Analysis Fatigue Life on Casing Subjected to Cyclic Steam Injection

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Petroleum Engineering Programme
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Approved by,

____

(Dr Sonny Irawan)

Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January, 2015

CERTIFICATION OF ORIGINALITY

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

____________________ (M. Galih Adi Samudera)

ABSTRACT

Casing may experiences failure during its life on specific project. Failure of casing varies from buckling, collapse, leak, and fatigue. Steam injection is one of the causes casing failure due to its thermal expansion, especially in cyclic steam injection. The heating and cooling process from steam injection may results tension and strain in casing interval. The analysis of Stress-Strain & fatigue life on 7” L-80 casing for cyclic steam injection well is presented on this study. A finite element analysis (FEA) is carried out to evaluate the stress-strain and fatigue life of the casing. With given temperature range of 30°-350°C of steam injection, stress-strain is analysed on this study. The subjected casing becomes hot-yielded as the axial compressive stress developed during the injection phase and becomes tensile when the temperature decrease on the soak period or cooling phase. The stresses generated from the thermal expansion load of steam determine the equivalent total strain of the casing and fatigue life of casing is determined using empirical equation. From the results of the analysis, it is obtained 7” L-80 production casing will fail after 811 cycles of heating-cooling process. Moreover, for the steam injection well higher material ultimate strength and ductility shall be taken into consideration in order to get a better and longer fatigue life.

ACKNOWLEDGEMENT

Firstly, the author would like to thank Universiti Teknologi PETRONAS for the support in ensuring this project is successfully made. My sincere thanks are always directed to my parents who always support me during my study. Dr. Sonny Irawan, my supervisor for this project, will always find my grateful feelings for endless support in making sure this project run smoothly. I would like to extend my gratitude to Abilash, ANSYS instructors for teaching me how to use ANSYS and assisting me in solving problems regarding to the project. Lastly, I would like to thanks all parties which are directly or indirectly involved during this project.

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NOMENCLATURE

ε	= Thermal Strain(dimensionless)
εf	= True fatigue strain (dimensionless)
$\Delta\varepsilon t$	= Total cyclic change of local strain (dimensionless)
$\Delta\sigma$	= Casing Thermal Stress (psi)
$\Delta\sigma t$	= Total cyclic change of local stress (psi)
ΔT	= Temperature Change (deg. F)
K'	= Casing material cyclic strength coefficient (psi)
α	= Casing Thermal Expansion coefficient (6.9×10^{-6} / deg. F)
E	= Casing material Young's modulus, 30000 (Kpsi)
SU	= Casing Tensile Strength(psi)
N	= Number of cycle
σmax	= Maximum principal stress (psi)
σx and σy	= Normal Stress in X and Y direction (psi)
Txy	= Shear stress in XY plane (psi)
σut	= Ultimate Tensile Strength (psi)

CHAPTER 1

INTRODUCTION

1.1 Project Background

Casing is one of the main components in the oil & gas well construction. All wells drilled have to be cased with sufficient material strength for safety operation. Shen X [9] stated on his study, casing is needed to be set to maintained borehole stability, prevent contamination of pressure from the formation, isolate water from producing formations, as well as to control well pressures during drilling, production and work over operations.

In some EOR well especially, steams are common method and has been used for many years in oil and gas wells to improve hydrocarbon production not only on heavy oil wells, but also light oil nowadays. Steams are being injected to the reservoir and heat is generated through the casing, cement and formation.

Casing failure is often found on heavy oil field or EOR well of steam flooding or steam injection due to the thermal expansion stress and it resulted to casing failure. The casing failures vary, it could be from casing leak rupture or wear due to fatigue and casing collapse/buckling. The continuous heating and cooling process from the cyclic steam thermal injection may result tension in the casing and tubing interval and failure. From the industry perspective, the compressive axial stress and axial compressive-tensile are generated due to the continuous steam injection and it is the one of the cause of casing failure. The casing axial compressive stress increases when the steam injection started and the casing becomes hot-yielded at final temperature and the casing axial compressive-tensile stress developed at the soak period and becomes cold-yielded [3].

In this study, fatigue analysis approach is carried out to identify the life on 7” L-80 production casing strain-stress base design for steam injection or steam flooding well.

1.2 Problem Statement

The production of hydrocarbons in reservoir decreases over time. This phenomenon may happen because of the decreasing reservoir pressure along the production time; therefore the reservoir has no ability to produce.

EOR is widely used nowadays, to enhance the production and produce more hydrocarbons from the reservoir. The recovery using thermal is commonly used to extract heavy oil hydrocarbons. During the practice for extracting the hydrocarbon from the reservoir well using thermal injection (steam), it is recognized that, the casing axial compressive stress developed once the steam is injected to the wellbore and the casing becomes hot-yielded at the certain to final temperature. Figure 1 shows the number of casing failure in steam injection project. Each of casing failure occurred after 21 cycles to 108 cycles [11].

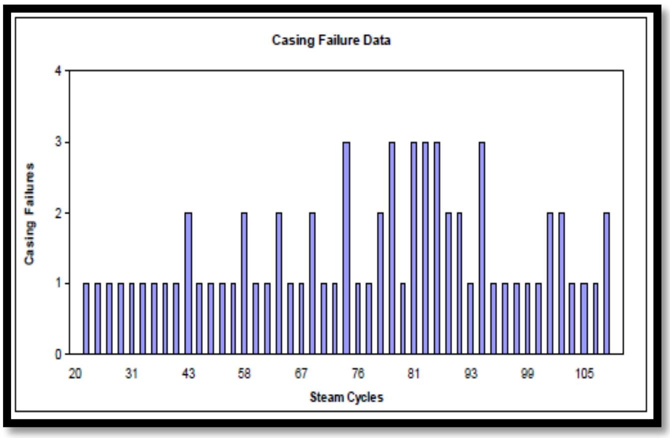


Figure 1: Casing Failure vs Steam Injection Cycles

According to Placido, *et al* [7], failures that occurred on casing subjected to cyclic steam injections are of various, such as collapse, connection leaking and corrosion. This statement is supported by Wu , J. *et al* [3] in his study that, high thermal axial compressive stress/strain in steam injection well lead to casing hot-yield and resulted to casing buckling/collapse, meanwhile compressive-tensile stress/strain alternation in cyclic steam injection well can cause casing fatigue and will result to casing parted (leak).

1.3 Objectives

The objective of this research is to analyse the stress-strain analysis of casing generated by thermal expansion of steam flooding or steam injection. The core objectives are:

a. To simulate thermal stress-strain analysis model of 7” L-80 production casing design on cyclic steam injection.
b. To analyse the fatigue life based on cyclic steam injection.

1.4 Scope of Study

The preliminary study which is carried out in this project is limited to simulation of stress on fatigue analysis of casing for specific well subjected to cyclic steam injection. The technical performance criteria, which is the injection temperature of steam from 30ºC - 350º C is simulated throughout the well to see its effect on the casing. The fatigue life then will be calculated after the stress analysis result is attained from the ANSYS Workbench simulation.

CHAPTER 2

LITERATURE REVIEW

2.1 Casing Specification

Generally the standard of casing and tubing are developed by American Petroleum Institute (API) in which have been accepted internationally by the drilling industry. Accordance to the international standard, the specification of casing and tubing are represented on API 5CT/ISO. The properties included in the API 5 included in API Standards are strength, physical dimensions, and quality-control test procedures [2].

Referred to API 5CT/ISO 11960, Casing and tubing must be manufactured to the minimum specifications. The properties of casing must meet or exceed the standards in API Bulletin 5C2 [2]. The physical and performance requirements for different API Classes are summarized in *table 1 & 2* below (*API Specification 5CT,* June, 2011, p.23).

Table 1: Casing Properties.

API Grade	Yield Strength (psi)		Minimum Ultimate Tensile Strength (psi)	Minimum* Elongation (%)
	Minimum	Maximum		
H-40	40,000	80,000	60,000	29.5
J-55	55,000	80,000	75,000	24.0
K-55	55,000	80,000	95,000	19.5
C-75	75,000	90,000	95,000	19.5
L-80	80,000	95,000	95,000	19.5
N-80	80,000	110,000	100,000	18.5
C-90	90,000	105,000	100,000	18.5
C-95	95,000	110,000	105,000	18.0
P-110	110,000	140,000	125,000	15.0

*Test specimen with area greater than 0.75 sq. in.

Table 2: Casing Specification (Source ; API 5 CT table)

American Petroleum Institute
Purchasing Guidelines
API® Monogram® Equipment — Purchase API Spec 5CT online at www.api.org/publications

API Specification 5CT 9th Edition, June 2011
Specification for Casing and Tubing

Table C.5 — Tensile and hardness requirements

Group	Grade	Type	Total elongation under load	Yield strength MPa		Tensile strength min.	Hardness [a] max.		Specified wall thickness	Allowable hardness variation [b]
			%	min.	max.	MPa	HRC	HBW	mm	HRC
1	2	3	4	5	6	7	8	9	10	11
1	H40	—	0,5	276	552	414	—	—	—	—
	J55	—	0,5	379	552	517	—	—	—	—
	K55	—	0,5	379	552	655	—	—	—	—
	N80	1	0,5	552	758	689	—	—	—	—
	N80	Q	0,5	552	758	689	—	—	—	—
	R95	—	0,5	655	758	724	—	—	—	—
2	M65	—	0,5	448	586	586	22	235	—	—
	L80	1	0,5	552	655	655	23	241	—	—
	L80	9Cr	0,5	552	655	655	23	241	—	—
	L80	13Cr	0,5	552	655	655	23	241	—	—
	C90	1	0,5	621	724	689	25,4	255	≤ 12,70 12,71 to 19,04 19,05 to 25,39 ≥ 25,40	3,0 4,0 5,0 6,0
	T95	1	0,5	655	758	724	25,4	255	≤ 12,70 12,71 to 19,04 19,05 to 25,39 ≥ 25,40	3,0 4,0 5,0 6,0
	C110	—	0,7	758	828	793	30	286	≤ 12,70 12,71 to 19,04 19,05 to 25,39 ≥ 25,40	3,0 4,0 5,0 6,0
3	P110	—	0,6	758	965	862	—	—	—	—
4	Q125	1	0,65	862	1034	931	b	—	≤ 12,70 12,71 to 19,04 ≥ 19,06	3,0 4,0 5,0

[a] In case of dispute, laboratory Rockwell C hardness testing shall be used as the referee method.
[b] No hardness limits are specified, but the maximum variation is restricted as a manufabrbcturing control in accordance with 7.8 and 7.9.

In addition, apart of API grade standard, there are many casing & tubing grades that do not conform from API specification and widely used in drilling industry known as non-API grades or premium. It is more expensive compared to the API grades and the use of this type of casing / tubing is dependent upon the requirement of the operation usually in gas well.

2.2 Casing Load Design Criteria

There are three basic actual forces in which the casing is subjected to; internal force, external force and axial force. All the basic forces / pressure must be calculated and shall be maintained below or comply the safety factor of casing strength properties. During the operation and the whole life of the well, some parameters such as thermal expansion, subsidence of the pore pressure, and any other boundary condition might affects the alteration of all basic forces.

