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

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in
the Graduate School of The Ohio State University

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2010

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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 shear forces evaluated by using finite element method (FEM-Deform 3D) simulations provided 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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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

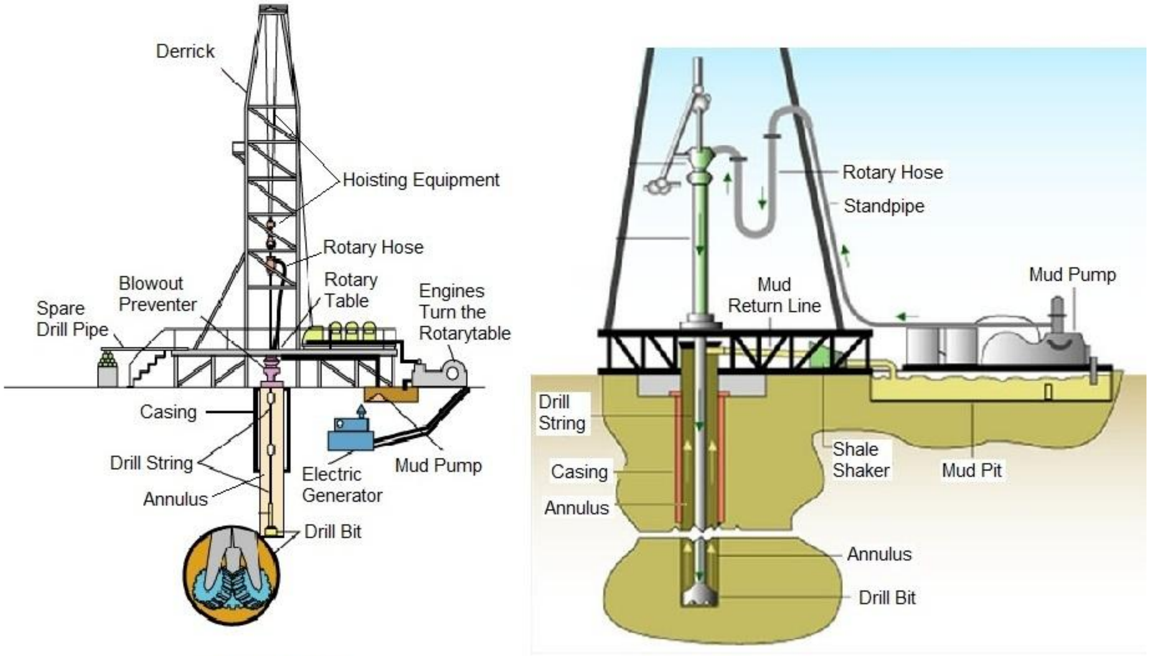
Oil and Gas Exploration

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].



Drillig Equipment

Mud Circulation

Figure 1 Land Drilling Rig [HSW 2001, PetroleumOnline 2010]

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

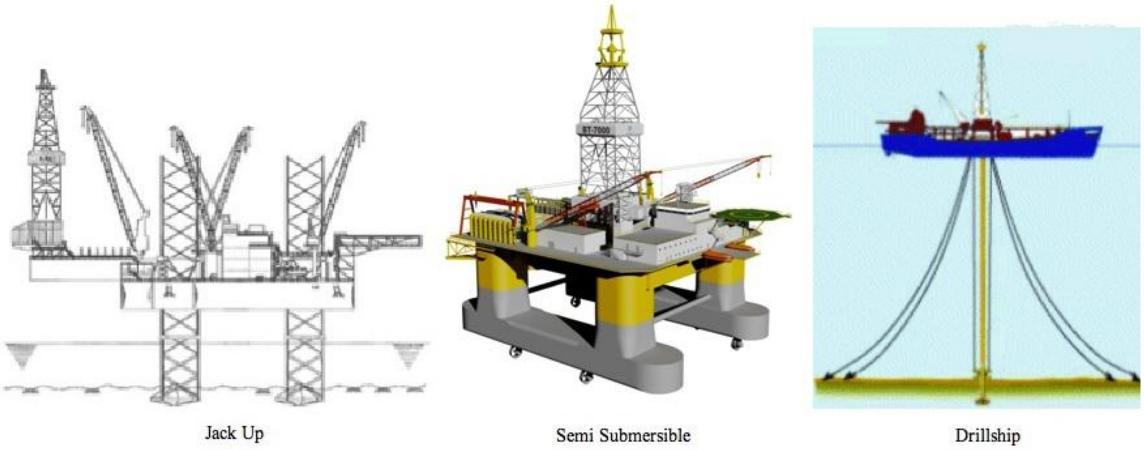
There are two main differences between semi-submersible and jack-up oil rigs; water depth and stabilizing issue.

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].



Jack Up

Semi Submersible

Drillship

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.

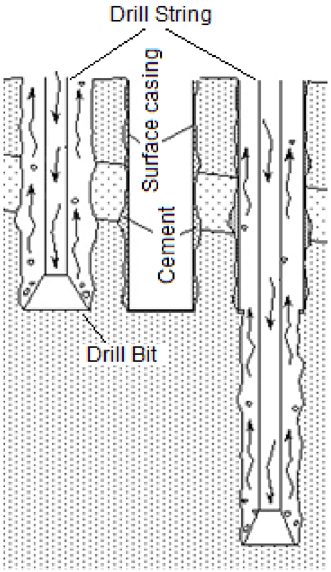


Figure 3 Surface Casing and Drilling Sequence

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].

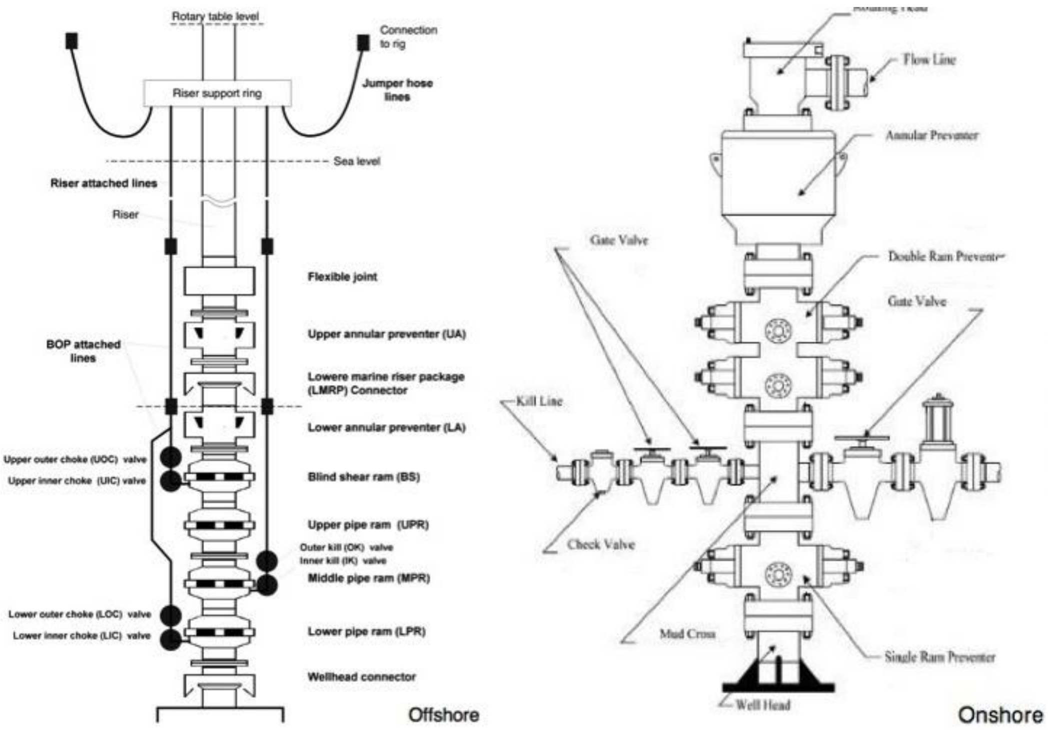


Figure 4 BOP Stack Configurations [Holand 1999, Lyons 1996]

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.

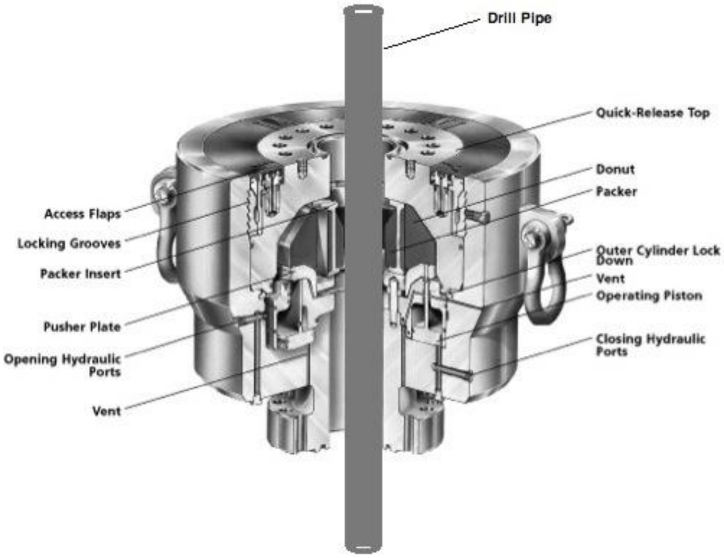


Figure 5 Annular Type BOP [Cameron 2010]

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.

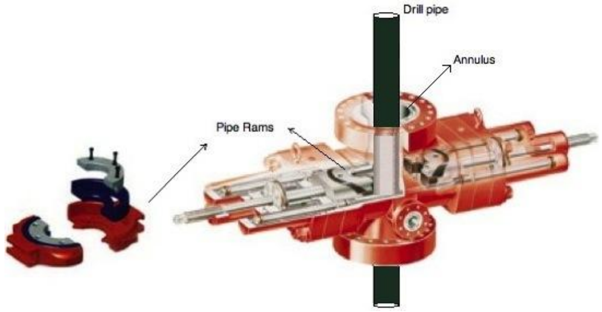


Figure 6 Pipe Rams [Cameron 2010]

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).

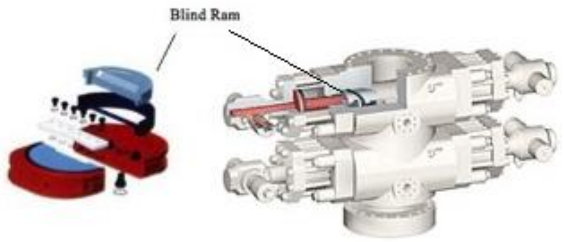


Figure 7 Blind Rams [Cameron 2010]

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).

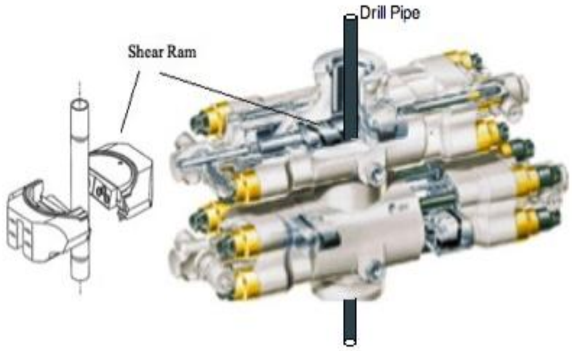


Figure 8 Shear Rams [Cameron 2010]

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.

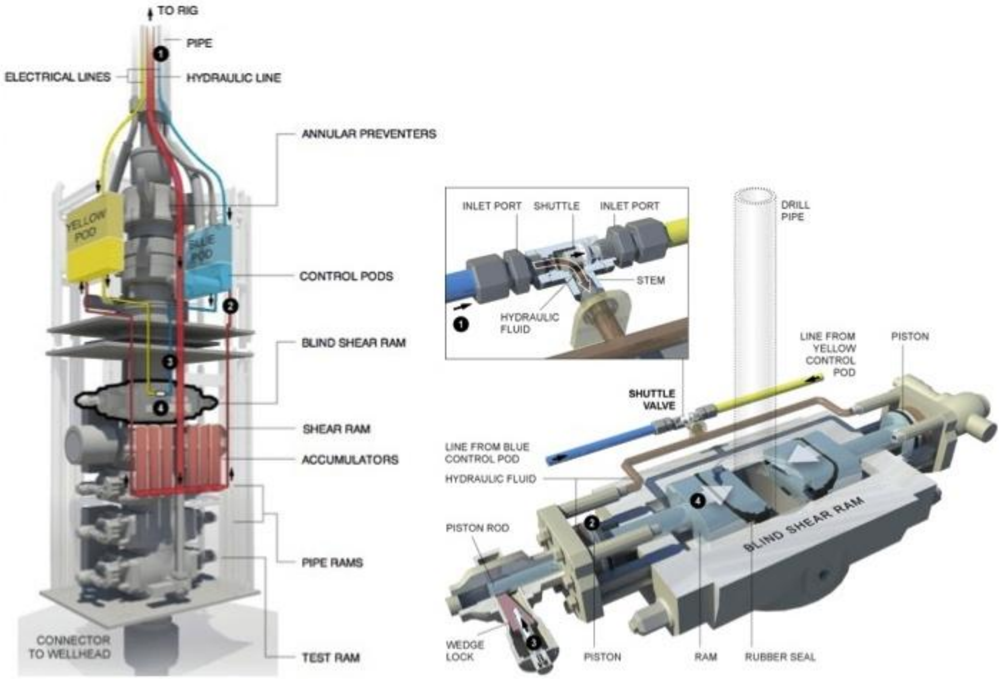


Figure 9 Blind Shear Rams Working Principle [Grondahl et al., 2010]

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.

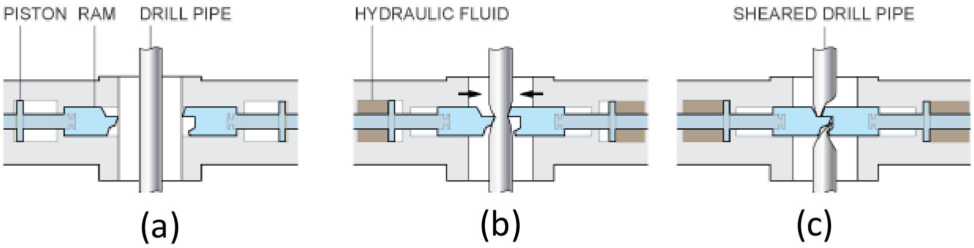


Figure 10 Blind shear ram shearing process: (a) shear rams open, (b) shear rams closing, and (c) shear rams closed and sealed the wellbore

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:

[illegible] Area [illegible]

Where:

S_y = Drill pipe material yield strength

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.

(a) (b)

Figure 11 Two sheared tubes with same material grade and cross sectional area:

(a) Required 1,950 psi to shear, (b) Required 3,930 psi [Childs et. al., 2004]

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.

