Analysis of Casing and Tubing Buckling in Inclined Well

by

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CERTIFICATION OF APPROVAL

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Approved by,

____

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2014

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 that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Muhammad Zubair Bin Khalid

ABSTRACT

This report presents an analysis on the effect of different angle of well inclination towards the buckling effects on the casing. The buckling effects are including the stress, shear stress, strain and minimum buckling force required for the casing to start buckle. It is essential to analyse the buckling effect on the inlined well as failure in tubing and casing will cause loss of wells, which give a negative impact economically. J. D. Clegg (1971) mentioned in his paper that combination of non-uniform load and hydrostatic external pressure is believed to have caused most of the casing and tubing failures. The interaction between angle of inclination and minimum buckling force required for the casing to start buckle is calculated theoritically, while the effect of different angle of inclination on stress distribution were simulated and observed using ANSYS 14. ANSYS software has proven to be a successful tool in studying and simulating the effect of different angle of inclination towards the stress distribution of on the casing surface. The result obtained from the simulations are succesful. As the angle of the well inclination increases, the stress exerted on casing surface was changed. Besides, increase in the angle of inclination also increased the shear stress on the casing surface. The distribution of the stress also changed as the angle is changed.

ACKNOWLEDGEMENT

I would like to express my gratitude to those whose their presence have made the completion of this Final Year Project is a success. First and foremost would be my Final Year Project Supervisor, Dr. Sonny Irawan. Dr. Sonny has been very supportive and understanding. He has earnestly guided me through the obstacles, problems and issues faced in this project. I would be looking forward to cooperate with Dr. Sonny in near future. In addition to that, I would like to extend my gratitude to Universiti Teknologi PETRONAS for this is the sole reason I started and completed this project. Next, I would like to thank to Mr. Hariz, research officer in Block 17. He has been very helpful and patient in providing me all the information and guidance I need for this project. I would also like to thank all my friends and coursemate especially Akmal, who kept me company while we are working inside the lab.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

1.1.1 Casing and Tubing Failure

Casing and tubing strings are the main parts of the well construction. All wells that are drilled for the purpose of oil or gas production must be cased with casing and produced through tubing. Therefore, it is essential that both be made up from material with sufficient strength and functionality to prevent them from any liabilities and problems.

The problem is, failure of tubing or casing in the offshore wells can lead to loss of wells and platforms in some instances, which will heavily affected in terms of economy and expenses. According to Chen et al. (1988), it is well known that tubulars structures, when subjected to its minimum compressive axial loads due to stress, thermal or pressure effects, will buckle. Thus, knowledge of these factors is important to prevent buckle from happened.

Many analyses have been performed on the mechanics of pipe in oil and gas wells since 1950. Lubinski, et al. defined the helical buckling behavior of pipes in vertical wells by performing severals analytical solution. However, it was only limited to the vertical wells, and was not applicable for horizontal and deviated wells.

Therefore, this proposal aims to analyse on how these factors affect the tubing or casing buckling in inclined wells. The factors including the casing angle or degree of inclination and pressure in terms of stress or axial loads.

1.1.2 Buckling Definition

Buckling is defined as mathematically instability, which can lead into some structures failures. But in theory, buckling is something that caused sudden failures subjected to some compressive loads or stress, beyond the capability of the material to withstand. Besides, buckling can also happened due to several factors, such as temperature and pressure inside the pipe or casing.

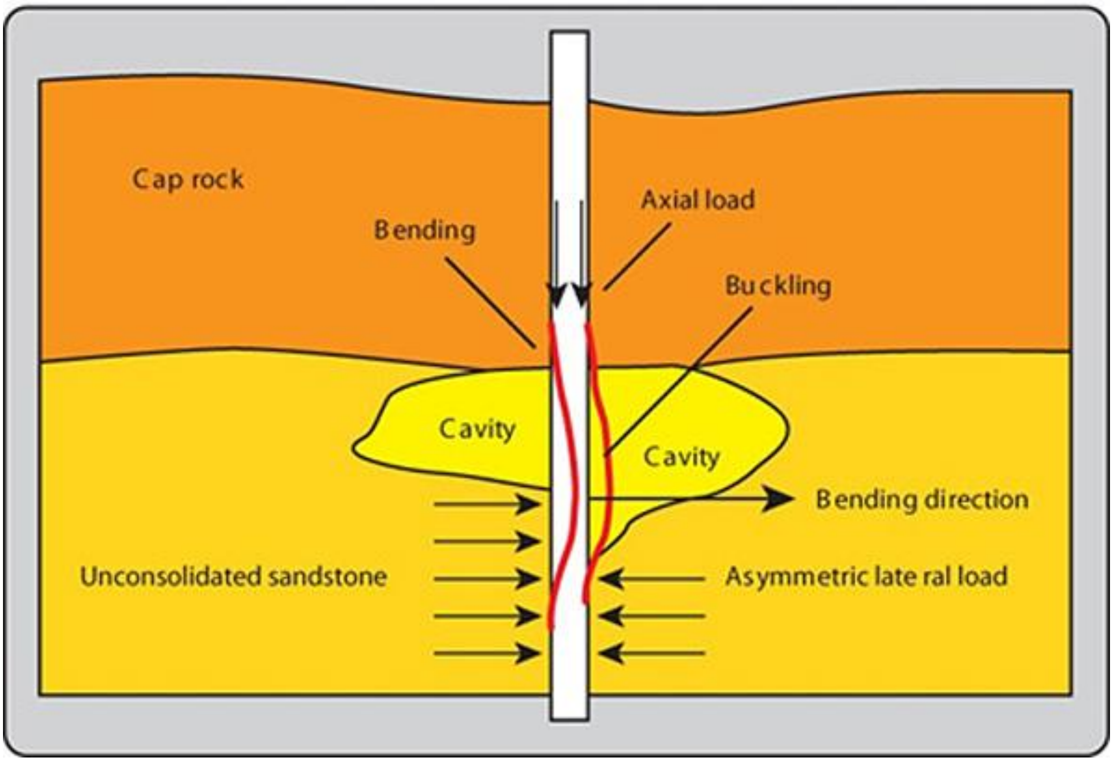

Figure 1: Buckling effect on the casing in a well

In simpler words, buckling is when a vertical elements collapsing when subjected to compression, leading to sudden sideways deflection as shown figure above.

1.1.3 ANSYS Workbench v14.0

ANSYS has been playing an essential and important role in understanding modern engineering studies and it has been used considerably in most of the engineering predictions. It can performs a lot of engineering simulation by using subproduct in the ANSYS. ANSYS is a platform for many other analysis components, and one of its most significant products is ANSYS CFD, computational fluid dynamics (CFD) program. In CFD, engineers can simulate the fluid flows in a virtual environment such as fluid dynamics of gas turbine engines, vacuum cleaners, mixing vessels and others.

Moreover, in petroleum engineering, the use of ANSYS software is not something new. For example, Clem, Coronado & Mody (2006) carried out their project on frac-packing tool inside high profile deepwater well at high pump rates and proppant loads by analyzing the velocity, fluid path and erosion occur.

For this project, the software used are Structural Mechanics, where different amount of force will be applied, stress and strain will be analysed, and intergrate the results into another software, Linear Buckling (Mechanical Solver) where the deformation of the pipe will be analysed in term of buckling effect.

The oil industry needs an experimentally verified analytical expression on the tubing and casing buckling in inclined wells. The first step should be the calculations of the theory, before comparing the results with the simulation, using some related softwares. The analysis of tubing or casing buckling will be performed by changing the degree of inclination, while some assumptions and constant are applied during the research.

By having this analysis, we can predict the behaviour of tubing and casing buckling on stress or pressure, temperature and degree of inclination

1.2 Problem Statement

Most of the gas wells and flowing oil wells are completed and treated through a string of casing, tubing and a packer. Type of casing, inside diameter of tubing, size of packer, packer fluids as well as temperature of the formation are the considerations need to take into account during the the well completion. Therefore, a lot of factors can influence the casing and tubing in the wells, either in positive of negative ways such as:

- If free motion of the tubing inside the packer is permitted, increase or decrease the length of tubing
- If free motion is prevented, induce the forces in the tubing.
- Casing failure due to bending movement of the tubing inside.
- Casing wear

Those scenario will caused the entire operation become costly and not be profitable. Basically, the tubing and casing will always buckle, depends on the situations and conditions of the well along the formation and much more severely if the free motion is permitted. But the question of the day is that, how much will these factors such as pressure and degree of inclination of the well will affect the buckling?

Therefore, it is essential to produce an analytical expression regarding the situation. The two fundamental questions about tubing buckling are;

- What is the critical load ?
- What is the post-buckled configuration ?

The critical load will tells us what the minimum force required for the tubing to start buckle, and the post-buckled configuration tells us about how the tubing move, how much the bending stresses will yield, axial-load distribution along the casing or tubing, as well as the amount of contact force on the casing and tubing.

The first publication of analysis of helical buckling (Lubinski et al. 1962) answered two basic questions about tubing buckling

1. How does fluid pressure influence buckling ?
2. What is the pitch of helically buckled tubing ?

Therefore, the author decided to analyse the buckling based on the theory calculations, and applied the theory into the simulation. The buckling solution model proposed by the Lubinski in 1960s cannot be taken into consideration, as it was not accurate and not applicable for the deviated wells. Thus, a modification need to be made in order to applied the same concept proposed by Lubinski into this research.

1.3 Objective of Study

Based on the previous problem statements, the author come up with a few objectives. The objectives of this study are as follows :

- To determine the minimum force required for the tubing and casing to start buckle in the inclined wells.
- To predict the effect of degree of inclination on tubing and casing on the buckling force required and compare simulated results with experimental observation

1.4 Scope of Study

To develop the study, few parameters must be studied first in order to obtain the optimum conditon for the casing before the buckling effect happened. The parameters are stress or force, applied in axial direction and degree of inclination of the wells. Simulation will be done by changing the angle of well inclination while others are kept constant. The results of the simulation will be analyse to understand the effect of the parameters towards the casing buckling, thus be able to come up with a complete analysis on the buckling effect in the inclined well.

