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ABSTRACT

With aging oil fields, the Norwegian petroleum authorities are focusing on Plug and Abandonment (P&A) plans. Therefore efforts are being made, by relevant authorities, to improve standards and procedures for the P&A operations. Regulations for UK part of the North Sea define the P&A operation plans and execution phases in a way that may help improve the standards on the Norwegian Continental Shelf.

Halliburton like its competitors is focusing on the development of tool that would allow safe and efficient P&A operations. For using it efficiently with coiled tubing, accurate positioning of the tool in both axial and radial directions is important.

Finite Element Analysis (FEA) which is based on numerical problem solving technique is used for positioning of the tool down hole at the end of coiled tubing. Ansys 13.0(academic version) and Autodesk Inventor (academic version) have been used to model and analyze the case. With the results presented in the subsequent chapters, an analytical approach for determining the position has also been presented that can form basis for further development.

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NOMENCLATURE

A	cross sectional area
D	diameter of pipe
E	Young's modulus
EI	Bending stiffness
I	moment of inertia
J	polar moment of inertia
g	acceleration due to gravity
r	radial clearance, radius of pipe
T	torque
F	applied force
w	weight per unit length
α	inclination
β	azimuth
ρ	density
τ	torque
P&A	plug and abandonment
DL	dog leg angle
TF	tool face angle

CHAPTER 1 INTRODUCTION

This thesis presents an overview of requirements and technologies currently used in the industry for performing plug and abandonment (P&A) operations. Plug and abandonment is last activity in a well life cycle. To execute this operation, the depth and position placement of the plug needs to be determined that would ensure efficient and safe plug and abandonment of the well.

1.1 Background

An estimated 6500 platforms exist worldwide today. Besides thousands of well offshore, tens of thousands of well onshore add to the tally of the wells that need to be abandoned due to the ageing fields around the world. (D liversidge 2008).

Operations for offshore abandonment can be divided into 3 main categories:

- P&A from a fixed platform
- P&A operations from a support vessel
- P&A from a floating installation

Whereas operations onshore can be divided into 2 broad divisions:

- P&A using rig
- Rig less P&A operations

The toughest aspect of P&A activity in the north sea is subsea production wells, as this type of operations enhances the difficulties that operators face when evolving the strategy for P&A. The cost of P&A operation for a subsea production well is multiple times that of P&A for exploration and appraisal well.

From the start of petroleum activities in the Norwegian continental shelf to this date, approximately 5200 wells have been drilled. However no reliable figure has been established by the Norwegian petroleum directorate (NPD) (as of June 2013) that can give an account of the number of wells that have been abandoned. A conservative figure estimates the number of wells to be plug and abandoned at around 3000 wells. Even with use of current technology and efficient operations, the activity time plan estimates the time for plugging activities to be in decades.(Ferg 2013)

As of today, among various techniques being considered in the industry for managing P&A operations; is the use of coiled tubing using a tool developed by Halliburton. The technique utilizes the concept of abrasive cutting of the casing down hole instead of traditional milling operation that subsequently complicates safe operations due to creation of tons of swarf in the process.

1.2 Problem definition

Plug setting depth is an important parameter for P&A operation. At setting depth, the area of the well bore needs to be cleared of all debris/material that can result in inefficient bonding of plug material and wellbore. Traditionally, milling, a mechanical cutting process, is used to remove casing/tubing at a determined depth.

A tool developed by Halliburton employs jetting nozzles for abrasive cutting of the casing down hole. This tool needs to make two (top and bottom) radial cuts along the circumference of the casing at the specified depths, which define the interval of the plug. Within this interval, cuts need to be made along the length of the casing/tubing. This would eventually help cut casing in pieces of long strips from the well bore, that would fall inside the well.

Tool positioning is therefore important when using this tool with coiled tubing. The well path, the fluids inside the well, the effective forces, temperature, pressure and friction, effect the position of the tool at the end of the coiled tube thousands of meters down hole.

In this work, a basic approach has been presented to analyze how the well path, the pulling/pushing forces including the friction effect, stresses in tubing, the temperature and buckling effects the end position of the tool.

1.3 Objective and scope

The primary objectives of this thesis are as follows:

1. Describe a model that may help in defining the exact axial and radial position of the tool down hole considering the expertise and data/knowledge available.
2. Stating and arguing the assumptions made with regards to the proposed model.

3. Proposing an alternate to obtain accurate axial and radial positioning while working with the tool down hole.

Whereas the secondary objective for this work would be:

1. Understanding the scope of Plug and Abandonment operations
2. Overview of the Regulations and Standards defined by authorities for P&A

The scope of the work is limited in analysis of the problem with Ansys 13.0 (academic version available the University of Stavanger (UiS) campus) and hand calculations . The work is limited by expertise and processing capacity available for modeling the environment completely using this FEA software; as this software is essentially a tool for mechanical engineering problem solving.

CHAPTER 2 REGULATIONS/ STANDARDS FOR P&A

As part of secondary objectives of this thesis work, this chapter deals with the basics of Plug and Abandonment (P&A) operations and the way they are implemented.

2.1 Framework Hierarchy for Norwegian Petroleum Activity

The requirement and standards to be followed for executing the plug and abandonment operations are set by the concerned local regulating authorities. In case of Norwegian continental shelf, Norwegian Petroleum Directorate (NPD) supervises the operations and activities offshore, in accordance with the NORSOK standards; in particular, the NORSOK D-010 requirements for P&A operations.

The framework for all the petroleum activities on the Norwegian continental shelf are based on the disposition of the constitution of Norway that is followed by acts, regulations, guidelines and finally the standards (NORSOK).

2.2 NORSOK D-010

NORSOK standards provide guidelines for petroleum activities and set minimum requirements for the solutions/equipment/methods to be used in well. It however leaves it open to the operating companies to choose the solutions that meet a particular case requirement. Moreover, deviations from the standard are also possible in case the new solution is equivalent or better compared to the requirement.

As defined in a document issued as "An Introduction to Well Integrity", according to NORSOK D-010,: "there shall be two well barriers available during all well activities and operations, including suspended or abandoned well where a pressure differential exists that may cause uncontrolled outflow from the borehole/well to the external environment."(Hans-Emil Bensnes Torbergsen December 2012)

Permanent plug and abandonment operations are carried out usually after the end of production life of a well when it has been established that there is insufficient potential of hydrocarbons to be produced, or the well has been drained off after years of production operations. Well control equipment from the top of the well are removed and thus operations in this case are performed with eternal perspective so that well integrity is intact and no unwanted travel of hydrocarbon occurs from the reservoir zone to the environment or even to a nearby permeable zone.

For permanent P&A, as per NORSOK D-010 standards:

- There should be no obstruction related to drilling and well activities left behind on the sea bed
- Well head and the following casings should be removed such that no parts of the well protrudes the seabed
- The cutting depth for the consequent casings should be 5m below the sea bed.

Suspension or temporary plug and abandonment of a well is done when activities, during the development phase of the well, are suspended without removing the well control equipment from the well. This marks the resumption of the activities after a specified time period. Reasons for suspension/ temporary abandonment of well may include wait on weather or waiting for equipment that is not available on site for carrying out the intended operation.

Well barriers are used during the drilling, production, intervention and plug and abandonment phases of the life cycle of the well to prevent leakages of the hydrocarbons from a potential reservoir zone. It is understood from NORSOK D-010 standards that the primary well barrier is the closest to the potentially pressurized hydrocarbon zone; whereas the secondary well barrier is a second defense line in case the primary barrier fails. Among several other requirements for the well barriers are the following two:

i. The position/status of the barriers shall be known at all times
ii. In the event of barrier failure; no activities for any other purposes than reestablishing two barriers shall be carried out in the well.

Illustration of these well barriers/well barrier elements (primary in blue and secondary in red) is done using well barrier schematics which form an important tool for reliability and risk assessment of the well for ensuring integrity of the well.

2.2.1 Requirements for Permanent Well Barriers:

According to NORSOK D-010 standards a permanent well barrier should have the following properties;

- Impermeable
- Long term integrity
- Non-shrinking
- Ductile
- Corrosion resistant
- Wetting

Besides the above mentioned mechanical characteristics, a steel tubular is not acceptable as a permanent well barrier element unless it is supported by cement or similar plugging material having required functional properties. Moreover elastomeric seals used as sealing components in various well barrier elements are not acceptable for permanent well barrier elements.(Standards Norway; OLF 2004)

2.2.2 Types Of Well Barriers

Various types of well barriers used for plugging operations are:

- Primary well barrier
- Secondary well barrier
- Well barrier between reservoirs
- Open hole to surface well barrier

In case where there are more than two reservoir zones in a well, a secondary well barrier for one reservoir formation may act as a primary well barrier for a shallower formation provided it meets the requirements as shown in figure 1.

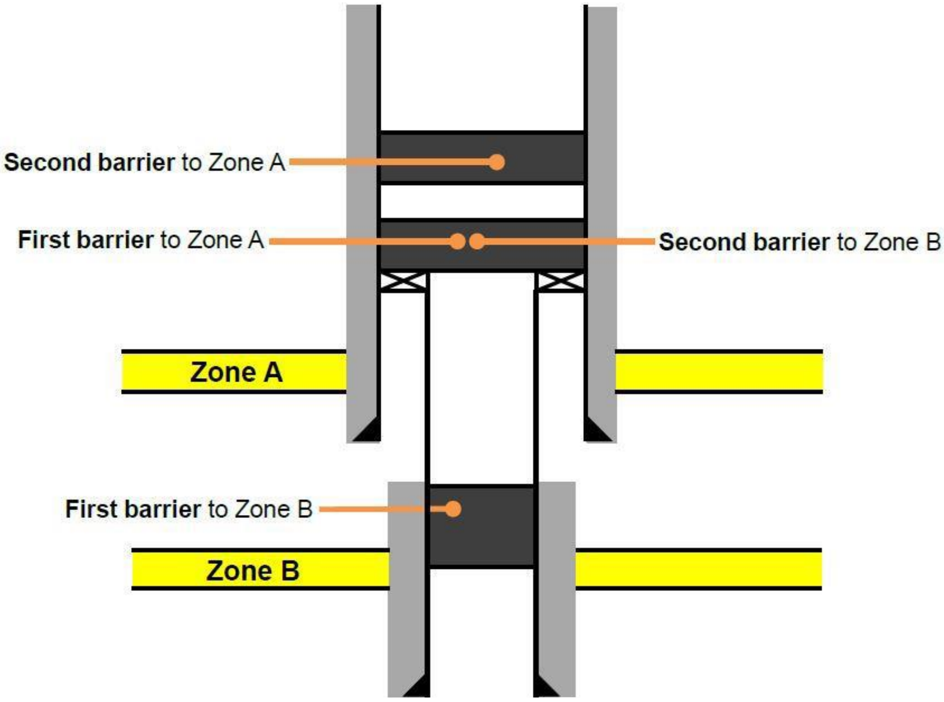

Figure 1 Primary and secondary barrier configuration for two reservoir zones

2.2.3 Positioning Of Well Barriers

To ensure reliable plug and abandonment operation, the well barriers should be installed as close to the source of potential hydrocarbons as possible and it should cover all possible leak paths. More importantly it shall extend across the full cross-sections of the well and include all annuli between casing string / tubing as shown in figure 2.

The general requirements for both the primary and secondary well barriers, is the same i.e. isolation of formation, pressures and fluids. (Khalifeh 2013) However the choice of barrier elements to be used for these purposes is different depending upon whether the well is abandoned permanently or the activities need to be resumed after a specified time period.

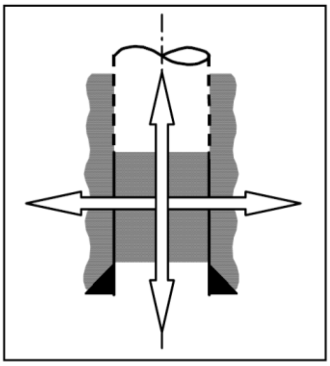

Figure 2 Barrier extending axially and radially

2.2.4 Leak Testing Of Well Barrier

According to the requirements set by NORSOK D-010 the status of the well barrier needs to be known at all times. So a requirement has been establish that would verify whether the barrier is in good shape and is able to perform its intended function under the given circumstances. In NORSOK D-010 the general requirements for testing of the well barriers are:

i. Before the barriers are exposed to pressure differentials
ii. After replacement of pressure confining components of the barriers
iii. When there is a suspicion of a leak
iv. When an element will become exposed to pressure/load other that it was originally designed for
v. Static leak pressure test shall be observed and recorded for a minimum 10 minutes.

2.2.5 Required Information for P&A Operations

Before executing the planned operations for permanent P&A, detailed information with regards to the status of the well should be available. NORSOK D-010 outlines the information required to assess condition of the well as;

i. Accurate information with regards to well configuration; which includes the original, intermediate and present condition of the well, should be known. This should include depths, formations permeabilities, casing string specifications, side tracks, well bore etc.
ii. Stratigraphic table of the wellbore to be abandoned, showing the sequence of reservoirs and information of their current and future potential. It should also include information about the reservoir fluid type and pressures.
iii. Information about the primary cement jobs performed in the well in the form of logs and other data
iv. An estimate of formation fracture gradient
v. Additional well information that includes the scale build up, the collapsed casing, casing wear or similar issues.

2.2.6 Design Considerations for P&A Operations

As with all other type of real world operations, uncertainties should be considered, that cause to change the course of desired operations and intended results. The NORSOK D-

010 lists the factors that should be taken into consideration while executing the abandonment operations which include;

i. Contamination of fluids used for abandonment operations
ii. Surface volume control
iii. Minimum volumes required for the slurry and for efficient operations
iv. Down hole placement techniques
v. Pump efficiency/parameter
vi. Shrinkage of cement/cement like material

2.2.7 Various Configurations for P&A

i. Temporary abandonment of a non perforated well with/without liner
ii. Temporary abandonment of perforated well with /without liner
iii. Permanent abandonment of open hole with no source of outflow
iv. Permanent abandonment of open hole with a source of outflow/reservoir
v. Permanent abandonment of perforated well with liner and tubing left inside
vi. Permanent abandonment of perforated well with liner and no tubing
vii. Permanent abandonment of well with multi bores and slotted liner or sand screens
viii. Permanent abandonment of well with slotted liners in multiple reservoirs and intermediate casing cemented to previous casing shoe
ix. Permanent abandonment of well with slotted liner in multiple reservoirs and intermediate casing **not** cemented to previous casing shoe.

2.3 Oil and Gas UK (United Kingdom Offshore Operators Association)

In the United Kingdom (UK) part of North Sea the operations are supervised by United Kingdom Offshore Operators Association (UKOOA).

As in many other part of the world where offshore petroleum operations are underway, the guidelines in the UK part of the north sea have been set to avoid any possible disastrous event that would not only cause huge financial and economic loss but would also leave environmental effects that may not be possible to reverse fully. According to the guidelines issued in 2012;

i. Two permanent barriers from surface or seabed are required if a permeable zone is hydrocarbon bearing or over pressured and water bearing. The second permanent barrier is a backup to the first.

ii. Moreover the two permanent barriers may be combined into one single large permanent barrier in case it is possible.

iii. The barriers should be placed as close to the reservoir zone as possible.

2.3.1 Permanent Abandonment Barrier

The best practices are shown in the blue boxes where as the barrier elements are shown in the orange boxes in figure 3 below:

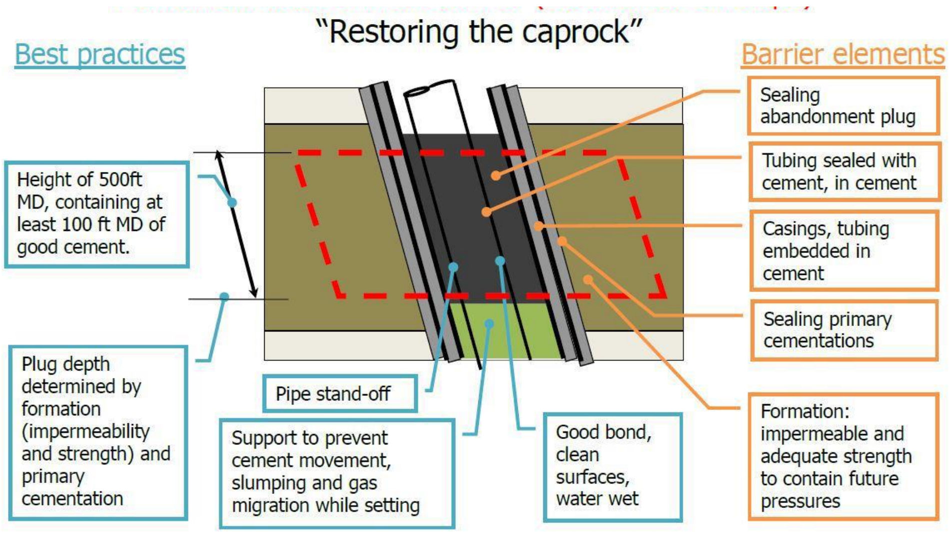

Figure 3: Best practices and barrier elements (taken from UKOOA)

In addition to the above, it requires two barriers for each permeable zone in case where more than two hydrocarbon bearing zones are present, which have a potential to flow. It also allows the use of bridge plug to prevent the slumping of cement slurry down the well and even prevents gas migration upwards.

Various Requirements for Permanent Abandonment

i. For an open hole, where the potential internal pressure does not exceed the casing shoe fracture pressure two variations of barrier solutions can be employed as shown in figure 4.

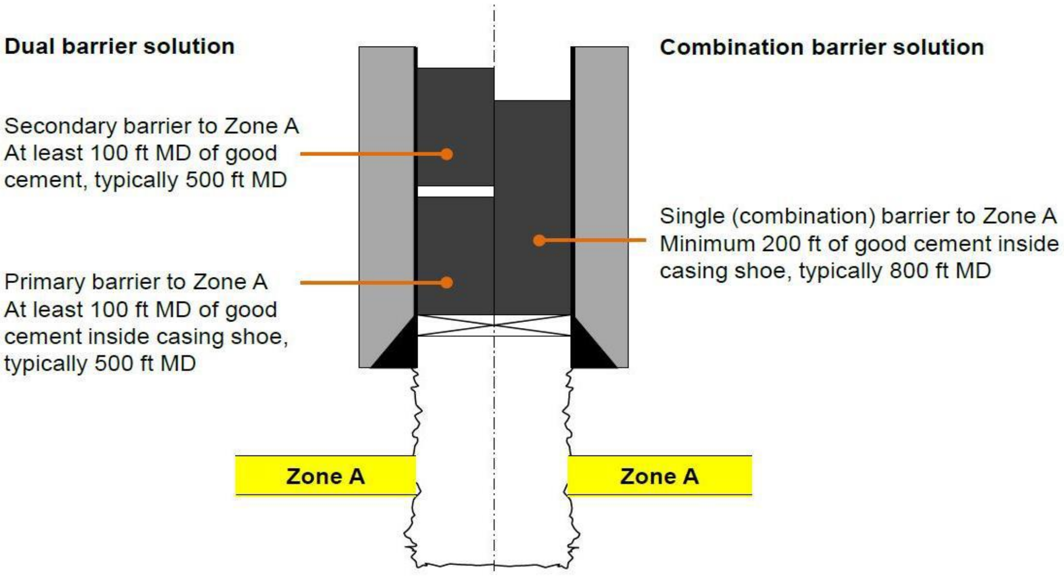

Figure 4: Open hole with two barrier solutions

ii. For open hole where the potential internal pressure from both zone does not exceed the casing shoe fracture pressure configurations for barrier placement as shown in figure 5 can be used.

