Blind Shear Ram Blowout Preventers:
Estimation of Shear Force and Optimization of Ram Geometry

THESIS

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By
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Abstract

The explosion of the Deepwater Horizon oil rig in the Gulf of Mexico showed once again that during the oil drilling operation any failures of surface equipment which is called blowout preventers (BOPs) may result in death, injury and massive oil spills that have huge impact on the environment. The blowout preventers are devices that are supposed to close off the wellbore and seal it in an emergency to prevent formation fluid from reaching the surface of the well. In a blowout preventer stack, which consists of several types of blowout preventers, the last line of defense is the blind shear ram that is supposed to close and seal the wellbore by shearing through the drill string or any other tubing when they are in the wellbore.

According to a recent report prepared for the U.S. Minerals Management Services (MMS) by [Childs et al., 2004], two of the three BOP manufacturers rely on a very basic equation “the Distortion Energy Theory shear equation” to estimate the shear force requirement for shearing operation. However with recent advancement in drill pipe materials, it might not be sufficient to estimate the actual shear force to shear a specific drill pipe using yield or tensile stress by itself and the Distortion Energy Theory shear equation.

Using finite element method to analyze the drill pipe materials and dimensions and simulate the entire shearing and sealing operation with blowout preventer working
conditions through the finite element method can provide good approximation for actual shear force and sealing pressure to secure the well. Also, the finite element method could be used to optimize shear ram geometry so that minimum force and energy are used to shear the tube by plastic deformation.

Fourteen task studies are presented throughout this research. The first two tasks were studied to develop a methodology to evaluate the required shear force to shear a certain drill pipe without considering blowout preventer working conditions effect on shearing operation. The results of these studies were compared with actual shear forces that were obtained from BOP manufacturers [Childs et al., 2004]. The next three tasks were studied to determine a relation between drill pipe diameters and shear force requirement for shearing operations. Tasks 6 to 9 were studied to evaluate the effect of the vertical load that stems from the weight of drill string on shear force requirement. The last five tasks were studied to optimize tool clearance to minimize the actual shear force.

It is shown that evaluated shear force evaluated by using finite element method (FEM-Deform 3D) simulations gave fairly accurate results for actual shear force. Also, it is found that by using FEM simulation the effect of the blowout preventer working condition on shearing operation can be estimated and ram geometries can be optimized. Therefore, FEM simulation can be used to design more reliable and efficient ram type blowout preventers.
Dedication

This document is dedicated to my sister Sumeyra Tekin and brother Kudbeddin Tekin.
Acknowledgments

I would like to thank my advisor Prof. Taylan Altan who was the key to my success. The support of Dr. Changhyok Choi, along with other friends of the Engineering Research Center for Net Shape Manufacturing (ERC/NSM), was also very important in my academic development. I therefore would like to thank them all for their time and efforts. Lastly, I would like to thank my family for years of support and encouragement for which I could never repay. They are the foundation to which my education is built on and will continue to push me to bigger and better things.
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Fields of Study

Major Field: Mechanical Engineering
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Chapter 1: Introduction

The explosion of the Deepwater Horizon oil rig in the Gulf of Mexico showed once again that failures of surface equipment called blowout preventers (BOPs) that are suppose to close off a well spewing out of control may result in death, injuries, and massive oil spills that have a huge impact on the environment. At least one worker of Deepwater Horizon oil rig hit an emergency button on the explosion day, which was supposed to activate the blind shear ram type blowout preventer and disconnect the rig from the well but it never deployed [Grondahl et al., 2010]. Although the reason that caused the blowout preventer to fail has not been clarified, investigators focused on the blind shear ram type blowout preventer’s force requirement to shear the drill pipe.

The blind shear ram is generally located at the top of the ram type blowout preventers in the BOP stack. They are supposed to shear whatever is in the wellbore (usually different diameters of drill pipes) and seal the borehole when they are activated. Therefore, evaluation of shear force requirement to shear a specified drill pipe is extremely important to improve reliability of blowout preventers.

According to a recent report prepared for the U.S. Minerals Management Services (MMS) by West Engineering Services, two of the three blowout preventer manufacturers rely on a very basic equation “the Distortion Energy Theory shear equation” to estimate shear force requirement for shearing operation [Childs et al., 2004].
However with recent advancement in drill pipe materials, it might not be sufficient to estimate actual shear force using yield or tensile stress by itself and the Distortion Energy Theory shear equation.

Analyzing the drill pipe materials and dimensions and simulating the entire shearing and sealing operation with blind shear ram working conditions through the finite element method can provide good approximation to estimate actual shear force that is require to shear a specific drill pipe and sealing pressure to secure the wellbore. Also, the finite element method can be used to optimize the blind shear ram geometry so that minimum shear force and energy are used to shear the drill pipe by plastic deformation.
Chapter 2: Background

*Oil and Gas Exploration*

Scientific exploration for oil, in the modern sense, began with the discovery of the Cushing Field in Oklahoma, USA in 1912. Although the fundamentals of exploration process remains the same, modern technology and engineering have greatly improved exploration performance [Borthwick et al., 1997]. There are mainly three steps to explore oil or gas reservoir; desk study, geological survey, and drilling. Once the drilling location has been decided according to the data that is gathered in the desk study and geological survey, the main stage, drilling operation, can begin.

*Drilling*

The drilling operation is a very sophisticated operation and can begin only after the drilling program has been decided, the drilling site has been prepared and all drilling equipment that comprises the drilling rig has been put in place at drilling site.

Although the most common land drill rigs are of the rotary rig type in which the rotary table is the main driver to rotate the drill string, in some cases top drive is preferred instead of rotary table to increase the efficiency of the drilling operation. Basically a land drill rig consists of multiple diesel engines that supply power, hoisting equipment that raises and lowers the drill string, rotary equipment that turns the drill string and drill bit,
and drilling mud handling equipment, which is used to prepare mud and pump it down the hole [Tidal 2008].

As can be seen in Figure 1, mud pumps force drilling fluid (mud) down the annular space through the inside of the drill string and out the bit upward around the drill string (annulus). Since pump pressure, hydrostatic pressure of mud, and friction pressure loss in the annulus, balance the formation fluid pressure, mud circulation is a very important process in terms of preventing blowout.
Offshore drilling operation can be conducted using a variety of self-contained mobile offshore drilling rigs. The choice of drilling rig depends on the depth of water, seabed conditions and prevailing meteorological conditions, particularly wind speed, wave height and current speed [Borthwick et al., 1997]. Mainly there are three types of offshore drilling rigs; jack-up, semi-submersible and drillship.

**Jack Up**

Jack-up oil drilling rigs are used for shallow water drilling typically less than 300 feet. These units are towed to the drilling location and then jacked up into position as their name suggest.

A typical jack-up has three or four long legs that run through the air when jack up is not in drilling mode. These legs, each of which can support the weight of the entire unit, are jacked down to sea floor when the jack-up is over the proposed well location. When the weight of the entire unit is fully supported, the legs are jacked down further until the unit rises out of the water about 10 – 4 feet in the air. After checking all safety issues, the unit will switch to drilling mode and begin drilling the well [TFOM 2010].

**Semi Submersible**

There are two main differences between semi-submersible and jack-up oil rigs; water depth and stabilizing issue.

