATIGUE LIFE STATISTICAL ANALYSIS

In current study, the statistical analysis for strain-life was conducted to ensure that the experimental data fall within the confidence level limits, the scatter factor is within the acceptable range, and if the linear model of fatigue life is valid (i.e., accepted or not). This analysis was carried out in compliance with ASTM E739–10 standards [ASTM E739, 2010].

The linear model $Y=A+BX$, represents the log-normal fatigue life distribution with constant variance along the entire interval of $X$ used in testing; $Y$ is the logarithm of fatigue life $N$ (dependent, random variable), and $X$ is the logarithm of strain amplitude $\varepsilon_a$ (independent variable), and assumes that no run-outs (run out: no failure at a specified
number of load cycles) and/or suspended tests occurred and a completely randomized design for the test program. This model of fatigue life represents any of the following.

(a) The fatigue life data are from a random sample (all $Y_i$ are independent on each other)

(b) There is no missing data for the entire interval of $X$ used in testing

(c) The $\varepsilon$-$N$ relationship is described by the linear model $Y = A + BX$

(d) The log-normal distribution of the two parameters ($\varepsilon_a$ and $N$) describes the fatigue life $N$, and

(e) The variance of this log-normal distribution is constant across the entire range of $X$ (i.e., the amount of scatter for $Y$ (log $N$) is assumed to be the same at low and high levels of $\varepsilon$).

The experimental data were obtained from experimental tests carried out on G40.21 350WT steel. Table (5.8) shows the strain-life data including the plastic strain amplitude ($\Delta\varepsilon_{pl}/2$) vs. fatigue life ($N$). The plastic strain refers to the plastic part of the total strain applied experimentally. The plastic strain was estimated as the difference between the total and elastic strain amplitude of a stabilized cycle (plastic shakedown region) for each case.

For example, the command for total strain amplitude on the last specimen in Table (5.8) is 0.001, while the actual total strain amplitude is 0.00086 (from experimental data). The elastic strain amplitude was 0.00025 (derived from the cyclic stress-strain curve). Hence, the plastic strain amplitude can be calculated as $0.00086-0.00025=0.00061$.

The Coffin-Manson equation (Equation 2.5) cannot be applied here to estimate the plastic strain. This equation is used to determine the suggested strain history which may be applied in order to obtain a specific fatigue life. However, this equation can also be applied to estimate fatigue life from a specific strain history (elastic and plastic strains). In each case, information about the strain-life fatigue parameters ($\sigma_f$, $\varepsilon_f$, $b$, and $c$) should be available. In this study each fatigue test was replicated and hence, there are two fatigue lives for the strain amplitudes listed in Table (5.8).
Table (5.8) Strain-life data for G40.21 350WT steel

<table>
<thead>
<tr>
<th>$\Delta \varepsilon/2$</th>
<th>$\Delta \varepsilon/2$</th>
<th>$\Delta \varepsilon_p/2$</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Strain Amplitude (command)</td>
<td>Total Strain Amplitude (actual)</td>
<td>Plastic Strain Amplitude (actual)</td>
<td>Fatigue Life (Cycles)</td>
</tr>
<tr>
<td>0.0024</td>
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<td>0.00214</td>
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</tr>
<tr>
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<td>0.00243</td>
<td>0.00214</td>
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<td>0.00205</td>
<td>18,000</td>
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<td>0.00235</td>
<td>0.00205</td>
<td>20,000</td>
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<td>903,000</td>
</tr>
<tr>
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<td>0.00123</td>
<td>0.00094</td>
<td>936,000</td>
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<td>0.00077</td>
<td>1,520,000</td>
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<td>0.00106</td>
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<td>1,474,000</td>
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<td>0.00061</td>
<td>8,600,000</td>
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<td>0.00061</td>
<td>2,017,000</td>
</tr>
</tbody>
</table>

The following steps illustrate the ASTM E739–10 standard procedures using strain-life data from the current study. The final objective is to decide whether or not to accept or reject the linear model for fatigue life after analysing the experimental results from this study. Section 4 and Example 1 in section 8.3.1 of the ASTM E739-10 standard practice guidelines provide more information. Furthermore, this example is rearranged and included in Appendix F (Examples F1).
The procedure may start with calculation of the maximum estimators of A and B, which denoted \( \hat{A} \) and \( \hat{B} \), respectively as follows.

\[
\hat{A} = \bar{Y} - \hat{B}\bar{X} = -12.59994
\]

\[
\hat{B} = \frac{\sum_{i=1}^{k} (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^{k} (X_i - \bar{X})^2} = -6.34909
\]

Where the symbol “caret” (^) denotes an estimate (estimator) and the symbol “overbar” (¯) denotes an average.

For example:

\[
\bar{Y} = \sum_{i=1}^{k} (Y_i/k), \text{ and } \bar{X} = \sum_{i=1}^{k} (X_i/k),
\]

\[
Y_i = \log N_i, \text{ and } X_i = \log \epsilon_i,
\]

In which \( k \) is the total number of test specimens or total sample size which equal 30 in this study.

The variance of the normal distribution (for log \( N \)) is estimated as follows.

\[
\hat{\sigma}^2 = \frac{\sum_{i=1}^{k} (Y_i - \bar{Y})^2}{k - 2}
\]

In which \( \bar{Y}_i = \hat{A} + \hat{B}X_i \) and the \((k - 2)\) term in the denominator is used instead of \( k \) to make \( \hat{\sigma}^2 \) an unbiased estimator of the normal population variance \( \sigma^2 \). The variance of un-notched specimens generally increases with decreasing strain level. Then the standard deviation (\( \sigma \)) can be estimated as a square root of the variance (\( \sigma = \sqrt{\hat{\sigma}^2} \)).

\[
\hat{\sigma}^2 = \frac{\sum_{i=1}^{k} (Y_i - \bar{Y})^2}{k - 2} = \frac{0.342735}{28} = 0.02215
\]

Hence, the standard deviation is \( \sigma = 0.148728 \)

**5.5.1 Confidence Intervals for Parameters A and B**

The estimators \( \hat{A} \) and \( \hat{B} \) are normally distributed with expected values \( A \) and \( B \), respectively (regardless of total sample size \( k \)) when conditions (a) through (e) described in section 5.5 (Fatigue Life Statistical Analysis) are met. Accordingly, the confidence intervals for parameters \( A \) and \( B \) can be established using the \( t \) distribution [Table (E3) in
Appendix E]. Using Table (E3) the value of \( t_p \) is 2.0739 (for \( n=k-2=30-2=28 \), and \( P=95\% \)).

The confidence interval for \( A \) is given by the following relationship.

\[
\hat{A} \pm t_p (\hat{\sigma}_A)
\]

\[
\hat{\sigma}_A = (\hat{\sigma}) \left[ \frac{1}{k} + \frac{\hat{X}^2}{\sum_{i=1}^{k} (x_i - \bar{X})^2} \right]^{1/2}
\]

From Equation (5.15a), for \( B \):

\[
\hat{B} \pm t_p (\hat{\sigma}_B)
\]

\[
\hat{\sigma}_B = (\hat{\sigma}) \left[ \sum_{i=1}^{k} (x_i - \bar{X})^2 \right]^{-1/2}
\]

Hence, the 95 % confidence interval for \( A \) is \([-13.955675 \text{ to } -11.244204]\)

The confidence interval for \( B \) is given by:

\[
\hat{B} \pm t_p (\hat{\sigma}_B)
\]

From Equation (5.15a), for \( B \):

\[
\hat{B} - t_p (\hat{\sigma}_B) = -6.34909-2.0739 (0.234568) = -6.83556
\]

\[
\hat{B} + t_p (\hat{\sigma}_B) = -6.34909+2.0739 (0.234568) = -5.862619
\]

So, the 95 % confidence interval for \( B \) is \([-6.83556 \text{ to } -5.862619]\).

If in each instance, to assert that \( B \) lies within the interval computed, it should be expected to be correct 95 times out of 100 and in error 5 times out of 100. In other words, the statement “\( B \) lies within the computed interval” has a 95 % probability of being correct.

For a given total sample size \( k \), it is evident that the width of the confidence interval for \( B \) will be minimal whenever
\[ \sum_{i=1}^{\theta} (X_i - \bar{X})^2 \] is at its maximum level (5.18)

Since the \( X_i \) levels (strain) are selected by the investigator the width of the confidence interval for \( B \) may be reduced by appropriate test planning. For example, the width of the interval for \( B \) will be minimized when the experimental design emphasizes diverse \( X_i \) (strain) levels rather than focusing on the mid-range. For example, if the available test specimens are limited to a fixed number, \( k \), then the variability around \( B \) could be reduced if half of the samples are tested at each of the extreme levels, \( X_{\min} \) and \( X_{\max} \). However, this allocation should be used only when there is strong \textit{a priori} knowledge that the \( \varepsilon-N \) curve is indeed linear. This allocation precludes a statistical test to confirm linearity. Nevertheless, consideration of these issues in experimental design can improve the power or likelihood of obtaining significant outcomes by ensuring that the range and number of experimental conditions and the allocation of samples will produce effects of the appropriate size and will reduce the variability or scatter of the response data within the confidence limits.

### 5.5.2 Confidence Band for the Entire Median \( \varepsilon-N \) Curve

If conditions (a) through (e) in section 5.5 are met, an exact confidence band for the entire median \( \varepsilon-N \) curve (i.e., all points on the linear or linearized median \( \varepsilon-N \) curve considered simultaneously) may be computed using the following equation.

\[ \hat{A} + \hat{B}X \pm \sqrt{2F_p\delta} \left[ \frac{1}{k} + \frac{(X-\bar{X})^2}{\sum_{i=1}^{\theta}(X_i-\bar{X})^2} \right]^{1/2} \] (5.19)

The value of the parameter \( F_p \) is for the 95% confidence level; the critical value for \( F_{2,28}=3.6823, \alpha=0.05 \).

The value of the parameter \( F_p \) is given in Table (E4) of Appendix E. This table involves two entry parameters (the statistical degrees of freedom \( n_1 \) and \( n_2 \) for \( F \)). For Equation 5.18, \( n_1 = 2 \) and \( n_2 = (k - 2) \). In the current study \( k = 30 \), so \( n_2=30-2=28 \) and \( n_1 = 2 \) thus \( F_{0.95} = 3.6823 \) (from Table E4 for the 95% confidence level).
5.5.3 Testing the Adequacy of the Linear Model

In section 5.5, it was assumed that a linear model for fatigue life \( Y = A + BX \) is valid. If the experimental design includes more than one observed value of \( Y \) (life) at some of the \( X_i \) levels where \( i \geq 3 \), then a statistical test for linearity can be made based on the \( F \) distribution shown in Table (E4). The log life of the \( j \)th replicate specimen tested in the \( i \)th level of \( X \) is subsequently denoted \( Y_{ij} \).

Suppose that fatigue tests are conducted at \( l \) different levels of \( X \) and that \( m_i \) replicate values of \( Y \) are observed at each \( X_i \). Then the hypothesis of linearity (that \( Y = A + BX \) ) is rejected when the computed value of \( F \) exceeds the critical value of \( F \). The computed value of \( F \) is given by Equation (5.20), while the critical value of \( F \) is obtained from Table (E4) for the desired significance level.

\[
F = \frac{\sum_{i=1}^{l} m_i (\bar{Y}_i - \bar{Y})^2 / (l-2)}{\sum_{i=1}^{l} \sum_{j=1}^{m_i} (Y_{ij} - \bar{Y}_i)^2 / (k-l)} \tag{5.20}
\]

The significance level is defined as the probability (expressed as a percentage) of incorrectly rejecting the hypothesis of linearity when there is indeed a linear relationship between \( X \) and \( Y \). The total number of specimens tested, \( k \), is computed using Equation (5.21).

\[
k = \sum_{i=1}^{l} m_i \tag{5.21}
\]

For Equation 5.18, \( n_1 = (l - 2) = 13 \), and \( n_2 = (k - l) = 15 \), where, \( k = 30 \) and \( l = 15 \).

The \( F \) test (Equation 5.20) compares the variability of average values around the fitted straight line, as measured by their mean square. A mean square value is a specific sum of squares divided by its statistical degrees of freedom (the numerator in Equation 5.20) to the variability among replicates, as measured by their mean square (the denominator in Equation 5.20). The latter mean square is independent of the form of the model assumed for the \( \varepsilon - N \) relationship. If the relationship between \( Y \) and \( X \) is indeed linear, then Equation (5.20) fits the \( F \) distribution for degrees of freedom, \( (l - 2) \) and \( (k - l) \). Otherwise, Equation (5.20) is larger on average than would be expected by random sampling from this \( F \) distribution. Consequently, a linear model is rejected if the
computed value for $F$ (Equation 5.20) exceeds the critical value of $F_p$ from Table (E4). If the linear model is rejected, then it is recommended that a nonlinear model (e.g. Equation 5.22) be considered.

$$Y=A + BX + CX^2$$

(5.22)

In the current study, the critical value for $F_{0.95}=3.6828$ (Table E4), and the computed $F=2.29195$ (Equation 5.20). As $F_{\text{computed}} < F_{\text{table}}$, the linear model of fatigue life is accepted.

The fitted line, the upper and lower 95% confidence bands, and plastic strain amplitude data are illustrated in Figure (5.35). This figure is a semi-log plot which considered the ordinate as the plastic strain amplitude ($\Delta \varepsilon_p/2$) and the abscissa as the logarithmic value of fatigue life ($\log N$). All data points (i.e., the test data) for fatigue life are included in Figure (5.35) to show the amount of scatter in all of the data. Some of the experimental data (circular markers in Figure 5.35) fell slightly outside the 95% confidence bands. The highest scatter was observed at the lower strain levels (i.e. strain < 0.0012). The highest scatter factor found was 4 which pertained to strain of 0.001. This observation agrees with the findings reported by Sinclair and Dolan (1953) in their study of 7075-T6 Aluminum alloy, although the scatter factors reported were higher than the scatter factors found in the current study.


5.6 SUMMARY

This chapter included two main sections. The first section presented and discussed the derivation of empirical formulae to predict changes in mechanical properties due to application of strain cycles. The second section presented the statistical analysis of fatigue-life experimental data.

In the first section, two methods of deriving multiple nonlinear regression models were illustrated and discussed: the traditional method and Eureqa method. The traditional method produced inaccurate predictions and was time-consuming and hence, it was not used for further analyses. The Eureqa method was accurate and efficient and hence, all subsequent analyses were based on Eureqa procedure. The experimental data for tensile strength was chosen to demonstrate the derivation of single and multiple regression models. Then the predictions of these models were compared with the experimental data. These inferential statistical analyses showed changes in the statistical parameters as the

Figure (5.35) The 95% confidence bands for the $\varepsilon$-$N$ curve of G4.21 steel

Fitted line $Y^\wedge = -7.741063 -4.43069 \log \Delta \varepsilon_p/2$

Plastic strain amplitude - Life

Fatigue life (log N)

Plastic strain amplitude ($\Delta \varepsilon_p/2$)

0.95 Upper confidence band

0.95 Lower confidence band

0 2 4 6 8

0.0025

0.002

0.0015

0.001

0.0005

0

185
models were converted from single to multiple nonlinear regression models by including one and more than one predictor variable. Subsequently, universal models were derived to predict several post-cyclic properties which include tensile strength, yield strength, fracture strength, toughness, and ductility. The best universal model found with the Eureqa application was the universal regression model for post-cyclic tensile strength which exhibited the least error when compared with the experimental data.

The second section of this chapter describes the analyses carried out to ensure that the fatigue-life experimental data fall within the specified confidence level of 95%, the scatter factor is within the acceptable range, and to determine if the linear model for fatigue life is valid. The analysis was conducted in compliance with ASTM Standard 739-10. The results of the analysis found that although some of the experimental data fell slightly outside of the 95% confidence limits, the scatter factor did not exceed a value of 4.0, which is considered an acceptable level. Finally, the linear model was accepted as shown in Figure (5.35) in compliance with the procedure provided by ASTM Standard 739-10.
CHAPTER 6: NUMERICAL MODELING

This chapter presents the numerical modeling and analyses carried out to obtain the strain-life relationship. Fatigue tests are expensive and time consuming; hence, developing a Finite Elements (FE) model which can be used as numerical tool for subsequent analysis is beneficial. *ABAQUS* software was used to find the numerical solution for stress-strain relationship. Then, the results file of *ABAQUS* were exported as (*.odb) file to the “fe-safe” software in order to conduct fatigue life analysis.

6.1 STRESS ANALYSIS USING COMMERCIAL SOFTWARE

*ABAQUS* pre-processor or CAE which has capabilities in modeling and analysing a variety of problems including two and three dimensional geometries was used for modeling. It allows both linear and nonlinear Finite Element Analysis (FEA) in both explicit and implicit time integration schemes. The relative simplicity and steps consistency in *ABAQUS/CAE* was the primary reason for choosing this software.