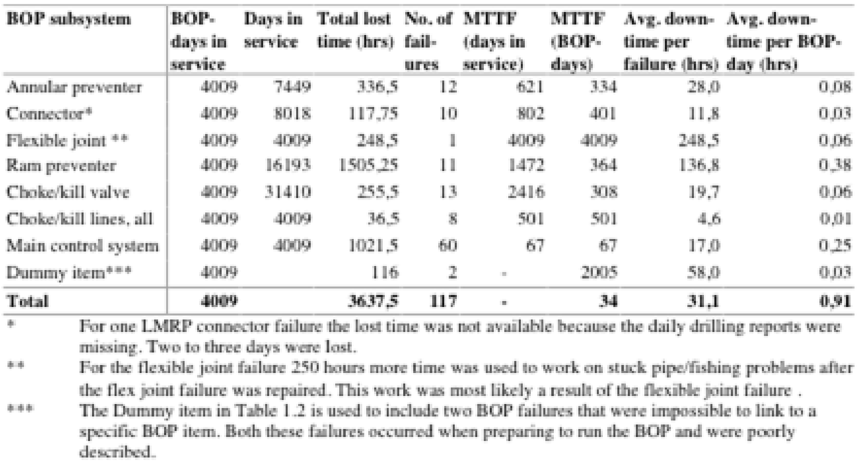
BOP Manufacturer Information																			
#	Pipe Description				BOP Manufacturer	BOP and RAM Description			Pipe Material Properties						Actual Shear Pressure (psi)	Actual Shear Force (kips)	Shear Force Calculated Using Yield Strength (kips	Shear Force Calculated Using UTS (kips)
	O.D. (in.)	Thickness (in.)	Weight/ Length Ratio (PPF)	Material Grade		BOP Bore (in.)	Working Pressure (psi)	BOP Type	BOP Close Area (in^2)	Shear Ram Type	Yield Strength (psi)	U.T.S (psi)	Charpy, cvn	Elongation %				
83	3.5	0.368	13.3	S-135	HYDRIL	13.62	5000	14 1/4	159.48	Blind	138600	147800		20.2	1708	272.4	289.57	308.8
5	3.5	0.368	13.3	E-75	HYDRIL	18 3/4	10000	14 1/4	159.48	Blind	87700	106600		22	1425	227.27	183.23	222.72
124	4.5	0.43	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19	1725	275.11	491.72	531.38
110	5	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1	1404	264.62	447.69	485.43
14	5	0.362	19.5	E-75	HYDRIL	13.62	10000	14 1/4	159.48	Blind	83100	111800		22.3	1212	193.3	252.91	340.26
39	5	0.362	19.5	G-105	HYDRIL	13.62	10000	14 1/4	159.48	Blind	113700	125500		23.5	2213	352.94	346.04	381.95
214	6.63	0.362	27.7	S-135	HYDRIL	13.62	15000	19	283.53	Blind	149500	161900		20.6	2203	624.62	614.9	665.9
10	3.5	0.449	15.5	E-75	VARCO	18 3/4		SLX	153.9	"V"	89800	117900		23	1750	269.33	222.99	292.77
89	5	0.362	19.5	S-135	VARCO	18 3/4		SLX	153.9	"V"	156200	165300	48	21	2500	384.75	475.39	503.08
135	5.5	0.361	21.9	S-135	VARCO	18 3/4		SLX	153.9	"V"	152700	159800	51.3	20	2150	330.89	513.51	537.39
151	6.63	0.33	25.2	S-135	VARCO	18 3/4		SLX	153.9	"V"	150800	160900		19	2850	438.62	567.86	605.89
86	5	0.362	19.5	S-135	CAMERON	18 3/4	5K	TL	214	DVS	141800	157400	45	17.1	1900	406.6	431.56	479.04
34	5	0.362	19.5	G-105	CAMERON	18 3/4	5K	TL	214	DVS	113000	132500	75	21.2	1660	355.24	343.91	403.26
209	6.63	0.362	27.6	S-135	CAMERON	18 3/4	15K	TL	254	DVS	135000	145000			2100	533.4	555.26	596.39

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.

Reliability of BOP Systems

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.



BOP subsystem	BOP-days in service	Days in service	Total lost time (hrs)	No. of failures	MTTF (days in service)	MTTF (BOP-days)	Avg. down-time per failure (hrs)	Avg. down-time per BOP-day (hrs)
Annular preventer	4009	7449	336,5	12	621	334	28,0	0,08
Connector*	4009	8018	117,75	10	802	401	11,8	0,03
Flexible joint **	4009	4009	248,5	1	4009	4009	248,5	0,06
Ram preventer	4009	16193	1505,25	11	1472	364	136,8	0,38
Choke/kill valve	4009	31410	255,5	13	2416	308	19,7	0,06
Choke/kill lines, all	4009	4009	36,5	8	501	501	4,6	0,01
Main control system	4009	4009	1021,5	60	67	67	17,0	0,25
Dummy item***	4009		116	2	-	2005	58,0	0,03
Total	**4009**		**3637,5**	**117**	-	**34**	**31,1**	**0,91**

* For one LMRP connector failure the lost time was not available because the daily drilling reports were missing. Two to three days were lost.

** For the flexible joint failure 250 hours more time was used to work on stuck pipe/fishing problems after the flex joint failure was repaired. This work was most likely a result of the flexible joint failure .

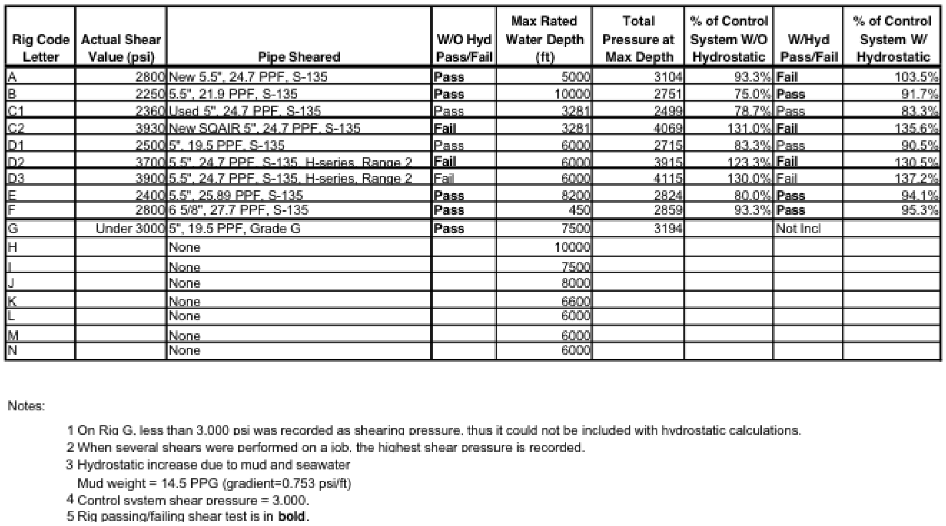
*** The Dummy item in Table 1.2 is used to include two BOP failures that were impossible to link to a specific BOP item. Both these failures occurred when preparing to run the BOP and were poorly described.

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.



Rig Code Letter	Actual Shear Value (psi)	Pipe Sheared	W/O Hyd Pass/Fail	Max Rated Water Depth (ft)	Total Pressure at Max Depth	% of Control System W/O Hydrostatic	W/Hyd Pass/Fail	% of Control System W/ Hydrostatic
A	2800	New 5.5", 24.7 PPF, S-135	**Pass**	5000	3104	93.3%	**Fail**	103.5%
B	2250	5.5", 21.9 PPF, S-135	**Pass**	10000	2751	75.0%	**Pass**	91.7%
C1	2360	Used 5", 24.7 PPF, S-135	Pass	3281	2499	78.7%	Pass	83.3%
C2	3930	New SQAIR 5", 24.7 PPF, S-135	**Fail**	3281	4069	131.0%	**Fail**	135.6%
D1	2500	5", 19.5 PPF, S-135	Pass	6000	2715	83.3%	Pass	90.5%
D2	3700	5.5", 24.7 PPF, S-135, H-series, Range 2	**Fail**	6000	3915	123.3%	**Fail**	130.5%
D3	3900	5.5", 24.7 PPF, S-135, H-series, Range 2	Fail	6000	4115	130.0%	Fail	137.2%
E	2400	5.5", 25.89 PPF, S-135	**Pass**	8200	2824	80.0%	**Pass**	94.1%
F	2800	6 5/8", 27.7 PPF, S-135	**Pass**	450	2859	93.3%	**Pass**	95.3%
G	Under 3000	5", 19.5 PPF, Grade G	**Pass**	7500	3194		Not Incl	
H		None		10000				
I		None		7500				
J		None		8000				
K		None		6600				
L		None		6000				
M		None		6000				
N		None		6000				

Notes:

1 On Rig G, less than 3,000 psi was recorded as shearing pressure, thus it could not be included with hydrostatic calculations.
2 When several shears were performed on a job, the highest shear pressure is recorded.
3 Hydrostatic increase due to mud and seawater
Mud weight = 14.5 PPG (gradient=0.753 psi/ft)
4 Control system shear pressure = 3,000.
5 Rig passing/failing shear test is in **bold**.

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.

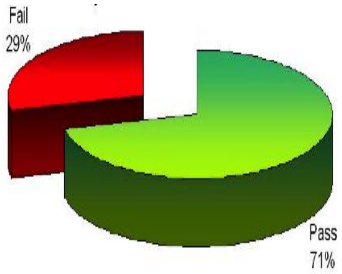


Figure 12 Shear Testing Results on the Surface [Childs et al., 2002]

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.

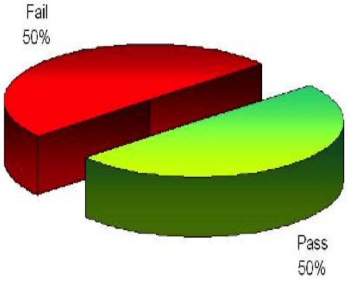


Figure 13 Shear Testing Results with Hydraulic Pressures Considered
[Childs et al., 2002]

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. Beside 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 ($T_{seawater}$) 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.

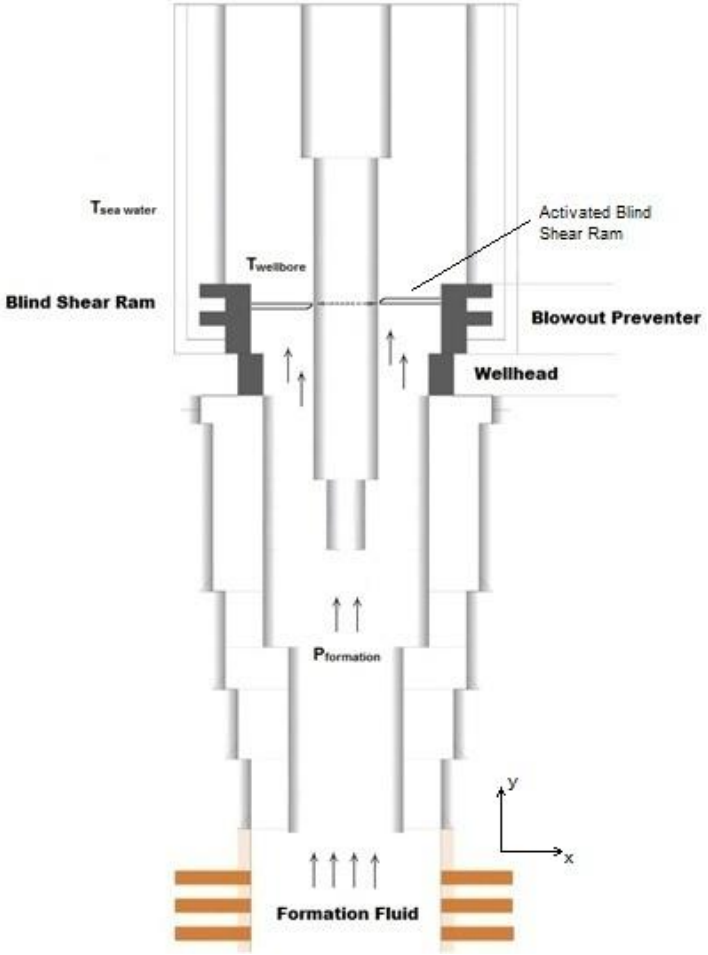


Figure 14 Pressure and Temperature Gradients at the Blind Shear Ram Position

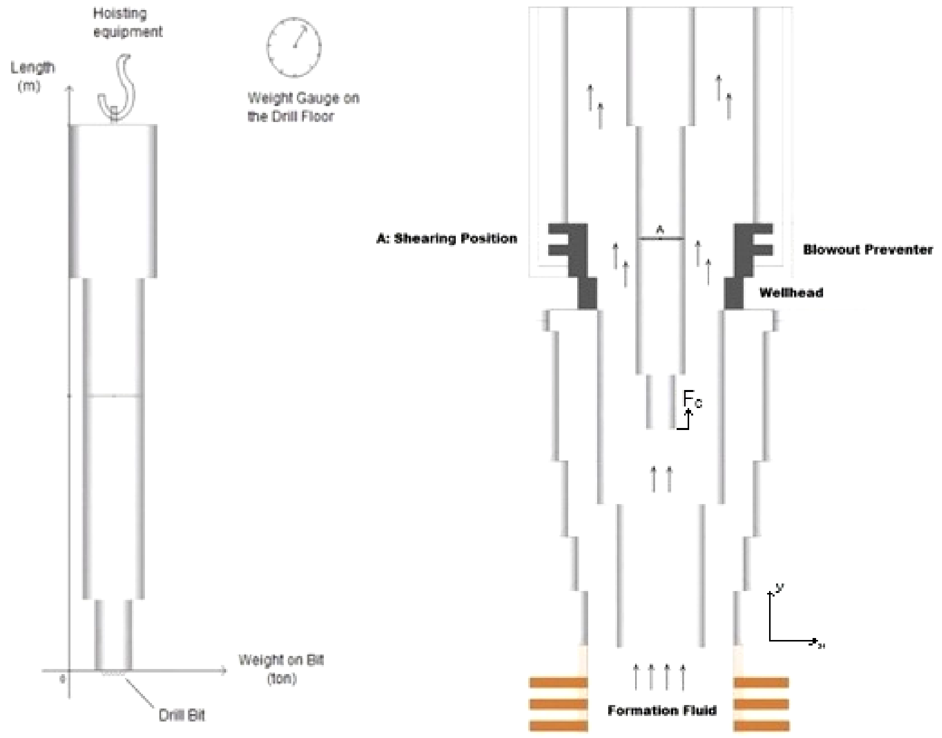
Pressure Gradient

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.



Weight of drill string is carrying by hoisting equipment.

Some weight of drill string is carrying by formation fluid that causes tension load to decrease and create compression load on drill string.

Figure 15 Effect of Formation Fluid on Axial Load

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.

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.

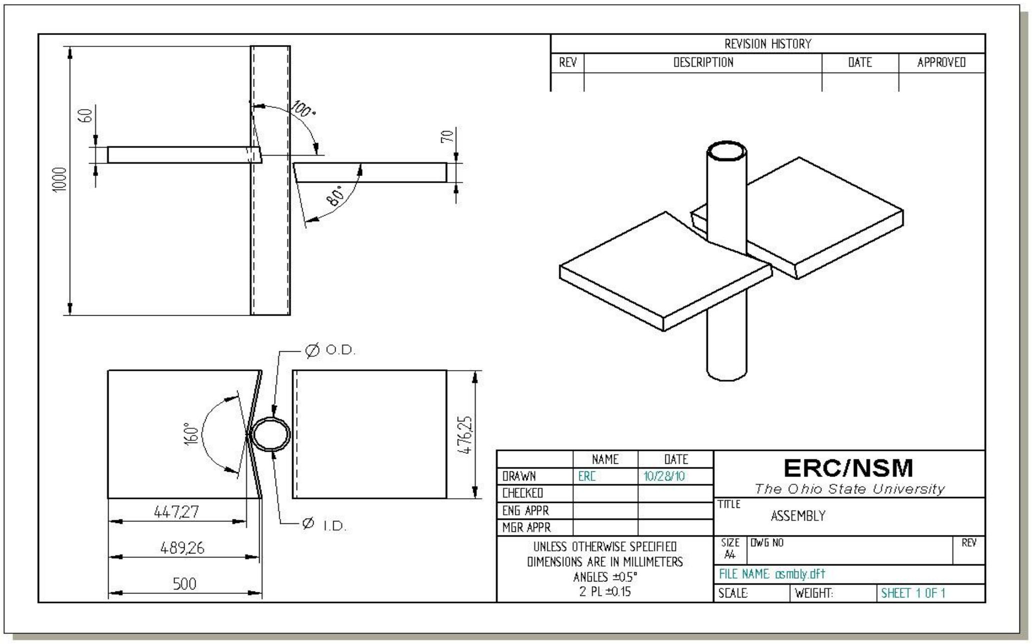


Figure 16 Tool (Shear Ram) and Drill Pipe Geometries

The variables are drill pipe diameter and tool clearance so other tool and pipe parameters will remain constant during studies.

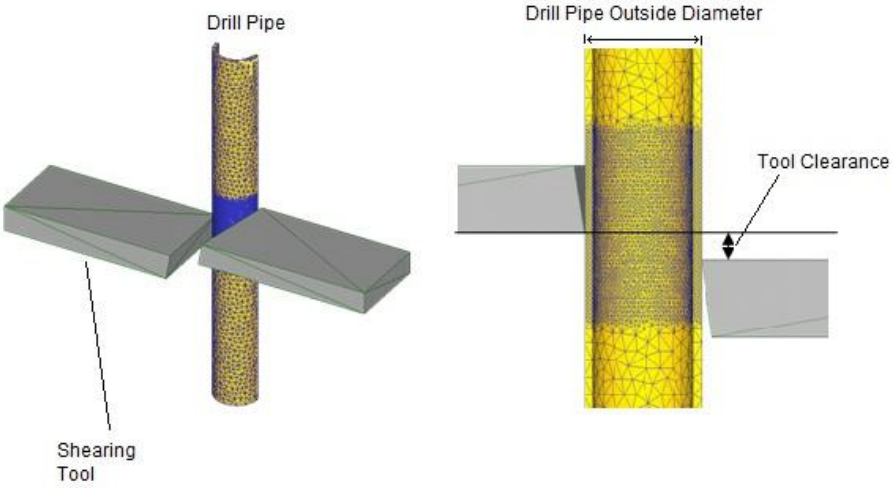


Figure 17 Drill Pipe O.D. and Tool Clearance

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.

