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EXECUTIVE SUMMARY

The Bureau of Safety and Environment Enforcement (BSEE) has contracted MCS Kenny to execute a Technology Assessment and Research Project (TA&RP) in the areas of Blowout Preventer (BOP) stack sequencing, monitoring and kick detection. The project has been developed to assess three key areas of a Blowout Preventer (BOP), including:

Topic 1 - Ram Sequencing and Shearing Performance

Topic 2 - BOP Monitoring and Acoustic Technology

Topic 3 - Kick Detection and Associated Technologies

This report addresses Topic 1 and covers the following areas:

- Industry practices and requirements for stacking and sequencing of subsea BOPs.
- Assessment of pipe centralization and the potential limitations of existing shear ram designs
- Development of an FE model to simulate BOP shear ram performance
- Validation of the FE model with physical shear tests.
- Assessment of the critical parameters that influence the shearing process
- Assessment of shear ram performance and design
- Computer simulation of the flowing well condition and its impact on shearing

This report is divided into two sections, Section 1 – Stack Design and Sequencing and Section 2 – Shear Ram Performance and Design.

Section 1 – Stack Design and Sequencing

Section 1 examines the current BOP standards, their requirements and the implications for BOP design. It looks at the various stack configurations and examines the pros and cons of different arrangements.

As per API 53 [3] the subsea BOP shall be class 5 or greater and shall include a minimum of one annular preventer, two pipe rams (excluding test rams) and two sets of shear rams for shearing the pipe of which at least one shall be capable of sealing.

Many drilling contractors are having BOPs built to rigorous design specifications, with multiple redundant rams with an attempt to stay ahead of the regulatory and industry requirements. One drilling contractor interviewed is building 6 new rigs with 7 ram stacks. The class 7 stack has a five ram configuration and a dual annular or a six ram configuration and a single annular.

These large class 7 or 8 subsea stacks have many implications. None more important than the implications for future workover, sidetrack or P&A of wells; particularly as the older wells may not have been designed to support the loads from a new generation stack. The larger stack also has implications for rig design. The height of the 6 ram BOP stack is approximately 50 ft compared to an 8 ram stack which is approximately 63 ft. Stacks of this size and weight impact deck design, handling and deployment equipment design as well as bringing operational challenges associated with working at increased heights for maintenance and testing.

In addition, larger stacks with an increased number of rams mean the BOP system becomes more complex which could increase the chances of failure. The BOP maintenance time also goes up substantially as the system becomes more complex. Many drilling contractors have begun to order new rigs with two BOP stacks to reduce BOP maintenance delays and shorten drilling time. The cost of BOP downtime can lead to a significant expense to the drilling contractor. The total BOP downtime cost for one of the drilling contractors was around $80 million in 2012. So there is huge benefit in having dual BOPs on the rig.

The BOP standards are not specific about the placement of rams. But per API 53 [3], a documented risk assessment shall be performed by the equipment user and the equipment owner for all classes of BOP arrangements to identify ram placements and configurations, and take into account annular and large tubulars for well control management. Also per API 53, if a single ram is incapable of both shearing and sealing, two rams shall be closed; one that is capable of shearing the drill pipe and one that will seal against Rated Working Pressure (RWP).

The number of rams which are installed in a BOP stack is determined by the number of drill pipe and casing sizes, operator and regulatory requirements, moored or dynamically positioned rig, rig limitations, stripping and hang off capability of the rams, shear capability of rams, sealing capability of ram and choke and kill outlet placement and variable bore rams.

Of the thirty seven stacks reviewed in [23] only three of the stacks used one annular. Five of the thirty seven had more than one blind shear ram. Double annular arrangements appear to be in the majority with potential benefits of well control and centralization. The majority of the stacks are reliant on a single blind shear ram to shear and seal the stack.

Blind shear rams were developed to allow rapid disconnect from the well by shortening the time required to shear and seal. This dual function operation does bring uncertainty around potential damage to seals while shearing, requirements to fold over the lower drill pipe section and remove the fish before sealing and manual sequencing to relocate non shearables. The performance of blind shear rams is looked at in Section 2.0.

The blind shear ram is typically at the top of the stack for well control, drill pipe hang-off, shearing and sealing. The pros and cons of using the BSR in conjunction with other rams have been examined.

For dynamically positioned vessels two BSR could be used, the first to shear the drill pipe and the second to seal the well in an emergency disconnect. This may be favorable with the risk of loss of station keeping and the narrow drilling margin when working in deepwater. The redundancy of the dual BSR would also provide for a second seal system should the first fail. The dual BSR also provides an option for actuating both simultaneously; where two BSR are closed without regard to the location of the drill pipe. This is all premised by the BSR being able to shear what is across it. With new BSR designs, this should be possible. Also, dead man system or autoshear operation of the two sets of BSR on a subsea stack would require adequate functional subsea accumulator capacity with individual redundancy for both systems.

For casing, potentially outside the shear capability of the BSR, casing shear rams (CSR) are required. These non-sealing rams must be used with a BSR (or blind ram). Multiple scenarios should be considered when using the CSR such as stuck casing, black-out leading to draw works failure, locking and the sheared casing not being picked up. Some vessels have adopted the practice of having a BSR both above and below the CSR.

If the BSRs are located above the CSRs, the cut pipe must be lifted above the BSRs prior to closing the BSRs. If pipe is not moved, the risk is that the BSRs will not close fully, if the tube is bigger than the BSRs can shear, or that they may not seal.

If the BSRs are below the CSR, then the cut pipe can fall away from the BSR, allowing closure of the BSR, provided the cut pipe is not either stuck, or suspended on the pipe rams (such as the case for drill pipe suspended on hang off ram).

Any automatic sequencing involving BSR and CSR together is problematic in nearly all cases the sequencing must be influenced by conditions and equipment besides the BOP control system. The correct response for sequencing differs with situation and pipe movement. Incorrect operation or sequence may be worse than no sequence, particularly in a potential blow out scenario.

Section 2 – Shear Ram Performance and Design

In this section shear ram design challenges are evaluated through a combination of physical shear tests and calibrated finite element and computational fluid dynamic analysis

Shearing tests were conducted at Archer's test shop to shear 3-1/2" drill pipes using a standard surface 13-5/8" bore BOP. The objective of the tests was to capture information such as shearing force, shearing time, and deformed shape of sheared pipe which would be used to validate the computer simulation model. All the tests were conducted under static non-flowing well conditions with drill pipe centralized in the BOP bore.

Two shear tests of the 3-1/2" OD, S-135 drill pipe in a 13-5/8" BOP were performed. The shearing force ranged from 280,000 lbf to 313,600 lbf. A slight variation in thickness of the drill pipe specimen and some variation in material properties are credited with this difference. The average maximum shearing force is 296,800 lbf.

The pressure required to shear the 3-1/2" drill pipe is calculated using the OEM shearing formulas (Figure 6.7) and compared with the shop test. For the 3-1/2" drill pipe, the calculated shearing pressure is 1844 psi and shearing pressure observed during the two tests are 1250 and 1400 psi. The calculated force required by the OEM formulation is 417,984 lbf. The calculated shearing pressure values from the OEM formulas are conservative and could be considered as the maximum pressure that could be seen during the shearing operation.

Laser scanning of the shear test rams was performed to create an exact CAD replica of the shear rams. A benchmark FE model of the physical shearing test is developed using Abaqus/Explicit, an explicit dynamic finite element solver program. The model is set to replicate the shearing of the 3-1/2" drill pipe in a 13-5/8" BOP, performed at the Archer test shop. The maximum shearing force obtained from computer simulation was 336,160 lbf and is comparable (13% higher than the average) to the physical shearing tests performed.

The sheared cross sections of the drill pipe were compared with the physical tests and they were found to be similar in shape and size. Shearing simulations were also performed for 5-1/2" and 6-5/8" drill pipes using the bench marked shear ram model and good consistency with OEM calculated shear force values were also found. The OEM calculated shear force value was consistently higher and is believed to be conservative. This benchmarked model is used as the base case to examine the effect of various parameters on the shearing process.

Non-centralization of the drill pipe in the BOP under no-flow condition is examined by positioning the drill pipe at different positions in the well bore. The existing set of shear rams do not cover the entire BOP bore and when the drill pipe was non-centralized and positioned against the wall of the BOP the corner of the upper ram punctured the pipe and the resulting shearing force was reduced. A similar phenomenon was observed for all three pipe sizes (3-1/2", 5-1/2" and 6-5/8"). While the puncturing of the ram reduces the shearing force, a large force is required to squash the uncut drill pipe and close the rams. Failure to keep the drill pipe within the cutting zone could result in the drill pipe being stuck between the closing rams and damaging the sealing elements. In addition, the final deformed shapes of the drill pipes are unpredictable and can cause difficulty while removing the sheared lower drill pipe fish. The negative effect of not having full bore coverage and the benefit of puncturing the drill pipe are noted from these simulations.

Full bore coverage with the shearing rams is recommended to guarantee successful shearing and sealing. Full bore coverage does present a design challenge due to alternate sealing requirements. If full bore shearing is not achievable then some method of centralization to move the pipe within the shearing zone and protect the sealing elements is essential.

A series of pre-load cases (tension, compression, buckling) have been analyzed with the benchmark model. The most critical pre-load case was the buckled pipe condition. In this case the load required to shear the drill pipe was more than 40% greater than the base case. The maximum shear force required to shear the buckled pipe also exceeded the OEM calculated shear force by approximately 13.7%. It is recommended that the OEM consider the buckled pipe case in its shear force calculation and shear ram design safety margin.

Flow simulations are performed to study the effect of flowing fluid on the shearing process. The flow simulations assume the pressure on either side of the BOP rams to be the same i.e. a stabilization of pressure is assumed to have occurred when the rams are activated. As the shear rams propagate through the well bore, the flow cross section reduces which increases the velocity of the fluid and exerts a higher force on the rams, particularly in the vertical direction. The lateral force resisting the closure of the shear rams is computed through steady state CFD simulations. The magnitude of this resistance pressure is compared with the shearing pressure of the rams and found to be minimal (<1%).

Note while the pressure increase on the ram face due to the flowing fluid is small the effects of well bore pressure and hydrostatic pressure on the piston and rod will increase the pressure required by the actuator to perform the shearing operation. Both of these effects are captured in standard BOP OEM shear calculations. A linear increase in required shearing pressure is observed for increasing wellbore pressure for the benchmark shear ram. For 10,000psi bore pressure the required shear pressure increased 32%, equivalent to approximately 130,000 lbf of additional shear force. While this force calculated and accounted in OEM shear force requirements, is not insignificant, it is worth noting that the force exerted by the wellbore on the ram face (projected area) would be much larger than this. It is believed that shear ram design minimizes the pressure differential between the front and back of the ram and hence a less significant shear pressure increase is required. However, due to the large number of variables in the design of BOP shear ram systems it is recommended that a thorough review of different designs and how they compensate for wellbore pressure be performed. Particularly as significant pressure may be in the bore when the shear operation is performed, especially if the annular(s) have been closed.

It should also be noted that the dynamic fluid flow conditions such as fluid hammer effect is not considered in this study. Moreover any abrupt pressure drop above the BOP rams is not considered. Such a drop would result in a steep pressure gradient across the rams during their shearing action. Additionally, it is assumed that an equalization of pressure on either side of the rams has occurred. The results of the flow simulations should be seen as a precursor to further investigation on the effects of these flow uncertainties on the shearing process. The feasibility of occurrence of these uncertainties during shearing ram activation should also be taken into account during this investigation.

A series of models have been created to assess some of the features of the newer shear ram designs from T3, NOV, GE and Cameron. Only the shearing ability of the rams is assessed; sealing of the rams is outside the scope of this study.

Ram Design 1, which includes some of the features of the Cameron Type U blind shearing ram, had similar shearing performance to the benchmark model for both the centralized and non-centralized cases. Post shearing, as this ram does not have the fold over lip, the energy required to close the rams is much higher than the bench mark.

Ram Design 2, which included some of the features of the T3 shear all ram performed well for both the centralized and non-centralized cases. For the centralized pipe the required maximum shearing force reduced by 27% from 336,160 lbf for the base case design to 244,643 lbf for Ram Design 2. This reduction in force is believed to be a result of the higher contact area between the shear ram and drill pipe due to the curved blade profile.

The force required post shearing is also much lower with Ram Design 2 as it does not try to fold the lower drill pipe section. The sealing elements of the T3 shear all ram are toward the back of the ram, away from the shearing surfaces. This reduces the risk of the sheared drill pipe from damaging the sealing elements and T3 believes this also reduces the need to fold the lower drill pipe section. Ram sealing performance, post shearing has not been evaluated.

A qualitative review of the NOV low force shear technology has been performed. The principle behind low force shear ram is that it is shearing the drill pipe instead of crushing the entire pipe to initiate brittle fracture, the blade profile raises stress in a limited region and allows the crack to then propagate hence reducing the required shear force. This puncturing effect was also observed in some of the bench mark model non-centralized cases. The corner of the shear ram punctured the drill pipe and the force required to shear the pipe was much less as a result of the puncturing. The results published (by the OEM) show a significant improvement over traditional v-shear systems. This design can significantly reduce the required shear force which would reduce the size and weight of rams or potentially increase the envelope of what can be sheared.

The GE 5k Blind Shear ram utilizes guide arms to move the pipe within the cutting zone of the upper and lower v-blades. The guide arms extend beyond the leading edge of the shearing blade and have an inner wedge surface which moves the drill pipe inward toward the shearing zone. The distance between the tips of the guide arms, measured on the inside, is greater than the BOP bore diameter to facilitate full bore coverage.

The industry has been developing bigger and more efficient shear rams to shear pipe and tool joints such as NOV's low force shear ram, T3's shear all ram, GE's 5K BSR. Technologies are also being developed to shear non shearables subsea using laser shearing, shearing using explosives and shearable drill collar.

GE is working on a hydrostatic pressure assisted shearing system. This system is still under development and would use the hydrostatic pressure of the sea water to significantly increase the shearing forces without the requirement for additional accumulator bottles.

The En-Tegrity Shear Seal Valve system replaces the ram-type valves in conventional BOPs by utilizing gate valves to allow for greater shearing force. Testing with a 7 3/8” size system has been validated by several major operators.

1.0 INTRODUCTION

1.1 GENERAL

This report is written in response to Objective 1 of the Bureau of Safety and Environmental Enforcement (BSEE) Broad Agency Announcement Number E12PS00004 regarding Assessment of Subsea BOP Well Control Technology.

The project assesses three key areas of a Blowout Preventer (BOP), including:

- Topic 1 - Ram Sequencing and Shear Performance
- Topic 2 - BOP Monitoring and Acoustic Technology
- Topic 3 - Kick Detection and Associated Technologies

1.2 OBJECTIVE OF THE REPORT

The objective of the report is to document in detail the findings from Topic 1 of this project. This report addresses Topic 1 and covers the following areas:

- Industry practices and requirements for stacking and sequencing of subsea BOPs.
- Assessment of pipe centralization and the potential limitations of existing shear ram designs
- Development of an FE model to simulate BOP shear ram performance
- Validation of the FE model with physical shear tests.
- Assessment of the critical parameters that influence the shearing process
- Assessment of shear ram performance and design
- Simulation of the flowing well condition and its impact on shearing:

This report is divided in two discreet sections. The first addresses Stack Design and Sequencing. The second covers Shear Ram Performance and Design.