The casing design process involves three distinct operations; selection of the casing sizes; the specification of required inputs e.g. setting depths; the operational scenarios which will result in burst, collapse and axial loads being applied to the casing string(s); the calculation of the magnitude of these loads and finally the selection of appropriate weight and grade of casing string(s) suitable for the loads introduced [10].

On conventional design, [6] an equation derived from a limited set of experimental data are being used to predict the material properties, and limited number of grades and did not address special grades or duplex steels. It is common practice when designing casing to assume maximum well loading and minimum material resistance. Eventually, it would be result of redundancy in the design process without compromising safety.

McSpadden, A.R, *et al* [7] in his study for casing design with Finite Element Analysis (FEA) mentioned that, some physical parameters are always inherent compared to the load calculations for all phases of casing design. Pressure conditions result in burst and collapse load and may induce resultant axial load as well. Likewise downhole temperature affects pipe material resistance and may induce axial loads depending on the well conditions. This statement is supported by Heathman, J [4], that all forces exerted on the casing, cement and formations are caused by pressure and thermal changes.

2.3 Casing failures on steam injection wells

Casing may experience failure during the life of the well if it is not designed in proper way. The casing failure is often found in steam injection well due to thermal expansion, especially in cyclic steam injection wells. A fatigue failure mostly begins at local discontinuity and when the stress at the discontinuity exceeds elastic limit there is plastic strain. The cyclic plastic strain is responsible for crack propagation and fracture.

The casing will easily fail under hot-yield period in axial compression stress, or under the cold-yielded period in axial tension stress-strain no matter whether cement is good or not. The casing failures related to hot-yielded include casing wear due to collapse or severe buckling [11]. The previous statement is also stated by Placido [7] on his researched that, the stress cycle is a function of temperature. It is further explained on the following figure.

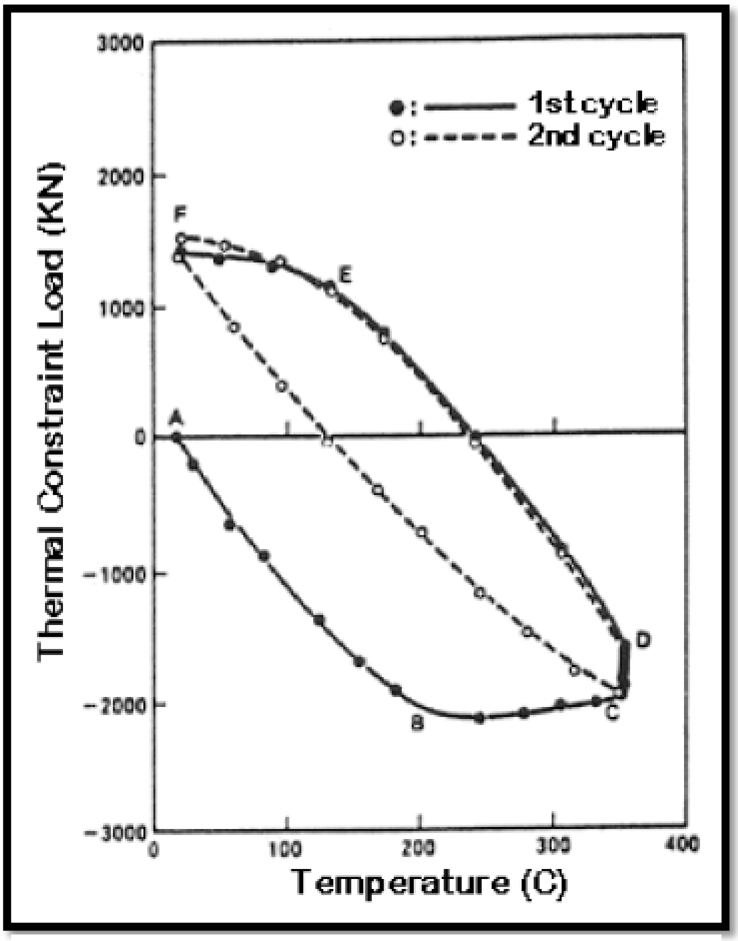


Figure 2 : Typical cyclic thermal loading.

Beginning from initial temperature at point (A), the steam is injected to the wellbore. The casing stress is developed due to thermal expansion of the steam injection, and when the yield stress is reached at point (B), the material is experienced to plastic deformation that continues until the maximum temperature at point (C). From point (C) to (D), temperature is kept constant and stress relaxation is observed (stress decreases at constant temperature). At point (D) temperature starts cooling down and the material deforms elastically until to reach point (E), which is the compressive yield stress. From point (E) to (F) occurs plastic deformation. When it reaches the initial pressure, the material is already under a tension [7].

Wu J, *et al* [11] conducted the similar research on cyclic steam injection well operation (steam, soak, and production) for 7” production casing as shown in the figure 3 below.

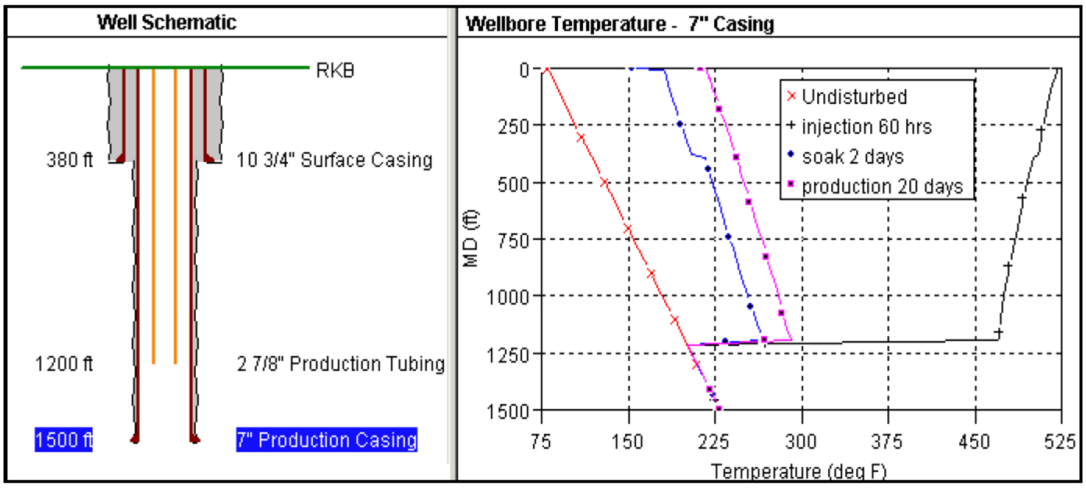


Figure 3: Casing Temperature Profile.

Based on the research [11], as the temperature increases on injection period, the larger casing thermal compressive axial stress is developed. Once the tension stress increase, it will lead to casing fatigue and moreover the casing resistance to collapse pressure would be significantly reduced and the casing could be easily collapsed by external pressure.

This research further will be used as the based case of the analysis in order to validate the result.

2.4 Finite Element Analysis (FEA)

Finite element analysis or finite element method plays a big role on the industry nowadays. In general, the finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It uses to minimize an error function and produce a stable solution [12].

In oil industry, the application of FEA is utilize to define the stress analysis for both static (casing, tubing, drillstring) and dynamic model (fluid). The application of FEA on casing design referred by Albert R, *et al* [6], includes shear moments, axial force, and stresses along the interval of the casing and also the radial displacement of the casing centreline from the wellbore centreline.

In the model, the system composed of the casing is divided into a finite number of parts, or elements, so that the governing equations can be solved in order to analyse the stress-strain [4]. The model of FEA is shown on the following figure.

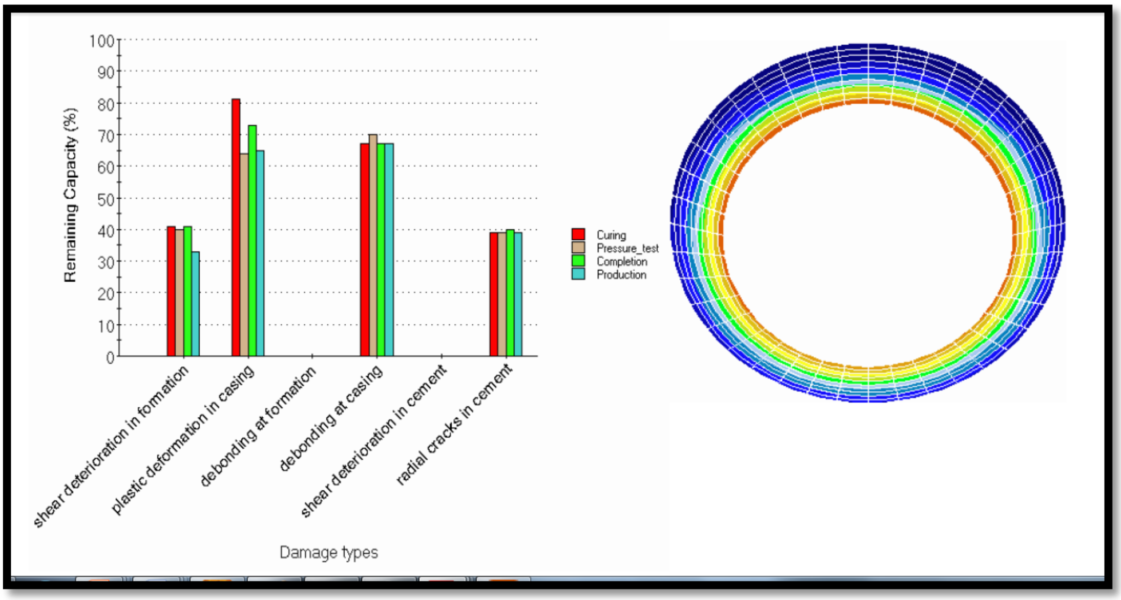


Figure 4: Casing Design using FEA

On the cyclic steam injection well, the repetition of the stress applied at casing under compressive and tensile strength will eventually result to casing fatigue on the particular location along the casing interval. Referred to Wu, J [11], the accurate model to analyse the strain change on total cyclic strain change may be obtain by Finite Element Analysis (FEA).

2.5 Steam

Steam is defined as a vapour arising from a heated substance. The substance that forming steam are varies, such as water, methane, carbon dioxide, nitrogen, etc. Steam is traditionally created by heating a substance via steam generator.

In order to change the water to steam, thermal energy is generated to increase the temperature which is called *sensible heat*. The boiling point of water universally 100°C and the steam will be generated once the temperature increased above the boiling point (*figure* 5).