Semi-submersibles are typically limited to drilling in water depths less than 8,000 feet while jack-up is around 300 feet.
Jack-up drilling rigs maintain its position with help of their legs, while semi-submersible rigs flood their huge ballast tanks with seawater to submerge them below the surface of the water and use anchors or dynamic positioning (DP) system to maintain their position.

*Drillship*

These drilling rigs are basically built on traditional ship bodies to meet the growing demand for highly capable ultra deepwater drilling rigs. Although they are not quite as stable as semi-submersibles, drillships have larger storage capacities that enable to work for extended periods without the need for constant resupplying. Also drillships have advantages in terms of speed and maneuverability. They can maintain their operation in a very harsh weather condition where most semi-submersibles must be evacuated [TFOM 2010].

![Figure 2 Offshore Drilling Rigs](Hempel 2005, BassTech 2010)

Once the drilling rig is set up and its position is secured, the drilling operation can begin.
As can be seen in Figure 3, the drill bit is connected to drill string which runs all the way back to the drilling rig. The drill bit is rotated with drill string in the wellbore to cuts through the earth as high pressure mud is pumped down the center of the drill string and out through nozzles in the drill bit. After several hundred meters of drilling (the depth depends the casing plan), large diameter metal tubing called “surface casing” is placed into the ground. Surface casing forms the backbone of the well, provides structural support to maintain the integrity of the borehole, and isolated underground formations from the well. Once surface casing is installed its place, drilling operation can continue to drill deeper.

During the drilling operation the drill bit cuts away the ground formations, while the drilling fluid carries the small rock pieces out of the hole to prevent them from building up on the bottom of the well.
Besides carrying rock pieces out of the hole, mud has several other important functions:

- Providing hydrostatic pressure to prevent formation fluids or gas from entering into the wellbore (well kick).
- Cleaning the drill bit and keeping it cool during the drilling operation.
- Keeping drill pipe lubricated to prevent it from getting stuck in the ground [Lyons 1996].

The all sections of the well are drilled the same way as the surface casing was drilled in the earlier step. Each time, after drilling deep enough, a new casing with a diameter smaller than the previous casing is installed the end of the previous casing and cemented. This process is repeated until the drill bit reaches the oil and/or gas reservoir.

**Blowout**

All formations that are penetrated during drilling operations are permeable to some degree and under tremendous pressure. The borehole pressure, which consists of the hydrostatic pressure of the mud, pump pressure, and friction pressure loss in the annulus, balances the formation fluid pressure. If for any reason the borehole pressure falls below the formation fluid pressure, the formation fluids might enter the wellbore. Such an event is known as a first signal of blowout “well kick”. There are several reasons that might cause well kick:

- Mud weight less than formation pore pressure
- Lost circulation
- Swabbing in during tripping operation
• Failure to fill up the hole while pulling out the drill string
• Recirculation of gas or oil cut mud.
• Encountering abnormally high formation pressure [Lyons 1996].

_Mud Weight Less Than Formation Pore Pressure_

In order to maximize penetration rates, drilling mud weight is chosen very near to and, in some cases, below the formation pore pressures if there is enough data about specific pore pressure and reservoir fluid composition in the drilling location. But in many areas the mud weight requirement is not known since there might not be enough data about formation pore pressure. In such cases, the drilling operation group decides the mud weight by examining all collected geological data for this specific drilling location. If the formation pore pressure exceeds the drilling operation group’s expectation, well kick may occur.

_Lost Circulation_

Lost circulation means the loss of returned mud, which is pumped through the inside the drill string down and back to the surface through the annulus. From a pressure balance standpoint, it means that the ability of the ground formation to resist injection has fallen below the mud circulation pressure. Therefore mud penetrates the formation zone, which might be naturally fractured formations or high-permeability formations.
If for any reason return is lost, the resulting loss of hydrostatic pressure in the wellbore might cause any formation fluid, which contains greater pressure, to flow into the wellbore, which means well kick will occur.

*Failure to Keep the Hole Full and Swabbing While Tripping*

Tripping is a procedure of removing and/or replacing the drill string from the well. During the tripping procedure there might be a vacuum in the wellbore, which can cause an imbalance in pressure between wellbore and formation. Therefore, if rig crews don’t take proper precaution, formation fluid might enter the wellbore, which means well kick might exist.

*Mud Cut*

Mud cut is a drilling fluid that has gas (air or natural gas) bubbles in it. Mud cut has been considered a warning signal, but not necessarily a serious problem for well kick. But intense gas-cut mud causes essential reductions in bottom hole pressures because a gas-cut mud has lower density than a mud not cut by gas. Thus, there would be reductions in total hydrostatic pressures when a productive oil or gas zone is present and this could cause serious well kick problem [Lyons 1996].

If a kick cannot be controlled properly, uncontrolled formation fluid would reach to the surface. Such a catastrophic event is known as blowout.
**Blowout Preventer**

A well kick can be kept under control if the proper pressure control equipment, which is called a blowout preventer stack, is installed at the surface. The blowout preventer stacks are massive devices with steel reinforced rubber goods. When they are activated they are required to close/seal the borehole and secure the well. The contacting sealing pressure must be greater than formation fluid pressure. In some cases this pressures might be more than 20,000 psi [Abernethy 2000].

![Figure 4 BOP Stack Configurations](holand1999 Lyons1996)

As can be seen in Figure 4, a blowout preventer stack generally utilizes several different types of blowout preventers; annular and ram types.
**Annular Type BOP**

An annular BOP is a device used in combination with hydraulic system that can seal off different sizes of annulus whether drill pipe is in use in the wellbore or not.

Upon command, high-pressure fluid is directed to the closing hydraulic ports positioned in the lower side of the piston. This causes the operating piston to move upward so the moving piston compresses the packer (Figure 5). Because of a cap at the top of annular blowout preventer, the packer can only move toward the center of the wellbore to pack off a drill pipe or seal off the wellbore.

![Figure 5 Annular Type BOP](Cameron 2010)

**Ram Types Blowout Preventer**

Except for using a pair of opposing steel rams, a ram type blowout preventer is similar in operation to a gate valve. When they are activated, the rams are pulled toward the center
of the wellbore to close and seal the wellbore. To seal the wellbore the top faces and/or inside of the rams are fitted with elastomeric material so rams can be pressed against each other or around the drill pipe through the wellbore.

There are four types of ram blowout preventer: pipe, blind, shear, and blind shear.

Pipe Ram

The pipe ram is a device that is used to close and seal around a drill pipe to restrict flow in the annulus which is a space between drill string and borehole. Thus, when the pipe ram is activated mud cannot flow through the annulus but there is no restriction within the drill pipe (Figure 6).

The size of the pipe ram depends on the outside diameter of drill pipe that is used in the drilling operation.

![Figure 6 Pipe Rams](Cameron 2010)

Blind Ram

The blind ram is a device which, upon command, closes off and seals the well when there is not any tube in the wellbore (Figure 7).
Shear Ram

The shear ram, upon command, cuts the drill pipe or casing with hardened steel blades (rams) in an emergency but does not seal the wellbore (Figure 8).