1.5 The Relevancy of The Project

The buckling effect on tubing and casing have become an attention since 1950s. But during the earlier periods, experiments and theoritical calculations are much preferred than modelling and computational simulations for higher accuracy. Lubinski (1950) was the first person to introduced a mathematical model of buckling in the oil and gas well operations but its only applicable for short strings and vertical well, not for deviated and horizontal well, as well as long strings of tubing and casing. The buckling effect on tubing and casing is very complex process. The interaction between the axial loads applied, the presence of cavity on the formation along the string, and other factors are complicated and there exists various and different wellbore conditions.

Therefore, to conduct an experiment needs expensive laboratory setups to simulate each of the conditions. Thus, modelling and simulating through software is widely accepted.

CHAPTER 2

LITERATURE REVIEW AND THEORY

This chapter outlines the fundamental concepts on tubing buckling as well as the factors that lead to the buckling effect. It reports on the previous studies done by other researcher on this aspect of the study. This information will be the benchmark for the analysis of the tubing and casing buckling in inclined wells.

2.1 Casing Failure

Casing failure is one of the factors that caused a wells plugged or abandoned. A combination of non-uniform load and hydrostatic external pressure is believed to have caused most of the casing failures as mentioned by J.D Clegg (1971). He proposed a solution that the casing to be design for withstanding the applied pressure differential when the casing is deformed one wall thickness.

Besides that, H.G Texter (1955) found out that if a string of casing is placed in heavy longitudinal compression in its lower part, and if there is a sizable cavity at that point, the string will most surely buckle into cavity. He also proposed a solution to the respective failure by keeping the casing in full tension from top to bottom all the times, to prevent it from buckling.

2.2 Tubing Buckling

Tubing or casing buckling is resulted due to external factors such as temperature, stress loads and pressure over time. As mention by Robert F. Mitchell (2008), in general, structures loaded above their critical load fail catastrophically. Yet, both tubing and drillstrings are commonly operated above the critical load due to the wellbore provides the necessary support. Besides that, change in pressure and temperature inside or outside the tubing will increase or decrease the length of tubing, or induce the forces on tubing, depends on the free motion of the tubing, either permitted or prevented (Lubinski et al. 1962).

2.3 Tubing Buckling in Inclined Holes.

The solution by Lubinski et. Al (1962) does not provide enough asnwer as it only applies on vertical wells. When we have a deviated well, there is possiblity of lateral buckling. At what axial load / stress does tubing buckling begin in deviated wells? The first explicit calculation for deviated wells was published by Dawson and Paslay (1984). They came up with two types of buckling analysis for inclined wells. The first analysis shows the casing is very resistant to buckling in inclined holes, the second analysis shows that, under some conditions, casing can buckle without harmless consequences.

2.4 Effect of Temperature on Tubing Buckling

Formation temperature is an important parameter in casing and tubing installation since it affects the casing material, operations and equipment. The temperature is governed primarily by the formation's proximity to the earth's mantle, by means, as the depth increases, the temperature also increases.

In most hydrocarbon-producing areas, the temperature gradient is usually in the range of 0.6 to 1.6°F per 100 ft of depth increase (**Figure 1**). Areas where the earth's crust is thinner than average, such as volcanic and geothermal areas, have much higher gradients.

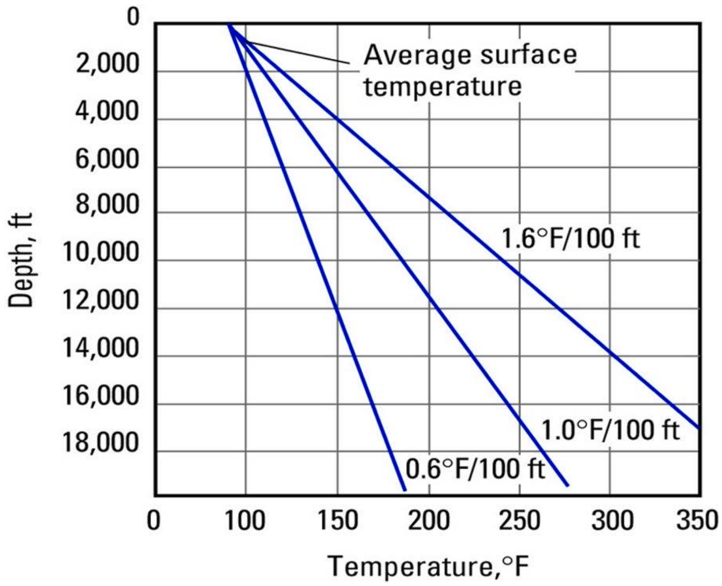

FIGURE 2 : Definition of an average geothermal gradient.

Based on the temperature gradient, the casing material can be predicted in order to prevent the casing from buckling. According to Gunnar Skúlason Kaldal et al. (2011), during installation, stimulation and production of oil, problems can arise due to geothermal environment, which is plastic buckling of the production casing.

2.5 Tubing Buckling in Horizontal Well

As mention before, many analyses have been performed on the mechanics of pipe in oil and gas wells. Lubinski et. Al defined the helical buckling behavior of pipes in vertical wells. However, the postbuckling behavior of casing or pipes in horizontal wells is different from that in nearly vertical well. Chen et. Al (1990) describe the methods to analyze these problems in the horizontal well. Two modes of buckling can occur for tubulars in horizontal or steeply inclined wells; helical and sinusoidal. They found that axial compressive force required to buckle the casing into sinusoidal configuration depends on pipe stiffness and weight on the hole size. As the axial force is increased, the buckling mode changes from sinusoidal to helical.

2.6 Theory Calculations

To have a good analysis of the buckling, the accuracy and comprehensiveness of the buckling model is important. The most common buckling solution used is the model developed by Lubinski in 1950s. Unfortunately, the model is only accurate for vertical well, therefore for the deviated well, modifications need to be made.

The basic theory is that buckling will only be occur if the buckling force, F_b is greater than threshold force, F_p , also known as Paslay Buckling Force.
The buckling force, F_b is the minimum force where the buckling will start to initite, different for each casing and tubing size, and is defined as :

$$F_b = F_a + p_i A_i - p_o A_o \qquad \text{………………….} \ (1)$$

where ;

F_b = buckling force, lbf,

F_a = axial force (tension positive), lbf,

p_i = internal pressure, psi,

$A_i = r_i^2$, where r i is the inside radius of the tubing, in.^{2},

p_o = external pressure, psi,

and

$A_o = r_o^2$, where r_o is the outside radius of the tubing, in.

For the Paslay Buckling force, F_b, it is defined as ;

$$F_p = \sqrt{\frac{4 w_e EI}{r}} \qquad \text{………………….} \ (2)$$

F_p = Paslay buckling force, lbf,

w_c = casing contact load, lbf/in.,

w_e = distributed buoyed weight of casing, lbf/in.,

Φ = wellbore angle of inclination, radians,

Θ = wellbore azimuth angle, radians,

E = Young's Modulus, psi,

I = Moment of Inertia of tubing, in^4,

EI = pipe bending stiffness, lbf-$in.^2$,

r = radial annular clearance, in.

To calculate the value of distributed buoyed weight of the casing, w_e, a few assumptions and considerations need to be made such as the tubing is submerged in 10-lbm / gal packer fluid with no other pressures applied. Thus, the packer fluid will reduce the tubing weight of buoyancy. The equation for calculating the distributed weight of the casing is defined as:

$$w_e = w + A_i\gamma_i - A_o\gamma_o \qquad \text{………………….} \ (3)$$

where,

W_e = effective weight per unit length, lbm/inch,

A_i = inside area of tubing, in^2,

γ_i = density of fluid inside of tubing, lbm/gal,

A_o = outside area of tubing, in^2,

γ_o = density of fluid outside of tubing, lbm/gal.

After calculating the the value of distributed buoyed weight of the casing, w_e from equation 3, the value will be substituted into equation 2 and Paslay Buckling force, F_b is calculated. The asnwer obtained will be the bukling force for horizontal well. To calculate the minimum buckling force required for different angle, the equation will be as below:

$$F(\theta) = F_{p(horizontal)} \times \sqrt{\sin\theta} \qquad \text{………………….} \; \textbf{\textit{(4)}}$$

where,

F(θ) = Buckling force for respective angle, lbf,

$F_{p(horizontal)}$ = Buckling force for horizontal well, lbf,

θ = angle in degree, ^{o} .

The angle will be in range of $0^o < \theta < 90^o$. Therefore, the value obtained from equation 4 will be the value of force required for the casing with respective angle to start buckle. The value obtained will collected and tabulated.

CHAPTER 3

METHODOLOGY

3.1 Simulation Flows

The simulation of the effect of different angle of well inclination on the stress distribution is carried out using the ANSYS software. The simulation steps can be detailed down into the followings:

a) Sketching two circle, with each circle has different diameters. Those circle represent the inside diameter and outside diameter.
b) Both circle is extruded to form a long tube with a hollow path inside.
c) The long tube, or casing is meshed to detailed down the structure of it into lots of particles.
d) Modelling the casing geometry and input of required parameters such as axial force, material of the casing and tubing, standard gravititional acceleration and fixed support.
e) Running the simulations and variation of design and axial loads.
f) Data recording
g) Data analysis and consultation. Repeat the set up and/or simulations from step (d) to step (g) if necessary.
h) Validation of collected data with experimental data.
i) Report compilation.

3.2 Simulation Setup

The casing and tubing model is developed based on the parameters that has been used.

Table 1 : Constant Parameters

Parameters	Value
Casing Length	100 ft
Casing Inside Diameter	6.094 inch
Casing Outside Diamter	7 inch
Degree of Inclination	0^o, 15^o, 30^o, 45^o, 90^o
Casing Material	Structural Steel
Young's Modulus	30×10^6 psi
Temperature	2000^o F

3.2.1 Model Setup

This section describes the steps taken to set up the casing model for simulations. There are two (2) cases for this project, thus there will be two (2) diferent model. The first step involved in setting up the model is to design the casing with 7 inch diameter and 45^o degree of inclination from X axis. The total length of the casing is 100 ft as per standard requirement. The geometry is defined in Design Modeler.

For the second model, the design will be a directional casing on a directional well. The diameter will be the same as the first case.