#	Material Grade	Dimensions (mm)		Thickness (mm)	Area (cm^2)	Weight/ Length Ratio (kg/m)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation %
		O.D.	I.D.						
110	S-135	127	108.61	9.1948	34.0257	29.019	1014.219	1099.714	23.1
135	S-135	139.7	121.3	9.1694	37.6	32.590	1052.829	1101.782	20

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:

$$\sigma = K \times \varepsilon^{n} \qquad (2)$$

Where,

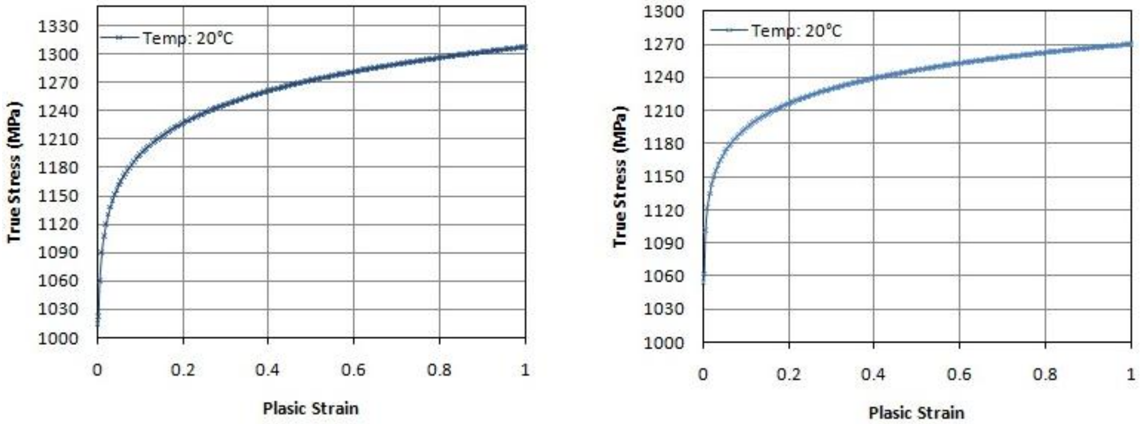
σ : True Stress

ε : True Strain

K: Strength Coefficient

n : Strain Hardening Exponent

The approximated flow stress curves are presented in Figure 18.



a) 5" O.D. Drill Pipe Flow Stress Curve

b) 5.5" O.D. Drill Pipe Flow Stress Curve

Figure 18 Flow Stress Curves Obtained by Using Equation (2)

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

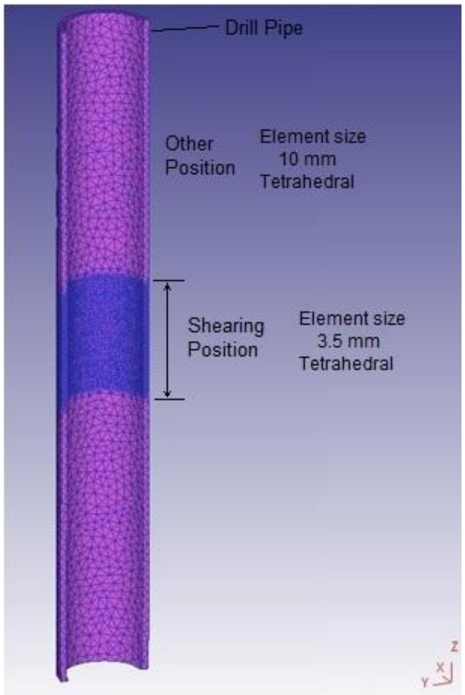


Figure 19 Mesh Conditions

Task 1

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

Drill pipe outside diameter	5” (127 mm)
Drill Pipe Thickness	0.362 in. (9.19 mm)
Area	5.27 in.^{2} (34.03 cm^2)
Drill pipe material properties	#110 (Table 4)
Tool clearance	0 mm
Load on shearing position	0 ton

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)

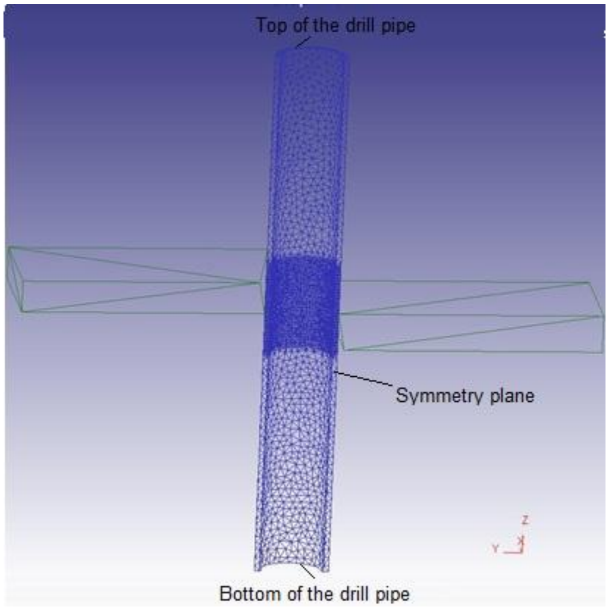


Figure 20 Boundary Conditions

The results of Task 1 are shown in Figure 21.

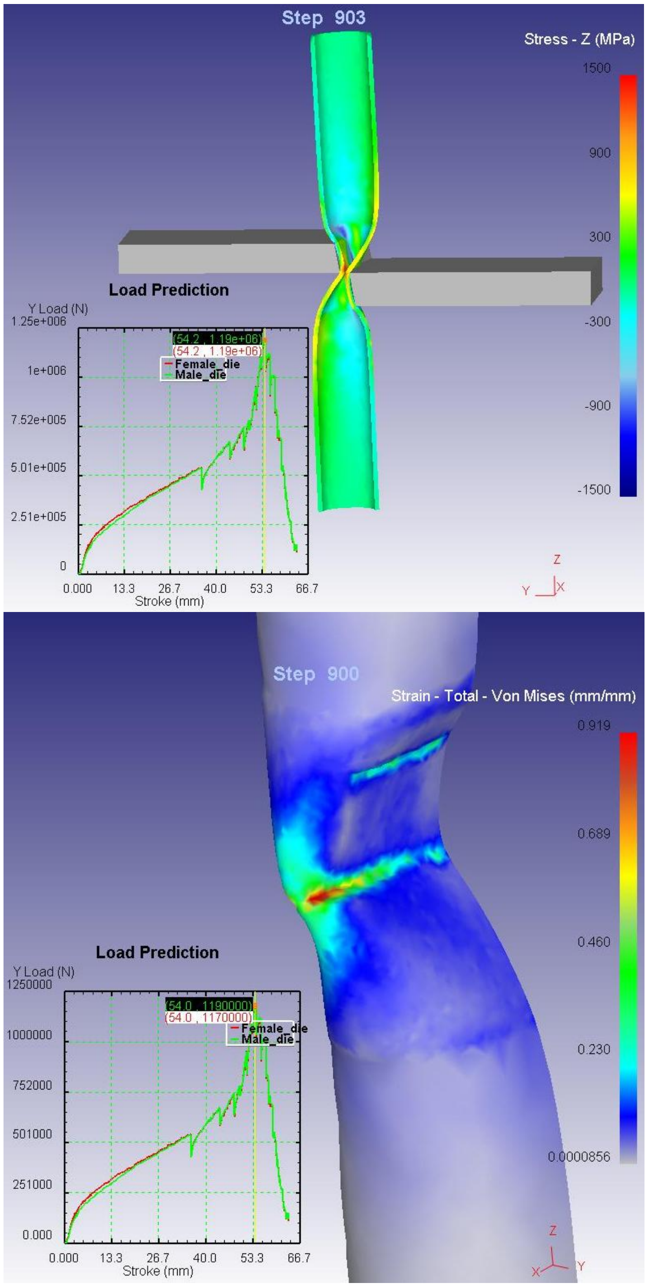


Figure 21 Obtained Maximum Shear Force and Strain for Task 1

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.

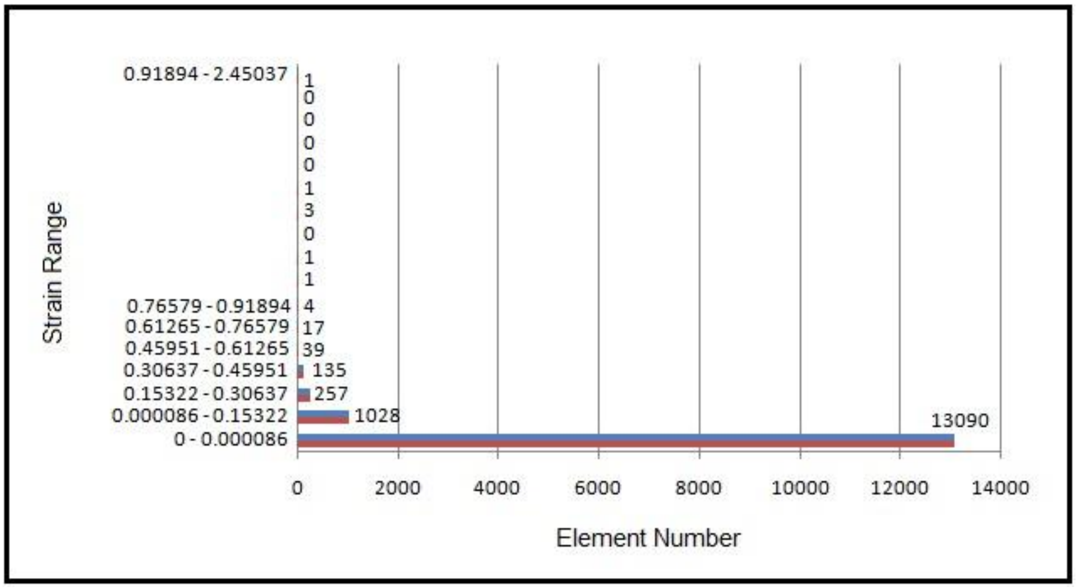


Figure 22 Evaluation of Maximum Strain

Task 2

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

Drill pipe outside diameter	5.5" (139.7 mm)
Drill Pipe Thickness	0.361 in. (9.17 mm)
Area	5.83 in.^{2} (37.60 cm^2)
Drill pipe material properties	#135 (Table 4)
Tool clearance	0 mm
Load on shearing position	0 ton

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.

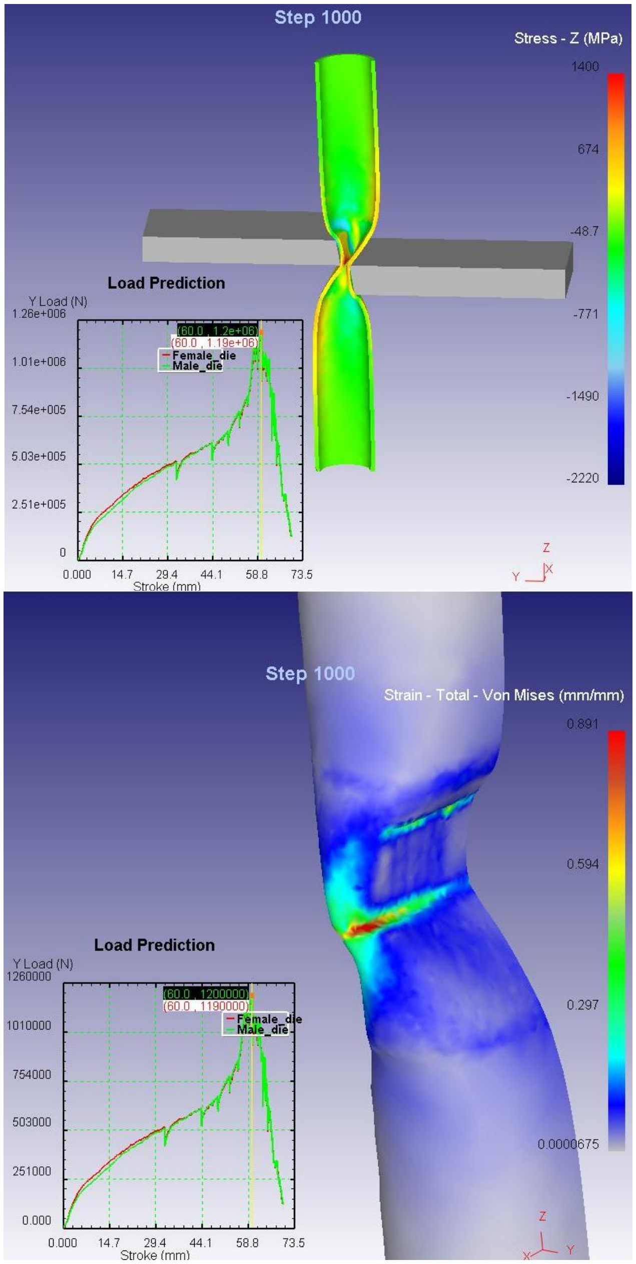


Figure 23 Obtained Maximum Shear Force and Strain for Task 2

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.

Drill pipe outside diameter	3.5” (88.9 mm)		
Drill Pipe Thickness	0.368” (9.35 mm)		
Area	3.62 in.^{2} (23.36 cm^2)		
Drill pipe material properties	Yield Strength (MPa)	UTS (MPa)	Elongation %
	1052.829	1101.782	20
Tool clearance	0 mm		
Load on shearing position	0 ton		

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.

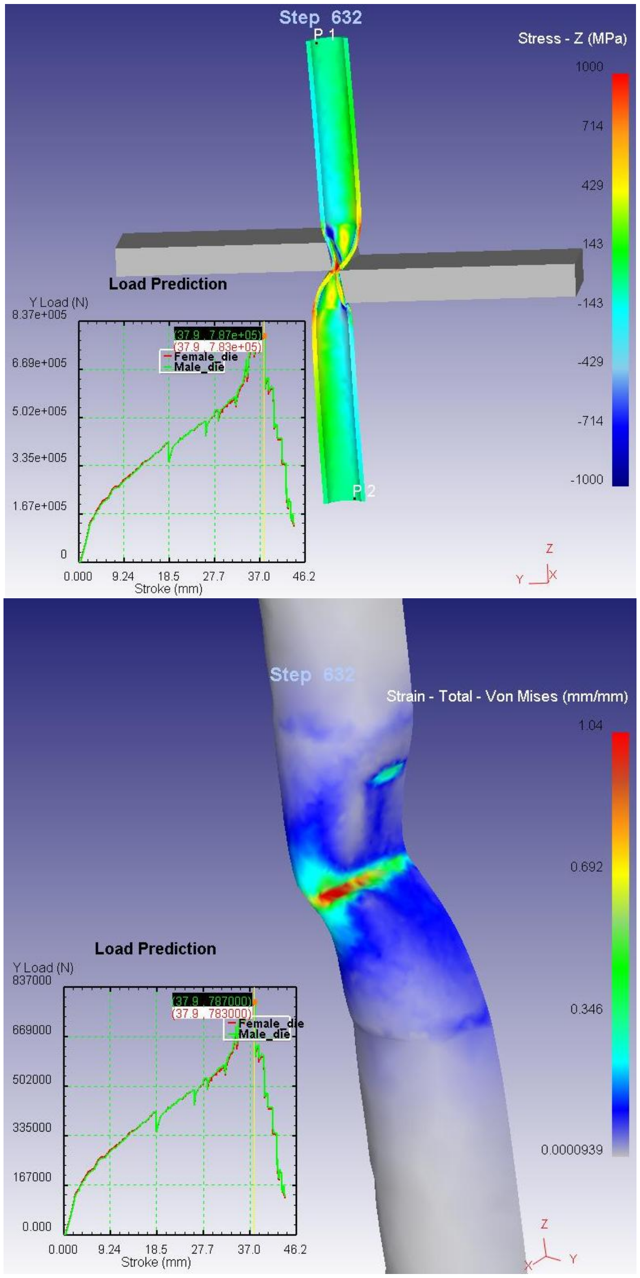


Figure 24 Obtained Maximum Shear Force and Strain for Task 3

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.