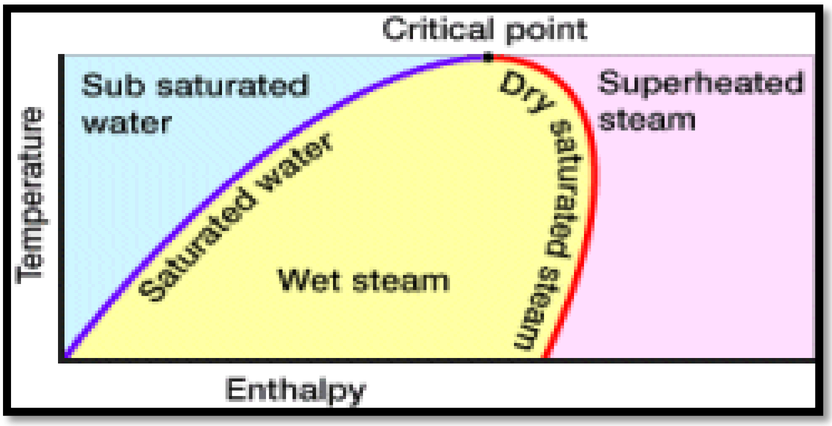


Figure 5: Steam Shceme

2.6 Fatigue Life

2.6.1 Casing Thermal Stress

Casing thermal stress is developed as high temperature steam is injected into the wells through tubing and/or production casing, heating-up the casing to expand (Jiang Wu, 2005). The casing thermal stress is calculated as:

$$\varepsilon = \alpha \Delta T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\Delta\sigma = -\alpha E \Delta T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

The material will be safe if: $\Delta\sigma < \sigma UT$

The casing thermal stress will be used for fatigue life calculation. Moreover, the casing string in length (ΔL), diameter (Δd) and reduced strength (σy) due to thermal expansion can be calculated as :

$$\Delta L = \varepsilon * L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$\Delta d = \varepsilon * d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$\sigma y = \sigma y * (1 - \frac{T - T\ at\ Soak}{2333.3}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

The alteration of casing in length (ΔL) and diameter (Δd) will be found under the specific temperature given. It will show how much the length or diameter has expanded under the thermal stress. The continuation of thermal expansion subjected to cyclic steam injection will result to casing fatigue.

2.6.2 Low Cycle Fatigue Life

The strain-life Manson equation is used to determine the low-cycle fatigue life at casing subjected to cyclic steam injection operation. The formula is stated as:

$$\Delta\varepsilon t = 3.5 \frac{SU}{E} (N)^{-0.12} + \varepsilon f^{0.6} (N)^{-0.6} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

The $\Delta\varepsilon t$ can be estimated using:

$$\Delta\varepsilon t = \frac{\Delta\sigma t}{E} + 2 \left(\frac{\Delta\sigma t}{2K\prime}\right)^{\frac{1}{n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

$$K' = \frac{\sigma f}{(\varepsilon f)^n} \quad \ldots\ldots (8)$$

$$n = \frac{b}{c} \quad \ldots\ldots (9)$$

With b = -0.085, c= -0.6, and $\sigma f = SU + 50ksi$

The total cyclic change of local strain ($\Delta\varepsilon t$) can be found using equation (7), and the total life cycle (N) is calculated by arranging equation (6). The maximum cycle will indicates the maximum stress in which the casing could withstand under thermal stress.

CHAPTER 3

METHODOLOGY

This project is done by simulation work to analyze the fatigue life for specific design 7” L-80 production casing subjected to cyclic steam injection at 1400 ft. There are some procedures to be followed in order to carry out and implement the project. The author intended to accomplish the project within two steps:

1. Stress-strain analysis by using ANSYS software;
2. Fatigue Life analysis by using manual calculation;

Appropriate recommendations will be done based on the results from both steps.

3.1 Stress-Strain Analysis

This research for stress strain analysis using ANSYS Workbench will be conducted based on the following activities.

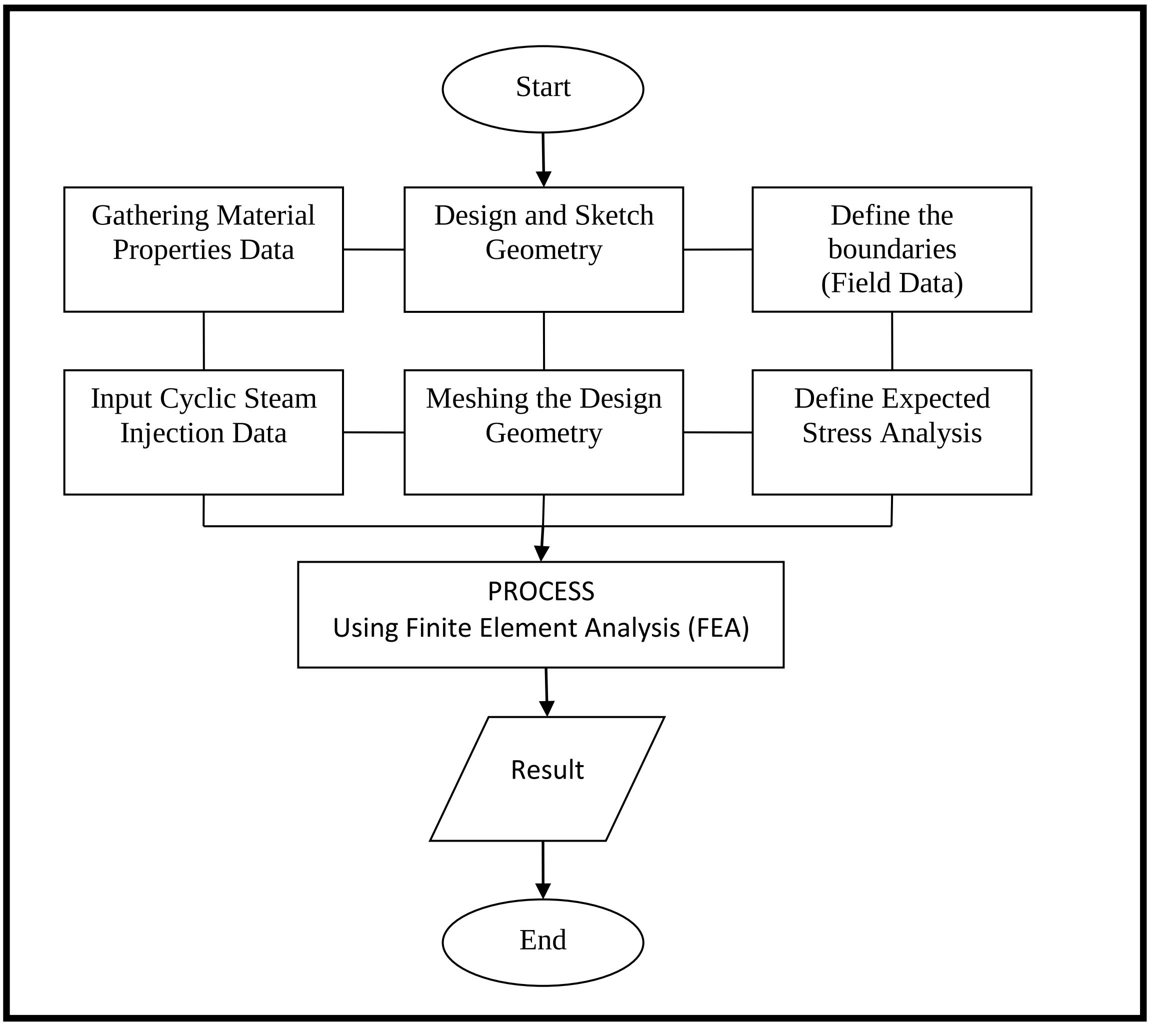


Figure 6 : Methodology of Thermal Analysis

ANSYS Workbench – is software that provides the stress-strain analysis by applying the finite element method (FEM). In order to get the best result, ANSYS divide the casing into thousand to million elements to analyse the stress-strain subjected to boundaries and the availability data.

All required data will be entered to perform a Stress-Strain analysis and interpretation will be carried out based on results. At the end of interpretation, it is expected to obtain; casing *equivalent total strain, equivalent stress, and maximum principal stress.*

A workflow used in the *ANSYS Workbench* software is shown below:

1. Enter the engineering data (material properties);
2. Design the casing (Geometry) ;
3. Define boundaries (Field Data);
4. Meshing the subjected casing;
5. Define the expected stress-strain analysis;
6. Define the cyclic steam injection temperature;
7. Solve the input;
8. View results of the analyzed case;

The result of Stress analysis of subjected casing will be used for determination on fatigue life for the second objectives.

3.2 Fatigue Life Analysis

This research for Fatigue Life analysis using Manson's equation will be conducted based on the following activities.