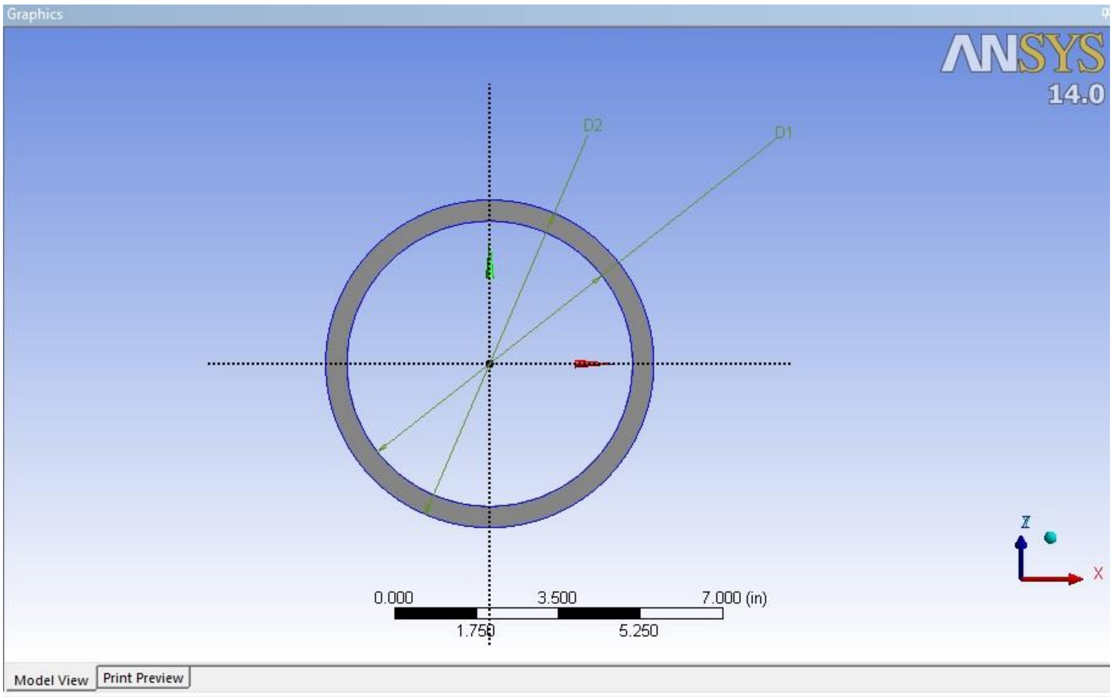

FIGURE 3.0 : Design Modeller in ANSYS 14

After the geometry of the casing is design with the diameter needed, the sketch is extruded into 3 dimensional object as show in figure below.

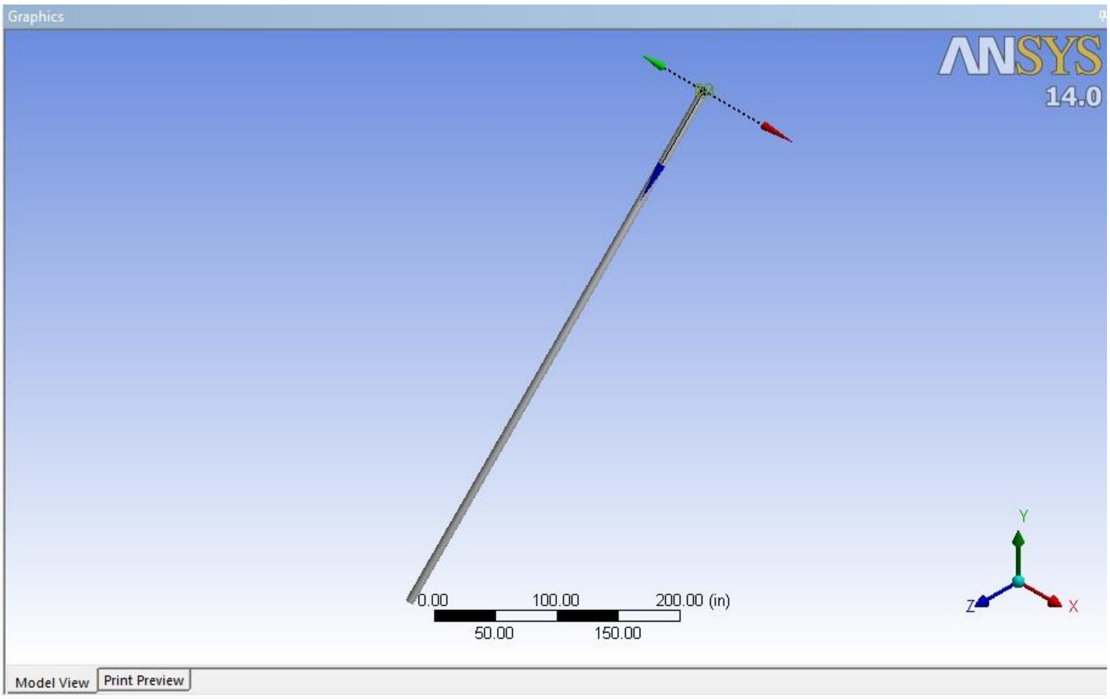

FIGURE 3.1 : Extruding the sketch into 3 dimensional object.

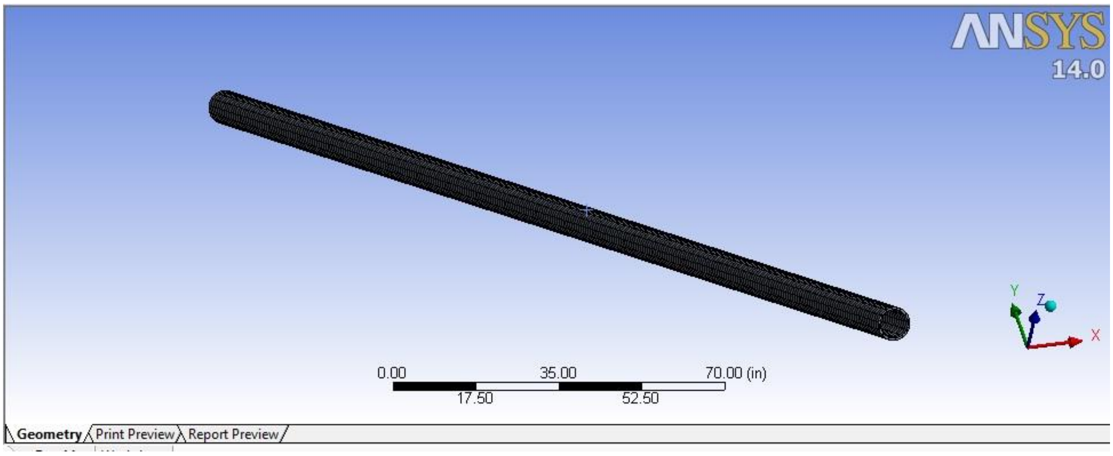

FIGURE 3.2 : Meshing phase of the model in ANSYS 14.

After the geometry is extruded, the model is discretized in meshing. The total numbers of element meshed in this project is xxxxx. Figure 3.3 above shows the casing meshing.

Next the set up of the simulation is defined first, by applying the axial force at both of the end of the casing along with other parameters such as gravititional acceleration, support and etc.

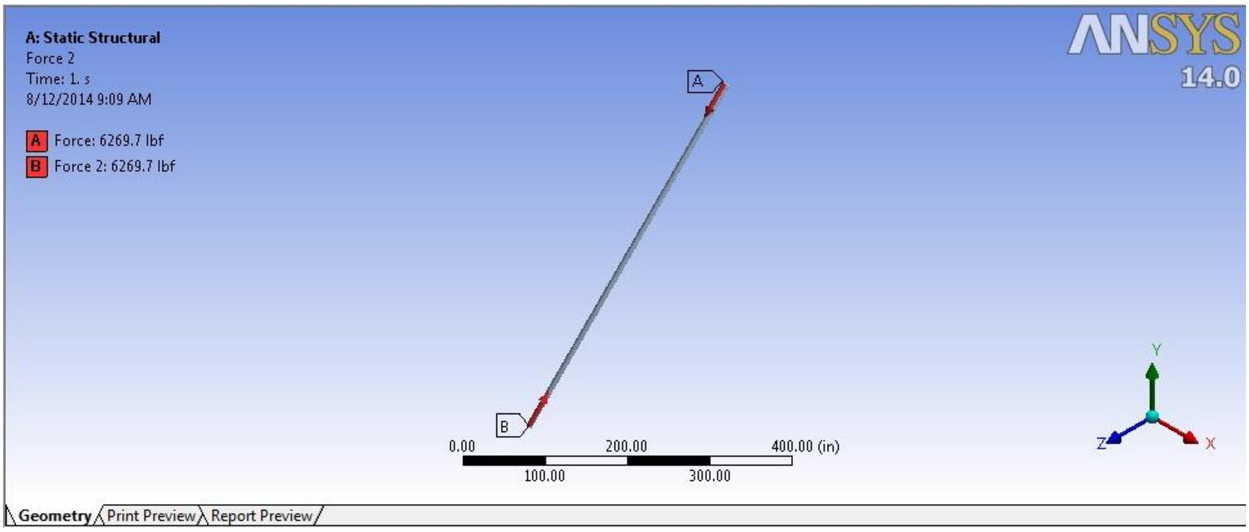

FIGURE 3.3 : Extruding the sketch into 3 dimensional object.

After the set up is complete, the simulation is ready for run. From ANSYS workbench, the APDL Mechanical Solver is initiated. Figure below shows the working panel for Mechanical Solver when the simulation has completed.