6.1.1 Modeling, Loading, and Element Selection

6.1.1.1 Modeling and Loading

The part was drawn as a 2D sheet and revolved to create 3D part according to geometry and dimensions suggested by ASTM E8/E8M and A370 standard [ASTM E8/E8M, 2008 and A370, 2009]. Then the material properties were assigned to the model as well as section type. The materials properties included are: density of 7770 kg/m³ for steels, modulus of elasticity of 205 GPa, and Poisson’s ratio of 0.3. Further details of hardening and damage rules assignment are discussed in the subsequent sections. The upper end of the specimen was fixed while the bottom end was subjected to one directional displacement as applied to the test specimen. The experimental test was carried out in strain control mode and the gauge length of the strain measurement was 50.8 mm (2.0 inches). In the FE model, an equivalent displacement was applied to the lower end nodes. An example of calculations for equivalent displacement is shown below.
Example of calculation numerical strain

This example is for specimen subjected to zero mean strain and strain amplitude of 1500 µε. Figure (6.1) shows that the specimen length is 300 mm. The specimen length between machine grips is equal to \([300-(2\times63.5)=173 \text{ mm}]\) which is the effective length of the specimen in FE model. The extension estimations are illustrated in the following relations.

\[
\text{Strain} = \frac{\text{extension}}{\text{length}} \quad (6.1)
\]

\[\text{Extension (on 50.8 mm gauge length)} = (50.8) \times (\varepsilon_a)\]

\[\text{Extension (on 173 mm)} = [300-(2\times63.5)] \times (\varepsilon_a)= (173) \times (\varepsilon_a)\]

For example, if the strain amplitude is 1500 µε the extension is:

\[\text{Extension (on 50.8 mm)} = (50.8) \times (1500 \times 10^{-6})=0.0762 \text{ mm (applied experimentally)}\]

\[\text{Extension (on 173 mm)} = (173) \times (1500 \times 10^{-6})=0.2595 \text{ mm (in FEA model)}\]

![Figure (6.1) Specimen geometry according to ASTM standards E8 and A370](image)

Table (6.1) shows the extension applied on the test specimen (experimentally) and the extension applied on the numerical model to produce the strain amplitude (listed in the first column). The differences in the values of extensions in this table are due to the difference in the effective lengths (that carried the strain) of the test specimen and numerical model.
Table (6.1) Extensions applied on the test specimen and numerical model

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Strain amplitude ($\varepsilon_a$)</th>
<th>Experimental extension (mm)</th>
<th>Numerical extension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0010</td>
<td>0.0508</td>
<td>0.173</td>
</tr>
<tr>
<td>2</td>
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<td>0.1903</td>
</tr>
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<tr>
<td>15</td>
<td>0.0024</td>
<td>0.1219</td>
<td>0.4152</td>
</tr>
</tbody>
</table>

6.1.1.2 **Element Selection**

The solid element C3D4 (four node linear tetrahedral element) was chosen for discretization. The tetrahedral element is compatible with *fe-safe* software [fe-safe, 2002]. The default seed size which provided a relatively fine mesh was chosen for meshing. Figure (6.2) shows a typical mesh of E8 specimen in *ABAQUS* interface.
6.1.2 Material Properties

A linear elastic material model is valid for small elastic strains (normally less than 5%). These models can be isotropic, orthotropic, or fully anisotropic and can have properties that depend on temperature and/or other field variables.

There are seven elastic models available in ABAQUS 6.8-1 which summarized below.

- **Isotropic**: to characterize isotropic elastic properties, (data required are: Young's modulus, $E$, and Poisson's ratio, $\nu$).
- **Engineering Constants**: to characterize orthotropic elastic properties by giving the engineering constants, (data required are: the generalized Young's moduli in the principal directions, $E_1$, $E_2$, $E_3$; the Poisson's ratios in the principal directions, $\nu_{12}$, $\nu_{13}$, $\nu_{23}$; and the shear moduli in the principal directions, $G_{12}$, $G_{13}$, $G_{23}$).
- **Lamina**: to characterize orthotropic elastic properties in plane stress, (data requires are: the Young’s moduli, $E_1$, $E_2$; the Poisson's ratio, $\nu_{12}$; and the shear moduli, $G_{12}$, $G_{13}$, $G_{23}$). The $G_{13}$ and $G_{23}$ shear moduli are needed to define transverse shear behaviour in shells.
• **Orthotropic:** to characterize orthotropic elastic properties directly (data required are: the 9 elastic stiffness parameters: $D_{1111}$, $D_{1122}$, etc. [units of $FL^{-2}$]).

• **Anisotropic:** to characterize anisotropic elastic properties (data required are: the 21 elastic stiffness parameters: $D_{1111}$, $D_{1122}$, etc. [units of $FL^{-2}$]).

• **Traction:** to characterize orthotropic elastic properties for warping elements, entries depend on the element type that is being modeled.

• **Coupled Traction:** to characterize coupled elastic properties for cohesive elements, (data required are: the six elastic moduli $K_{nn}$, $K_{ss}$, $K_{tt}$, $K_{ns}$, $K_{nt}$, $K_{st}$).

The **isotropic linear elastic** material model was selected as the steels used in this study are isotropic and the elastic strain did not exceed 5% (the maximum total strain was 0.0024 = 0.24%). The elastic strain was estimated as the strain associated to the yield stress in the quasi-static test.

### 6.1.3 Hardening Rules

The five hardening rules available in ABAQUS 6.8-1 are mentioned below.

- **Isotropic:** to model hardening where the yield surface changes size uniformly in all directions such that the yield stress increases (or decreases) in all stress directions as plastic straining occurs.

- **Kinematic:** to model the cyclic loading of a material with a constant rate of hardening.

- **Johnson-Cook:** to model isotropic hardening in ABAQUS/Explicit, where the yield stress is provided as an analytical function of equivalent plastic strain, strain rate, and temperature.

- **User defined:** to describe the yield stress for isotropic hardening through user subroutine “UHARD”.

- **Combined:** to model the cyclic loading of a material with nonlinear isotropic/kinematic hardening.

Predicting ratcheting or mean stress relaxation is very important in the design of components subject to cyclic loading in the inelastic domain. The plastic strain can accumulate continuously with an increasing number of cycles and may eventually cause material failure. Therefore, many cyclic plastic models have been developed in ABAQUS.
with the goal of modeling ratcheting correctly. Example “1.1.8 uniaxial ratcheting under tension and compression” in “ABAQUS Example Problems Manual” shows that the combined isotropic/kinematic hardening model can predict ratcheting well. The results obtained using this model correlated very well with the experimental results. This example considers two loading conditions: monotonic deformation and uniaxial cyclic tension and compression [ABAQUS Example Problems Manual].

Furthermore, as the number of cycles increases, the mean stress tends to zero (see Figure 4.28 in Chapter 4). The nonlinear kinematic hardening component of the nonlinear isotropic/kinematic hardening model accounts for this behaviour [ABAQUS user’s manual].

As the type of loading in the current study is similar to that of the above example the Combined hardening model was chosen as a hardening rule. The only difference between this example and the current study is that specimens in the current study were subjected to strain controlled load cycles. Hence, the specimens experienced mean stress relaxation rather than ratcheting. It was assumed that the yield surface changes size uniformly in all directions while the hardening occurs in a nonlinear fashion. Two steps are required to define the combined hardening model. First, the kinematic hardening component is defined and calibrated by specifying half-cycle test data [ABAQUS Example Problems Manual]. Table (6.2) shows a sample of the half cycle stress-strain experimental data of specimen made of G40.21 350WT steel. This specimen was subjected to mean strain of zero and strain amplitude of 0.001 (1000 µε).

<table>
<thead>
<tr>
<th>Stress (MPa)</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.05</td>
<td>0.0001528</td>
</tr>
<tr>
<td>62.14</td>
<td>0.0003254</td>
</tr>
<tr>
<td>94.87</td>
<td>0.0004325</td>
</tr>
<tr>
<td>122.88</td>
<td>0.0005554</td>
</tr>
<tr>
<td>147.93</td>
<td>0.0006566</td>
</tr>
<tr>
<td>169.26</td>
<td>0.0007810</td>
</tr>
<tr>
<td>186.49</td>
<td>0.0008000</td>
</tr>
<tr>
<td>197.50</td>
<td>0.0008542</td>
</tr>
<tr>
<td>198.62</td>
<td>0.0008600</td>
</tr>
</tbody>
</table>
The data of 10 consistent cycles after applying strain history were considered as recommended by *ABAQUS*. The objective of this numerical analysis is to compare the model predictions with test data over many cycles. The stabilized cycle (at the cycle count of 1000) was therefore; chosen for calibration, as the actual strain history reached the command values at this count [*ABAQUS* benchmark manual-3.2.8 Simple proportional and non-proportional cyclic tests]. The yield stress was found using graphical representation of the experimental data, while the strain was linearly interpolated.

The data were entered in *ABAQUS* as values of yield stress, $\sigma_0^i$, versus plastic strain, $\varepsilon_{pl}^i$, on the data lines of the Plastic; Hardening: Combined, Data type: Stabilized option, where:

$$
\varepsilon_{pl}^i = \varepsilon_i - \left( \frac{\sigma_0^i}{E} \right) - \varepsilon_0^p
$$

(6.2)

where $\varepsilon_i$ is the total strain for data point $i$, and

$$
\varepsilon_0^p = \varepsilon_i - \left( \frac{\sigma_0^i}{E} \right)
$$

(6.3)

The onset of yield was taken as $\sigma_0^1 = 90$ MPa from the cyclic stress-strain plot. The corresponding total strain in the first point ($\varepsilon_1$) of 0.0004166 was interpolated from the experimental data. The modulus of Elasticity of G4.21 350WT steel is 205GPa. Therefore, from Equation (6.3) it can be concluded that $\varepsilon_0^p = 0.0000224$. The yield stress-plastic strain data for the 10 cycles are shown in Table (6.3).
Table (6.3) Yield stress-plastic strain data of 10 cycles of G40.21 350WT steel

<table>
<thead>
<tr>
<th>Cycle count</th>
<th>Yield Stress, $\sigma^0_i$ (MPa)</th>
<th>Plastic Strain, $\varepsilon^{pl}_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>1001</td>
<td>92</td>
<td>7.22075E-06</td>
</tr>
<tr>
<td>1002</td>
<td>94</td>
<td>9.13707E-06</td>
</tr>
<tr>
<td>1003</td>
<td>96</td>
<td>1.20945E-05</td>
</tr>
<tr>
<td>1004</td>
<td>99</td>
<td>2.64591E-05</td>
</tr>
<tr>
<td>1005</td>
<td>101</td>
<td>1.71108E-05</td>
</tr>
<tr>
<td>1006</td>
<td>104</td>
<td>3.66298E-05</td>
</tr>
<tr>
<td>1007</td>
<td>105</td>
<td>2.42146E-05</td>
</tr>
<tr>
<td>1008</td>
<td>107</td>
<td>2.3227E-05</td>
</tr>
<tr>
<td>1009</td>
<td>110</td>
<td>3.49558E-05</td>
</tr>
</tbody>
</table>

Similarly, the yield stresses and corresponding strains were found for each case of the other 14 applied strains which were listed in Table (6.1). Then these strains were assigned to the ABAQUS-CAE files of each specific case.

The isotropic hardening component is calibrated next. Isotropic hardening defines the evolution of the elastic range as a function of equivalent plastic strain. The size of the elastic range can be determined easily at points where the loading is reversed as half the difference between the yield stress in tension and compression. For the stabilized cycle, the size of the elastic stress range is 180 MPa (double of the yield stress). The corresponding values of equivalent plastic strain are obtained by assuming that the test is approximately performed as a symmetric plastic strain-controlled experiment.

Where,

$$
\Delta \varepsilon^{pl} = \Delta \varepsilon - 2(\bar{\sigma} / E)
$$

(6.4)

and $\bar{\sigma}$ is an average yield stress over all the cycles. The value of $\bar{\sigma}$ is taken as 100 MPa for this steel corresponding to yield stresses in Table (6.3). With this assumption, the equivalent plastic strain is obtained as follows.

$$
\bar{\varepsilon}^{pl} = 0.5 \left( 4i - 3 \right) \Delta \varepsilon^{pl}
$$

(6.5)
Where, \( i \) is the cycle number. This approximation yields a value of \( \bar{\varepsilon}^{pl} = 25.99\% \) for the last cycle \((i=10)\). The resulting data are entered in tabulated form on the data lines of the “Cyclic Hardening” option in ABAQUS. The change in elastic range during the first half-cycle is specified as zero to compensate for difference in shape of this cycle compared to subsequent cycles.

Table (6.4) Yield stress-equivalent plastic strain data of G40.21 350WT steel

<table>
<thead>
<tr>
<th>Cycle count</th>
<th>Yield Stress, ( \sigma^0_i ) (MPa)</th>
<th>Equivalent Plastic Strain, ( \varepsilon^{pl}_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>90</td>
<td>7.0231E-05</td>
</tr>
<tr>
<td>1001</td>
<td>92</td>
<td>0.00035115</td>
</tr>
<tr>
<td>1002</td>
<td>94</td>
<td>0.00063208</td>
</tr>
<tr>
<td>1003</td>
<td>96</td>
<td>0.00091300</td>
</tr>
<tr>
<td>1004</td>
<td>99</td>
<td>0.00119392</td>
</tr>
<tr>
<td>1005</td>
<td>101</td>
<td>0.00147485</td>
</tr>
<tr>
<td>1006</td>
<td>104</td>
<td>0.00175577</td>
</tr>
<tr>
<td>1007</td>
<td>105</td>
<td>0.00203669</td>
</tr>
<tr>
<td>1008</td>
<td>107</td>
<td>0.00231762</td>
</tr>
<tr>
<td>1009</td>
<td>110</td>
<td>0.00259854</td>
</tr>
</tbody>
</table>

6.1.4 Ductile Damage

The Ductile damage initiation model is required for predicting the onset of damage due to nucleation, growth, and coalescence of voids in ductile metals. The model assumes that the equivalent plastic strain at the onset of damage is a function of stress triaxiality and strain rate. The ductile damage initiation model can be used in conjunction with the Mises, Johnson-Cook, Hill, and Drucker-Prager plasticity models, including the equation of state.

**Fracture Strain:** Equivalent fracture strain at damage initiation (from experimental stress strain curve of G40.21 350WT steel is equal to 0.4).

**Stress Triaxiality:** The stress triaxiality is defined as \( \eta = -p/q \), where \( p \) is the pressure stress and \( q \) is the Mises equivalent stress. Performing simple calculations produced: \( P=load/area= 24,349/126=193 \) MPa, and \( q= 350 \) MPa, therefore the stress triaxiality \( \eta= -193/350 = -0.552 \).
**Strain Rate:** The equivalent plastic strain rate, $\dot{\varepsilon}^{pl}$, was maintained at 0.048 s$^{-1}$ for all strain-life tests.

6.1.5 Damage Evolution

The damage evolution defines how the material degrades after one or more damage initiation criteria are met. Multiple forms of damage evolution may act on a material at the same time—one for each damage initiation criterion that was defined. The procedure below includes data entries for every type of damage evolution available in the “Property” module. The selections vary with the current damage initiation form.

1. **Types of damage evolution**
   - **Displacement:** Displacement damage evolution defines damage as a function of the total or the plastic displacement after damage initiation. The total displacement is for elastic materials in cohesive elements while the plastic displacement is for bulk elastic-plastic materials.
   - **Energy:** Energy damage evolution defines damage in terms of the energy required for failure (fracture energy) after the initiation of damage.

2. **Softening methods**
   - **Linear:** Linear softening specifies a linear softening stress-strain response for linear elastic materials or a linear evolution of the damage variable with deformation for elastic-plastic materials. Linear softening is the default method.
   - **Exponential:** Exponential softening specifies an exponential softening stress-strain response for linear elastic materials or an exponential evolution of the damage variable with deformation for elastic-plastic materials.
   - **Tabular:** Tabular softening specifies the evolution of the damage variable with deformation in tabular form and is available only when the user selects the type “Displacement”. The Displacement at Failure field in the Data table is replaced by a Damage Variable field and a Displacement field, and the user can add additional rows to define the displacements [ABAQUS Analysis user’s manual].

Although damage was not expected in strain-life tests of the current study from the first cycle as a result of application cyclic load, the damage evolution was set in the software as one of the basic requirements. The *Displacement damage evolution* was selected.
whereas the damage occurrence was a result of displacement (extension) application. The default method namely the linear softening method was used. The displacement at failure was assigned as 17 mm which was estimated as the average value from maximum displacements at fracture in the experimental quasi-static tests conducted on G40.21 350WT steel.

After the analysis was completed, the deformed specimen is shown in Figure (6.3) as a screen shot extracted from ABAQUS. This model is for specimen made of G40.21 350WT steel and subjected to a displacement (extension) of 0.173 mm which is equivalent to strain amplitude of 0.001 (1000 $\mu\varepsilon$). Figure (6.3) shows the von-Mises stress and displacement contours. The stress contour illustrates the maximum stress occurrence in the gauge length region. However, the displacement contour shows the maximum displacement occurred in the lower end of the specimen. The experimental results indicated that the maximum stress after the cycle count of 1000 and for the subsequent nine cycles was 213.8 MPa. However, the numerical analysis (Figure 6.3) shows that the maximum stress was 239.2 MPa. The difference between experimental and numerical analysis is 10.62%. This percentage was estimated as the difference between maximum stress found in one of the ten cycles from the experimental data and maximum stress resulted from numerical analysis, divided by the maximum stress resulted from numerical analysis. The von-Mises stress resulted from numerical simulation was the same as that applied on the specimen’s longitudinal axis (axis 2 in ABAQUS results, or y in Figures 6.3 and 6.4). This equality was expected as the loading was uniaxial. Therefore, the von-Mises stress found from numerical analysis was considered in the error calculations.

Figure (6.4) shows the von-Mises stress and displacement contours of specimen made of G40.21 350WT steel and subjected to a displacement of 0.1903 mm which is equivalent to strain amplitude of 0.0011 (1100 $\mu\varepsilon$). The experimental results produced maximum stress of 245.62 MPa, while the numerical analysis shows that the maximum stress was 260.8 MPa. The difference in this case was 5.8%. The plots of numerical analyses for the other 13 strain amplitudes are illustrated in Figures G1 to G13 in Appendix (G).
Figure (6.3) *ABAQUS* results of specimen subjected to strain of 1000 µε

Figure (6.4) *ABAQUS* results of specimen subjected to strain of 1100 µε
Table (6.5) lists the error in maximum stress found from experimental and numerical results for the 15 strain amplitudes which were considered in strain-life tests of this study. The table shows that for the higher strain amplitudes, the error is relatively high as compared to that of lower strain amplitudes specimens. The maximum error recorded was 37.6% and it was found from the specimen tested with strain amplitude of 0.0023. The higher error in the higher strain amplitude specimens may be due to the fact that the experimental data considered were extracted from the cycle 1000th to 1009th. In these cycles, the specimens experienced plastic shake down. This fact is clarified more in the following paragraphs.

At the beginning of cyclic tests the strain was controlled to be increased gradually until occurrence of its full value, this was done to avoid overloading in the first few cycles as recommended by ASTM E606. As mentioned above, as the data of the half cycle (which was used in numerical stress calculation) was extracted from the cycles where the specimens experienced plastic shake down the stress required to perform the applied strain was relatively less than that required to perform the applied strain in the earlier cycles.