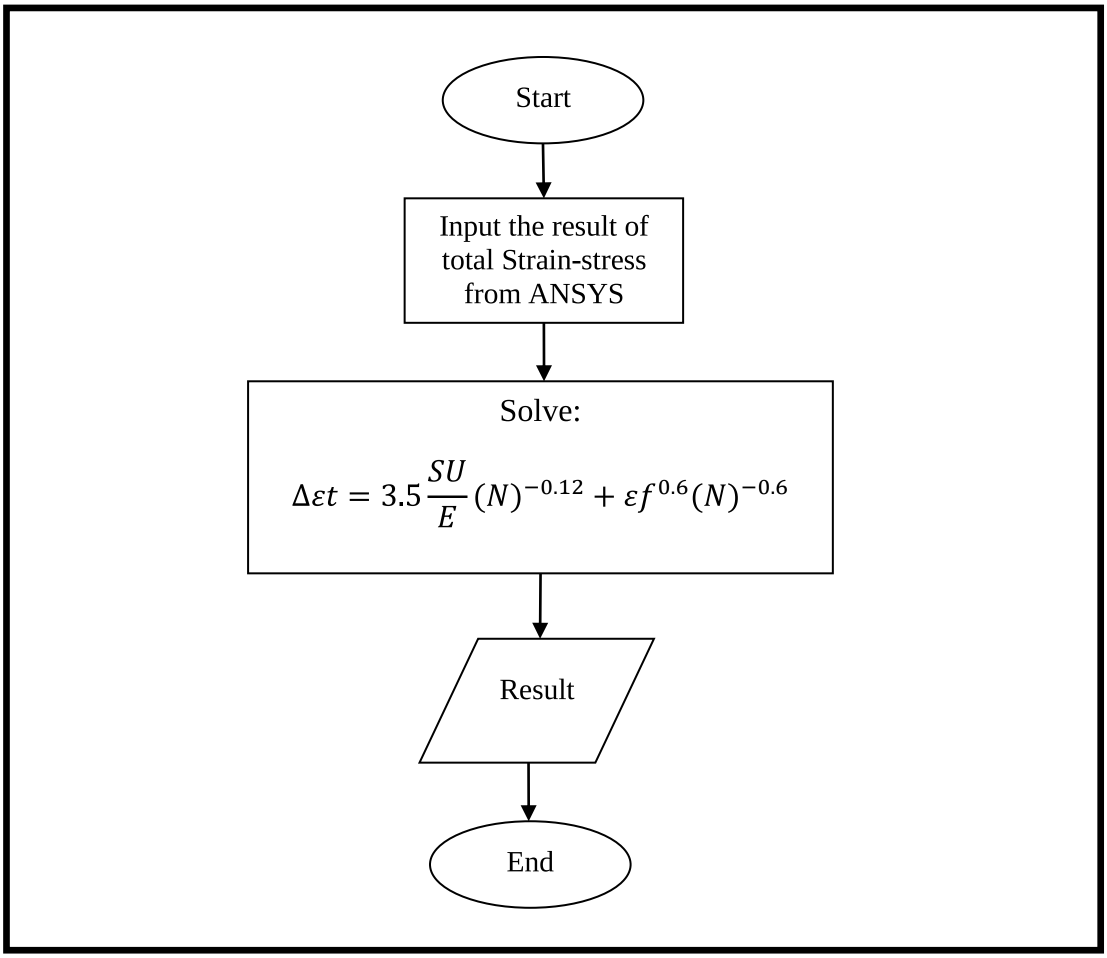


Figure 7: Methodology of Calculating Fatigue Life

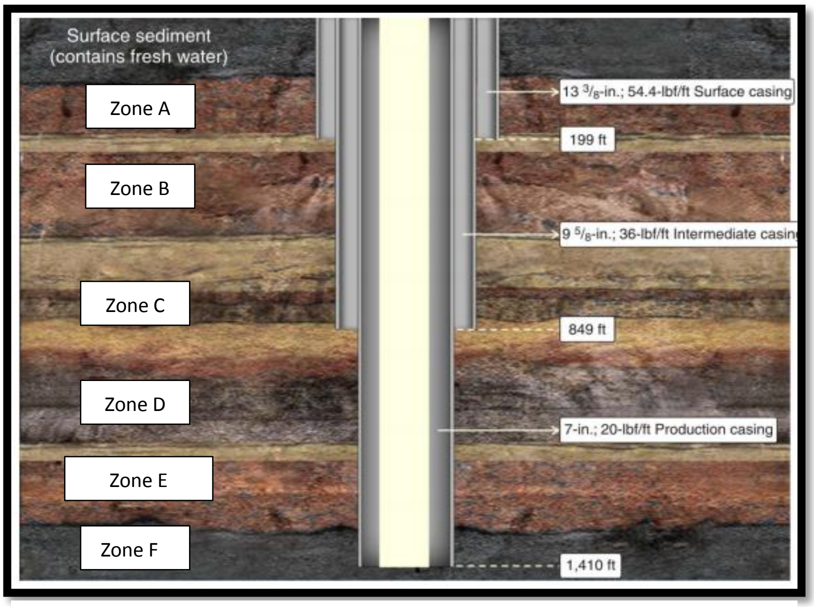
After obtaining all relevant result, the calculation can be processed to determine fatigue life on casing by applying the theories and formulas. Calculation on cyclic thermal stress-strain will be referred to Low-cycle fatigue life equation (5), as mentioned in the previous chapter.

By substituting ($\Delta\varepsilon t$) value in which found from the ANSYS workbench simulation, the total life cycle (N) is calculated by re-arranging Manson's equation (5). The maximum cycle will indicates the maximum stress-strain in which the casing could withstand under thermal stress.

3.3 Data Collection

3.3.1 Gathering Material Properties Data

For this research, following field data were obtained for evaluation purpose.



Well: ABC

Field: Duri, Indonesia

Operator: Chevron

Figure 8: Well Scheme

Well schematic of the analysis is shown in the *figure 8* above. The casing will be modelled based on the available data at the final depth 1410 ft of casing shoe of the production casing. The casing length is modelled around 10 ft length and the properties of the casing are described in the *table 3 and table 5*, furthermore the formation will be modelled following the data on the *table 4*.

Table 3: Well Design & Properties

String	Casing	Interval (ft-TVDDF)		Cement
	Size / Grade / Weight	From	To	Weight (ppg)
Surface Casing	13-3/8”, K55, 54.4 ppf	0	199	-
Intermediate	9-5/8”,K55, 36.0 ppf	199	849	12.5
Production Casing	7" , L-80, 23.0 ppf	849	1,410	15.8

Table 4: Formation data

Formation Material Name	Unconsolidated Sandstone
Density	142.3357 Ibm/ft3
Young Modulus	0.1 - 0.3 Mpsi
Poisson Ratio	0.44
Thermal Conductivity	1.0574 Btu/h.degF.ft
Specific Heat Capacity	0.1696 Btu/(lbm.degF)
Thermal Expansion Coefficient	7.2222 1E-6 1/degF

Material Properties

Production Casing 7” L-80

On this study, the analysis will be focus on 7”production casing.

Table 5: 7-inch L-80 Casing Properties

String	Casing	Casing Properties				
	Size / Grade / Weight	Burst (psi)	Collapse (psi)	Young Modulus	Yield Strength (psi)	Tensile Strength (psi)
Production Casing	7"(6.241”) L-80 23.0 ppf	6340	3830	30 x 10^6	85000	95000

Properties	API L-80
Length (ft)	10
Density(lb/ft^3)	473.28
Young Modulus (kpsi)	30000
Poisson Ratio	0.3
Yield Strength (psi)	85000
Tensile Strength (psi)	95000
Thermal Conductivity (W/mC)	28
Thermal Expansion (C^-1)	1.09E-05
Specific Heat (J/Kg)	453

The analysis conducted on this study is using non-linear 7” L-80 casing in order to find the proper result of cyclic steam injection from ANSYS workbench simulator. The properties of the casing and the field profile are shown on the *figure 8* and *table 5* above. The field data used on this study is taken for the study purpose

3.3.2 Design Geometry

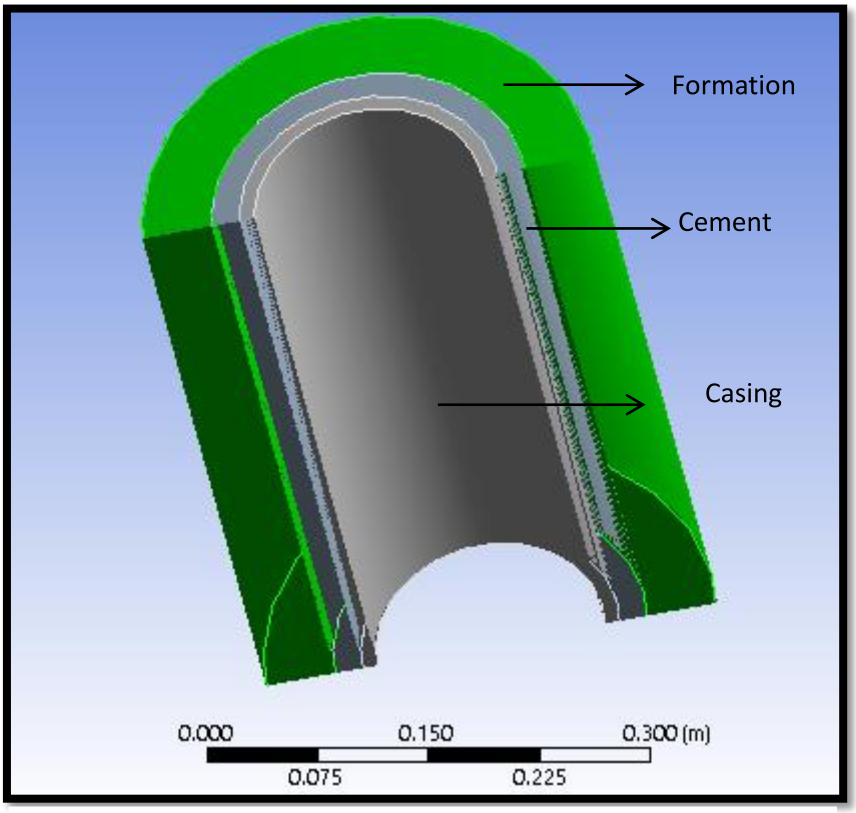


Figure 9: Geometry of the well

Figure 9 shown above is the geometry design of the project. The 10-ft of 7” L-80 casing is modelled followed with 8-1/2” x 7” annulus filled with cement and the formation on the outside boundary is about 30 inch on diameter.

3.3.3 Boundaries

The boundaries concerned on this study are shown in *figure 8,* in which cement and formation outside the casing. The cement and the formation properties are shown in *table 3* & *table 4.*

3.3.4 Meshing

GENERAL MESHING – To run an analysis it is required for the model to be mesh first. A displacement field compatible with applied boundary condition is produced from 26 displacement polynomial which represented by meshing field variable. For this research, element size sets to default setting so it will automatically generated. The procedure and the output of the mesh are shown in the *figure 10 & 11* below.

General Meshing procedure:

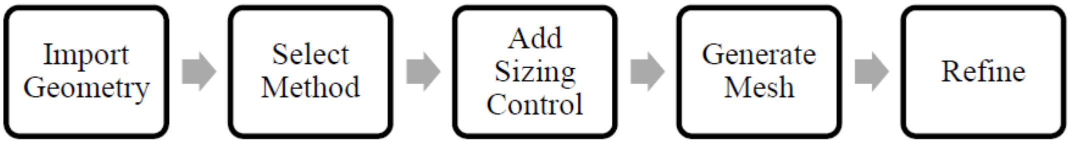


Figure 10: Meshing Procedure

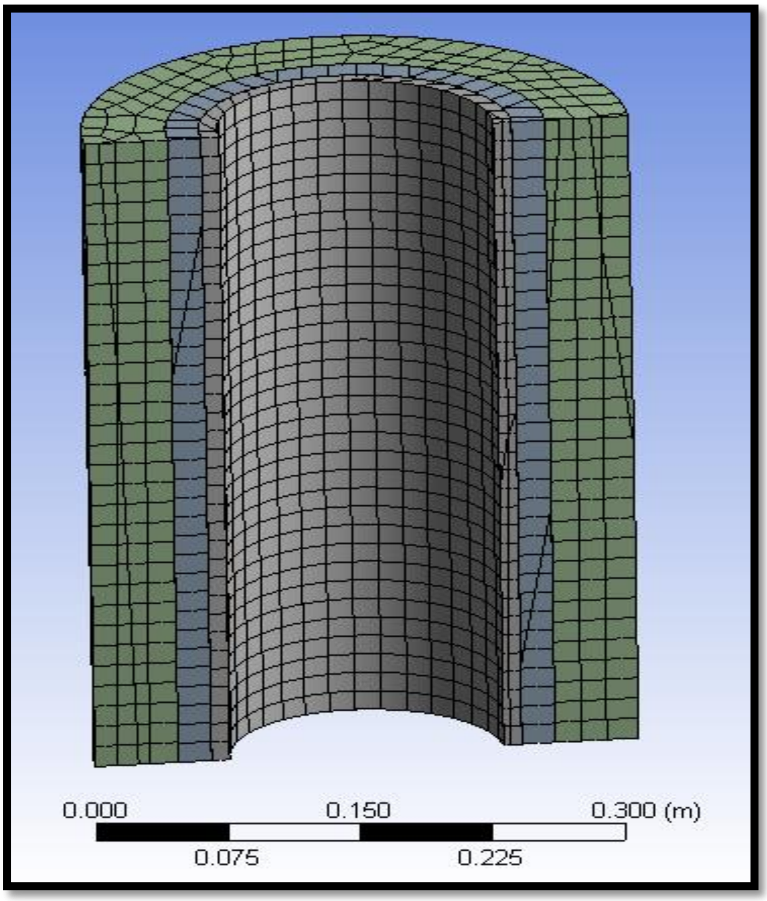


Figure 11: Meshing Result

3.3.5 Steam Properties

On this research the type of steam being used is dry steam with the range of temperature starting from the initial temperature 50°C until the maximum temperature 350°C. The properties of the steam are shown on the *table 6* below

Steam Properties	
Density of Steam (Kg/m3)	36.5107
Specific Entropy of Steam (Kj/Kg K)	5.81334
Specific Heat of Steam (kJ/Kg)	5.1192
Specific Enthalphy of Steam (kJ/Kg)	2771.89
Injection Pressure (psi)	1000
Temperature (°C)	50°-350°