Blind Shear Ram

Blind shear ram, upon command, cuts the drill pipe or casing and then seal the wellbore.
Chapter 3: Principles of the Blind Shear Ram

Once formation fluid begins to enter the wellbore different types of blowout preventers can be used to seal the annulus when the drill pipe is in use in the wellbore, but only the blind shear ram was designed to close (by cutting the drill pipe) and seal the wellbore in case of a sudden blowout. As a result, the last option for the blowout preventer stack to close the borehole is activating the blind shear ram. Therefore, failure of the blind shear ram might cause a catastrophe as recently happened in the Gulf of Mexico.

Figure 9 Blind Shear Rams Working Principle [Grondahl et al., 2010]
As can be seen in Figure 9, in a typical blowout preventer stack there is at least one blind shear ram, which is generally located at the top of the ram type blowout preventer. When it is activated it is supposed to shear whatever is in the borehole (drill string or any other tubing) and close/seal the wellbore to avoid formation fluid and/or gas from entering the well.

When a blowout is detected, an emergency button must be activated to start the shearing process. A sequence of events follows.

I. The signal, which was produced by activating the emergency button, is sent from the rig down an electrical line to the control pods.

II. The control pod directs hydraulic fluid from the rig and accumulators. The fluid flows through a valve, called a shuttle valve (1), and into the blind shear ram behind pistons (2), which drive the ram to shear the drill pipe.

III. The blind shear ram (4) cuts through the drill pipe and wedge locks (3) slide in to avoid the pistons from moving back [Grondahl et al., 2010].

IV. At the end of the cutting process, the rams continue to move against each other to close/seal the borehole against release of formation fluid and/or gas.
Figure 10 Blind shear ram shearing process: (a) shear rams open, (b) shear rams closing, and (c) shear rams closed and sealed the wellbore

BOPs have been traditionally developed using conventional design methodology. Today the industry’s needs are rapidly changing, forcing some fundamental paradigm shifts. Emerging technologies give way to new manufacturing techniques and innovation of design of operation. For example, sealing technology has improved radically with new materials and compounds that have been developed so sealing elements are able to withstand extreme temperatures and hostile fluid environments. On the other hand improved strength in drill pipe material, in combination with larger and heavier sizes, adversely affects the ability of a given blind shear ram blowout preventer to successfully shear and seal the pipe in use [Childs et al., 2004]. Therefore shear rams developed using traditional design methods might not be able to shear the new-technology drill pipe. To be reliable, shear ram type blowout preventers need to be designed with a new methodology, which can provide better approximation for estimation of shear force requirement to shear the drill pipe.
Evaluation of Shear Force

Drill pipe properties have been improved dramatically to reduce probability of drill pipe failure during drilling operation. These improvements increase material strength and ductility. As a result, high shear forces are required to shear a specific drill pipe. But traditional methods have been used to estimate required shear forces, which might not give a good approximation for actual shear force for newly-developed drill pipes.

[Childs et al., 2004] reported that the two of the three blowout preventer manufacturers use the Distortion Energy Theory shear equation to estimate the required shear force for shearing operation:

\[ F = 0.577 \times S_y \times \text{Area} \]  \hspace{1cm} (1)

Where:

\( S_y \) = Drill pipe material yield strength

\( \text{Area} \) = Cross-sectional area of drill pipe

As it was mentioned before, with recent development in tube materials, the yield or tensile strength by itself and the Distortion Energy Theory shear equation might not be sufficient to estimate the shear forces that are require to shear a specific drill pipe.
As is shown in Figure 11, although two sheared drill pipes have same cross sectional area and same material grade, which means similar yield and tensile strength, the high ductility pipe (b) required almost double the shear force than the low ductility pipe (a).

To compare actual shear force and calculated shear force by using Distortion Theory Energy shear equation for a specific drill pipe, [Childs et. al., 2004] gave some useful experimental data that obtained from the three major blowout preventer manufacturer, Cameron, Hydril, and Varco. Table 1 shows some data that was taken from blowout preventer manufacturer information provided by [Childs et al., 2004].

As can be seen in Table 1, calculated shear force using Distortion Energy Theory shear equation might not provide accurate results for actual shear force. For instance, in case number 5 calculated shear forces are smaller than actual shear force although calculated forces are much higher than the actual shear force in case number 110.
Table 1 BOP Manufacturer Shear Force Information’s [Childs et. al., 2004]

* For different types of drill pipe and blowout preventer, actual shear force and calculated shear force can be found in Appendix A.

<table>
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<td>5K</td>
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<td>214</td>
<td>DVS</td>
<td>141800</td>
<td>157400</td>
</tr>
<tr>
<td>34</td>
<td>5</td>
<td>0.362</td>
<td>19.5</td>
<td>G-105</td>
<td>CAMERON</td>
<td>18 3/4</td>
<td>5K</td>
<td>TL</td>
<td>214</td>
<td>DVS</td>
<td>113000</td>
<td>132500</td>
</tr>
<tr>
<td>209</td>
<td>6.63</td>
<td>0.362</td>
<td>27.6</td>
<td>S-135</td>
<td>CAMERON</td>
<td>18 3/4</td>
<td>15K</td>
<td>TL</td>
<td>254</td>
<td>DVS</td>
<td>135000</td>
<td>145000</td>
</tr>
</tbody>
</table>
Several reports have been published that investigate the reliability of both surface and subsea BOP equipment in Norway by the Foundation for Scientific & Industrial Research at the Norwegian Institute of Technology (SINTEF). One set of the data is shown in Table 2.

Table 2 Overview of the number of BOP failures [Holand 1999]

Table 2 presents the equipment failures recorded on three surface blowout preventer stacks installed in Norway between 1987 and 1991. During this study, [Holand 1999] observed a total of 117 failures 11 of which were observed from ram type blowout preventers. Also he indicated that two ram type blowout preventers that were relatively new designs, failed far more frequently than older types of ram preventers.

Another important study about reliability of BOP stack was conducted by [Childs et al., 2002]. [Childs et al., 2002] had experience with 14 blowout preventers that were
manufactured by two major BOP manufacturers. Seven of the 14 blowout preventers were tested to confirm shear ram capabilities.

API Specification 16A Specification for Drill Through Equipment, 2nd Edition, December 1997 was used as a test procedure. The study results are presented in Table 3.

Table 3 The Results of Blowout Preventers Reliability [Childs et al., 2002]

As can be seen from Table 3, five of the rig’s blowout preventers passed and two failed to shear the pipe on the surface (without hydrostatic pressures of the borehole considered) and results are shown graphically in Figure 12.
Table 3 shows that when the supplementary effect of hydrostatic pressure of borehole is added to the surface sharing pressure, six of the rig’s blowout preventers were able to be tested and three of the six passed in this case. This is shown graphically in Figure 13.

Although one single failure of a blowout preventer might cause disaster in terms of injury, the environment, and the economy, and injury, [Holand 1999] and [Childs et. al., 2002] found in the same cases half of the tested blowout preventers are not able to secure the well in an emergency situation. Both of these studies illustrate the lack of preparedness in the industry to shear the drill pipe in the well and seal the borehole as the last line of defense against a blowout.
Chapter 4: Research Focus and Objectives

Attributing Factors to Shear Force

As discussed in the earlier chapters, the Distortion Energy Theory shear equation might not be sufficient with newly-developed drill pipes that have highly advanced material properties. Besides material properties, there would be some other factors for which contributions to the required shear force to shear a specific drill pipe could be significant. Therefore, they should be considered during evaluation of shear force for the shearing operation.