1.3 ABBREVIATIONS

API	American Petroleum Institute
BOP	Blowout Preventer
BPD	Barrels Per Day
BSEE	Bureau of Safety and Environmental Enforcement
BSR	Blind Shear Ram
CAD	Computer Aided Design
CAE	Complete Abaqus Environment

CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CPU	Central Processing Unit
CSR	Casing Shear Ram
EDS	Emergency Disconnect Sequence
DP	Drill Pipe
FEA	Finite Element Analysis
FSI	Fluid Structure Interaction
Ft	Feet
GOMR	Gulf of Mexico Regional
GOM	Gulf of Mexico
HSE	Health Safety Environmental
IADC	International Association of Drilling Contractors
IFR	Interim Final Rule
kHz	Kilo Hertz
Ksi	Kilo pound per square inch
Lbs	Pounds
LMRP	Lower Marine Riser Package
MASP	Maximum Anticipated Surface Pressure
MMS	Mineral Management Service
OD	Outer Diameter
OCS	Outer Continental Shelf
OEM	Original Equipment Manufacturer
RANS	Reynolds Averaged Navier Stokes
SA	Spalart Allmaras
SBR	Shearing Blind Rams
SBOP	Surface Blowout Preventer
SPE	Society of Petroleum Engineers
SPM	Subsea Plate Mount
TA&RP	Technology Assessment and Research Project

2.0 RESULTS, CONCLUSIONS & RECOMMENDATIONS

2.1 RESULTS AND CONCLUSIONS

- There are many ways to configure a BOP stack. As per API 53 the subsea BOP shall be class 5 or greater and shall include a minimum of one annular preventer, two pipe rams (excluding test rams) and two sets of shear rams for shearing the pipe of which at least one shall be capable of sealing.
- Many drilling contractors are having BOPs built to rigorous design specifications, with multiple redundant rams with an attempt to stay ahead of the regulatory and industry requirements. One drilling contractor interviewed is building 6 new rigs with 7 ram stacks.
- The BOP standards are not specific about the placement of rams. But per API 53 [3], a documented risk assessment shall be performed by the equipment user and the equipment owner for all classes of BOP arrangements to identify ram placements and configurations, and take into account annular and large tubulars for well control management. Also per API 53, if a single ram is incapable of both shearing and sealing, two rams shall be closed; one that is capable of shearing the drill pipe and one that will seal against rated working pressure (RWP).
- For dynamically positioned vessels two BSR could be used, the first to shear the drill pipe and the second to seal the well in an emergency disconnect. This may be favorable with the risk of loss of station keeping and the narrow drilling margin when working in deepwater.
- The redundancy of the dual BSR would also provide for a second seal system should the first fail. The dual BSR also provides an option for actuating both simultaneously; where two BSR are closed without regard to the location of the drill pipe.
- A robust methodology for the FE simulation of the shearing process has been successfully developed and validated with physical shearing tests.
- This methodology has been applied to different drill pipe sizes and different shear ram designs.
- Some variation in the physical shear test results was observed and is believed to be due to dimensional differences in the test pipe. Note also that variations in the toughness (charpy) of the S-135 drill pipe material may be a factor. This is a documented phenomenon [8] with some scatter in results depending on the charpy V-notch impact energy of the drill pipe.
- Good consistency with OEM calculated shear force values are observed for drill pipe sizes 3-1/2", 5-1/2" and 6-5/8".
- The benchmark ram has a lower lip which helps to fold the lower dill pipe section (fish) away from the sealing elements. A large increase in shearing force is required to create this fish but the force does not exceed the shearing force.
- The upper ram does not cover the full width of the BOP bore such that shearing of the non-centralized case results in the ram slicing through the drill pipe.

- When the drill pipe was non-centralized and positioned against the wall of the BOP the corner of the upper ram punctured the pipe and the resulting shearing force was reduced. A similar phenomenon was observed for all three pipe sizes (3-1/2", 5-1/2" and 6-5/8").
- While the puncturing of the ram reduces the shearing force a large force is required to close the squash the uncut drill pipe and close the rams. Failure to keep the drill pipe within the cutting zone could result in the drill pipe being stuck between the closing rams and damaging the sealing elements. This is not recommended.
- The tensioned drill string is easier to shear. A compressive force in the drill pipe increases the force required to shear the pipe. This is due in part to the increased friction between the blades and the pipe sections.
- The most critical compressive case was the buckled pipe condition. In this case the load required to shear the drill pipe was more than 40% greater than the base case. The maximum shear force required to shear the buckled pipe also exceeded the OEM calculated shear force by approximately 13.7%.
- Flowing well conditions were simulated. The flow simulations assume the pressure on either side of the BOP rams to be the same i.e. a stabilization of pressure is assumed to have occurred when the rams are activated. Only a small pressure rise (~1.5psi) is found when the annulus flow was constricted with and the shear rams were close to the drill pipe. This effect of fluid flow through the annulus on the shearing process is very small (less than 1%) and can be neglected.
- The flow velocity increases significantly as the flow is constricted. The potential erosional effects have not been analyzed as part of this study.
- Note while the pressure increase on the ram face is small due to the flowing fluid. The effects of well bore and hydrostatic pressure on the piston and rod will increase the pressure required by the actuator to perform the shearing operation. These effects are captured in standard OEM shear calculations. A linear increase in required shearing pressure is observed for increasing wellbore pressure for the benchmark shear ram. For 10,000psi bore pressure the required shear pressure increased 32%, equivalent to approximately 130,000 lbf of additional shear force. While this force, calculated and accounted in OEM shear force requirements, is not insignificant, it is worth noting that the force exerted by the wellbore on the ram face (projected area) would be much larger than this. It is believed that shear ram design minimizes the pressure differential between the front and back of the ram and hence a less significant shear pressure increase is required.
- Ram Design 1, which includes some of the features of the Cameron Type U blind shearing ram, had similar shearing performance to the benchmark model for both the centralized and non-centralized cases.
- Post shearing as this ram does not have the fold over lip, the energy required to close the rams is much higher than the bench mark. For Ram Design 1 the force to shear approaches 390,000 lbf, higher than the force to shear. It takes considerable force to squash the lower fish into the packer groove. While the constraints of the model are such that they prevent the lower pipe from falling after it has sheared the process and force required to form the lower fish can potentially impact the ability of the rams to close and seal.

- Ram Design 2, which included some of the features of the T3 shear all ram performed well for both the centralized and non-centralized cases. For the centralized pipe the required maximum shearing force reduced by 27% from 336,160 lbf for the base case design to 244,643 lbf for ram design 2. This reduction in forces is believed to be a result of the higher contact area between the shear ram and drill pipe due to the curved blade profile.
- The shearing force from both non-centralized cases is lower than that for the centralized case. In the non-centralized positions the rams cause an initial bending of the pipe and the knife like action of the curved blades help in the shearing process.
- The force required post shearing is also much lower with Ram Design 2 as it does not try to fold the lower drill pipe section. The sealing elements of the T3 shear all ram are toward the back of the ram, away from the shearing surfaces. This reduces the risk of the sheared drill pipe from damaging the sealing elements and T3 believes this reduces the need to fold the lower drill pipe section is reduced. Ram sealing performance, post shearing has not been evaluated.
- A qualitative review of the NOV low force shear technology has been performed. The results published (by the OEM) show a significant improvement over traditional v-shear systems. This design can significantly reduce the required shear force which would reduce the size and weight of rams or potentially increase the envelope of what can be sheared.
- The GE 5k Blind Shear ram utilizes guide arms to move the pipe within the cutting zone of the upper and lower v-blades. The guide arms extend beyond the leading edge of the shearing blade and have an inner wedge surface which moves the drill pipe inward toward the shearing zone. The distance between the tips of the guide arms, measured on the inside, is greater than the BOP bore diameter to facilitate full bore coverage.
- The industry has been developing bigger and more efficient shear rams to shear pipe and tool joints such as NOV's low force shear ram, T3's shear all ram, GE's 5K BSR. Technologies are also being developed to shear non shearables subsea using laser shearing, shearing using explosives and shearable drill collar.
- GE is working on a hydrostatic pressure assisted shearing system. This system is still under development and would use the hydrostatic pressure of the sea water to significantly increase the shearing forces without the requirement for additional accumulator bottles.
- The En-Tegrity Shear Seal Valve system replaces the ram-type valves in conventional BOPs by utilizing gate valves to allow for greater shearing force. Testing with a 7 3/8" size, has been validated by several major operators. The En-Tegrity system enhances safety by separating the shearing and sealing functions, ensuring that the sealing area of the gates is unaffected by any metallic fragments.

2.2 RECOMMENDATIONS

- There are no published standards to cover BOP equipment rated above 15ksi. API RP 6HP, which addresses the design verification methodology for HPHT drilling and completion equipment was developed in 2005 but has not yet been published. Releasing the API RP 6HP would help the industry in standardizing the design methodology for HPHT BOP equipment.

- Full bore coverage with the shearing rams is recommended to guarantee successful shearing and sealing. If full bore shearing is not achievable then some method of centralization to move the pipe within the shearing zone and protect the sealing elements is essential.
- It is recommended that the OEM calculation consider the buckled pipe case in its shear force calculation and shear ram design.
- It has been suggested that V-shape shear rams are particularly sensitive to variations in toughness in contrast to other ram designs [26]. A more detailed evaluation of the mechanics of shearing and its sensitivity to toughness is recommended.
- Uplift on the drill pipe reduces the chances of the drill pipe falling down hole post shearing. It has been shown that this has the potential to impact the sealing performance of the ram. In one case the force required to close the rams was higher than the force required to shear. Further evaluation of this effect is recommended.
- The shearing process of different ram designs results in many fish profiles. Some fold the pipe, others leave clean open sections. It is recommended that a study of the desired fish profile be performed taking account requirements for sealing, re-access, and intervention via the sheared pipe.
- Ram sealing performance is outside the scope of this study. A detailed evaluation of BOP ram sealing performance is recommended.
- The dynamic fluid flow conditions such as fluid hammer effect are not considered in this study. Moreover any abrupt pressure drop above the BOP rams is not considered. Such a drop would result in a steep pressure gradient across the rams during their shearing action. Additionally, it is assumed that an equalization of pressure on either side of the rams has occurred. The results of the flow simulations should be seen as a precursor to further investigation on the effects of these flow uncertainties on the shearing process. The feasibility of occurrence of these uncertainties during shearing ram activation should also be taken into account during this investigation.
- Due to the large number of variables in the design of BOP shear ram systems it is recommended that a thorough review of different designs and how they compensate for wellbore pressure be performed. Particularly as significant pressure may be in the bore when the shear operation is performed, especially if the annular(s) have been closed.
- The erosional effects of the increased fluid velocity as the rams are closed should be evaluated in more detail. This has the potential to impact the shear ram sealing performance.

STACK DESIGN AND SEQUENCING

3.0 BLOWOUT PREVENTER FUNCTIONAL DESCRIPTION

3.1 INTRODUCTION

Well control in drilling operations is accomplished by hydrostatic pressure imparted by the weight of the drilling mud which holds the pressure from the formation and prevents hydrocarbons from entering the well bore. If the counterbalance mud weight is lower than the formation pressure then a well control situation will occur.

Blowout preventers (BOP) are pressure control equipment used as a safety barrier by controlling the formation pressures and fluid encountered in the well. A blowout is an uncontrolled release of crude oil, natural gas or well fluids into the atmosphere or into an underground formation (underground blowouts) following failure of all well barriers. There have been 173 blowouts which have occurred during January 1980 to January 2008 in the United States (US) Gulf of Mexico (GOM) Outer Continental Shelf (OCS) [32].

BOP’s have been in use since they were developed in 1922 to control well pressure and fluids while drilling on land. The BOP technology has been adapted and used for offshore use since 1960’s [4].

The BOP is a conduit to the well bore and acts as a barrier device. On onshore land rigs, surface BOP is connected directly on the wellhead. In offshore rigs, the surface BOP (SBOP) is located below the rig deck and connects the surface well head to the rig. In subsea wells, the BOP is placed close to the sea floor and connects the well head and the riser. This section focuses on subsea BOP systems.

The BOP stack is used as a secondary means of well control. The primary means to control the well is through the hydrostatic pressure imparted by the mud weight. When there is a well control event, the BOPs rams are activated to seal the wellbore. Heavy "kill" mud is circulated into the well to regain control of the well. The heavy mud is pumped down the drill string, up the annulus (gap between drill pipe and casing or open hole), through the choke line, high pressure riser lines, choke manifold until the well pressure is controlled by circulating the influx out of the well. Once the heavy “kill weight” mud is fully filled from top of the well to the bottom, the well is in control and has been “killed” and the drilling operations can begin [31].

3.2 SUBSEA BLOWOUT PREVENTER

The principal functions of the subsea BOP stack (Figure 3.1) are [31]:

- Restraining the fluid in the well
- Delivering a way to add fluid in the well
- Removing precise amount of fluid from the well

Some of the other functions performed by the BOP stack are [31]:

- Monitor and control the well pressure
- Centralize and hang off the drill string in the well. This is done during a well control situation where the pipe ram is closed on the drill pipe to support its weight before the drill pipe is sheared by the shear rams
- Close the well by sealing the annulus between the drill pipe and casing
- Stop the additional influx from the formation into the wellbore
- Seal the well when there is no pipe in the hole
- Shear the pipe or casing to seal the well in emergency situation such as emergency disconnect or loss of station keeping

Subsea BOP stacks are divided into two sections as shown in Figure 3.1.

- Lower Marine Riser Package (LMRP)
- Lower Blowout Preventer (LBOP)

The LMRP and LBOP are designed to work together in a drilling operation. The maximum working pressure of a BOP stack is determined by the maximum well bore pressure expected.

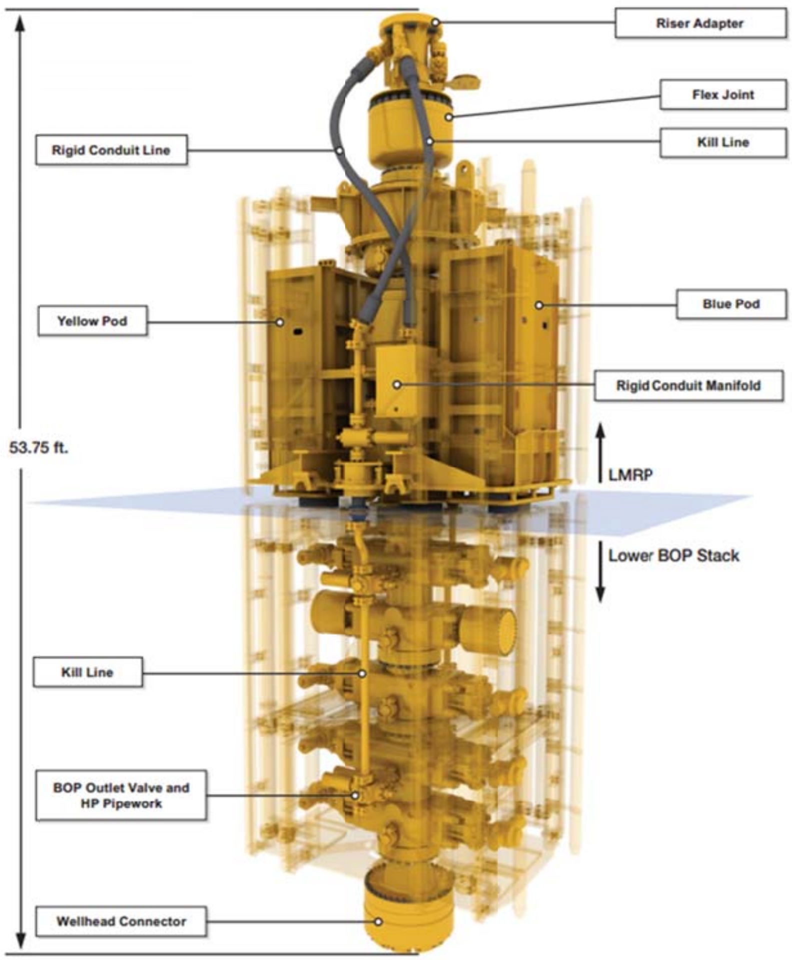


Figure 3.1: Typical Subsea BOP Stack [31]

3.2.1 Lower Marine Riser Package [1]

The major components of the LMRP stack from top to bottom are (Figure 3.2):

Riser Adapter - Connects the LMRP to the riser and holds the kick out subs. The kick out sub is the interface connection for the auxiliary and mud boost lines, choke and kill lines and conduit lines.