As ABAQUS considers stress softening without taking into account the behaviour of a specific material, the stress in numerical simulation kept increasing as the applied strain increased. Thus, the rise in stress occurs in way that differs from that of the experimental tests. For low strain amplitude specimens the stress in ABAQUS model did not reach higher values as the strain is relatively low. However, numerical stress in ABAQUS approached high values for the high strain amplitudes as shown in Table (6.5). Therefore, the difference between experimental and numerical stresses increased. This led to rising numerator value in the error relationship which introduced higher error in the higher strain amplitudes tests.
Table (6.5) Stress difference of experimental and numerical analyses of G40.21 steel

<table>
<thead>
<tr>
<th>Strain amplitude ($\varepsilon_a$)</th>
<th>Experimental extension (mm)</th>
<th>Numerical extension (mm)</th>
<th>Maximum Experimental Stress (MPa)</th>
<th>Maximum Numerical Stress (MPa)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0010</td>
<td>0.0508</td>
<td>0.173</td>
<td>213.8</td>
<td>239.2</td>
<td>10.62</td>
</tr>
<tr>
<td>0.0011</td>
<td>0.0559</td>
<td>0.1903</td>
<td>245.6</td>
<td>260.8</td>
<td>5.83</td>
</tr>
<tr>
<td>0.0012</td>
<td>0.0610</td>
<td>0.2076</td>
<td>266.7</td>
<td>282.4</td>
<td>5.54</td>
</tr>
<tr>
<td>0.0013</td>
<td>0.0660</td>
<td>0.2249</td>
<td>276.0</td>
<td>303.8</td>
<td>9.17</td>
</tr>
<tr>
<td>0.0014</td>
<td>0.0711</td>
<td>0.2422</td>
<td>289.8</td>
<td>325.3</td>
<td>10.91</td>
</tr>
<tr>
<td>0.0015</td>
<td>0.0762</td>
<td>0.2595</td>
<td>299.9</td>
<td>346.7</td>
<td>13.50</td>
</tr>
<tr>
<td>0.0016</td>
<td>0.0813</td>
<td>0.2768</td>
<td>296.3</td>
<td>367.2</td>
<td>19.31</td>
</tr>
<tr>
<td>0.0017</td>
<td>0.0864</td>
<td>0.2941</td>
<td>295.1</td>
<td>389.1</td>
<td>24.19</td>
</tr>
<tr>
<td>0.0018</td>
<td>0.0914</td>
<td>0.3114</td>
<td>293.1</td>
<td>410.2</td>
<td>28.56</td>
</tr>
<tr>
<td>0.0019</td>
<td>0.0965</td>
<td>0.3287</td>
<td>322.2</td>
<td>431.3</td>
<td>25.28</td>
</tr>
<tr>
<td>0.0020</td>
<td>0.1016</td>
<td>0.3460</td>
<td>357.0</td>
<td>452.3</td>
<td>21.08</td>
</tr>
<tr>
<td>0.0021</td>
<td>0.1067</td>
<td>0.3633</td>
<td>349.7</td>
<td>473.4</td>
<td>26.11</td>
</tr>
<tr>
<td>0.0022</td>
<td>0.1118</td>
<td>0.3806</td>
<td>332.1</td>
<td>494.4</td>
<td>32.85</td>
</tr>
<tr>
<td>0.0023</td>
<td>0.1168</td>
<td>0.3979</td>
<td>321.8</td>
<td>515.4</td>
<td>37.57</td>
</tr>
<tr>
<td>0.0024</td>
<td>0.1219</td>
<td>0.4152</td>
<td>339.4</td>
<td>536.5</td>
<td>36.74</td>
</tr>
</tbody>
</table>

6.2 FATIGUE ANALYSIS USING *fe-safe* SOFTWARE

6.2.1 *fe-safe* Capabilities

*fe-safe* is a suite of software for fatigue analysis from finite element models. It is able to calculate the following data.

- Fatigue life at each node on the model and thereby it identifies fatigue crack sites
- Stress-based factors of strength for a specified design life. These show how much the stresses must be changed at each node to achieve the design life
- Probability of failure at the design life, at each node
- Probability of failure at a specified series of lives, to produce a ‘warranty curve’
The results of these calculations can be plotted as 3-D contour plots using the FEA graphics or third party plotting suites. The fatigue results can be calculated from nodal stresses or elemental stresses.

In addition, *fe-safe* can generate the following data:

- The effect of each load on the fatigue life at critical locations to show if fatigue testing can be simplified, and for load sensitivity analysis
- Detailed results for critical elements, in the form of time histories of stresses and strains, orientation of critical planes, etc [fe-safe, 2008].

For critical elements, *fe-safe* can provide comprehensive graphical output, including fatigue cycle and damage distributions, calculated stress histories and crack orientation. To simplify component testing and to aid re-design *fe-safe* can evaluate which loads and loading directions contribute most to the fatigue damage at critical locations.

Typical application areas include the analysis of machined, forged and cast components in steel, aluminum and cast iron, high temperature components, welded fabrications and press-formed parts. Complex assemblies containing different materials and surface finishes can be analysed in a single run [fe-safe, 2008].

### 6.2.2 Compatibility with other Software

*fe-safe* can import files from several source FE software such as (ABAQUS.odb, fil, ANSYS.rst, IDEAS.unv, NASTRAN.f06, op2 and Pro/Engineer.s01, s02, d01). *fe-safe* reads stresses, temperatures and group information from its source files. It does not read strain datasets (by default). Hence, if the user would like *fe-safe* to read the strain the “Read strains from FE Model in the General FE Option” dialogue should be checked or allowing pre-scanning of files.

As data is being extracted from the FE model, the message log reports the following:

- Maximum and minimum direct and shear stresses in each dataset
- Names of element or node groups (for nodal datasets, node groups are imported; and for elemental datasets, element groups are imported)
- A summary of the temperature datasets found [fe-safe, 2008]
6.2.3 fe-safe Interface

The General fe-safe screen is shown in Figure (6.5). There are five windows:

- **Open Data Files**: displays the loading files (data files)
- **Open FE Models**: displays details of the open FE files
- **Open Data Bases**: displays the materials data base
- **Fatigue from FEA**: displays the FEA-fatigue dialogue box
- **Message log**: displays messages

![Figure (6.5) Screen shot of fe-safe software interface](image)

6.2.4 Analysis Requirements

fe-safe requires three inputs to perform a fatigue analysis and these are as follows

- The stresses at each point in the model: fe-safe can use elastic stresses from an elastic finite element (FE) analysis, or elastic-plastic stresses and strains from an
elastic-plastic FE analysis. If necessary, *fe-safe* will perform a plasticity correction in order to use elastic FE stresses with strain based fatigue algorithms

- A description of the loading: load histories can be imported from industry-standard file formats or entered with the keyboard. Complex loading conditions can also be defined, including combinations of superimposed load histories, sequences of FEA stresses and block loading. Loading histories and other time-series data are contained in files referred to as data files

- Materials data: fatigue properties of the component material(s) are required. A comprehensive material database is provided with *fe-safe* [fe-safe, 2008]

### 6.2.5 Analysis Process of Stress-life Calculations

The fatigue life of stress controlled tests for each node was calculated in *fe-safe* software as follows.

1) The stress tensors were multiplied by the time history of the applied loading to produce a time history of each of the 6 components of the stress tensor.
2) The time histories of the in-plane principal stresses were calculated.
3) The time histories of the three principal strains were calculated from the stresses.
4) A multi-axial cyclic plasticity model was used to convert the elastic stress-strain histories into elastic plastic stress-strain histories.
5) A “critical plane” method was used to identify the most damaging plane by calculating the damage on planes at 10° intervals between 0° and 180° in the surface of the component.
6) For each of the critical planes stresses were resolved onto the three shear planes (1-2, 2-3 and 1-3).
7) Time history of the damage parameter (which in this case, using the Brown-Miller algorithm which is the shear and normal strain) was cycle counted.
8) Individual fatigue cycles are identified using a “Rainflow” cycle algorithm the fatigue damage for each cycle was calculated and the total damage was summed.
9) The plane with the shortest life defines the plane of crack initiation and this life is written to the output file.
During this calculation *fe-safe* may modify the endurance limit amplitude. If all cycles (on a plane) are below the endurance limit amplitude there is no calculated fatigue damage on this plane. If any cycle is causes damage the endurance limit amplitude is reduced to 25% of the constant amplitude value and the damage curve extended to this new endurance limit.

### 6.2.6 Analysis Process of Strain-life Calculations

The current experimental study used strain controlled mode in carrying out fatigue life tests in order to plot strain-life curve of G40.21 350WT steel. Therefore, numerical fatigue analysis was conducted using strain-life category in *fe-safe*. The strain-life process in *fe-safe* software can be summarized as follows:

1. The program first searches for the absolute maximum value in the selected section of the signal (positive or negative).
2. This data point is converted into local stress and strain using the cyclic stress strain curve, the stress concentration factor, and Neuber's rule.
3. The program then takes each data point and checks if it is a turning point (a peak or valley). For each turning point, the program checks if it has closed a cycle. For each closed cycle the endurance is calculated. The cycle and its damage are added to the output histograms.
4. Once all the cycles closed by the data point have been analyzed the data point is converted into local stress and strain using the hysteresis loop curve, the stress concentration factor, and Neuber's rule.
5. At the end of the selected section of the signal, the program returns to the start point of the section and carries on the analysis until the absolute maximum data point is reached again.
6. The calculated fatigue damage for each cycle is summed and used to calculate the life to crack initiation.
7. To form the time-correlated damage file, as each cycle is closed, the times for the three points which form the cycle are used to position the fatigue damage in time.
8. Half the damage for the cycle is presumed to occur mid-way between the first two points, and another half of the damage is presumed to occur mid-way between the
2nd and 3rd points. The damage is added to any previously calculated damage at these points [fe-safe, 2008]

6.2.7 General Strain-life Analysis Properties

These functions are accessed from the “Gauge Fatigue” menu of fe-safe tools bar.

• Input strains can be a micro-strain history or a micro-strain-based cycle histogram
• Analysis can use a Smith-Watson-Topper, Morrow or no mean stress correction
• Sensitivity analysis can be carried out to investigate the effect of different stress concentrations or signal scale factors
• Cycle histograms produced by the signal functions in this section can be used as input to the histogram analysis functions, as can cycle histograms from the Rainflow cycle counting program. It may be quicker for “what-if” analysis to use a histogram input, then confirm the results with analysis of the full signal
• A peak-picked strain signal can be used as input instead of a strain signal. Therefore, analysis will be quicker however, the time-correlated damage file will not have a true time axis
• If nominal strains have been measured a stress concentration factor can be entered
• Local measured strains can be converted from one material to another [fe-safe, 2008]

6.2.8 Signal Processing for Fatigue Analysis

Measurements of service histories (loads, strains, and accelerations) are required so that general information on service loading can be obtained and so that the fatigue life of specific components can be determined. Modern signal processing uses a cycle counting algorithm to extract these cycles quickly and accurately.

The fatigue cycles are closed stress-strain hysteresis loops. The closure of these loops is quite complex in that the loop tips can be formed from points in the signal which is separated by a large number of intermediate points. An algorithm is required which correctly determines the cycles present in a signal. As the tips of the cycle are formed by a peak and a valley in the signal, the intermediate data points between each peak and valley need not be considered as shown in Figure (6.6).
Modern signal processing for fatigue analysis uses *Rainflow* cycle counting. The term *Rainflow* derives from an earlier algorithm, proposed by Endo et al. (1974). In this algorithm the signal was turned through 90° and rain was imagined as falling on the signal and dropping from surface to surface. Various rules were proposed for what happened to the rain and the resulting algorithm correctly extracted each half-cycle which eventually paired with another half cycle to make a complete cycle. The Rainflow method was a most important development at the time because it provided a genuine method of extracting fatigue cycles from measured signals (*fe-safe*, 2002).

![Figure (6.6) Fatigue peak-valley and Hysteresis loops (*fe-safe*, 2002)](image)

**6.2.9 Fatigue Analysis from FE Models**

As mentioned before the tetrahedral elements were selected to analyse stress numerically in the current study. Figure (6.7) shows a tetrahedral element with a node at each corner. The separate elements in a finite element model are connected together at the nodes. The stresses in the element may be calculated at one or more points inside the element called *integration points* or *Gauss points*. Nodal stresses are calculated by extrapolating the internal integration point stresses to the nodes of the element. The user may select to write integration point stresses and/or nodal stresses to the FEA results file.
Surface stresses are required for the analysis of fatigue crack initiation from the surface of a component. There will always be nodes at the surface of the FE model and hence, nodal stresses should be used for the fatigue calculation rather than integration point stresses. It is possible to output strains as well as stresses from the FE analysis and the strains could also be used for fatigue analysis. The accuracy with which surface nodal stresses are extrapolated from integration point stresses may have a significant influence on the subsequent fatigue analysis.

Since elements are connected at the nodes each node may have several values of stress extrapolated from the adjacent elements. It is common for FE codes and post-processing software to average these extrapolated stresses giving a single ‘nodal average’ stress tensor at each node [fe-safe, 2002]

6.2.10 Fatigue Analysis in the Current Study

Figure (6.8) illustrates an example of a sinusoidal signal used in the strain-life numerical analysis. In Figure (6.8) the mean strain is zero while the strain amplitude is 2400 µε. The strain amplitude varies for a set of specimens used in the strain-life study of G4.21 350WT from 1000 µε to 2400 µε as listed in Table 6.1. The frequency was changed accordingly to maintain the strain rate at value of 0.048 s⁻¹. For the frequencies assigned to match strain amplitudes, see Table (3.6) in Chapter 3.
Materials properties of G40.21 350WT steel were assigned to a file created in the “Open Databases” window. The values of tensile strength, yield strength, and modulus of elasticity were entered to *fe-safe* code as listed in Table (3.3). Poisons ratio of 0.3 was used as well. Strain-life fatigue parameters of G40.21 350WT steel were found using different methods (see Tables 2.2 and 6.5). Some of these methods were chosen in undertaking *fe-safe* analyses due to their compatibility to steels as well as availability of their required parameters. All methods indicated in Tables (2.2) and (6.6) were utilized in estimation fatigue life numerically except “Bäumel-Seeger-Al and Ti (1990)” which is suitable for Aluminum and Titanium only. Below, an example of calculation of the strain-life fatigue parameters as well as strain hardening parameters is provided.

Using *Roessle–Fatemi* model for steels, the strain-life fatigue parameters were estimated as follows.

Fatigue strength coefficient, 
\[ \sigma_f = 4.25HB + 225MPa = 4.25 \times 125 + 225MPa = 756 \, MPa \]

Fatigue ductility coefficient
\[ \varepsilon_f = \frac{\sigma_f}{E} = \frac{[0.32 \, HB^2 - 487HB + 191,000 \, MPa]}{205000} = 0.659 \]

The fatigue strength exponent \((b)\) and fatigue ductility exponent \((c)\) are constants (considering *Roessle–Fatemi* method) and equal to -0.09 and -0.56, respectively (as
shown in Table 6.6). Accordingly, the cyclic strain hardening coefficient ($k'$) and the cyclic strain hardening exponent ($\dot{n}$) were calculated as follows.

$$k' = \frac{\sigma_f}{(\dot{\varepsilon}_f)^{b/c}} = \frac{756}{(1.253)^{-0.09/-0.56}} = 729$$

$$\dot{n} = \frac{b}{c} = \frac{-0.09}{-0.56} = 0.161$$

Note that the last two relations are general and not associated to any of the strain-life fatigue parameters methods.

The complete estimation results of strain-life fatigue parameters of G40.21 350WT steel using the methods mentioned in Table (2.2) are shown in Table (6.6).

<table>
<thead>
<tr>
<th>Method</th>
<th>Fatigue strength coefficient $\sigma_f$ (MPa)</th>
<th>Fatigue strength exponent $b$</th>
<th>Fatigue ductility coefficient $\varepsilon_f$</th>
<th>Fatigue ductility exponent $c$</th>
<th>Cyclic Harden coeff. $k'$</th>
<th>Cyclic Harden exp. $n'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manson's universal slopes (1965)</td>
<td>995.60</td>
<td>-0.12</td>
<td>0.473</td>
<td>-0.60</td>
<td>1156.27</td>
<td>0.200</td>
</tr>
<tr>
<td>Manson's 4-point correlation (1965)</td>
<td>798.93</td>
<td>-0.162</td>
<td>0.334</td>
<td>-0.525</td>
<td>1121.49</td>
<td>0.309</td>
</tr>
<tr>
<td>Mitchell – steels (1977)</td>
<td>869.00</td>
<td>-0.087</td>
<td>0.365</td>
<td>-0.60</td>
<td>1005.38</td>
<td>0.145</td>
</tr>
<tr>
<td>Modified universal slopes (1988)</td>
<td>889.91</td>
<td>-0.09</td>
<td>0.464</td>
<td>-0.56</td>
<td>1006.90</td>
<td>0.161</td>
</tr>
<tr>
<td>Bäumel-Seeger-steels (1990)</td>
<td>786.00</td>
<td>-0.087</td>
<td>0.59</td>
<td>-0.58</td>
<td>850.74</td>
<td>0.150</td>
</tr>
<tr>
<td>Bäumel-Seeger-Al and Ti (1990)</td>
<td>875.08</td>
<td>-0.095</td>
<td>0.35</td>
<td>-0.69</td>
<td>1011.16</td>
<td>0.138</td>
</tr>
<tr>
<td>Ong (1993)</td>
<td>715.26</td>
<td>-0.128</td>
<td>0.365</td>
<td>-0.519</td>
<td>917.10</td>
<td>0.247</td>
</tr>
<tr>
<td>Roessle-Fatemi-steels (2000)</td>
<td>756.25</td>
<td>-0.09</td>
<td>0.659</td>
<td>-0.56</td>
<td>808.64</td>
<td>0.161</td>
</tr>
<tr>
<td>Medians- steels (2002)</td>
<td>786.00</td>
<td>-0.09</td>
<td>0.45</td>
<td>-0.59</td>
<td>887.81</td>
<td>0.153</td>
</tr>
<tr>
<td>Medians Al alloys (2002)</td>
<td>995.60</td>
<td>-0.11</td>
<td>0.28</td>
<td>-0.66</td>
<td>1230.91</td>
<td>0.167</td>
</tr>
</tbody>
</table>
The numerical analyses using *fe-safe* were carried out with different strain amplitudes and different methods of strain-life fatigue parameters. The results of the experimental and numerical fatigue lives of G40.21 350WT steel are listed in Table (6.7).