Table 6: Steam Properties

3.4 Analysis Setting

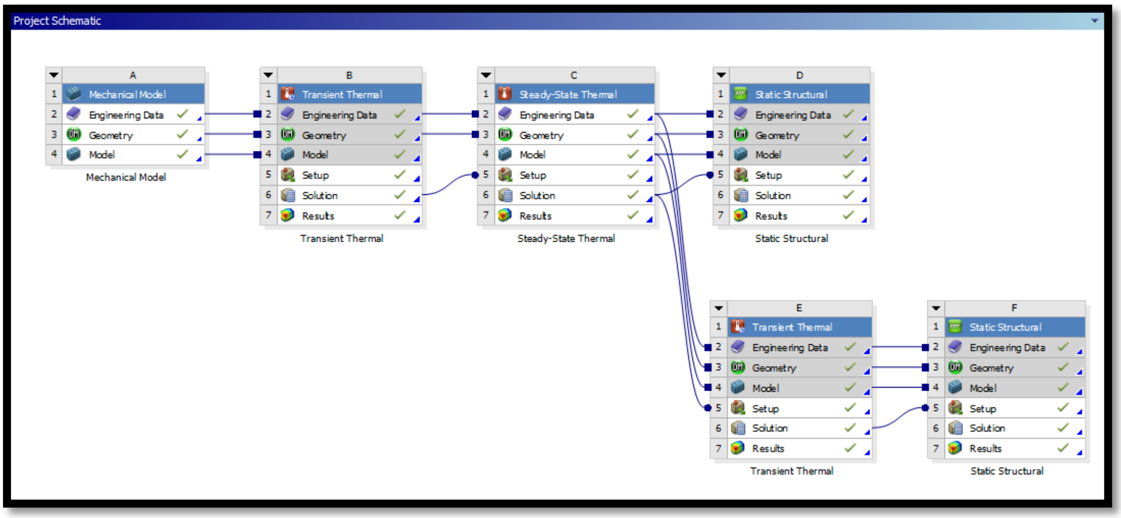


Figure 12: Project Schematic

The sequence of analysis is shown in the *figure 12*. Beginning with mechanical model, transient thermal, steady-state thermal and static structural. Every section will be described further as follow:

Mechanical Model consists of engineering data, geometry design, and meshing. The simulation is modelled and all necessary data are input, including the material properties, boundary properties, etc. The geometry is designed and meshed through this section.

Transient Thermal Analysis calculates the effect of thermal loads of the system or component with the changes of temperature. It is used to generate the thermal applied during the heating and cooling period.

Steady State Thermal Analysis calculates the effect of temperature on system or component that does not vary over time. It is being used to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in the casing during injection phase.

Static Structural Analysis is performed to get the response of the casing structure under applied static loads. This analysis is used to determine the displacements, reaction forces, stresses, and strains.

3.5 Defining Load

One load is applied on the inner casing surface. The load was applied on the internal surface of the casing to represent the internal pressure subjected by the steam injection pressure which is 1000 psi (6.896 mpa). The internal pressure applied is equal along 10-ft casing. *Figure 13* below the modeled casing under injection pressure.

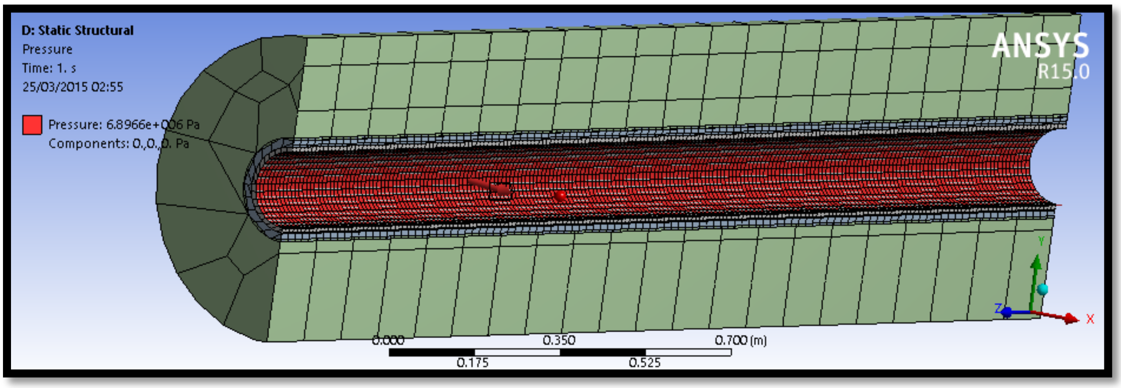


Figure 13: Applied Internal Pressure

The initial temperature of the pipe is set to be 50°C. The temperature then set to be transient with assumption of injected steam from 50°C - 350°C for the steam injection phase and will decrease to 100°C at the end of the soak phase or before the production phase.

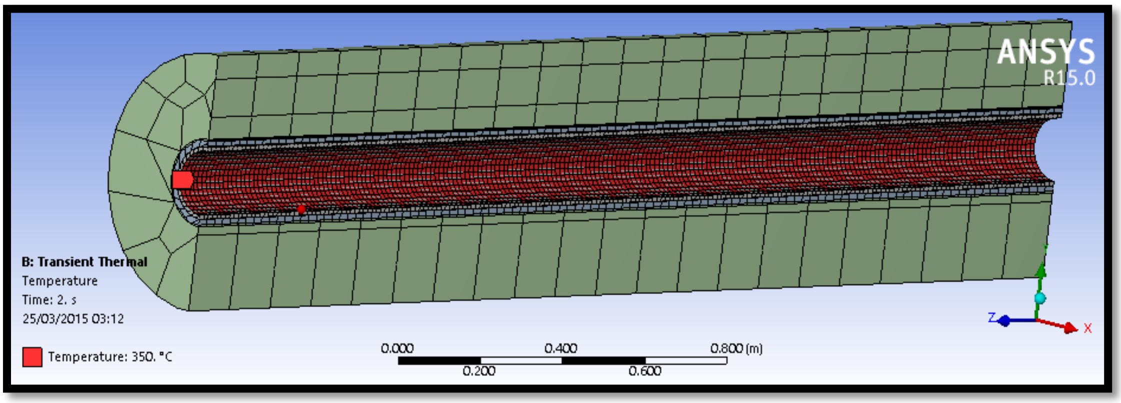


Figure 14: Heating Thermal Loading

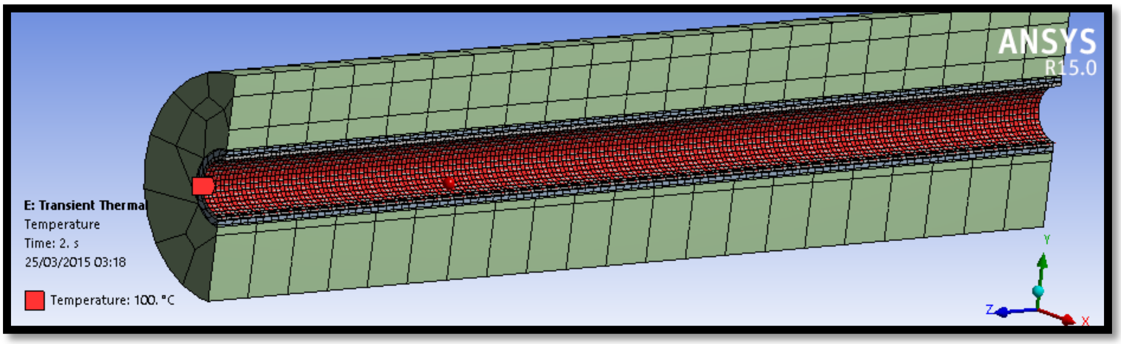


Figure 15: Cooling Thermal Loading

Figure 14 and 15, shows the model with applied transient temperature for both heating period when the steam is being injected, and the cooling period once the well is ready to be produced.

3.6 Solution

After the analysis has been set, the solution is defined to obtain the expected result. The stress-strain analysis using finite element model analysis then can be obtained using maximum principal stress and equivalent strain in which described as follow:

In this case, the failure of material will occur when maximum principal stress developed in a body exceeds uniaxial ultimate tensile/compressive strength of the material. Maximum principal stress of any stress system could be expressed as:

$$\sigma \max = (\sigma x + \sigma y)/2 + \sqrt{}\{[(\sigma x - \sigma y)\,/2]^2 + Txy^2\}$$

The material will be safe if: $\sigma \max < \sigma ut$

Total equivalent strain is the summation of equivalent elastic, plastic, creep (and thermal) equivalent strains.

Both solution for Maximum Principal Stress and Total Equivalent Strain will be analysed in ANSYS workbench in order to find the result. Finally, Manual calculation will be carried out in order to obtain the objectives of the study.

CHAPTER 4

RESULT AND DISCUSSION

Analysis was divided into 2 (two) procedures:

1. To simulate thermal stress-strain analysis model of 7” L-80 production casing;
2. To analyse the fatigue life based on cyclic steam flooding/ injection and result comparison;

Evaluation on the effect of thermal load for one cycle on casing has been carried out. The purpose of the evaluation is to determine the stress/strain developed in casing body based on steam injection effects. The result of first objectives is utilized in order to find the fatigue life of the casing. To validate the results of the simulation, comparison study will be carried out and will be discussed in the discussion part.

The results in this research that is included in this section gives high emphasis on the interpretation and discussion of the effect of thermal expansion of steam injection towards the 7-inch production casing body.

4.1 Stress-Strain Analysis on 7-inch L-80 Production Casing

During the heating process or steam injection phase, the temperature surrounds the wellbore is modelled from the initial (50°C) until the maximum (350°C). Stress begins to develop when the thermal expanding into the casing until maximum temperature. The temperature then modelled to be steady for a while at maximum temperature. After some time, the temperature then decrease to 100°C and one cycle is attained. Stress generated on casing is analysed to see the effect of the thermal load of steam injection.

Stress

The figures on next page are the simulated stress analysis for 7-inch L-80 production casing.

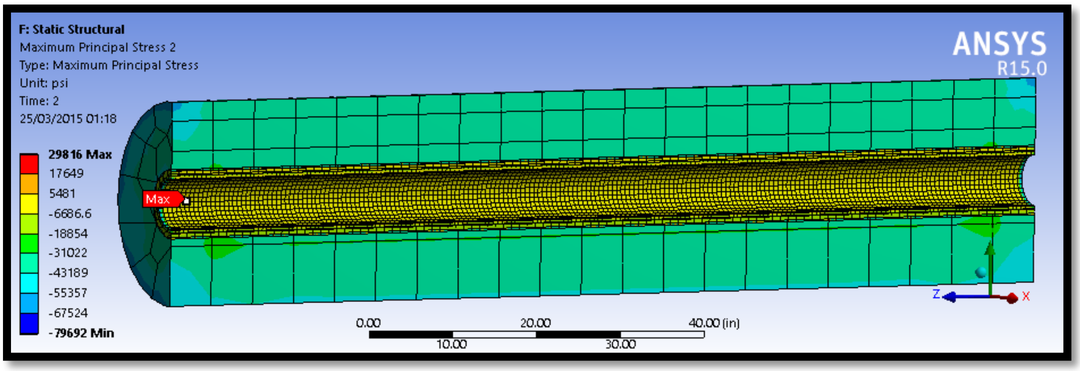


Figure 16: Stress on Design Geometry

The simulated model is shown in the *Figure 16* above. It represents the stresses that generated on the model by using maximum principal stress theory. The theory is used to obtain the compressive and tensile on the casing body. From the legend, the minus value and the blue color indicate compressive stress while the positive value and the red color means the tensile stress is undergone. The thermal load produced from steam injection result on stress from the casing through the formation. Tensile stresses occurred mostly in casing and cement body but not in the formation.