Drill pipe outside diameter	5” (127 mm)		
Drill Pipe Thickness	0.362 in. (9.19 mm)		
Area	5.27 in.^{2} (34.03 cm^2)		
Drill pipe material properties	Yield Strength (MPa)	UTS (MPa)	Elongation %
	1052.829	1101.782	20
Tool clearance	0 mm		
Load on shearing position	0 ton		

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.

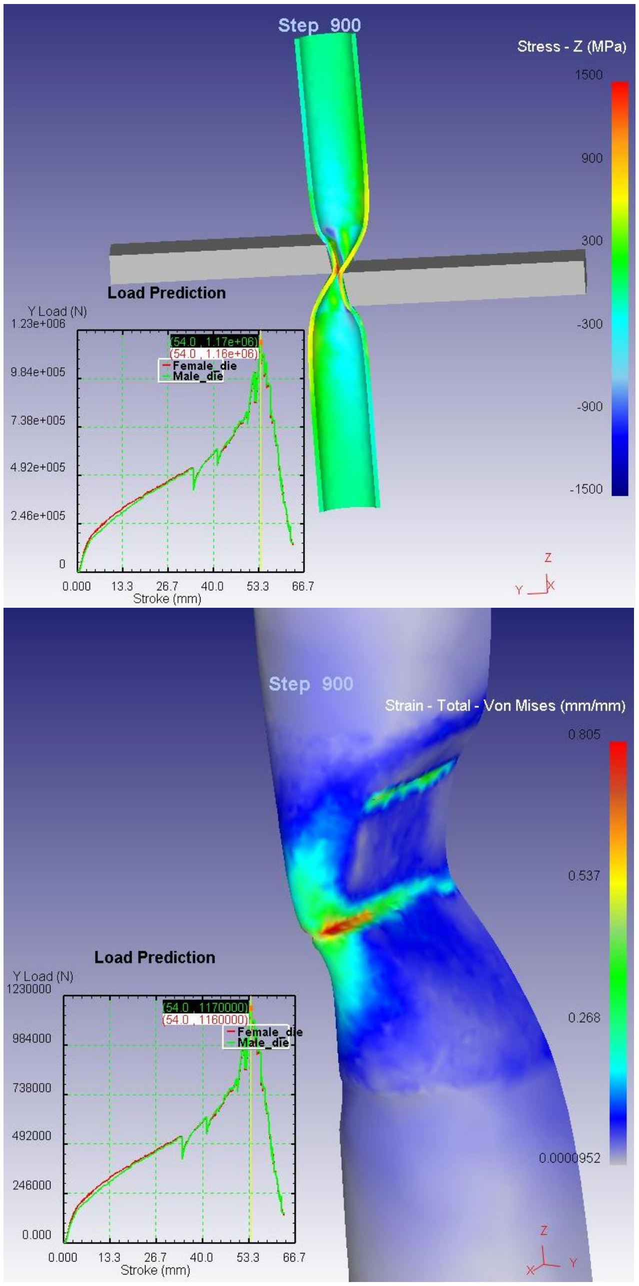


Figure 25 Obtained Maximum Shear Force and Strain for Task 4

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.

Drill pipe outside diameter	6.625” (168.27 mm)		
Drill Pipe Thickness	0.362 in. (9.19 mm)		
Area	7.12 in.^{2} (45.95 cm^2)		
Drill pipe material properties	Yield Strength (MPa)	UTS (MPa)	Elongation %
	1052.829	1101.782	20
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.

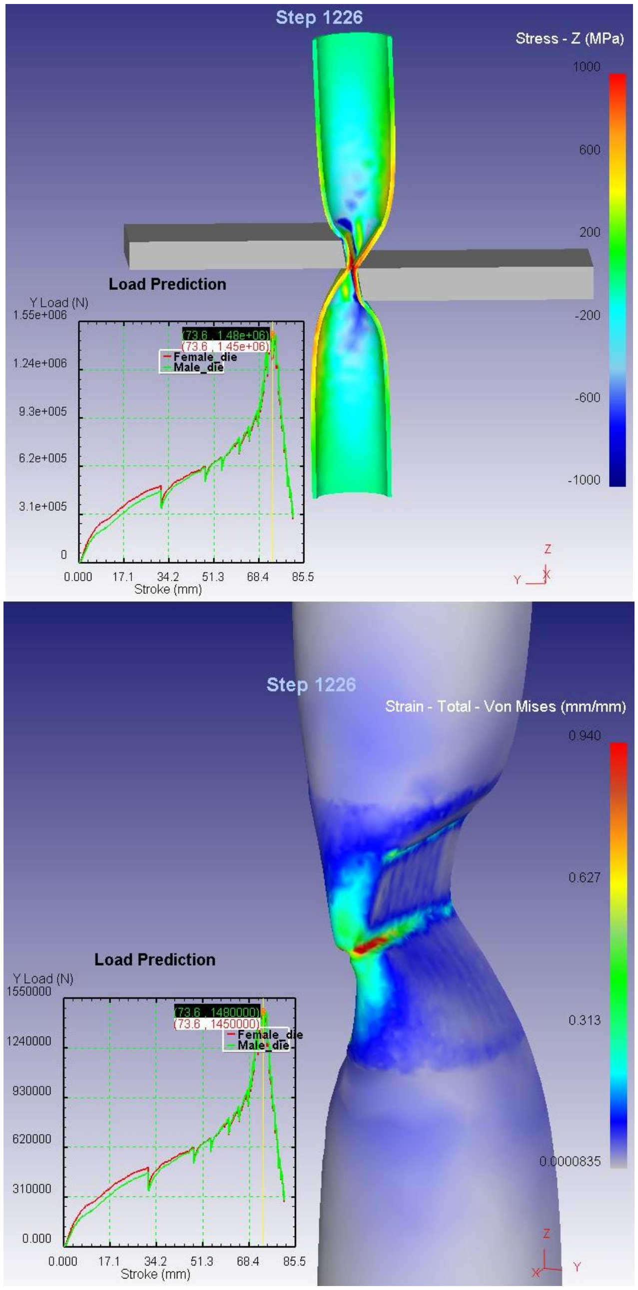


Figure 26 Obtained Maximum Shear Force and Strain for Task 5

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.

Drill pipe outside diameter	5.5” (139.7 mm)
Drill Pipe Thickness	0.361 in. (9.17 mm)
Area	5.82 in.^{2} (37.60 cm^2)
Drill pipe material properties	#135 (Table 4)
Tool clearance	0 mm
Load on shearing position	47.74 ton compression load

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.

#	Pipe Descriptions						
	O.D.		Wall Thickness		Weight Length Ratio		Material Grade
	(in.)	(mm)	(in.)	(mm)	(ppf)	(kg/m)	
209	6 5/8	168.3	0.362	9.195	27.6	41.073	S-135
135	5 ½	139.7	0.361	9.169	21.9	32.591	S-135
83	3 ½	88.9	0.368	9.347	13.3	19.793	S-135

Table 11 Pipe Properties used in the Well Configuration

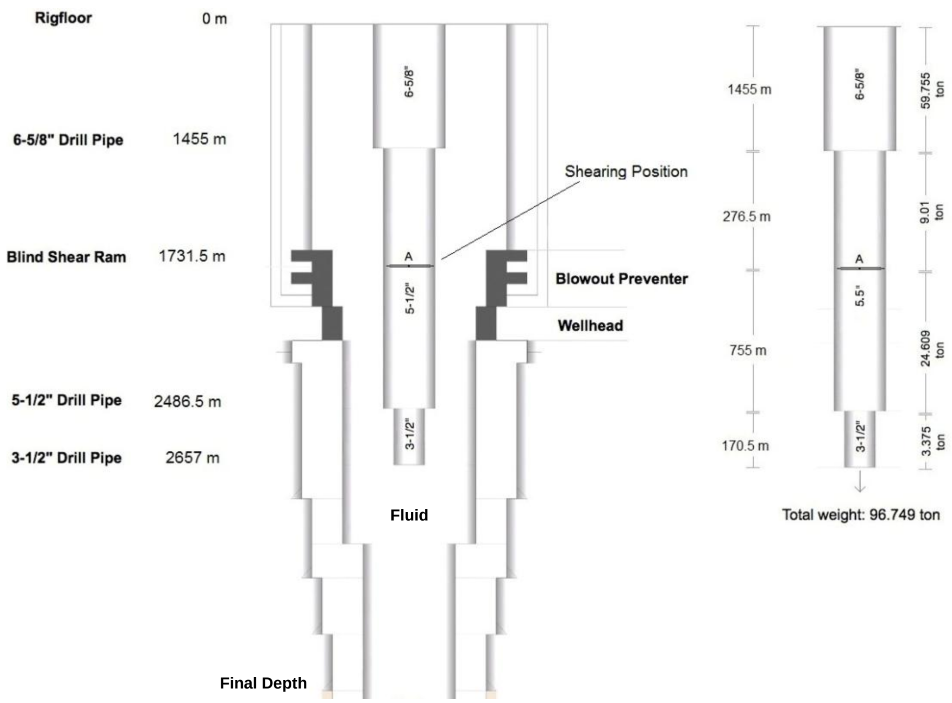


Figure 27 Examined Well Configuration

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.

$$Buoyancy\ Factor = 1 - \frac{\rho_{fluid}}{\rho_{pipe}} \qquad (3)$$

Where;

ρ_{fluid} : Fluid Density,

ρ_{pipe} : Pipe Density

Fluid density is assumed to be 14 ppg (1677.2 kg/cm^3) and drill pipe density was taken as the average drill pipe density 8030 kg/cm^3.

$$Buoyancy\ Factor = 1 - \frac{1677.2}{8030} = 0.79 \qquad (4)$$

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).

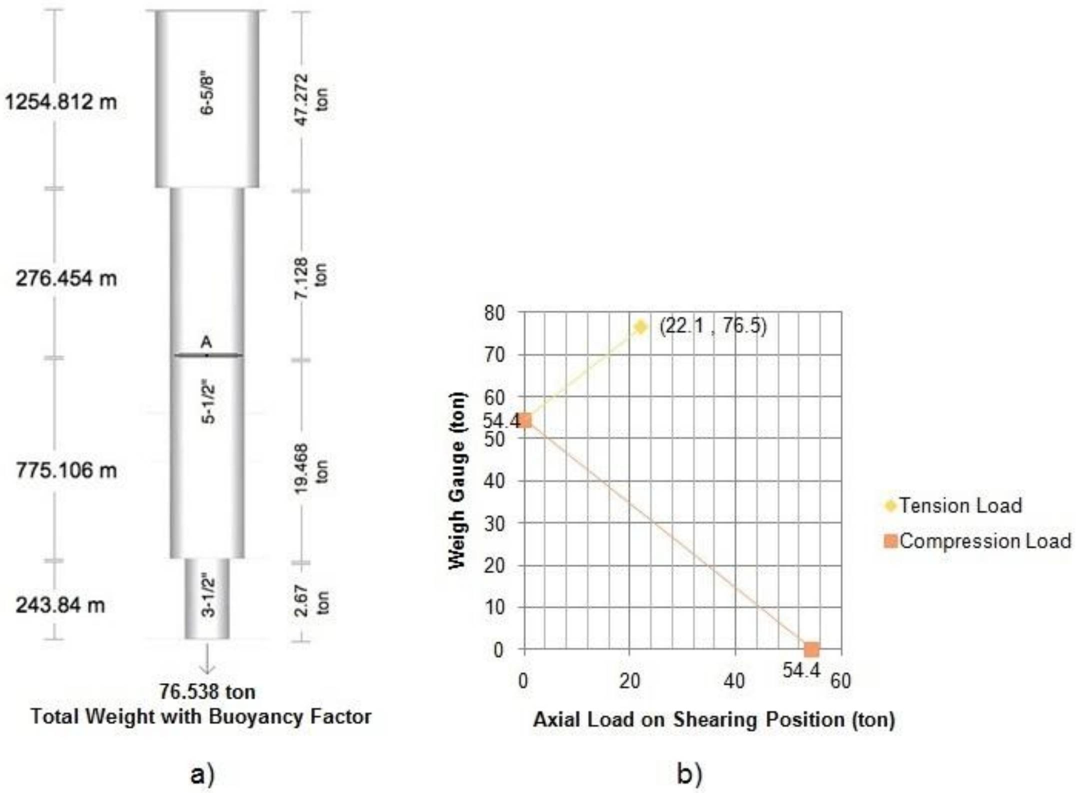


Figure 28 a) Calculated Weight of the Drill String in the Well, b) Evaluated Axial Load on Shearing Position

As can be seen in Figure 28 (b), the load on shearing position is 22.1tons (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.

Pipe Type #	Weight Gauge (ton)	Axial Load on Shearing Position		Pipe Area (cm^2)	Axial Stress on Shearing Position (MPa)
		(ton)	(kN)		
135	19.13	-47.74	-468.33	37.601	-124.55
	38.27	-9.01	-88.39	37.601	-23.51
	53.58	5.67	55.62	37.601	14.79
	76.54	22.1	216.80	37.601	57.66

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)

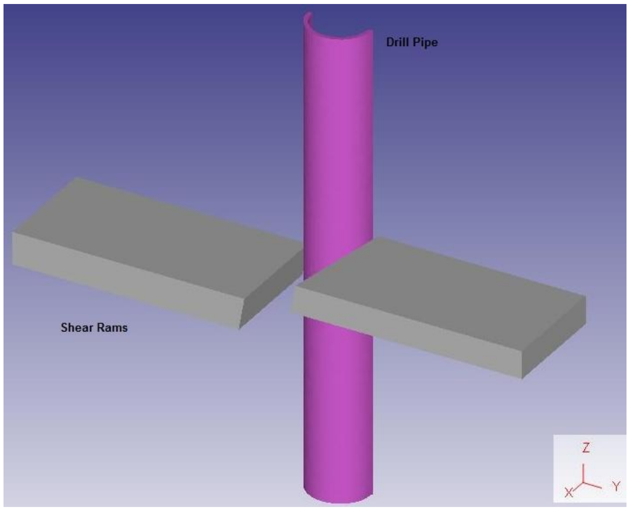


Figure 29 Applied Boundary Conditions Directions

The results of Task 6 are shown in Figure 30.

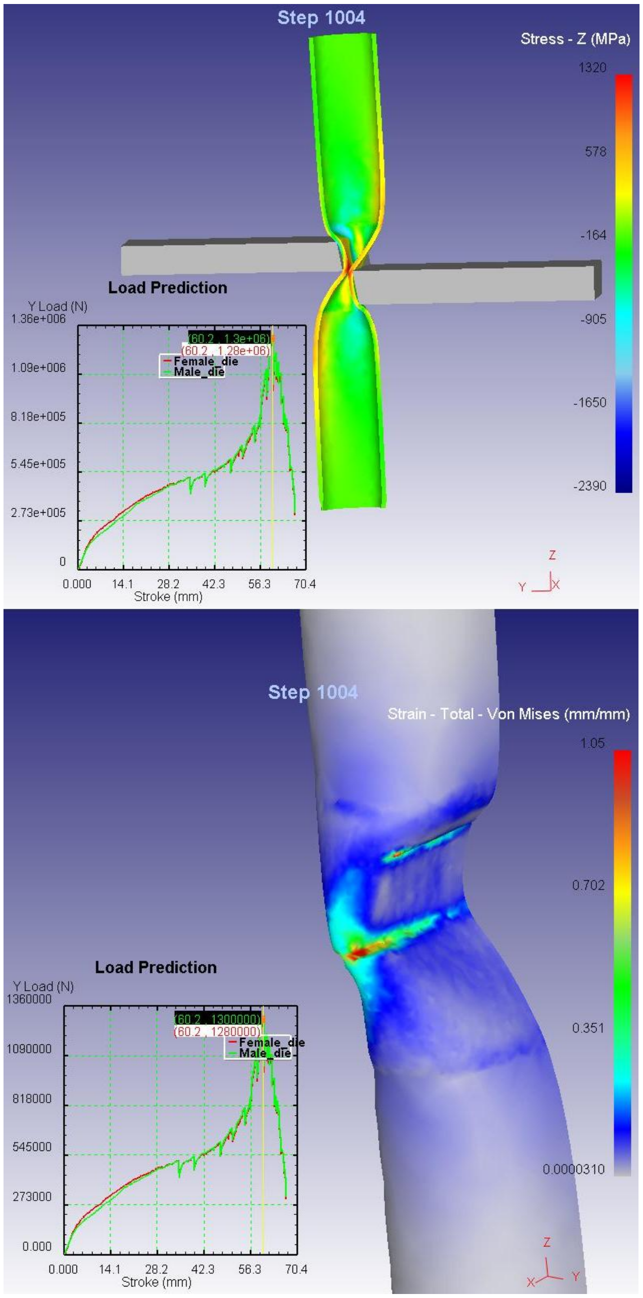


Figure 30 Obtained Maximum Shear Force and Strain for Task 6

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.