**Table (6.7) Experimental and numerical fatigue life of G40.21 350WT steel**

<table>
<thead>
<tr>
<th>Strain Amp (µε)</th>
<th>Experimental</th>
<th>Manson Univ.</th>
<th>Manson 4 points</th>
<th>Mitchell Mod Univ slopes</th>
<th>Bäumel-steels</th>
<th>Ong Medians steels</th>
<th>Roessle-Fatemi</th>
<th>Medians steels</th>
<th>Medians All</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>2,153,000</td>
<td>643,826</td>
<td>128,694</td>
<td>9,699,000</td>
<td>4,771,000</td>
<td>299,267</td>
<td>3,200,000</td>
<td>2,609,000</td>
<td>1,036,000</td>
</tr>
<tr>
<td>1100</td>
<td>1,520,000</td>
<td>371,351</td>
<td>97,379</td>
<td>3,634,410</td>
<td>2,132,860</td>
<td>212,859</td>
<td>1,675,150</td>
<td>1,194,590</td>
<td>476,706</td>
</tr>
<tr>
<td>1200</td>
<td>903,000</td>
<td>235,041</td>
<td>75,959</td>
<td>1,552,950</td>
<td>1,977,410</td>
<td>1,098,780</td>
<td>157,731</td>
<td>612,579</td>
<td>241,874</td>
</tr>
<tr>
<td>1300</td>
<td>766,000</td>
<td>157,825</td>
<td>60,728</td>
<td>760,135</td>
<td>1,071,290</td>
<td>629,080</td>
<td>120,814</td>
<td>613,463</td>
<td>134,237</td>
</tr>
<tr>
<td>1400</td>
<td>254,000</td>
<td>110,902</td>
<td>49,168</td>
<td>409,087</td>
<td>392,500</td>
<td>95,042</td>
<td>415,540</td>
<td>220,448</td>
<td>81,238</td>
</tr>
<tr>
<td>1500</td>
<td>165,000</td>
<td>82,367</td>
<td>40,946</td>
<td>239,312</td>
<td>410,572</td>
<td>265,241</td>
<td>76,562</td>
<td>296,663</td>
<td>148,006</td>
</tr>
<tr>
<td>1600</td>
<td>72,000</td>
<td>62,776</td>
<td>34,552</td>
<td>152,208</td>
<td>279,433</td>
<td>187,042</td>
<td>62,808</td>
<td>220,260</td>
<td>104,281</td>
</tr>
<tr>
<td>1700</td>
<td>62,000</td>
<td>49,201</td>
<td>29,515</td>
<td>102,271</td>
<td>198,626</td>
<td>138,434</td>
<td>52,357</td>
<td>169,309</td>
<td>76,763</td>
</tr>
<tr>
<td>1800</td>
<td>56,000</td>
<td>39,535</td>
<td>25,481</td>
<td>72,382</td>
<td>146,501</td>
<td>105,884</td>
<td>44,249</td>
<td>133,663</td>
<td>58,727</td>
</tr>
<tr>
<td>1900</td>
<td>45,000</td>
<td>32,098</td>
<td>22,205</td>
<td>53,209</td>
<td>112,089</td>
<td>83,253</td>
<td>37,513</td>
<td>107,236</td>
<td>46,132</td>
</tr>
<tr>
<td>2000</td>
<td>30,000</td>
<td>26,796</td>
<td>19,511</td>
<td>40,349</td>
<td>87,961</td>
<td>66,945</td>
<td>32,471</td>
<td>88,439</td>
<td>37,085</td>
</tr>
<tr>
<td>2100</td>
<td>24,000</td>
<td>22,671</td>
<td>17,269</td>
<td>31,637</td>
<td>70,559</td>
<td>54,465</td>
<td>28,346</td>
<td>74,079</td>
<td>30,382</td>
</tr>
<tr>
<td>2200</td>
<td>27,000</td>
<td>19,409</td>
<td>15,388</td>
<td>25,365</td>
<td>57,663</td>
<td>45,589</td>
<td>24,958</td>
<td>62,864</td>
<td>25,179</td>
</tr>
<tr>
<td>2300</td>
<td>18,000</td>
<td>16,792</td>
<td>13,794</td>
<td>20,736</td>
<td>47,866</td>
<td>38,672</td>
<td>22,123</td>
<td>53,951</td>
<td>21,356</td>
</tr>
<tr>
<td>2400</td>
<td>14,000</td>
<td>14,660</td>
<td>12,430</td>
<td>17,235</td>
<td>39,962</td>
<td>33,191</td>
<td>19,736</td>
<td>46,787</td>
<td>15,505</td>
</tr>
</tbody>
</table>

Simple checks of the data listed in Table (6.7) shows that the numerical fatigue lives found using “Medians method for steels” provided best fit and smallest error as compared to the experimental fatigue lives. Furthermore, Roessle-Fatemi method produced a considerable fit. The results of those two methods as well as experimental lives with their “power” trend lines are shown in Figures (6.9) and (6.10) which present normal and semi-log plots, respectively.
Figure (6.9) *fe-safe* and experimental strain-life (normal) plot of G40.21 steel

Other methods such as “Mitchell”, “Modified universal slopes” and “Baumel-Seeger-steels” produced fair fit with the experimental results as shown in Figures (6.11) and
(6.12) for normal and semi-log plots, respectively. These three methods overestimated the fatigue life. This difference in life is very clear in the low strain amplitudes runs.

Figure (6.11) fe-safe and experimental strain-life (normal) plot (cont’d)

Figure (6.12) fe-safe and experimental strain-life (semi-log) plot (cont’d)
However, Figures (6.13) and (6.14) illustrate the results of “Manson’s universal”, “Manson’s four points”, “Ong”, and “Medians-all alloys” which exhibit poor fit with the experimental results. The latter methods underestimated fatigue life especially in the low strain amplitudes runs. The significant difference between experimental and numerical fatigue life for some of the methods listed in Table (6.6) which indicates that the strain-life fatigue parameters play significant role in fatigue life numerical analysis. It may be noticed that relatively new methods such as Roessle-Fatemi (2000) and Medians for steels (2002) produced better results than earlier methods.

![Figure (6.13) fe-safe and experimental strain-life (normal) plot (cont’d)](image)
Figure (6.14) *fe-safe* and experimental strain-life (semi-log) plot (cont’d)

Figure (6.15) illustrates an example of life contour of specimen made of G40.21 350WT steel which subjected to zero mean strain and strain amplitude of 2400 µε with frequency of 5.0 Hz. The “Medians method for steels” was used to calculate the strain-life fatigue parameters. The fatigue analysis was conducted in *fe-safe* while the result was displayed using *ABAQUS/CAE* interface. The minimum life was 15,505 cycles which recorded in the gauge length region as shown in Figure (6.15).
6.3 SUMMARY

The numerical analyses were carried out in order to determine the strain-life relationship of G40.21 350WT steel and using numerical tools. The stress analyses were carried out using ABAQUS/CAE software while the fatigue analyses were carried out using fe-safe software. ABAQUS/CAE results exhibited good accuracy in low strain amplitudes while it showed a relatively large difference in the higher strain amplitudes. Nine methods for calculation of strain-life fatigue parameters were utilized in order to evaluate its impact on strain-life fatigue analysis. Some of these methods produced adequate fit between the numerical and experimental strain-life curves. However, other methods produced fair to poor fit. It can be concluded that the strain-life fatigue parameters play significant role in strain-life numerical analysis. The relatively new methods used in calculations of strain-life fatigue parameters such as Roessle-Fatemi (2000) and Medians for steels (2002) produced better results than the earlier methods.

Figure (6.15) Life contour of specimen made of G40.21 350WT steel

![Life contour of specimen](image-url)
CHAPTER 7: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY

7.1.1 Experimental Results

The results of experimental tests that were conducted on AISI 1022 HR and G40.21 350WT steels can be summarized in the following sub-sections.

7.1.1.1 Stress-strain Curve

In the quasi-static tensile test, the monotonic tensile strength and yield strength of G40.21 350WT steel increased at low temperatures. Both AISI 1022 HR and G40.21 350WT steels strain hardened until necking began, then they softened until rupture. The modulus of elasticity did not change as a result of application of strain cycles for both steels.

7.1.1.2 Tensile Strength

The tensile strength increased as a result of application of strain cycles on both steels. However, the effect of the mean strain on the tensile strength was negligible. The lower mean strain produced higher increase in tensile strength of both steels. The strain amplitude affected the tensile strength more than that of the mean strain for G40.21 350WT steel. The higher strain amplitude led to higher increase in tensile strength. The tensile strength for the fatigue-damaged (post-cyclic) specimens made of G40.21 350WT steel increased at low temperatures similar to the increase at room temperature.

7.1.1.3 Yield Strength

The yield strength increased for the fatigue-damaged specimens in both steels. Both mean strain and strain amplitude showed significant effect on the yield strength. The higher strain amplitude of G40.21 350WT steel led to the higher yield strength for the fatigue-damaged specimens. The low temperature produced higher yield strength of the fatigue-damaged steel if compared with the room temperature.
7.1.1.4 Fracture Strength

The fracture strength of the fatigue-damaged specimens increased as well for both steels. The effect of mean strain on the fracture strength depends on the type of steel. However, the higher strain amplitude produced higher fracture strength. The low temperature produced a smaller increase in fracture strength than that at room temperature.

7.1.1.5 Ductility

In general, the ductility in terms of percentage elongation of the fatigue-damaged specimens reduced more than the ductility measured in terms of percentage reduction in area. The maximum reduction in percentage elongation occurred in specimens tested with the higher mean strains. Furthermore, the higher strain amplitude led to more reduction in percentage elongation. Low temperatures caused the most reduction in percentage elongation compared to room temperature.

7.1.1.6 Toughness

The toughness decreased as the strain cycle count increased for both steels. The toughness plateau of the higher strain amplitude shifted down as compared to that of the lower strain amplitude. The lower temperatures produced higher toughness of the fatigue-damaged specimens compared with room temperature.

7.1.1.7 Stress Softening and Mean Stress Relaxation

The stress softened in both steels as a result of application strain cycles. The stress wave of G40.21 350WT steel exhibited lower range than that of AISI 1022 HR steel. The strain amplitude did not affect the stress softening of G40.21 350WT steel. The stress softening in low temperatures was higher than that of room temperature. The mean stress relaxed in room temperatures with lower plateau than that of low temperature tests.

7.1.2 Derivation of Empirical Formulae

Two methods were considered in the derivation of empirical formulae for predicting the changes in mechanical properties due to application cyclic loading. These are the traditional method and Eureqa method. The traditional method produced inaccurate formulae and therefore, was excluded from the subsequent analysis. Eureqa method
produced accurate and reliable formulae and adopted for all the considered mechanical properties. Test series A1 of AISI 1022 HR steel, G1 to G4 and C0 to C-30 of G40.21 350WT steel are included to derive every universal model. The comparisons between predictions generated by the derived formulae and experimental data exhibited accurate fit as well as low error. The predictions of the universal regression model of tensile strength showed the best fit with the experimental data if compared with other universal models which were derived for the considered mechanical properties.

7.1.3 Strain-Life Relationship

The strain-life relationship is represented in three categories and these are experimental, statistical, and numerical.

7.1.3.1 Strain-Life Experimental Analysis

The strain-life relationship was studied experimentally using three approaches. In the first approach, the mean strain was considered for AISI 1022 HR and G40.21 350WT steels. AISI 1022 HR steel revealed higher fatigue lives than those of G40.21 350WT steel in the high strains region. However, the fatigue strain limit was almost similar for both steels.

In the second approach, the strain amplitude was considered using G40.21 350WT steel. The maximum life was 2.017 million cycles while the minimum life was 14 thousand cycles. The fatigue limit in terms of strain amplitude was less than 1000 µε.

In the third approach, the effect of temperature on strain-life relationship of G40.21 350WT steel was studied. The fatigue life increased by a factor from 7 to 12 as test temperature reduced from +25°C to -30°C.

7.1.3.2 Strain-Life Statistical Analysis

The ASTM standard 739-10 was considered to analyze the experimental strain-life data statically as well as some other statistical references. It was found that some of the experimental data fell slightly outside the 95% confidence levels. However, the scatter factor did not exceed a value of 4.0 which is an acceptable level if compared with
the previous studies. The linear model was accepted; hence there is no need to consider the nonlinear model in the strain-life relationship.

7.1.3.3 Strain-Life Numerical Modeling

The stress and fatigue analyses were carried out using commercial software. Nine methods of calculation strain-life fatigue parameters were utilized in order to evaluate its effect on strain-life fatigue analysis. Some of these methods produced adequate fit between the numerical and experimental strain-life curves. However, other methods produced fair or poor fit. It is then concluded that the strain-life fatigue parameters play significant role in the numerical analysis of strain-life relationship. The relatively newer methods of strain-life fatigue parameters such as Roessle-Fatemi (2000) and Medians for steels (2002) produced better results than earlier methods for the targeted steels.

7.2 CONCLUSIONS

The results and observations of the current study which was carried out in three parts: experimental, statistical, and numerical can be concluded in the following points.

- In the monotonic quasi-static test, the tensile strength and yield strength of the monotonic (damage-free) specimens made of G4.21 350WT steel increased at low temperatures as compared to that at room temperature.
- The hardness and modulus of elasticity did not change as a result of application strain cycles for AISI 1022 HR and G4.21 350WT steels.
- The tensile strength of the post cyclic (fatigue-damaged) specimens increased for both steels. The mean strain showed a negligible effect on the tensile strength while the strain amplitude exhibited considerable effect. The temperature did not affect the tensile strength.
- The yield strength of the post cyclic specimens increased for both steels. Both mean strain and strain amplitude showed a significant effect on the yield strength. The yield strength increased at room temperature if compared to low temperature.
- The fractures strength increased for both steels as a result of application strain cycles. The effect of the mean strain on the fracture strength was negligible while
the effect of strain amplitude was significant. The fracture strength increased at room temperature more than that at low temperature.

- The ductility of the *post cyclic* specimens decreased for both steels by almost same amount. In general, the ductility in terms of percentage elongation decreases more than that in terms of percentage reduction in area. The strain amplitude affected the percentage elongation; the higher reductions were found in specimens tested to the higher strain amplitude. The test temperature affected the ductility as well; the highest reduction in percentage elongation was found in specimens tested at lower temperatures.

- The toughness of the *post cyclic* specimens for G40.21 350WT steel reduced more than its reduction for AISI 1022 HR steel. The higher strain amplitude caused higher reduction in toughness. The specimens tested at room temperature exhibited higher reduction if compared with those at lower temperatures.

- The stress softened in both steels as a result of application strain cycles. The softening of G40.21 350WT steel was almost double if compared with that of AISI 1022 HR steel. The lower mean strain produced higher stress softening for both steels. The strain amplitude did not affect the stress softening. The lower temperatures caused more stress softening if compared with room temperature.

- The maximum increase or reduction in the mechanical properties was found in specimens tested with higher strain amplitude. In other words, the higher strain amplitude leads to the higher change in the mechanical property.

- The higher increase of most mechanical properties (tensile, yield and fracture strengths) was recorded in specimens tested at room temperature. However, the higher reduction of other mechanical properties (ductility and stress softening) was recorded in specimens tested at -30°C. Furthermore, the higher reduction in toughness was recorded in specimens tested at room temperature.

- AISI 1022 HR steel showed higher fatigue lives than those of G40.21 350WT steel in high strain region. However, the fatigue strain limit was almost similar for both steels.

- The fatigue life of G40.21 350WT steel increased significantly at low temperatures if compared with that at room temperature.
• The experimental results were used to derive empirical formulae for predicting the changes in mechanical properties of the post cyclic steels. The predictions from these formulae showed accurate fit with the experimental data.

• The numerical strain-life plots showed accurate fit with the experimental plots when a relatively new methods of the calculations of strain-life fatigue parameters were used.