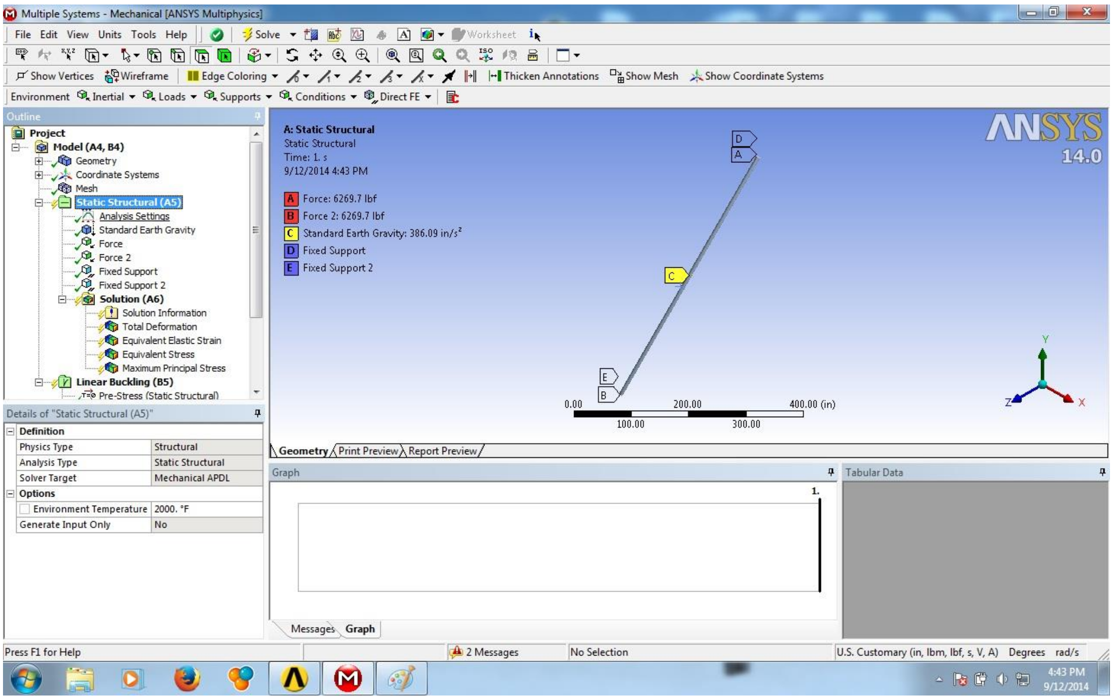

FIGURE 3.4 : Working Panel in Mechanical Solver

Finally the results are obtained from the Linear Buckling deformation results. Figure 3.6 shows the panel for Linear Buckling.

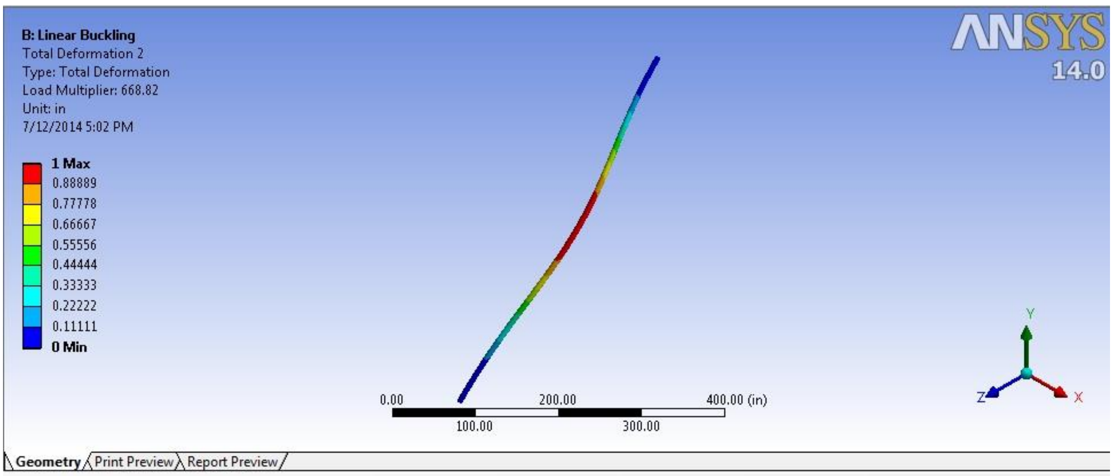

FIGURE 3.5 : Linear Buckling analysis component.

Flowchart below summarizes all the methodologies involved in the set up of the simulation model.

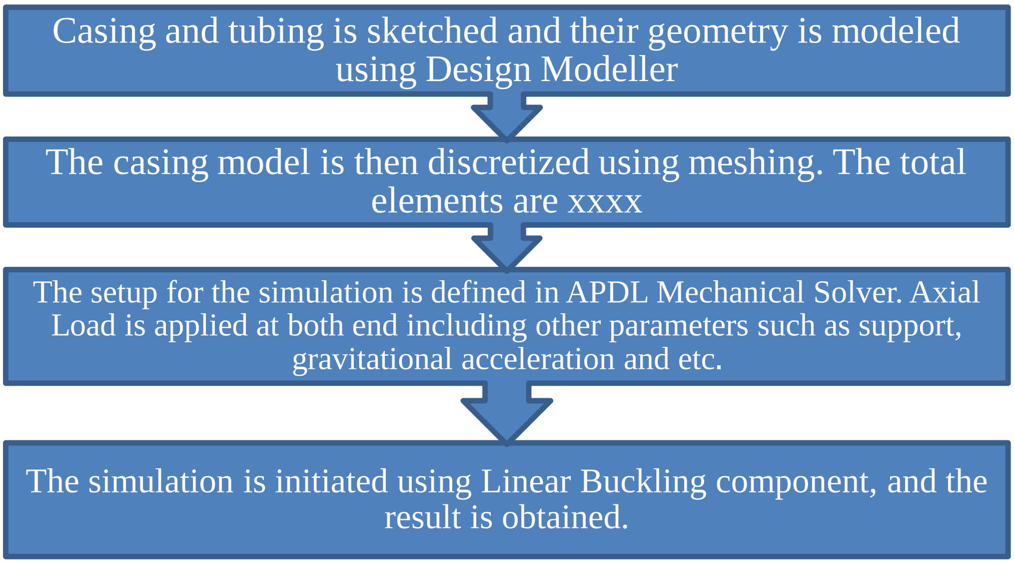

FIGURE 3.6 : Steps taken in ANSYS Linear Buckling for the project.

ANSYS Linear Buckling performance is limited by the host computer memory space. A finer meshing would take up a lot of computing power in solving the iterations to reach convergence. However, rough meshing would produce a decent results compare to finer meshing.

Thus, a proper meshing is required to yield a good result.

3.3 Project Key Milestone

The following flow chart is showing the project milestone with a targeted week to complete. Gantt Chart used as a work guidelines through the eight (8) months.

Table 2 : Project milestones

		2014							
	ACTIVITY	***MAY***	***JUN***	***JULY***	***AUG***	***SEPT***	***OCT***	***NOV***	***DIS***
1	**Literature Research**								
2	Study on Buckling Effects								
3	Study on stress distribution on object's surface.								
4	Prepare the parameters for simulations.								
5	Theory research and calculation.								
6	**Simulation Setup**								
7	Drawing and sketching the casing								
8	Modeling the casing								
9	Meshing the casing								
10	**Simulation Conduct**								
11	Applied parametes required on the casing: • Loads / Force • Fixed Support • Earth Gravity								
12	Data collection								
13	**Result Analysis**								
14	Minimum buckling force calculations								
15	Angle of Inclination vs Stress								
16	Angle of Inclination vs Shear Stress								
17	Angle of Inclination vs Strain								
18	**Report Writing**								

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Analysis on Effect of Angle of Inclination on Buckling Force

The two (2) main equation is used, to calculate the Buckling Force, which are equation 2 and equation 4 in Chapter 2.

The casing and tubing dimension used for the calculation in equation 3 is $2\ ^{7}/_{8}$ inch ID, 6.5 lbm/ft of tubing inside of casing with 7 inch ID, 32 lbm/ft. Other information is that radial clearance = r = 1.61 inch, moment of inertia = I = 1.611 $inch^4$ and Young's Modulus = 30 x 10^6 psi, and the tubing is submerged in 10-lbm/gal packer fluid with the assumption of no other pressures applied.

By using equation 3 in the Chapter 2, the calculation for the effective weight of tubing per unit length, w_e , is performed. From the equation, the value obtained will be **w_e = 0.463 lbm / inch**.

After that, the value of Paslay force for horizontal well is calculated, by using equation 2.0, and the result will be **F_p = 7456 lbf.**

Based on the asnwer above, the author can conclude that the axial buckling force, F_b must exceed 7500 lbf for the tubing to buckle.
In order to evaluate other angles of inclination, equation 4 is used for angles ranges from 0^o to 90^o . For 10^o of angle, the value obtained from equation 4 will be 3107 lbf (refer to Appendix 3).

∴ Therefore, if the well is 10^o deviated from the vertical, the buckling force is 3107 lbf, nearly half as much as the buckling force for horizontal well.

By using the same equation, we can evaluate other angles to determine the minimun force required before the tubing start to buckle. Table 3 was developed with this procedure.

Table 3 : Deviation Angles vs Minimum Buckling Force.

Deviation Angles, degree	Minimum lateral buckling Force, lbf
0	0
5	2201
10	3107
15	3793
30	5272
45	6269
90	7456

Based on

Table 3 is observed, and the results show the value of lateral buckling force required for the casing to start buckle. Noted that for 90^o of angle, the highest force is obtained with a value of 7456 lbf, while the lowest value of lateral buckling force obtained is when the angle of inclination is 0^o of angle.

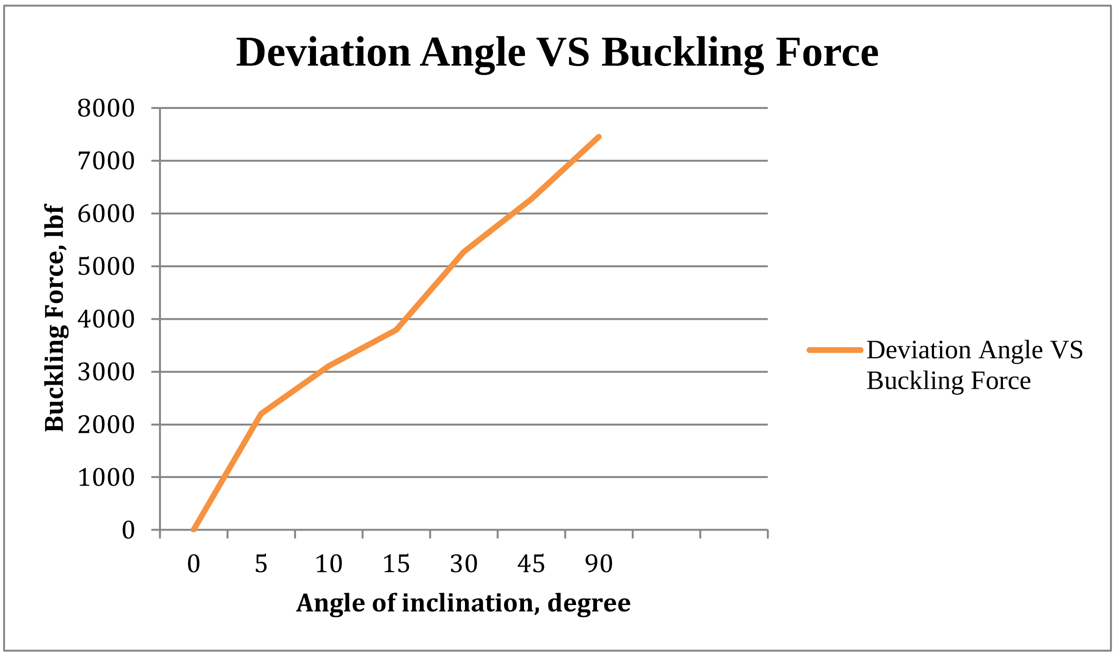

Figure 4.1 : Deviation Angles vs Minimum Lateral Buckling Force

From the graph plotted, it shows that as the degree of inclination is increasing towards the horizontal direction, the minimum lateral buckling force required for the casing to start buckle is also increased. This is due to formation support to the contact area of the casing. As the degree of inclination increases, the contact area of the casing on the formation also increase. As per say, horizontal well, will have a better support from the formation, compare to vertical well when any loads is applied, thus horizontal well will have lower tendency to buckle as its required a higher amount of force to start buckle.