Drill pipe outside diameter	5.5" (139.7 mm)
Drill Pipe Thickness	0.361 in. (9.17 mm)
Area	5.82 in.^{2} (37.60 cm^2)
Drill pipe material properties	#135 (Table 4)
Tool clearance	0 mm
Load on shearing position	9.01 ton Compression

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.

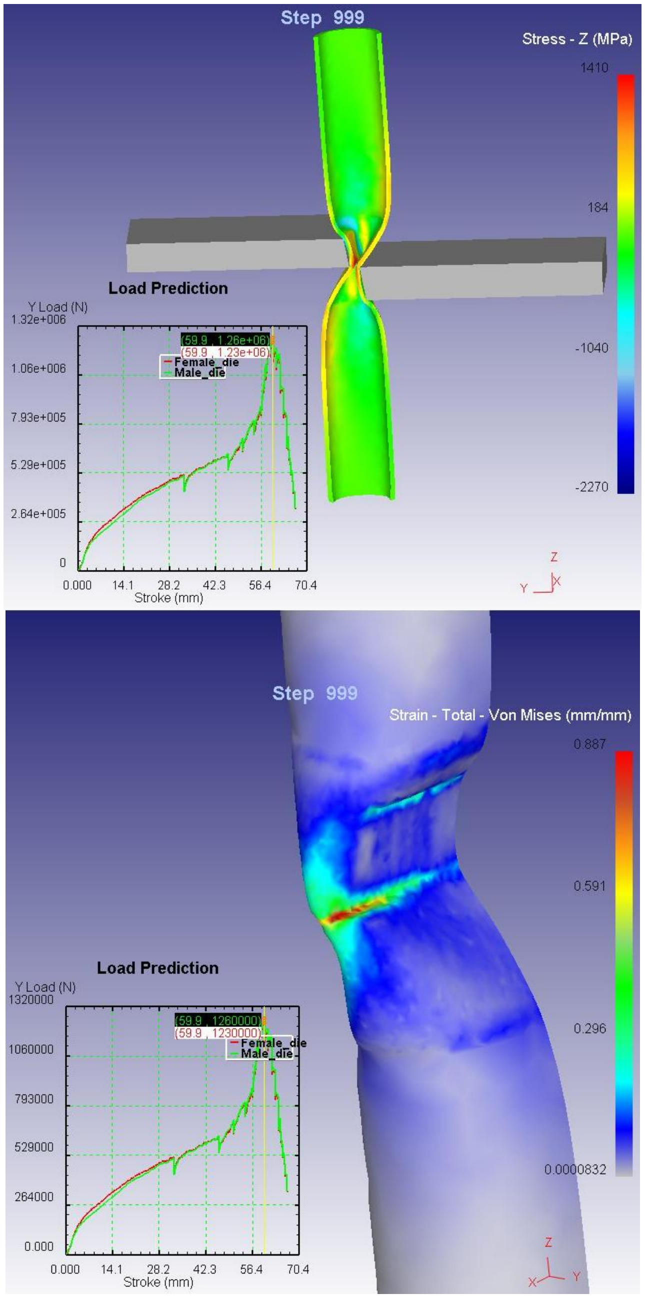


Figure 31 Obtained Maximum Shear Force and Strain for Task 7

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.

Drill pipe outside diameter	5.5” (139.7 mm)
Drill Pipe Thickness	0.361 in. (9.17 mm)
Area	5.82 in.^{2} (37.60 cm^2)
Drill pipe material properties	#135 (Table 4)
Tool clearance	0 mm
Load on shearing position	22.1 ton Tension

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.

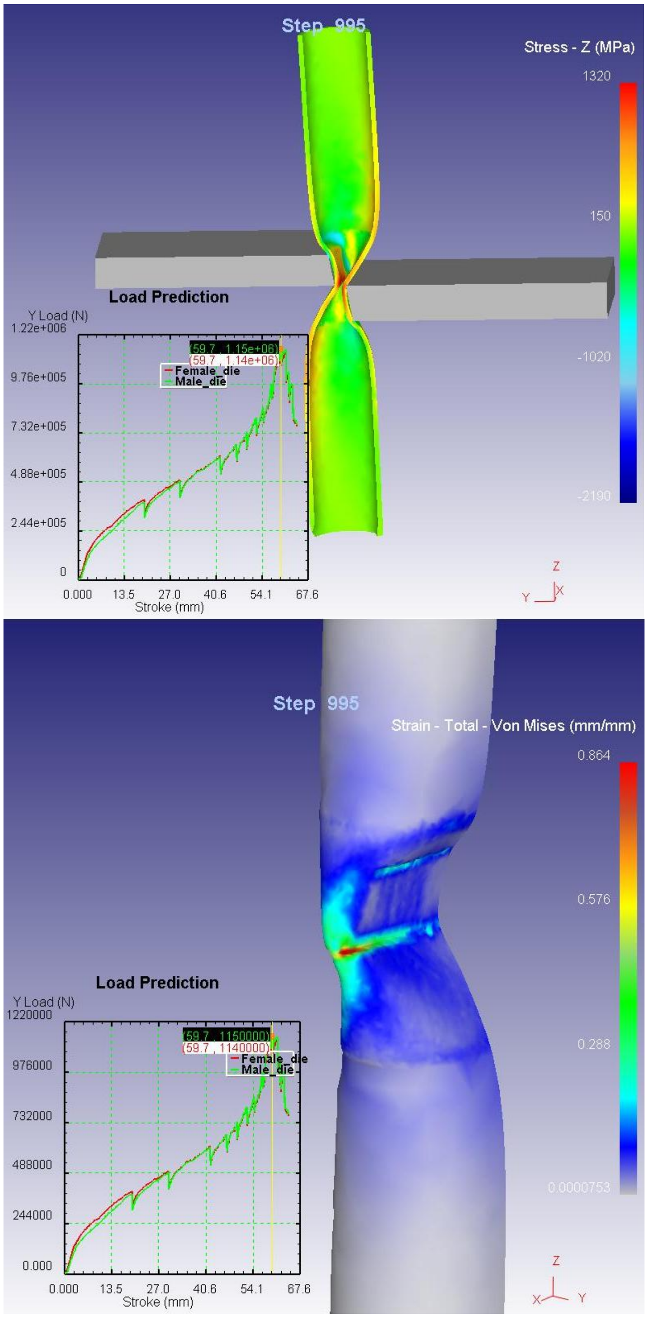


Figure 32 Obtained Maximum Shear Force and Strain for Task 8

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.

Drill pipe outside diameter	5.5” (139.7 mm)
Drill Pipe Thickness	0.361 in. (9.17 mm)
Area	5.82 in.^{2} (37.60 cm^2)
Drill pipe material properties	#135 (Table 4)
Tool clearance	0 mm
Load on shearing position	5.67 ton Tension

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.

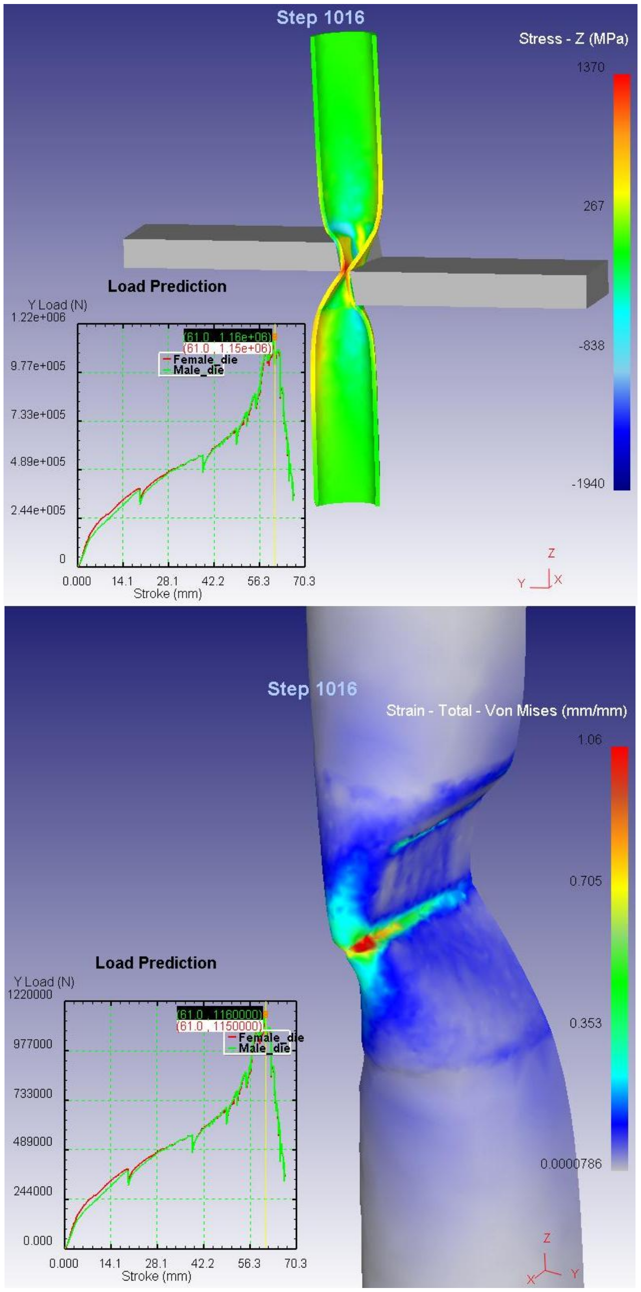


Figure 33 Obtained Maximum Shear Force and Strain for Task 9

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.

	Pipe Properties (Table 4) #	Drill Pipe O.D.	Thickness (mm)	Area (cm^2)	Tool Clearance
Task 10	135	139.7 mm (5.5 in.)	9.17	37.6	0.05
Task 11	135	139.7 mm (5.5 in.)	9.17	37.6	0.1
Task 12	135	139.7 mm (5.5 in.)	9.17	37.6	0.2
Task 13	135	139.7 mm (5.5 in.)	9.17	37.6	0.4
Task 14	135	139.7 mm (5.5 in.)	9.17	37.6	0.6

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.

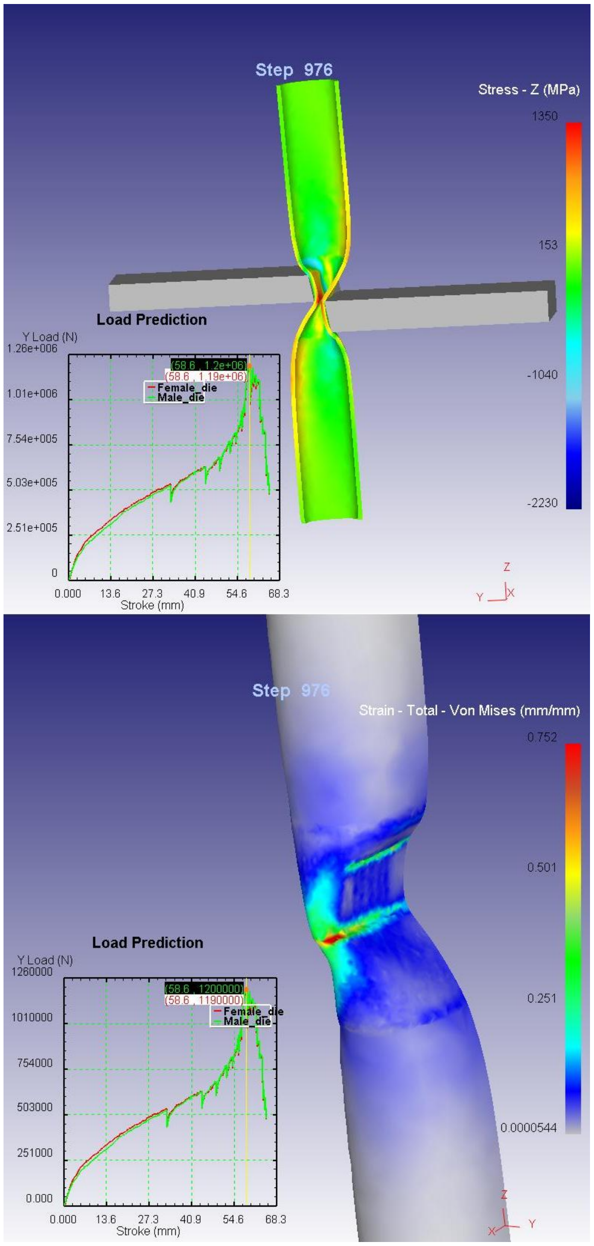


Figure 34 Obtained Maximum Shear Force and Strain for Simple Shearing with 0.05 mm tool clearance

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.

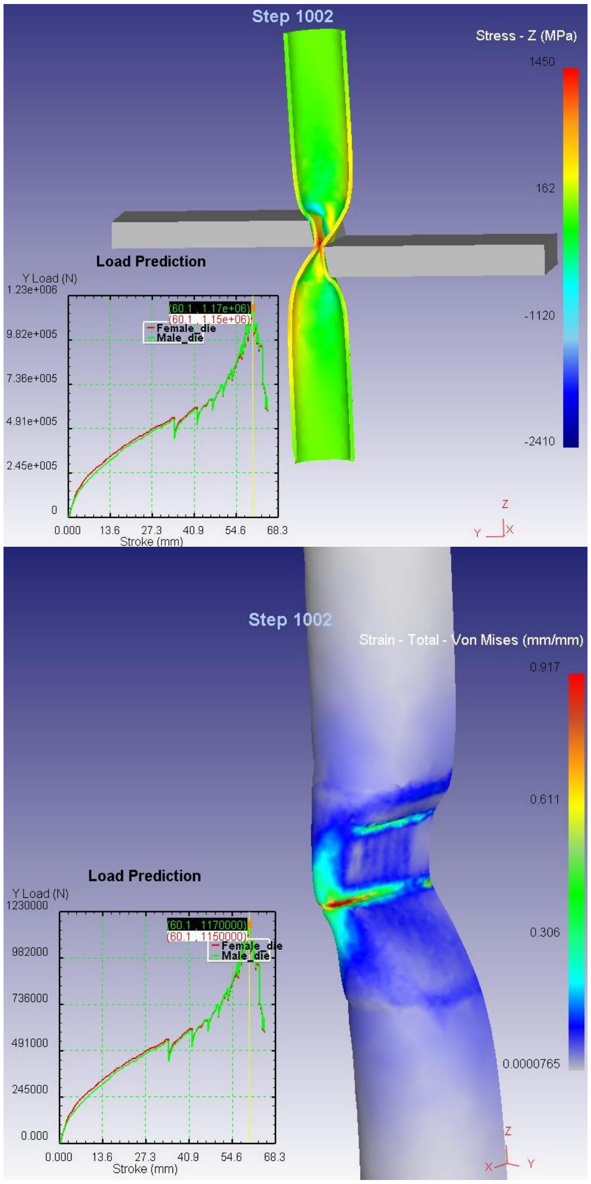


Figure 35 Obtained Maximum Shear Force and Strain for Simple Shearing with 0.1 mm Tool Clearance

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.