### 7.3 RECOMMENDATIONS FOR FUTURE WORK

The current study accomplished its goals. However, following future research activities are recommended.

a) The effect of cyclic loading on the mechanical behaviour of HSLA 65 steel which is used in the US ship hull building especially in aircraft carriers. The study can follow the same procedure used for G40.21 350WT steel. The results of the these two steels will provide more information to the ship designers and builders.

b) The effect of cyclic loading on the mechanical and fatigue properties of structural steels by applying stress controlled cyclic loading. This study will provide a database that can be used to determine the impact of fatigue load control method.

c) The crystallographic changes due to application of cyclic loading using transmission electron microscope (TEM). This study will lead to better understanding the dislocation movements within the grains and its effects on the mechanical behaviour of the targeted steels.

d) The current study considered the uniaxial load for all tests conducted to investigate steels behaviour after cyclic loading as well as fatigue-life relationship. The consideration of another type of loading such as rotating bending, plane bending, or torsion will enhance the analyses and add a new parameter to the derived empirical formulae.

e) In the current study, all specimens tested were in the as-received condition. Following the recent study approach on heat treated groups of specimens will produce an additional database that can be useful in prediction the behaviour of heat treated structural steels. The suggested heat treatments are: carbonizing,
normalizing, and tempering, which are the most familiar treatments for these types of steel.

f) Other software for stress analysis such as “LsDyna” and fatigue analysis such as “Fatigue calculator” can be used. The results of the new software have to be assessed and compared with the results of current study that relied on ABAQUS and fe-safe. This suggested study will assist in determine the effect of software type on the numerical strain-life relationship. It will enhance the accuracy of selecting the best method required to estimate strain-life fatigue parameters.
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APPENDICES

APPENDIX (A) AMERICAN BUREAU OF SHIPPING (ABS)

Ai) Ordinary-strength Hull Structural Steel:

Table (Ai-1) Chemical properties of ordinary strength hull structural steel 100 mm (4.0 in) and under (1996)

<table>
<thead>
<tr>
<th>Grade</th>
<th>A</th>
<th>B</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deoxidation</td>
<td>Killed or semi-killed (1) (t ≤ 50 mm (2.0 in.)) Killed (t &gt; 50 mm (2.0 in.))</td>
<td>Killed or semi-killed (t ≤ 50 mm (2.0 in.)) Killed (t &gt; 50 mm (2.0 in.))</td>
<td>Killed (t ≤ 25 mm (1.0 in.)) Killed and fine grain (t &gt; 25 mm (1.0 in.))</td>
<td>Killed and fine grain (2)</td>
</tr>
<tr>
<td>C</td>
<td>0.21 (3)</td>
<td>0.21</td>
<td>0.21</td>
<td>0.18</td>
</tr>
<tr>
<td>Mn</td>
<td>2.5 × C</td>
<td>0.80 (4)</td>
<td>0.60</td>
<td>0.70</td>
</tr>
<tr>
<td>Si</td>
<td>0.50</td>
<td>0.35</td>
<td>0.10–0.35 (5)</td>
<td>0.10–0.35 (5)</td>
</tr>
<tr>
<td>P</td>
<td>0.035</td>
<td>0.035</td>
<td>0.035</td>
<td>0.035</td>
</tr>
<tr>
<td>S</td>
<td>0.035</td>
<td>0.035</td>
<td>0.035</td>
<td>0.035</td>
</tr>
<tr>
<td>Ni</td>
<td>See Note 6</td>
<td>See Note 6</td>
<td>See Note 6</td>
<td>See Note 6</td>
</tr>
<tr>
<td>Cr</td>
<td>See Note 6</td>
<td>See Note 6</td>
<td>See Note 6</td>
<td>See Note 6</td>
</tr>
<tr>
<td>Mo</td>
<td>See Note 6</td>
<td>See Note 6</td>
<td>See Note 6</td>
<td>See Note 6</td>
</tr>
<tr>
<td>Cu</td>
<td>See Note 6</td>
<td>See Note 6</td>
<td>See Note 6</td>
<td>See Note 6</td>
</tr>
<tr>
<td>C + Mn/6</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Marking</td>
<td>AB/A</td>
<td>AB/B</td>
<td>AB/D (7)</td>
<td>AB/E</td>
</tr>
</tbody>
</table>

Notes:
1. For Grade A, rimmed steel sections may be accepted up to and including 12.5 mm (0.5 in).
2. Grade D steel over 25 mm and Grade E steel are to contain at least one of the grain refining elements in sufficient amount to meet the fine grain practice requirements.
3. A maximum carbon content of 0.23% is acceptable for Grade A sections.
4. For Grade B steel of cold flanging quality or where fully killed, the lower limit of manganese may be reduced to 0.60%.
5. Where the content of soluble aluminum is not less than 0.015%, the minimum required silicon content does not apply.
6. The contents of nickel, chromium, molybdenum and copper are to be determined and reported. When the amount does not exceed 0.02%, these elements may be reported as ≤0.0(4,4),(997,991)
7. Grade D hull steel which is normalized, thermo-mechanical control processed or control rolled is to be marked AB/DN.
8. Intentionally added elements are to be determined and reported [ABS, part 2, sec 2].

Deoxidized steel: is steel that has a certain degree of oxygen removed from the melt during the steelmaking process. There are four types, ranging from fully deoxidized to slightly deoxidized: killed, semi-killed, capped, and rimmed.
**Killed** steel is steel that has been completely deoxidized by the addition of an agent before casting, so that there is practically no evolution of gas during solidification. They are characterized by a high degree of chemical homogeneity and freedom from gas porosity. The steel is said to be "killed" because it will quietly solidify in the mould, with no gas bubbling out. It is marked with a "K" for identification purposes. Common deoxidizing agents include aluminium, ferrosilicon and manganese. Aluminium reacts with the dissolved gas to form aluminium oxide. Aluminium also has the added benefit of forming pin grain boundaries, which prevent grain growth during heat treatments. For steels of the same grade a killed steel will be harder than rimmed steel.

The main disadvantage killed steels is that it suffers from deep pipe shrinkage defects. To minimize the amount of metal that must be discarded because of the shrinkage, a large vertical mold is used with a "hot top" refractory riser. Typical killed-steel ingots have a yield of 80% by weight. Commonly killed steels include alloy steels, stainless steels, heat resisting steels, steels with a carbon content greater than 0.25%, steels used for forgings, structural steels with a carbon content between 0.15 and 0.25%, and some special steels in the lower carbon ranges. It is also used for any steel castings. Note that as the carbon content decreases the greater the problems with non-metallic inclusions

**Semi-killed** steel is mostly deoxidized steel, but the carbon monoxide left leaves blowhole type porosity distributed throughout the ingot. The porosity eliminates the pipe found in killed steel and increases the yield to approximately 90% by weight. Semi-killed steel is commonly used for structural steel with a carbon content between 0.15 to 0.25% carbon, because it is rolled, which closes the porosity. It is also used for drawing applications.

**Rimmed steel**, also known as *drawing quality steel*, has little to no deoxidizing agent added to it during casting which causes carbon monoxide to evolve rapidly from the ingot. This causes small blow holes in the surface that are later closed up in the hot rolling process. Another result is the segregation of elements; almost all of the carbon, phosphorus, and sulfur move to the center of the ingot, leaving an almost perfect "rim" of pure iron on the outside of the ingot. This gives the ingot an excellent surface finish because of this iron rim, but also form the most segregated composition. Most rimmed steel has a carbon content below 0.25% carbon, a manganese content below 0.6%, and is not alloyed with aluminum, silicon, and titanium. This type of steel is commonly used for cold-bending, cold-forming, cold-heading and, as the name implies, drawing. Due to the non-uniformity of alloying elements it is not recommended for hot-working applications

**Capped steel** starts as rimmed steel but part way through the solidification the ingot is capped. This can be done by literally covering the ingot mold or by adding a deoxidizing agent. The top of the ingot then forms into a solid layer of steel, but the rim of the rest of the ingot is thinner than in a rimmed steel. Also there is less segregation of impurities.

The yield of rimmed and capped steel is slightly better than that of semi-killed steel. These types of steels are commonly used for sheet and strip metal because of their excellent surface condition. It is also used in most cold-working applications.

Due to production processes, as the carbon content of rimmed and capped steel increases above 0.08%, the cleanliness decreases. [Wikipedia, killed steel]

Table (Ai-2) Tensile properties of ordinary strength hull structural steel 100 mm (4.0 in.) and under (2008)

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile Strength N/mm² (kgf/mm², ksi)</th>
<th>Yield Point min. N/mm² (kgf/mm², ksi)</th>
<th>Elongation min. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, B, D, E</td>
<td>400-520 (41-53, 58-75)</td>
<td>235 (24, 34)</td>
<td>22</td>
</tr>
</tbody>
</table>

**Notes:**
1 Based on alternative A flat test specimen or alternative C round specimen in 2-1-1/Figure 1.
2 For Grade A sections, the upper limit of tensile strength may be 550 N/mm² (56 kgf/mm², 80 ksi).
3 Minimum elongation for alternative B flat specimen in 2-1-1/Figure 1 is to be in accordance with 2-1-2/Table Ai-3.
4 (2008) Minimum elongation for ASTM E8M/E8 or A370 specimen is 2-1-2/Table Ai-3 for 200 mm (8 in.) specimen and 22% for 50 mm (2 in.) specimen.
5 Steel ordered to cold flanging quality may have tensile strength range of 380-450N/mm$^2$ (39-46 kgf/mm$^2$, 55-65 ksi) and a yield point of 205N/mm$^2$ (21 kgf/mm$^2$, 30 ksi) minimum. [ABS, part 2, sec 2].

**Table (Ai-3) Elongation requirements for alternative b specimen (1995)**

<table>
<thead>
<tr>
<th>Thickness in mm (in.)</th>
<th>exceeding</th>
<th>not exceeding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 (0.20)</td>
<td>10 (0.40)</td>
</tr>
<tr>
<td></td>
<td>15 (.60)</td>
<td>20 (.80)</td>
</tr>
<tr>
<td></td>
<td>25 (1.0)</td>
<td>30 (1.2)</td>
</tr>
<tr>
<td></td>
<td>40 (1.6)</td>
<td>50 (2.0)</td>
</tr>
<tr>
<td>elongation (min. %)</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>22</td>
</tr>
</tbody>
</table>

**Table (Ai-4) Impact properties of ordinary-strength hull structural steel 100 mm (4.0 in) and under (2008)**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Temp. °C (°F)</th>
<th>Long’l (2)</th>
<th>Transv (2)</th>
<th>Long’l (2)</th>
<th>Transv (2)</th>
<th>Long’l (2)</th>
<th>Transv (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20 (68)</td>
<td>---</td>
<td>---</td>
<td>34 (3.5, 25)</td>
<td>24 (2.4, 17)</td>
<td>41 (4.2, 30)</td>
<td>27 (28, 20)</td>
</tr>
<tr>
<td>B</td>
<td>0 (32)</td>
<td>27 (2.8, 20)</td>
<td>20 (2.0, 14)</td>
<td>34 (3.5, 25)</td>
<td>24 (2.4, 17)</td>
<td>41 (4.2, 30)</td>
<td>27 (28, 20)</td>
</tr>
<tr>
<td>D</td>
<td>-20 (-4)</td>
<td>27 (2.8, 20)</td>
<td>20 (2.0, 14)</td>
<td>34 (3.5, 25)</td>
<td>24 (2.4, 17)</td>
<td>41 (4.2, 30)</td>
<td>27 (28, 20)</td>
</tr>
<tr>
<td>E</td>
<td>-40 (-40)</td>
<td>27 (2.8, 20)</td>
<td>20 (2.0, 14)</td>
<td>34 (3.5, 25)</td>
<td>24 (2.4, 17)</td>
<td>41 (4.2, 30)</td>
<td>27 (28, 20)</td>
</tr>
</tbody>
</table>

**Notes:**
1 The energy shown is minimum for full size specimen. See 2-1-2/ 11.5 for subsize specimen requirements.
2 Either direction is acceptable.
3 Impact tests for Grade A are not required when the material is produced using a fine grain practice and normalized.
4 CVN test requirements for Grade B apply where such test is required by 2-1-2/Table Ai-5.
## Higher-strength Hull Structural Steel

### Table (Aii-1) Chemical properties of higher-strength hull structural steel 100 mm (4.0 in) and under (1996)

<table>
<thead>
<tr>
<th>Grades</th>
<th>AH/DH/EH 32, AH/DH/EH 36 and AH/DH/EH 40</th>
<th>FH 32/36/40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deoxidation</td>
<td>Killed, Fine Grain Practice (4)</td>
<td></td>
</tr>
<tr>
<td>Chemical Composition (2) (Ladle Analysis), % max. unless specified in range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>Mn</td>
<td>0.90–1.60 (3)</td>
<td>0.90–1.60</td>
</tr>
<tr>
<td>Si</td>
<td>0.10–0.50 (4)</td>
<td>0.10–0.50 (4)</td>
</tr>
<tr>
<td>P</td>
<td>0.035</td>
<td>0.025</td>
</tr>
<tr>
<td>S</td>
<td>0.035</td>
<td>0.025</td>
</tr>
<tr>
<td>Al (acid Soluble) min (5, 6)</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Nb (6, 7)</td>
<td>0.02–0.05</td>
<td>0.02–0.05</td>
</tr>
<tr>
<td>V (6, 7)</td>
<td>0.05–0.10</td>
<td>0.05–0.10</td>
</tr>
<tr>
<td>Ti</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Cu (8)</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Cr (8)</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Ni (8)</td>
<td>0.40</td>
<td>0.80</td>
</tr>
<tr>
<td>Mo (8)</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>N</td>
<td>—</td>
<td>0.009 (0.012 if Al present)</td>
</tr>
</tbody>
</table>

### Marking (9)

AB/XHYY (X = A, D, E or F YY = 32, 36 or 40)

### Notes:

1. The steel is to contain at least one of the grain refining elements in sufficient amount to meet the fine grain practice requirement.
2. The contents of any other element intentionally added is to be determined and reported.
3. AH steel 12.5 mm (0.50 in.) and under in thickness may have a minimum manganese content of 0.70%.
4. Where the content of soluble aluminum is not less than 0.015%, the minimum required silicon content does not apply.
5. The total aluminum content may be used in lieu of acid soluble content, in accordance with 2-1-3/5.
6. The indicated amount of aluminum, niobium and vanadium applies when any such element is used singly. When used in combination, the minimum content in 2-1-3/5 will apply.
7. These elements need not be reported on the mill sheet unless intentionally added.
8. These elements may be reported as ≤ 0.02% where the amount present does not exceed 0.02%.
9. The marking AB/DHYYN is to be used to denote Grade DHYY plates which have either been normalized, thermomechanically control rolled or control rolled in accordance with an approved procedure.
10. See 2-1-3/7 for carbon equivalent and cold cracking susceptibility requirements for thermomechanically controlled steel.
11. For other steels, the carbon equivalent (Ceq) may be calculated from the ladle analysis in accordance with the equation below. Selection of the maximum value of carbon equivalent for these steels is a matter to be agreed between the fabricator and steel mill when the steel is ordered.

\[
C_{eq} = C + \frac{\text{Mn}}{6} + \frac{\text{Cr} + \text{Mo} + \text{V}}{5} + \frac{\text{Ni} + \text{Cu}}{15} \%
\]
Table (Aii-2) Tensile properties of higher-strength hull structural steel 100 mm (4.0 \text{ in}) and under (2008)

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile Strength N/mm$^2$ (kgf/mm$^2$, ksi)</th>
<th>Yield Point min. N/mm$^2$ (kgf/mm$^2$, ksi)</th>
<th>Elongation$^{(1, 2, 3)}$ min. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>AH 32, DH 32</td>
<td>440-590 (45-60, 64-85)</td>
<td>315 (32, 46)</td>
<td>22</td>
</tr>
<tr>
<td>EH 32, FH 32</td>
<td>490-620 (50-63, 71-90)</td>
<td>355 (36, 51)</td>
<td>21</td>
</tr>
<tr>
<td>AH 36, DH 36</td>
<td>510-650 (52-66, 74-94)</td>
<td>390 (40, 57)</td>
<td>20</td>
</tr>
</tbody>
</table>

Notes:
1. Based on alternative A flat test specimen or alternative C round specimen in 2-1-1/Figure 1.
2. Minimum elongation for alternative B flat specimen in 2-1-1/Figure 1 is to be in accordance with 2-1-3/Table Aii-3.
3. (2008) Minimum elongation for ASTM E8M/E8 or A370 specimen is 2-1-3/Table Aii-3 for 200 mm (8 in.) specimen and 20% for 50 mm (2 in.) specimen.

Table (Aii-3) Elongation requirements for alternative b specimen (1996)

<table>
<thead>
<tr>
<th>Thickness in mm (in.)</th>
<th>Grade Steel</th>
<th>elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exceeding:</td>
<td>XH 32</td>
<td>14 16 17 18 19 20 21 22</td>
</tr>
<tr>
<td>not exceeding:</td>
<td>XH 36</td>
<td>13 15 16 17 18 19 20 21</td>
</tr>
<tr>
<td></td>
<td>XH 40</td>
<td>12 14 15 16 17 18 19 20</td>
</tr>
</tbody>
</table>

Note: “X” denotes the various material grades, A, D, E and F.
Table (Aii-4) Impact properties of higher-strength steel 100 mm (4.0 in) and under (2005)

<table>
<thead>
<tr>
<th>Grade</th>
<th>Temp</th>
<th>Long' (1)</th>
<th>Transv (1)</th>
<th>Long' (2)</th>
<th>Transv (2)</th>
<th>Long' (2)</th>
<th>Transv (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AH 32</td>
<td>0 (32)</td>
<td>31 (3.2, 23)</td>
<td>22 (2.3, 16)</td>
<td>38 (3.9, 28)</td>
<td>26 (2.7, 19)</td>
<td>46 (4.7, 34)</td>
<td>31 (3.2, 23)</td>
</tr>
<tr>
<td>AH 36</td>
<td>34 (3.5, 25)</td>
<td>24 (2.4, 17)</td>
<td>41 (4.2, 30)</td>
<td>27 (2.8, 20)</td>
<td>50 (5.1, 37)</td>
<td>34 (3.5, 25)</td>
<td></td>
</tr>
<tr>
<td>AH 40</td>
<td>39 (4.0, 29)</td>
<td>26 (2.7, 19)</td>
<td>46 (4.7, 34)</td>
<td>31 (3.2, 23)</td>
<td>55 (5.6, 41)</td>
<td>37 (3.8, 27)</td>
<td></td>
</tr>
<tr>
<td>DH 32</td>
<td>-20 (-4)</td>
<td>31 (3.2, 23)</td>
<td>22 (2.3, 16)</td>
<td>38 (3.9, 28)</td>
<td>26 (2.7, 19)</td>
<td>46 (4.7, 34)</td>
<td>31 (3.2, 23)</td>
</tr>
<tr>
<td>DH 36</td>
<td>34 (3.5, 25)</td>
<td>24 (2.4, 17)</td>
<td>41 (4.2, 30)</td>
<td>27 (2.8, 20)</td>
<td>50 (5.1, 37)</td>
<td>34 (3.5, 25)</td>
<td></td>
</tr>
<tr>
<td>DH 40</td>
<td>39 (4.0, 29)</td>
<td>26 (2.7, 19)</td>
<td>46 (4.7, 34)</td>
<td>31 (3.2, 23)</td>
<td>55 (5.6, 41)</td>
<td>37 (3.8, 27)</td>
<td></td>
</tr>
<tr>
<td>EH 32</td>
<td>-40 (-40)</td>
<td>31 (3.2, 23)</td>
<td>22 (2.3, 16)</td>
<td>38 (3.9, 28)</td>
<td>26 (2.7, 19)</td>
<td>46 (4.7, 34)</td>
<td>31 (3.2, 23)</td>
</tr>
<tr>
<td>EH 36</td>
<td>34 (3.5, 25)</td>
<td>24 (2.4, 17)</td>
<td>41 (4.2, 30)</td>
<td>27 (2.8, 20)</td>
<td>50 (5.1, 37)</td>
<td>34 (3.5, 25)</td>
<td></td>
</tr>
<tr>
<td>EH 40</td>
<td>39 (4.0, 29)</td>
<td>26 (2.7, 19)</td>
<td>46 (4.7, 34)</td>
<td>31 (3.2, 23)</td>
<td>55 (5.6, 41)</td>
<td>37 (3.8, 27)</td>
<td></td>
</tr>
<tr>
<td>FH 32</td>
<td>-60 (-76)</td>
<td>31 (3.2, 23)</td>
<td>22 (2.3, 16)</td>
<td>38 (3.9, 28)</td>
<td>26 (2.7, 19)</td>
<td>46 (4.7, 34)</td>
<td>31 (3.2, 23)</td>
</tr>
<tr>
<td>FH 36</td>
<td>34 (3.5, 25)</td>
<td>24 (2.4, 17)</td>
<td>41 (4.2, 30)</td>
<td>27 (2.8, 20)</td>
<td>50 (5.1, 37)</td>
<td>34 (3.5, 25)</td>
<td></td>
</tr>
<tr>
<td>FH 40</td>
<td>39 (4.0, 29)</td>
<td>26 (2.7, 19)</td>
<td>46 (4.7, 34)</td>
<td>31 (3.2, 23)</td>
<td>55 (5.6, 41)</td>
<td>37 (3.8, 27)</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
1. The energy shown is minimum for full size specimen. See 2-1-2/11.5 for sub size specimen requirement.
2. Either direction is acceptable.