Flex Joint – Located between LMRP and riser adapter. The main function of the flex joint is to allow the riser adapter and riser system to pivot on top of the LMRP up to 10 degrees off center to reduce the bending moments on the BOP stack and the well head.

Choke and Kill Lines – These lines run vertically through the riser, LMRP and LBOP. Choke and kill lines are used to circulate wellbore fluid when BOP is closed or to pump heavier mud to kill well.

Control Pods - Controls the supply of hydraulic fluid for the operation of LMRP and LBOP. There are two redundant control pods used in the BOP.

Auxiliary Control Equipment - Accumulators are auxiliary equipment used to provide pressurized control fluid for various LMRP and LBOP functions.

Annular Preventer – Annular preventer are rubber sealing element to seal around the pipe to close the wellbore or an open hole. It is located on the top part of the stack (Figure 3.3). Annular preventer can seal on any size of drill string and are the first to seal against the well pressure. The annular has a donut shaped rubber seal called elastomeric packing element reinforced with steel ribs or inserts. Even though one annular is required by API 53, some BOP stacks have two annular preventers for redundancy.

Riser Connector - Connects the LBOP and the LMRP and allows the LMRP to lock or unlock from the BOP stack.

Subsea Gate Valves - Also called isolation valves are used to test riser connections while running the BOP stack.

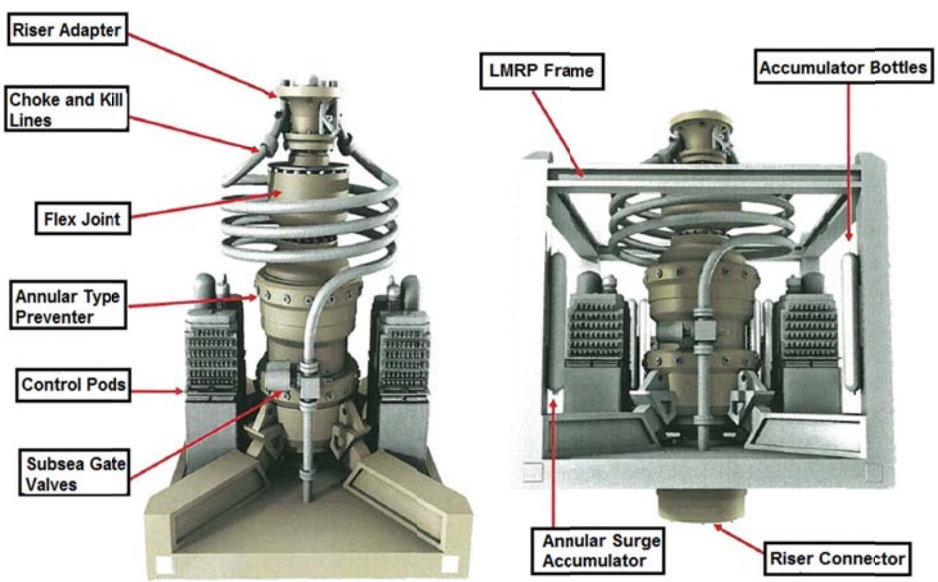


Figure 3.2: LMRP Components [1]

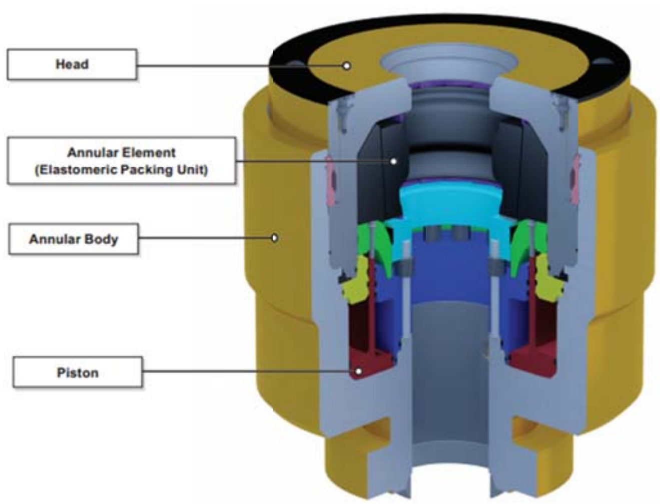


Figure 3.3: Typical Annular Preventer [31]

3.2.2 Lower Blowout Preventer [1]

The major components of LBOP (Figure 3.4) are:

BOP Mandrel – Acts as a mandrel connection between the LMRP and the LBOP.

Choke and Kill Lines - Choke line is used to circulate the fluid from the well and kill line is used to pump fluid into the well when the rams are closed.

Multiple Ram Type BOP’s – There are different types of rams to shear and seal the well.

Subsea Gate Valves – The main function is to circulate wellbore fluid when the ram BOP’s have sealed the well bore.

Wellhead Connector – The main function is to connect and create a seal between the wellhead the LBOP.

The upper connection of the LMRP connects with the marine riser system through the riser adapter and lower connection of the LMRP is connected to the LBOP through the LBOP mandrel (typically a GE H4 or Cameron interface).

The LMRP contains control pods and auxiliary equipment that control the LMRP and LBOP components. The LMRP also connects the LBOP to the riser system. LMRP’s get unlatched from the LBOP in emergency situations (drift-off, drive-off, well control situation) and the shear ram in the LBOP would shear the pipe and seal the wellbore.

The LMRP and BOP are designed to work together in a drilling operation. The maximum working pressure of a BOP stack is determined by the maximum well bore pressure expected. The upper connection on the LBOP connects to the LMRP through the connector and the lower connection of the LBOP connects to the subsea wellhead through the wellhead connector (typically GE SDH4 or equivalent). The LBOP is designed to contain and circulate well bore pressure without allowing excess pressure to the surface.

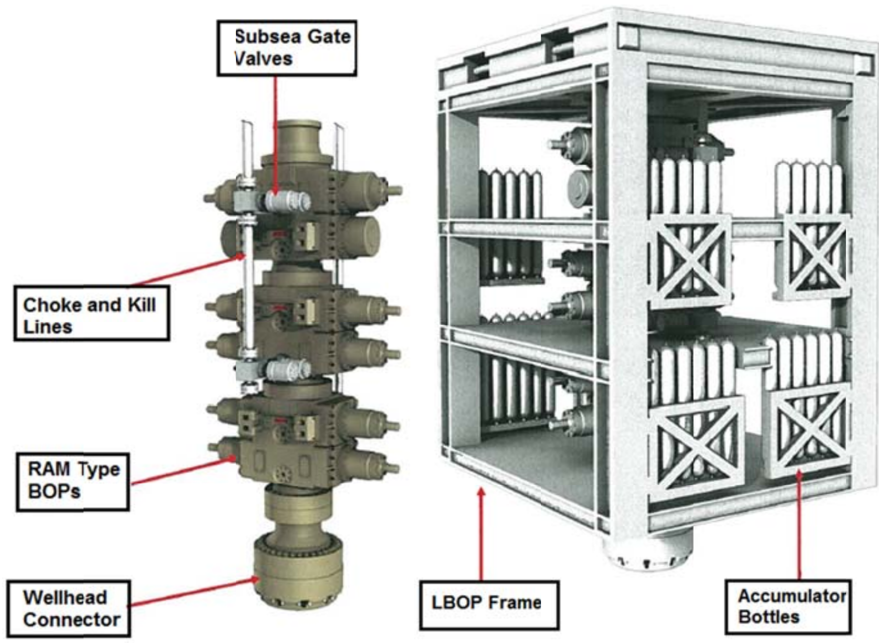


Figure 3.4: LBOP Components [1]

3.2.3 Shear Rams

Shear rams are positioned in the lower BOP stack and their operation is similar to a gate valve. When the rams are activated, the rams are pushed to the center of the wellbore to close and seal the wellbore.

Blind Rams also called sealing rams are designed to seal the well when the well does not contain a pipe. They have no openings for pipe and are designed to seal an open hole.

Blind Shear Rams (BSR) also called shear seal rams are designed to shear the pipe and seal the well during a well control situation. BSR's are used as a last resort to seal the well (Figure

3.5). The upper portion of the cut pipe is released from the ram and the lower portion is crimped and the fish tail is captured to hang off the drill string in the BOP. The ram inner and top faces have elastomeric seals called packers. These packers press against each other, the open hole and around any pipe in the well bore to seal the well.

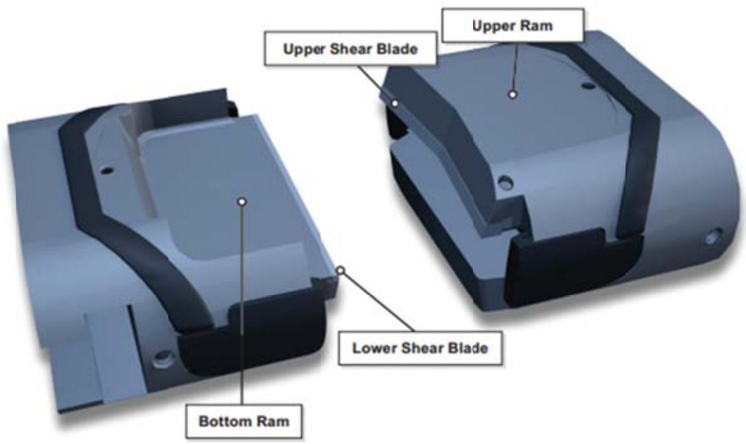


Figure 3.5: Typical Blind Shear Ram [31]

Casing Shear Rams (CSR) also called super shear rams are designed to shear the casing or heavy walled bigger size drill pipe. They cannot be used to seal the well bore (Figure 3.6).

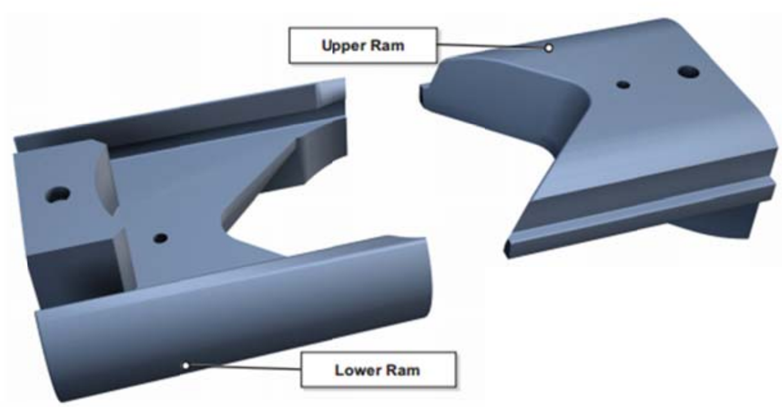


Figure 3.6: Typical Casing Shear Ram [31]

3.2.4 Pipe Rams

Pipe Rams are designed to create a seal around the outer diameter of the drill pipe to seal the pressure from the well bore. The outer diameter of the drill pipe determines the size of pipe ram which will be used.

Variable Bore Pipe Rams (VBR) can seal around multiple sizes of pipe with some loss of pressure capacity and longevity (Figure 3.7).

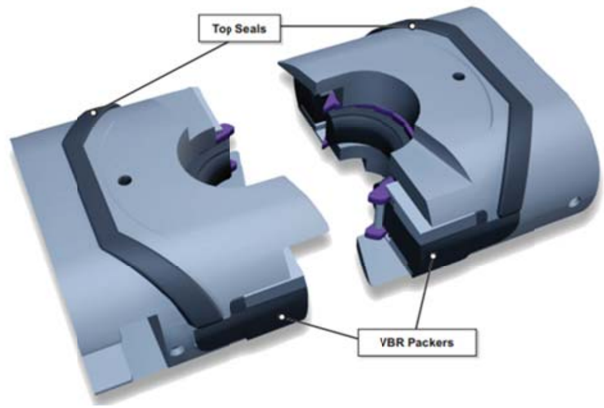


Figure 3.7: Typical Variable Bore Ram [31]

Upper Pipe Rams (UPR) are designed to close on a range of drill pipe and seal the well bore. Middle Piper Rams (MPR) are similar to UPR but can be used to strip through to hang off drill pipe. Lower Pipe Rams (LPR) are similar to UPR.

Test rams are upside down pipe rams which permit the BOP to hold pressure from the top of the rig. The test ram can be closed and the annular and all the rams can be pressure tested against the drill string and the annulus without exposing the BOP to well pressures. Using test rams at the bottom of the stack can lead to significant time and cost savings as multiple trips in and out of the well can be avoided.

Figure 3.8 shows a typical subsea BOP stack with riser, flex joint, two annular preventers, LMRP connector, BSR, CSR, two VBR, test ram and well head connector.

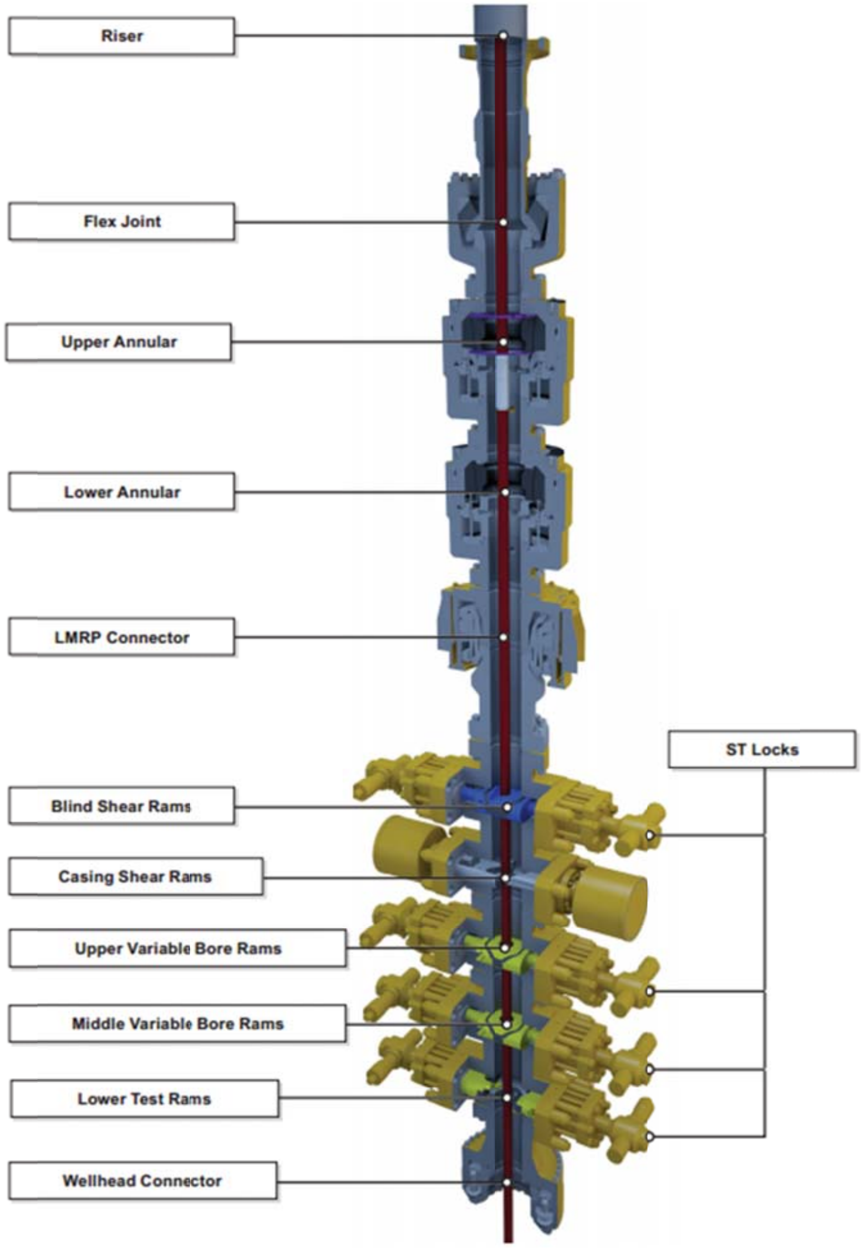


Figure 3.8: Typical Subsea BOP Stack [31]

4.0 BLOWOUT PREVENTER CONFIGURATION AND DESIGN

4.1 General Requirements

The purpose of API Standard 53 [3] is to provide requirements on the installation and testing of blowout prevention equipment systems.