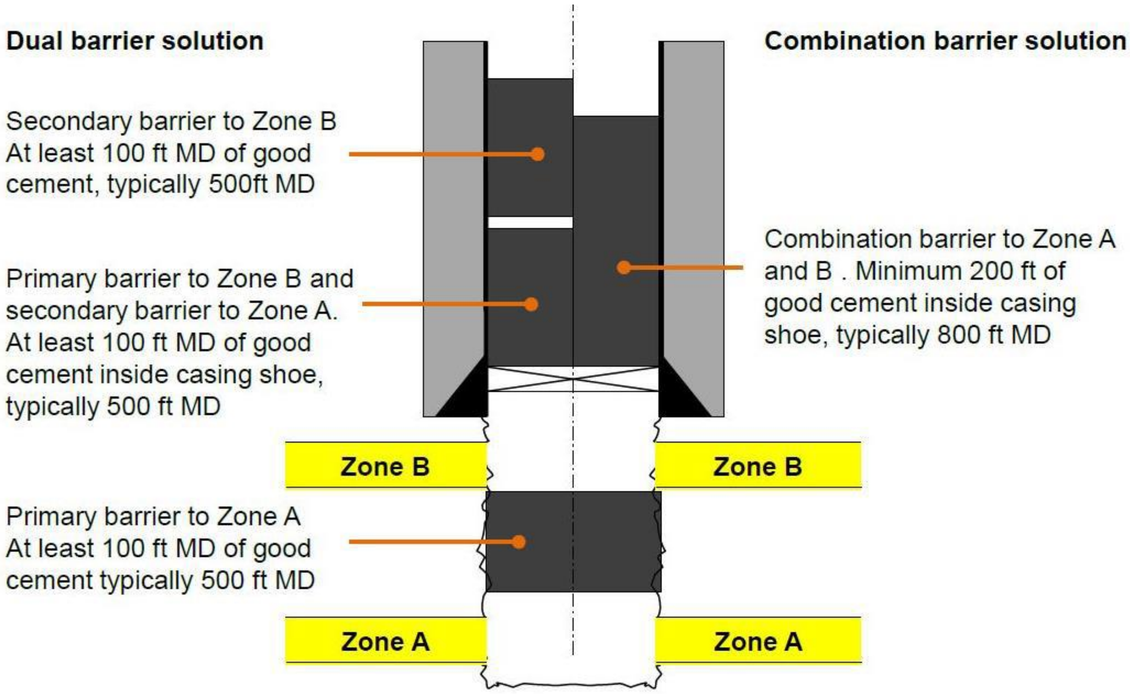

Figure 5: Open hole with two zones and two barrier solutions

iii. For open hole where the potential internal pressure from the producing zone exceeds the casing shoe fracture pressure the barrier configuration as shown in figure 6 is recommended.

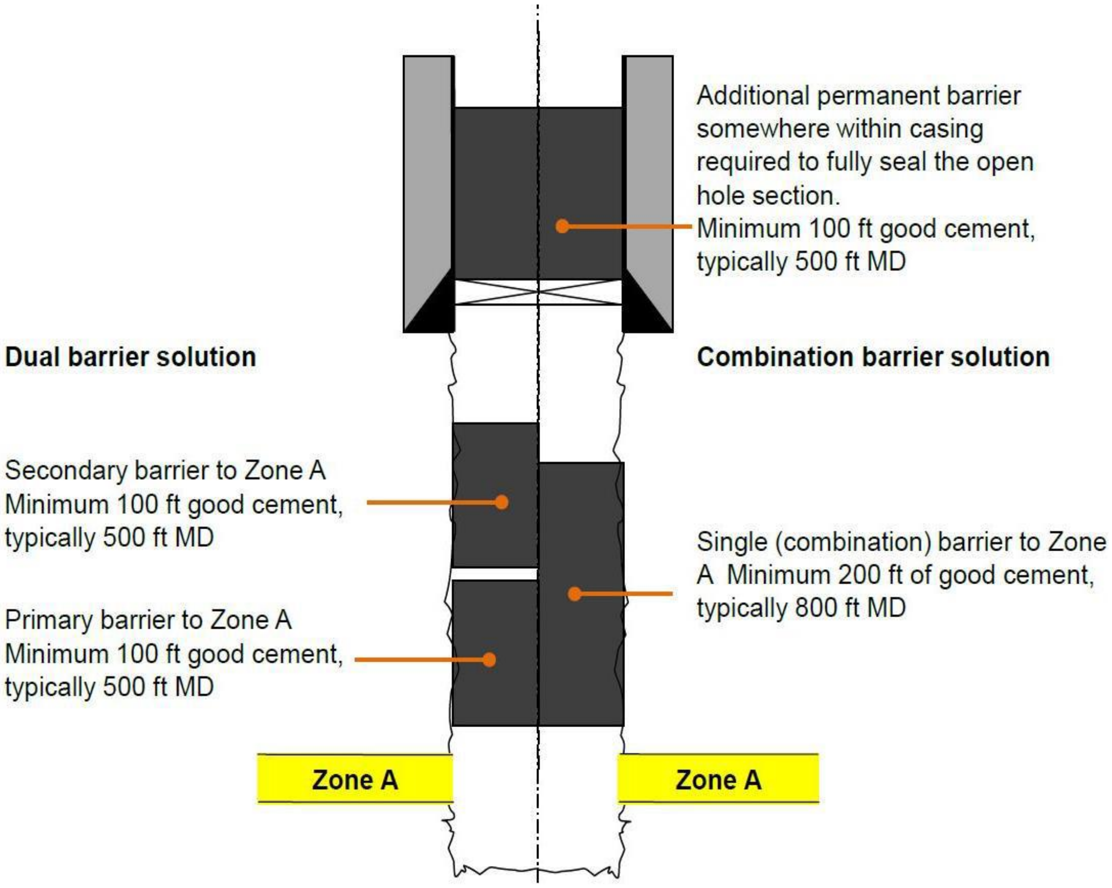

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Figure 6: Open hole with pressure exceeding that of casing shoe

iv. For cased hole, the casing cement is a sufficient barrier, as shown in figure 7, to prevent the flow as long as the quality of cement is verified.

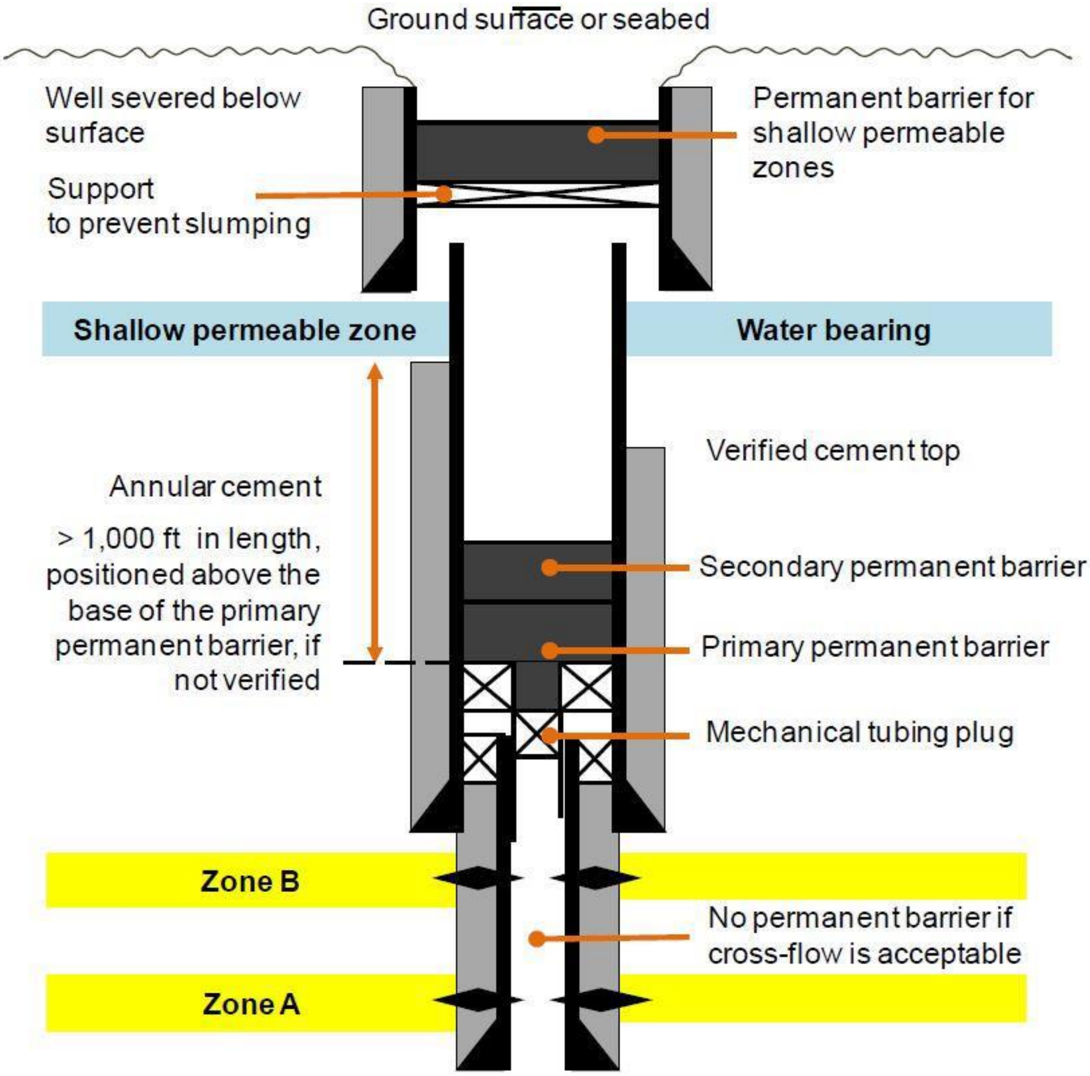


Figure 7: Barrier solution for cased hole

2.4 North Sea standards for P&A (NORSOK, UKOOA and Dutch Guidelines)

Offshore operations in the UK part of the North Sea are controlled by the Department of Trade and Industry (DTI) whereas the Norwegian Petroleum Safety Authority under the Norwegian Petroleum Directorate supervises the offshore petroleum activities on the Norwegian Continental Shelf.

The UKOOA guidelines divide the P&A operation into three phases (explained in next chapter). It then requires a sufficient length of plug extending laterally and across the entire well bore. At least 100m of length should be verified, and a continuous plug would serve the purpose. A plug may be verified either by tagging top of cement or an inflow test or by applying pressure of greater than 500psi (0.1 psi/ft). Moreover, any plugging material, besides the frequently used Portland cement can be used as plugging material as far it serves the purpose can be used for completing operations. It does not even require squeezing perforations. In case of more than one pressurized zones, a primary plug for shallower zone can be used as secondary plug for the deeper zone.

The NORSOK standards on the other hand require the use of Portland cement in particular (rev 3) to be used for the plugging operations. It also requires the perforations to be isolated using a mechanical barrier and squeeze cemented. It moreover requires the well head/casings to be cut and removed 5m below the surface of the sea bed so that there is no protrusion above the sea bed of any petroleum activity.

The Dutch mining authority in the Netherlands asks for the plug to be tested with a min. 5MPa inflow pressure test or a 100kN tag force. The Dutch sector also allows for cement to be substituted with an equal or a better sealing material. It also requires perforations to be separated by a plug on top. In case the cement quality in the annulus between two strings cannot be verified, the smallest string has to be retrieved as far possible. Moreover, these guidelines require offshore strings to be retrieved 6m under the seabed in addition to 100m of cement plug in all string for the top hole section of the well.

It can be established from the preceding paragraphs that all these guidelines require achievement of common objectives:

- prevent leakage of hydrocarbon to the surface
- prevent movement of hydrocarbon between layers of different permeability and porosity
- prevent contamination of aquifers

Thus the underlying requirement for all of them is proof of the existence of a plug and its verified length to ensure safety of ecological and aquatic environments.(D liversidge 2008)

2.5 Comparison of Plug & Abandonment Regulatory Requirements

With different regularity authorities monitoring petroleum activities in different parts of the world, no standards for plug and abandonment operations have been established. Table 1 gives plug length requirements in different part of the world.(Vela 2014)

Table 1 Well barrier criteria

	Brazilian Regulations	**Norwegian Regulations**	**UK Guidelines**	**Gulf of Mexico Requirements**
Zones in OH reservoir	30m above and below	50-100m above	100ft above and below	100ft above and below
Cased hole plug	60m or30m over retainer packer	Over retainer packer 50m if not 100m	100 ft good cement or 500ft	200ft length with minimum 100ft above perforated interval
Transition from cased to open hole	60m, 30 m above casing shoe	100m, 50m above casing shoe	100ft good cement or 500ft	100 ft above and below casing shoe
Test Requirement	7 ton force or 7Mpa pressure for 15 min	Tag in Open hole - Tag and 1000psi above LOT for cased hole	10-15 k.lb weight(DP) or 500psi above injection pressure	15 k.lbs weight 1000psi

CHAPTER 3 METHODS & PROCEDURES

Plug and abandonment operations cost approximately a quarter of the total cost of drilling exploration wells offshore, and for production wells the cost impact is similar to the cost of drilling operations offshore Norway(Arild Saasen 2013).

The quality of P&A operations can be judged by two strategies, depending upon:

- The type of plugging material used
- Placement technique used for plugging operations

The NORSOK D-010 standards define the scope for the plugging material that can be used for Norwegian part of the North Sea that specifies only cement to be used as plugging material in permanent plug and abandonment operations. On the UK part of the North Sea however, the standards allow "cement" or "cement like material" to be used for the abandonment operations as long it fulfills the requirements stipulated by the UKOOA.

Details about the plugging material will not be discussed in this thesis as that is not defined in the scope of this work.

For the placement technique of the plug and abandonment material, various methods have been used by the industry that allows the use of innovative techniques to make them cost effective and safe.

The basics, however, of a plug and abandoned well is that the quality of cement behind the casing should be ensured; if that is poor, it becomes important to remove the casing from that section of the well. For this, milling is a traditional operation executed to achieve an axial and lateral plug across the borehole. Following this, plug is set and cement squeezed at specified depth, in specific quantity across the intended zones to act as permanent barrier. However, the biggest challenge during this operation is the "swarf" generation during the milling operation. This in addition to the basic operations would require attention to hole cleaning, surface handling equipment and well control safety issues.

3.1 Operational Phases

In accordance with the oil and gas UK (UKOOA,2011) the well abandonment operations can be divided into three broad categories(Max Baumert April 2011):

Phase 1

It is also known as the reservoir abandonment phase. The status of the well needs to be known before execution of this phase. This would include checking well head, preparing for waste handling and running wire line operation for investigation of cement behind the wall of casing strings. The tubing may be left in the well depending upon that particular case. The producing or the injecting zones are then sealed with barriers by squeezing cement through the perforations and ensuring that it has plugged the zone as per requirements.

Phase 2

This is the intermediate abandonment phase. The purpose is to seal any reservoir zones that may have the potential of producing hydrocarbons at a later stage or if there is any water bearing permeable zone. It may well include setting of the intermediate and near surface barriers which is followed by milling operation of the intermediate casing and retrieving it.

Phase 3

In the last stage of P&A operations efforts are mainly focused on retrieval of the well head and casing from the near surface of the sea bed. A cut is made below the sea bed level and the casings are pulled out so that there is no extrusion of the well activities left behind when the area is abandoned as per standards. Light well intervention techniques have been in use for some time now and developments in this regard have been made in recent years. Efforts are also being made in making it a cost and time effective operation for both the operator and contractor responsible for the activity.

3.2 Traditional P&A Methods

Traditionally, a cement plug is used in a cased hole for permanent plug and abandoning of a well. This typically involves section of the casing to be milled where the plug is to be placed. This process of milling itself affects any activities carried out afterwards.

3.2.1 Section Milling

Milling can be defined as the process to grind up or pulverize down hole using diamond or tungsten carbide cutting edges. As with any other petroleum activity, milling can be required in a variety of situations. A mill can be used to dress a fish, ream out a collapsed casing and remove section of casing for side tracking or to remove cement plugs. Each of these milling operations has its own challenges that require different parameters and equipment types to be used. (Weatherford 2006)

In our case of section milling, where a predetermined section of the casing needs to be milled at a certain depth, the milling rates and cutting return speed should be optimized for efficient operations. General operation recommendations for adjustment of parameter during operations are given in the Table 2.

Table 2 General recommendations for parameter adjustment during section milling

Challenges	Recommendations
Cemented casing	Increase weight on mill and milling speed to improve rate of penetration
Un-cemented casing	Reduce milling speed with and operate with less weight on mill
Severely corroded casing	To prevent tearing and splintering of casing decrease the weight on mill and increase milling speed
Unstable mill	Add a stabilizer to the milling assembly used for operation. The diameter of the stabilizer should not exceed that of mill
Older model liner hangers, centralizers and scratchers	Liners with slips and rotating parts can cause problems. When these are encountered pick up the string and spud

	the mill frequently to reposition and break up the hanger parts for effective milling.
Bouncing or rough operation	Reduce the weight on mill and decrease speed to make milling smoother. Slowly increase speed and weight on mill after sometime until acceptable rate of penetration is achieved. A shock sub can be used above the mill to reduce vibrations.

Rotary speeds are usually determined by the operators depending on the situation and the speed required for effective milling rates. Usually it is kept around 100 rpm to prevent any damages, as at high speed the mill can stick momentarily that can cause the pipe to twist and untwist resulting in breaking the tool joint connections or twisting of pipe. Therefore the drill string size and hole conditions limit the rotary speed. For weight on mill, the size and strength of cutters should be taken into consideration as excessive weight can damage the tungsten carbide that mills the steel.

For optimizing cutting returns if the cuttings are thin and the rate of penetration is low, increase the weight on tool. The ideal cutting is usually 3/32 to ¼ inch thick and 2 to 4 inch long. For optimizing cutting returns out of the wellbore oil based mud should be avoided. Additives can be added to increase the mud weight and increasing the flow rate can also help in improving returns.

3.3 Alternate Methods for P&A

Section milling for plug and abandonment operation includes milling of the casing section, cleaning and under reaming of the open hole where the cement plug is to be placed. The swarf produced during the process compromises the safety of the operations that need to be carried out afterwards as the equipment for well control may become damaged or malfunction. Therefore methods have been introduced that would avoid risk of damaged equipment and loss of time due to circulation to ensure cleaning of swarf from the well.