Temperature Gradient

In the offshore drilling operation subsea blowout preventer is placed on seabed and seawater temperature ($T_{\text{seawater}}$) at this depth might be around 3-5 °C while formation fluid temperature that flows through the wellbore in case of blowout could be higher than 200 °C [Dowling 1998]. Therefore the temperature difference between seawater and formation fluid could be considerable when blind shear ram is activated (Figure 14). This temperature difference would cause to material properties to change and create a thermal stress on the pipe and shear ram as well. As a result there would be some differences in the shear force requirement for shearing operation which should be taken into account in evaluation of actual shear force.
Figure 14 Pressure and Temperature Gradients at the Blind Shear Ram Position

**Pressure Gradient**

If the hydrostatic pressure of the wellbore falls below the formation fluid pressure, formation fluid begins to flow through the wellbore to the surface with a flow rate that is determined by pressure gradient. Because of high formation fluid pressure (in some cases it might be more than 20,000 psi [Abernethy 2000]), the pressure gradient could be so high to cause a pressure shock on the blind shear ram when it begins to close the
wellbore. This pressure shock would create some forces on shearing direction (x) and y direction as well (Figure 15) depending on the shape of the blind shear ram. The contribution of these forces to the required shear force could be significant and thus they should be considered as supplementary forces for the shearing operation. The contribution of y direction force to the required shear force would be small (since it would affect only the ram friction force) relative to the x direction force during the shearing operation. But once the blind shear ram cuts the drill pipe successfully, it needs to seal the wellbore against the formation fluid pressure. This means the blind shear ram must remain stable under the y direction force that is created by formation fluid pressure.

Load on Shearing Position

During drilling operation the weight of the drill string is on hoisting equipment (traveling block – hook) and bit weight is adjusted by weight gauge that shows the load on the bit (Figure 15). Thus, except for weight on the drill bit that create compression load on drill bit section, drill string is under axial (vertical) tension load during the drilling operation. Once formation fluid begins to enter the wellbore, it will create some forces in the y direction, which pushes the drill string to upward. Therefore axial tension load will decrease gradually while compression force is increasing (this phenomenon is presented in Task 6 in more details). As a result when blowout preventer is activated higher shear force would be required to shear the drill pipe, if there is compression load on shearing position.
Shear Ram Velocity

The shearing operation occurs in a very short time because of high velocity of the shear ram (it could be higher than 300 m/s). Thus the real time properties of drill pipe would change during the shearing operation depending on the ram velocity. Changing drill pipe properties might cause the required shear force to increase. Therefore the effect of the shear ram velocity on the shearing operation should be considered in evaluation of required shear force.

Figure 15 Effect of Formation Fluid on Axial Load
Tool Joints Area

The ends of drill pipe joints are called tool joints. One end of a length of drill pipe is screwed on the male section and the other end is screwed on the female section so diameter and thickness of the tool joints area are greater than the drill pipe body. Also, to provide numerous cycles of tightening and loosening, tool joints have been manufactured separately from the pipe body and welded onto the pipe and are made of steel that has been heat treated to a higher strength than the steel of the pipe body. Therefore, if the shear ram attempts to cut the tool joints area, it might not be successful unless it was designed according to tool joint material properties since required shear force to cut the tool joint area would be much higher than the drill pipe body.

Generally, shear ram types BOPs are designed to shear drill pipe in the second attempt by changing drill pipe position (moving drill string upward or down) in the blowout preventer if the first attempt was on the tool joint area and unsuccessful. But the unsuccessful first attempt might result in some damage to the shear ram that would cause the require shear force for the second attempt to become higher. Thus, the effect of the first unsuccessful attempt should be considered as a supplementary force for shearing operation.

Analyzing the possible contributions of blind shear ram working conditions, drill pipe materials and dimensions to the shear force requirement to shear a specific drill pipe, simulating the entire shearing and sealing operation through the finite element method could provide accurate results to estimate actual shear force.
There are fourteen task studies presented in the following research in these four categories:

1. Developing a methodology to evaluate required shear force to shear a certain drill pipe on the surface, which means contribution of working condition is neglected. This is called simple sharing throughout this research (Task 1 and Task 2)

2. Determining a relation between drill pipe diameter and required shear force (Task 3 to 5)

3. Evaluation of the effect of axial load, which comes from the weight of drill string, on required shear force (Tasks 6 to 9)

4. Optimizing the clearance between shear rams which is called tool clearance throughout this research (Tasks 10 to 14)

The results of these studies are compared with experimental data that obtained from [Childs et al., 2004] and Distortion Energy Theory shear equation.
Chapter 5: Finite Element Analyses

Throughout this research, Deform 3D is used as a tool to determine required shear force to shear a specific drill pipe and evaluate the effect of some conditions on shear force. As was mentioned previously, there are fourteen task studies presented in this research. Tasks 1 and 2 were studied to develop a methodology to evaluate required shear force for the shearing operation. Tasks 3 to 5 were studied to determine effect of drill pipe diameters on the shearing operation. Tasks 6 to 9 were studied to estimate the effect of drill string weight on the shearing operation. And Tasks 10 to 14 were studied to optimize tool clearance to reduce the required shear force for the shearing operation.

Shear Ram and Drill Pipe Geometries

Tool (shear ram) and drill pipe geometries are shown in Figure 16.
The variables are drill pipe diameter and tool clearance so other tool and pipe parameters will remain constant during studies.
Drill Pipe Properties

Two different material properties that were obtained from [Childs et al., 2004] were used to develop a methodology for a simple shearing operation. The drill pipe properties are shown in Table 4.

<table>
<thead>
<tr>
<th>#</th>
<th>Material Grade</th>
<th>Dimensions (mm)</th>
<th>Thickness (mm)</th>
<th>Area (\text{cm}^2)</th>
<th>Weight/Length Ratio (kg/m)</th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>S-135</td>
<td>127</td>
<td>108.61</td>
<td>9.1948</td>
<td>34.0257</td>
<td>29.019</td>
<td>1014.219</td>
<td>23.1</td>
</tr>
<tr>
<td>135</td>
<td>S-135</td>
<td>139.7</td>
<td>121.3</td>
<td>9.1694</td>
<td>37.6</td>
<td>32.590</td>
<td>1052.829</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4 Drill Pipe Properties [Childs et al., 2004]

Since there was not enough data available to draw the flow stress curve, it is approximated by using the equation:

\[ \sigma = K \times \varepsilon^n \]  

Where,

\( \sigma \) : True Stress

\( \varepsilon \) : True Strain

\( K \) : Strength Coefficient

\( n \) : Strain Hardening Exponent

The approximated flow stress curves are presented in Figure 18.
Friction Factor and Mesh Condition

Constant shear friction is used as a friction theory throughout this research; the friction factor was taken as 0.12.

Two types of mesh conditions are used throughout the research (Figure 19).