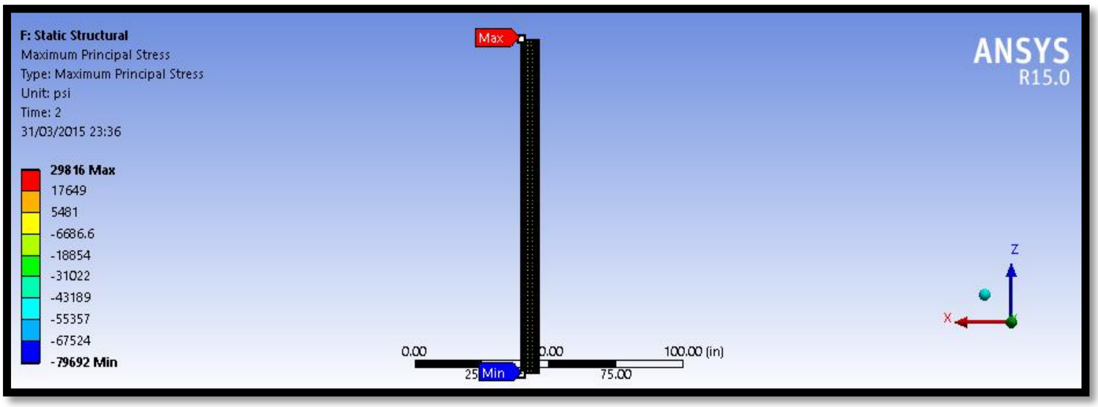


Figure 17: Stress on casing

The casing experienced tensile and compressive altogether along the body. From *figure 17*, it is shown that the maximum compressive stress occurred in the bottom of the end fit of the casing against z-axis and the most tensile occurred on the top of the end fit of the casing along z-axis. This phenomenon happened because end fit is known as the weakest area of the casing. Therefore, the stress is accumulated in that area.

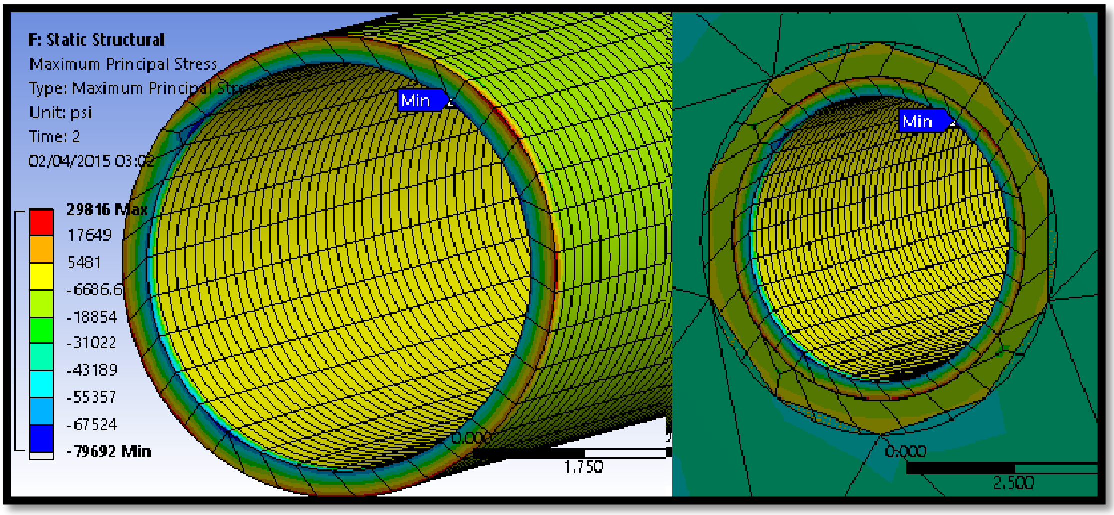


Figure 18: Maximum Compressive Stress on Casing

From *figure 18* above, the maximum compressive stress is generated on the end fit of the casing at the inner body, and the rest of the casing body is under tension. As the compressive stress is generated on the inner casing, the maximum tensile stress is observed at the end fit of outer casing as shown in *figure 19.*

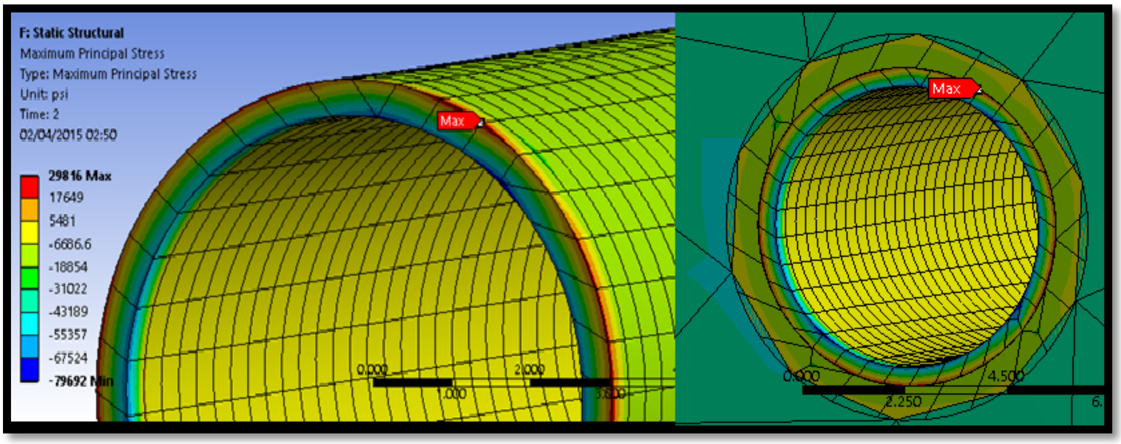


Figure 19: Maximum Tensile Stress on Casing

The result of maximum compressive stress generated on casing is around 79692 psi and 29816 psi for the tensile (*table 7*), in which almost approaching the L-80 grade casing material yield strength of 80000 psi. It means the casing will hot-yielded under the maximum temperature and would failure easily on the connection area.

Table 7: Thermal axial Stress of Casing Cyclic Steam Injection

Results	
Minimum	-79692 psi
Maximum	29816 psi
Minimum Occurs On	Casing
Maximum Occurs On	Casing

The *table 7* shown above is the result of thermal stress experienced in casing. Moreover, the result of thermal stress generated can be validated using equation (2) as mentioned in the chapter 2.

$$\Delta\sigma = -\alpha E \Delta T$$

The material will be safe if: σ max $< \sigma ut$

$\Delta\sigma =$ - 85.698 psi

Error percentage:

$$\frac{-85698-(-79692)}{-85698} x\ 100\% = 7\ \%$$

The manual calculation and the result from simulation have different value with maximum error of 7%. From the empirical theory, it is shown the stress generated exceeding the yield stress of material (80000 psi), but still under the maximum ultimate strength which is 95000 psi. The casing will experience hot-yield under the corresponding condition (maximum temperature) and plastic deformation will occur. Under this condition the cement outside the casing and the contact pressure generated between casing and the cement would depend on the cement and formation properties. For poor cemented or uncemented section, the casing might expand due its hot-yield compressive stress.

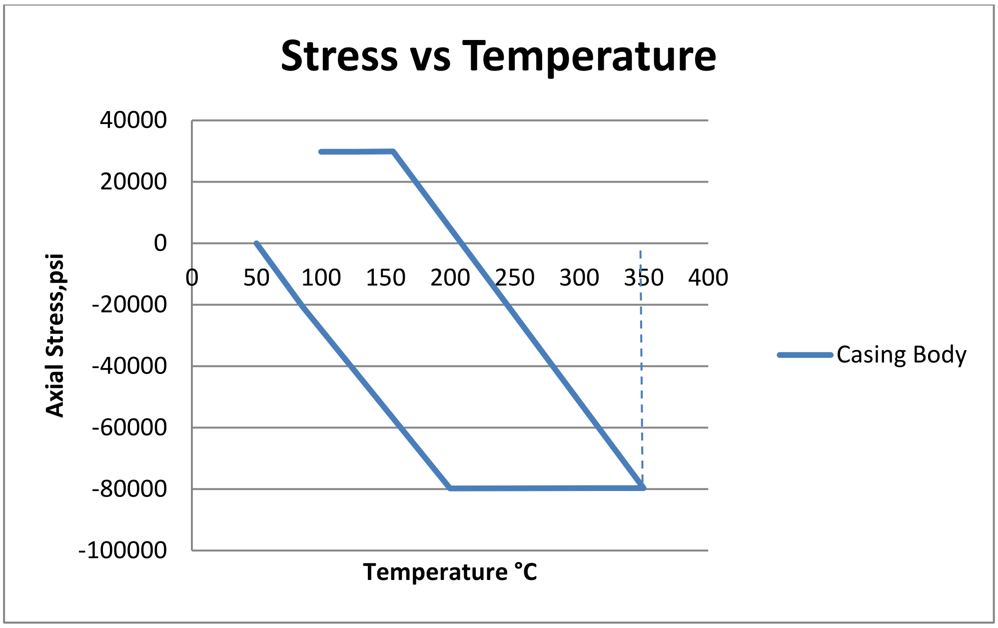


Figure 20: Casing Thermal Stress

Plotted graph in *figure 20* shows stress generated on the casing body during the injection phase and the soak period for 1 cycles steam injection. The casing body will experienced compressive when it is being heated by steam injection and will experienced tensile once the temperature decreased. As have been discussed, the compressive stress will accumulated on the fix end of the casing during the thermal phase and tension will develop after the soak temperature decrease (soak period).

On the continuous cyclic steam injection, the thermal load applied to the casing will be repeated, if the stresses develop on the casing are at the same location, it will result in casing failure at fix end or connection.

Strain

The figures below are the simulated strain analysis for 7-inch L-80 production casing.

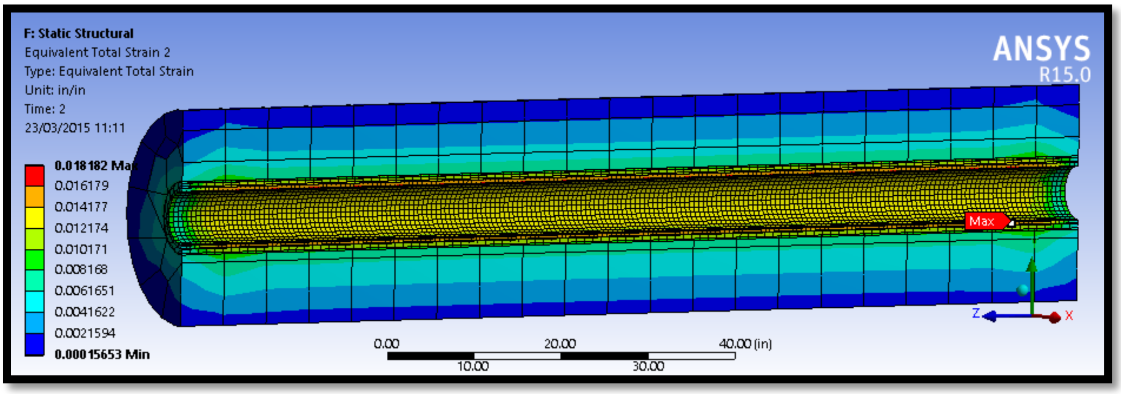


Figure 21: Equivalent Total Strain of Design Geometry

The simulated model is shown in the *Figure 21* above represents the strain that generated due to stress under thermal load. Equivalent total strain is used to obtain the maximum strain generated along the body. From the legend, it is seen that the strain develop depends on the color. Red color indicates the maximum strain occurred, while the blue is vice versa. The model shows that the strain is mostly develop at casing and cement, and less at formation.