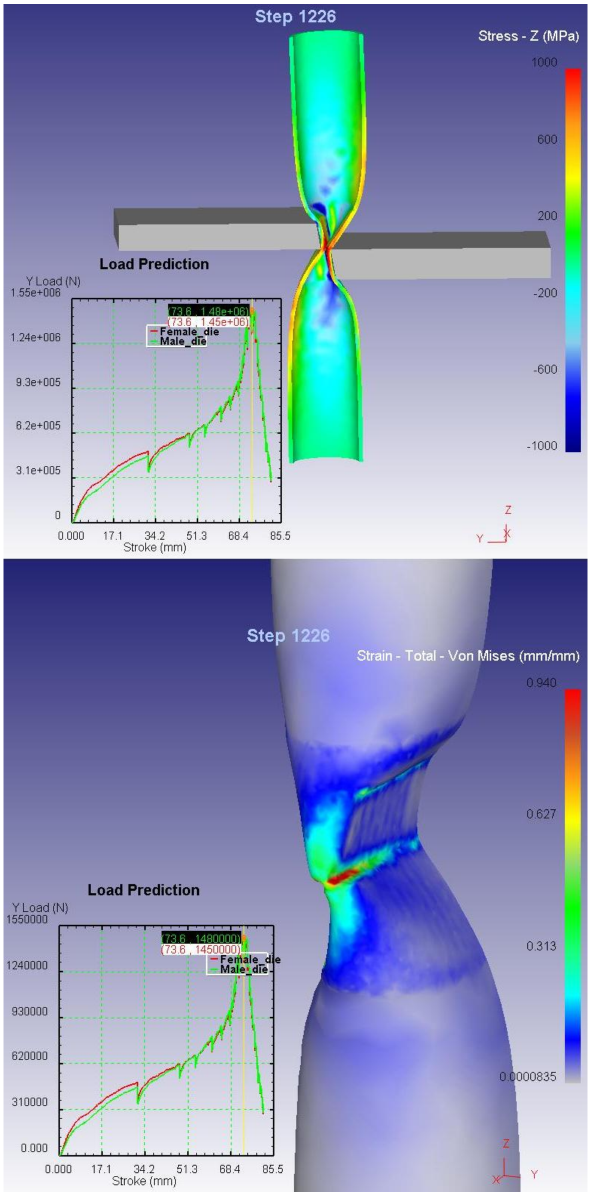


Figure 36 Obtained Maximum Shear Force and Strain for Simple Shearing with 0.2 mm Tool Clearance

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.

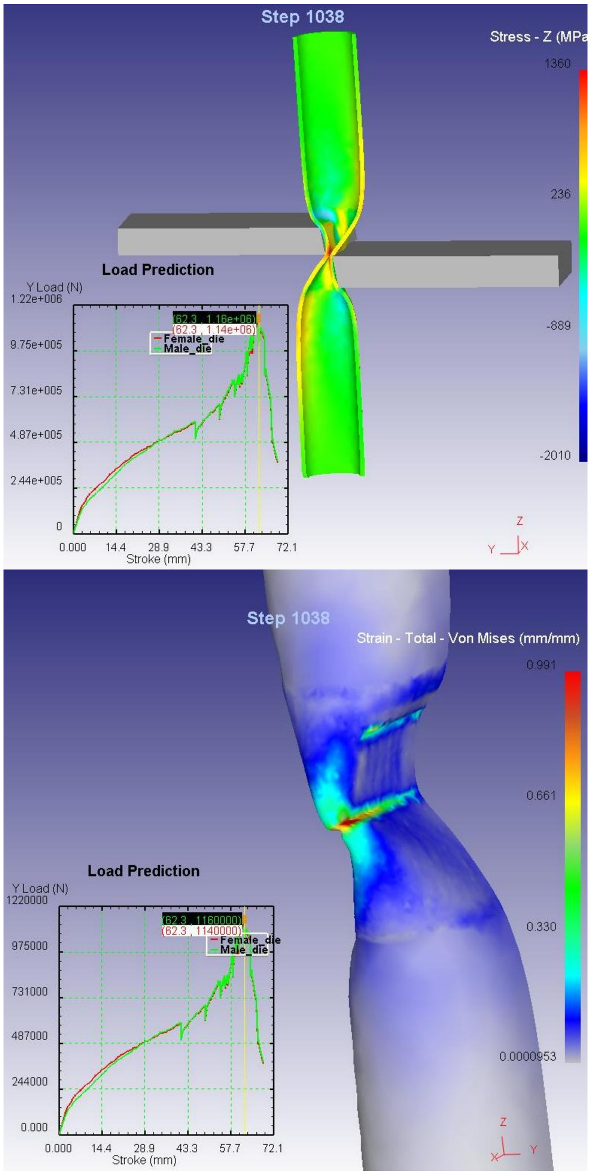


Figure 37 Obtained Maximum Shear Force and Strain for Simple Shearing with 0.4 mm Tool Clearance

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.

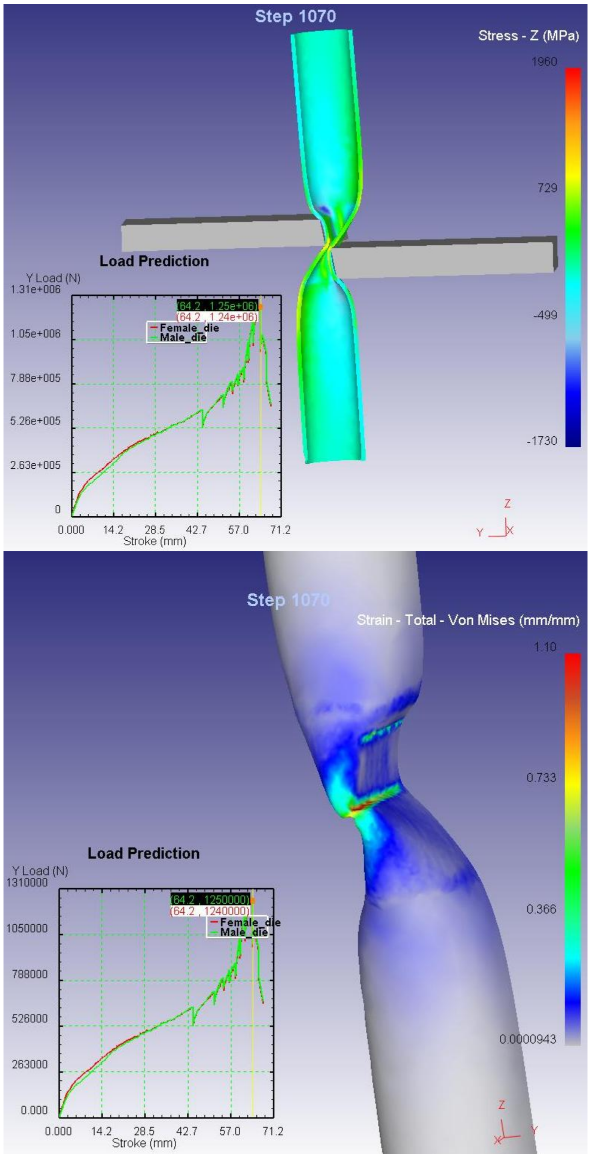


Figure 38 Obtained Maximum Shear Force and Strain for Simple Shearing with 0.6 mm Tool Clearance

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.

#	O.D.	Pipe Area (cm^2)	Actual Shear Force [Childs et al., 2004] (kN)	Calculated Shear Force Using Distortion Theory Equation (kN)		Obtained shear force from F.E.M. Simulations (Deform 3D) (kN)
				Using Yield Strength	Using Ultimate Tensile Strength	
110	5” (127 mm)	34.03	1177	1991	2159	1193
135	5.5” (139.7 mm)	37.60	1472	2284	2390	1197

Table 17 Shear Force Comparison

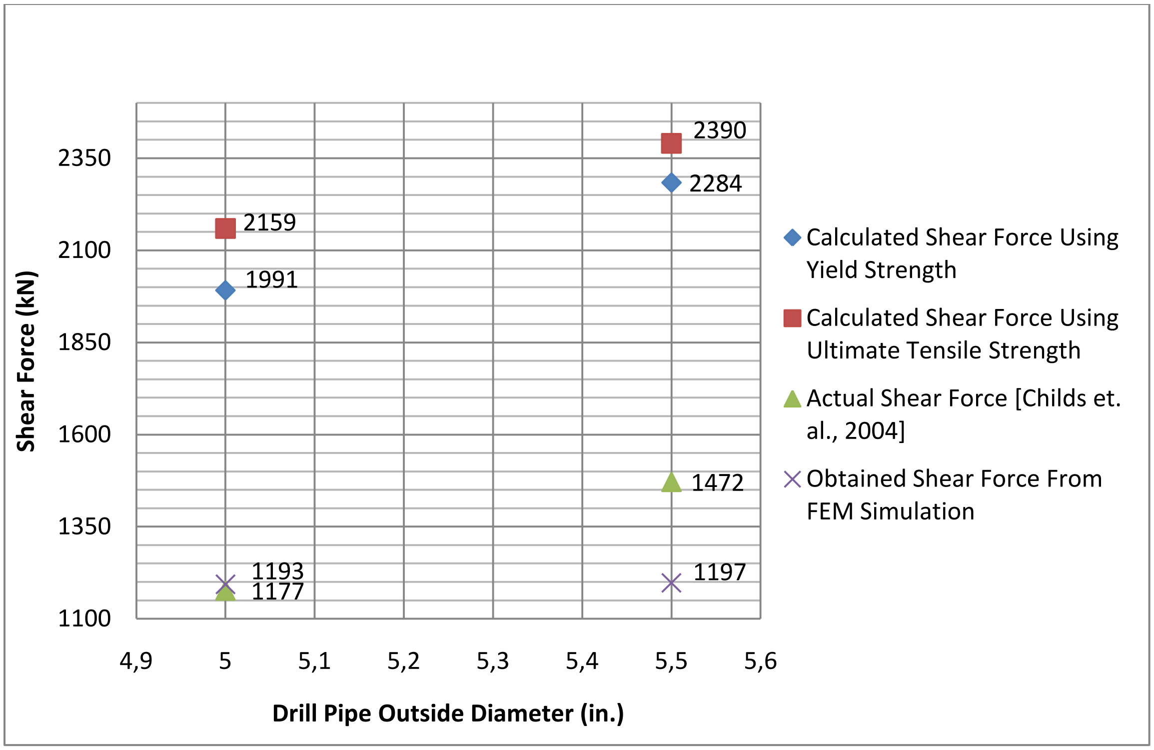


Figure 39 Shear Force Comparison

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

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.

Material Properties #	Drill Pipe O.D.	Pipe Area (cm^2)	Calculated Shear Force Using Distortion Theory Equation (kN)		Obtained shear force from F.E.M. Simulation (Deform 3D) (kN)
			Using Yield Strength	Using Ultimate Tensile Strength	
135	3.5” (88.9 mm)	23.36	1419	1485	769
	5” (127 mm)	34.03	2067	2163	1171
	5.5” (139.7 mm)	37.60	2284	2390	1197
	6.625” (168.3 mm)	45.95	2791	2921	1475

Table 18 Shear Forces for Different Outside Diameter Drill Pipe

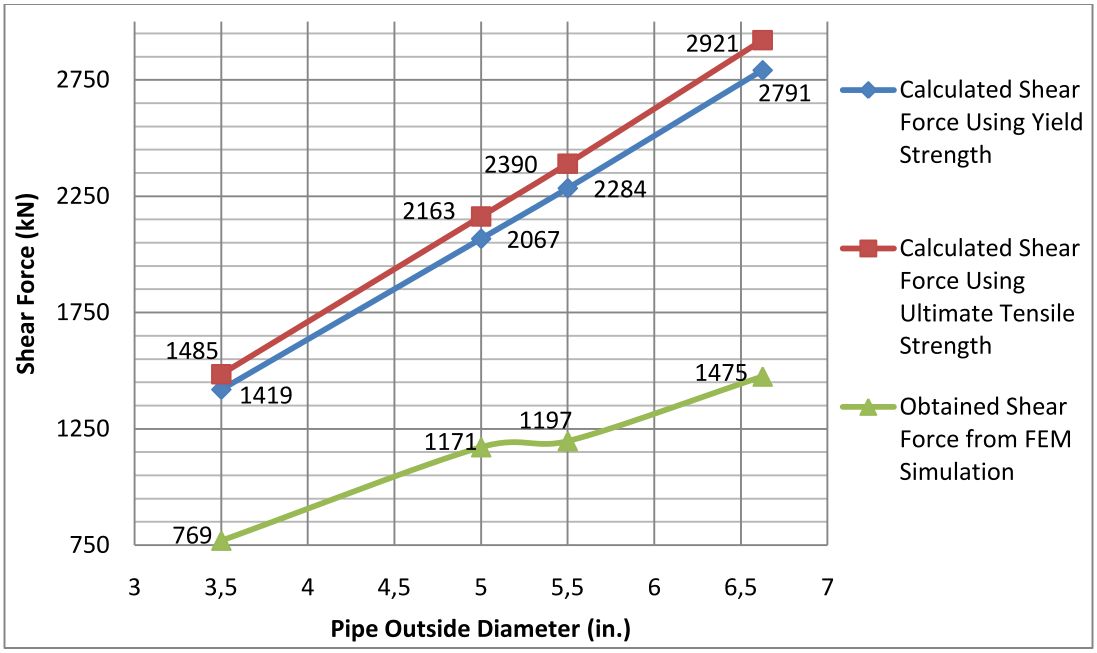


Figure 40 Shear Forces for Different Outside Diameter Drill Pipe

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.

#	Axial Load on Shearing Position	Pipe Area (cm^2)	Axial Stress on Shearing Position (MPa)	Obtained shear force from F.E.M. Simulation (Deform 3D) (kN)
135	0 ton (Simple Sharing)	37.601	0	1197
	47.74 ton Compression	37.601	-124.55	1297
	9.01 ton Compression	37.601	-23.50	1259
	5.67 ton Tension	37.601	14.79	1163
	22.1 ton Tension	37.601	57.66	1140

Table 19 Shear Forces for Different Axial Load on Shearing Position

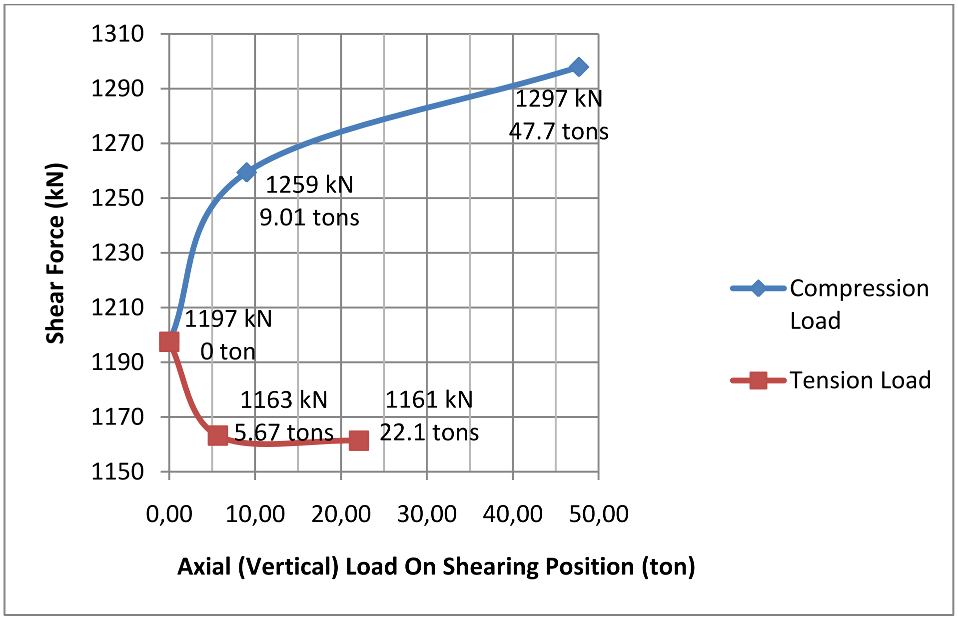


Figure 41 Shear Forces for Different Axial Load Applied on Shearing Position

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.