3.3.1 Using Sand Slurry

Exploration wells drilled in the Norwegian part of the North Sea have been permanently abandoned by setting series of plugs to isolate the pressurized zones from each other. Bingham plastic unconsolidated material for plugging of an open hole well has been successfully used(Arild Saasen 2013). The material is non-consolidating concentrated sand slurry which does not undergo any chemical reaction, does not shrink and does not even fracture. Natural fracture/faults, tectonic stresses and changes in well pressure and temperature are a common cause of well barrier failure. This sand slurry is therefore self-healing, thermodynamically stable and satisfying the standards defined in NORSOK D-010 according to the author.

However, this unconsolidated sand slurry is not suitable to be placed behind casing because of its low shear strength neither can it be placed on top of liquid. It therefore requires a foundation (mechanical plug) that can act as base for it. The slurry is placed using a drill string, which is then pulled out above the top of the plug. Tagging cannot be done due to its low shear strength; therefore mud circulation is carried out for its verification. The plug placement is shown in figure 8. Further details can be found from the reference provided.

3.3.2 Perforate, Wash and Cement Technology

Milling process is an essential and problematic requirement, for traditional plugging operation. A new perforate, wash and cementing technology has been introduced that performs all these three mentioned operations in a single run. And more importantly it eliminates the expensive milling operation requirement.

Starting from bottoms up, the jointed system has 50m length which has drill pipe conveyed perforating guns, followed by a wash tool and then finally at the top is the cement stinger.

The first perforation process is initiated by dropping a ball that results in 12 shots per foot in 135/45 degree phase. Ball release mechanism is used again which initiates the washing mechanism, cleaning the wellbore both on the inside and outside the casing, up to and including the exposed formation face. This greatly reduces the chances of possible "pack off" during further operations. Another drop ball releases the wash tool from the assembly so that it is left in the hole and serves as a base for the cement job which is carried out by the cement stinger at the end. Balanced plug method is used to place the cement with the stinger at the bottom. (Thomas E. Ferg 2011)

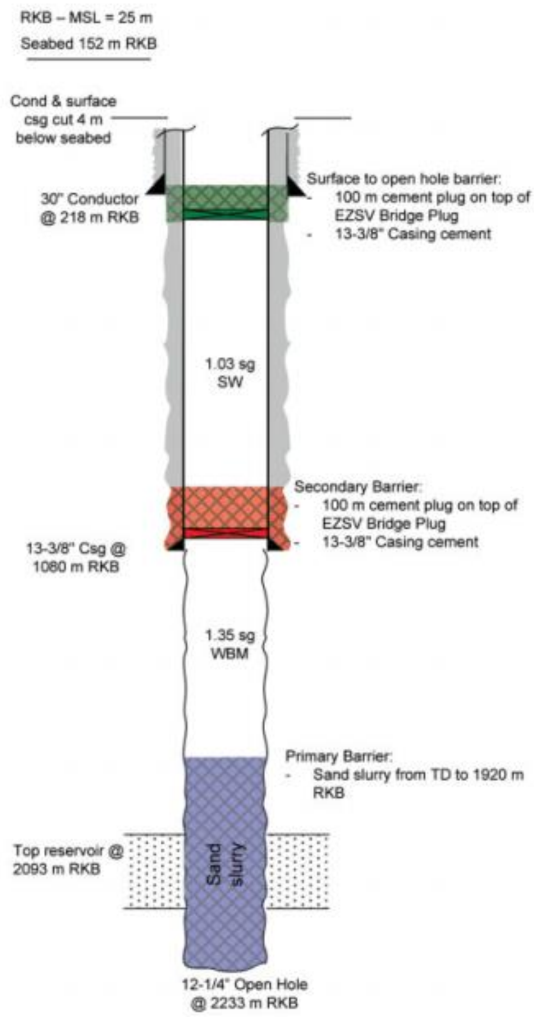


Figure 8: Well schematic for well abandoned using sand slurry

The placement of an effective barrier is difficult when there is no competent external barrier behind the casing already. This improved method allows effective isolation without casing removal. With this system:

1. Effective washing behind the casing can be achieved by engineering the function as a parameter of perforation diameter.
2. Exposure of personnel to swarf handling is eliminated which reduces potential lacerations
3. Swarf handling, disposal and transport is eliminated

4. Significant cost and time savings are achieved as the essential operation is performed in a single run
5. Better well control is achieved as the tools are deep inside the hole and there is no surge swab effects and any fluctuations in the fluid pressure down hole.

3.3.3 Cementing through Bottom hole Drilling Assembly

The jobs performed by cementing through bottom hole drilling assemblies can be divided into two broad categories:

1. Plugging back pilot holes
2. Planned plugs

The operations have been performed at different offshore installations and under a variety of operating conditions. Along with successful plugging operations, managing critical mud losses to regain well control have also been achieved. The most severe case has been handling the HPHT condition of operations. Following the experience gained over a period of several years of un-planned incidents, a best practice has been developed and adopted to take care of un planned events. Efforts have focused on taking total risk of operations into account during the planning phase of drilling operations.(Rune Godoy 2012)

Pilot holes are sometimes required during drilling operations where there is unreliable data available with regards to either location of shallow water/gas bearing zones, natural fractures or lithology and formation tops. Plugging the pilot hole afterwards requires re-entry into the well with a cement stinger to perform the operation. So there is an increased risk of being unable to enter the open hole or even the risk of not find it at all due to uncertainty down hole. This risk is reduced if the plug cement slurry is pumped through the drilling BHA. This in addition would also save rig time as there is no extra tripping in and out of the hole required.

However, this is also accompanied by a risk of plugging the string during the pumping operations. The reasons for this could be contaminants in the fluid pumped, or it could be "flash setting" while passing through the bit nozzles. In any case, these considerations should be taken into account during the design phase of drilling and cementing operations.

In case a load test is required, a deep set cement plug can be set by pumping cement through a bit without nozzles. It takes less time to set a plug and load test it with a bit without nozzles. To avoid swabbing effect, the pump and pull method is recommended when pulling the bit through the placed cement. As with the previous case of "plugging pilot holes", this procedure also has a risk of plugging the BHA while pumping cement. This however can be taken care of by considering the following:

- BHA should be above the loss zone and inside the previous casing shoe
- Filtration of cement slurry/spacer through a 500 micron filter
- Drilling fluid properties and spacer design

3.3.4 Abrasive Jet Cutting

Abrasive jetting technology has found extensive applications in recent decades because of its being cold, damage free and sensitive cutting technique. Getting optimum operative performance requires controlling various functional parameters that include the traverse velocity and pump pressure with respect to the depth of cut.(Y. Ozcelik 2012)

Jet cutting can be classified in two main types: pure water jet (WJ) and abrasive water jet (AWJ). The basic difference between the two is addition of abrasive medium/particles to increase the cutting ability of the water jet. This addition makes water jet more powerful as a cutting method resulting in its investigation to be used for drilling and other petroleum activities. Documentation and use of this method started in 1960's when advantage of jetted perforations over explosive perforations was established.(Mirjam Zwanenburg 2012)

An abrasive water jet system may include a high pressure pump; that provides high pressure fluid, a cutting head; responsible for producing abrasive water jet, an abrasive delivery system; carrying abrasive grits to the cutting head and a control unit/system; that controls the motion of cutting head as desired. Fluid laden with abrasive particles is pumped through the system and the abrasive jet exits the nozzles (in the cutting head) and cuts the steel tubular.

A potential problem lies in the erosive nature of the technique as the nozzles get eroded due to abrasive particles and the discharge coefficient (nozzle design parameter) changes which in turn effects the pressure drop and the resulting cut made. Experiments established that depth of penetration is reduced by increasing the hydrostatic pressure and that longer jetting times achieves deeper penetration.(Hough 1965) It was further established that a deeper and faster cutting rate could be achieved with a jetting tool that is slightly moving. This moving of the tool creates a flow path for the returning fluid that would not then interfere with the jetting stream that is cutting the casing.(S 1961) This moving of streams referred to as the weep hole effect along with nozzle erosion and the pressure effect forms the basis for the new abandonment method.

As required by the NORSOK standards the integrity of the well needs to be ensured at all times and thus the status of the well barriers needs to be known throughout the life cycle of a well. A good quality of cement during the well construction operations can make plug and abandonment operations easier by eliminating the need for expensive and time consuming procedures that include the milling operation. The slots cut in the casing using the tool developed by Halliburton can help avoid milling problems due to cutting of steel. Use of abrasive jetting with coiled tubing as proposed in this thesis can provide a rig less well abandonment technique.

3.4 Abandonment of Offshore Wells - No More Petroleum Activity

After decades of drilling activities, the industry is shifting focus on new techniques and procedures to plug and abandon wells, in parallel with innovative technology that accounts for safer, economical and higher recovery of the assets buried deep beneath the surface.

Much needed research is underway to bring an alternate to the traditional and reliable Portland cement which is used in huge quantities in operations throughout the life cycle of the well, especially during drilling operations. Along with the innovative techniques for plugging the potential hydrocarbon zone or the over pressure zones underground, materials that would satisfy the requirements and standards are being experimented to make these operations more reliable and cost effective.

Executing procedures that may help in getting out of a particular troubling scenario may sometimes form the basis for future course of action resulting in development of a new field of study and research. Until recently the "plug and abandonment" process is considered to be a petroleum activity; but abandoning of a well with a dedicated vessel (not a rig) is not regarded as a petroleum activity.

Exploration well 6609/10-2 Troll-A was drilled with a semi-submersible rig at a water depth of 265m. Problems were encountered during the P&A of the well when the casing hanger got stuck and soon a dedicated vessel appeared as the best option to retrieve the stuck hanger. The vessel, Olympic Zeus arrived on the site, performed the intended cutting operation according to the designed plan without any major problems and finally recovered the well head (Odde Inge Sorheim 2011). Use of a dedicated offshore vessel with the cutting and recovery equipment installed, proved to be a cost effective method of abandoning well as compared to a drilling rig being used for the purpose. Based on this experience, the process is now being implemented as a standard method for abandonment of exploration wells.

In accordance with the NORSOK D-010 standards, the well head needs to be cut 5m below the sea bed. Use of abrasive cutting technology for cutting purpose has been developed since over a decade, and is now being used for well head cutting.

The tool assembly used in Trolla case consists of a stinger with cutting nozzle and a purpose built wellhead connector. The connector is latched on to the profile of the wellhead, and the stinger is designed to execute the cut in accordance with the specified standards. An active heave compensated crane is used on the dedicated vessel that operates the tool assembly via umbilical. Depending upon the casing program used in a particular well, the cutting operation typically takes from 4 to 12 hours. With the abrasive cutting technology, water is pressurized from 60mpa up to 120mpa, mixed with abrasive particles and is then pumped through nozzles resulting in high kinetic energy of the abrasives. These high energy water abrasive jet cuts through the casing steel. This technology using dedicated vessels allows the drilling rigs to be used for purely drilling activities. It has been assessed that on an average for 3 years, a semi-submersible rig would be able to drill at least 3 more standard North Sea exploration wells if the wellheads are removed using dedicated vessels. Time distribution for plug and abandoning operation of well can be categorized according to activities shown in figure 9.

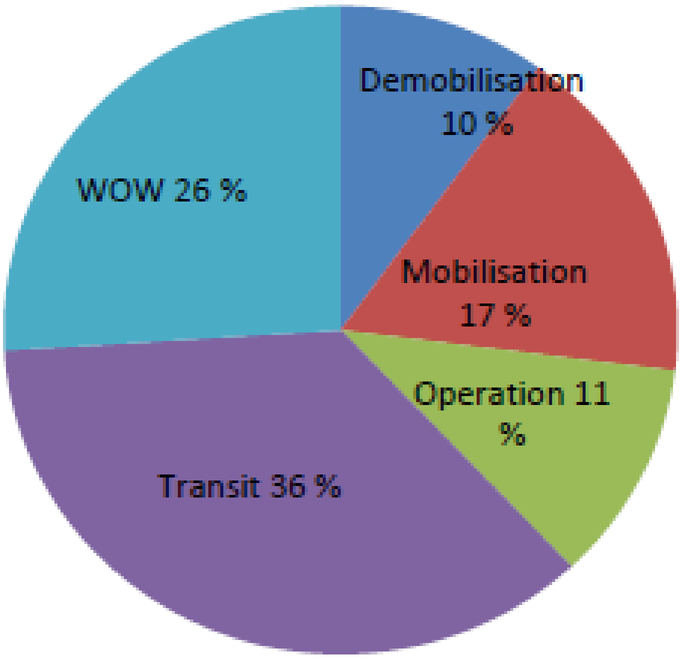


Figure 9: Time distribution for complete P&A activities

Moreover, it becomes even more economical if the well heads are removed in a campaign rather than going in for operations for each particular well. It has been established, as shown in figure 10 that campaigns where 3-5 wellheads are removed at each time, makes it more cost productive for the concerned contractor. (Odde Inge Sorheim 2011)

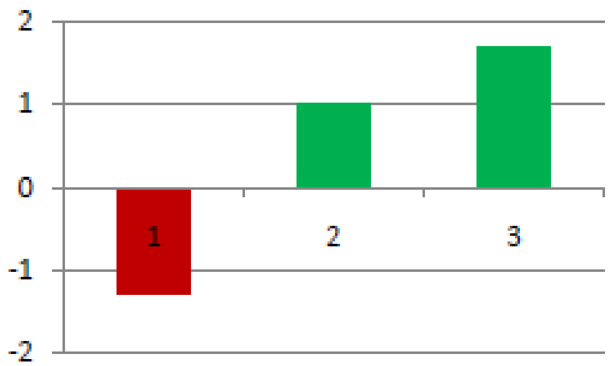


Figure 10: Economic feasibility of wellhead removal in campaigns

CHAPTER 4 FINITE ELEMENT ANALYSIS (FEA) FOR AXIAL AND RADIAL POSITIONING

Tool positioning defined as primary objective for this thesis, is important for efficient P&A operations. Positioning the abrasive cutting tool with coil tubing to cut steel tubular thousands of meters beneath the sea bed requires knowledge of various forces acting on the coiled tubing, the pressures acting through the length and the effect of wellbore path/curvature on the tubing. Finite Element Analysis defined in this chapter is one method that can be used to predict final position the tool down hole.

4.1 Introduction to FEA

Different mechanical components and basic structures can be easily analyzed by methods described in mechanics. However, actual components/ assemblies are not as simple and the approximation of solutions are obtained through either experimentations or numerical methods.

Finite element method for solving a problem begins with dividing the structure/problem into a number of small pieces, called elements. These elements which are simpler to solve, make up a "mesh" which is an approximation of the original problem. These

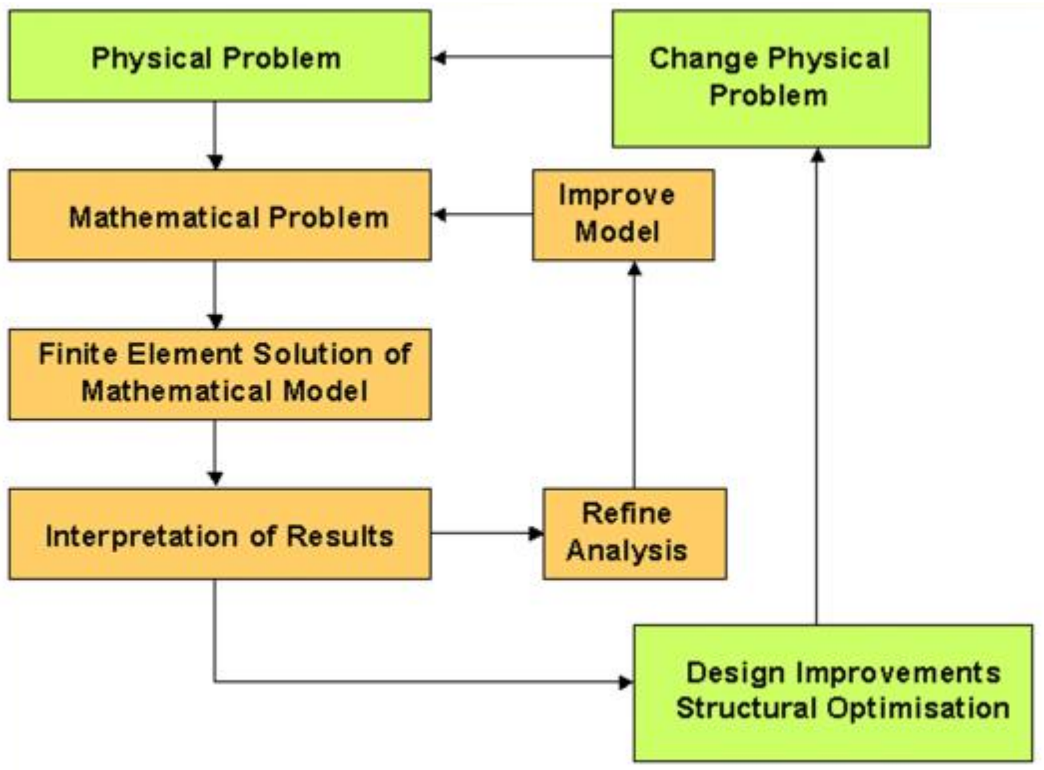


Figure 11: Flow diagram showing processing steps in Numerical problem solving

elements are then analyzed using equations of "stress" and "strain". An important configuration in the technique is that as the number of elements (mesh size) of the original problem increases, it corresponds to smaller size of the individual elements which as a result would give a more accurate solution to the problem.(Donald 2011)

4.2 Practical Finite Element Analysis Procedure

The problem solving stages shown in figure 11 begins with the identification of the physical problem in hand and understanding the design objective and it ends with a model of the problem satisfying the design criteria. The various stages of the solution include:

- Understanding the physical problem

All the distinctive features of the structure and the design objectives should be defined. Various issues that need to be considered in this step are:

  - Dimensions of the structure
  - Symmetry exhibited by the structure- if any
  - Loading type present
  - Whether the loads are constant or vary with time
  - If the structure is in contact with other structures as a result of the loading and the results of impact etc.
  - Environmental effects that can have significance on the structures response.

- Generating the mathematical model

This stage involves translating the important features identified in the previous step into a mathematical representation of the problem. This includes identifying the type of elements to be used for the solution and its formulation. The factors that can influence the selection of mathematical model used for the solution are:

  - Geometry of the structure
  - Structure material
  - Loads exerted on the structure
  - The supports of the structure
  - Interaction of the structure with other structure and environment

- Discretisation of the model/generating the finite element model

Having decided the element type and formulation to be used, in this step the model is actually split into these elements. The geometric model of the problem is converted into the required geometry for the finite element analysis of the mathematical model. For this purpose advantage should be taken of any symmetry present in the system and removing any (small) geometric features that do not affect the analysis. Consideration should be given to ensure that the mesh produced adequately represents the changes in stress throughout the geometry.

The next step here involves application of the loads and boundary conditions that have been identified in the previous step.