Table (Aii-6) Carbon Equivalent for Higher-strength Hull Structural Steel 100 mm (4.0 in.) and under produced by TMCP (2005)

<table>
<thead>
<tr>
<th>Grade</th>
<th>Carbon Equivalent, Max. (t%) (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>t ≤ 50 mm (2.0 in.)</td>
<td>50 mm (2.0 mm (2.0 in.) &lt; t ≤ 100 mm (4.0 in.)</td>
</tr>
<tr>
<td>AH 32, DH 32, EH 32, FH 32</td>
<td>0.36</td>
</tr>
<tr>
<td>AH 36, DH 36, EH 36, FH 36</td>
<td>0.38</td>
</tr>
<tr>
<td>AH 40, DH 40, EH 40, FH 40</td>
<td>0.40</td>
</tr>
</tbody>
</table>

**Note:** It is a matter for the manufacturer and shipbuilder to mutually agree in individual cases as to whether they wish to specify a more stringent carbon equivalent
**Aiii) Low Temperature Materials:**

**Table (Aiii-2) Chemical Composition**

<table>
<thead>
<tr>
<th>PLATES, SECTIONS AND FORGINGS (1) FOR CARGO TANKS, SECONDARY BARRIERS AND PROCESS PRESSURE VESSELS FOR DESIGN TEMPERATURES BELOW 0°C AND DOWN TO -55°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CHEMICAL COMPOSITION AND HEAT TREATMENT</strong></td>
</tr>
<tr>
<td><strong>CARBON - MANGANESE STEEL</strong></td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>0.16% max. (1)</td>
</tr>
<tr>
<td>Optional additions</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>0.80% max.</td>
</tr>
<tr>
<td>Normalized or quenched and tempered (4)</td>
</tr>
</tbody>
</table>

**NOTES**

1. The Charpy V-notch and chemistry requirements for forgings may be specially considered by the Administration.
2. For material thickness of more than 25 mm, Charpy V-notch tests should be conducted as follows:
   - Material thickness (mm) Test temperature (°C)
   - 25 < t ≤ 30 10° below design temperature or -20° whichever is lower
   - 30 < t ≤ 35 15° below design temperature or -20° whichever is lower
   - 35 < t ≤ 40 20° below design temperature
   - The impact energy value should be in accordance with the table for the applicable type of that specimen.
   - For material thickness of more than 40 mm the Charpy V-notch values should be specially considered.
   - Materials for tanks and parts of tanks which are completely thermally stress relieved after welding may be tested at a temperature 5°C below the design temperature or -20°C whichever is lower.
   - For the thermally stressed relieved reinforcements and other fittings the test temperature should be the same as that required for the adjacent tank-shell thickness.
3. By special agreement with the Administration, the carbon content may be increased to 0.18% maximum provided the design temperature is not lower than -40°C.
4. A controlled rolling procedure may be used as an alternative to normalizing or quenching and tempering, subject to special approval by the Administration.

**Guidance:**

For materials exceeding 25 mm in thickness for which the test temperature is -60°C or lower, the application of specially treated steels or steels in accordance with 5C-8-6/Table Aiii-3 may be necessary.
Table (Aiii-2) (ABS) Requirements for Design Temperatures below 0°C (32°F) and Down to -55°C (-67°F) (1995)

<table>
<thead>
<tr>
<th>Test</th>
<th>Requirement 1</th>
<th>Requirement 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension Test</td>
<td>400 – 490 N/mm²</td>
<td>490 – 620 N/mm²</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>(41 – 50 kgf/mm², 58,000 – 71,000 psi)</td>
<td>(50 – 63 kgf/mm², 71,000 – 90,000 psi)</td>
</tr>
<tr>
<td>Yield Strength (2)</td>
<td>235 N/mm²</td>
<td>355 N/mm²</td>
</tr>
<tr>
<td></td>
<td>(24 kgf/mm², 34,000 psi)</td>
<td>(36 kgf/mm², 51,000 psi)</td>
</tr>
<tr>
<td>Elongation (%) in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 mm (8 in.) or</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>50 mm (2 in.) or</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td>5.65 (\sqrt{\frac{A}{I}})</td>
<td>22</td>
<td>20</td>
</tr>
</tbody>
</table>

Notes:

1. Control Rolled (for sections only) or Thermo-Mechanical Controlled Process may also be considered as an alternative to normalizing or quenching and tempering.

2. For materials which exhibit a definite yield point exceeding 80% of the tensile strength, a letter “Y” is to be added at the end of the marking thus AB/V-OXXY or ABVH-OXXY.
APPENDIX (B) AMERICAN SOCIETY FOR TESTING AND MATERIALS
ASTM A945.709-1 (2006E1)

Table (B1) Chemical Requirements

NOTE—Where “...” appears in this table, there is no requirement

<table>
<thead>
<tr>
<th>Element</th>
<th>Thickness</th>
<th>Composition, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Grade 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grade 65</td>
</tr>
<tr>
<td>Carbon (max)†</td>
<td>All</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.10</td>
</tr>
<tr>
<td>Manganese</td>
<td>All</td>
<td>1.10–1.65</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>1.10–1.65</td>
</tr>
<tr>
<td>Phosphorus (max)†</td>
<td>All</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.025</td>
</tr>
<tr>
<td>Sulfur (max)†</td>
<td>All</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.010</td>
</tr>
<tr>
<td>Silicon</td>
<td>All</td>
<td>0.10–0.40</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.10–0.40</td>
</tr>
<tr>
<td>Nickel</td>
<td>1¼ in. [32 mm] max.††</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Over 1 ¼ in. [32 mm] max.††</td>
<td></td>
</tr>
<tr>
<td>Chromium (max)</td>
<td>All</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.20</td>
</tr>
<tr>
<td>Molybdenum (max)</td>
<td>All</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.08</td>
</tr>
<tr>
<td>Copper (max)</td>
<td>All</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.35</td>
</tr>
<tr>
<td>Vanadium (max)</td>
<td>All</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.10</td>
</tr>
<tr>
<td>Columbium (max)</td>
<td>All</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.05</td>
</tr>
<tr>
<td>Aluminum (max)</td>
<td>All</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.08</td>
</tr>
<tr>
<td>Titanium</td>
<td>All</td>
<td>0.007–0.020</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.012</td>
</tr>
</tbody>
</table>

††Value corrected editorially.

Table (B2) Tensile Requirements

<table>
<thead>
<tr>
<th>Grade</th>
<th>Yield Point or Yield Strength(^A) min, ksi [MPa]</th>
<th>Tensile Strength ksi [MPa]</th>
<th>Minimum Elongation, %(^B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>65 [450]</td>
<td>78 [540]–100 [690]</td>
<td>18 [22]</td>
</tr>
</tbody>
</table>

\(^A\) Measured at 0.2 % offset or 0.5 % extension under load as described in Section 13 on yield strength of Test Methods and Definitions A 370.

\(^B\) For plates wider than 24 in. [600 mm], the elongation requirement is reduced two percentage points. See elongation requirement adjustment in the Tension Tests section of Specification A 6/A 6M.

Table (B3) Charpy V-Notch Impact Test Requirements

<table>
<thead>
<tr>
<th>Grade</th>
<th>Temperature °F [°C]</th>
<th>Longitudinal Specimens, min avg</th>
<th>Transverse Specimens, min avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>–40 [–40]</td>
<td>90 [41]</td>
<td>20 [27]</td>
</tr>
<tr>
<td>65</td>
<td>–40 [–40]</td>
<td>... [...</td>
<td>70 [95]</td>
</tr>
</tbody>
</table>
APPENDIX (C) CANADIAN STANDARDS ASSOCIATION (CSA)

Table (C1) Chemical composition by heat analysis of plates

<table>
<thead>
<tr>
<th>Grade</th>
<th>Metric</th>
<th>Imperial</th>
<th>C, max</th>
<th>Mn</th>
<th>P</th>
<th>S, max</th>
<th>Si(wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>260W</td>
<td>38W</td>
<td>38W</td>
<td>0.20</td>
<td>0.50-1.50</td>
<td>0.04 max</td>
<td>0.05</td>
<td>0.40 max</td>
</tr>
<tr>
<td>300W</td>
<td>44W</td>
<td>44W</td>
<td>0.22</td>
<td>0.50-1.50</td>
<td>0.04 max</td>
<td>0.05</td>
<td>0.40 max</td>
</tr>
<tr>
<td>350W</td>
<td>50W</td>
<td>50W</td>
<td>0.23</td>
<td>0.50-1.50</td>
<td>0.04 max</td>
<td>0.05</td>
<td>0.40 max</td>
</tr>
<tr>
<td>400W</td>
<td>60W</td>
<td>60W</td>
<td>0.23</td>
<td>0.50-1.50</td>
<td>0.04 max</td>
<td>0.05</td>
<td>0.40 max</td>
</tr>
<tr>
<td>480W</td>
<td>70W</td>
<td>70W</td>
<td>0.26</td>
<td>0.50-1.50</td>
<td>0.04 max</td>
<td>0.05</td>
<td>0.40 max</td>
</tr>
<tr>
<td>550W</td>
<td>80W</td>
<td>80W</td>
<td>0.15</td>
<td>1.75 max</td>
<td>0.04 max</td>
<td>0.05</td>
<td>0.40 max</td>
</tr>
<tr>
<td>260WT</td>
<td>38WT</td>
<td>38WT</td>
<td>0.20</td>
<td>0.80-1.50</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>300WT</td>
<td>44WT</td>
<td>44WT</td>
<td>0.22</td>
<td>0.80-1.50</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>350WT</td>
<td>50WT</td>
<td>50WT</td>
<td>0.22</td>
<td>0.80-1.50</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>400WT</td>
<td>60WT</td>
<td>60WT</td>
<td>0.22</td>
<td>0.80-1.50</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>480WT</td>
<td>70WT</td>
<td>70WT</td>
<td>0.26</td>
<td>0.80-1.50</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>550WT</td>
<td>80WT</td>
<td>80WT</td>
<td>0.15</td>
<td>1.75 max</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>350R</td>
<td>50R</td>
<td>50R</td>
<td>0.16</td>
<td>0.75 max</td>
<td>0.05-0.15</td>
<td>0.04</td>
<td>0.75 max</td>
</tr>
<tr>
<td>350A</td>
<td>50A</td>
<td>50A</td>
<td>0.20</td>
<td>0.75-1.35</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.50</td>
</tr>
<tr>
<td>400A</td>
<td>60A</td>
<td>60A</td>
<td>0.20</td>
<td>0.75-1.35</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.50</td>
</tr>
<tr>
<td>480A</td>
<td>70A</td>
<td>70A</td>
<td>0.20</td>
<td>1.00-1.60</td>
<td>0.025 max</td>
<td>0.035</td>
<td>0.15-0.50</td>
</tr>
<tr>
<td>550A</td>
<td>80A</td>
<td>80A</td>
<td>0.15</td>
<td>1.75 max</td>
<td>0.025 max</td>
<td>0.035</td>
<td>0.15-0.50</td>
</tr>
<tr>
<td>350AT</td>
<td>50AT</td>
<td>50AT</td>
<td>0.20</td>
<td>0.75-1.35</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.50</td>
</tr>
<tr>
<td>400AT</td>
<td>60AT</td>
<td>60AT</td>
<td>0.20</td>
<td>0.75-1.35</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.50</td>
</tr>
<tr>
<td>480AT</td>
<td>70AT</td>
<td>70AT</td>
<td>0.20</td>
<td>1.00-1.60</td>
<td>0.025 max</td>
<td>0.035</td>
<td>0.15-0.50</td>
</tr>
<tr>
<td>550AT</td>
<td>80AT</td>
<td>80AT</td>
<td>0.15</td>
<td>1.75 max</td>
<td>0.025 max</td>
<td>0.035</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>700Q</td>
<td>100Q</td>
<td>100Q</td>
<td>0.20</td>
<td>1.50 max</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>700QT</td>
<td>100QT</td>
<td>100QT</td>
<td>0.20</td>
<td>1.50 max</td>
<td>0.03 max</td>
<td>0.04</td>
<td>0.15-0.40</td>
</tr>
</tbody>
</table>

Cont'd
Cont’d-Table (C1) Chemical composition by heat analysis of plates

<table>
<thead>
<tr>
<th>Grade</th>
<th>Metric</th>
<th>Imperial</th>
<th>Grain refining elements</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Grain-size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>max</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>260W</td>
<td>38W</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>300W</td>
<td>44W</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>350W</td>
<td>50W</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>400W</td>
<td>60W</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>480W</td>
<td>70W</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>550W</td>
<td>80W</td>
<td>0.15</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>260WT</td>
<td>38WT</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>300WT</td>
<td>44WT</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>350WT</td>
<td>50WT</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>400WT</td>
<td>60WT</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>480WT</td>
<td>70WT</td>
<td>0.10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>550WT</td>
<td>80WT</td>
<td>0.15</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>350R</td>
<td>50R</td>
<td>0.10</td>
<td>0.30-1.25</td>
<td>0.90 max</td>
<td>0.20-0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>350A</td>
<td>50A</td>
<td>0.10</td>
<td>0.70 max</td>
<td>0.90 max</td>
<td>0.20-0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>400A</td>
<td>60A</td>
<td>0.10</td>
<td>0.70 max</td>
<td>0.90 max</td>
<td>0.20-0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>480A</td>
<td>70A</td>
<td>0.12</td>
<td>0.70 max</td>
<td>0.25-0.50</td>
<td>0.20-0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>550A</td>
<td>80A</td>
<td>0.15</td>
<td>0.70 max</td>
<td>0.25-0.50</td>
<td>0.20-0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>350AT</td>
<td>50AT</td>
<td>0.10</td>
<td>0.70 max</td>
<td>0.90 max</td>
<td>0.20-0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>400AT</td>
<td>60AT</td>
<td>0.10</td>
<td>0.70 max</td>
<td>0.90 max</td>
<td>0.20-0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>480AT</td>
<td>70AT</td>
<td>0.12</td>
<td>0.70 max</td>
<td>0.25-0.50</td>
<td>0.20-0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>550AT</td>
<td>80AT</td>
<td>0.15</td>
<td>0.70 max</td>
<td>0.25-0.50</td>
<td>0.20-0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>700Q</td>
<td>100Q</td>
<td>–</td>
<td>Boron</td>
<td>–</td>
<td>–</td>
<td>0.0005-0.005</td>
<td>Fine grain</td>
</tr>
<tr>
<td>700QT</td>
<td>100QT</td>
<td>–</td>
<td>Boron</td>
<td>–</td>
<td>–</td>
<td>0.0005-0.005</td>
<td>Fine grain</td>
</tr>
</tbody>
</table>

Legend
(a) A silicon content of 0.15 to 0.40% is required for Type W steel over 40mm (11/2 in.) in thickness or bar diameter, except as modified by footnote (b).
(b) At the purchaser’s request or at the producer’s discretion, the steel may be made with no minimum silicon content, provided that the steel contains a minimum of 0.015% acid soluble aluminum or 0.020% total aluminum content.
(c) Aluminum may be used as a grain refining element without prior approval by the purchaser and, when so used, shall not be included in the summation of grain refining elements included in Table 3. The elements columbium (also known as niobium) and vanadium may be used singly or in combination up to the total percentage indicated, except where columbium is used singly or in combination with vanadium in plates thicker than 14mm (1/2 in) or shapes heavier than Group 1, in which case the silicon content shall be 0.15% minimum. This restriction does not apply if the steel fulfills the requirements of footnote (b).
(d) A minimum copper content of .20% may be specified by the purchaser on all grades.
(e) For thicknesses over 100mm (4 in), the carbon maximum shall .22%.

(f) For thicknesses over 100mm (4 in), the carbon maximum shall .23%.

(g) With the prior agreement of the purchaser, the manganese content may be increased, provided that the sum of the carbon content plus \( \frac{1}{6} \) of the manganese content does not exceed 0.40% for Grade 350WT (50WT) or .42% for Grades 400WT (60WT), 480WT (70WT), 550W (80W), 550WT (80WT), 550A (80A), and 550AT (80AT).

(h) See Clauses 5.3 and 5.4.

(i) A nitrogen content of 0.01 to 0.02% may be used if the nitrogen content does not exceed \( \frac{1}{4} \) of the vanadium content.

(k) Types WT, A, AT, Q, and QT steel shall be supplied using a fine grain practice.

(m) The combined contents of chromium, nickel, and copper shall be not less than 1.00%.

(n) The manganese content may be increased to 1.60% maximum, provided that the sum of the carbon content plus \( \frac{1}{6} \) of the manganese content does not exceed 0.43%. 