1. On shearing position
   - Tetrahedral mesh
   - 3.5 mm element size

2. Other position
   - Tetrahedral mesh
   - 10 mm element size
Task 1

The simulation parameters for Task 1 are presented in Table 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill pipe outside diameter</td>
<td>5” (127 mm)</td>
</tr>
<tr>
<td>Drill Pipe Thickness</td>
<td>0.362 in. (9.19 mm)</td>
</tr>
<tr>
<td>Area</td>
<td>5.27 in.² (34.03 cm²)</td>
</tr>
<tr>
<td>Drill pipe material properties</td>
<td>#110 (Table 4)</td>
</tr>
<tr>
<td>Tool clearance</td>
<td>0 mm</td>
</tr>
<tr>
<td>Load on shearing position</td>
<td>0 ton</td>
</tr>
</tbody>
</table>

Table 5 Simulation Parameters for Task 1

Boundary conditions:

Two kinds of boundary conditions were applied in two categories to get accurate results (Figure 20).
1. Step 1 to 50
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)

2. Step 51 to 1062
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X,Y fixed
   - Symmetry plane (-1,0,0)

Figure 20 Boundary Conditions

The results of Task 1 are shown in Figure 21.
Figure 21 Obtained Maximum Shear Force and Strain for Task 1

It can be seen that the maximum shear force (1193 kN) occurred at a stroke of 54 mm for both rams, which means 108 mm total stroke.
To determine maximum true strain at this point, it is necessary to evaluate the effective range of true strain because the maximum true strain might change depending on element size, element type, and remesh criteria. It might even differ if the same simulation is run a second time because the remesh time would differ. But the effective range would not change significantly. Therefore, through these studies the effective range for true strain is evaluated as a 99% of element size and maximum strain is obtained from this range. For instance, the total element number for Task 1 is 14577 and %99 of total element number is 14431. Thus, the calculated maximum true strain is 0.46 mm/mm. This is presented graphically in Figure 22.

Figure 22 Evaluation of Maximum Strain
Task 2

The simulation parameters for Task 2 are presented in Table 6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill pipe outside diameter</td>
<td>5.5” (139.7 mm)</td>
</tr>
<tr>
<td>Drill Pipe Thickness</td>
<td>0.361 in. (9.17 mm)</td>
</tr>
<tr>
<td>Area</td>
<td>5.83 in.² (37.60 cm²)</td>
</tr>
<tr>
<td>Drill pipe material properties</td>
<td>#135 (Table 4)</td>
</tr>
<tr>
<td>Tool clearance</td>
<td>0 mm</td>
</tr>
<tr>
<td>Load on shearing position</td>
<td>0 ton</td>
</tr>
</tbody>
</table>

Table 6 Simulation Parameters for Task 2

Boundary conditions:

1. Step 1 to 50
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)

2. Step 51 to 1171
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X,Y fixed
   - Symmetry plane (-1,0,0)

The results of Task 2 are shown in Figure 23.
As can be seen in Figure 23 the maximum shear force of 1197 kN occurred at 120 mm total stroke. Maximum strain was evaluated by using the same method as Task 1 and the obtained maximum strain is 0.47 mm/mm.
Task 3

The simulation parameters for Task 3 are presented in Table 7. It should be noted that as can be seen in Tables 7 to 9 the material properties used for Tasks 3 to 5 are same as used in Task 2.

<table>
<thead>
<tr>
<th>Drill pipe outside diameter</th>
<th>3.5” (88.9 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill Pipe Thickness</td>
<td>0.368” (9.35 mm)</td>
</tr>
<tr>
<td>Area</td>
<td>3.62 in.² (23.36 cm²)</td>
</tr>
<tr>
<td>Drill pipe material properties</td>
<td></td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>1052.829</td>
</tr>
<tr>
<td>UTS (MPa)</td>
<td>1101.782</td>
</tr>
<tr>
<td>Elongation %</td>
<td>20</td>
</tr>
<tr>
<td>Tool clearance</td>
<td>0 mm</td>
</tr>
<tr>
<td>Load on shearing position</td>
<td>0 ton</td>
</tr>
</tbody>
</table>

Table 7 Simulation Parameters for Task 3

Boundary conditions:

1. Step 1 to 50
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)

2. Step 51 to 734
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X,Y fixed
   - Symmetry plane (-1,0,0)

The results of Task 3 are shown in Figure 24.
As can be seen in Figure 24 the maximum shear force of 796 kN occurred at 74 mm total stroke. The obtained maximum strain is 0.66 mm/mm.
Task 4

Simulation parameters for Task 4 are presented in Table 8.

<table>
<thead>
<tr>
<th>Drill pipe outside diameter</th>
<th>5” (127 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill Pipe Thickness</td>
<td>0.362 in. (9.19 mm)</td>
</tr>
<tr>
<td>Area</td>
<td>5.27 in.² (34.03 cm²)</td>
</tr>
<tr>
<td>Drill pipe material properties</td>
<td></td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>UTS (MPa)</td>
</tr>
<tr>
<td>1052.829</td>
<td>1101.782</td>
</tr>
<tr>
<td>Tool clearance</td>
<td>0 mm</td>
</tr>
<tr>
<td>Load on shearing position</td>
<td>0 ton</td>
</tr>
</tbody>
</table>

Table 8 Simulation Parameters for Task 4

Boundary conditions:

1. Step 1 to 50
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)

2. Step 51 to 1059
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X,Y fixed
   - Symmetry plane (-1,0,0)

The results of Task 4 are shown in Figure 25.
As can be seen in Figure 24 maximum shear force of 1171 kN occurred at 108 mm total stroke. The obtained maximum strain is 0.36 mm/mm.
Task 5

Simulation parameters for Task 5 are presented in Table 9.

<table>
<thead>
<tr>
<th>Drill pipe outside diameter</th>
<th>6.625” (168.27 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill Pipe Thickness</td>
<td>0.362 in. (9.19 mm)</td>
</tr>
<tr>
<td>Area</td>
<td>7.12 in.² (45.95 cm²)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drill pipe material properties</th>
<th>Yield Strength (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1052.829</td>
<td>1101.782</td>
<td>20</td>
</tr>
</tbody>
</table>

| Tool clearance                  | 0 mm     |
| Load on shearing position       | 0 ton    |

Table 9 Simulation Parameters for Task 5

Boundary conditions:

1. Step 1 to 50
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)

2. Step 51 to 1363
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X,Y fixed
   - Symmetry plane (-1,0,0)

The results of Task 5 are shown in Figure 26.
As can be seen in Figure 26 the maximum shear force of 1475 kN occurred at 147 mm total stroke. The obtained maximum strain is 0.35 mm/mm.
Task 6

Simulation parameters for Task 6 are presented in Table 10.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill pipe outside diameter</td>
<td>5.5” (139.7 mm)</td>
</tr>
<tr>
<td>Drill Pipe Thickness</td>
<td>0.361 in. (9.17 mm)</td>
</tr>
<tr>
<td>Area</td>
<td>5.82 in.² (37.60 cm²)</td>
</tr>
<tr>
<td>Drill pipe material properties</td>
<td>#135 (Table 4)</td>
</tr>
<tr>
<td>Tool clearance</td>
<td>0 mm</td>
</tr>
<tr>
<td>Load on shearing position</td>
<td>47.74 ton compression load</td>
</tr>
</tbody>
</table>

Table 10 Simulation Parameters for Task 6

Boundary conditions:

To determine the effect of drill string weight on required shear force, a well configuration that is shown in Figure 26 was taken as a sample and the drill pipe properties that are used in well are presented in Table 11. It should be noted that the drill pipe, which is in shearing position, is the same as the drill pipe used in Task 2. Thus, the maximum shear force for simple shearing for this drill pipe has already been studied.