The fourth edition of the API 53 was published as a requirement as opposed to a recommended practice to bring consistency to the industry on how BOP systems are inspected, maintained, tested and operated. In this revision, consideration was given to recommendations made by the Joint Industry Equipment Task Force and other organizations following the Macondo incident. International oil and gas operators, manufacturers, and contractors participated in this revision and incorporated those recommendations that were pertinent to the standard.

API 53 focuses on the items specific to BOP equipment systems for drilling operations and is reorganized into major sections that contain provisions for surface BOP systems, subsea BOP systems, and those that apply to both.

Some of the regulatory recommendations were:

- BOP design and testing should require ability to shear any size drill pipe in compression that will be used in the well plan, for dynamic conditions, worst case scenario and hydrostatic pressures
- Create regulatory document for the repair of BOP's
- Basic design and implementation of BOP's to include; flow detection, automatic functioning, human control and decision making, Black box recorders on all vessels that require surface or subsea BOP's
- Operational experience/training requirement
- Requirement to reduce/eliminate known failures of BOP/Control systems

As per 30 CFR §250.416(e) [4], operators/contractors are required to submit "Information that shows the blind shear rams installed in the BOP stack (both surface and subsea stacks) are capable of shearing the drill pipe in the hole under maximum anticipated surface pressures." Independent third party verification and supporting documentation that show the blind shear rams installed in the BOP stack are capable of shearing any drill pipe in the hole under maximum anticipated surface pressure (MASP). The documentation must include test results and calculations of shearing capacity of all pipe to be used in the well including correction for MASP. These tests include the following:

- Review of operations to ensure that they are performed in a safe and appropriate manner as required by 30 CFR 250.107(a) (1).
- Submit blowout preventer and well control system configuration information for the drilling rig that will be used.
- Have a detailed physical inspection and design review of the blowout preventer performed by an independent third party.
- Obtain an independent third party verification concerning the blowout preventer's compatibility with the drilling rig to be used and the specific well design.
- Have in place a secondary control system with remote operated vehicle (ROV) intervention capabilities for the blowout preventer as well as an emergency shut-in system.
- Test the mechanism for the ROV capabilities while the blowout preventer is onboard the rig prior to placement subsea.
- Obtain an independent verification that the blowout preventer's blind-shear rams are capable of shearing the drill pipe under the maximum anticipated conditions.
- If the blowout preventer's blind shear rams are activated in a well control situation, the blowout preventer must be physically inspected to ensure continued ability to operate.
- Certify through a Professional Engineer that all well casing designs and cementing procedures are appropriate for the purpose of the well under expected conditions.

4.2 Stack Classification

The number of pressure containment components in the BOP stack is used to identify the classification for the BOP system installed. The stack class is determined by the total number of ram cavities and annulars in the BOP stack.

As per API 53 [3], subsea BOP stacks shall be class 5 or greater and shall consist of the following:

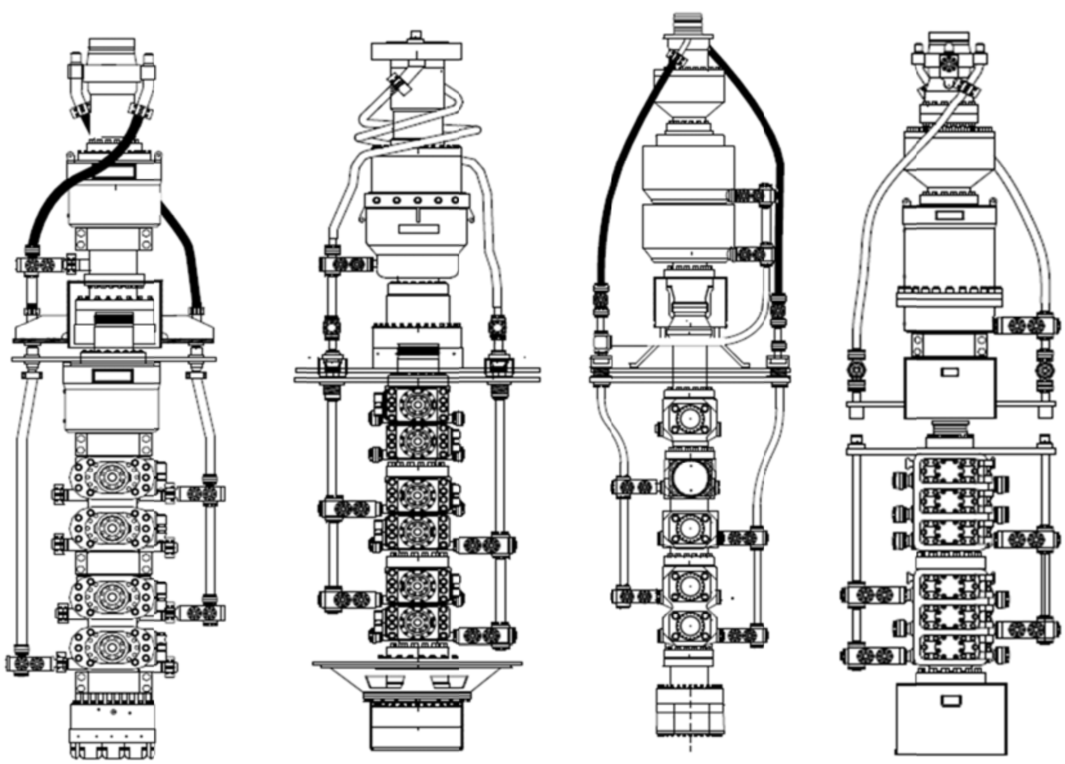
- A minimum of one annular preventer.
- A minimum of two pipe rams which excludes the test rams.
- A minimum of two sets of shear rams for shearing the drill pipe and tubing in use, of which at least one shall be capable of sealing.

The class 6, 7, 8 BOP stack is designed for well operations in the pressure rating of 10,000 - 15,000 psi with use of tapered work strings (Figure 4.1). The pipe-ram preventers can be fixed or variable rams. The height of the stack can be reduced by using double or triple ram preventers. The bottom ram preventer can be used as a top or dual-sealing test ram. If the bottom ram is a test ram, the two remaining ram preventers should be capable of sealing around the larger size drill string, and one set of the pipe rams should be capable of sealing around the smaller size drill string.

The class 6 stack has a five ram configuration and single annular or can have four ram configuration and two annulars. The five ram cavities can consist of a blind/shear ram and non-sealing casing ram or second blind/shear ram, and three pipe ram preventers, or any combination of the above.

The class 7 stack has a five ram configuration and a dual annular or a six ram configuration and a single annular. The five ram cavities can consist of a blind/shear ram and non-sealing casing ram or second blind/shear ram, and three pipe ram preventers, or any combination of the above.

The class 8 stack has a six ram configuration and a dual annular. The six ram cavities can consist of a blind/shear ram and non-sealing casing ram, or two blind/shear rams and four pipe ram cavities, or any combination of the above.



(a) (b) (c) (d)

Figure 4.1: BOP Stack classification, (a) Class 6, (b) Class 7- One Annular, (c) Class 7 - Two Annular, (d) Class 8[23]

4.3 STACK CONFIGURATION

West Engineering [23] has collected BOP stack configuration information from contractors, operators and through its own internal database (Table 4.1) and identified different configurations of BOP stacks used by the industry and found that:

- Three of the thirty-seven listed stacks had only one annular.
- Five of the thirty-seven stacks had more than one blind shear ram (BSR).
- Four of the rigs were equipped with inverted test rams.
- The variable and fixed bore rams occurred in a variety of combinations within the stacks.

The data illustrates the many different ways to configure the BOP stack.

Table 4.1: BOP Stack Configuration [23]

BOP in Study	BOP Class	Control Systems Type	Number Annulars	Number Rams	Number BSR	Number Pipe Rams	Number VBR	Number Fixed Pipe Rams	Number of Inverted Test Rams	Number Casing Rams	Number Valves
1	VII	Mux	2	5	1	4	3	0	0	1	12
2	VII	Mux	1	6	2	4	3	0	0	1	12
3	VI	Piloted	2	4	1	3	2	0	0	1	12
4	VI	Mux	2	4	1	3	2	1	0	0	12
5	VI	Piloted	2	4	1	3	2	1	0	0	8
6	VIII	Mux	2	6	2	4	3	0	0	1	12
7	VI	Mux	2	4	1	3	1	2	0	0	12
8	VI	Piloted	2	4	1	3	2	1	0	0	12
9	VI	Piloted	2	4	1	3	2	1	0	0	10
10	VI	Piloted	2	4	1	3	2	1	0	0	10
11	VI	Mux	2	4	1	3	1	2	0	0	12
12	VI	Piloted	2	4	1	3	2	1	0	0	8
13	VI	Piloted	2	4	1	3	2	1	0	0	10
14	VI	Piloted	2	4	1	3	3	0	0	0	10
15	VI	Piloted	2	4	1	3	2	1	0	0	10
16	VI	Piloted	2	4	1	3	3	0	0	0	8
17	VII	Mux	2	5	1	4	2	1	0	1	12
18	VI	Mux	2	4	1	3	2	1	0	0	8
19	VI	Mux	2	4	1	3	2	1	0	0	12
20	VII	Mux	2	5	1	4	3	0	1	1	12
21	VI	Mux	2	4	1	3	2	0	0	1	12
22	VI	Mux	2	4	1	3	3	0	0	0	12
23	VI	Mux	2	4	1	3	1	2	0	0	4
24	VI	Mux	2	4	1	3	2	1	1	0	10
25	VII	Mux	2	4	1	3	2	1	0	0	10
26	VI	Piloted	2	4	1	3	1	2	0	0	4
27	VI	Piloted	2	4	1	3	2	1	0	0	12
28	VII	Mux	2	5	1	4	3	0	1	1	12
29	VII	Mux	2	5	1	4	3	0	0	1	12
30	VII	Mux	2	5	2	3	3	0	0	0	12
31	VII	Mux	2	5	1	4	3	1	0	0	12
32	VII	Mux	2	5	1	4	3	0	0	1	12
33	VII	Mux	1	6	2	4	2	1	0	1	12
34	VII	Mux	1	6	2	4	3	0	0	1	12
35	VI	Piloted	2	4	1	3	2	1	0	0	12
36	VII	Piloted	2	5	1	4	3	0	0	1	8
37	VII	Mux	2	5	1	4	3	1	1	0	12

4.3.1 Stack Configuration Issues

Drilling contractors are building new rigs with additional BOP stacks. The drilling contractors major concern is how the future regulations might make them change the BOP specifications on their rig, so they are building there equipment to rigorous specifications. Some drilling contractors are spending billions of dollars in equipment upgrades to meet the current regulations. The new regulations would affect the drilling contractors the most as they own the BOP equipment. In the newer stack design, multiple redundant rams are used, so that if one ram leaks, then the ram can be isolated and drilling can be continued. One drilling contractor is building 6 rigs with 7 ram stacks.

Some of the limitations of having extra number of rams are that the BOP system becomes more complex which could increase the chances of failure. The BOP maintenance time also goes up substantially as the system becomes more complex.

Having 7 or 8 ram stacks on the rig creates problem when intervention work is done on older wellheads in shallow waters. The older wellheads cannot handle the increase in weight of the heavier stacks.

Many drilling contractors have begun to order new rigs with two BOP stacks to reduce BOP maintenance delays and shorten drilling time. The cost of BOP downtime can lead to a significant expense to the drilling contractor. The total BOP downtime cost for one of the drilling contractors was around $80 million for year 2012. So there is huge benefit in having dual BOPs on the rig.

4.3.2 20 ksi Stack

Around 4 years ago one major operator was working on a well which had a formation pressure of around 14,700 psi. This means that using a 15,000 psi BOP the operator had only 300 psi if bull heading (forcing fluids in the pipe to displace a kick out of the pipe when wellbore and wellhead pressure limits permits) was adopted for well control issues. So the operator would need a higher pressure rated BOP to do well control. Many operators would like to have the BOP equipment rated for 20% safety margin over the expected formation pressure.

To meet the increasing demand for higher pressure BOPs, OEM's are building 20,000 psi (20 ksi) BOPs. To meet this higher pressure rating, the BOP size and weight has to increase significantly. Comparing a BOP stack with 18-3/4-inch bore 15,000 psi, 6 ram with 2 annular has an approximate weight of 800,000 lbs to 18-3/4-inch bore 20,000 psi, 8 ram with 1 annular with the approximate weight of 1,160,000 lbs. This additional weight of 360,000 lbs for 20 ksi BOP stack would warrant a major change of the rig specification. The BOP weight increase would also increase the load rating on the handling equipment on the rig.

Referring to the above example again, the height of the 6 ram BOP stack was 50 ft compared to the 8 ram stack which is approximately 63 ft. This increase in height would require modification/redesign of the moon pool area on the rig. The moon pool area is a hole in the center of the rig directly below the derrick and is used for storing and staging the BOP and other equipment before they are lowered subsea. The taller stack height would also result in higher bending moments when exposed to the subsea environment.

There are no published standards to cover equipment rated above 15 ksi. API RP 6HP, which addresses the design verification methodology for HPHT drilling and completion equipment was developed in 2005 but has not yet been published. API RP 6HP is based on the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3 (ASME VIII-3) which is used for evaluating pressure integrity of high pressure equipment and service life of equipment through fatigue and fracture-mechanics analyses. ASME VIII-3 methodology accounts for anticipated failure modes of high-pressure equipment as well as reduced material properties, which are expected in environments with extreme pressures and temperatures [36, 37]. Releasing the API RP 6HP would help the industry in standardizing the design methodology for HPHT BOP equipment.

4.4 Number and Placement of Ram sets in BOP Stacks

The BOP standards are not specific about the placement of rams. But per API 53 [4], a documented risk assessment shall be performed by the equipment user and the equipment owner for all classes of BOP arrangements to identify ram placements and configurations, and take into account annular and large tubulars for well control management. Also per API 53 [10], if a single ram is incapable of both shearing and sealing, two rams shall be closed; one that is capable of shearing the drill pipe and one that will seal against rated working pressure (RWP). Additional functions may be added but shall not interfere with the main purpose of shearing drill pipe and sealing the well.