(p) The combined total of the chromium and nickel contents shall be not less than 0.40%.

Notes

(1) In order to meet the required mechanical properties, the manufacturer may use additional alloying elements with the prior approval of the purchaser.

(2) The usual deoxidation practice is fully killed.
Table (C2) Mechanical properties of plates

<table>
<thead>
<tr>
<th>Grade</th>
<th>Metric</th>
<th>Imperial</th>
<th>Tensile strength, ksi</th>
<th>Yield point, ksi, minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Up to 2½ in</td>
</tr>
<tr>
<td>260W</td>
<td>38W</td>
<td>60-85‡</td>
<td>38 36 36 36</td>
<td></td>
</tr>
<tr>
<td>300W</td>
<td>44W</td>
<td>65-90‡</td>
<td>44 40 40 40</td>
<td></td>
</tr>
<tr>
<td>350W</td>
<td>50W</td>
<td>65-95‡</td>
<td>50 46 46</td>
<td></td>
</tr>
<tr>
<td>400W</td>
<td>60W</td>
<td>75-100</td>
<td>60 – – –</td>
<td></td>
</tr>
<tr>
<td>480W</td>
<td>70W</td>
<td>85-115</td>
<td>70 – – –</td>
<td></td>
</tr>
<tr>
<td>550W</td>
<td>80W</td>
<td>90-125</td>
<td>80 – – –</td>
<td></td>
</tr>
<tr>
<td>260WT</td>
<td>38WT</td>
<td>60-85*</td>
<td>38 36 36</td>
<td></td>
</tr>
<tr>
<td>300WT</td>
<td>44WT</td>
<td>65-90*</td>
<td>44 40 40</td>
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<tr>
<td>350WT</td>
<td>50WT</td>
<td>70-95*</td>
<td>50 46 46</td>
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<tr>
<td>400WT</td>
<td>60WT</td>
<td>75-100</td>
<td>60 – – –</td>
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</tr>
<tr>
<td>480WT</td>
<td>70WT</td>
<td>85-115</td>
<td>70 – – –</td>
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<td>70-95</td>
<td>50 50 – –</td>
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<td>480A</td>
<td>70A</td>
<td>85-115</td>
<td>70 – – –</td>
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<td>80A</td>
<td>90-125</td>
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<td>50 50 – –</td>
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<td>90-125</td>
<td>80 – – –</td>
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</tr>
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<td>100Q</td>
<td>110-130</td>
<td>100 90 – –</td>
<td></td>
</tr>
<tr>
<td>700QT</td>
<td>100QT</td>
<td>110-130</td>
<td>100 90 – –</td>
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Cont'd
Cont’d-Table (C2) Mechanical properties of plates

<table>
<thead>
<tr>
<th>Grade</th>
<th>Metric</th>
<th>Imperial</th>
<th>Elongation*† % minimum</th>
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<tr>
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<td>Longitudinal</td>
<td>Transverse‡</td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td>8 in</td>
<td>2 in</td>
<td>8 in</td>
<td>2 in</td>
</tr>
<tr>
<td>260W</td>
<td>38W</td>
<td>20</td>
<td>23</td>
<td>18</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>300W</td>
<td>44W</td>
<td>20</td>
<td>23</td>
<td>18</td>
<td>21</td>
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<td>50W</td>
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<td>22</td>
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<td>18</td>
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<tr>
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<td>15</td>
<td>10</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>260WT</td>
<td>38WT</td>
<td>20</td>
<td>23</td>
<td>18</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>300WT</td>
<td>44WT</td>
<td>20</td>
<td>23</td>
<td>18</td>
<td>21</td>
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<tr>
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<td>50WT</td>
<td>19</td>
<td>22</td>
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<td>20</td>
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<tr>
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<td>20</td>
<td>15</td>
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</tr>
<tr>
<td>480WT</td>
<td>70WT</td>
<td>15</td>
<td>17</td>
<td>12</td>
<td>14</td>
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<td>80WT</td>
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<td>10</td>
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<td>50R</td>
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<td>18</td>
<td>21</td>
<td>15</td>
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<tr>
<td>480A</td>
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<td>17</td>
<td>12</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>550A</td>
<td>80A</td>
<td>13</td>
<td>15</td>
<td>10</td>
<td>12</td>
<td></td>
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<td>50AT</td>
<td>19</td>
<td>21</td>
<td>17</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>400AT</td>
<td>60AT</td>
<td>18</td>
<td>21</td>
<td>15</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>480AT</td>
<td>70AT</td>
<td>15</td>
<td>17</td>
<td>12</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>550AT</td>
<td>80AT</td>
<td>13</td>
<td>15</td>
<td>10</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>700Q</td>
<td>100Q</td>
<td>–</td>
<td>18</td>
<td>–</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>700QT</td>
<td>100QT</td>
<td>–</td>
<td>18</td>
<td>–</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

* Per cent elongation is not specified or required for rolled floor plate.
† Where per cent elongation in both 8 in and 2 in is specified, only one gauge length needs to be determined and reported.
‡ Transverse values apply only to plate wider than 24 in.
§ Plates for API applications shall have an upper limit of tensile strength 20 ksi above the specified minimum.

Notes:
(1) For material having a thickness less than 0.312 in, see Clause 8.3.1.1 of CSA G40.20. For material having a thickness greater than 3.5 in, see Clause 8.3.1.2 of CSA G40.20.
(2) The yield strength value may be measured by 0.5% extension-underload or 0.2% offset method.
Table (C3) Structural quality steels

<table>
<thead>
<tr>
<th>Metric</th>
<th>Imperial</th>
<th>J</th>
<th>Ft. Lbs.</th>
<th>Category 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>260WT</td>
<td>38WT</td>
<td>20</td>
<td>15</td>
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<tr>
<td>300WT</td>
<td>44WT</td>
<td>20</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>350WT</td>
<td>50WT</td>
<td>27</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>380WT</td>
<td>55WT</td>
<td>27</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>400WT</td>
<td>60WT</td>
<td>27</td>
<td>20</td>
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<tr>
<td>480WT</td>
<td>70WT</td>
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<td>20</td>
<td></td>
</tr>
<tr>
<td>550WT</td>
<td>80WT</td>
<td>27</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>350AT</td>
<td>50AT</td>
<td>27</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>400AT</td>
<td>60AT</td>
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<td>20</td>
<td></td>
</tr>
<tr>
<td>480AT</td>
<td>70AT</td>
<td>27</td>
<td>20</td>
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<tr>
<td>550AT</td>
<td>80AT</td>
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<td>20</td>
<td></td>
</tr>
<tr>
<td>700QT</td>
<td>100QT</td>
<td>34</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

* Energy levels given are for Charpy V-notch longitudinal specimens.
† Before specifying, availability of product should be verified.

Note: Absorbed energy values obtained from Charpy V-notch tests conducted at a particular testing temperature cannot be used to determine expected values at any other temperature. Values other than those shown and transverse testing may be available upon consultation between the purchaser and the manufacturer, and shall be ordered as category 5 material.

Table (C4) Charpy impact test – temperature*

<table>
<thead>
<tr>
<th>Category</th>
<th>Standard test temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-20</td>
</tr>
<tr>
<td>3</td>
<td>-30</td>
</tr>
<tr>
<td>4</td>
<td>-45</td>
</tr>
<tr>
<td>5</td>
<td>To be specified by purchaser †</td>
</tr>
</tbody>
</table>

* Temperatures given are for Charpy V-notch longitudinal specimens. By agreement between manufacturer and purchaser, specimens may be cut transverse to the rolling direction.
† Before specifying, availability of product should be verified.

Note: At the manufacturer’s discretion, the actual test temperature may be lower than the standard test temperature, provided that the minimum average absorbed energy specified for the category is obtained at the lower temperature. Actual test temperatures shall be reported together with the absorbed energy values.
### APPENDIX (D) DET NORSKE VERITAS (DNV) AND (IACS)

#### Table (D1) Mechanical properties of hull steels

<table>
<thead>
<tr>
<th>Steel grades for plates with $t \leq 100$ mm</th>
<th>Minimum yield stress $R_{eH}$, in N/mm$^2$</th>
<th>Ultimate tensile strength $R_m$, in N/mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-B-D-E</td>
<td>235</td>
<td>400 – 520</td>
</tr>
<tr>
<td>AH32-DH32-EH32-FH32</td>
<td>315</td>
<td>440 – 570</td>
</tr>
<tr>
<td>AH36-DH36-EH36-FH36</td>
<td>355</td>
<td>490 – 630</td>
</tr>
<tr>
<td>AH40-DH40-EH40-FH40</td>
<td>390</td>
<td>510 – 660</td>
</tr>
</tbody>
</table>

#### Table (D2) Material factor $k$

<table>
<thead>
<tr>
<th>Minimum yield stress $R_{eH}$, in N/mm$^2$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>235</td>
<td>1.0</td>
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<tr>
<td>315</td>
<td>0.78</td>
</tr>
<tr>
<td>355</td>
<td>0.72</td>
</tr>
<tr>
<td>390</td>
<td>0.68</td>
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</table>

#### Table (D3) Material grade requirements for classes I, II and III

<table>
<thead>
<tr>
<th>Class</th>
<th>As-built thickness (mm)</th>
<th>NSS</th>
<th>HSS</th>
<th>NSS</th>
<th>HSS</th>
<th>NSS</th>
<th>HSS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t \leq 15$</td>
<td>A</td>
<td>AH</td>
<td>A</td>
<td>AH</td>
<td>A</td>
<td>AH</td>
</tr>
<tr>
<td></td>
<td>$15 &lt; t \leq 20$</td>
<td>A</td>
<td>AH</td>
<td>A</td>
<td>AH</td>
<td>B</td>
<td>AH</td>
</tr>
<tr>
<td></td>
<td>$20 &lt; t \leq 25$</td>
<td>A</td>
<td>AH</td>
<td>B</td>
<td>AH</td>
<td>D</td>
<td>DH</td>
</tr>
<tr>
<td></td>
<td>$25 &lt; t \leq 30$</td>
<td>A</td>
<td>AH</td>
<td>D</td>
<td>DH</td>
<td>D</td>
<td>DH</td>
</tr>
<tr>
<td></td>
<td>$30 &lt; t \leq 35$</td>
<td>B</td>
<td>AH</td>
<td>D</td>
<td>DH</td>
<td>E</td>
<td>EH</td>
</tr>
<tr>
<td></td>
<td>$35 &lt; t \leq 40$</td>
<td>B</td>
<td>AH</td>
<td>D</td>
<td>DH</td>
<td>E</td>
<td>EH</td>
</tr>
<tr>
<td></td>
<td>$40 &lt; t \leq 50$</td>
<td>D</td>
<td>DH</td>
<td>E</td>
<td>EH</td>
<td>E</td>
<td>EH</td>
</tr>
</tbody>
</table>

**Notes:**

NSS = Normal strength steel  
HSS = Higher strength steel
<table>
<thead>
<tr>
<th>Structural member category</th>
<th>Material class</th>
<th>Within 0.4L amidship</th>
<th>Outside 0.4L amidship</th>
</tr>
</thead>
<tbody>
<tr>
<td>SECONDARY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal bulkhead strakes, other than that belonging to the Primary category</td>
<td>I</td>
<td>A/AH</td>
<td></td>
</tr>
<tr>
<td>Deck Plating exposed to weather, other than that belonging to the Primary or Special category</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side plating (7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRIMARY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom plating, including keel plate</td>
<td>II</td>
<td>A/AH</td>
<td></td>
</tr>
<tr>
<td>Strength deck plating, excluding that belonging to the Special category</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous longitudinal members above strength deck, excluding hatch coamings</td>
<td>II</td>
<td>A/AH</td>
<td></td>
</tr>
<tr>
<td>Uppermost strake in longitudinal bulkhead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical strake (hatch side girder) and uppermost sloped strake in top wing tank</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SPECIAL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheer strake at strength deck (1), (6)</td>
<td>III</td>
<td>II (I outside 0.6L amidships)</td>
<td></td>
</tr>
<tr>
<td>Stringer plate in strength deck (1), (6)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Deck strake at longitudinal bulkhead (5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength deck plating at corners of cargo hatch openings in bulk carriers</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Carriers, ore carriers, combination carriers and other ships with similar hatch openings configuration (2)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Bilge strake (3), (4), (6)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Longitudinal hatch coamings of length greater than 0.15L (5)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Lower bracket of side frame of single side bulk carriers having additional service feature BC-A or BC-B (5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End brackets and deck house transition of longitudinal cargo hatch coamings (5)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: 1) Not to be less than grade E/EH within 0.4L amidships in ships with length exceeding 250 m.
2) Not to be less than class III within 0.6L amidships and class II within the remaining length of the cargo region.
3) May be of class II in ships with a double bottom over the full breadth and with length less than 150 m.
4) Not to be less than grade D/DH within 0.4L amidships in ships with length exceeding 250 m.
5) Not to be less than grade D/DH. 6) Single strakes required to be of class III or of grade E/EH and within 0.4L amidships are to have breadths, in m, not less than 0.8 + 0.005L, need not be greater than 1.8 m, unless limited by the geometry of the ship’s design.
7) For BC-A and BC-B ships with single side skin structures, side shell strakes included totally or partially between the two points located to 0.125L above and below the intersection of side shell and bilge hopper sloping plate are not to be less than grade D/DH, l being the frame span.
Table (D5) Application of material classes and grades - Structures exposed at low temperature

<table>
<thead>
<tr>
<th>Structural member category</th>
<th>Material class</th>
<th>Within 0.4L amidship</th>
<th>Outside 0.4L amidship</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SECONDARY</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deck plating exposed to weather, in general</td>
<td>I</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>Side plating above BWL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse bulkheads above BWL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PRIMARY</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength deck plating (1)</td>
<td>II</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>Continuous longitudinal members above strength deck, excluding longitudinal hatch coamings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal bulkhead above BWL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top wing tank bulkhead above BWL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SPECIAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheer strake at strength deck (2)</td>
<td>III</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>Stringer plate in strength deck (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deck strake at longitudinal bulkhead (3)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Continuous longitudinal hatch coamings (4)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1) Plating at corners of large hatch openings to be specially considered. Class III or grade E/EH to be applied in positions where high local stresses may occur.
2) Not to be less than grade E/EH within 0.4L amidships in ships with length exceeding 250 m.
3) In ships with a breadth exceeding 70 m at least three deck strakes to be class III.
4) Not to be less than grade D/DH.
Table (D6) Material grade requirements for class I at low temperature

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>-20 / -25 °C</th>
<th>-26 / -35 °C</th>
<th>-36 / -45 °C</th>
<th>-45 / -55 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>t ≤ 10</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>10 &lt; t ≤ 15</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>15 &lt; t ≤ 20</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>20 &lt; t ≤ 25</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>25 &lt; t ≤ 30</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>30 &lt; t ≤ 35</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>35 &lt; t ≤ 45</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>45 &lt; t ≤ 50</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
</tbody>
</table>

Note: "NSS" and "HSS" mean, respectively “Normal Strength Steel” and “Higher Strength Steel”

Table (D7) Material grade requirements for class II at low temperature

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>-20 / -25 °C</th>
<th>-26 / -35 °C</th>
<th>-36 / -45 °C</th>
<th>-45 / -55 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>t ≤ 10</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>10 &lt; t ≤ 20</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>20 &lt; t ≤ 30</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>30 &lt; t ≤ 40</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>40 &lt; t ≤ 45</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
<tr>
<td>45 &lt; t ≤ 50</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
<td>NSS</td>
</tr>
</tbody>
</table>

Note: "NSS" and “HSS” mean, respectively “Normal Strength Steel” and “Higher Strength Steel”
### Table (D8) Material grade requirements for class III at low temperature

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>-20 / -25 °C</th>
<th>-26 / -35 °C</th>
<th>-36 / -45 °C</th>
<th>-45 / -55 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSS</td>
<td>HSS</td>
<td>NSS</td>
<td>HSS</td>
</tr>
<tr>
<td>t ≤ 10</td>
<td>D</td>
<td>DH</td>
<td>D</td>
<td>DH</td>
</tr>
<tr>
<td>10 &lt; t ≤ 20</td>
<td>D</td>
<td>DH</td>
<td>E</td>
<td>EH</td>
</tr>
<tr>
<td>20 &lt; t ≤ 25</td>
<td>E</td>
<td>EH</td>
<td>E</td>
<td>EH</td>
</tr>
<tr>
<td>25 &lt; t ≤ 30</td>
<td>E</td>
<td>EH</td>
<td>E</td>
<td>EH</td>
</tr>
<tr>
<td>30 &lt; t ≤ 40</td>
<td>E</td>
<td>EH</td>
<td>-</td>
<td>FH</td>
</tr>
<tr>
<td>40 &lt; t ≤ 45</td>
<td>E</td>
<td>EH</td>
<td>-</td>
<td>FH</td>
</tr>
<tr>
<td>45 &lt; t ≤ 50</td>
<td>-</td>
<td>FH</td>
<td>-</td>
<td>FH</td>
</tr>
</tbody>
</table>

**Note:**

"NSS" and “HSS” mean, respectively “Normal Strength Steel” and “Higher Strength Steel”
APPENDIX (E) EMPIRICAL FORMULAE

Table (E1) Comparison between Eureqa I and Eureqa II

[http://formulize.nutonian.com/formulize-eureqa-comparison]

<table>
<thead>
<tr>
<th>Feature</th>
<th>Eureqa I</th>
<th>Eureqa II (Formulize)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price</td>
<td>Free</td>
<td>Free</td>
</tr>
<tr>
<td>Explicit Equations</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Differential Equations</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Windows Client</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Linux Client</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Mac OS X Client</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Multiple Functions</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Multiple Datasets</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Multiple Searches</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Parallel Searches</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Cloud Computing</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Report and Analysis Tools</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Security</td>
<td>None</td>
<td>SSL 1024-bit</td>
</tr>
<tr>
<td>Raw Performance*</td>
<td>10M e/s</td>
<td>10M e/s</td>
</tr>
<tr>
<td>Floating-point Precision</td>
<td>Single</td>
<td>Double</td>
</tr>
<tr>
<td>Smoothing Options</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Missing Values Options</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Open-source API</td>
<td>Yes</td>
<td>Coming Soon</td>
</tr>
<tr>
<td>Private Servers</td>
<td>Yes</td>
<td>Coming Soon</td>
</tr>
</tbody>
</table>
When Eureqa I first released in April 2009, it was fed information on a double pendulum and in just a few hours it inferred Newton's second law of motion and the law of conservation of momentum from the data. Given other data, it could find laws that have so far eluded scientists [www.physorg.com]

Toted as something of a virtual scientist, Eureqa finds hidden mathematical relations in large spreadsheets of data. The software uses a technique, symbolic regression, that slowly evolves equations over time to see which best fits the information that give it [www.singularityhub.com].