- Numerical analysis of FEA model / selecting computational method

A variety of computational procedures and strategies are available for solving a problem. These include:

  - **Static analysis:** the most basic type that assumes no dynamic effects on the system and thus all loads are applied slowly without introducing any dynamic effects. This analysis can be both linear and non linear.
  - **Model analysis:** used to determine the natural frequencies and associated mode shapes of a structure. Different mathematical models are further available to formulate the problem and obtaining solution for a variety of problems.
  - **Harmonic analysis:** this type of analysis allows prediction of response of a structure to sustained cyclic loads. It thus gives information whether the design will overcome fatigue, resonance or other harmful effects of forced vibrations.
  - **Transient dynamic analysis:** this analysis method allows measurement of a dynamic response of a structure as a result of any time dependent loadings being applied. This type of analysis allow determination of time varying displacements, stresses, strains and forces in structure in response to any type of loads.

- **Explicit dynamic analysis:** this method is used for more complex problems that are not easily solved using the transient dynamic analysis.

Selection from among the computational methods mentioned above, (or any other type available) depends on the particular type of problem being analyzed.

- Post-processing, model verification and validation

This step gives information whether the solution obtained is acceptable or not and for further modification of the input data in order to obtain a more satisfactory solution. This step helps determine if the model accurately models the real problem and also if there is any problem with the modeling or solution process. Results of the whole operations should be analyzed and considerations should be given to the following points:

- Are the displacements too large?
- Is the stress transitioning smoothly through the model in element plots?
- Are error estimations plots in an acceptable level?

Following the above mentioned analysis method, finite element analysis of a particular problem can be solved. The next stage would be to validate the analysis results against experimental result which would authenticate the assumptions and considerations taken into account during the modeling of the problem.

4.2.1 Elements

A fundamental decision to be made before starting a finite element analysis is to select the type of element that should be used to model the problem. Further investigation of the problem that includes the material model, the mathematical model and the type of loadings that can be used depends, to some extent on the chosen element type and its behavior.

Basic element types available for the analysis in most commercial software packages are as shown in figure 12(Donald 2011).

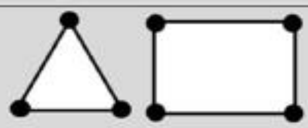
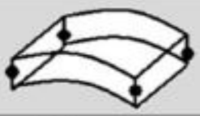
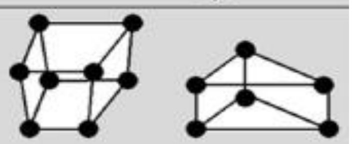
Basic Shape	*Subtypes*	*Representative Geometry*
Point	Mass Element	
Line	Spar/Truss Element Spring Element Beam Element Pipe Elements Axisymmetric Shell Element 2D Contact/Gap Element 2D Surface Effect Element	
Area	2D Solid Element - Plane Stress - Plane Strain - Axisymmetric Plate Element	
Curved Area	Shell Element 3D Contact Element 3D Surface Effect Element	
Volume	3D Solid Element	

Figure 12: Element types used in FEA

4.2.2 Material Model

Various material models are available for the finite elements analyses of stress strain problem. These include linear Elastic models:

- Linear Elastic isotropic
- Linear Elastic orthotropic
- Linear Elastic Anisotropic

And the non-linear elastic models, among others include:

- Neo-Hookean model
- Mooney - Rivlin model

4.2.3 Modeling and Meshing

As has been described earlier, the process of analyzing a problem using FEA starts with translating a physical problem into a mathematical model. It is then followed by deciding the type of element that can be used to solve the case appropriately. Afterwards the material model is defined that describes how the elements would interact with each other. Once all these preliminary stages have been completed, the next stage is to model geometry for the problem and then divide it into respective finite elements; a process known as meshing or discretisation.

Modeling

The type of geometric model to be used for analysis depends on the element type chosen for analysis. A line or set of lines would be required to represent a spar or a beam element. Whereas a 2D planar geometry would be required for 2D elements, that include plane stress, plain strain or axis symmetric element. A 3D solid model is selected if a shell element has been identified as appropriate for solving the problem or if, a solid model has been deemed necessary for representation of the original problem.

Among several things that should be considered for this stage include:

- checking the model dimensions
- checking if the element type assumption is valid for the model
- if there is any symmetry exhibited by the model
- whether a cylindrical or spherical system of coordinates make modeling easier
- Would it make analysis easier if the problem is split into several simple analyses i.e. sub-modeling?

Meshing

Earlier in the procedure one decides what element type needs to be used and after completing modeling, one would know how the geometry looks like. This step is concerned with putting both these decisions together to create a mesh of finite elements.

During meshing, the following considerations should be taken into account:

- be aware of areas in the mesh that require finer mesh due to stress concentrations
- be aware of any special considerations for meshing a particular type of element

- ensure there is smooth transition between element type and size
- know the difference between a good and bad quality mesh

4.2.4 Loading

For a stress analysis problem the applied loads can be divided into the following distinct categories:

Body Loads

These are loads acting on the whole body as is suggested by the name. The simplest example is the weight of the body itself which is applied by every single element that makes up the body if it is divided into elements for a finite element analysis purpose. This body force acts as force per unit volume. This body force is then distributed on to the nodes that make up the elements.

Surface Loads

These types of load act on a surface or an edge of a body that is being analyzed. Example includes internal pressure on the inside of a pressure vessel or external pressure being applied on a coiled tubing that is empty. These surface loads, in contrast with the body loads are therefore just applied on to the elements at the face of the body under investigation. However as with the previous case, the load is finally transferred onto the nodes that make up the shape of the elements.

Point Loads

These are concentrated loads that act through or at a particular point in the body. A typical example of these loads includes forces or moments applied to a specific node in the mesh of finite elements.

Dynamic Loads:

Besides the static loads described previously for a static analysis, during a dynamic analysis the applied forces change as a function of time. In such case, equilibrium has to be defined over the period of analysis time and thus has the same requirements in order to obtain a model solution.

4.2.5 Boundary conditions

In a model investigation, environments that are not explicitly defined to perform analysis are defined by the boundary conditions. These conditions therefore should not restrict the deformation of the specimen that would otherwise be allowed by the problem environment. However they should also be defined so that they do restrict deformations that are not of interest in the problem environment.

4.3 Theoretical Model Analysis

The finite element method is a numerical method for solving a system of governing equations. These systems of equations require a basic understanding of vector calculus and linear algebra that form the mathematical preliminaries for the subject.

Design analysis of a simple structure can be performed by hand calculations and experiments, however for solution to complex real life problems, FEA or FEM(finite element method) is more commonly and widely used using application of computer simulation methods of engineering. Therefore it is closely integrated with the CAD(computer aided design)/CAM(computer aided manufacturing) applications.

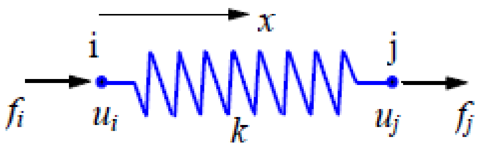
Besides Ansys 13.0(university license) and Autodesk Inventor used for this work, several other software packages are available that can be used or even custom designed to perform specific analysis. Examples include Abaqus, Nastran, Cosmos and others.

The 3 methods used to derive FE (finite element) equations of a problem are(Kim 2009):

1. Direct Method
2. Variational Method
3. Weighted Residual Method

Direct Method is simplest of solution methods that provides an insight to the Finite Element Analysis (FEA) method and is limited to solving one-dimensional problems. In this work, this method will be used to present the basic analysis method.

To begin with the analysis, consider a linear spring element:



Where "i" and "j" are the two nodes with u_i and u_j as the nodal displacements respectively. The nodal forces f_i and f_j act on the spring with a spring constant "k".

This force-displacement relationship can be represented as:

$$\boldsymbol{F} = \boldsymbol{k} * \boldsymbol{u} \qquad \textbf{(4.1)}$$

Considering equilibrium at the two nodes, we have the following equations for nodes i &j respectively:

$$f_i = -F = -k(u_j - u_i) = ku_i - ku_j \qquad (4.1a)$$

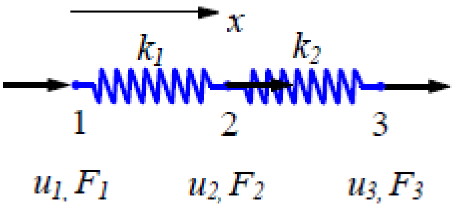
$$f_j = F = k(u_j - u_i) = -ku_i + ku_j \qquad (4.1b)$$

The above relations can be rewritten in matrix form as:

$$\begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{Bmatrix} u_i \\ u_j \end{Bmatrix} = \begin{Bmatrix} f_i \\ f_j \end{Bmatrix} \qquad (4.2)$$

where k is the "stiffness matrix", u the "nodal displacement vector" and f the " force vector". This matrix representation is same as equation (4.1)

If stiffness matrix defined in (4.2), is defined for a 2 spring and 3 nodes system, the resulting matrix is given as;



Considering the equilibrium forces at node 1: $F_1 = f_1^1$

At node 2, $F_2 = f_2^1 + f_1^2$

At node 3, $F_3 = f_2^2$

Giving the following equilibrium equations:

$$F_1 = k_1 u_1 - k_1 u_2 \tag{4.3a}$$

$$F_1 = -k_1 u_1 + (k_1 + k_2) u_2 - k_2 u_3 \tag{4.3b}$$

$$F_1 = -k_2 u_2 + k_2 u_3 \tag{4.3c}$$

And in matrix form:

$$\begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1 + k_2 & -k_2 \\ 0 & -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \\ F_3 \end{Bmatrix} \tag{4.4a}$$

$$\begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1 + k_2 & -k_2 \\ 0 & -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = \begin{Bmatrix} f_1^1 \\ f_2^1 + f_1^2 \\ f_2^2 \end{Bmatrix} \tag{4.4b}$$

Following this, if the number of forces that correspond to the nodes and their respective displacements is defined for a larger system, a linear system of algebraic equations is developed that describes the given situation:

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = b_1 \tag{4.5a}$$

$$a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n = b_2 \tag{4.5b}$$

$$a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nn}x_n = b_n \tag{4.5c}$$

where "x" with the subscripts are the unknown with the constants "a" and "b".

This system of equations that takes a matrix form of:

$$\boldsymbol{A} = \boldsymbol{x} * \boldsymbol{b} \tag{4.6}$$

where A, x, and b take the form;

$$\mathbf{A} = [a_{ij}] = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad \mathbf{x} = \{x_i\} = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{Bmatrix} \quad \mathbf{b} = \{b_i\} = \begin{Bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{Bmatrix} \tag{4.6a}$$

Now this system of equations must be solved as all the terms in stiffness matrix are known. The applied forces are known and the displacements are the only unknown in these set of equations.

Moving on from 1-dimensional problems to 2-D and then to 3-D real life problems, stiffness matrices, as defined in equation (4.6a), need to be transformed into local coordinates and then further into global coordinate system to be able to solve the problem.(Newman March 2004)

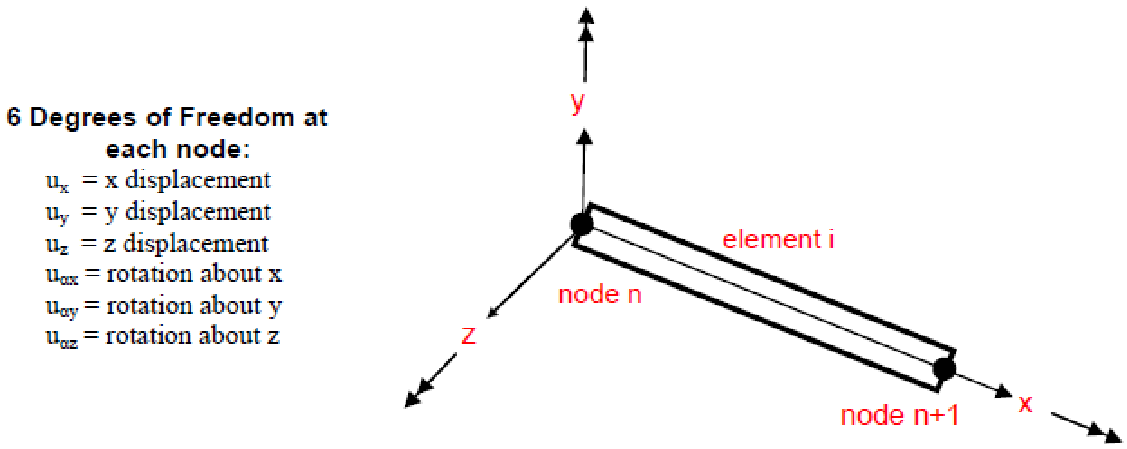


Figure 13: Nodes and degrees of freedom for each element

Figure 13 shows the design aspects of one element that makes up a larger complex real problem. So, the direct method of numerically solving problems becomes impractical when complicated and multidimensional problems are considered. For complex real life scenarios a systematic approach for constructing finite element equations is used which is done by the methods mentioned previously i.e. weighted residual method and Energy method. Energy method is a more powerful and amenable method for approximating solutions when solving more realistic structures.

4.4 Overview of Ansys Workbench 13.0 and Autodesk Inventor - University License

Ansys Workbench is one of the several softwares available in the market that can be used for simulations purposes using the Finite Element Analysis technique. This software is basically for structural and mechanical purposes where in the real life model is simulated and tested for its functionality, material compatibility and performance over a variety of test conditions. This allows for saving time and money.

The software version however, available at the University of Stavanger (UiS) has an academic license. This license limits its usage and functionality for academic purposes only. The version of software used for commercial applications has all the features and functionalities available depending on the usage requirements for that particular organization. As will be explained later in detail, the software allows the problem model to be divided into small elements that has nodes at the corners. The number of nodes associated with each element depends on the element type being used for analysis.

Ansys Workbench available for use has its limitations for processing only 32000 nodes. This limits the overall problem solving/simulation capacity of the software. Software with commercial usage license has ability to process several hundred thousand nodes.

This software has several systems for analysis that have different sub-projects as shown in figure 14.

Static structural system of analysis was selected for our work in this thesis. Several steps which are involved in completing the process are shown in the sub-table shown in figure 14. These main steps for analyzing any model are described in detail later in this chapter.

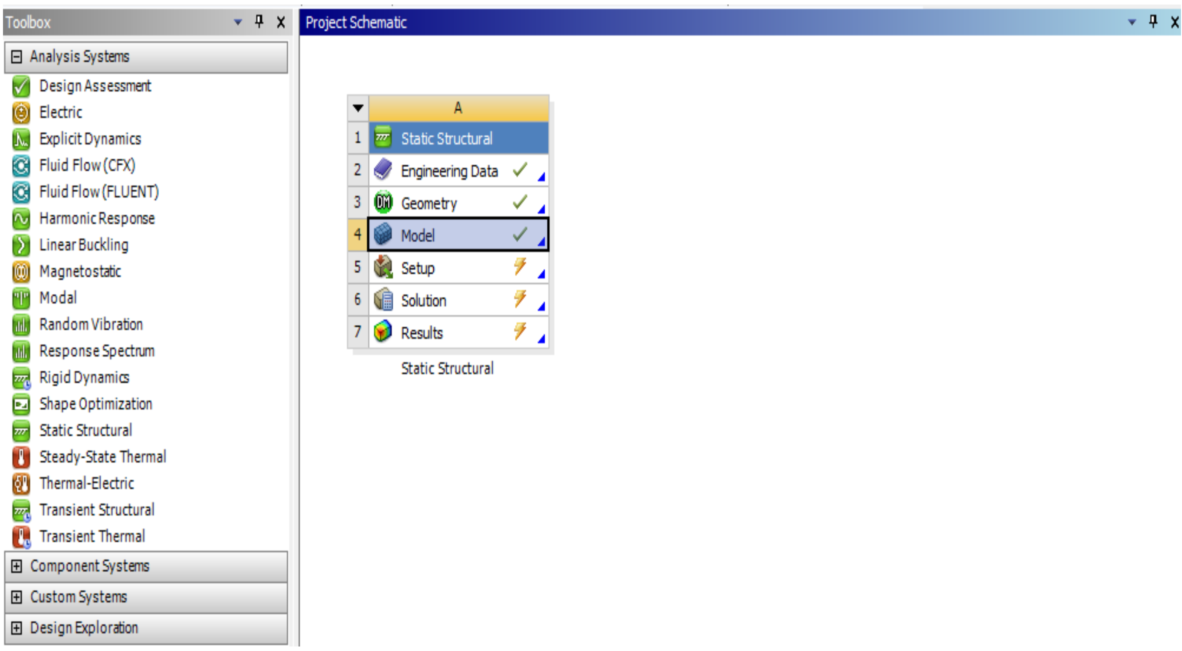


Figure 14 Static Structural analysis used in Ansys13.0

The basic engineering data defines the type of unit system used for dimensioning various parameters of the model. This data has been predefined in the software and allow usage of length dimensions of millimeters (mm), inch (") or meters (m). The next step 'geometry', requires generating a model that defines the shape and physical appearance of the real problem. This geometry can be drawn either by using the functions inside the Ansys Workbench 13.0 software, or it can also be modeled using any Computer Aided Design (CAD) software.

Autodesk Inventor (academic license) is one such CAD software that is available at the University of Stavanger (UiS) for this purpose. The easy to use user interface window allows easy usage and modeling of various mechanical designs. As for the Ansys software, the length dimensions are pre-defined for this software too and thus has its usage limitation for designing.

4.5 Model development:

One of the primary aims of this work was to define a model that may help in predicting accurate positioning of the tool down hole. This in particular, involves using coiled tubing to run deep under the earth's surface and take into account the various environmental effects that are prevalent in the hole.

Simulation software that are particularly designed for mechanical and structural analysis in general are used for modeling of seemingly simple items from household tools to complex objects like the gear box of a vehicle or designing of an aircraft. This technology not only saves time but also helps in protecting environment and resources that may be utilized in testing actual scale models for a variety of test conditions.

Ansys Workbench 13.0 and Autodesk Inventor has been used in this work for analyzing the petroleum activity that we need to consider. Autodesk inventor is CAD software that has been used to model and Ansys analysis the model using FEA method.