It is also can relate all those tables and graph with the objectives of this research. For 30^o of inclination of the well, the lateral buckling force must be exceed 5272, for the tubing to start buckle, and for 90^o of inclination of the well (horizontal), the lateral buckling force must be exceed 7456 lbf for the tubing to buckle. As per say, the higher the degree of inclination of the well towards horizontal (90^o), the higher the axial load / force needed to buckle the tubing.

But, for the calculations to be accurate and valid, some conditions and assumptions need to be followed, such as :

- Only applied for tubing size 2 $^7/_8$ inch of inside diameter,
- Only applied for casing size 7 inch of inside diameter,
- Assumed tubing and casing submerge in the 10-lbm/gal of packer fluid
- Assumed no other pressures applied.

4.2 Analysis on Casing Deformation for Different Angle of Well Inclination

The simulation was performed using the ANSYS softwares, which loads are applied on the tubing and casing, while the structural deformation and stress distributions are studied. The simulations are divided into 5 cases with different angle of inclination while a few parameters are kept constant as show in the table below.

Table 4 : Constant parameters throughout the simulations

Parameters	**Value**
Axial Load	6269.7 lbf
Temperature	2000^{o} F
Gravitional Acceleration	386.09 in/s^2
Yield Strenght of Structural Steel	36,259.425 psi

By applying the parameters above, the buckling effect, shear stress and stress distribution can be predicted.

Figure below shows the predicted buckling deformation for different angle of inclination of the well.

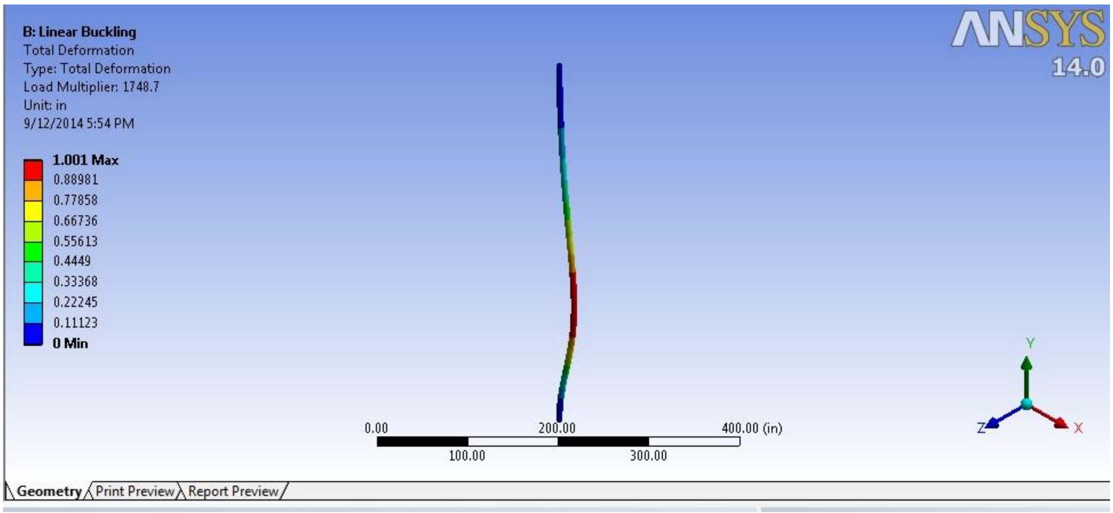

FIGURE 4.2 : Deformation on 0^o of inclination

For 0^o angle, the buckling is observed to be around the bottom part of the casing. The red area indicate the maximum deformation experienced on the casing while the blue area indicate the minimum deformation or buckling experienced on the casing. This kind of buckling post-configuration is due to gravititional attraction which directed downwards. Thus, the loads exerted from the top part of the casing is higher than the bottom part, resulted in imbalance of the force or loads, ($F_{top} > F_{Bottom}$). As a result, the buckling happened near the bottom part of the casing.

The result also shows that both top and bottom part of the casing is experienced the minimum deformation.

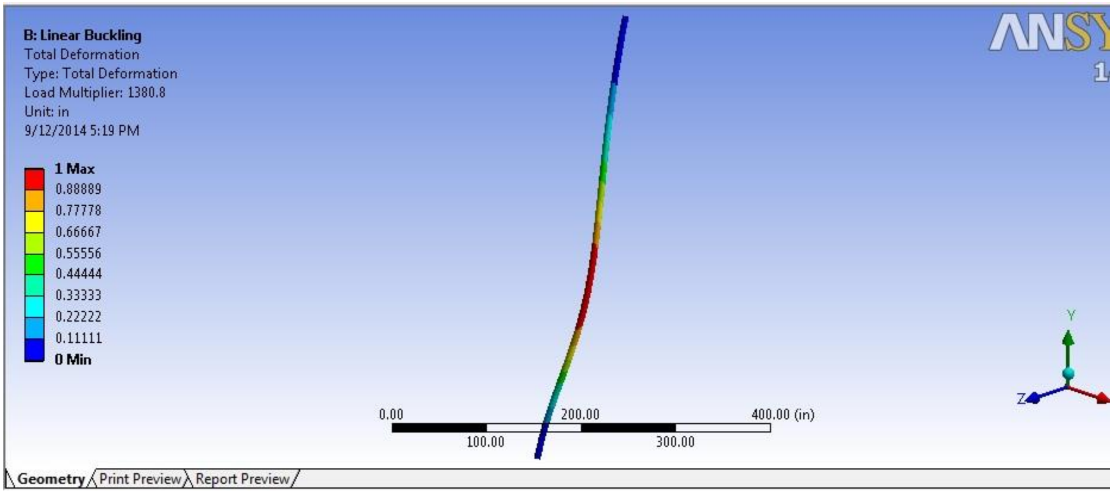

FIGURE 4.3 : Deformation on 15^o of inclination

For 15^o angle of inclination of the well, the post-configuration is observed and looks likely the same configuration as 0^o angle of inclination. The deformation is experienced near the bottom part of the casing due to imbalance force exerted on the top part of the casing and bottom part of the casing.

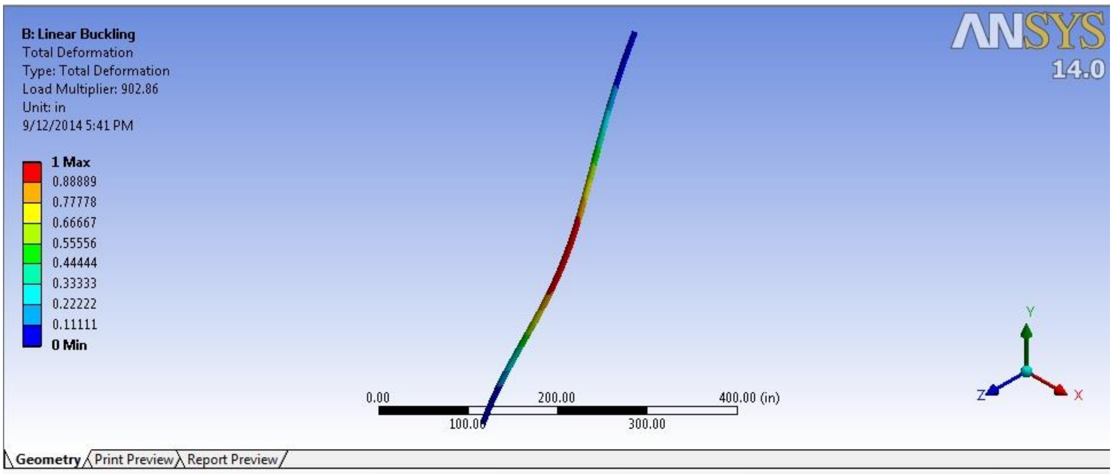

FIGURE 4.4 : Deformation on 30^o of inclination

For 30^o angle of inclination of the well, the post-configuration is observed to be experienced mostly in the middle part of the casing. This results shows the force is more balance compared to previous angle, 0^o and 15^o . From the simulation, it is also can be observed that the gravitional attraction is not acting along the casing direction anymore. Therefore, the force between the top and the bottom part of the casing is the same, resulted deformation on the middle part, and in the direction of the gravititional attraction.