Eureqa is descended from Hod Lipson and Michael Schmidt’s work on self-contemplating robots that figure out how to repair themselves. Lipson is an associate professor of mechanical and aerospace engineering, Cornell University, and Schmidt was his graduate student [www.Cornell.edu]. The same algorithms that guide the robots’ solution-finding computations have been customized for analyzing any type of data.
REGRESSION MODELS AND PLOTS FOR OBSERVED AND PREDICTED MECHANICAL PROPERTIES

Figure (E1) Results screen shot of Tensile strength empirical formula for G40.21 350WT steel series G1. File: SUT (G40.21 G1-RT)

Figure (E2) Results screen shot of Tensile strength empirical formula for G40.21 350WT steel series G2. File: SUT (G40.21 G2-RT)
Figure (E3) Results screen shot of Tensile strength empirical formula for G40.21 350WT steel series G3. File: SUT (G40.21 G3-RT)

Figure (E4) Results screen shot of Tensile strength empirical formula for series A1 and G1. File: SUT (both steels-A1 & G1-RT)
Figure (E5) Results screen shot of Tensile strength empirical formula for both steels—Universal model. File: SUT (9 ser-both steels)

Figure (E6) Results screen shot of Yield strength empirical formula for both steels—Universal model. File: SY (9 ser-both steels)
Figure (E7) Results screen shot of Fracture strength empirical formula for both steels—Universal model. File: SF (9 ser-both steels)

Figure (E8) Results screen shot of Toughness empirical formula for both steels—Universal model. File: TGH (9 ser-both steels)
Figure (E9) Results screen shot of Percentage Elongation empirical formula for both steels—Universal model. File: %El (9 ser-both steels)

Figure (E10) Results screen shot of Percentage Reduction in Area empirical formula for both steels—Universal model. File: % RED (9 ser-both steels)
Table (E2) $F$ distribution. Entries in the table are values of $F$ for which area in upper tail is 0.05 (roman type) or 0.01 (boldface type) [Wesolowsky, pp.282].
Table (E3) Values of $t_p$ [ASTM 739-10]

<table>
<thead>
<tr>
<th>$n^a$</th>
<th>$P %^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>2.1318</td>
</tr>
<tr>
<td>5</td>
<td>2.0150</td>
</tr>
<tr>
<td>6</td>
<td>1.9432</td>
</tr>
<tr>
<td>7</td>
<td>1.8946</td>
</tr>
<tr>
<td>8</td>
<td>1.8595</td>
</tr>
<tr>
<td>9</td>
<td>1.8331</td>
</tr>
<tr>
<td>10</td>
<td>1.8125</td>
</tr>
<tr>
<td>11</td>
<td>1.7959</td>
</tr>
<tr>
<td>12</td>
<td>1.7823</td>
</tr>
<tr>
<td>13</td>
<td>1.7709</td>
</tr>
<tr>
<td>14</td>
<td>1.7613</td>
</tr>
<tr>
<td>15</td>
<td>1.7530</td>
</tr>
<tr>
<td>16</td>
<td>1.7459</td>
</tr>
<tr>
<td>17</td>
<td>1.7396</td>
</tr>
<tr>
<td>18</td>
<td>1.7341</td>
</tr>
<tr>
<td>19</td>
<td>1.7291</td>
</tr>
<tr>
<td>20</td>
<td>1.7247</td>
</tr>
<tr>
<td>21</td>
<td>1.7207</td>
</tr>
<tr>
<td>22</td>
<td>1.7171</td>
</tr>
</tbody>
</table>

$^a$ $n$ is the degrees of freedom of $t$, that is, $n = k - 2$.

$^b$ $P$ is the probability in percent that the random variable $t$ lies in the interval from $-t_p$ to $+t_p$. 
<table>
<thead>
<tr>
<th>Degrees of Freedom, $n_1$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>161.45</td>
<td>199.50</td>
<td>215.71</td>
<td>224.58</td>
</tr>
<tr>
<td>2</td>
<td>19.513</td>
<td>19.000</td>
<td>19.164</td>
<td>19.247</td>
</tr>
<tr>
<td>3</td>
<td>8.503</td>
<td>9.000</td>
<td>9.166</td>
<td>9.249</td>
</tr>
<tr>
<td>4</td>
<td>10.128</td>
<td>9.5521</td>
<td>9.2766</td>
<td>9.1172</td>
</tr>
<tr>
<td>5</td>
<td>34.116</td>
<td>30.817</td>
<td>29.467</td>
<td>28.710</td>
</tr>
<tr>
<td>6</td>
<td>7.7086</td>
<td>6.9443</td>
<td>6.5914</td>
<td>6.9883</td>
</tr>
<tr>
<td>7</td>
<td>21.198</td>
<td>18.000</td>
<td>16.644</td>
<td>15.977</td>
</tr>
<tr>
<td>8</td>
<td>6.6709</td>
<td>5.7681</td>
<td>5.4065</td>
<td>5.1922</td>
</tr>
<tr>
<td>9</td>
<td>16.258</td>
<td>13.274</td>
<td>12.060</td>
<td>11.392</td>
</tr>
<tr>
<td>10</td>
<td>5.6874</td>
<td>5.1433</td>
<td>4.7571</td>
<td>4.5337</td>
</tr>
<tr>
<td>12</td>
<td>5.5914</td>
<td>4.7374</td>
<td>4.3468</td>
<td>4.1203</td>
</tr>
<tr>
<td>13</td>
<td>12.246</td>
<td>9.5466</td>
<td>8.4513</td>
<td>7.8467</td>
</tr>
<tr>
<td>14</td>
<td>5.3177</td>
<td>4.4590</td>
<td>4.0662</td>
<td>3.8378</td>
</tr>
<tr>
<td>15</td>
<td>11.259</td>
<td>8.6491</td>
<td>7.5910</td>
<td>7.0600</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Degrees of Freedom, $n_2$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.1174</td>
<td>4.2565</td>
<td>3.8626</td>
<td>3.6331</td>
</tr>
<tr>
<td>2</td>
<td>10.561</td>
<td>8.0215</td>
<td>6.6019</td>
<td>6.4221</td>
</tr>
<tr>
<td>3</td>
<td>4.0446</td>
<td>4.1028</td>
<td>3.7083</td>
<td>3.4790</td>
</tr>
<tr>
<td>4</td>
<td>10.044</td>
<td>7.5594</td>
<td>6.5593</td>
<td>5.9043</td>
</tr>
<tr>
<td>5</td>
<td>4.8449</td>
<td>3.9629</td>
<td>3.5874</td>
<td>3.2967</td>
</tr>
<tr>
<td>6</td>
<td>9.6460</td>
<td>7.2057</td>
<td>6.2167</td>
<td>5.6683</td>
</tr>
<tr>
<td>7</td>
<td>4.7472</td>
<td>3.8993</td>
<td>3.4903</td>
<td>3.2592</td>
</tr>
<tr>
<td>8</td>
<td>9.3302</td>
<td>6.9256</td>
<td>5.5626</td>
<td>5.1119</td>
</tr>
<tr>
<td>9</td>
<td>4.6672</td>
<td>3.8056</td>
<td>3.4105</td>
<td>3.1791</td>
</tr>
<tr>
<td>10</td>
<td>9.0798</td>
<td>6.7010</td>
<td>5.7304</td>
<td>5.2053</td>
</tr>
<tr>
<td>11</td>
<td>4.6001</td>
<td>3.7399</td>
<td>3.3499</td>
<td>3.1122</td>
</tr>
<tr>
<td>12</td>
<td>8.8616</td>
<td>6.5442</td>
<td>5.5639</td>
<td>5.0354</td>
</tr>
<tr>
<td>13</td>
<td>4.5451</td>
<td>3.6223</td>
<td>3.2874</td>
<td>3.0556</td>
</tr>
<tr>
<td>14</td>
<td>9.6831</td>
<td>6.3989</td>
<td>5.4170</td>
<td>4.8932</td>
</tr>
</tbody>
</table>

In each row, the top figures are values of $F$ corresponding to $P = 95\%$, the bottom figures correspond to $P = 99\%$. Thus, the top figures pertain to the 5% significance level, whereas the bottom figures pertain to the 1% significance level (The bottom figures are not recommended for use in Equation 5.16).
APPENDIX (F) STATISTICAL ANALYSIS OF STRAIN-LIFE RELATIONSHIP

Example F1: [Ex. 1 sec. 8.3.1 ASTM 739-10, pp 6]

Consider the following low-cycle fatigue data. Estimate parameters A and B and the respective 95% confidence intervals.

<table>
<thead>
<tr>
<th>( \Delta \varepsilon_p/2 )</th>
<th>( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Strain Amplitude</td>
<td>Fatigue Life</td>
</tr>
<tr>
<td>Unitless</td>
<td>Cycles</td>
</tr>
<tr>
<td>0.01636</td>
<td>168</td>
</tr>
<tr>
<td>0.01609</td>
<td>200</td>
</tr>
<tr>
<td>0.00675</td>
<td>1 000</td>
</tr>
<tr>
<td>0.00682</td>
<td>1 180</td>
</tr>
<tr>
<td>0.00179</td>
<td>4 730</td>
</tr>
<tr>
<td>0.00160</td>
<td>8 035</td>
</tr>
<tr>
<td>0.00165</td>
<td>5 254</td>
</tr>
<tr>
<td>0.00053</td>
<td>28 617</td>
</tr>
<tr>
<td>0.00054</td>
<td>32 650</td>
</tr>
</tbody>
</table>

First, restate (transform) the data in terms of logarithms (base 10 used in this practice due to its wide use in practice).

\[
X_i = \log (\Delta \varepsilon_p/2) \quad Y_i = \log N_i
\]

<table>
<thead>
<tr>
<th>( X_i ) =\text{log} (( \Delta \varepsilon_p/2 ))</th>
<th>( Y_i ) =\text{log} ( N_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( -1.78622 )</td>
<td>( 2.22531 )</td>
</tr>
<tr>
<td>( -1.79344 )</td>
<td>( 2.30103 )</td>
</tr>
<tr>
<td>( -2.17070 )</td>
<td>( 3.00000 )</td>
</tr>
<tr>
<td>( -2.16622 )</td>
<td>( 3.07188 )</td>
</tr>
<tr>
<td>( -2.74715 )</td>
<td>( 3.67486 )</td>
</tr>
<tr>
<td>( -2.79588 )</td>
<td>( 3.90499 )</td>
</tr>
<tr>
<td>( -2.78252 )</td>
<td>( 3.72049 )</td>
</tr>
<tr>
<td>( -3.27572 )</td>
<td>( 4.45662 )</td>
</tr>
<tr>
<td>( -3.26761 )</td>
<td>( 4.51388 )</td>
</tr>
</tbody>
</table>

\[
\bar{X} = (-1.78622-1.79344-2.17070-2.16622-2.74715-2.79588-2.78252-3.27572-3.26761)/9
\]
\[
\bar{X} = -2.53172
\]
\[
\bar{Y} = (2.22531+2.30103+3.0+3.07188+3.67486+3.90499+3.72049+4.45662+4.51388)/9
\]
\[
\bar{Y} = 3.42990
\]
\[ \sum_{i=1}^{9} (X_i - \bar{X})^2 = 2.63892 \]

\[ \sum_{i=1}^{9} (X_i - \bar{X})(Y_i - \bar{Y}) = -3.83023 \]

Then, from Equations (5.14b) and (5.14a) respectively:
\[ \hat{B} = -1.45144 \quad \text{and} \quad \hat{A} = -0.24474 \]

And from Equation (5.15) the variance:
\[ \hat{\sigma}^2 = \frac{\sum_{i=1}^{k} (Y_i - \hat{\bar{Y}})^2}{k - 2} = \frac{0.07837}{7} = 0.011195 \]

Then the standard deviation \( \hat{\sigma} = 0.1058 \)

Where \( \hat{Y}_i = \hat{A} + \hat{B}X_i \) (so we have nine values of \( \hat{Y}_i \))

Now from Equations (5.16c) and (5.17c):
\[ \hat{\sigma}_A = (\hat{\sigma}) \left[ \frac{1}{k} + \frac{\bar{X}^2}{\sum_{i=1}^{k} (X_i - \bar{X})^2} \right]^{1/2} = (0.1058) \left[ \frac{1}{9} + \frac{(-2.53172)^2}{2.63892} \right]^{1/2} = 0.1686 \]

\[ \hat{\sigma}_B = (\hat{\sigma}) \left[ \sum_{i=1}^{k} (X_i - \bar{X})^2 \right]^{-1/2} = (0.1058)[2.63892]^{-1/2} = 0.06513 \]

From Table (5.10): read \( t_p = 2.3646 \) (for n=k-2=9-2=7 and P=95%).

Now, using Equation (5.16a), for A:
\[ \hat{A} - t_p \left( \hat{\sigma}_A \right) = -0.24474 - 2.3646(0.1686) = -0.6435 \]
\[ \hat{A} + t_p \left( \hat{\sigma}_A \right) = -0.24474 + 2.3646(0.1686) = 0.1540 \]

So the 95 % confidence interval for A is [−0.6435, 0.1540].

Similarly from equation (5.15a), for B:
\[ \hat{B} - t_p \left( \hat{\sigma}_B \right) = -1.45144 - 2.3646(0.06513) = -1.6054 \]
\[ \hat{B} + t_p \left( \hat{\sigma}_B \right) = -1.45144 + 2.3646(0.06513) = -1.2974 \]

So the 95 % confidence interval for B is [−1.6054, −1.2974].

The fitted line \( \hat{Y} = \logN = \hat{A} + \hat{B}X_i = -0.24474 - 1.45144 \log (\Delta e_p/2) = -0.24474 - 1.45144X_i \) is displayed in Figure (E1) bellow, where the 95 % confidence band computed using Equation (5.19) is also plotted.

For example, when \( \Delta e_p/2 = 0.01 \), \( X = \log (\Delta e_p/2) = \log (0.01) = -2.000 \), \( \hat{Y} = 2.65814 \)
\[ \hat{Y}_{\text{lower band}} = \hat{Y} - 0.15215 = 2.65814 - 0.15215 = 2.50599 \]

and \[ \hat{Y}_{\text{upper band}} = \hat{Y} + 0.15215 = 2.65814 + 0.15215 = 2.81029 \]

The fitted line can be transformed to the form given in Appendix X1 of ASTM Practice E606 as follows:

\[
\log N = -0.24474 - 1.45144 \log \Delta \varepsilon_p/2
\]

\[
\log \Delta \varepsilon_p/2 = -0.16862 - 0.68897 \log N
\]

\[ \Delta \varepsilon_p/2 = 0.67823 (N)^{-0.68897} \]

Substituting cycles (N) to reversals (2\(\bar{N}_f\)) gives

\[ \Delta \varepsilon_p/2 = 0.67823 (2\bar{N}_f/2)^{-0.68897} \]

\[ \Delta \varepsilon_p/2 = 0.67823 (1/2)^{-0.68897} (2\bar{N}_f)^{-0.68897} \]

\[ \Delta \varepsilon_p/2 = 1.09340 (2\bar{N}_f)^{-0.68897} \]

The above alternative equation is shown on Figure (E1) bellow.

**Test for linearity at the 5% significance level.**

The slight differences among the amplitudes of plastic strain will ignore and assume that \( l = 4 \) and \( k = 9 \).

Then, at each of the four \( X_i \) levels, we shall compute \( \hat{Y} \) using \( \hat{Y} = -0.24414 - 1.45144 X_i \) and then estimating \( \tilde{Y}_i \) using \( \tilde{Y}_i = (Y_{ij}/m_i) \). Accordingly, and from Table (5.11) the tabulated value of \( F_{0.95} = 5.79 \), whereas \( F \) computed (using Equation 5.17) = 3.62

\( F_{\text{computed}} < F_{\text{table}} \)  **Hence the linear model in this example is accepted.**
Figure (E1) Fitted relationship between the fatigue life $N$ ($Y$) and the plastic strain amplitude $\Delta \varepsilon_p/2$ ($X$) for the example data given.

NOTE: The 95% confidence band for the $\varepsilon$-$N$ curve as a whole is based on Equation 5.16. (Note that the dependent variable, fatigue life, is plotted here along the abscissa to conform to engineering convention.)
APPENDIX (G) NUMERICAL MODELING OF STRAIN-LIFE RELATIONSHIP

Figure (G1) ABAQUS results of specimen subjected to strain of 0.0012
Figure (G2) ABAQUS results of specimen subjected to strain of 0.0013

a) Stress contour (MPa)

b) Displacement contour (mm)
Figure (G3) *ABAQUS* results of specimen subjected to strain of 0.0014
Figure (G4) ABAQUS results of specimen subjected to strain of 0.0015
Figure (G5) ABAQUS results of specimen subjected to strain of 0.0016
Figure (G6) *ABAQUS* results of specimen subjected to strain of 0.0017
Figure (G7) ABAQUS results of specimen subjected to strain of 0.0018
Figure (G8) *ABAQUS* results of specimen subjected to strain of 0.0019
Figure (G9) ABAQUS results of specimen subjected to strain of 0.0020
Figure (G10) *ABAQUS* results of specimen subjected to strain of 0.0021
Figure (G11) ABAQUS results of specimen subjected to strain of 0.0022
Figure (G12) ABAQUS results of specimen subjected to strain of 0.0023
Figure (G13) ABAQUS results of specimen subjected to strain of 0.0024
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