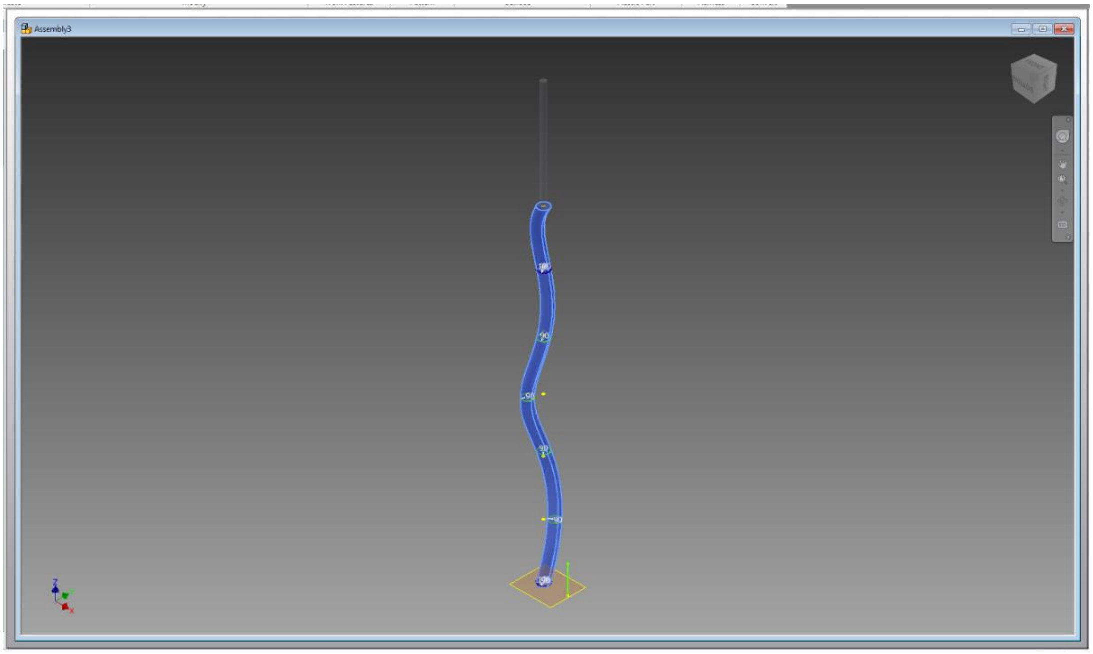


Figure 15 Well path (blue highlighted) and coiled tubing (straight on top)

Our main concern; as defined earlier is the deformations that are being made in the coiled tubing either due environmental effects that includes temperature and fluid flow, or due to impact forces as a result of its impact with the casing that defines the well path to be followed. Casing and coil tubing geometry is shown in figure 15.

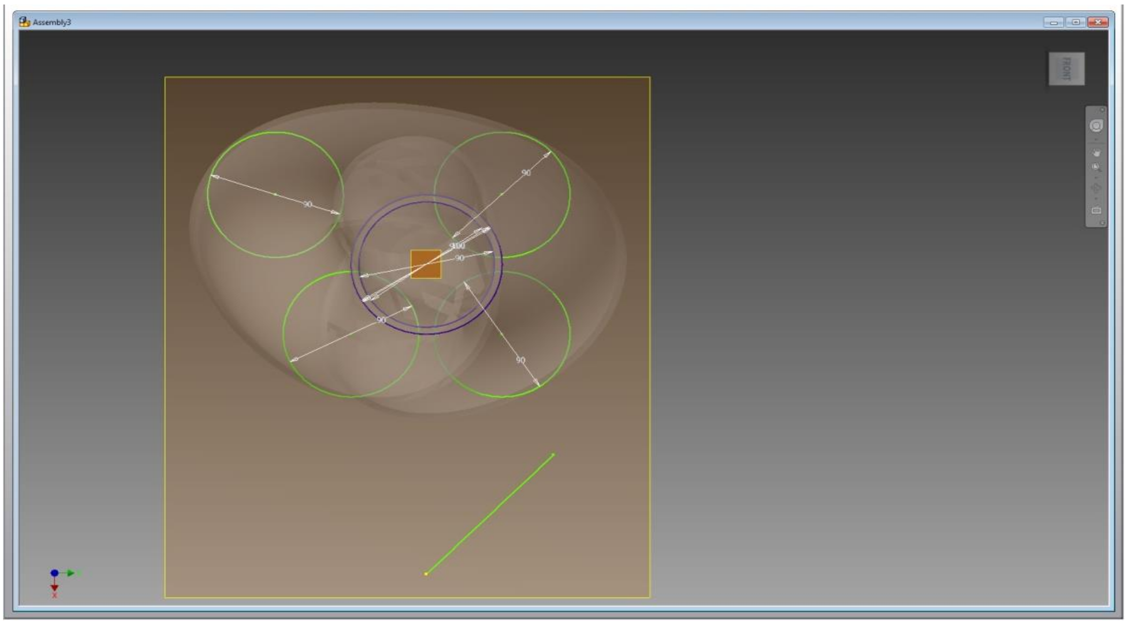


Figure 16: Top view of well path

The initial well path model developed in inventor uses the basic '*spline'* command. The casing in the wellbore is modeled using the shell geometry with rigid attributes as we are not concerned with the deformations and environmental effects on it. Along the length of the casing, the vertices that define its path have been modeled in 3-d that would reflect both the change in azimuth and inclination of the well path as in real case. These changes in well path allow modeling for any shape of well path that may have a change in inclination, azimuth or a combination of both.

Figure 16 shows the top view of the casing that indicates positioning at different sections. Important to note is that an arbitrary shape of a well path was used that would help examine the prototype. Once successful, it can be used to define the real shape of the well also.

The diameter of the casing shell model was taken as 7" which reflects the original casing diameter in use. The length increments after which a section has been defined to account for change in azimuth and inclination is 500mm (0.5m) each. And the well path has then been defined for a total length of 3000mm (3m) only.

Next, the coiled tubing model was developed using the basic '*extrude'* command in the inventor. The tubing is designed at the top section of the well casing and is defined as deformable body developed as a solid. As the tubing is forced into the shell geometry of the casing, it comes into contact with its walls, experiences forces and is made to deform as it forces its way down hole.

The outer diameter of the coiled tubing was taken as 2-7/8" which reflects the original OD of the coiled tubing to be used. The length taken is just 2000mm (2m) only. It has been modeled as a solid at the top of casing. It should be noted that the initial vertical part of a typical well has not been taken into account. Reason being that the coiled tubing is considered to be in the center of the casing and therefore does not undergo any impact due to contact forces with the casing. It is only through the bends and turns in the casing, following the well path, that forces from the casing wall are applied onto the outer surface of the coiled tubing. Therefore the model used considers the coiled tubing at the very start of the bend where it touches and is forced by the rigid casing to deform.

After the two geometries are developed in the CAD software (Autodesk inventor), these are imported into the Ansys software for simulation. As defined afterwards, the model is refined for the said analysis:

- contact points are defined in the geometries that would allow interaction of the coiled tubing with the casing
- Boundary conditions are applied that define the movements and the deformation of the system.

The force-displacement model used in analyzing the case can have two different scenarios in which it can be used:

- Force is applied at one end of the coiled tubing and it is pushed through the bends inside the casing which causes it to deform accordingly.
- Or the simulation program is asked to simulate certain displacement of the coiled tubing inside the casing. As a result it automatically deforms during the motion.

The second scenario (force convergence) was chosen for analysis (as we are not concerned with the initial applied force, but the deformation that takes place in the coiled tubing as it makes its way through the bends in the well path) and initially the program was asked to displace a total of 200mm of coiled tubing length inside the casing.

Following this, 'mesh' is generated for the model, whereby the geometries are divided into discrete elements for analysis that define the procedure of FEA. Of note is the number of elements and the corresponding nodes that were generated for just a 3m long casing model and 2 meter long tubing model. The number of nodes challenged the processing capability of the software version available for use.

Next is to define the 'solutions' that are of interest in the analysis. The options available with this particular version included:

- deformations/stress in x-direction
- deformations/stress in x-direction
- deformations/stress in x-direction
- axial deformation/stress and
- von-Mises stress.

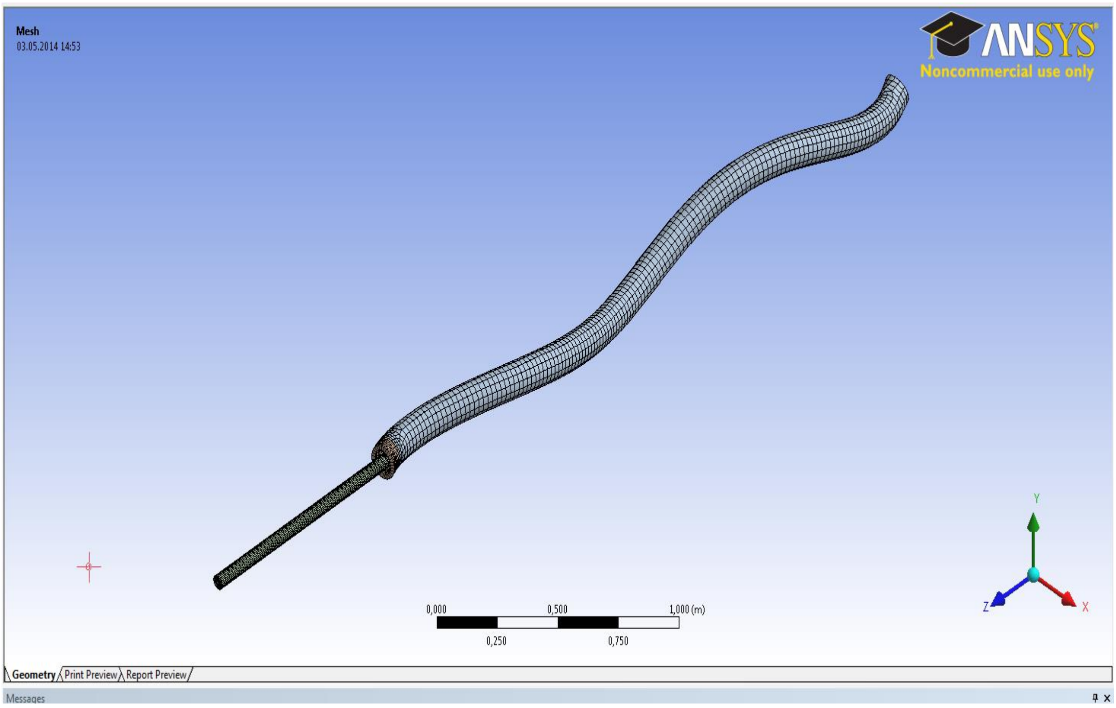


Figure 17 Meshed Model

Having done all the above, the mesh model as shown in figure 17 is then ready to be run in the simulation program. The results of simulations are seen as graphs. Several attempts were made to get desired results.

Results for each simulation showed varying graphical results (shown in appendix A). Therefore several points that need to be considered here before proceeding with analysis using this license of the software include:

- Software gives results for deformations and stresses produced in the 3-dimensions and along the axis only. It does not give information about stress/deformation in radial positioning of the coiled tubing
- Limited capacity to simulate models (that is defined by number of nodes and elements. The software allowed processing 32000 nodes only whereas the nodes generated for the model defined previously were also of the same order).
- Graphical results for each similar simulation give different output (this is attributed to software processing capability being limited).
- Limited time to complete the thesis using this method/technique including all the desired effects for simulation of a real well. As this course is for Master's program in Mechanical engineering and there was no background knowledge about this subject.

Following this limitation that is attributed to the software license available and time limitation for this work, it was argued and decided that another method for delivering with our stated objectives need to be used.

Considerable amount of the total work time had been spent on this part of the thesis work because of no experience of using simulation software and no background knowledge of the numerical techniques used for such analysis. Therefore, for reasons mentioned above the activity could not satisfy the objectives of the thesis as desired.

This however does not mean that there is shortfall in the technique and method used. Simulation software using finite element method of analysis is being increasingly used for designing of various petroleum activities. Examples of various studies that have been undertaken at petroleum research institutes like the University of Tulsa are provided in the references that indicate the vast application of simulation software using FEA that can be put into use for petroleum activities to make them economical, safer and environmental friendly.

CHAPTER 5 AXIAL AND RADIAL POSITIONING OF TOOL DOWN HOLE

Coiled tubing drilling operations had started in early 60's, and the use of coiled tubing saw a great expansion over decades. It is now being used for a variety of operations that include drilling, logging, perforation, stimulation, sand control, wellbore cleanout and fishing.

Abandonment operations using coiled tubing, in particular abrasive cutting operations, present a particular challenge related to tool positioning down hole. In chapter 4 simulation method was proposed that can be developed for detailed analysis and research on the problem. The results of the FEA analysis presented in appendix A were not as expected due to reasons defined at the end of chapter 4. Therefore in this chapter, a basic analytical approach; which is an alternate approach required by the objectives of this work, has been described that can form basis for further study and development of a solution to the problem.

The coiled tubing is spooled onto a reel for storage and transportation purpose. The strings can be several thousand meters in length and can have a range in diameters from 1" up to 4 1/2". A power pack in the control cabin drives the injector head to run the coiled tubing and pull it out from a well in petroleum activities. The continuous coiled tubing passes over a goose neck and through the injector head before it is inserted into the well. In almost all coiled tubing operations there are six bending events as it runs in hole and is pulled out of the hole

1. Run in hole(RIH) off the reel - bent to straight
2. RIH onto the gooseneck - straight to bent
3. RIH off the gooseneck onto the injector - bent to straight
4. Pull out of hole(POOH) from the injector onto the gooseneck - straight to bent
5. POOH off the gooseneck towards the reel - bent to straight
6. POOH onto the reel - straight to bent

Besides these repeated loads, during petroleum activities, several other load components add up to the effect on the coiled tubing which include, the tensile loads, compressive loads, effect of fluids travelling through/outside the coiled tubing, the contact forces being experienced by the tubing through the bends as it forced through the well path etc

Therefore coiled tubing endures a history of unique cyclic stresses and strains. These loadings can result in deformation mechanisms resulting in plastic diametric growth and/or elongation. This deformation can occur in spite of both hoop and axial stress being below the limits of material yield stress. A change in structure of coiled tubing results in corresponding change in mechanical properties. The loadings on the tubing can thus be divided into two categories:

- Above surface environment
- Sub-surface environment

Various plasticity theories and models have been developed to define the mechanism of deformation of the coiled tubing. As the coiled tubing is used in the petroleum activities, the six bending effects described previously have a significant effect of the curvature on tubing as the tubing is reel onto a spool of some radius (or diameter). Section of the tubing wrapped near to the core of the spool has a tighter radius of curvature than the subsequent layers wrapped on top. Going further, the convex side of the tubing is loaded in tension while the concave side of the tubing is in compression. The effect of this and the forces it experiences while passing through other equipment before it finally enters the well can result in residual bending stresses.

In this study however, we will be concerned with the general *sub-surface environment* effects and the deformations it can cause and the affect it can have on the actual positioning of the tool down hole at depth of several thousand meters.

5.1 Positioning of Tool down Hole

As described in chapter 4 FEA (finite element analysis) is one of the techniques that can be used to predict the deformation in the tubing. The simulation softwares, like the Ansys 13.0 used to model the behavior in this work, can be used to model the whole environment of the well and its condition down hole which would give a more accurate result of various forces and their effects on coiled tubing operations. Following this an analytical approach has been described that may help in predicting the deformations.

5.1.1 *Radial Positioning:*

Advances in directional drilling techniques in recent decades have contributed immensely to increase petroleum activities around the globe. Directional drilling requires the art and science to deflect the wellbore in a particular direction to reach a pre-defined target down hole. Measurement while drilling is the process by which relevant information is measured down hole near the tool and it is transmitted back to the surface without interrupting the ongoing operations(Inglis 1987). The various types of information that can be gathered include:

- directional data (inclination, azimuth)
- formation characteristics (gamma ray, resistivity logs)
- drilling parameters (down hole weight on bit, torque, rpm)

When planning the trajectory of a well, it is important to have the tool pointed in the required direction before the drilling begins. The information required to set the tool face properly, a directional driller requires the directional data. A series of surveys can then be taken during operations to ensure accurate drilling operations.

With the scope of work defined in the first chapter of this work, we would make use of the directional data gathered from MWD to determine accurate positioning of the tool down hole.

To calculate the tool face angle from the dog-leg and the change in inclination the following equation can be used:

$$TF = cos^{-1}\left(\frac{cos \propto_1 \;\; cos \propto_2 \;\; DL - cos \propto_2}{sin \propto_1 \sin(DL)}\right) \qquad (5.1)$$

where α_1, α_2corresponds to initial and final inclination angle and "DL" corresponds to the dog-leg angle.

Using the basics of directional drilling technique, the accurate radial positioning of the tool can be determined down hole. For a well "AA" defined later, change in tool face angle through its well path is shown in figure 18.

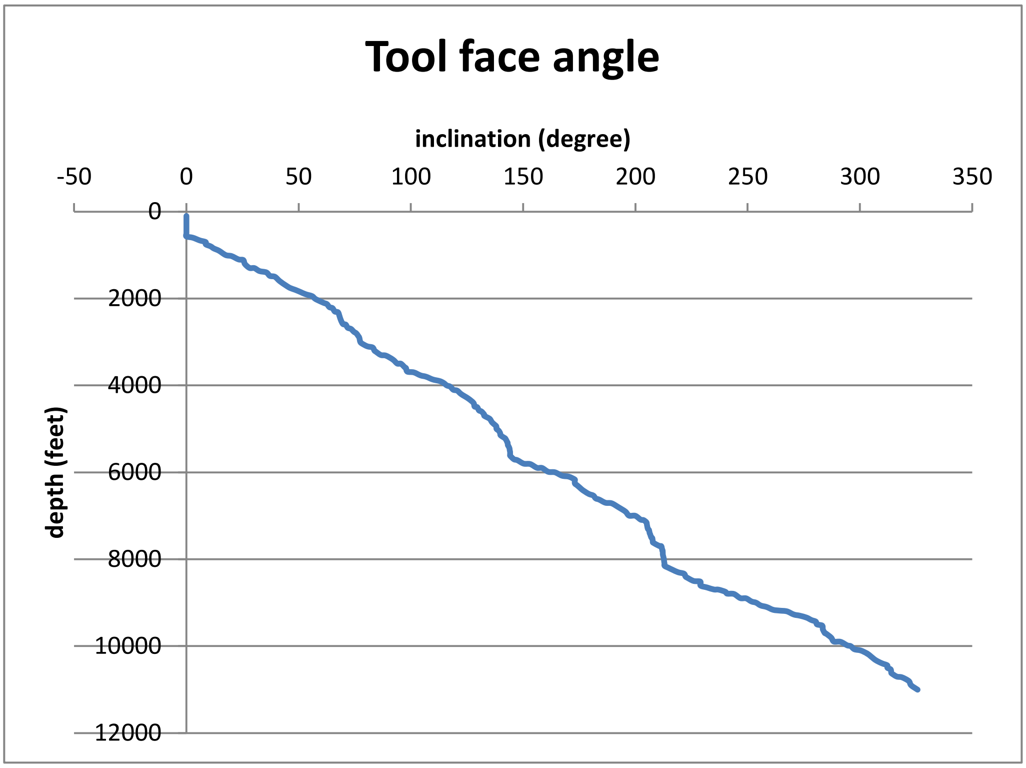


Figure 18 Changing tool face position with inclination and azimuth

5.1.2 Axial Positioning

Coiled tubing is a continuous pipe that is, reeled on to a spool, to be used in various well activities. Limitations of coiled tubing life determine the overall coiled tubing working parameters and durability. The most important property of CT is its value for axial, collapse and burst pressure ratings.