<table>
<thead>
<tr>
<th>#</th>
<th>O.D. (in.)</th>
<th>Wall Thickness (in.)</th>
<th>Weight Length Ratio (ppf)</th>
<th>Material Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>209</td>
<td>6 5/8</td>
<td>168.3</td>
<td>0.362 9.195</td>
<td>S-135</td>
</tr>
<tr>
<td>135</td>
<td>5 ½</td>
<td>139.7</td>
<td>0.361 9.169</td>
<td>S-135</td>
</tr>
<tr>
<td>83</td>
<td>3 ½</td>
<td>88.9</td>
<td>0.368 9.347</td>
<td>S-135</td>
</tr>
</tbody>
</table>

Table 11 Pipe Properties used in the Well Configuration
Since there is fluid (mud and/or formation fluid) inside the well, drill string loses some of its weight. Lost weight can be calculated by determining the buoyancy factor.

\[
Buoyancy\ Factor = 1 - \frac{\rho_{\text{fluid}}}{\rho_{\text{pipe}}}
\]

Where;

\(\rho_{\text{fluid}}\) : Fluid Density,

\(\rho_{\text{pipe}}\) : Pipe Density

Fluid density is assumed to be 14 ppg (1677.2 kg/cm³) and drill pipe density was taken as the average drill pipe density 8030 kg/cm³.
Buoyancy Factor = \(1 - \frac{1677.2}{8030} = 0.79\) \(\text{ (4)}\)

The total weight of the drill string in the well with buoyancy factor is represented graphically in Figure 29 (a). The calculated vertical load on shearing position (A) depending on weight gauge (once formation fluid pressure increases through the wellbore, measured weight will decrease) is shown in Figure 29 (b).

Figure 28 a) Calculated Weight of the Drill String in the Well, b) Evaluated Axial Load on Shearing Position

As can be seen in Figure 28 (b), the load on shearing position is 22.1 tons (tension) when weight gauge shows 76.5 tons which means all the weight of the drill string is carried by
hoisting equipment. Then measured weight decreases gradually to the 0 ton depending on the formation fluid pressure and flow rate. After this point, load on the shearing position is compression that will end with maximum 54.4 tons.

Four different axial loads (5.7 tons and 22.1 tons tension load, 9 tons and 47.7 tons compression load) applied to the shearing position to determine their effect on the shearing operation. The axial stresses are calculated by using the area of the drill pipe on shearing position and the result is presented in the Table 12.

<table>
<thead>
<tr>
<th>Pipe Type #</th>
<th>Weight Gauge (ton)</th>
<th>Axial Load on Shearing Position (ton)</th>
<th>Pipe Area (cm²)</th>
<th>Axial Stress on Shearing Position (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>135</td>
<td>19.13</td>
<td>-47.74</td>
<td>37.601</td>
<td>-124.55</td>
</tr>
<tr>
<td></td>
<td>38.27</td>
<td>-9.01</td>
<td>37.601</td>
<td>-23.51</td>
</tr>
<tr>
<td></td>
<td>53.58</td>
<td>5.67</td>
<td>37.601</td>
<td>14.79</td>
</tr>
<tr>
<td></td>
<td>76.54</td>
<td>22.1</td>
<td>37.601</td>
<td>57.66</td>
</tr>
</tbody>
</table>

Table 12 Calculated Axial Stresses on Shearing Position

In this task, 47.74 tons compression load is assumed to be on the shearing position.

Applied boundary conditions are:

1. Step 1 to 50
   - Top of the drill pipe: X, Y fixed and 124.55 MPa stress applied in –Z direction (Figure 29)
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)
2. Step 51 to 1170

- Top of the drill pipe: X, Y fixed and 124.55 MPa stress applied in \(-Z\) direction
- Bottom of the drill pipe: X,Y fixed and 124.55 MPa stress applied in Z direction
- Symmetry plane \((-1,0,0)\)

Figure 29 Applied Boundary Conditions Directions

The results of Task 6 are shown in Figure 30.
As can be seen in Figure 30 the maximum shear force of 1297 kN occurred at 120 mm total stroke. The obtained maximum strain is 0.5 mm/mm.
Task 7

Simulation parameters for Task 7 are presented in Table 13.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill pipe outside diameter</td>
<td>5.5&quot; (139.7 mm)</td>
</tr>
<tr>
<td>Drill Pipe Thickness</td>
<td>0.361 in. (9.17 mm)</td>
</tr>
<tr>
<td>Area</td>
<td>5.82 in.$^2$ (37.60 cm$^2$)</td>
</tr>
<tr>
<td>Drill pipe material properties</td>
<td>#135 (Table 4)</td>
</tr>
<tr>
<td>Tool clearance</td>
<td>0 mm</td>
</tr>
<tr>
<td>Load on shearing position</td>
<td>9.01 ton Compression</td>
</tr>
</tbody>
</table>

Table 13 Simulation Parameters for Task 7

Boundary conditions:

1. Step 1 to 50
   - Top of the drill pipe: X, Y fixed and 23.51 MPa stress applied in –Z direction (see Figure 29 for directions)
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)

2. Step 51 to 1170
   - Top of the drill pipe: X, Y fixed and 23.51 MPa stress applied in –Z direction
   - Bottom of the drill pipe: X,Y fixed and 23.51 MPa stress applied in Z direction
   - Symmetry plane (-1,0,0)

The results of Task 7 are shown in Figure 31.
As can be seen in Figure 31 the maximum shear force of 1259 kN occurred at 119 mm total stroke. The obtained maximum strain is 0.3 mm/mm.
Task 8

The simulation parameters for Task 8 are presented in Table 14.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill pipe outside diameter</td>
<td>5.5&quot; (139.7 mm)</td>
</tr>
<tr>
<td>Drill pipe Thickness</td>
<td>0.361 in. (9.17 mm)</td>
</tr>
<tr>
<td>Area</td>
<td>5.82 in.² (37.60 cm²)</td>
</tr>
<tr>
<td>Drill pipe material properties</td>
<td>#135 (Table 4)</td>
</tr>
<tr>
<td>Tool clearance</td>
<td>0 mm</td>
</tr>
<tr>
<td>Load on shearing position</td>
<td>22.1 ton Tension</td>
</tr>
</tbody>
</table>

Table 14 Simulation Parameters for Task 8

Boundary conditions:

1. Step 1 to 50
   - Top of the drill pipe: X, Y fixed and 57.66 MPa stress applied in –Z direction (see Figure 29 for directions)
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)

2. Step 51 to 1170
   - Top of the drill pipe: X, Y fixed and 57.66 MPa stress applied in –Z direction
   - Bottom of the drill pipe: X,Y fixed and 57.66 MPa stress applied in Z direction
   - Symmetry plane (-1,0,0)

The results of Task 8 are shown in Figure 32.
Figure 32 Obtained Maximum Shear Force and Strain for Task 8

As can be seen in Figure 32 the maximum shear force of 1161 kN occurred at 118 mm total stroke. The obtained maximum strain is 0.37 mm/mm.
**Task 9**