#	Drill Pipe O.D.	Tool Clearance (mm)	Obtained shear force from F.E.M. Simulation (Deform 3D) (kN)
135	5.5” (139.7 mm)	0	1197
		0.005	1197
		0.1	1168
		0.2	1116
		0.4	1160
		0.6	1251

Table 20 Obtained Maximum Shear Force for Different Tool Clearance

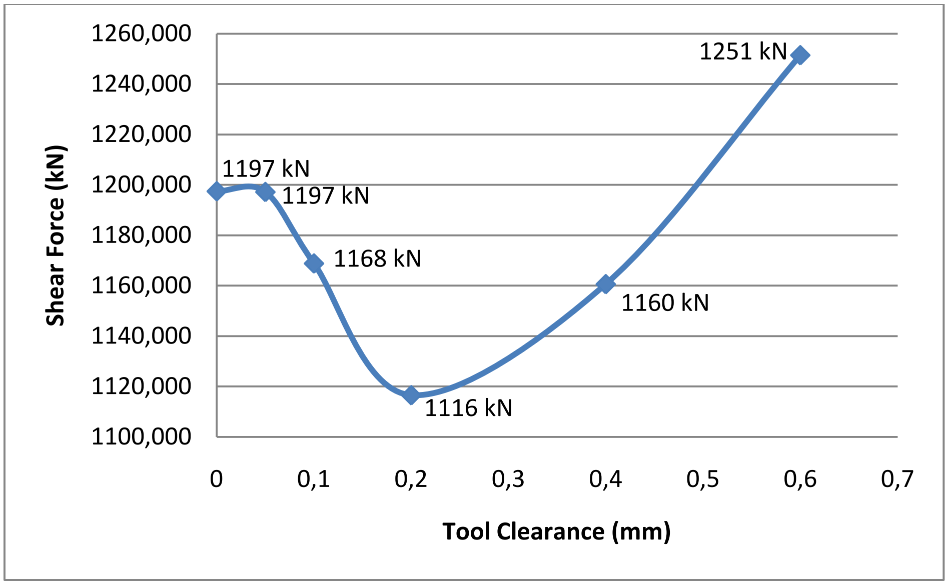


Figure 42 Obtained Maximum Shear Force for Different Tool Clearance

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).

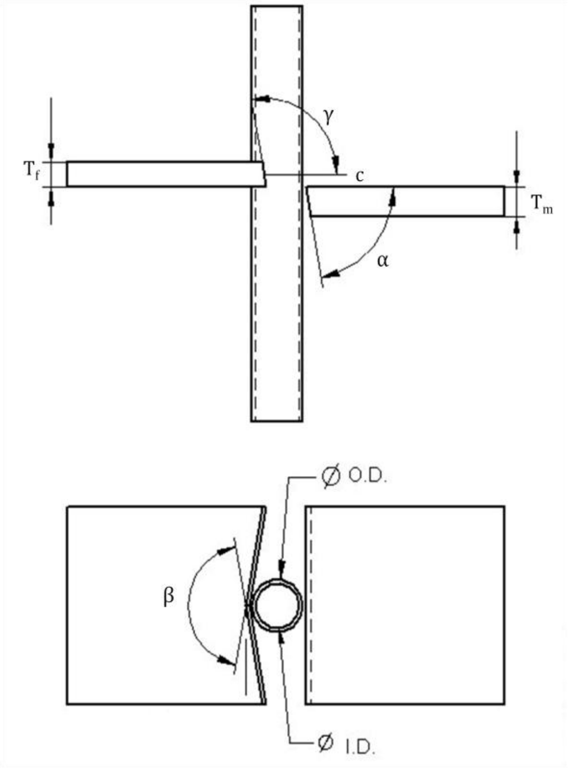


Figure 43 Tool Parameters

T_f : Female ram thickness

T_m: Male ram thickness

γ : Female ram lip angle

α : Male ram rip angle

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

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.

	PIPE DESCRIPTION					BOP and RAM DESCRIPTION					PIPE MATERIAL PROPERTIES										
#	DIA. (IN.)	WALL (IN.)	PPF	MATERIAL GRADE	BOP MANUFACTURER	BOP BORE	WORKING PRESSURE	BOP TYPE	BOP CLOSE AREA	SHEAR RAM TYPE	YIELD STRENGTH (PSI)	ULTIMATE TENSILE STRENGTH (PSI)	CHARPY, CVN	ELONGATION %	HARDNESS RC	ACTUAL SHEAR PRESSURE (PSI)	ACTUAL SHEAR FORCE (KIPS)	SHEAR FORCE CALCULATED USING YIELD (KIPS)	SHEAR FORCE CALCULATED USING ULTIMATE (KIPS)	SOURCE OF INFORMATION	COMMENTS
1	5.00	0.500	25.6	E?	HYDRIL	18.75	10000	14 1/4	159.48	Blind	83100	112800		26.0		1455	232.05	338.93	460.06	1983	
2	5.00	0.500	25.6	E?	HYDRIL	18.75	10000	14 1/4	159.48	Blind	83100	112800		26.0		1530	244.01	338.93	460.06	1983	
3	5.00	0.500	25.6	E?	HYDRIL	18.75	10000	14 1/4	159.48	Blind	83100	112800		26.0		1620	258.37	338.93	460.06	1983	
4	5.00	0.500	25.6	E?	HYDRIL	18.75	10000	14 1/4	159.48	Blind	83100	112800		26.0		1530	244.01	338.93	460.06	1983	
5	3.50	0.368	13.3	E-75	HYDRIL	18.75	10000	14 1/4	159.48	Blind	87700	106600		22.0		1425	227.27	183.23	222.72	1983	
6	3.50	0.368	13.3	E-75	HYDRIL	18.75	10000	14 1/4	159.48	Blind	87700	106600		22.0		1310	208.93	183.23	222.72	1983	
7	3.50	0.368	13.3	E-75	HYDRIL	18.75	10000	14 1/4	159.48	Blind	87700	106600		22.0		1820	290.26	183.23	222.72	1983	
8	3.50	0.368	13.3	E-75	HYDRIL	18.75	10000	14 1/4	159.48	Blind	87700	106600		22.0		1775	283.09	183.23	222.72	1983	
9	3.50	0.368	13.3	E-75	HYDRIL	18.75	10000	14 1/4	159.48	Blind	87700	106600		22.0		1470	234.44	183.23	222.72	1983	
10	3.50	0.449	15.5	E-75	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	89800	117900		23.0		1750	269.33	222.99	292.77	ER 522, RD23	
11	3.50	0.449	15.5	E-75	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	89800	117900		23.0		1850	284.72	222.99	292.77	ER 522, RD23	
12	5.00	0.362	19.5	E-75	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	80200	110200		28.0		1750	269.33	244.08	335.39	ER 522, RD17	
13	5.00	0.362	19.5	E-75	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	80200	110200		28.0		2100	323.19	244.08	335.39	ER 522, RD17	
14	5.00	0.362	19.5	E-75	HYDRIL	13.625	10000	14 1/4	159.48	Blind	83100	111800		22.3		1212	193.30	252.91	340.26	1987	
15	5.00	0.362	19.5	E-75	HYDRIL	13.625	5000	14 1/4	159.48	Blind	91800	108900		26.0		2398	382.44	279.39	331.43	1989	
16	5.00	0.362	19.5	E-75	HYDRIL	13.625	5000	14 1/4	159.48	Blind	91800	108900		26.0		2490	397.12	279.39	331.43	1989	
17	5.00	0.362	19.5	E-75	HYDRIL	13.625	5000	14 1/4	159.48	Blind	91800	108900		26.0		2467	393.45	279.39	331.43	1989	
18	5.00	0.362	19.5	E-75	HYDRIL	21.25	5000	14 1/4	159.48	Blind	91800	108900		26.0		2203	351.35	279.39	331.43	1990	
19	5.00	0.362	19.5	E-75	HYDRIL	21.25	5000	14 1/4	159.48	Blind	91800	108900		26.0		2146	342.25	279.39	331.43	1990	
20	5.00	0.362	19.5	E-75	HYDRIL	21.25	5000	14 1/4	159.48	Blind	91800	108900		26.0		2173	346.56	279.39	331.43	1990	
21	5.00	0.362	19.5	E-75	HYDRIL	21.25	5000	14 1/4	159.48	Blind	91800	108900		26.0		2203	351.35	279.39	331.43	1990	
22	5.00	0.362	19.5	E-75	HYDRIL	21.25	5000	14 1/4	159.48	Blind	91800	108900		26.0		2146	342.25	279.39	331.43	1990	
23	5.00	0.362	19.5	E-75	HYDRIL	21.25	5000	14 1/4	159.48	Blind	91800	108900		26.0		2173	346.56	279.39	331.43	1990	
24	5.00	0.362	19.5	E-75	HYDRIL	13.625	15000	14 1/4	159.48	Blind	91800	108900		26.0		2315	369.21	279.39	331.43	1990	
25	5.00	0.362	19.5	E-75	HYDRIL	13.625	15000	14 1/4	159.48	Blind	91800	108900		26.0		2311	368.57	279.39	331.43	1990	
26	5.00	0.362	19.5	E-75	HYDRIL	13.625	15000	14 1/4	159.48	Blind	91800	108900		26.0		2229	355.49	279.39	331.43	1990	
27	5.00	0.362	19.5	E-75	HYDRIL	18.75	5000	20	314.16	Blind	95700	109600		26.0		1412	443.59	291.26	333.56	1992	
28	5.00	0.362	19.5	E-75	HYDRIL	18.75	5000	20	314.16	Blind	95700	109600		26.0		1469	461.50	291.26	333.56	1992	
29	5.00	0.362	19.5	E-75	HYDRIL	18.75	5000	20	314.16	Blind	95700	109600		26.0		1459	458.36	291.26	333.56	1992	
30	5.00	0.500	25.6	E-75	HYDRIL	18.75	10000	14 1/4	159.48	Blind	94600	109500		30.0		2220	354.06	385.83	446.60	1983	
31	5.00	0.500	25.6	E-75	HYDRIL	18.75	10000	14 1/4	159.48	Blind	94600	109500		30.0		2340	373.19	385.83	446.60	1983	
32	5.00	0.500	25.6	E-75	HYDRIL	18.75	10000	14 1/4	159.48	Blind	94600	109500		30.0		2610	416.26	385.83	446.60	1983	
33	5.00	0.500	25.6	E-75	HYDRIL	18.75	10000	14 1/4	159.48	Blind	94600	109500		30.0		2730	435.39	385.83	446.60	1983	
34	5.00	0.362	19.5	G-105	Cameron	18-3/4"	5K	TL	214	DVS	113000	132500	75	21.2	25.0	1660	355.24	343.91	403.26	ER 2209	
35	5.00	0.362	19.5	G-105	Cameron	18-3/4"	5K	TL	214	DVS	113000	132500	75	21.2	25.0	1775	379.85	343.91	403.26	ER 2209	
36	5.00	0.362	19.5	G-105	Cameron	18-3/4"	5K	TL	214	DVS	113000	132500	75	21.2	25.0	1775	379.85	343.91	403.26	ER 2209	
37	5.00	0.362	19.5	G-105	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear						2600	400.14			ER 522, RD15-1	
38	5.00	0.362	19.5	G-105	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear						2575	396.29			ER 522, RD15-3	
39	5.00	0.362	19.5	G-105	HYDRIL	13.625	10000	14 1/4	159.48	Blind	113700	125500		23.5		2213	352.94	346.04	381.95	1987	
40	5.00	0.362	19.5	G-105	HYDRIL	13.625	5000	14 1/4	159.48	Blind	123100	137200		19.5		2337	372.72	374.65	417.56	1989	
41	5.00	0.362	19.5	G-105	HYDRIL	13.625	5000	14 1/4	159.48	Blind	123100	137200		19.5		2162	344.81	374.65	417.56	1989	
42	5.00	0.362	19.5	G-105	HYDRIL	13.625	5000	14 1/4	159.48	Blind	123100	137200		19.5		2276	362.99	374.65	417.56	1989	
43	5.00	0.362	19.5	G-105	HYDRIL	21.25	5000	14 1/4	159.48	Blind	123100	137200		19.5		1935	308.60	374.65	417.56	1990	
44	5.00	0.362	19.5	G-105	HYDRIL	21.25	5000	14 1/4	159.48	Blind	123100	137200		19.5		1948	310.68	374.65	417.56	1990	
45	5.00	0.362	19.5	G-105	HYDRIL	21.25	5000	14 1/4	159.48	Blind	123100	137200		19.5		1927	307.33	374.65	417.56	1990	
46	5.00	0.362	19.5	G-105	HYDRIL	21.25	5000	14 1/4	159.48	Blind	123100	137200		19.5		1935	308.60	374.65	417.56	1990	
47	5.00	0.362	19.5	G-105	HYDRIL	21.25	5000	14 1/4	159.48	Blind	123100	137200		19.5		1948	310.68	374.65	417.56	1990	
48	5.00	0.362	19.5	G-105	HYDRIL	21.25	5000	14 1/4	159.48	Blind	123100	137200		19.5		1927	307.33	374.65	417.56	1990	
49	5.00	0.362	19.5	G-105	HYDRIL	13.625	15000	14 1/4	159.48	Blind	123100	137200		19.5		1953	311.47	374.65	417.56	1990	
50	5.00	0.362	19.5	G-105	HYDRIL	13.625	15000	14 1/4	159.48	Blind	123100	137200		19.5		2443	389.62	374.65	417.56	1990	
51	5.00	0.362	19.5	G-105	HYDRIL	13.625	15000	14 1/4	159.48	Blind	123100	137200		19.5		2164	345.13	374.65	417.56	1990	
52	5.00	0.362	19.5	G-105	HYDRIL	18.75	5000	20	314.16	Blind	129400	141800		23.0		1450	455.53	393.82	431.56	1992	

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.

	PIPE DESCRIPTION					BOP and RAM DESCRIPTION					PIPE MATERIAL PROPERTIES										
#	DIA. (IN.)	WALL (IN.)	PPF	MATERIAL GRADE	BOP MANUFACTURER	BOP BORE	WORKING PRESSURE	BOP TYPE	BOP CLOSE AREA	SHEAR RAM TYPE	YIELD STRENGTH (PSI)	ULTIMATE TENSILE STRENGTH (PSI)	CHARPY, CVN	ELONGATION %	HARDNESS RC	ACTUAL SHEAR PRESSURE (PSI)	ACTUAL SHEAR FORCE (KIPS)	SHEAR FORCE CALCULATED USING YIELD (KIPS)	SHEAR FORCE CALCULATED USING ULTIMATE (KIPS)	SOURCE OF INFORMATION	COMMENTS
53	5.00	0.362	19.5	G-105	HYDRIL	18.75	5000	20	314.16	Blind	129400	141800		23.0		1456	457.42	393.82	431.56	1992	
54	5.00	0.362	19.5	G-105	HYDRIL	18.75	5000	20	314.16	Blind	129400	141800		23.0		1327	416.89	393.82	431.56	1992	
55	5.00	0.362	19.5	G-105	HYDRIL	13.625	15000	19	283.53	Blind	128800	137900		21.3		2017	571.88	392.00	419.69	2003	
56	5.00	0.500	25.6	G-105	HYDRIL	18.75	10000	14 1/4	159.48	Blind	120700	135400		24.0		1830	291.86	492.28	552.24	1983	
57	5.00	0.500	25.6	G-105	HYDRIL	18.75	10000	14 1/4	159.48	Blind	120700	135400		24.0		1910	304.62	492.28	552.24	1983	
58	5.00	0.500	25.6	G-105	HYDRIL	18.75	10000	14 1/4	159.48	Blind	120700	135400		24.0		1770	282.29	492.28	552.24	1983	
59	5.00	0.500	25.6	G-105	HYDRIL	18.75	10000	14 1/4	159.48	Blind	120700	135400		24.0		1940	309.40	492.28	552.24	1983	
60	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2135	402.86	474.75	589.76	1993	
61	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2408	454.37	474.75	589.76	1993	
62	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2335	440.60	474.75	589.76	1993	
63	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2362	445.69	474.75	589.76	1993	
64	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2355	444.37	474.75	589.76	1993	
65	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2315	436.82	474.75	589.76	1993	
66	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2339	441.35	474.75	589.76	1993	
67	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2325	438.71	464.55	581.61	1993	
68	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2413	455.31	464.55	581.61	1993	
69	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2368	446.82	464.55	581.61	1993	
70	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2298	433.61	464.55	581.61	1993	
71	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2316	437.01	464.55	581.61	1993	
72	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2242	423.05	464.55	581.61	1993	
73	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2367	446.63	464.55	581.61	1993	
74	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2344	442.29	464.55	581.61	1993	
75	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2363	445.88	464.55	581.61	1993	
76	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	113900	142600		21.4		2395	451.92	464.55	581.61	1993	
77	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2393	451.54	474.75	589.76	1993	
78	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2372	447.58	474.75	589.76	1993	
79	5.00	0.500	25.6	G-105	HYDRIL	18.75	15000	15 1/2	188.69	Blind	116400	144600		22.4		2254	425.31	474.75	589.76	1993	
80	3.50	0.368	13.3	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138600	147800		20.2		1878	299.51	289.57	308.80	1994	
81	3.50	0.368	13.3	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138600	147800		20.2		1892	301.75	289.57	308.80	1994	
82	3.50	0.368	13.3	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138600	147800		20.2		1860	296.64	289.57	308.80	1994	
83	3.50	0.368	13.3	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138600	147800		20.2		1708	272.40	289.57	308.80	1994	
84	3.50	0.368	13.3	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138600	147800		20.2		1702	271.44	289.57	308.80	1994	
85	3.50	0.368	13.3	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138600	147800		20.2		1691	269.69	289.57	308.80	1994	
86	5.00	0.362	19.5	S-135	Cameron	18-3/4"	5K	TL	214	DVS	141800	157400	45	17.1	34.0	1900	406.60	431.56	479.04	ER 2209	
87	5.00	0.362	19.5	S-135	Cameron	18-3/4"	5K	TL	214	DVS	141800	157400	45	17.1	34.0	1900	406.60	431.56	479.04	ER 2209	
88	5.00	0.362	19.5	S-135	Cameron	18-3/4"	5K	TL	214	DVS	141800	157400	45	17.1	34.0	1875	401.25	431.56	479.04	ER 2209	
89	5.00	0.362	19.5	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	156200	165300	48	21		2500	384.75	475.39	503.08	ER 522, Heat B67552	Charpy @ 72
90	5.00	0.362	19.5	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	156200	165300	48	21		2145	330.12	475.39	503.08	ER 522, Heat B67552	Charpy @ 72
91	5.00	0.362	19.5	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	148800	159000	49	18.8		1850	284.72	452.87	483.91	ER 522, NOBLE	
92	5.00	0.362	19.5	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	135600	157400		22.0		3050	469.40	412.69	479.04	ER 522, RD16-1	
93	5.00	0.362	19.5	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	135600	157400		22.0		3025	465.55	412.69	479.04	ER 522, RD16-2	
94	5.00	0.362	19.5	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	143600	160100		20.0		2700	415.53	437.04	487.26	ER 522, RD07-3	
95	5.00	0.362	19.5	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	140700	162000		21.0		2900	446.31	428.21	493.04	ER 522, RD18-1	
96	5.00	0.362	19.5	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	140700	162000		21.0		2950	454.01	428.21	493.04	ER 522, RD18-2	
97	5.00	0.362	19.5	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear						2650	407.84			ER 522, RD08-1	
98	5.00	0.362	19.5	S-135	HYDRIL	13.625	10000	14 1/4	159.48	Blind	138600	179300		22.0		1350	215.30	421.82	545.69	1980	
99	5.00	0.362	19.5	S-135	HYDRIL	13.625	10000	14 1/4	159.48	Blind	138600	179300		22.0		1300	207.33	421.82	545.69	1980	
100	5.00	0.362	19.5	S-135	HYDRIL	13.625	10000	14 1/4	159.48	Blind	138600	179300		22.0		1250	199.36	421.82	545.69	1980	
101	5.00	0.362	19.5	S-135	HYDRIL	18.75	5000	20	314.16	Blind	156300	164900		20.0		1127	354.06	475.69	501.86	1992	
102	5.00	0.362	19.5	S-135	HYDRIL	18.75	5000	20	314.16	Blind	156300	164900		20.0		1189	373.54	475.69	501.86	1992	
103	5.00	0.362	19.5	S-135	HYDRIL	18.75	5000	20	314.16	Blind	156300	164900		20.0		1212	380.76	475.69	501.86	1992	
104	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1445	272.66	447.69	485.43	1992	