A simple tubing force model can be described for understanding the forces that can act on during coiled tubing operations. The model assumes a straight pipe pushed into a hole. The forces required to push are divided into components, as shown in figure 19, where the friction component increases as the pipe is pushed farther into the hole provided it is in contact with the outer boundary i.e. in an inclined or horizontal hole and not a vertical hole where the tube is considered concentric with the hole.

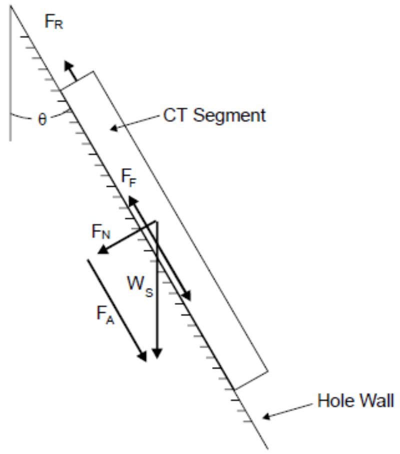


Figure 19 Force components for a section of coiled tubing

The weight component can be broken into two component forces F_A (force component in axial direction) and F_N (force component in normal direction) given as:

$$F_A = W_s cos\theta \quad (5.2a)$$

$$F_N = W_s sin\theta \quad (5.2b)$$

The friction force (F_F) is then given as following:

$$F_F = \mu F_N \quad (5.2c)$$

It is this basic model that describes the forces for one segment of the coiled tubing. Summing these results for the entire length of coiled tubing would give axial forces through the well path.(Ken Newman 2003)

Besides these direct contact forces, internal and external pressure are acting during operations due to fluids circulating in and around the coiled tubing that result in indirect forces. These are in addition to the tension or compression in string caused by axial forces described in the tubing force model above. This axial stress in tension is given by:

$$\sigma_a = \frac{F_a}{A} \quad (5.3)$$

where "A" is the cross-sectional area of the Coiled tubing. When the forces are in compression, a "negative" sign is added to the expression.

Furthermore, to find stresses due to fluid pressures, coiled tubing are categorized as thick wall cylinders (in this particular case). To find stress fields a combination of equilibrium equations, compatibility equations and appropriate boundary conditions are used.

These radial and hoop stresses that act in the body of the tubing are given by Lame's equations as:

Radial Stress

$$\sigma_r = \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2} - \frac{(P_i - P_o) r_i^2 r_o^2}{(r_o^2 - r_i^2) r^2} \tag{5.4}$$

Hoop Stress

$$\sigma_h = \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2} + \frac{(P_i - P_o) r_i^2 r_o^2}{(r_o^2 - r_i^2) r^2} \tag{5.5}$$

In these equations, P_i, is the internal pressure associated with r_i as internal radius, P_o, is the external pressure associated with r_o external radius and r is the radial location of the coiled tubing wall. The location can be taken as either the inner or outer surface of the tubing. Calculations made in this work take external surface as area of interest as the bending and loads due to force in the well first act at the outer body of the coiled tubing.

Axial Stress considering forces due to pressure affects

The axial stresses are defined by two types of forces known as "real force" and the "effective force" or "fictitious force". The real force is the actual axial force in the pipe wall calculated by summing up the weight component of the coiled tubing. The effective force is the axial force if the effect of pressure is ignored in the calculations.

The relationship between the effective and real force is given by:

$$F_e = F_a + p_a A_a - p_b A_b \tag{5.6}$$

Bending Stress

Bending stresses are caused by drilling doglegs or by buckling. One reason for taking the outer boundary of the coiled tubing for calculations is that bending stresses are greater at the outer diameter of the pipe. They are given as:

$$\sigma_{DL} = \pm\frac{ED}{2R} = \pm(\pi.E.DL.D_o)/432000 \qquad (5.7)$$

Where DL is the dogleg, R- radius of curvature, "+"positive sign is used when in tension on the outside of the bend and "-" negative sign is used for compression-on the inner side of the bend. The bending stresses are added with the axial stresses to yield minimum and maximum axial stresses given as:

The minimum axial stress:

$$\sigma_{a\max} = \sigma_a - \sigma_{DL} \qquad (5.8a)$$

The maximum axial stress:

$$\sigma_{a\max} = \sigma_a + \sigma_{DL} \qquad (5.8b)$$

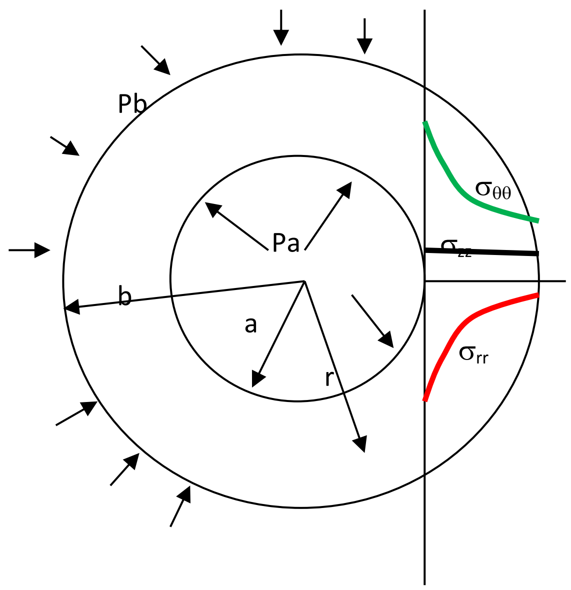


Figure 20 Tangential and radial stress distribution across wall thickness of tube

The stress distribution due to pressure effects across the thickness of the tubing is as shown in figure 20.

Special Case:

a) Internal pressure only, lame's equation (5.4) (5.5) reduces to:

$$\sigma_{rr} = \frac{P_a a^2}{b^2 - a^2}\left(1 - \frac{b^2}{r^2}\right) \quad (5.9a)$$

$$\sigma_{\theta\theta} = \frac{P_a a^2}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right) \quad (5.9b)$$

$$\begin{cases} \sigma_{zz} = 0 & \text{Open} - \text{Ends} \\ \sigma_{zz} = 2\upsilon \dfrac{P_a a^2}{b^2 - a^2} & \text{Closed} - \text{Ends} \\ \sigma_{zz} = \dfrac{P_a a^2}{b^2 - a^2} & \text{Closed} - \text{and} - \text{Open} - \text{ends} \end{cases} \quad (5.9c)$$

b) External pressure only, (P_a =0), equation(5.4) (5.5 reduces to:

$$\sigma_{rr} = -\frac{P_b b^2}{b^2 - a^2}\left(1 - \frac{a^2}{r^2}\right) \quad (5.10a)$$

$$\sigma_{\theta\theta} = -\frac{P_b b^2}{b^2 - a^2}\left(1 + \frac{a^2}{r^2}\right) \quad (5.10b)$$

$$\begin{cases} \sigma_{zz} = 0 & \text{Open} - \text{Ends} \\ \sigma_{zz} = -2\upsilon \dfrac{P_b b^2}{b^2 - a^2} & \text{Closed} - \text{Ends} \\ \sigma_{zz} = -\dfrac{P_b b^2}{b^2 - a^2} & \text{Closed} - \text{and} - \text{Open} - \text{ends} \end{cases} \quad (5.10c)$$

Burst pressure is calculated as minimum internal pressure that will cause coiled tubing to rupture in the absence of external pressure whereas the collapse pressure is defined as the minimum external pressure that causes the coiled tubing walls to collapse in the absence of any internal pressure. As a result of API collapse test data, four collapse models have been developed (Davorin Matanovic 1998):

Elastic collapse is the one in which the axial or hoop stress causes the tube to buckle below its yield stress of the material.

Plastic collapse results when the moment of inertia of the tube increases or as the diameter of cross section decreases and a point is reached where the buckling does not occur until the axial or hoop stress exceeds the yield strength of material

Transition collapse mode results from an error in statistical determination of minimum curves for elastic and plastic collapse and does not actually exist.

Yield Collapse is based on the initial yielding at the inner radius of the tube.

Failure Theories besides the above mentioned collapse limits are used for establishing design criteria for the coiled tubing. Among several theories, the one used for our design calculations is:

VON-MISES FAILURE

Von-Mises criteria is used to describe yielding of steel under a state of combined stress. The yield limit is based on a combination of the three principal stresses namely, the axial , radial and hoop stresses. Moreover the shear stress is caused by torque. The expression for von-mises criteria is given as:

$$\sigma_{\mathrm{VME}} = \sqrt{\frac{1}{2}\left\{(\sigma_\theta - \sigma_{\mathrm{r}})^2 + (\sigma_{\mathrm{r}} - \sigma_{\mathrm{a}})^2 + (\sigma_{\mathrm{a}} - \sigma_\theta)^2\right\} + 3\tau^2} \qquad (5.11)$$

In our case of calculating the critical stress using the above function, as there is no applied torque for the coiled tubing. Therefore the shear stress term drops out of the equation.

5.1.2.1 3D FRICTION MODEL

Well friction is a critical parameter during drilling, completion and work over operations during the lifetime of a well. Therefore knowledge and control of well friction is important and a simple method for computing well friction shown by (Fazaelizadeh 2010) has been used in this work for a particular well geometry. Soft string model analysis is used here.

Buoyancy Factor

The effective string weight in a fluid filled well is given by:

$$\beta = 1 - \frac{\rho_o A_o - \rho_i A_i}{\rho_{pipe}(A_o - A_i)} \qquad (5.12)$$

in which case the density of the fluid outside and inside the string is different.

Otherwise if the fluid density is equal at the outside/inside of the pipe, which is in this case;

$$\beta = 1 - \frac{\rho_o}{\rho_{pipe}} \qquad (5.13)$$

It has been shown by (Bernt S. Aadnoy 1999) that the static hook load of a pipe is equal to the product of buoyed pipe weight and the projected vertical height of the well regardless of the well bore orientation.

Two sets of equations (5.15) (5.15) give hook loads for hoisting and lowering operations which correspond to the axial stresses that are produced in the string (coiled tubing in our case) during operations. These equations include friction model for a straight well section and an oriented well section. (Aadnoy 2010)

A straight section is dominated by the weight component of the string where as the normal weight component is then responsible for the friction. The expression is given as:

$$F_2 = F_1 + \beta w \Delta l \{cos\alpha \pm \mu sin\alpha\} \qquad (5.14)$$

Where "+" is for hoisting operations and "-" is for lowering operations.

For a curved wellbore section that may have any arbitrary direction because of change in its azimuth and inclination the effect of dogleg angle is used in the expression. This accounts for pipe contact with either the high side or the low side of the well. Therefore for buildup, drop-off, side bends or a combination of any of these the expression is given as:

$$F_2 = F_1 e^{\pm\mu(\theta_2 - \theta_1)} + \beta w \Delta l \left\{\frac{sin\alpha_2 - sin\alpha_1}{\alpha_2 - \alpha_1}\right\} \qquad (5.15)$$

5.1.2.2 TEMPERATURE EFFECT

During well operations, as fluids are transported through the tubing and annulus, heat exchange takes place and the system can be taken as analogy to a heat exchanger. The major heat transportation takes place through the conduction and convection modes. A model was presented (Aadnoy 1997) to analyze and predict the temperature profiles during drilling operations. The results were comparable to the field data. The temperature profiles for the string and the annulus were given as:

Tubing String:

$$F_2 = F_1 e^{\pm\mu(\theta_2-\theta_1)} + \beta w \Delta l \left\{\frac{\sin\alpha_2 - \sin\alpha_1}{\alpha_2-\alpha_1}\right\} \quad (5.16)$$

Annulus:

$$T_a(z,t) = (1+\lambda_1 B)\alpha e^{\lambda_1 z} + (1+\lambda_2 B)\beta e^{\lambda_2 z} + g_G z - B g_G + T_s \quad (5.17)$$

λ_1, λ_2, α, β, A and B are given as:

$$\lambda_1 = \frac{1}{2A}\left(1-\sqrt{1+\frac{4A}{B}}\right) \quad (5.17a)$$

$$\lambda_2 = \frac{1}{2A}\left(1+\sqrt{1+\frac{4A}{B}}\right) \quad (5.17b)$$

$$\alpha = -\frac{(T_{in} + B g_G - T_{sf})\lambda_2 e^{\lambda_2 D} + g_G}{\lambda_1 e^{\lambda_1 D} - \lambda_2 e^{\lambda_2 D}} \quad (5.17c)$$

$$\beta = -\frac{(T_{in} + B g_G - T_{sf})\lambda_1 e^{\lambda_1 D} + g_G}{\lambda_1 e^{\lambda_1 D} - \lambda_2 e^{\lambda_2 D}} \quad (5.17d)$$

$$A = \frac{w C_{f1}}{2\pi r_c U_a}\left(1 + \frac{r_c U_a f(t_D)}{K_f}\right) \quad (5.17e)$$

$$B = \frac{wC_{f1}}{2\pi r_c U_a} \tag{5.17f}$$

Assuming steady state condition, temperature in the drill string can be calculated as:

$$T = \frac{(T_d - T_a)}{\ln(^d/_a)} \ln(^a/_r) + T_a \tag{5.18}$$

And the temperature change is the given by:

$$\Delta T = T - T_{sf} \tag{5.19}$$

Where T_d = temperature in drill string

α = coefficient of thermal expansion

z = vertical depth

g_G = geothermal gradient

T_{sf} = temperature at surface

A simple model which then shows the effect of temperature i.e. thermal expansion in 1D is given as:

$$\Delta L = \alpha L \Delta T \tag{5.20}$$

where ΔL is change in length and L is the original length.

Temperature profiles according to Eirik and Bernts model are given in figure 21.

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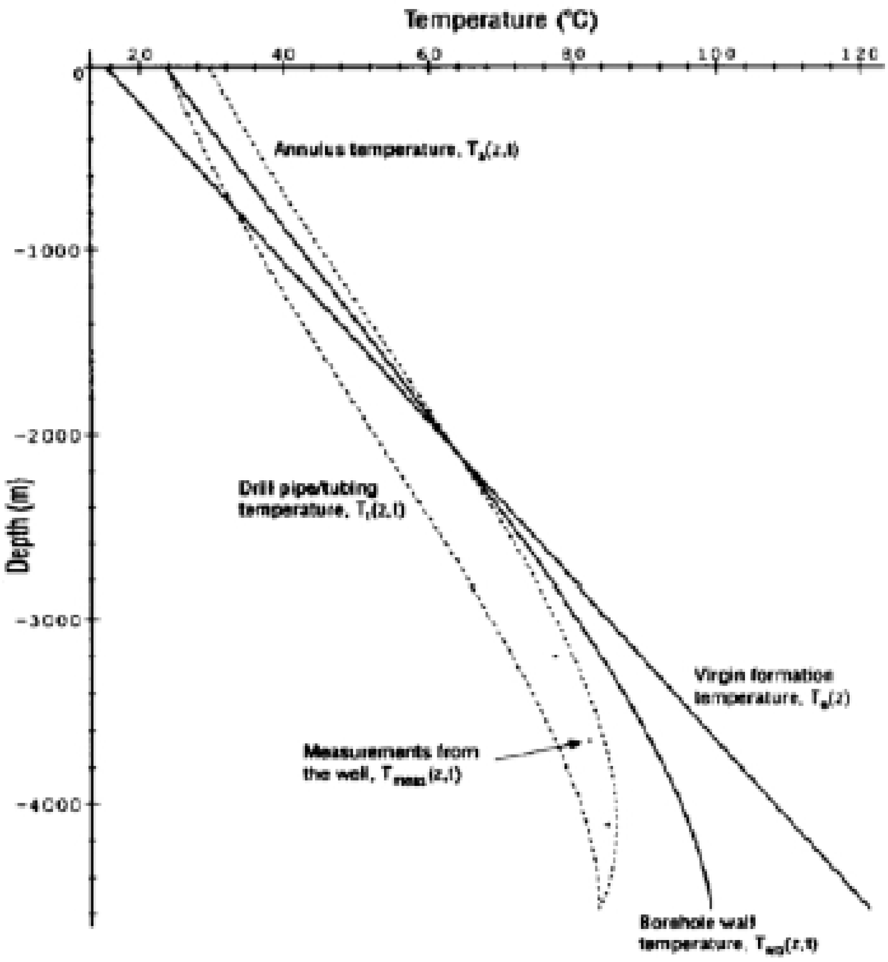


Figure 21 Temperature profiles

5.1.2.3 BUCKLING

Well operations are an integration of geo-mechanical engineering and drill string mechanical engineering discipline. Knowledge from both these fields, if coupled carefully can result in reducing expenditures related to drill string and formation related problems.

In this work we are concerned with the drill string related problems and in our case we will focus coiled tubing in particular. The failure with the string results either due to tensile or compressive loads or due to dynamic string vibrations. These problems in worst case may even cause a total abandonment of operations that may result in huge losses, financially and environmentally. Figure 22 shows the safe operating window for tubing during operations.

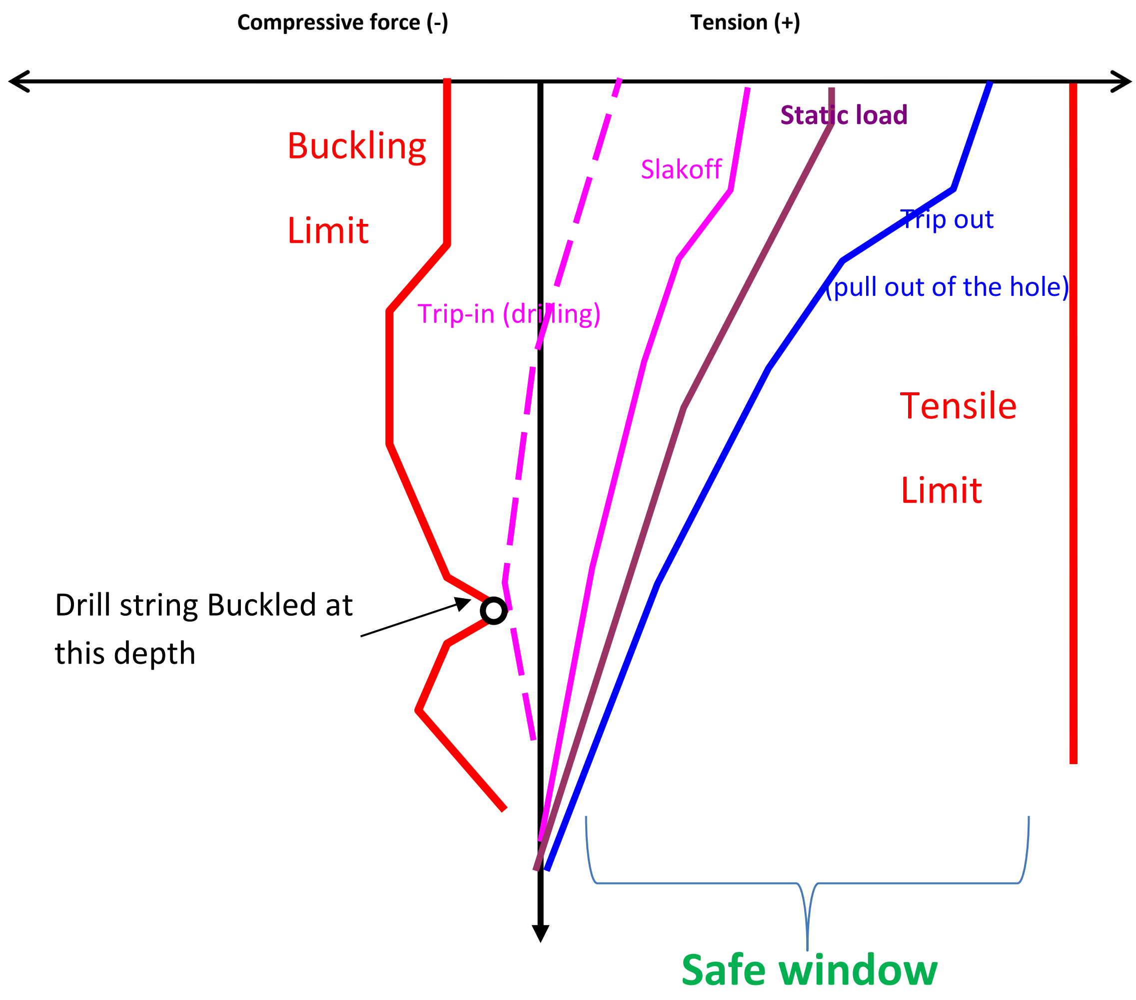


Figure 22 Limits defined during mechanical string analysis

EULERS CRITICAL BUCKLING LOAD

For Euler's buckling load, the column should be fixed at one end and the load is applied at the other end that causes it to deform as shown in figure 23.