As per CFR 250 [4], in the application for permit to modify (APM), the operator must include a schematic drawing, description of the BOP system and system components. Also, independent third-party verification should show that the BOP stack is designed for the specific equipment on the rig and for the specific well design.

Some of the variables dictating the number/placement of rams in the BOP stack include:

- Number of drill pipe and casing sizes (tapered work string)
- Operator’s requirements

- Local regulatory requirements
- Rig – Moored or Dynamically Positioned
- Rig limitations
- Stripping and hang off capability of the rams
- Shear capability of rams
- Seal capability of ram
- Choke and kill outlet placement
- Variable bore rams

Other considerations may include the following [38]:

- The location of the hang off point should be such that if the pipe has to be sheared then there is enough space between the hang off ram and the shear ram to allow enough fishing neck and not shear into the tool joint.
- As CSR do not seal the well bore, the location of CSR should be considered carefully with respect to BSR in a DP operation.
- Lower most pipe ram could be used as an emergency ram and not be used during regular well control operations.
- A test ram which is located below the lowest pipe ram may reduce the chances of a successful closure of the BOP as it will add more leakage paths in the stack.

4.4.1 Blind Shear Ram Options

Blind shear rams were developed to allow rapid disconnect from the well by shortening the time required to shear and seal, reducing the number of ram cavities required, and eliminating the need for technically complex sequential operations. In order to achieve the combined shearing and sealing, design compromises result in some form of reduced shear capacity and/or reduced sealing reliability. At the time of development, this was aimed almost exclusively at floating rig operations, due to station keeping risks and concerns. These systems also require manual sequence operations, starting with pipe hang off and lock, prior to initiating EDS.

Application of blind shear rams has expanded to encompass surface stacks, for mitigating the risk of not being able to control inside blowouts, and for tools which are shearable, but for which pipe rams are unavailable. Consideration must be given to the complication that some blind shear rams have shear capacity greater than the ability to seal; some rams can shear items that the rams cannot seal without first moving the lower fish out of the fold over pocket area (e.g. Cameron DVS). Blind shear ram designs without the fold over pocket might be perceived as either:

- superior, due to larger shear and seal capacity, or
- Inferior, due to perceived potential increased exposure to seal element damage from the sheared fish.

Two Blind Shear Rams

The general rule has been that the BSR should be at the top of the stack for well control, drill pipe hang off, shearing and sealing the wellbore. Two BSR could be used for DP operations, using the second set of BSR for sealing the well during an emergency disconnect. Due to loss of station keeping on the DP rig and narrow drilling margin in deep water, the two shearing and sealing rams in the BOP stack could be a preferred option. These rams should be able to shear any size drill pipe used in the well [30]. The dual BSR also provides an option for actuating both simultaneously; a one shot, non-sequence of operations, where two BSR are closed without regard to the location of the drill pipe tool joint.

For a 6-5/8 inch, 26.6 lbs/ft, V-150, HT65 drill pipe, the minimum distance from the top of the hang off to the bottom of the blind shear ram cavity is 53". For reference, the minimum space required between the bottom of the upper BSR and the top of the lower BSR is 71". With this spacing at least one of the BSR would be located to cut the pipe, if not both. The redundancy of the shear ram would also provide for a second seal system if one of the blind shear ram failed to seal. However, even this circumstance could be argued in favor of a sequence, first attempting to cut and seal with one ram, and then following this with pipe movement and closing the second set as blind only, with provision to shear only if the first set failed to cut the pipe.

This is provided that the tubular in the bore is within the shear capacity of the BSR. If this is not the case, then casing shear, pipe movement, and sequenced closing of the BSR after pipe movement would be indicated to have successful operation. Closing both BSRs on a tube size too large could have the effect of disabling both sets of blind rams.

A choke or kill valve outlet should be installed between the BSRs, to allow checking pressure and equalizing pressure below the upper BSR to allow initiating fishing operations if both BSRs were closed and cut pipe.

Dead man system or autoshear operation of two sets of BSR on a BOP stack would require functional subsea accumulator capacity adequate for the two large preventers. These separate systems should maintain individual redundancy.

CSR Used in Conjunction with BSR

CSR are non-sealing rams with large pistons. Since they do not seal, they typically do not require locking systems. Since the casing shears will not cut everything, and drill pipe tool joints in particular, the spacing between the upper blind shear rams and the casing shears would be the same.

Casing shears could be utilized in the event of:

- Loss of station keeping, and/or
- Well flow up the middle of the tubular without an inside BOP (or a leaking one)
- Well flow up the annulus either exceeding the pressure capacity of the annulars or other blowout preventers, or well fluids leaking past these units.
- The need to cut anything across the BOP, with reduced risk to sealing open hole, by avoiding potential damage to seals when shearing with BSR. The sealing reliability of the BSR is perceived to be much higher if it is not also shearing.

Since the casing shears do not seal, it is evident that they must be used in sequence with a sealing system, in this case, blind shear rams, (or possibly blind rams) and that movement of the cut tubular is required to allow closing of the blind shear ram.

In the event of use when the riser is connected and the control system operational, the sequencing is controlled by human operators. This sequencing also must be influenced by conditions and equipment besides the rams control system.

BSR Located Above CSR

If the BSRs are located above the CSRs, the cut pipe must be lifted above the BSRs prior to closing the BSRs. If pipe is not moved, the risk is that the BSRs will not close fully, if the pipe is bigger than the BSRs can shear, or that they may not seal. If the BSR can close and seal without moving the pipe, then the CSR is superfluous, and a short extra fish is generated if the tubular is cut by both the BSR and CSR. It would generally be desirable to have the tube cut in only one place, rather than two or three places, to simplify fishing operations and avoid extra junk in the hole.

CSR Located Above BSR

If the BSRs are below the CSR, then the cut pipe can fall away from the BSR, allowing closure of the BSR, provided the tube cut is not either stuck, or suspended on pipe rams (such as the case for drill pipe suspended on hang off ram).

Some vessels (usually DP vessels) have adopted the practice of having a BSR both above and below the casing shear, to allow for either situation. This arrangement commonly results in a six ram BOP stack.

Multiple scenario's should be considered when using the CSR such as casing becoming stuck in the BOP during an emergency disconnect scenario and sheared casing not being able to clear the stack before the BSR closes. In the situation where the rig experiences full black-out (power loss), the draw works would fail locked as such would not be able to pick up the sheared casing which will lead the BSR to close on the casing. The BSR will not be able to cut the casing leaving the well bore open which would cause a well control situation. Alternately if the CSR is placed above the BSR and if the casing gets stuck in the BOP and the casing has to be sheared; the casing may not fall enough to clear the BSR, again leaving the well bore open as the BSR cannot seal and close on the casing.

It is observed that the BSR should not be closed on tube that it cannot shear and seal on. To attempt the closure in this circumstance may:

- Irreparably damage the BSR, rendering it useless for further operation, or
- Discharge limited available dedicated hydraulic fluid, also rendering the BSR useless, at least for a period of time.

Hang Off Rams

Hang off rams should generally be used when shearing drill pipe or other tubulars which are within shearing range of the BSR, to ensure that the pipe is in a shearable position (not a tool joint in the shear rams) and to allow circulation of the well after shearing. The ability to move the pipe is required to assure proper hang off position. Hang off with a conventional passive compensator would proscribe adjustment of the compensator to avoid drill pipe recoil with the upper fish in the event of shearing. The compensating draw works would require adjustment to ensure that the fish would elevate above a second blind shear rams position. A kill line should be above the hang off ram to allow pumping fluid into the fish, and a choke line below the hang off ram to bleed off casing pressure. These outlets and one above the blind shear rams are also required to enable pressure equalization, in the event that the rams need to be opened.

Dropping the sheared pipe below the shear ram will make the following more difficult or impossible:

- well kill
- drill pipe or casing recovery

- well recovery after shear event

4.5 BOP Sequencing and LMRP Disconnect

Sequencing is a series of functions in a defined order. Each step of the sequence has a specified time in which it has to be executed, allowing the designer to create time lags between multiple sequences [23].

Sequencing is very important as it pre-determines the operational system procedures which will be conducted to ensure the safety of the personnel, well and the rig. All dynamically positioned and some moored rigs are equipped to trigger a pre-programmed sequence of functions to ensure that the BOP is left in a secure and safe mode. Fast actuation of this system is essential to ensure safety of the well and rig.

4.5.1 Ram Closing Sequence [29]

The ram closing sequence is very important as it determines the process followed to shear or close on the drill pipe to seal the well. The closing of rams is controlled by the BOP control system which is driven mainly by hydraulic power. The hydraulic fluid used to close the rams is carried from the accumulator into the subsea control pod and passes through the regulator, SPM valve and shuttle valve (Figure 4.2).

The closing of the BSR starts when the hydraulic fluid from the control pod passes through the shuttle valve and pushes both the pistons inward. The hydraulic fluid from the other side of the pistons is circulated into another shuttle valve and later to the surface (Figure 4.2). While the piston is moving inward, the wedge lock is moved behind the piston rod to prevent the piston from moving backwards. The well is shut completely when both rams are closed and seal the well.

The opening of the rams has the same principle like the closing of the rams. The hydraulic flow is now passed through the other side of the piston which pushes it outward. At the same time, the wedge lock is moved to its original position to allow the opening of the rams.

The operating sequence for closing and opening of other types of rams (such as variable bore rams or fixed pipe rams) is the same.

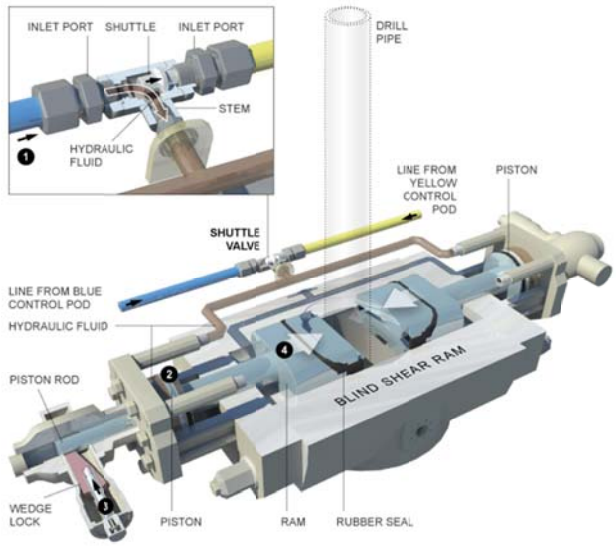


Figure 4.2: Ram Closing Sequence [29]

4.5.2 Emergency Disconnect Sequence [8, 38]

Emergency Disconnect Sequence (EDS) is a fully automated sequence initiated to close the well and disconnect the riser in a rapid sequence to avoid damage to all drilling equipment such as the wellhead, BOP and riser. Uninterrupted communication is needed between the rig and BOP control pods for the activation of the EDS. The failure to disconnect the riser when at a higher rig offset would result in full extension of the riser tensioning system causing damage to the riser or wellhead or exceeding the angular limitation of the lower flex joint [1].

During drilling operations offshore when the rig is unable to maintain station keeping due to extreme weather and rig motions or due to failure of the rig DP system the EDS is initiated to disconnect the riser from the BOP. All dynamically positioned rigs (DP) are equipped with an emergency disconnect switch which initiates a pre-programmed sequence of functions designed to secure the well in a minimum amount of time prior to disconnection of the LMRP riser connector. The amount of time required to complete the entire sequence varies from rig to rig depending on the complexity of the stack and can vary from 30 seconds to a minute or more. If a stack has dedicated shear accumulators, the time required to unlatch can be significantly reduced because the shear rams will continue to close even after the LMRP separates.

EDS is not generally considered a well control response but could be activated if the primary well control system fails. The well can be sealed using the BOP and the kick circulated out of the well. To ensure the safety of the riser and well head the disconnection sequence must be completed in a timely manner. The two typical modes for EDS are [8]:

- Pipe Mode (drill pipe across the BOP)
- Casing Mode (casing across the BOP)

Pipe Mode

The below EDS steps would be followed in a Pipe Mode:

Step 1

1. Make sure pod stingers are extended
2. Close shear ram
3. Close all choke and kill valves on the stack
4. Open riser fill valve if it is being used
5. Retract all acoustic stabs if it is being used
6. Make sure to block all additional ram and annular function

Step 2

1. Unlock both primary and secondary riser connector
2. Unlock and retract all choke and kills stabs if equipped with retractable type stabs
3. Make sure to block all choke and kill valves on the stack

Step 3

1. Block shear rams
2. Retract pod/stingers

The annular could be opened now to release the mud in the riser. Analysis need to be done to verify that the riser would not be damaged in deep water when heavy mud in the riser is released rapidly (riser collapse calculation based on data in API bulletin 5C3).

Casing Mode

The following EDS steps would be followed in a Casing Mode:

Step 1

1. Make sure pod stingers are extended

2. Close CSR
3. Close all choke and kill valves on the stack
4. Retract all acoustic stabs
5. Make sure to block all additional ram and annular functions

Step 2

1. Close shear rams to seal the well
2. Block CSR
3. Open riser fill valve

Step 3

1. Unlock both primary and secondary riser connector
2. Unlock/retract all choke and kills stabs if equipped with retractable type stabs
3. Make sure to block all choke and kill valves on the stack

Step 4

1. Block all shear rams
2. Retract pod/stingers

The annular could be opened now to release the mud in the riser. Analysis need to be done to verify that the riser would not be damaged in deep water when heavy mud in the riser is released rapidly (riser collapse calculation based on data in API bulletin 5C3).

4.5.3 Sequencing and Optimizing the Rams from a Blowout Perspective

Any automatic sequencing involving BSR and CSR together is problematic as described earlier. The correct response for sequencing differs with situation and pipe movement. Incorrect operation or sequence may be worse than no sequence.

- Arrangement 1: The auto shear and/or EDS do not engage the casing shear. This is the most common arrangement. For this arrangement, operational procedure is to disable the autoshear when BSR non-shearables are across the stack.
- Arrangement 2: The auto shear and/or EDS engage either the CSR or the BSR, but not both. This arrangement requires that the operator preselects which shear ram would be engaged when automatically sequenced.

A scenario for this example might be the auto shear has the BSR included in its sequence, while the EDS has a selection or pre-selection for either CSR or BSR. When running casing, the EDS/CSR mode would be used as long as tubes not shearable with the BSR are across the stack, and then switch to BSR mode when possible. If an EDS is initiated while the casing is across the stack, the CSR would cut the casing (which would drop down the hole), followed by the LMRP disconnect in sequence; when the LMRP lifts, the autoshear system would seal off the well by closing the BSR above the CSR. Note that for the case with two sets of BSRs, the lower BSR autoshear should be disabled when the EDS/CSR mode is selected. The initiation of the EDS/CSR would change the selection of the autoshear to BSR mode prior to disconnect.

If on the above example the EDS/BSR sequence is enabled, the EDS would shear pipe with the lower BSR, and the pipe would be lifted above the upper BSR. The autoshear would then be left to activate both sets of BSRs, the lowers already closed, and the uppers closing on open hole.

Note that for the specific cases described above, the CSR is always functioned with the surface accumulator, while the BSR might be functioned with either the surface or a subsea accumulator.

If the riser became disconnected or the control system totally failed while casing was across the stack, then the autoshear or deadman would close the casing shear.