The simulation parameters for Task 9 are presented in Table 15.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill pipe outside diameter</td>
<td>5.5” (139.7 mm)</td>
</tr>
<tr>
<td>Drill Pipe Thickness</td>
<td>0.361 in. (9.17 mm)</td>
</tr>
<tr>
<td>Area</td>
<td>5.82 in.² (37.60 cm²)</td>
</tr>
<tr>
<td>Drill pipe material properties</td>
<td>#135 (Table 4)</td>
</tr>
<tr>
<td>Tool clearance</td>
<td>0 mm</td>
</tr>
<tr>
<td>Load on shearing position</td>
<td>5.67 ton Tension</td>
</tr>
</tbody>
</table>

**Table 15 Simulation Parameters for Task 9**

Boundary conditions:

1. **Step 1 to 50**
   - Top of the drill pipe: X, Y fixed and 14.79 MPa stress applied in –Z direction (see Figure 29 for directions)
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)

2. **Step 51 to 1170**
   - Top of the drill pipe: X, Y fixed and 14.79 MPa stress applied in –Z direction
   - Bottom of the drill pipe: X,Y fixed and 14.79 MPa stress applied in Z direction
   - Symmetry plane (-1,0,0)

The results of Task 9 are shown in Figure 33.
As can be seen in Figure 33 the maximum shear force 1163 kN occurred at 121 mm total stroke. The obtained maximum strain is 0.5 mm/mm.

*Tasks 10 to 14*
The simulation parameters for Tasks 10 to 14 are presented in Table 16. In these five tasks various tool clearances are studied to minimize shear force requirement for shearing operation.

<table>
<thead>
<tr>
<th>Pipe Properties (Table 4) #</th>
<th>Drill Pipe O.D.</th>
<th>Thickness (mm)</th>
<th>Area (cm²)</th>
<th>Tool Clearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 10</td>
<td>135</td>
<td>139.7 mm (5.5 in.)</td>
<td>9.17</td>
<td>37.6</td>
</tr>
<tr>
<td>Task 11</td>
<td>135</td>
<td>139.7 mm (5.5 in.)</td>
<td>9.17</td>
<td>37.6</td>
</tr>
<tr>
<td>Task 12</td>
<td>135</td>
<td>139.7 mm (5.5 in.)</td>
<td>9.17</td>
<td>37.6</td>
</tr>
<tr>
<td>Task 13</td>
<td>135</td>
<td>139.7 mm (5.5 in.)</td>
<td>9.17</td>
<td>37.6</td>
</tr>
<tr>
<td>Task 14</td>
<td>135</td>
<td>139.7 mm (5.5 in.)</td>
<td>9.17</td>
<td>37.6</td>
</tr>
</tbody>
</table>

Table 16 Simulation Parameters for Tasks 10 to 14

Boundary conditions:

1. Step 1 to 50
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X, Y, Z fixed
   - Symmetry plane (-1,0,0)

2. Step 51 to 1170
   - Top of the drill pipe: X, Y fixed
   - Bottom of the drill pipe: X,Y fixed
   - Symmetry plane (-1,0,0)

The results of the Tasks 10 to 14 are shown in Figures 34 to 38.
As can be seen in Figure 34 for 0.05 mm tool clearance the maximum shear force of 1197 kN occurred at 117 mm total stroke. The obtained maximum strain is 0.42 mm/mm.
As can be seen in Figure 35 for 0.1 mm tool clearance the maximum shear force of 1168 kN occurred at 120 mm total stroke. The obtained maximum strain is 0.42 mm/mm.
Figure 36 Obtained Maximum Shear Force and Strain for Simple Shearing with 0.2 mm Tool Clearance

As can be seen in Figure 36 for 0.2 mm tool clearance the maximum shear force of 1116 kN occurred at 121 mm total stroke. The obtained maximum strain is 0.45 mm/mm.
As can be seen in Figure 37 for 0.4 mm tool clearance the maximum shear force of 1160 kN occurred at 124 mm total stroke. The obtained maximum strain is 0.5 mm/mm.
Figure 38 Obtained Maximum Shear Force and Strain for Simple Shearing with 0.6 mm Tool Clearance

As can be seen in Figure 38 for 0.6 mm tool clearance the maximum shear force of 1251 kN occurred at 128 mm total stroke. The obtained maximum strain is 0.65 mm/mm.
Chapter 6: Results and Conclusions

Task 1 and Task 2

The first two tasks were studied to determine a methodology that could provide good approximation for the actual shear force. The evaluated shear forces by using Finite Element Method, the calculated shear forces by using Distortion Energy Theory shear equation and the actual shear forces obtained from the BOP manufacturers are compared in Table 21 and presented graphically in Figure 39.

<table>
<thead>
<tr>
<th>#</th>
<th>O.D.</th>
<th>Pipe Area (cm²)</th>
<th>Actual Shear Force [Childs et al., 2004] (kN)</th>
<th>Calculated Shear Force Using Distortion Theory Equation (kN)</th>
<th>Obtained shear force from F.E.M. Simulations (Deform 3D) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Using Yield Strength</td>
<td>Using Ultimate Tensile Strength</td>
</tr>
<tr>
<td>110</td>
<td>5” (127 mm)</td>
<td>34.03</td>
<td>1177</td>
<td>1991</td>
<td>2159</td>
</tr>
<tr>
<td>135</td>
<td>5.5” (139.7 mm)</td>
<td>37.60</td>
<td>1472</td>
<td>2284</td>
<td>2390</td>
</tr>
</tbody>
</table>

Table 17 Shear Force Comparison
As can be seen in Table 17 and Figure 39 Finite Element Method simulations give fairly accurate result compare with calculated shear force using yield or ultimate tensile strength in the Distortion Energy Theory shear equation.

It should be noted that the simulation results were obtained by using approximated flow stress curves. Therefore, once the original flow stress curves are available these studies must be repeated to get more precise and reliable shear force.

In conclusion Task 1 and Task 2 studies showed that Finite Element Method can be used as a tool to estimate actual shear force with high accuracy.
Tasks 3 to 5 were studied to determine shear force requirement for the drill pipes that have the same material properties but different outside diameters. The results are presented in Table 22 and Figure 40.

<table>
<thead>
<tr>
<th>Material Properties #</th>
<th>Drill Pipe O.D.</th>
<th>Pipe Area (cm²)</th>
<th>Calculated Shear Force Using Distortion Theory Equation (kN)</th>
<th>Obtained shear force from F.E.M. Simulation (Deform 3D) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Using Yield Strength</td>
<td>Using Ultimate Tensile Strength</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>135</td>
<td>3.5” (88.9 mm)</td>
<td>23.36</td>
<td>1419</td>
<td>1485</td>
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<tr>
<td></td>
<td>5” (127 mm)</td>
<td>34.03</td>
<td>2067</td>
<td>2163</td>
</tr>
<tr>
<td></td>
<td>5.5” (139.7 mm)</td>
<td>37.60</td>
<td>2284</td>
<td>2390</td>
</tr>
<tr>
<td></td>
<td>6.625” (168.3 mm)</td>
<td>45.95</td>
<td>2791</td>
<td>2921</td>
</tr>
</tbody>
</table>

Table 18 Shear Forces for Different Outside Diameter Drill Pipe
Figure 40 Shear Forces for Different Outside Diameter Drill Pipe

As can be seen in Figure 40 shear force requirement for shearing operation is increased with drill pipe outside diameter as it was expected. Therefore to shear larger diameter drill pipe more energy is required but there is not linear relation between pipe diameter and shear force requirement as Figure 40 indicates.