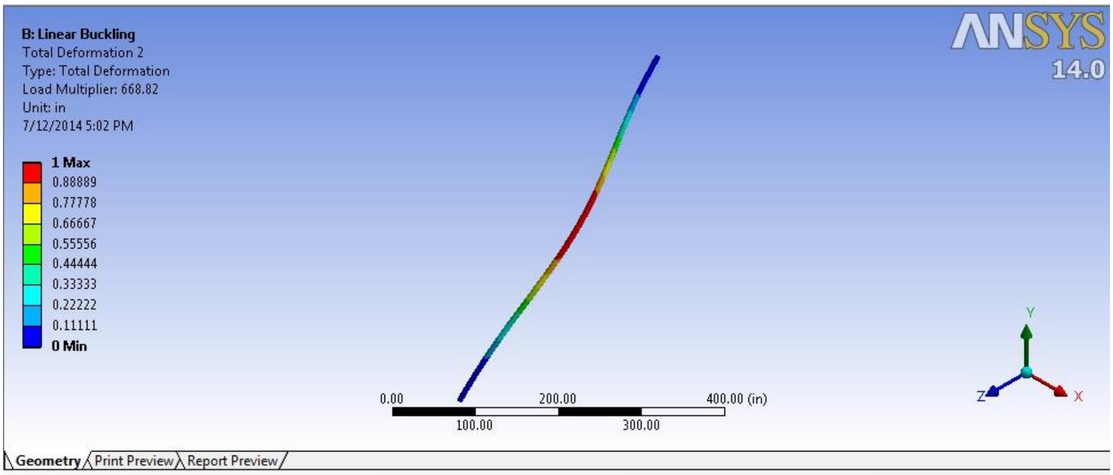

FIGURE 4.5 : Deformation on 45º of inclination

For 45º angle of inclination of the well, the post-configuration is almost the same as 30º post-configuration. The deformation is experienced mostly in the middle part of the casing. The minimum deformation is exerted at both top and bottom part of the casing. This is because at both top and bottom part of the casing, the direction of the force is still the same, does not experienced any opposite of force or the opposite force exerted is minimum, compare to the middle part of the casing.

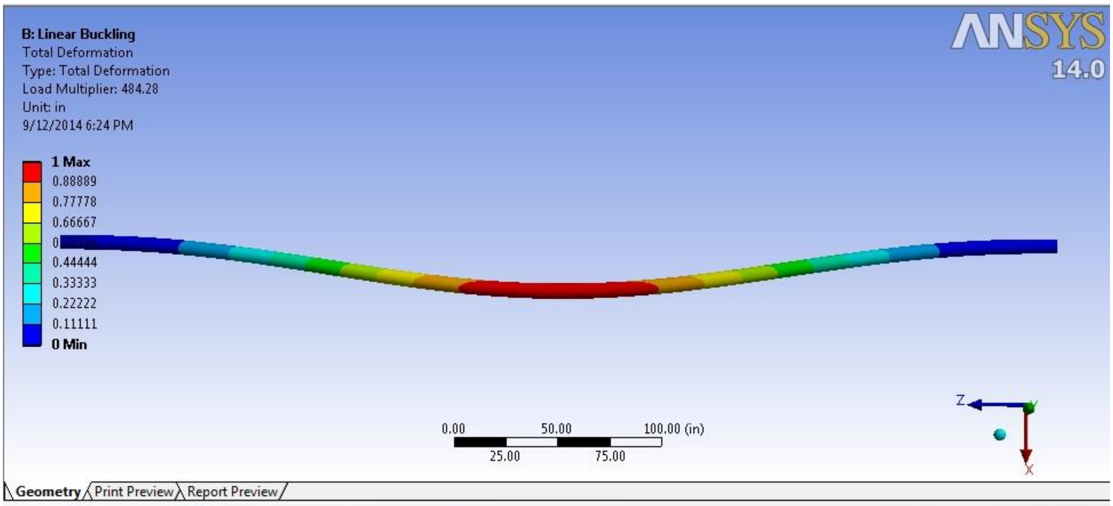

FIGURE 4.6 : Deformation on 90º of inclination

For 90º angle of inclination of the well, the casing is in horizontal arrangement. The post-configuration is still the same as previous angle. But the difference was horizontal arrangement of the casing will required higher force to experienced this kind of deformation.

As a summary, the simulations show the difference buckling configuration and deformation for each angle of inclination. For vertical arrangement of the casing (0^o of inclination) in Figure 4.2, the deformation of the casing can be seen clearly but its more towards the bottom part of the casing.

The red area represents the highest deformation experienced by the surface of the casing, and the blue area indicated the lowest deformation experienced by the surface of the casing. at both end of the casing, the deformation is minimum, but maximum near at the bottom of the casing. This might due to standard earth gravititional acceleration which directed downwards, thus its affected the direction of the deformation of the casing. It is also happened for 15^o of inclination where the deformation is experienced near to the bottom of the casing.

As the angle is approaching to horizontal direction, the defomartion is experienced mostly at the middle part of the casing. It can be seen clearly in Figure 4.4, Figure 4.5 and Figure 4.6, where the read area are distributed at the middle surface of the casing, and minimum deformation is at both end of the casing. Again, the difference in deformation pattern are likely due to earth gravity, which is constantly point downward, -Y axis. Thus, as the angle is increasing, the contact area that exerted the gravititional force is decreasing, and therefore the deformation pattern is changing.

4.3 Analysis on Stress Distribution with Different Angle of Well Inclination

Figure below shows the predicted stress distribution for different angle of inclination of the well.

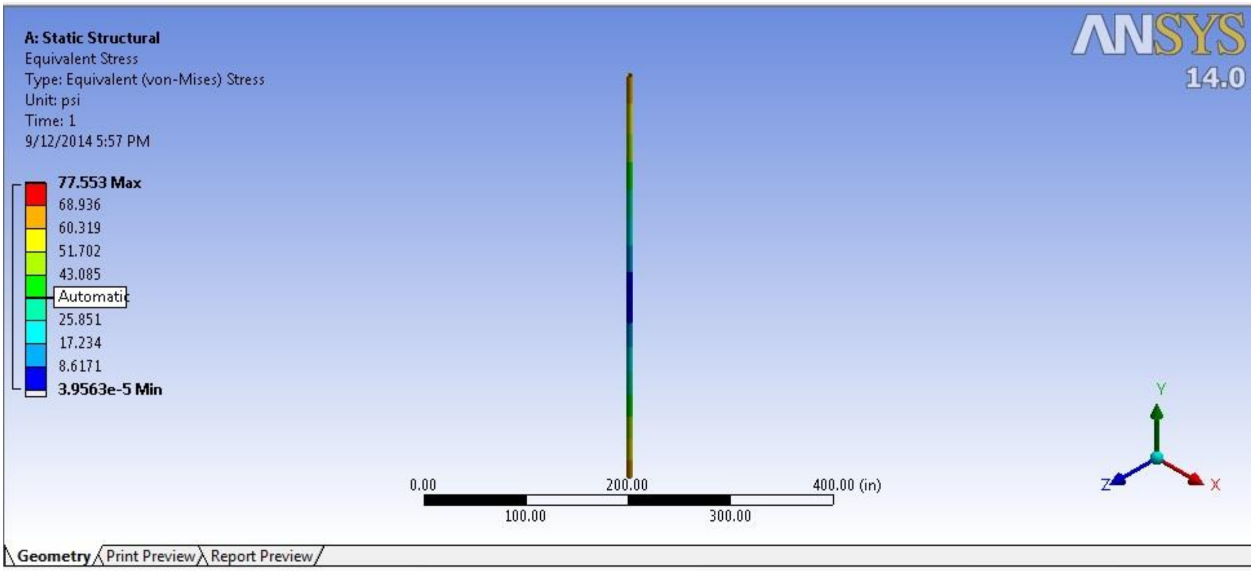

FIGURE 4.7 : Von Mises stress on 0º of inclination

Based on the Figure 4.7 above, the stress distribution are even, but more focusing on both end of the casing as the well is in vertical arrangement (0º of inclination). The red area represents the highest load exerted on the casing which located at the point where the loads are applied, and the blue area indicated the lowest stress exerted on the casing which is mostly in the middle part.

The maximum stress exerted is 77.53 psi and the lowest is 0.000004 psi.

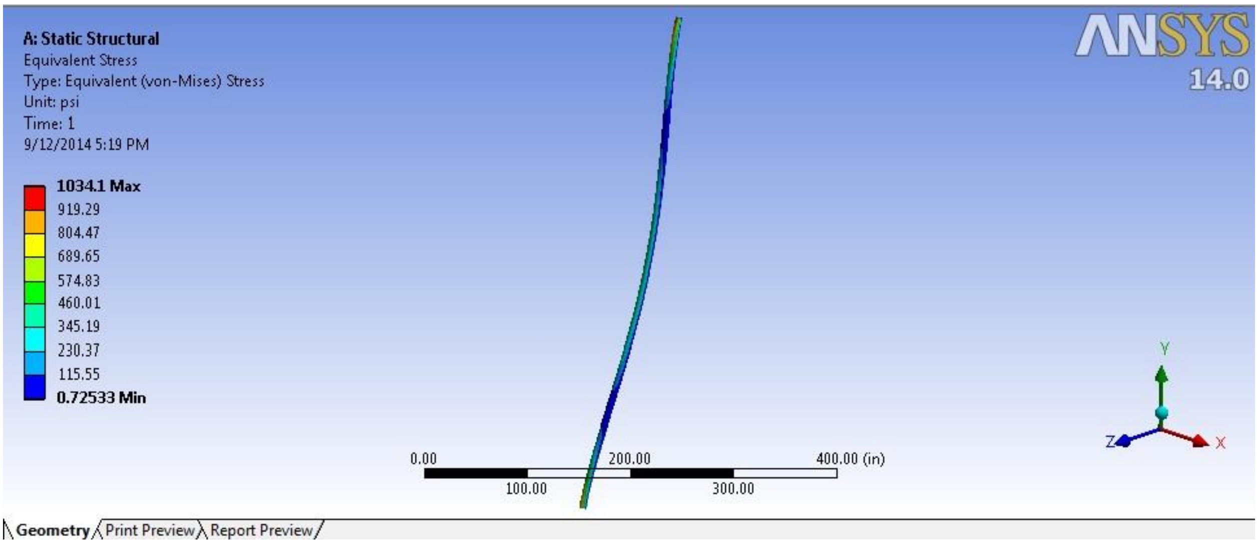

FIGURE 4.8 : Von Mises stress on 15^o of inclination

For 15^o angle of inclination of the well, the Von Mises stress distribution is totally different with 0^o angle of inclination of the well. In 0^o angle of inclination, the lowest stress exerted is at the middle part of the casing, but for 15^o angle of inclination, the middle part of the casing is not the minimum stress exerted. The minimum stress is now located as shown in above figures. The maximum value of Von Mises stress is also higher compared to previous angle which is 1034.1 psi. The minimum stress exerted is 0.72533 psi. The value of stress in the middle part of casing is around 230.37 psi.