What would be desired at this point, would be then to sequence the BSRs closing (after the casing dropped and lifted) and then locking the BSRs. The technology exists to make this sequence happen, if utilizing Cameron pods with integrated dead man system. Other manufacturers systems could be enhanced similarly with sufficient impetus.

Getting this type of sequence to automatically engage for the autoshear system (where the pods are disconnected and all the valving control is on the lower stack) has not been accomplished to date. As a result, the norm for this is then: the casing shear is closed, and the BSR closure must take place by other means, such as ROV or acoustic system. It is not desirable to close the BSRs simultaneously with the CSR, as damage to the BSR would be likely, and subsequent non-functionality of the BSR would be a likely result.

Also note that the requirement to move the pipe up after shearing would give preference to passive pipe compensation systems, or indicate the need for backup power for draw works heave compensation systems.

Location of shear rams and sequence order impact maximum required operating pressure and dedicated accumulator sizing requirements. Shear rams operated without a closed preventer above require surface shear pressure plus compensation for hydrostatic fluid column pressure (either sea water or mud, depending upon conditions). Shear rams operated with a closed preventer above need to add compensation for added well pressure.

SHEAR RAM PERFORMANCE AND DESIGN

5.0 SHEAR RAM DESIGN CHALLENGES

5.1 INTRODUCTION

Some of the present challenges facing BOP shear ram technology include:

- Pipe centralization
- Shearing of compressed/buckled pipe
- Shearing in flowing well conditions
- Non-shearables across the BOP
- Combined shearing and sealing
- Multiple rams needed to shear different grades of drill pipe and casing

Many of the BOP equipment manufacturers are developing new shear ram designs with the aim of addressing many of the above issues. Some of these new technologies are presented in Chapter 8.0.

5.2 CENTRALIZING PIPE DURING SHEARING

The ability to keep the pipe between the shearing surfaces of the BOP is essential. Depending on flow rates and pressures, if not too excessive, the driller may attempt closing the annular to centralize pipe followed by pipe rams and shear rams. This is a highly sensitive condition and never a guarantee.

To address this issue many of the BOP and Shear Ram manufacturers have introduced pipe centralization in their next generation series of shearing blind ram designs. This is addressed in numerous ways from full well bore coverage coupled with curved blades to the use of guide arms to move the pipe to the cutting zone. These features are examined in later sections of this report.

5.3 SHEARING OF COMPRESSED/BUCKLED PIPE

There are some procedures which can be applied to try and keep the pipe vertical through the bore of the BOP stack when the well is flowing under pressure. The applied weight plays an important part in keeping the drill string in the hole. The key is to prevent the well from flowing and applying hydraulic force and frictional force which is causing the pipe to lift. The driller does not have many options when the weight of the drill string comes off the bottom. If the weight comes off the bottom and the force is suitably high the drill pipe may become buckled in the well bore. Another potential scenario leading to pipe buckle maybe the loss of the drill pipe down hole. The shearing requirements for the buckled pipe condition are assessed in Section 7.3.3.

5.4 Shearing During Flowing Well Conditions

No testing has been performed to shear drill pipe with shear rams in a simulated pressurized flowing well condition as seen during blow out. The testing scenario is too dangerous for any existing facility to handle. Simulating a blowout condition, with high pressures and very high flow rates would need a purposefully built test facility. This report examines the flowing well effects on shear ram shearing performance in Section 7.4.

5.5 Non Shearables Across the BOP

As per CFR 250 [4], the BSR shall be capable of shearing any drill pipe including heavy weight drill pipe in the hole under maximum anticipated surface pressure (MASP). But the drill string is made up of multiple types of tubulars and not all of the tubulars can be sheared by the shear rams. Some of these non shearables include drill collars, casings, certain material grade and heavier types of drill pipe and tool joints.

Whenever a non shearable tubular is being moved through the BOP, the driller will contact the dynamic positioning operator to make sure the rig can maintain its positioning during running or pulling the non shearable through the BOP. If there are any potential rig positioning problems expected, the driller would keep the non shearable below the BOP when the drill string is pulled out of the hole. This is done to make sure that the drill string can be sheared in case of potential problems. If the non shearable is being run in the hole, the driller would keep the drillstring above the BOP until the rig problems are rectified.

Drilling contractors should have procedures for non-shearables in place. When a non-shearable is across the BOP these procedures should be followed. The non-shearables procedures should ensure the following:

- Time spent in this condition is minimized.
- Good communications between bridge/rig floor with all parties fully aware that non shearables across BOP.
- Bridge will review weather ahead of non shearable condition and where there are likely to be squalls then additional engines will be put on line as contingency.
- Close attention paid to weather radar and DP instrumentation.

- Project Manager will work on anything that could affect station keeping ability put on hold until shearables across BOP.
- Written procedure in place in the event of emergency yellow and red watch conditions in order that driller knows actions to be taken in the event of station keeping or well control issue.
- Drilling contractors “shearables across BOP” policy/procedures are reviewed by operator to ensure they are in-line with operator's policy.

Some of the BOP equipment manufacturers have developed new shear ram designs with the ability to shear tool joints. Other companies have made advancements in laser and explosive shearing as well as tool joint design.

5.6 SHEARING DATABASE

There are lots of challenges in getting shearing data from the BOP OEM’s. Due to the difficulty in getting information on actual shear capacities for drill pipe and casing strings from BOP OEM’s, drilling contractors and operators find it to be extremely time consuming. Some of problems and solutions are:

1. BOP OEM's require ultimate tensile strengths and charpy values etc. on the drill strings in order to calculate the shear forces using the OEMs BOP. It can be a struggle to get this information and some drilling contractors have not got shear pressures/charts specific for their drill strings.
2. BOP manufacturers are under significant workload as a result of the findings and future legislation from Macondo. Due to the complexity of shear calculations for specific drill pipe and tubulars the BOP OEM performs the shear calculations. Due to workload it is proving very difficult to get these calculations from the BOP manufacturer.
3. This could be simplified if each BOP manufacturer posted a shear calculator function on their website with contractor/operator inserting the appropriate information required/request to complete the calculation.

6.0 SHEAR RAM MODEL DEVELOPMENT AND CALIBRATION

6.1 INTRODUCTION

As part of this work, a series of physical shearing tests are performed using available BOP, shear rams and drill pipe. Laser scanning of the shear rams allows the development of a dimensionally accurate CAD model enabling the construction of a finite element model of the BOP shear rams using Abaqus CAE. In this section a series of calibration exercises are performed to investigate the models sensitivity to ram closing velocity, damage parameters, and the effect of load and displacement controlled motion of the rams. The calibrated model is then put through a number of shearing tests and the results are compared to the physical shear test results.

6.2 13-5/8 BOP SHEAR TESTS

6.2.1 Overview

The primary objective of the shear tests is to shear drill pipe using a set of BOP rams and to capture relevant information such as shearing force, shearing time, and deformed shape of the sheared pipes, which are then used to validate the computer simulation model.

Shearing tests are conducted with 3-1/2” drill pipe using a standard surface 13-5/8" bore BOP stack under static non-flowing well conditions. The tests are performed by placing the pipe in a centralized position inside the well bore. All tests are carried out at the Archer test shop in Amelia, Louisiana.

Extensive study was performed to find what size of BOP/blind shear rams and drill pipe should be used for the shear test. In typical deep-water wells, 18-3/4" bore subsea BOPs and 6-5/8" drill pipe is utilized. The cost of using a subsea BOP to conduct a shearing test is very expensive and beyond the scope of this project. Subsea and surface blind shear rams are very similar except the subsea blind shear rams are available in bigger sizes. So it was decided to use surface blind shear rams and 3-1/2” drill pipe to conduct the shear test.

The Shearing Blind Rams (SBR) used in the test are shown in Figure 6.1. The SBR has tandem boosters, which approximately doubles the force available to shear a pipe by using a two-part piston. The SBR blades are integral to the ram body and were designed to replace shear rams with bolt on blades. The upper shear ram consists of V shaped shearing edge and the lower shear ram consists of a straight shearing edge. The upper shear ram consists of a large blade packer which seals the front surface of the lower SBR blade [9].

The SBR used in the shear test is designed to fold the lower drill pipe fish to clear the sealing area and house the lower fish between the fold over shoulder and the bottom of the upper blade as depicted in Figure 6.2, [8].

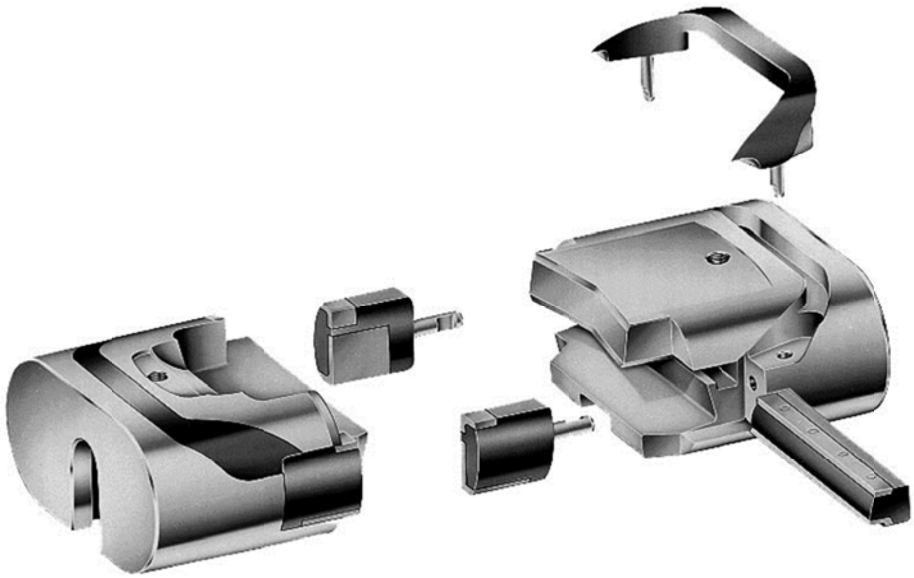


Figure 6.1: Shearing Blind Ram (SBR) [9]

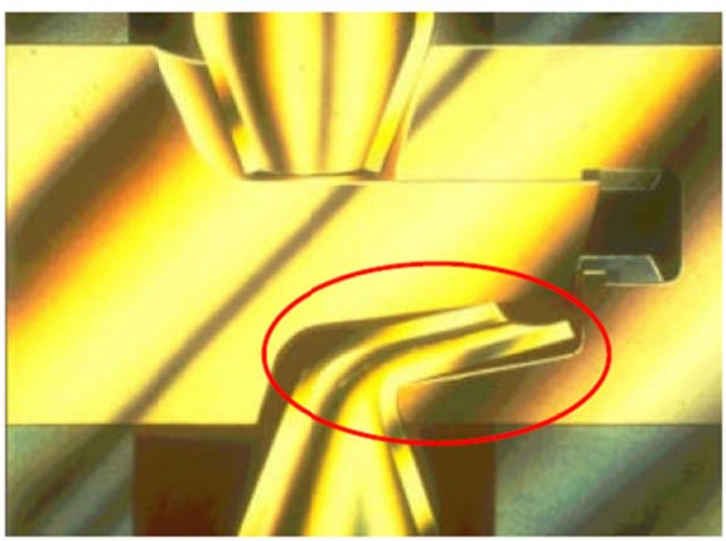


Figure 6.2 Shearing Blind Ram with Fold Over Shoulder [8]

6.2.2 Test Procedure

A total of two tests performed, both on 3-1/2" drill pipe. This size was selected so that the shear rams would not get damaged during the test. The replacement of these rams is outside the scope of the project. The following tasks were performed to meet the objective of the test:

- Shear 3-1/2", 13.3 lbs/ft, S-135 Drill pipe in a 13-5/8" BOP in a centralized non flowing condition
- Obtain the maximum pressure needed to shear the pipe
- Measure the total time to shear the pipe
- Obtain snap-shots and physical samples of the sheared drill pipe
- Measurements of the sheared pipe cross section

The schematic in Figure 6.3 shows the BOP shearing test setup. The BOP was connected to a control panel to control the opening and closing of the shear ram. The pressure chart recorder was also connected to the BOP and measured the pressure needed to close and open the ram.

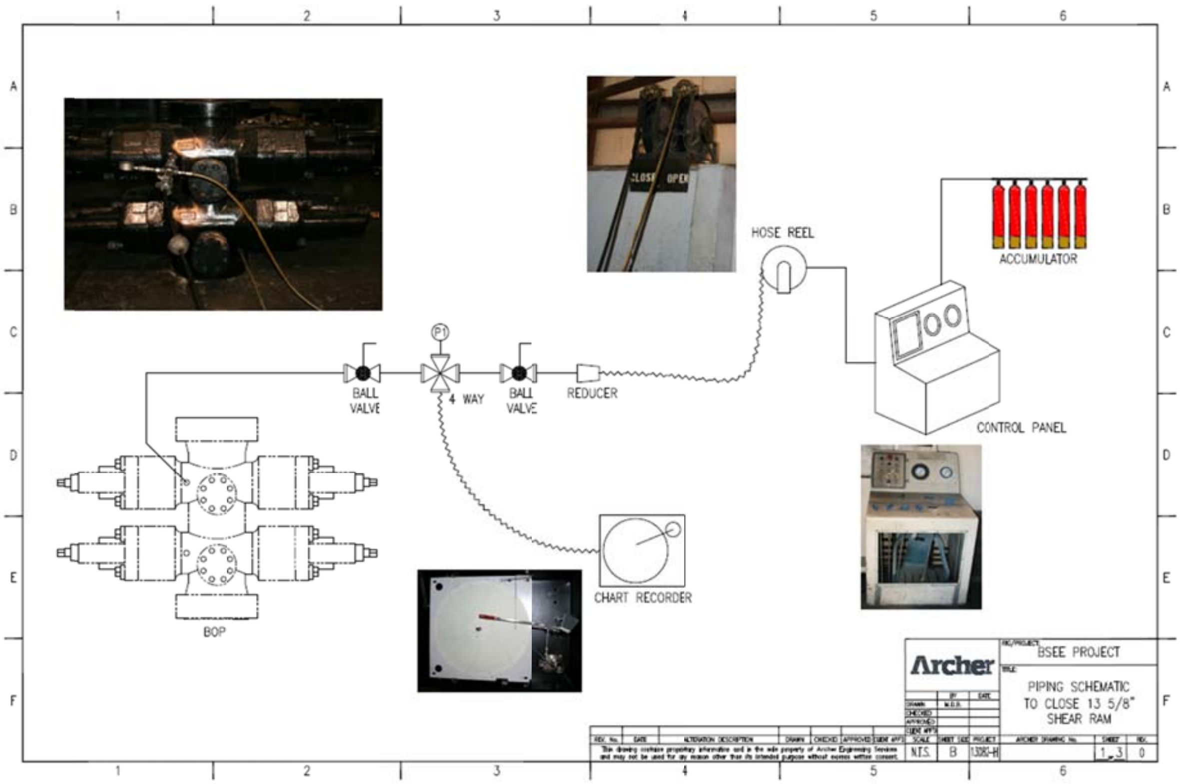


Figure 6.3: Shearing Test Schematic - 13-5/8" - To Close Shear Ram

Prior to testing the shear rams and pipe were inspected to ensure there was no damage, see Figure 6.4. The procedure set by Archer [5] was followed during the test and is presented in Appendix A.