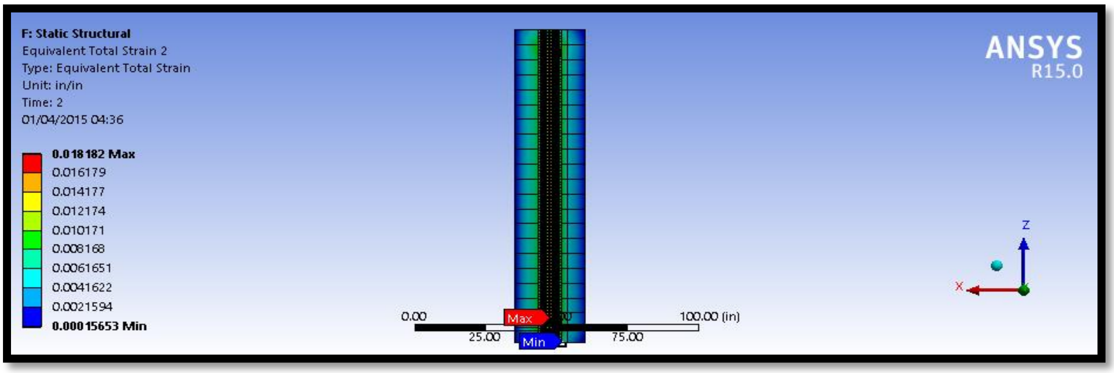


Figure 22: Equivalent Total Strain on Casing

From the analysis (*figure 22)* the maximum and minimum total strain developed on the casing located in the bottom of the casing, near casing connection. It is occurred on that particular area due to the maximum compressive stress generated on the end fit/ connection part.

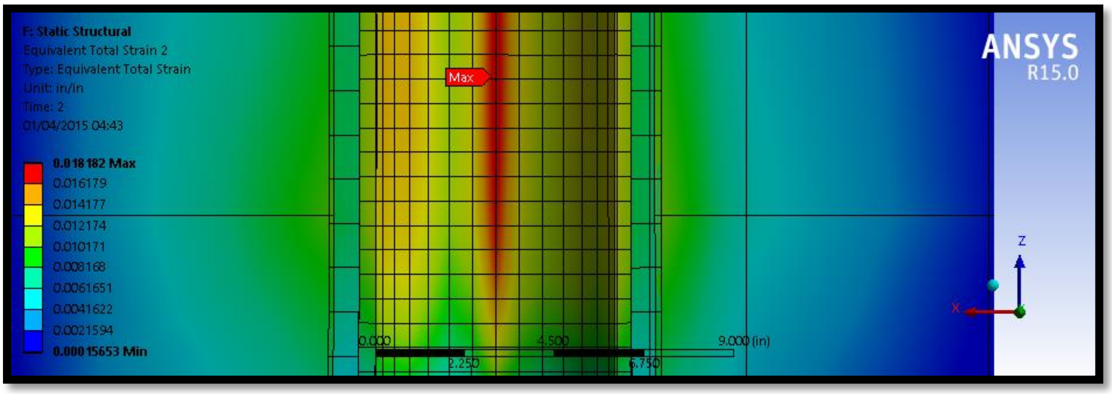


Figure 23: Maximum Equivalent Total Strain on Casing

The red color (*figure 23)* shows the maximum total strain develop on the casing as the thermal stress generated. The results of the strain developed on the model can be seen in *table 8* below.

Table 8: Strain of Casing Cyclic Steam Injection

Results	
Minimum	1.5653e-004 in/in
Maximum	1.8182e-002 in/in
Minimum Occurs On	Formation
Maximum Occurs On	Casing

It is found that the maximum strain occur on casing with 0.018182 in/in. The strain generated encompasses the whole model, from the casing through the cement. The results show that the strain mostly developed on casing and cement, and minimum at formation.

Overall results of stress-strain analysis on 7-inch L-80 production casing are summarized on the following table.

Table 9: Result of Stress-Strain L-80 Production Casing

Equivalent Total Strain	0.018182 inch/inch
Compressive Stress (Heating)	79692 psi
Tensile Stress (Cooling)	29816 psi

4.2 Fatigue Life

Manson's equation (6) is used to estimate the low-cycle fatigue life on 7-inch L-80 production casing for this analysis. It relates the fatigue life (cycles) to the total equivalent strain changes by axial stresses. By substituting the total equivalent strain, the total fatigue life of the casing is calculated. The result of total fatigue life is obtained and shown on the following table:

Table 10: Fatigue Life cycles of 7-inch L-80 production casing

7-inch L-80	
Life Cycles	**Equivalent Total Strain(in/in)**
1	0.7471
100	0.05281
811	0.018182
1000	0.016503
10000	0.0066

From the equivalent total strain, the total life cycle calculated is shown on the *table 10.* Moreover the total fatigue life against strain is calculated and plotted in the graph below.

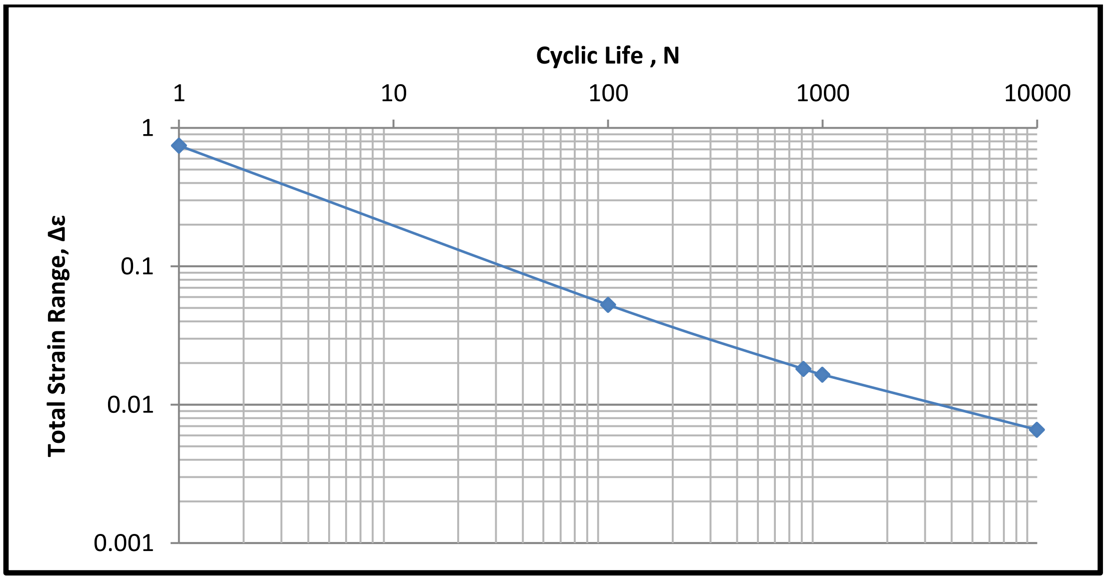


Figure 24: Cyclic Life vs Equivalent Total Strain

It is found that the cyclic life of 7-inch L-80 production casing will be around 811 cycles when the equivalent total strain developed from the thermal load is about 0.018182 in/in. From the *figure 24*, the life cycles of 7-inch L-80 casing is predicted to be about 100 cycles when the equivalent total strain developed is about 0.05281 in/in. Thus, the higher the strain is developed, the less the life cycle of the casing will be.

4.3 Comparison of Results

After the results have been obtained, then it is compared with previous study that has been carried out on "Casing Failures in Cyclic Steam Injection". The comparison study purpose is to validate the result of new analysis. As have been mentioned in the literature review. The well schematic of previous study is shown in the *figure 3*.

The analysis of previous study was conducted using the method that relates local stress and strain to nominal values [12]. Therefore, the comparison results are drawn in the table below.

Table 11: Comparison of Study

RESULTS	FEM	Previous Study
Equivalent Strain, $\Delta\varepsilon t$ (inch/inch)	0.018182	0.017
Life Cycles	811	930

The *table 11* gives the comparison result obtained from FEM analysis and previous study used relates local stress and strain to nominal values. From the results, Finite Element Method (FEM) analysis obtained higher equivalent strain than the previous study and given lower life for the casing eventually. Despite the total equivalent strain at casing would be more accurately modelled with FEM [12], it cannot be simply conclude that FEM is better method to use. The different data and boundaries applied (cement, formation, pressure, temperature, etc.) might be the indication of the different result.

4.4 Effect of Strength and Ductility on Fatigue Life

The analysis was conducted to see the effect of different material strength and ductility of the 7-inch L-80 production casing against the total life cycle. Manson's equation is used with the changes of material tensile strength and/or ductility in order to analyse the life cycle by maintaining the result of total equivalent strain (0.018182 in/in) from finite element analysis. Shows the distribution of each analysis result from Manson's equation with related to three different strengths and ductility that were being analyzed in this research.

Table 12: Effect of different material Strength with (0.6) ductility

95000 psi		125000 psi		135000 psi	
Life Cycles	**Total Strain** (in/in)	**Life Cycles**	**Total Strain** (in/in)	**Life Cycles**	**Total Strain** (in/in)
1	0.7471	1	0.75	1	0.75177
100	0.05281	100	0.0548	100	0.0555
811	0.018182	980	0.018182	1000	0.01854
1000	0.016503	1000	0.01803	1047	0.018182
10000	0.0066	10000	0.00775	10000	0.008145

Tensile Strength	**95000 psi**	**125000 psi**	**135000 psi**
Life Cycles	811	980	1047

Different material strength of the casing is calculated and analyzed as shown in the *table 12* above. Material strength of 95000 psi, 125000 psi, and 135000 psi are analyzed. It is obtained that higher material strength will have an impact to the better / longer life of casing subjected to the same ductility and thermal condition. The 125000 psi strength gives 980 cycles and 135000 psi strength gives 1047 cycles respectively. The comparison of the different material strength is plotted on the *figure 25*.