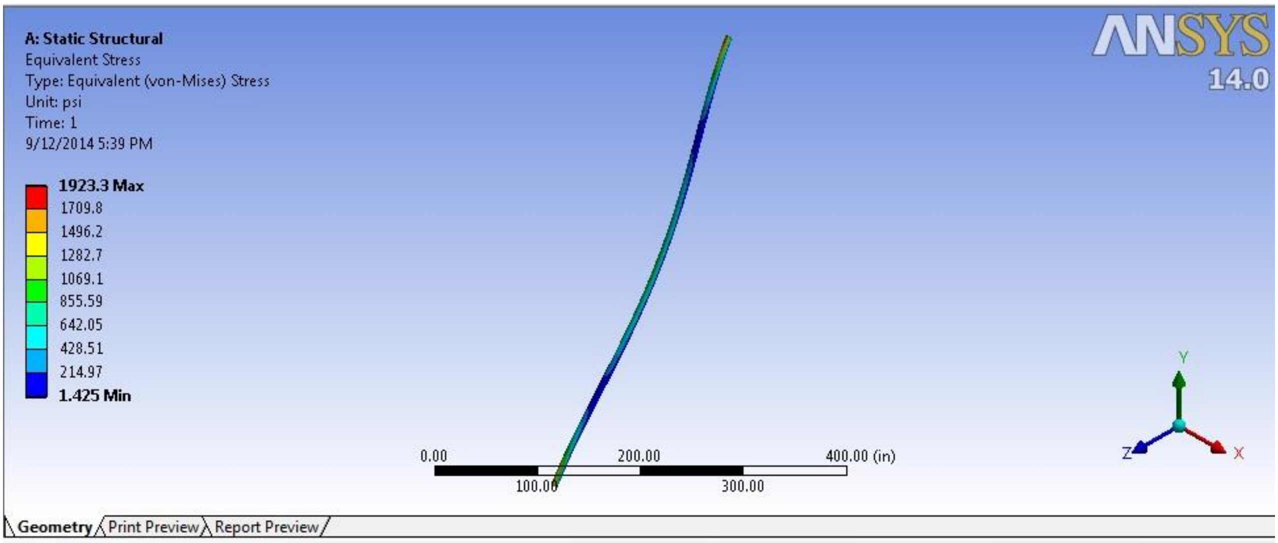

FIGURE 4.9 : Von Mises stress on 30º of inclination

For 30º angle of inclination of the well, the Von Mises stress distribution is the same as 15º angle of inclination of the well. In the above figure, the maximum value of Von Mises stress is also higher compared to previous angle which is 1923.3 psi. The minimum stress exerted is 1.425 psi. The value of stress in the middle part of casing is ranged around 428.51 – 642.05 psi.

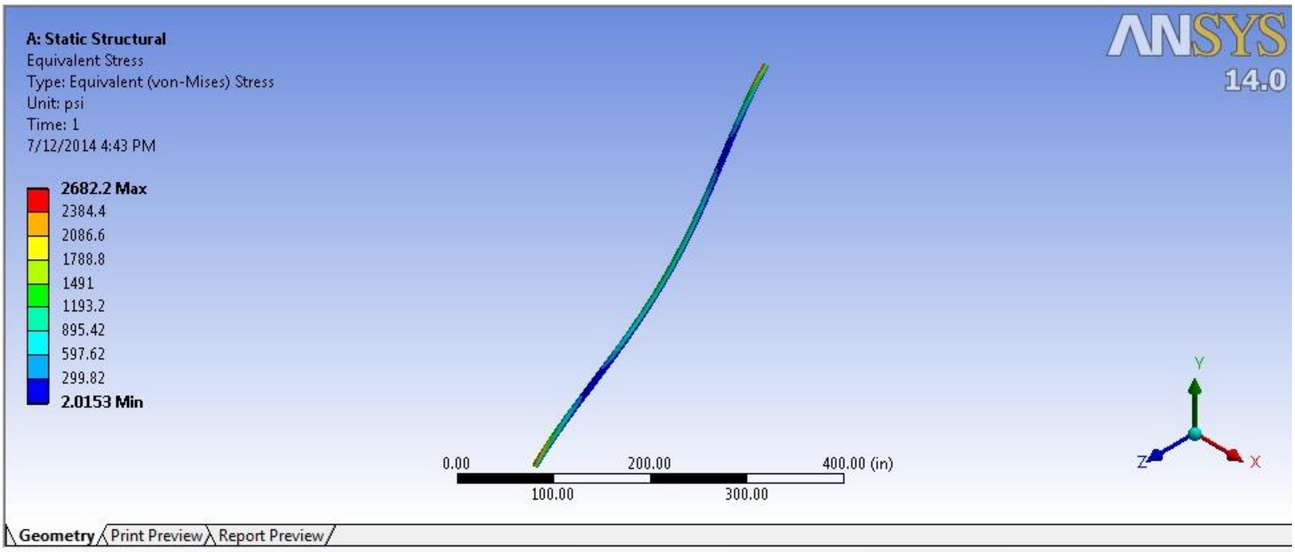

FIGURE 4.10 : Von Mises stress on 45º of inclination

For 45º angle of inclination of the well, the Von Mises stress distribution is also the same as 0º,15º,30º angle of inclination of the well. In the above figure, the maximum value of Von Mises stress is also higher compared to previous angle which is 2682.2 psi. The minimum stress exerted is 2.0153 psi. The value of stress in the middle part of casing is ranged around 597.42 – 895.42 psi.

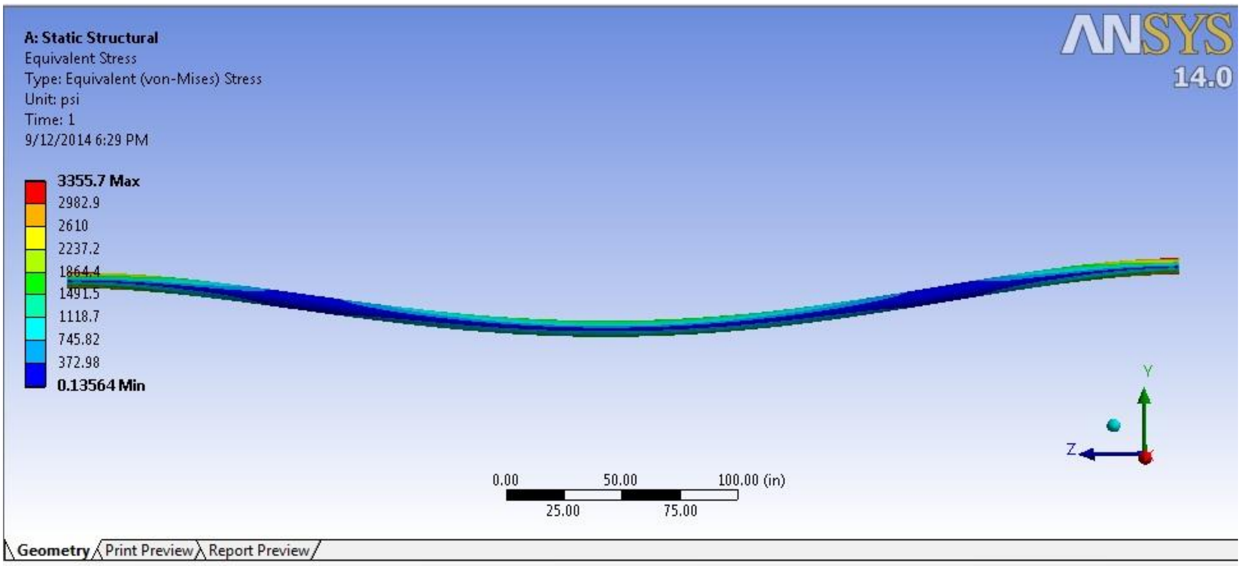

FIGURE 4.11 : Von Mises stress on 90^o of inclination

For 45^o angle of inclination of the well, the Von Mises stress distribution is also the same as 0^o,15^o, 30^o,45^o angle of inclination of the well. In the above figure, the maximum value of Von Mises stress is also higher compared to previous angle which is 3355.7 psi. The minimum stress exerted is 0.13564 psi. The value of stress in the middle part of casing is ranged around 745.82 – 1118.7 psi.

As for summary, the stress distribution are more focusing on both end of the casing as the well is in vertical arrangement (0^o of inclination). The red area represents the highest load exerted on the casing which located at the point where the loads are applied, and the blue area indicated the lowest stress exerted on the casing which is mostly in the middle part. As the well is started to increase its angle of inclination, the distribution of the stress on the casing is changing. The lowest exerted stress area on the casing are not in the middle anymore while the highest exerted stress are maintain a both end of the casing, where the loads are applied. But for all the cases, the stress distribution is the same except for vertical arrangement.

For vertical arrangement, the maximum stress exerted area is wider at both end of the casing, and the minimum stress exerted is in the middle part. Other than that, the stress distribution is the same. Most of casing surface exerting minimum stress and force, but at both end of the casing are exerting maximum stress and force.

4.4 Analysis on Von Mises Stress

The simulations also predicted the maximum Von Mises stress and shear stress behavior as the angle of inclination is increasing as tabulated below :

Table 5 : Maximum stress and shear stress on different angle of inclination

Angle of Inclination, θ	Von Mises Stress, psi	Shear Stress, psi
0^o	77.53	14.3
15^o	1034.1	104.9
30^o	1923.3	212.39
45^o	2682.2	342.94
90^o	3355.7	362.48

Based on the Table 5 above, the data can be plotted as below:

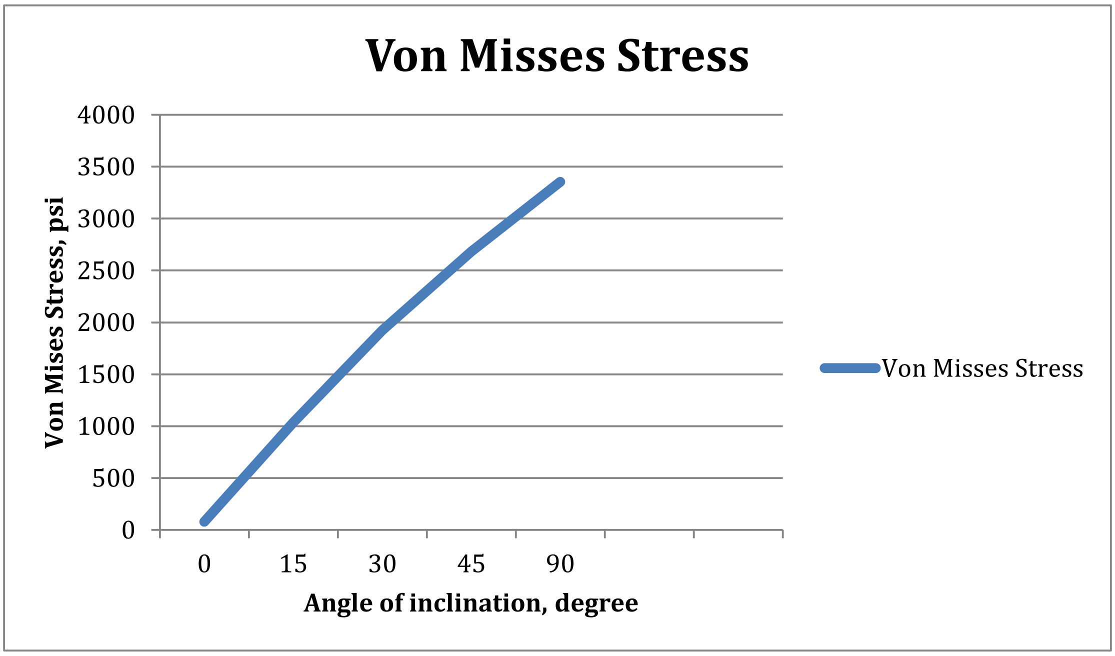

Figure 4.12 : Deviation Angles vs Von Mises Stress

Figure 4.12 shows that the Von Mises stress is increased as the angle of the inclination increase. Von Mises is defined as the measurement for designers to check whether their design can withstand a given load condition, which in this case is 6000lbf.

The maximum Von Mises stress is achieved at which the well is in horizontal arrangement with a value of 3355.7 psi. Nevertheless, the stress is at maximum towards the both end of the casing, and the value is less than the steel yield strength (36,259 psi) . Thus, the design can withstand with such loads and the casing will not be a failure with such conditions.

The design of the casing should focusing more on both ends of the casing, as they exerted the highest amount of force and stress. Besides, the maximum value of the stress induced in the material of the casing must be kept lower than its strength.

4.5 Analysis on Shear Stress

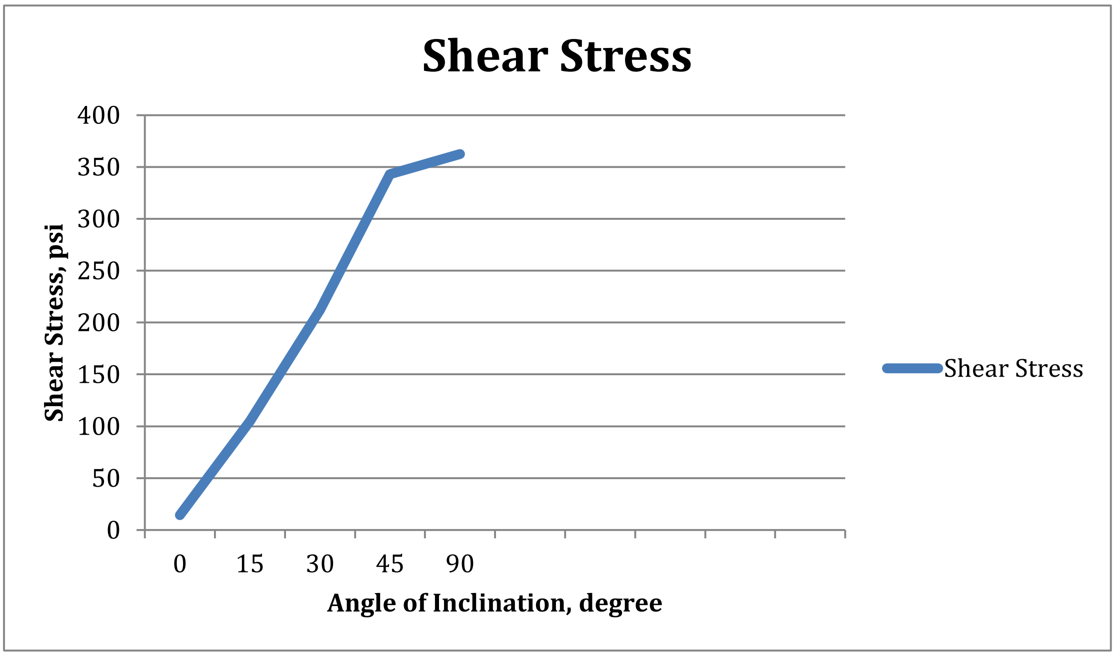

Figure 4.13 : Deviation Angles vs Shear Stress

Graph 3 shows the relationship between the shear stress and the deviation angle of the well. Shear stress is defined as a force or stress that is parallel to the surface of the material. As the angle approaching to 45 degree of inclination, the shear stress is increased rapidly. But the graph also shows that the shear stress difference between 45 degree and 90 degree of inclination is small.

The shear stress of the formation is acting horizontally, paralled to the surface of the earth. Since the casing is in vertical arrangement, the shear rate acting upon the casing surface is minimum, due to direction of shear stress is in perpendicular towards the casing surface. As the angle increase approaching 90^o, the shear stress that is parallel to the surface of the casing is increasing, and resulting in maximum shear stress at the horizontal arrangement of the casing.

CHAPTER 5

CONCLUSION & RECOMMENDATION

The objectives of this study is succesfully achieved. This project aims to analyse the buckling effect on the inclined well in terms of stress distribution, and type of deformation by using ANSYS 14 software. Besides, the objective of this study is also to determine the minimum force required for thecasing to start buckle, using theory calculations. Based on the results collected, the following conclusion can be made:

1). ANSYS 14 has succesfully modelled the casing, and applied the axial loads as per required.
2). Von Mises stress is maximum in the horizontal arrangement (90^o of inclination)
3). Von Misis stress is also increasing as the angle of inclination of the well approaching to horizontal arrangement.
4). Shear stress is maximum in the horizontal arrangement (90^o of inclination).
5). The effect of shear stress towards the casing is less as the angle is more than 45^o due to the direction of the shear stress which is horizontally.
6). It is also found some results on the effect of degree of inclination of the the wells on the tubing and casing buckling theoritically. Basically, the higher the inclination of the wells towards horizontal angles, (90^o), the higher the minimum required force for the tubing and casing to start buckle.

From the study, it has identified several improvements to be recommended in buckling analysis. The reccomendations for further studies as follows:

1). This study is only focused on type of resulting stress on the casing. Further studies can be conducted on type of buckling in the inclined well which either sinosidual or helical buckling.
2). This study can be focused on effect of temperature on the casing buckling.
3). The study can be involved with wider range of angle $0^o < \theta < 180^o$, thus a lot of more information can be gathered and analysed.
4). The studies can be conducted in terms of non – linear buckling instead of linear buckling.

REFERENCES

[1] Adams, A. J., & MacEachran, A. (1994). Impact on casing design of thermal expansion of fluids in confined annuli. *SPE Drilling & Completion*, *9*(03), 210-216.

[2] Chen, Y. C., Lin, Y. H., & Cheatham, J. B. (1990). Tubing and Casing Buckling in Horizontal Wells (includes associated papers 21257 and 21308). *Journal of Petroleum Technology*, *42*(02), 140-191.

[3] Clegg, J. D. (1971). Casing Failure Study-Cedar Creek Anticline. *Journal of Petroleum Technology*, *23*(06), 676-684.

[4] Dawson, R. (1984). Drill pipe buckling in inclined holes. *Journal of Petroleum Technology*, *36*(10), 1-734.

[5] Hajianmaleki, M., & Daily, J. S. (2014). Advances in critical buckling load assessment for tubulars inside wellbores. *Journal of Petroleum Science and Engineering*, *116*, 136-144.

[6] He, X., & Kyllingstad, A. (1995). Helical buckling and lock-up conditions for coiled tubing in curved wells. *SPE Drilling & Completion*, *10*(01), 10-15.

[7] Kaldal, G. S., Jónsson, M. Þ., Pálsson, H., & Karlsdóttir, S. N. Thermal (2012). Structural Analysis of the Casing in a High Temperature Geothermal Well During Discharge. *Thirty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, 2012.*

[8] Lubinski, A., & Althouse, W. S. (1962). Helical buckling of tubing sealed in packers. *Journal of Petroleum Technology*, *14*(06), 655-670.

[9] Mitchell, R. F. (2012, January). Buckling of Tubing Inside Casing. In *IADC/SPE Drilling Conference and Exhibition*. Society of Petroleum Engineers.

[10] Mitchell, R. F. (2008). Tubing Buckling--The State of the Art. *SPE Drilling & Completion*, *23*(04), 361-370.

[11] Peng, S., Fu, J., & Zhang, J. (2007). Borehole casing failure analysis in unconsolidated formations: A case study. *Journal of Petroleum Science and Engineering*, *59*(3), 226-238.

[12] Suman Jr, G. O., Klementich, E. F., & Broussard, L. P. (1970). Measurement of casing buckling in producing intervals. *Journal of Petroleum Technology*, *22*(03), 255-266.

[13] Texter, H. G. (1955). Oil-well casing and tubing troubles. *Drilling and Production Practice Handbook.*

APPENDICES

Appendix 1 - Effective weight per unit length calculations

w_e = 6.5 lbm/ft + (4.68 inch^2)(0.052 psi / ft / lbm / gal)(10.0 lbm / gal) –

(6.49 inch^2)(0.052psi / ft / lbm / gal)(10.0 lbm / gal)

w_e = 5.56 lbm/ft

$\therefore$ **w_e = 0.463 lbm / inch.**

Appendix 2 -Paslay force for horizontal well calculations

$$F_p = \sqrt{\frac{4(0.463)(30 \times 10^6)(1.611)}{1.611}}$$

$\therefore$ **F_p = 7456 lbf**

Appendix 3 - Buckling force for different angle of inclination

For 10^o angle;

F(10^o) = 7456 lbf x (sin 10)$^{1/2}$

$\therefore$**F(10^o) = 3107 lbf**

Appendix 4 – Project Gantt Chart.

Activities	Weeks													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Theory Research, Findings and Calculations														
Introduction and familiarization on related softwares: • ANSYS • Catia														
Performed theory calculations and softwares														
Progress Report submission														
Pre - Sedex														
Final Report Preparation														
Viva and Technical Paper submission														