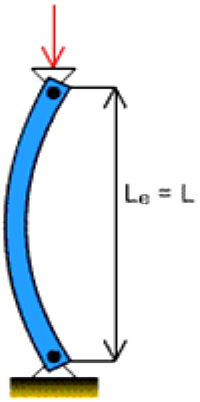


Figure 23 Euler beam buckling

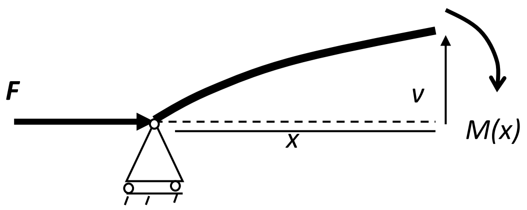


Figure 24 Beam free body diagram

The free body diagram shown in figure 24 depicts the moments and forces acting on the cross-sectional area of the buckled beam column. (Belayneh 2006) The relationship showing moment and transverse displacement is given as:

$$M = -EI\frac{d^2v}{dx^2} \quad (5.21)$$

where "I" moment of inertia is given as $I = \frac{\pi}{64}(OD^4 - ID^4) = \frac{\pi}{4}(OR^4 - IR^4)$

Substituting the above expression for "I" in the moment relationship (5.21) gives a second order homogenous ordinary differential equation with constants "A", "B" and is given as (Mesfin 2013):

$$v(z) = A\sin(\alpha x) + B\cos(\alpha x)$$

Applying boundary conditions and solving the equation gives force expression:

$$F = \frac{n^2\pi^2 EI}{L^2} \quad (5.22)$$

Equation (5.22) defines the buckling loads of a column.

The lowest buckling load is then called the "critical buckling load" given when "n=1":

$$F_{cr} = \frac{\pi^2 EI}{L^2} \tag{5.23}$$

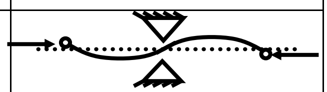
The associated shape in the buckled mode is given by:

$$v(x) = A\sin(\alpha x) \tag{5.24}$$

This gives a half sine wave for critical buckling load. The constant "A" in the equation above signifies the amplitude of the buckled shape.

Buckling loads greater than the critical buckling load (load that initiates the buckling process) would further damage the string/column, if there are physical restraints that do not allow lateral displacements. Table 3 below summarizes the buckling modes.

Table 3 Buckling modes

	n=0	**n=1**	**n=2**
$\boldsymbol{F_{cr}}$	$< F_{cr}$	$\frac{\pi^2 EI}{L^2}$	$\frac{4\pi^2 EI}{L^2}$
Mode			

5.1.3 Modes of Buckling In Oil Wells

Buckling in oil wells is different to Euler buckling which has been presented earlier. Figure 25 shows a typical orientation of oil well which comprises vertical, oriented and horizontal sections.

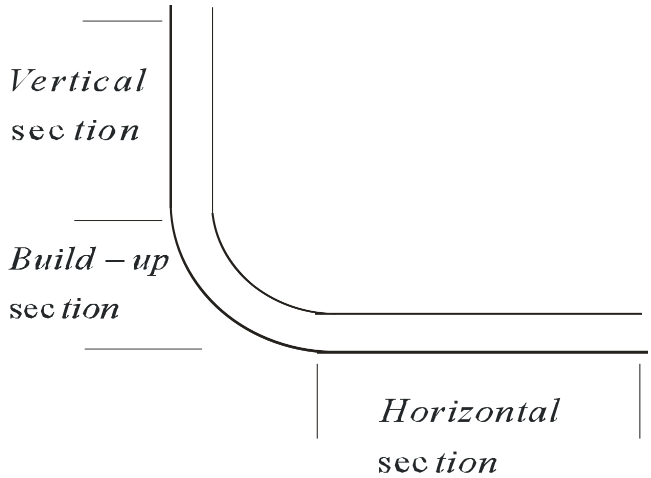


Figure 25 Orientation of a typical well

To calculate buckling loads, all the loads acting on the tube/string inside the well need to be known. Free body diagram of a section of string shown in figure 26 gives an idea of different kind of loads that need to be considered while designing the tubing string.

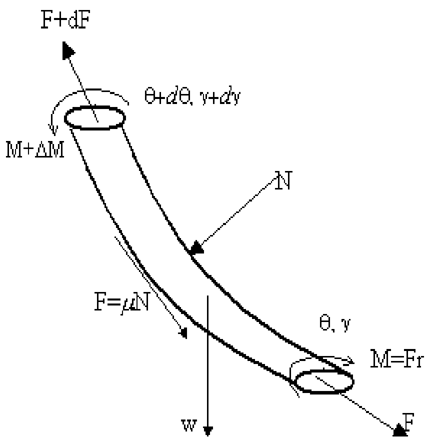


Figure 26 Force and moment vectors for a well section

An oil well tube/string can buckle either in sinusoidal or helical modes. Various stages of buckling are explained as under:

Sinusoidal Buckling:

This is the first phase of buckling with the applied load exceeding the critical buckling load for a particular case. The shape of buckled pipe would look like a sinusoidal if seen from a side view. In this case the axial force can still be transferred to the tool/bit at the end of tubing down hole. This is also known as snake buckling. Sinusoidal buckling occurs in that part of the well where the axial forces exceed the critical buckling limit. This however does not define a limit to which the pipe can be pushed into the well.

Helical Buckling:

This is the second phase of buckling. When the load increases sufficiently it forces the tube to form a helix inside the casing. The applied load is then referred to as the helical buckling load. The force applied at the top of the string is transferred to the tool down hole however at much smaller ratio. Much of it is consumed due to friction at the contact points. The walls of the wellbore/casing constrain sinusoidal buckling and the helix takes on the post buckling shape. Helical buckling also does not define the limit to which the tubing can pushed into the well.

Lock-up Stage:

This situation takes place when "no-force" is being transferred to the bottom of the string. The wall contact forces due to friction are so high that all the force applied from the top is lost in it. This stage defines the reach limit of tubing string in oil wells theoretically.

5.1.4 Buckling Models (Literature Review)

Lubinski (Lubinski 1950) was the pioneer for the treatment of drill string stability analysis. He was the first one who proposed critical load for first mode of buckling to be calculated as:

$$F = 1.94(EI)^{\frac{1}{3}}w^{\frac{2}{3}} \tag{5.25}$$

Afterwards Wang proposed that the constant in the above equation should be 1.018793 instead:

$$F = 1.018793(EI)^{\frac{1}{3}}w^{\frac{2}{3}} \tag{5.26}$$

It was not until 1962 that Lubinski published another fundamental paper in which he presented the force-pitch relation which was derived as:

$$F = \frac{8\pi^2 EI}{p^2} \tag{5.27}$$

Where E is material property and I is the polar moment of inertia. "p" in the denominator is the pitch length which is given as:

$$p^4 = \frac{8\pi^4 EIr}{wsin\alpha} \tag{5.28}$$

Where r is the radial clearance between the coil tubing and casing, w is weight per unit length and α is the inclination.

Furthermore, upon the application of external force given by equation (5.27), the displacement as function of pitch 'p', as shown in figure 27, is given as:

$$\Delta = \frac{2\pi^2 r^2 L}{p^2} \tag{5.29}$$

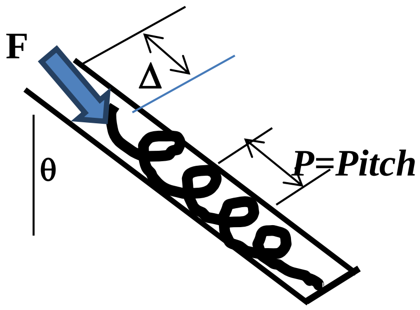


Figure 27 Force, displacement and pitch relationship

Equations (5.28) and (5.29) have been derived using the energy balance method.(Cunha 1995)

The work then carried on with contributions made by various people. Dawson and Paslay (Paslay 1982) who for the first time developed an expression for critical force of sinusoidal buckling of pipes. Mitchell took a step further in including the effect of friction into the problem. He also presented a generalized solution for helical buckling.

Chen made his contributions by presenting analysis of buckling in horizontal wells. They concluded that force necessary to cause helical buckling was 1.4 times greater than the force to cause sinusoidal buckling.(Cunha 2003)

A review of theories given by various authors for vertical and inclined well bores is given in the following section:

5.1.4.1 Buckling Models In Vertical Wells

Sinusoidal buckling

For a long pipe in a vertical well bore, Lubinski proposed critical load for sinusoidal buckling:

$$F_{\sin} = 1.94\left(EIw^2\right)^{1/3} \tag{5.28}$$

where

E = E-modulus

I = Axial moment of inertia of tubing

w = Buoyant weight per unit length of tubing

Wu et al, developed an expression for sinusoidal buckling for vertical wells:

$$F_{\sin} = 2.55(EIw^2)^{1/3} \tag{5.29}$$

The two equations are equal except for the coefficient. Wu et al.'s model gives a 31% higher limit than Lubinski's.

Helical buckling

For the onset of helical buckling Wu et al. found:

$$F_{hel} = 5.55(EIw^2)^{1/3} \tag{5.30}$$

Their critical load for helical buckling is thus about 2.2 times larger as the sinusoidal buckling load.

5.1.4.2 Buckling Models Inclined Wells

Sinusoidal Buckling

Dawson and Paslay analysed the stability of a drill string constrained in circular, inclined well.

$$F_{\sin} = 2\left(\frac{EIw\sin\alpha}{r}\right)^{0.5} \quad (5.31)$$

where α is angle of inclination, r is radial clearance & w is weight per unit length

Helical Buckling

Chen's model assumes a constant load vs. displacement history. Using an energy principle they derived the following equation for the onset of helically buckling in a horizontal well:

$$F_{hel} = 2\sqrt{2}(EI)^{0.5}(w\sin\alpha)^{0.5}(1/r)^{0.5} \quad (5.32)$$

This model scales the critical load for sinusoidal buckling in the model of Dawson and Paslay by the factor $\sqrt{2}$.

According to Wu and Juvkam-Wold the critical helical buckling force is presented by:

$$F_{hel} = 2(2\sqrt{2}-1)(EI)^{0.5}(w)^{0.5}(\sin\alpha/r)^{0.5} \quad (5.33)$$

5.1.4.3 Buckling in Curved sections

For curved sections the models predicted by Mitchell is as follows:

$$F_{sin} = \frac{2EI}{rR}\left[1 + \sqrt{1 + \frac{w\sin\alpha . r}{EIR}}\right] \quad (5.34)$$

where R is the curvature radius.

For Helical buckling in curved wellbores, the expression is given as:

$$F_{hel} = 2.83F_{sin} \tag{5.35}$$

5.2 Analysis of a Real Well

A real well "AA" is chosen for analysis. The directional data has been obtained and used for the purpose and it is established that the well needs to be plug and abandoned using coiled tubing for operations. Hand calculations have been done for coiled tubing design.

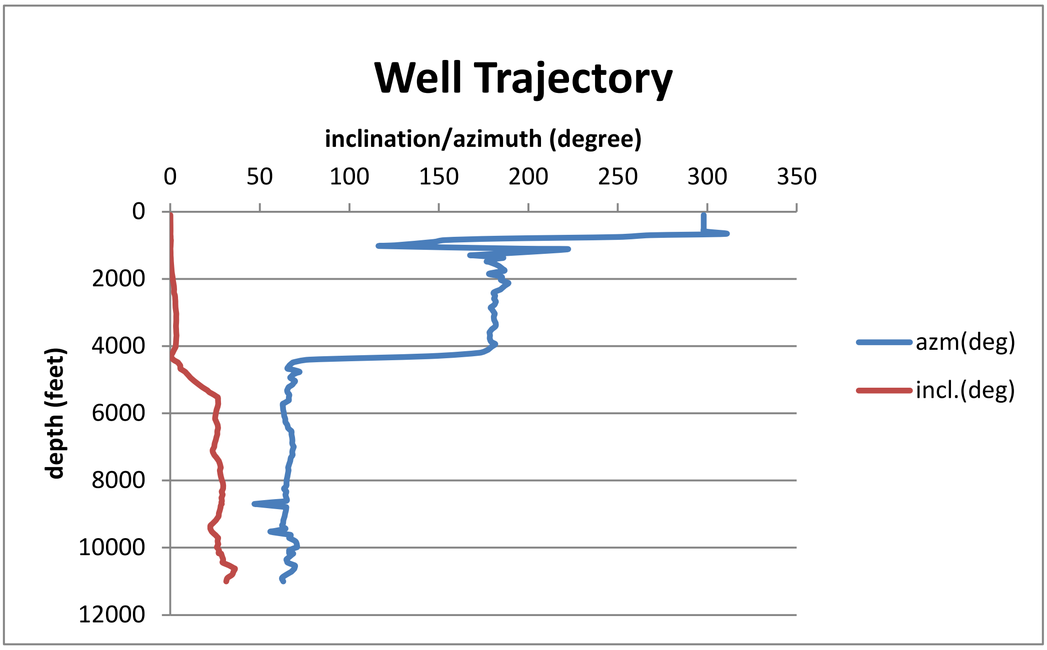


Figure 28 Well trajectory of real well AA

The well has a measured depth of 11003 ft / 3353 m. The well path is as shown in figure 28. The well is initially vertical; with deviation starting around 1600 ft goes up to 3.4 degrees at 3800ft. However the well path is adjusted and inclination is brought at near vertical at 4300ft. So for this section of 4300ft depth, we assume it to be a vertical well.

Alongside change in inclination, the azimuth has also been adjusted from around 300 degree north back to around 60 degree north and thereafter it is maintained till the final depth of the well. The dogleg angle for the well path is calculated and represented graphically in the figure 29.

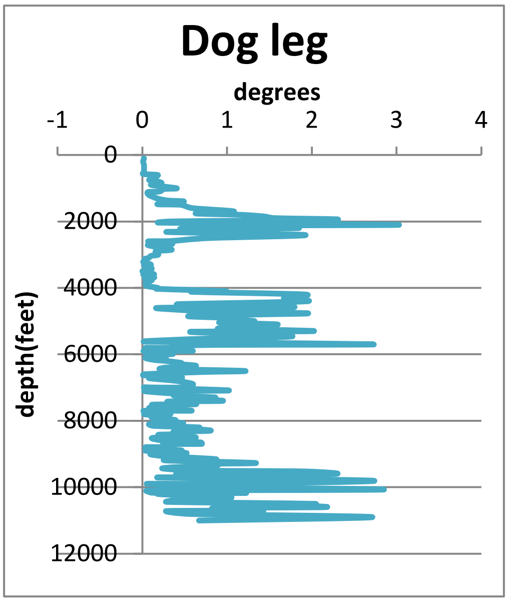


Figure 29 Dogleg variation

With the well path defined, the next step is to calculate the various stresses that are acting on the coiled tubing due to its own weight, the fluids pressure inside and outside, and effects due to temperature. All these have been defined in detail earlier. The graphical representation of the calculated values is given in figure 30.

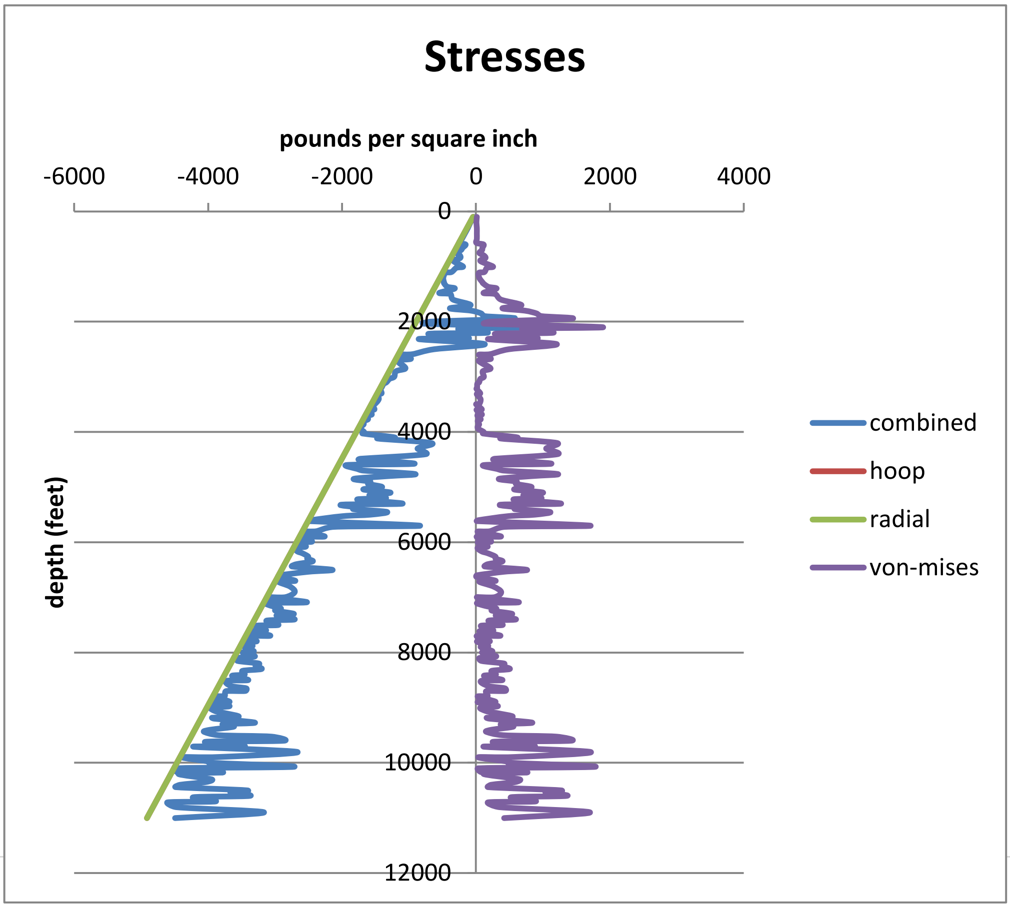


Figure 30 Stress variations with depth

With the fluid density inside and outside taken as same for the operation, the hoop and the radial stresses have the same values as pressure only depends on the fluid height. The combined stresses give an account of axial stresses that also includes the bending stresses.