Figure 6.4: Condition of the Bonnet and Shear Rams Before the Test

6.2.3 13-5/8" Shear Test Results

The highest pressure recorded to shear the pipe for Test 1 is 1,400 psi and for Test 2 is 1,250 psi (Figure 6.5 and Figure 6.6, respectively). The shearing process in the two tests was recorded and the time taken to shear the pipes noted. It took approximately 7 seconds and 6 seconds for Test 1 and Test 2, respectively. The time count starts when the shear ram touches the pipe and ends when the shearing process is complete. The required shear force (Table 6.1) needed to shear the pipe was calculated by multiplying the area of the large bore tandem piston (224 sq. in) by the maximum pressure needed to shear the pipe.

Table 6.1: 13-5/8" Shear Test Results

Test	Measured Shear Pressure (psi)	Calculated Shear force (lbs)
1	1,400	1400 psi X 224 sq. in = 313,600
2	1,250	1250 psi X 224 sq. in = 280,000

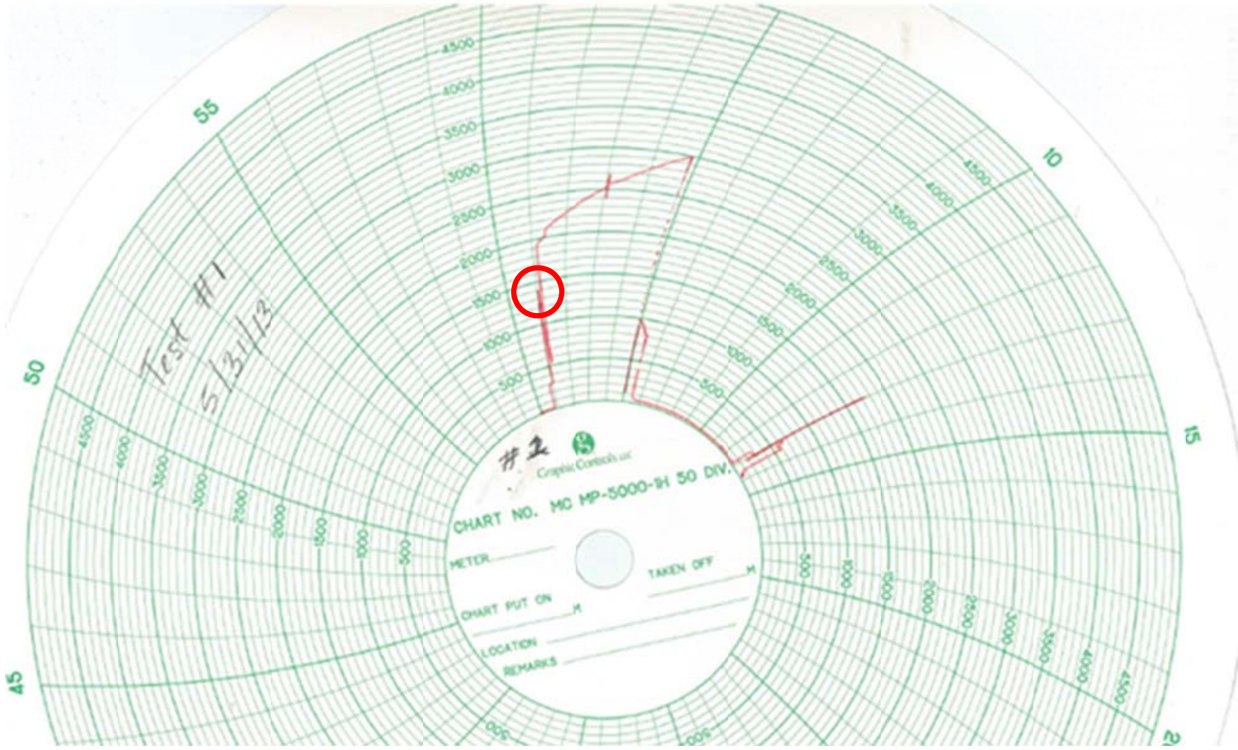


Figure 6.5: 13-5/8” Shear Test 1 - Time (Minutes, Radially) Versus Pressure (psi, Vertically)

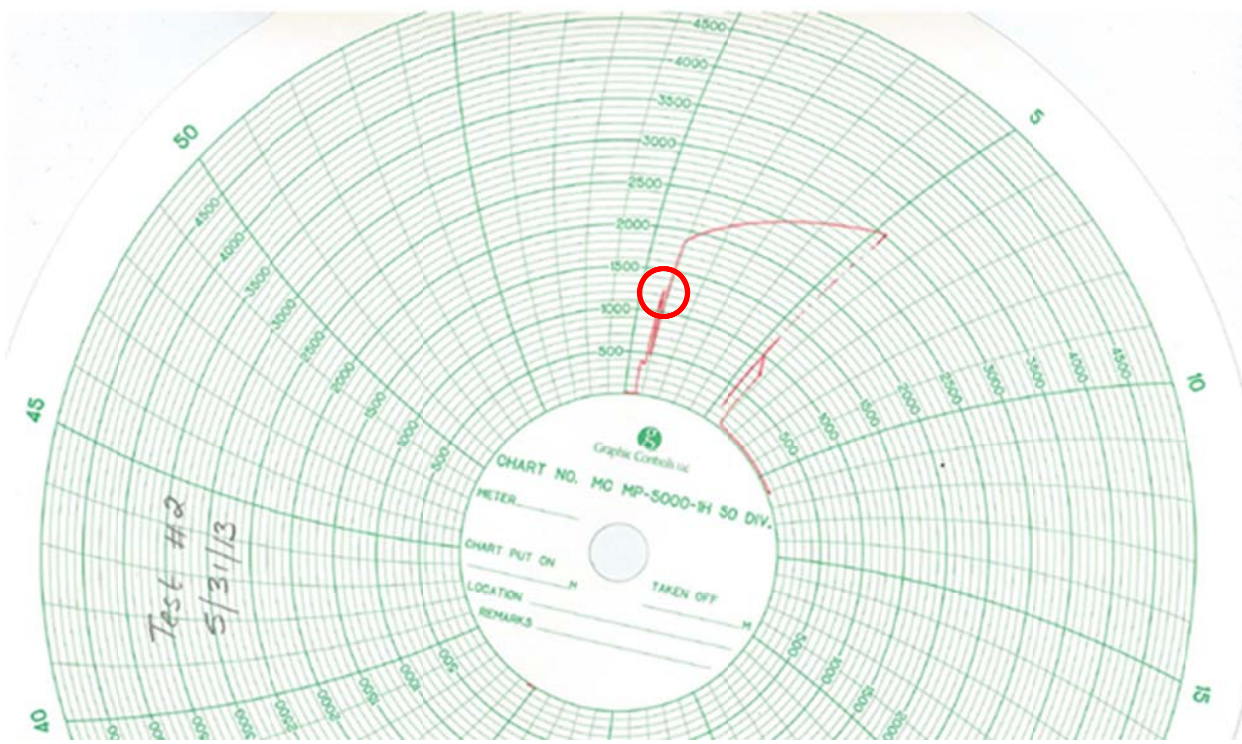


Figure 6.6: 13-5/8” Shear Test 2 - Time (Minutes, Radially) Versus Pressure (psi, Vertically)

Further, the pressure needed to shear the pipe was also calculated as per the OEM shearing formula and was found to be 1,844psi (Figure 6.7). The actual shearing pressures observed during the test are lower than the calculated pressures from the OEM shearing formulas. The calculated shearing pressure values used by OEM are conservative and can be considered as the upper bound pressure which may be seen during the shearing operation.

Required Shear Pressure Calculation Worksheet for Equation 1
(No Wellbore Pressure Effects)

IMPORTANT: ENSURE TUBULAR MEETS THE RERQUIREMENTS OF STEP 1 (PAGE 3) BEFORE PROCEEDING TO THE CALCULATIONS.

BOP TYPE 13-3M/10M U e.g 18-10M UBOP (REF. Table 2)

OPERATOR TYPE LBT e.g SBT (REF. Table 2)

MAXIMUM ALLOWABLE OPERATING PRESSURE OF OPERATOR 3,000 e.g 3000 psi

TUBULAR TYPE 3.5" 13.3ppf S135 e.g 5" 19.5 ppf S135

C_1 = 224 From Table 2 on page 6

C_3 = 0.23 From Table 3 on page 7

ppf = 13.3 Specified (lbf/ft)

σ_{yield} = 135,000 Minimum yield strength (psi) (reference section 3 on page 2)

Calculated Shear Pressure, P_{shear} is given by :

$$P_{shear} := \left[\frac{(C_3 \cdot ppf \cdot \sigma_{yield})}{C_1}\right]$$

P_{shear} = 1844 Operator shear pressure (psi)

Note: P_{shear} required to be less than the maximum allowable operator pressure

Figure 6.7: Calculations using OEM Shear Formula – 13-5/8" BOP [7]

The upper fish on the first test has a smooth shear surface (Figure 6.8) and had a shape of an ellipse. The major diameter of the upper fish was measured as 4-1/2" and the minor diameter was measured at 2-1/16". The SBR rams are designed to fold the lower drill pipe fish to clear the sealing area and house the lower fish between the fold over shoulder and the bottom of the upper blade. The folded lower drill pipe fish undergoes quite significant damage during this process, as shown in Figure 6.9. Similar profiles are observed during the second test (Figure 6.10).

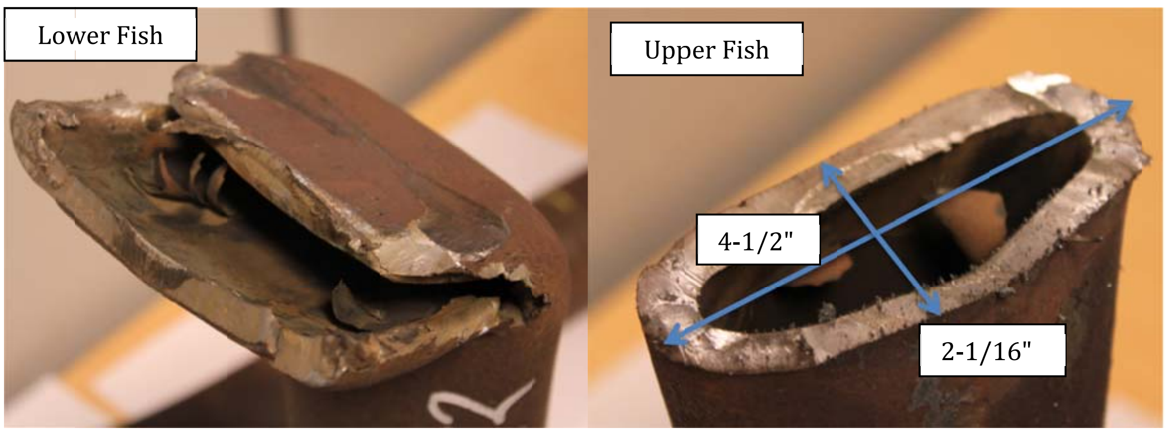


Figure 6.8: Shear Test 1 (Lower and Upper Fish, Close Up View)

Figure 6.9: Shear Test 1 (Lower and Upper Fish, Front View)

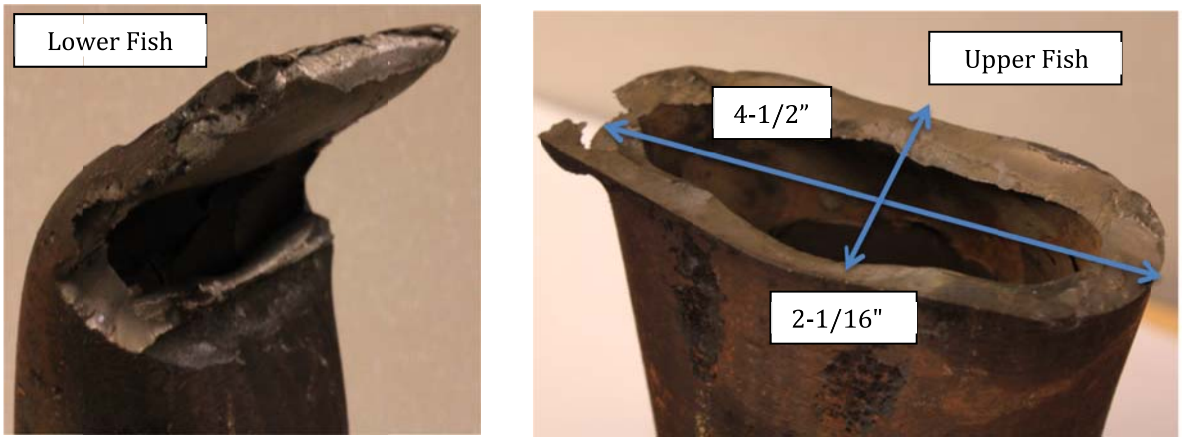


Figure 6.10: Shear Test 2 (Lower and Upper Fish, Close Up View)

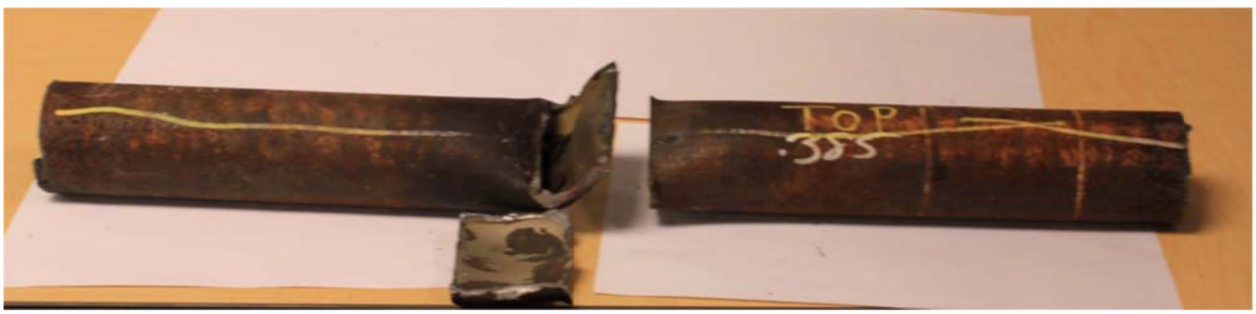


Figure 6.11: Shear Test 2 (Lower and Upper Fish, Front View)

The upper and lower shear rams were not damaged during the shear tests (Figure 6.12).

Figure 6.12: View of Upper and Lower Shear Rams After the Test

6.3 Validation of Computer Model with Shop Test

The simulation model is set up such that it replicates the shear test conducted in the test facility. The geometry of the 13-5/8” shear rams are obtained by laser scanning the actual model in the test facility. In this model, the drill pipe is centralized in the BOP bore and there is no flow through the drill pipe and well bore. The material properties, boundary conditions, loads and contact conditions used in the FEA model closely represent the ones in the physical test. The results obtained from Abaqus explicit simulations are then validated with the 3.5" drill pipe shear test data. The benchmarked model is then used as the base case for performing additional parametric studies.

6.3.1 Geometry Capture of Blind Shear Rams through Three Dimensional Imaging

Using three-dimensional scanners, point cloud files are created. The scanner automatically measures distance thus creating millions of points representing the object scanned. During this application, the point cloud files were used to re-create the 13-5/8” shear rams dimensionally. The point cloud data was then converted to hexagonal type file to smooth surfaces. To use the point cloud data, AutoCAD, Solid Works, 3D Studio and GeoMagic software were used to find edges, radii and contours for surface reconstruction.