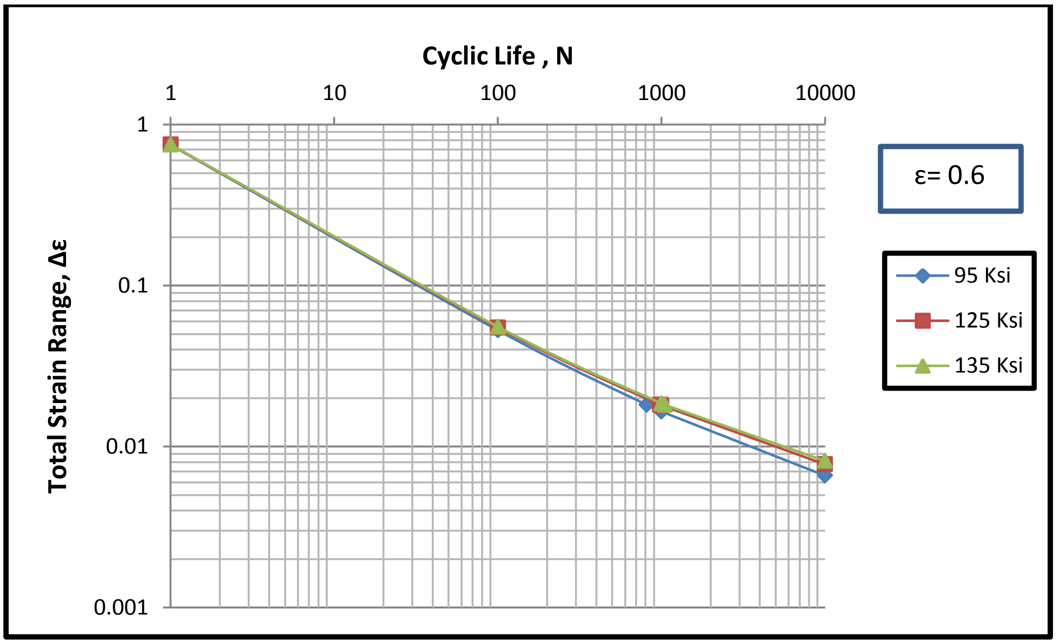


Figure 25: Effect of material tensile strength on fatigue life

The effect of various tensile strength were analysed as shown in *figure 25*. No significant change is seen to the fatigue life on the plotted range of variables if the high stress/strain is developed. But if the lower strain is generated, the higher material strength will give a different impact to the fatigue life. It is seen that from the graph, higher material strength is good for high-cyclic life.

Analysis on different ductility of the casing is calculated and shown in table below.

Table 13: Effect of different Ductility with 95000 psi Ultimate Strength

0.6		**0.7**		**0.8**	
Cycles	**Total Strain** (in/in)	**Cycles**	**Total Strain** (in/in)	**Cycles**	**Total Strain** (in/in)
1	0.7471	1	0.818	1	0.8857
100	0.05281	100	0.0573	100	0.06156
811	0.018182	937	0.018182	1000	0.0187
1000	0.016503	1000	0.01763	1061	0.018182
10000	0.0066	10000	0.006884	10000	0.007152

Ductility	**0.6**	**0.7**	**0.8**
Life Cycles	811	937	1061

Different ductility of the casing is calculated and analyzed as shown in the *table 13*. It is obtained that higher ductility of the material or casing will have an impact to the better / longer life of casing subjected to the steam injection. The calculation was done by maintaining the thermal load and material strength is set to be 95000 psi. The result of different ductility of the casing is plotted on the *figure 26*.

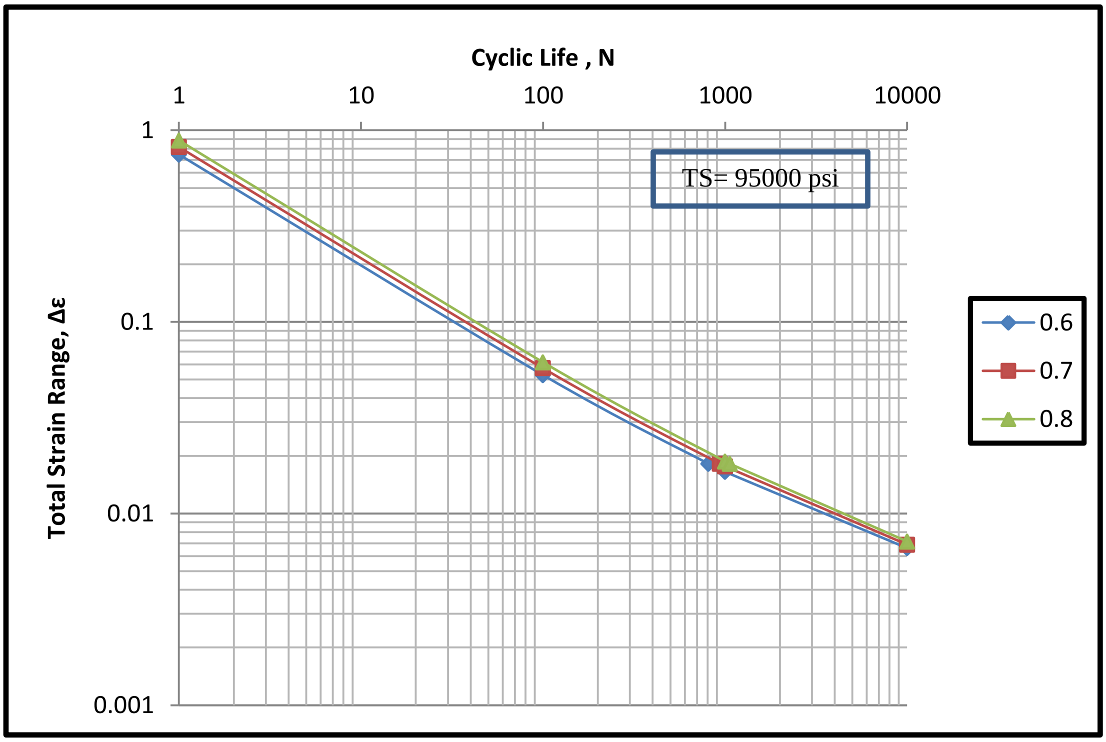


Figure 26: Effect of ductility on fatigue life

Different ductility is set, to be 0.6, 0.7, and 0.8. The 0.6 is the base case for L-80 production casing. Under the same condition, 0.7 ductility result to 937 life cycles and for 0.8 ductility, it gives 1061 life cycles respectively.

From the graph, it is seen that higher ductility could withstand the higher stress / strain that generated on the low cycle fatigue life. For 0,8 ductility, the strain that must be developed on the casing for to fail the casing in 1 cycle is around 0.8857 in/in, while with only 0.818 in/in and 0.7471 in/in strain for 0.6 and 0.7 material respectively, the casing has already fail. But for the high-cyclic life, higher ductility has no significant effect on the casing body.

CHAPTER 5

CONCLUSIONS & RECCOMENDATION

5.1 Conclusion

From the model of casing temperature, analysing the thermal stress-strain and casing fatigue life, the following conclusions may be described:

- Thermal axial compressive stress will developed during the heating period of steam injection phase, and during cooling period the thermal axial tensile-compressive stress will appeared and the casing will be under stress when it reaches initial temperature.
- The total equivalent strain is developed by the axial thermal compressive and compressive-tensile on the steam injection well. The more strain developed, the less life the casing will have.
- Total Fatigue Life of casing is resulted from the thermal load applied.
- In order to have a longer fatigue life on the casing for steam injection well, the higher tensile strength and ductility of the casing should be used for a better or longer fatigue life.

5.2 Recommendation for future study

The predicted fatigue life of the casing is higher if compared to the field data that casing usually fails below 100 cycles. The different outcomes may due to some factors in which be able to be used as a recommendation for the future study and it is summarized as follow:

- Imperfect casing body model
- Casing wear effect consideration
- Production phase of steam sequence
- Effect of cement and formation towards the casing
- Effect of casing buckling in cyclic steam injection well

APPENDICE

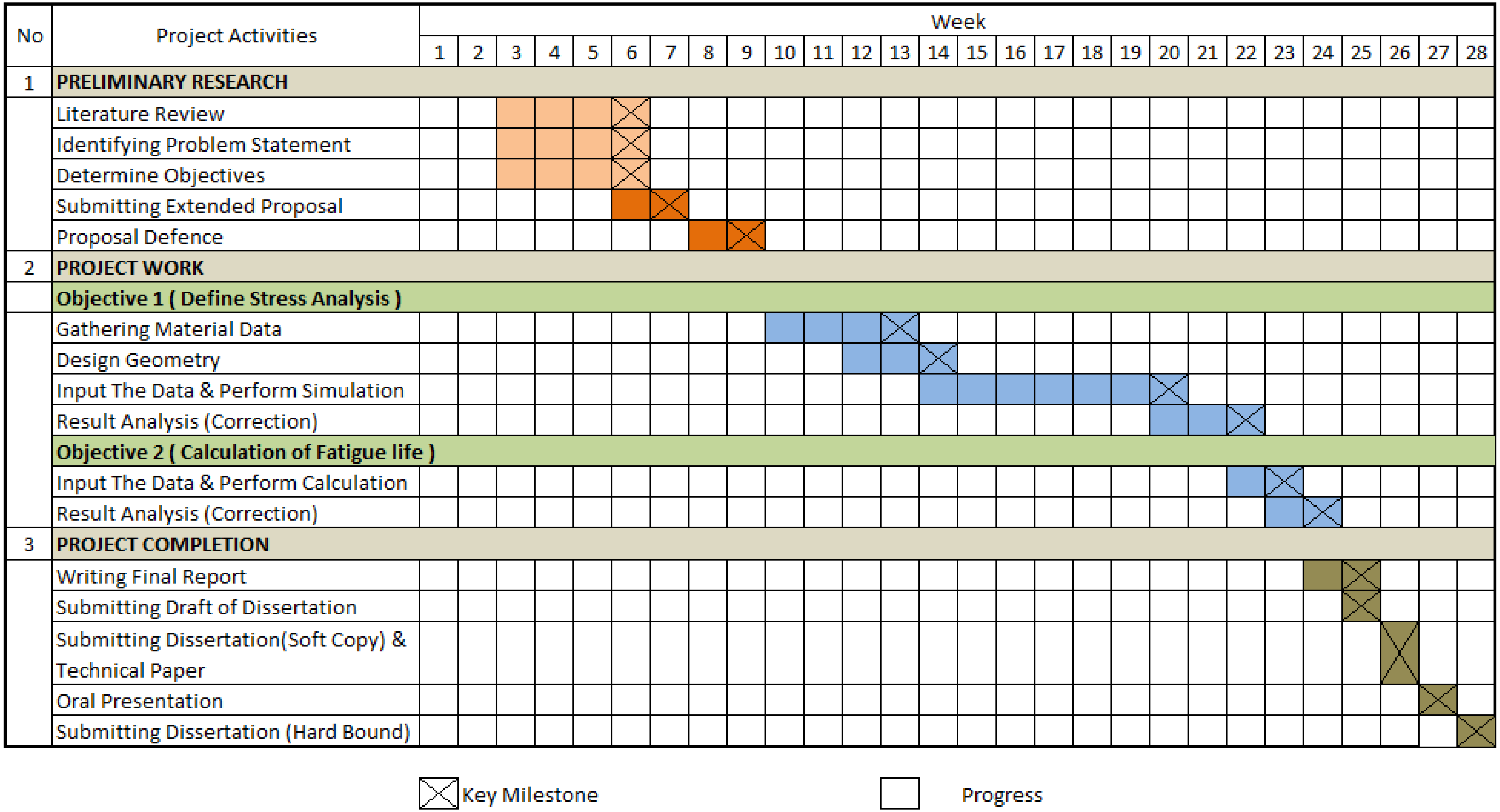


Figure 27: Gantt Chart

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