Tasks 6 to 9

Tasks 6 to 9 were studied to determine the effect of drill string weight on shear force requirement to shear 5.5” diameter drill pipe. Four different vertical loads were applied on shearing position. The applied vertical load and the corresponding simulation results are presented in Table 23 and Figure 41.
As can be seen in Table 19 and Figure 41 shear force requirement for shearing operation increases significantly with compression load that was applied on shearing position and decreases with tension load. Also Figure 41 shows that there is a non-linear relation between applied axial (vertical) load and shear force requirement. The shear forces
increase with compression load and decrease with tension load dramatically until some point but then they do not change considerably.

In conclusion the effect of drill string weight on shear force requirement could be significant depending on the drill pipe properties used for drilling operation. Therefore its contribution to the required shear force should be considered as supplementary forces for the shearing operation.

**Tasks 10 to 14**

Tasks 10 to 14 were studied to optimize tool clearance to minimize shear force requirement for shearing operation. The obtained shear forces from Finite Element Simulation for different tool clearances are presented in Table 23 and Figure 42.

<table>
<thead>
<tr>
<th>#</th>
<th>Drill Pipe O.D.</th>
<th>Tool Clearance (mm)</th>
<th>Obtained shear force from F.E.M. Simulation (Deform 3D) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>135</td>
<td>5.5” (139.7 mm)</td>
<td>0</td>
<td>1197</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.005</td>
<td>1197</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1</td>
<td>1168</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2</td>
<td>1116</td>
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<td>1160</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.6</td>
<td>1251</td>
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</tbody>
</table>

Table 20 Obtained Maximum Shear Force for Different Tool Clearance
As can be seen in Figure 42 the minimum required shear force obtained when tool clearance is 0.2 mm within the five tasks studies, although the smaller required shear force could be achieved with further investigation.

The results of Tasks 10 to 14 showed that Finite Element Method could be used as a tool to optimize shear ram geometry to reduce the shear force requirement for shearing operation.
Chapter 7: Future Works

1) Since the original flow stress curves of drill pipe materials were not available the approximated flow stress curves were used throughout the research. Therefore, once the original flow stress curves are available simulations should be repeated to get more accurate and reliable results.

2) It is determined that the impact of the axial compression load on shear force requirement is non-linear. Increase in the required shear force might not be significant for some compression loads. Thus, the effective range of compression load that has significant impact on the required shear force should be determined. Furthermore, the effective range of compression load might be expressed in terms of drill sting weight so the effect of the possible axial compression load on shear force requirement would be estimated by only drill string weight for any given well design.

3) As it was discussed in chapter 4 the possible pressure gradient on the blind shear ram can be evaluated for a given formation fluid pressure and well design. Therefore, the effect of pressure gradient on the shear force requirement should be studied depending on a given blind shear ram geometries.

4) Tool parameters and all edge angles should be optimized (Figure 43).
Figure 43 Tool Parameters

- $T_f$: Female ram thickness
- $T_m$: Male ram thickness
- $\gamma$: Female ram lip angle
- $\alpha$: Male ram rip angle
- $\beta$: Rake angle
- $c$: Clearance

5) As it was mentioned in chapter 4 the effect of the temperature gradient and shear ram velocity on shear force requirement should be studied.
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Figures

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Appendix A: Blowout Preventer Manufacturer Shear Information [Childs et al., 2004]

Below is a table showing BOP ( Blowout Preventer) Manufacturer Shear Information. The data includes pipe dimensions as found in API 5L or provided by Grant Prideco; only sealing shear rams with double V blades; and only material data meeting API requirements. Blank cells mean no data was provided by the manufacturer. Sorted by Material Grade and cross-sectional area.

<table>
<thead>
<tr>
<th>#</th>
<th>Dia (in)</th>
<th>Wall (in)</th>
<th>PPS</th>
<th>Material Grade</th>
<th>BOP MANUFACTURER</th>
<th>BOP CODE</th>
<th>Working Pressure</th>
<th>BOP Type</th>
<th>BOP CLOSE ASIA</th>
<th>SHEAR RAMP TYPE</th>
<th>YIELD STRENGTH (PSI)</th>
<th>ULTIMATE TENSILE STRENGTH (PSI)</th>
<th>CHAPPI</th>
<th>ELONGATION</th>
<th>HARDNESS</th>
<th>ACTUAL SHEAR PRESSURE (KPSI)</th>
<th>ACTUAL SHEAR FORCE (KFP)</th>
<th>SHEAR FORCE CALCULATED USING YIELD (KFP)</th>
<th>SHEAR FORCE CALCULATED USING ULTIMATE (KFP)</th>
<th>SOURCE OF INFORMATION</th>
<th>COMMENTS</th>
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<tr>
<td>1</td>
<td>6</td>
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<td>S1</td>
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<td>16000</td>
<td>14 A</td>
<td>3/4</td>
<td>Prf</td>
<td>12000</td>
<td>131900</td>
<td>24.0</td>
<td>2040</td>
<td>14.0</td>
<td>1350</td>
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<td>190.01</td>
<td>166.9</td>
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<td>6.062</td>
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<td>S1</td>
<td>Vestwell</td>
<td>071.77</td>
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<td>14 A</td>
<td>3/4</td>
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<td>16000</td>
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<td>3/4</td>
<td>Prf</td>
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<td>131900</td>
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<td>190.01</td>
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<td>Vestwell</td>
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<tr>
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<td>Vestwell</td>
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<td>16000</td>
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<td>API, SBI</td>
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</tr>
</tbody>
</table>

The table continues with similar data entries for other BOP manufacturers and models.
# BOP Manufacturer Shear Information

Data edited to include only drillpipe; only pipe dimensions as found in API 5L or provided by Grant Prideco; only sealing shear rams with double V blades; and only material data meeting API requirements. Blank cells mean no data was provided by the manufacturer. Sorted by Material Grade and cross-sectional area.

<table>
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<tr>
<th>PIPE DESCRIPTION</th>
<th>DOP and RAM DESCRIPTION</th>
<th>PIPE MATERIAL PROPERTIES</th>
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</tr>
</thead>
<tbody>
<tr>
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</table>

78
<table>
<thead>
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<th>BOP and RAM Description</th>
<th>Pipe Material Properties</th>
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## BOP Manufacturer Shear Information

Data edited to include: only drillpipe; only pipe dimensions as found in API SL or provided by Grant Prideco; only scaling shear rams with double V blades; and only material data meeting API requirements. Blank cells mean no data was provided by the manufacturer. Sorted by Material Grade and cross-sectional area.

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<th>PIPE MATERIAL</th>
<th>PROPERTIES</th>
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### Comments
- The table contains information on BOP manufacturer shear forces for different pipe descriptions and specifications.
- The data includes pipe dimensions, material grades, and shear force calculations using yield and ultimate tensile strength.
- The table is sorted by material grade and cross-sectional area for easy reference.

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