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.

	PIPE DESCRIPTION					BOP and RAM DESCRIPTION					PIPE MATERIAL PROPERTIES										
#	DIA. (IN.)	WALL (IN.)	PPF	MATERIAL GRADE	BOP MANUFACTURER	BOP BORE	WORKING PRESSURE	BOP TYPE	BOP CLOSE AREA	SHEAR RAM TYPE	YIELD STRENGTH (PSI)	ULTIMATE TENSILE STRENGTH (PSI)	CHARPY, CVN	ELONGATION %	HARDNESS RC	ACTUAL SHEAR PRESSURE (PSI)	ACTUAL SHEAR FORCE (KIPS)	SHEAR FORCE CALCULATED USING YIELD (KIPS)	SHEAR FORCE CALCULATED USING ULTIMATE (KIPS)	SOURCE OF INFORMATION	COMMENTS
105	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1425	268.89	447.69	485.43	1992	
106	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1434	270.58	447.69	485.43	1992	
107	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1460	275.49	447.69	485.43	1992	
108	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1440	271.72	447.69	485.43	1992	
109	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1459	275.30	447.69	485.43	1992	
110	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1404	264.92	447.69	485.43	1992	
111	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1410	266.06	447.69	485.43	1992	
112	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1430	269.83	447.69	485.43	1992	
113	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1406	265.30	447.69	485.43	1992	
114	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1367	257.94	447.69	485.43	1992	
115	5.00	0.362	19.5	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	147100	159500		23.1		1402	264.55	447.69	485.43	1992	
116	5.00	0.362	19.5	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	142600	155100		20.1		2051	327.10	434.00	472.04	1994	
117	5.00	0.362	19.5	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	142600	155100		20.1		1988	317.06	434.00	472.04	1994	
118	5.00	0.362	19.5	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	142600	155100		20.1		2024	322.80	434.00	472.04	1994	
119	5.00	0.362	19.5	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	142600	155100		20.1		1801	287.23	434.00	472.04	1994	
120	5.00	0.362	19.5	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	142600	155100		20.1		1690	269.53	434.00	472.04	1994	
121	5.00	0.362	19.5	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	142600	155100		20.1		1481	236.20	434.00	472.04	1994	
122	5.00	0.362	19.5	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	142600	155100		20.1		2200	350.87	434.00	472.04	1994	
123	5.00	0.362	19.5	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	142600	155100		20.1		2195	350.07	434.00	472.04	1994	
124	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1725	275.11	491.72	531.38	1983	
125	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1800	287.07	491.72	531.38	1983	
126	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1910	304.62	491.72	531.38	1983	
127	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1890	301.43	491.72	531.38	1983	
128	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1860	296.64	491.72	531.38	1983	
129	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1725	275.11	491.72	531.38	1983	
130	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1800	287.07	491.72	531.38	1983	
131	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1910	304.62	491.72	531.38	1983	
132	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1900	303.02	491.72	531.38	1983	
133	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1890	301.43	491.72	531.38	1983	
134	4.50	0.430	20/18.7	S-135	HYDRIL	18.75	10000	14 1/4	159.48	Blind	155000	167500		19.0		1860	296.64	491.72	531.38	1983	
135	5.50	0.361	21.9	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	152700	159800	51.3	20		2150	330.89	513.51	537.39	ER 522, Heat U82849	Charpy @ 72
136	5.50	0.361	21.9	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	152700	159800	51.3	20		2200	338.58	513.51	537.39	ER 522, Heat U82849	Charpy @ 72
137	5.50	0.361	21.9	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	152700	159800	51.3	20		2080	320.11	513.51	537.39	ER 522, Heat U82849	Charpy @ 72
138	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2101	396.44	504.43	549.83	1992	
139	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2122	400.40	504.43	549.83	1992	
140	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2431	458.71	504.43	549.83	1992	
141	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		1960	369.84	504.43	549.83	1992	
142	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2438	460.03	504.43	549.83	1992	
143	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2712	511.73	504.43	549.83	1992	
144	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2647	499.47	504.43	549.83	1992	
145	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2068	390.21	504.43	549.83	1992	
146	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2196	414.37	504.43	549.83	1992	
147	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2361	445.50	504.43	549.83	1992	
148	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2025	382.10	504.43	549.83	1992	
149	5.50	0.361	21.9	S-135	HYDRIL	18.75	15000	15 1/2	188.69	Blind	150000	163500		24.7		2587	488.15	504.43	549.83	1992	
150	6.63	0.33	25.2	S-135	Cameron	18-3/4"	5K	TL	214	DVS	142400	162100	45	18.5	34.0	1950	417.30	536.22	610.41	ER 2209	
151	6.63	0.33	25.2	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	150800	160900		19.0		2850	438.62	567.86	605.89	ER 522, RD03-1	
152	6.63	0.33	25.2	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	152400	163100		20.0		2600	400.14	573.88	614.17	ER 522, RD01-1	
153	6.63	0.33	25.2	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	152400	163100		20.0		2700	415.53	573.88	614.17	ER 522, RD01-2	
154	6.63	0.33	25.2	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	166500	178000		19.0		2750	423.23	626.98	670.28	ER 522, RD34-3	
155	6.63	0.33	25.2	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	166500	178000		19.0		2625	403.99	626.98	670.28	ER 522, RD34-1	
156	6.63	0.330	25.2	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	127200	157500		20.0		2519	401.74	478.99	593.08	1989	

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.

	PIPE DESCRIPTION					BOP and RAM DESCRIPTION					PIPE MATERIAL PROPERTIES										
#	DIA. (IN.)	WALL (IN.)	PPF	MATERIAL GRADE	BOP MANUFACTURER	BOP BORE	WORKING PRESSURE	BOP TYPE	BOP CLOSE AREA	SHEAR RAM TYPE	YIELD STRENGTH (PSI)	ULTIMATE TENSILE STRENGTH (PSI)	CHARPY, CVN	ELONGATION %	HARDNESS RC	ACTUAL SHEAR PRESSURE (PSI)	ACTUAL SHEAR FORCE (KIPS)	SHEAR FORCE CALCULATED USING YIELD (KIPS)	SHEAR FORCE CALCULATED USING ULTIMATE (KIPS)	SOURCE OF INFORMATION	COMMENTS
157	6.63	0.330	25.2	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	127200	157500		20.0		2522	402.22	478.99	593.08	1989	
158	6.63	0.330	25.2	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	127200	157500		20.0		2922	466.01	478.99	593.08	1989	
159	6.63	0.330	25.2	S-135	HYDRIL	21.25	5000	14 1/4	159.48	Blind	127200	157500		20.0		2444	389.78	478.99	593.08	1990	
160	6.63	0.330	25.2	S-135	HYDRIL	21.25	5000	14 1/4	159.48	Blind	127200	157500		20.0		2570	409.88	478.99	593.08	1990	
161	6.63	0.330	25.2	S-135	HYDRIL	21.25	5000	14 1/4	159.48	Blind	127200	157500		20.0		2397	382.29	478.99	593.08	1990	
162	6.63	0.330	25.2	S-135	HYDRIL	21.25	5000	14 1/4	159.48	Blind	127200	157500		20.0		2444	389.78	478.99	593.08	1990	
163	6.63	0.330	25.2	S-135	HYDRIL	21.25	5000	14 1/4	159.48	Blind	127200	157500		20.0		2570	409.88	478.99	593.08	1990	
164	6.63	0.330	25.2	S-135	HYDRIL	21.25	5000	14 1/4	159.48	Blind	127200	157500		20.0		2397	382.29	478.99	593.08	1990	
165	6.63	0.330	25.2	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138000	149000		21.3		2027	323.28	519.66	561.08	1994	
166	6.63	0.330	25.2	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138000	149000		21.3		1972	314.50	519.66	561.08	1994	
167	6.63	0.330	25.2	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138000	149000		21.3		2095	334.12	519.66	561.08	1994	
168	6.63	0.330	25.2	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138000	149000		21.3		1647	262.67	519.66	561.08	1994	
169	6.63	0.330	25.2	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138000	149000		21.3		2340	373.19	519.66	561.08	1994	
170	6.63	0.330	25.2	S-135	HYDRIL	13.625	5000	14 1/4	159.48	Blind	138000	149000		21.3		1401	223.44	519.66	561.08	1994	
171	6.63	0.33	25.2	S-135	Cameron	18-3/4"	5K	TL	214	DVS	142400	162100	45	18.5	34.0	1925	411.95	536.65	610.89	ER 2209	
172	6.63	0.33	25.2	S-135	Cameron	18-3/4"	5K	TL	214	DVS	142400	162100	45	18.5	34.0	1975	422.65	536.65	610.89	ER 2209	
173	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		178675	23.85	17		1960	301.64		683.49	ER 522, SES	Charpy @ -4
174	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		178675	24.85	17		1970	303.18		683.49	ER 522, SES	Charpy @ -4
175	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		177400	26.2	17		2140	329.35		678.61	ER 522, SES	Charpy @ -4
176	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		178350	26.65	17		2250	346.28		682.24	ER 522, SES	Charpy @ -4
177	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		173250	27.35	16		2360	363.20		662.73	ER 522, SES	Charpy @ -4
178	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		162850	32.35	18		2150	330.89		622.95	ER 522, SES	Charpy @ -4
179	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		172200	33	17		1950	300.11		658.72	ER 522, SES	Charpy @ -4
180	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		171275	34	17		1850	284.72		655.18	ER 522, SES	Charpy @ -4
181	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		169400	35.2	17		2175	334.73		648.01	ER 522, SES	Charpy @ -4
182	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		159000	41.8	19		4220	649.46		608.22	ER 522, SES	Charpy @ -4
183	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	155600	165000	46.3	22.2		2580	397.06	595.22	631.17	ER 522, Heat U82848	Charpy @ 72
184	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	155600	165000	46.3	22.2		3700	569.43	595.22	631.17	ER 522, Heat U82848	Charpy @ 72
185	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	155600	165000	46.3	22.2		3100	477.09	595.22	631.17	ER 522, Heat U82848	Charpy @ 72
186	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	155600	165000	46.3	22.2		2675	411.68	595.22	631.17	ER 522, Heat U82848	Charpy @ 72
187	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	155600	165000	46.3	22.2		2400	369.36	595.22	631.17	ER 522, Heat U82848	Charpy @ 72
188	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	155600	165000	46.3	22.2		3450	530.96	595.22	631.17	ER 522, Heat 657346	Charpy @ 72
189	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	149300	160083	48.13	18.91		2315	356.28	571.12	612.37	ER 522, RD-69	
190	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	152200	167800	63	18.9		3950	607.91	582.21	641.89	ER 522, Heat 308426	Charpy @ -4
191	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	152200	167800	63	18.9		3775	580.97	582.21	641.89	ER 522, Heat 308426	Charpy @ -4
192	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	148800	162000	63.5	19.1		2820	434.00	569.20	619.70	ER 522, Heat U01230	Charpy @ -4
193	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	148800	162000	63.5	19.1		3025	465.55	569.20	619.70	ER 522, Heat U01230	Charpy @ -4
194	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	159600	168800	64	21.3		3900	600.21	610.52	645.71	ER 522, Heat 657346	Charpy @ 72
195	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear	159600	168800	64	21.3		3200	492.48	610.52	645.71	ER 522, Heat 657346	Charpy @ 72
196	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		164375	65.35	21		3825	588.67		628.78	ER 522, SES	Charpy @ -4
197	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		160575	69	20		3700	569.43		614.25	ER 522, SES	Charpy @ -4
198	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		159975	73.85	20.0		3810	586.36		611.95	ER 522, SES	Charpy @ -4
199	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		156900	77	21.0		3710	570.97		600.19	ER 522, SES	Charpy @ -4
200	5.50	0.415	24.7	S-135	Varco Shaffer	18-3/4"		SLX	153.9	"V" Shear		149825	82	19.0		3930	604.83		573.13	ER 522, SES	Charpy @ -4
201	5.50	0.415	24.7	S-135	HYDRIL	13.625	15000	19	283.53	Blind	151300	160900		24.1		2090	592.58	578.77	615.49	2003	
202	6.63	0.362	27.6	S-135	HYDRIL	18.75	5000	20	314.16	Blind	157100	178900		18.2		1244	390.81	645.65	735.24	1992	
203	6.63	0.362	27.6	S-135	HYDRIL	18.75	5000	20	314.16	Blind	157100	178900		18.2		1303	409.35	645.65	735.24	1992	
204	6.63	0.362	27.6	S-135	HYDRIL	18.75	5000	20	314.16	Blind	157100	178900		18.2		1228	385.79	645.65	735.24	1992	
205	6.63	0.362	27.6	S-135	HYDRIL	18.75	5000	20	314.16	Blind	157100	178900		18.2		1250	392.70	645.65	735.24	1992	
206	6.63	0.362	27.6	S-135	HYDRIL	18.75	5000	20	314.16	Blind	157100	178900		18.2		1238	388.93	645.65	735.24	1992	
207	6.63	0.362	27.6	S-135	HYDRIL	18.75	5000	20	314.16	Blind	157100	178900		18.2		1232	387.04	645.65	735.24	1992	
208	6.63	0.362	27.6	S-135	Cameron	18-3/4"	15K	TL	254	DVS	135000	145000				1850	469.90	555.26	596.39	ER 2670	