The coiled tubing chosen for consideration is QT-900 that has yield strength of 90 kpsi. The graph above shows very clearly that the yield strength is not exceeded. The von-Mises failure curve further authenticates this for a case of similar density fluids on the inside and outside of the coiled tubing.

The diagram for 3D friction model, that has been described earlier, is in accordance with the typical graphical trends that it represents. It further gives us an idea that the axial tensile forces, which are greatest during POOH (pulling out of hole) operation does not exceed the yield strength. However even with these forces, the extension that can result during pulling operations is significant and thus is detrimental for knowing the axial position of the tool down hole.

A further complication is introduced into the operation with coiled tubing when the buckling effects are considered. Coiled tubing due to its dimensions and strength faces major operational limits due to buckling as it limits its reach in long wells for various operations. Using Lubinski model for vertical section of the well and Dawson and Pasley for the curved and inclined sections, the compressive forces are mere few kilo-Newton of force that may cause it to buckle. Therefore special consideration should be given so that the limits are not exceeded.

For buckling effect, it should be noted that the critical buckling forces are greater in the inclined and bend sections of the well than the vertical section.

The tensile forces generated during the RIH (run in hole) and POOH (pull out of hole) operations can be used to calculate the elastic elongations produced that range in a few meter in length. However, these need to be predicted accurately for each case to get accurate axial positioning of the tool down hole.

Table 4 shows the forces calculated using the 3D friction model and the buckling force limits, which is graphically represented in figure 31.

Dpeth(ft)	Force(pull)kN	Force(lower)kN	Force(static)kN	Buckling load(kN)
11003	0	0	0	--0.348
5500	87.77	72.07	81.54	-21.27
4300	104.99	81.93	97.9	-1.399
0	174.6	151.54	167.5	-1.399

Table 4 Forces with depth during operations

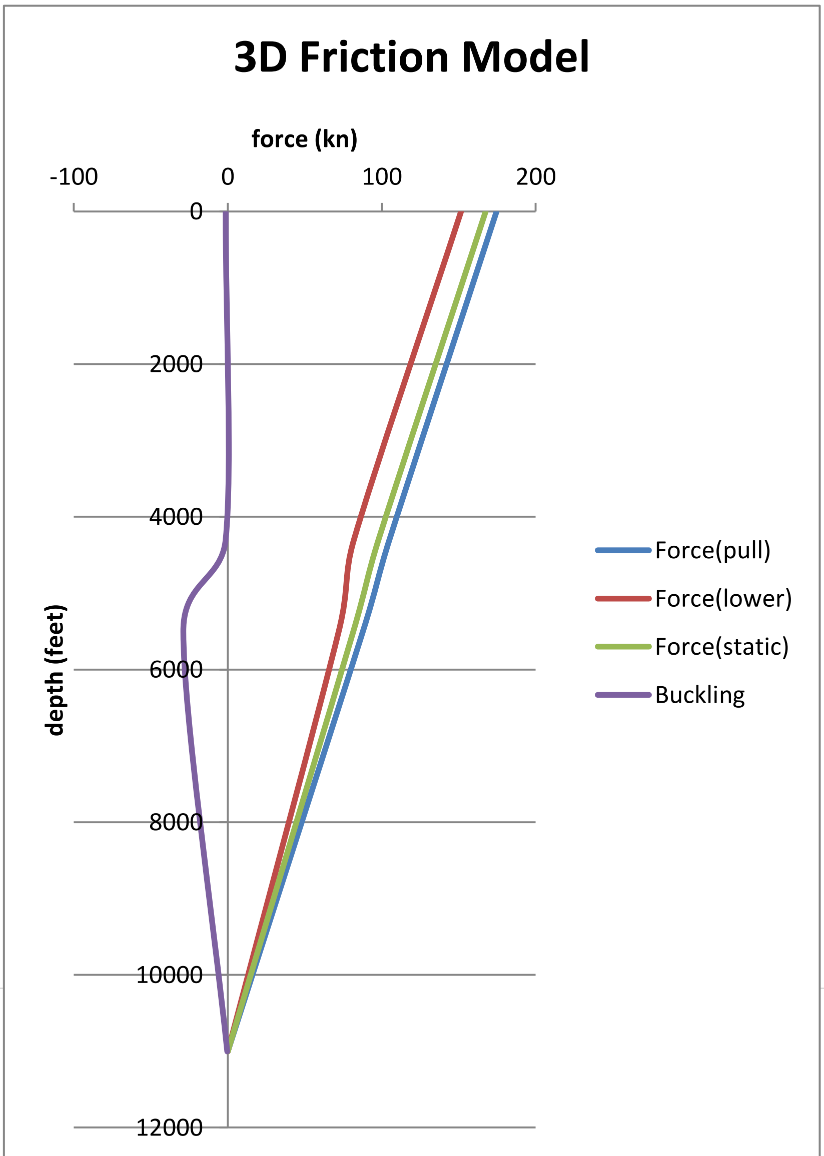


Figure 31 Loads during lowering, pulling and static conditions

CHAPTER 6 REVIEW AND DISCUSSION

Well integrity which needs to be ensured at all stages of a well life cycle is defined in NORSOK D-010 as: "Application of technical, operational organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well".

The NORSOK standards leave it up to various operating companies to come up with solutions that meet the desired minimum functional requirements. Therefore it is the responsibility of personnel involved in planning of drilling and completing wells to ensure well safety and integrity throughout and thus device a procedure of plug and abandonment of the well. So whenever well integrity has been lost due to malfunctioning of a component, the well needs to be shut in to avoid escalation or damage unless the integrity is restored.

According to a pilot study conducted by Petroleum Safety Authority (PSA) in 2006 about 25% of the wells audited had integrity issues. The study included around 400 wells. It further indicated that every 3rd injection well and every 5th production well had well integrity issue(Hans-Emil Bensnes Torbergsen December 2012). Keeping in mind that most of the well in the Norwegian part of the North Sea are have large production rates, the consequences for underestimating the integrity issue can cause human, environmental and financial damages that have costly and risky repairs.

It is for this reason that the field of Plug and Abandonment in petroleum activities is taking a centre stage with hundreds of wells waiting to be plugged after decades of production, which allows for new technologies and techniques to be tested and verified.

Like other services companies, Halliburton is also trying to develop a tested and verified tool/technique that may help it in performing the operations with safety and reliability. The tool essentially makes use of abrasive cutting technique which is not new to the industry. A set of jetting nozzles in the tool allows abrasive fluid to cut the tubing/casing around the tool down hole at the position decided for the operation. The tool is then supposed to reciprocate along the well path (for a desired length) so that the abrasive cutting operation is performed along the length of casing/tubing. Coiled tubing is intended to be used for this Halliburton tool.

Simulation softwares based on numerical problem solving technique, are being extensively used in the industry to simulate down hole environment. It allows to take into consideration, the fluid flows, the friction, the buckling, well path curvature and several other parameters that otherwise are difficult to take into consideration at the same time. Several advances have been made in research institutes like Tulsa Drilling Research Project (TUDRP) facility where besides full scale operation testing facilities, simulation softwares are being used to verify results and improve software processing capacity. (Mehdi Hajianmaleki 2013)

Over here a reference needs to be made to new concepts that are being developed using very basic analysis techniques. One such concept; which is still under development (in a PhD research thesis) is the use of shock wave equation that is defined in terms of force, mass and acceleration. Using a simple relation, displacement in a discrete element of a long structure can be related to the force that is being exerted, either as a function of time or for indefinite time period. This displacement for an initial element of the specimen is then transferred on to the next defined element thus making use of the vibration theory that allows for energy to be transferred between the building blocks (in this case the length element) of the complete structure.

To add up to new technologies/tools that are being, one such tool to find the exact radial positioning down hole has been manufactured by a collaboration between Halliburton and Statoil. The tool gives a signal, using the traditional telemetry system, after the radial position of the tool changes for 15 degrees with respect to its previous position. This would help determine exact tool face angle that is required for performing various operations down hole.

CHAPTER 7 CONCLUSIONS

Determining exact position of tool thousands of meters deep beneath the earth's surface requires detailed information and processing methods.

Numerical technique is one method that can be used for this purpose as it allows taking into account several different design parameters and the iterative nature of the solution allows for the errors to be reduced to a minimum. An attempt has been made to use simulation software based on numerical solving technique. The desired results however, could not be achieved due to reasons mentioned at the end of section 4.5.

Nevertheless it has been proved here, and also in other researches mentioned in the work, that simulation softwares can be used for predicting the position and state of tools down hole.

The analytical model described in the later part of this work defines various parameters that may be used to find the exact position of the tool down hole. For real well "AA" defined in this work, length reduction due to buckling effect and the extension in tubing length during pulling operation (as maximum tensile force is applied during pulling) is given in Table 5 below.

Table 5 Axial displacement of coil tubing at various sections during operations

Buckling		**Pull out of hole (POOH) operation**		
Inclined	Vertical	Sail section	Curved section	Vertical section
1.6m	2.1m	0.87m	0.22m	1.35m

So the total change in length adds up to 6m in the axial direction during operations. This is without taking into account the temperature effect, (because of the various parameters unavailable for its calculation) which is significant too.

As for the radial positioning, equation (5.1) gives change in tool face direction which gives *final orientation of 325 degrees with respect to an initial 0 degree tool face angle* at the top. This serves as very basic analysis for the objectives of this work defined in the beginning of this thesis work.

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APPENDIX - A

Simulation test result - 1

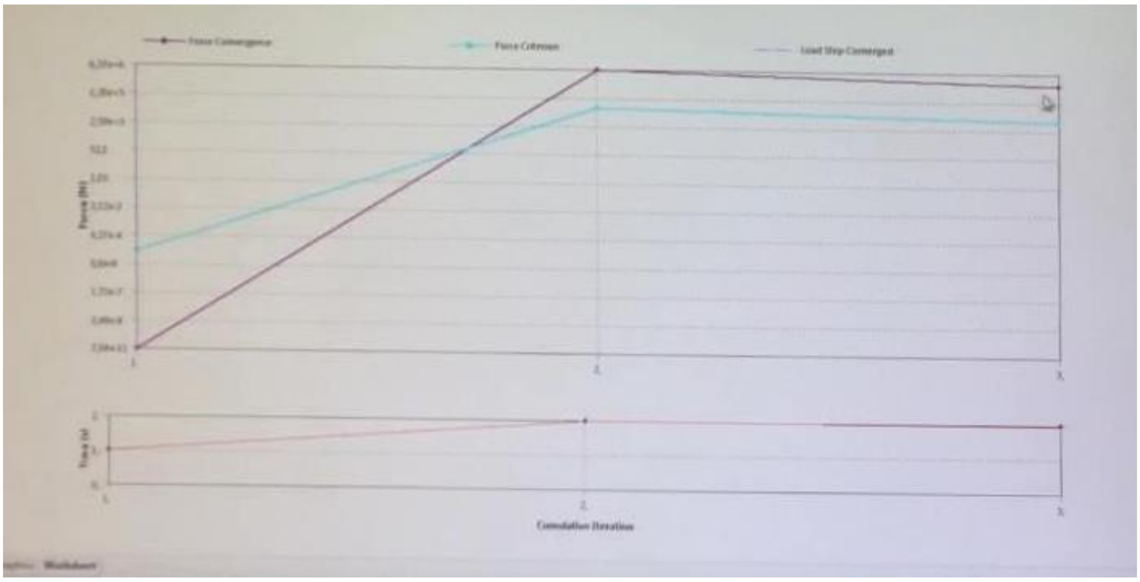

Figure 32 Simulation result with 2 iterative steps

Simulation test result - 2

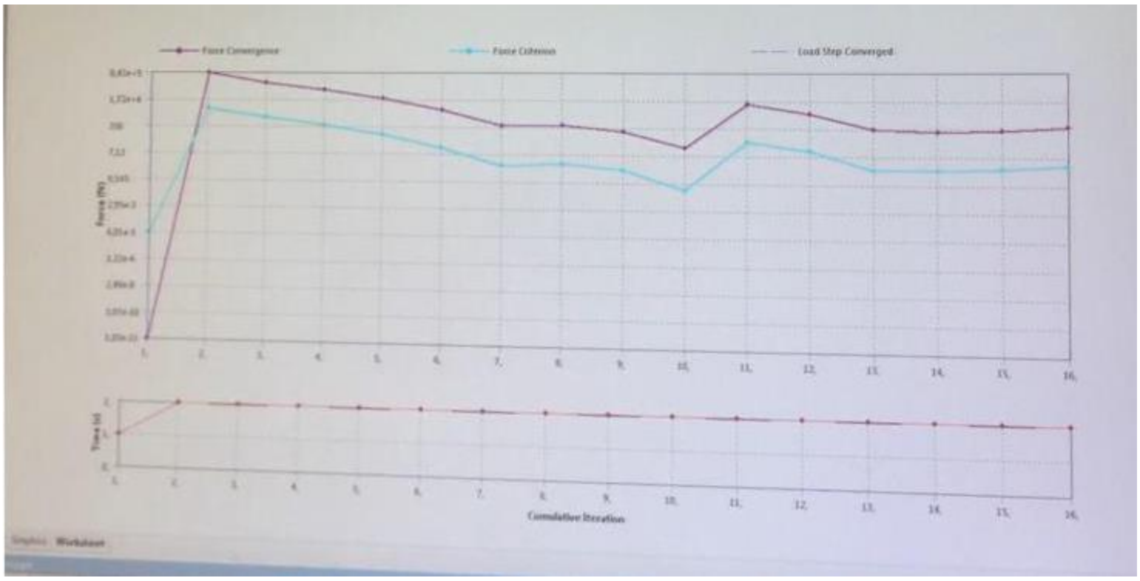

Figure 33 Simulation results with 16 iterative steps

Simulation test result - 3

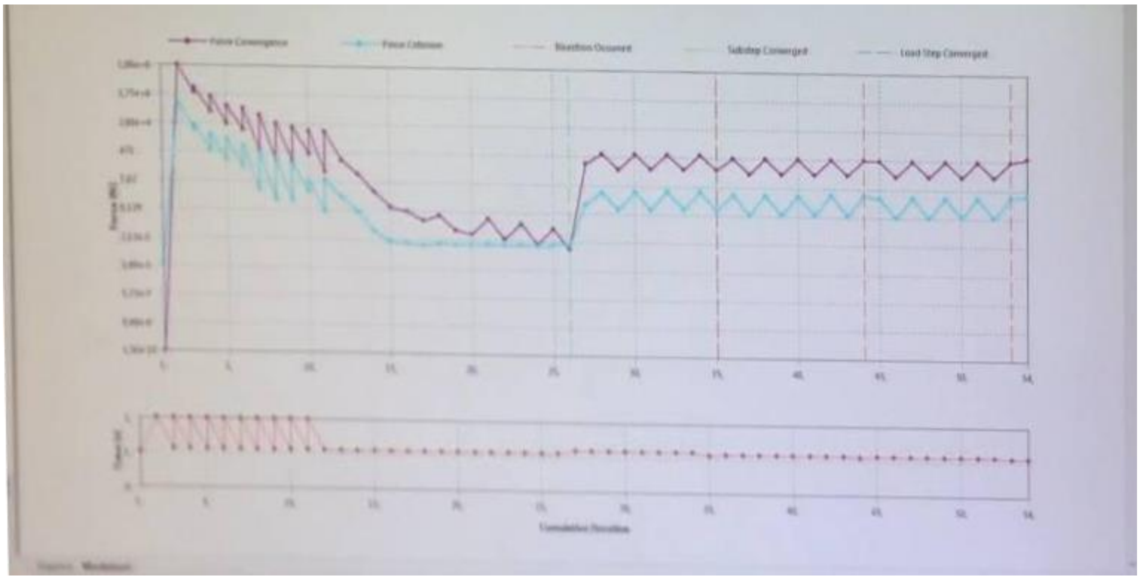

Figure 34 Simulation result with 54 iterative steps

Simulation test result - 4

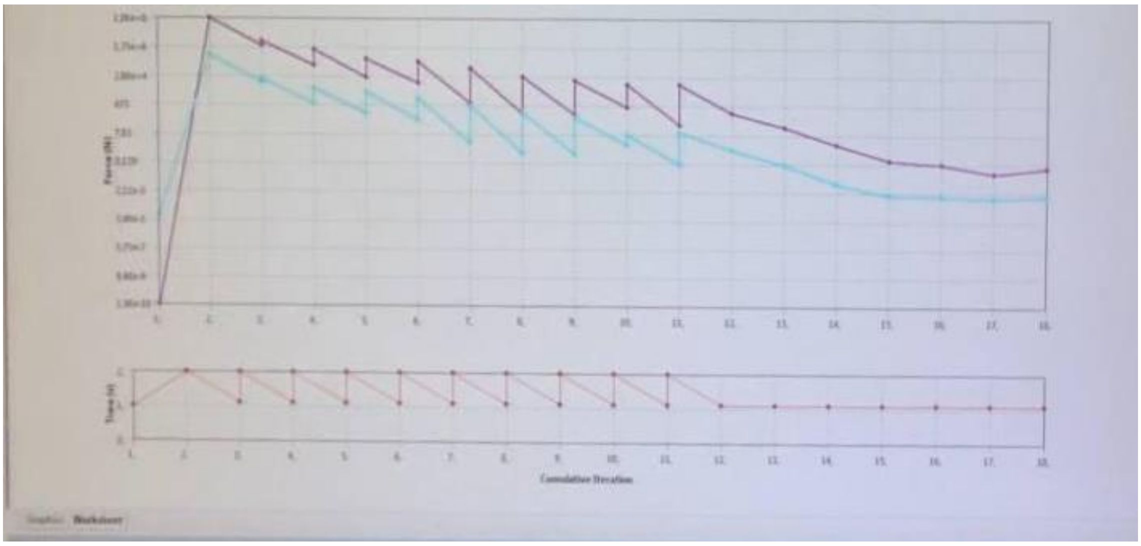

Figure 35 Simulation result with 18 iterative steps

The result pattern of all the simulations performed varied; with same input parameters, except the iterative steps and the time interval of these steps, as shown above. The force-convergence model used for the simulation (described in chapter 4) requires that the force convergence line (red colored) and the force criterion line (blue colored) converge at a point. This would mark the start of the solution procedure for the problem, which could not be achieved.