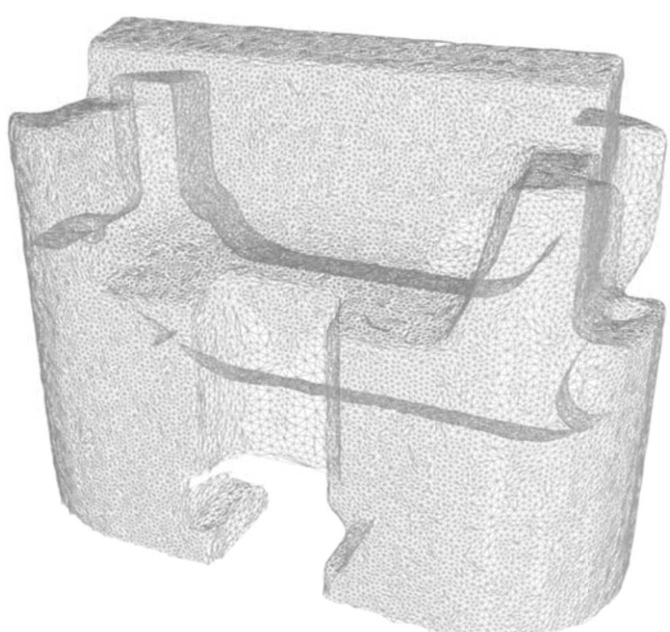


Figure 6.13: Initial Raw Hexagonal File Format

The original surfaces of the parts were gray and black in color with the rubber goods and packers having a sheen making scanning of the object a bit more challenging. It was found that spraying the reflective areas and dark colors with non-destructive developer used in non-destructive testing (NDT), enhanced the ability to capture all surfaces and edges using the 3D laser scanner (Figure 6.14).

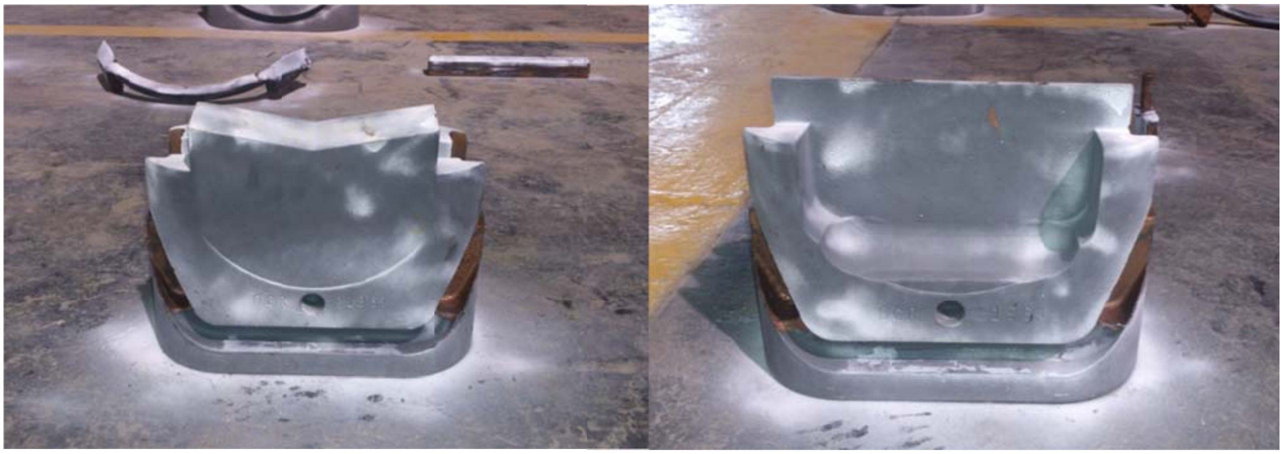


Figure 6.14: Upper and Lower Ram (from Left to Right)

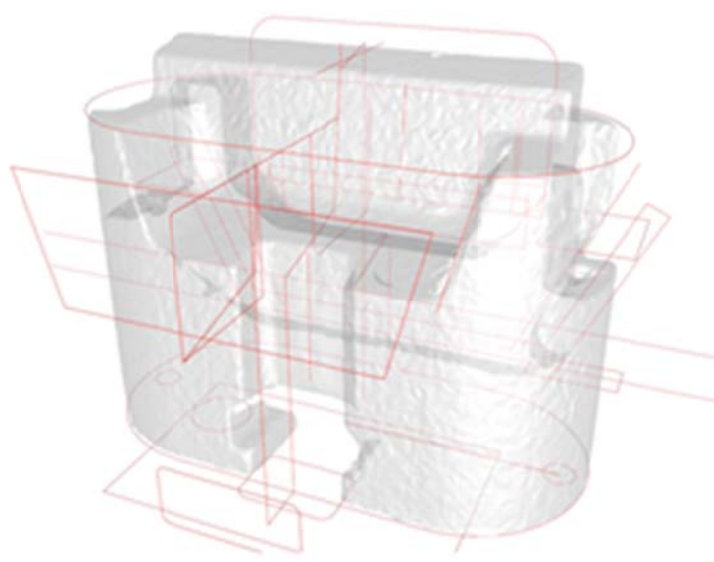


Figure 6.15: Defining the Edges and Faces with Lines of the Lower Blind Shear Ram

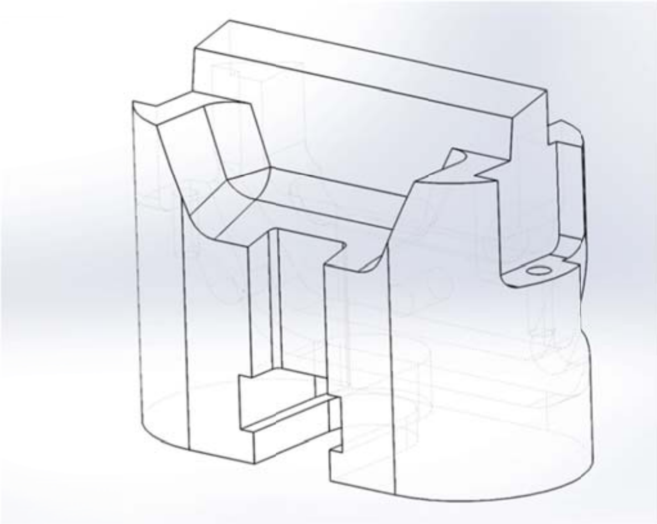


Figure 6.16: Schematic from CAD File Ready for Modeling

After completion of the scanning process, the laser scanning company combined all the files, capturing and meshing all the data into single part files. Upon receipt of the files from laser the scanning company, the process of smoothing of the surfaces was started. After the initial cleanup, the file were imported into Solidworks and 3D Studio to manipulate the data to obtain clean lines, edges, radii, contours and surfaces.

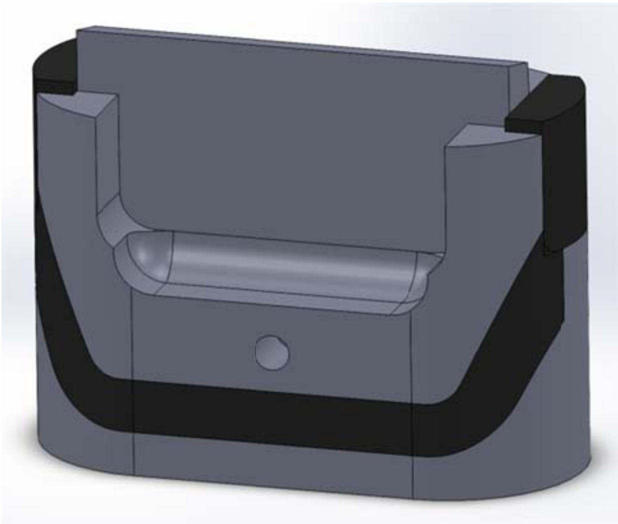


Figure 6.17: Modeled Lower Shear Blind Ram

After the final solid model format was complete, the process of modeling the BOP began. The modeling of the BOP bore and drill pipe allowed for basic calculation to be taken, such as volumetric capacities and weights.

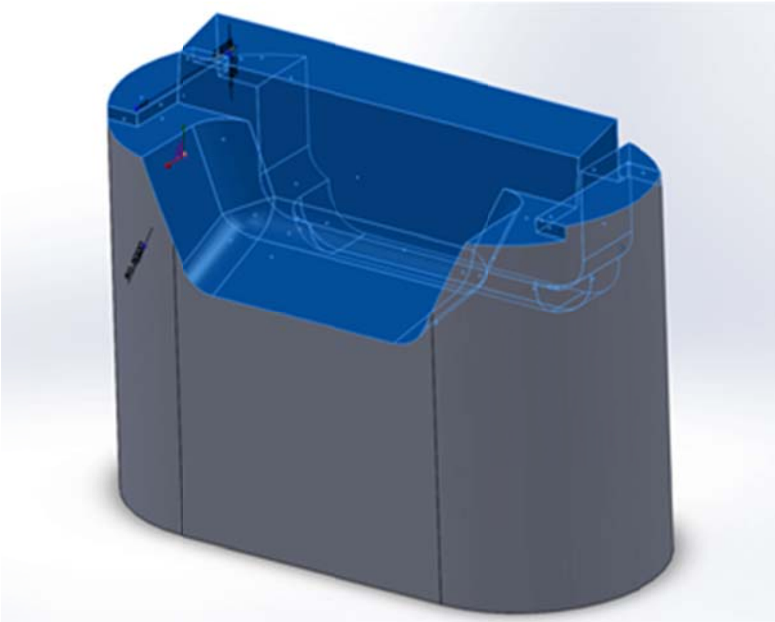


Figure 6.18: Face Definition

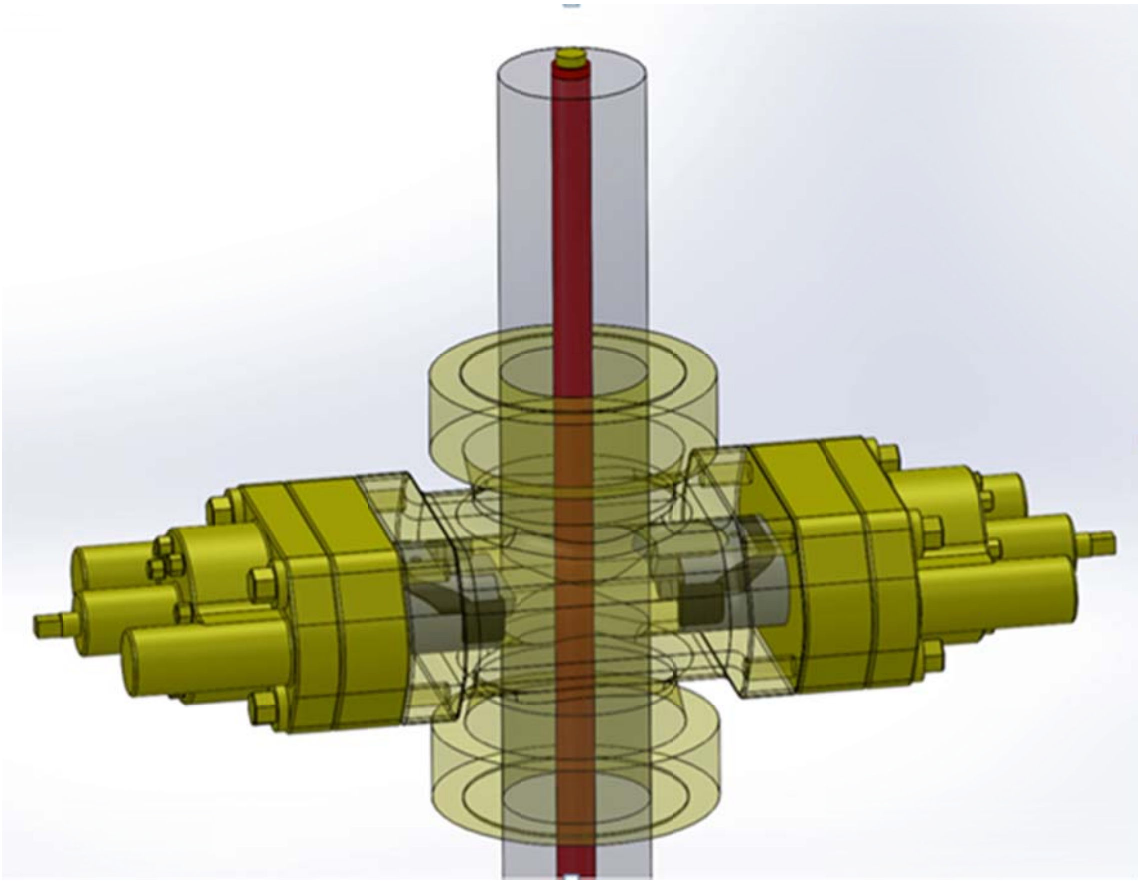


Figure 6.19: BOP Model

6.3.2 Drill Pipe and Shear Rams Geometry

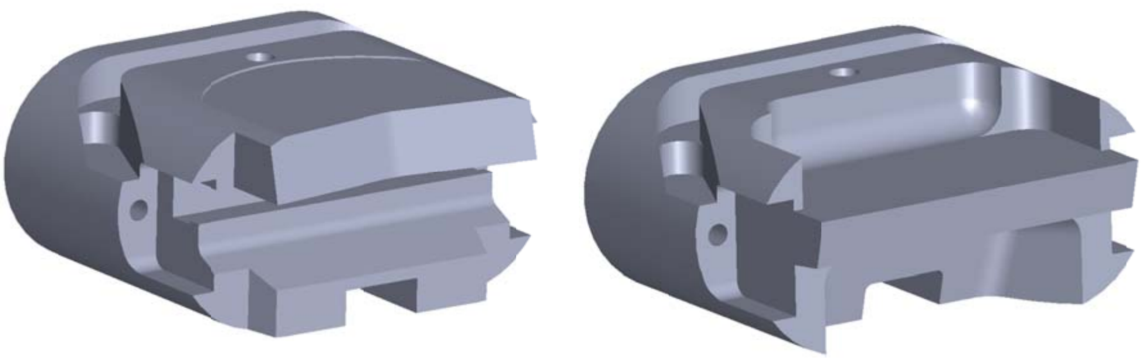
A 3.5" (OD) drill pipe of S-135 material with 13.3 lb/ft weight and with a wall thickness (t) equal to 0.368” is used to perform numerical analysis in Abaqus. The pipe dimensions replicate the ones used in the test (Table 11.3). The length of the drill pipe modeled is 9.84 ft which is also similar to the test pipe specimens. The dimensions of the drill pipe used for the FEA model are provided in Table 6.2.

Table 6.2: Drill Pipe Geometry

Geometry Parameter	Dimension
Nominal Diameter (D)	3.5”
Pipe Wall Thickness (t)	0.368”
Pipe Length	9.84 ft

The upper and lower shear rams used in the test are shown in Figure 6.20. The laser scanned cad geometry of the shear rams are used without elastomers as shown in Figure 6.21, as the elastomers have no impact on the shearing force needed to fracture the pipe. However, they do play a role in sealing the well after the pipes are sheared which is not the focus of the current study. The well bore and outer casing are not modeled for the benchmark study as they have no impact on the shearing force for a centralized drill pipe under no-flow conditions.

Figure 6.20: Upper and Lower Shear Ram Used in Shop Test



(a) **(b)**

Figure 6.21: Blind Shear Rams without Elastomers (a) Upper Shear Ram; (b) Lower Shear Ram

6.3.3 FEA Methodology

FEA simulations are performed using Abaqus/Explicit, an explicit dynamic finite element solver program. Abaqus/Explicit is generally used for solving non-linear, dynamic analyses. Although, the magnitude of inertia forces are small due to the slow motion of the rams, the FEA model does include pipe and shear ram masses to capture any such effect. Also, the effect of non-linear geometry was captured in the FEA model. Discussed below are some aspects of the FEA model.

6.3.3.1 MATERIAL RESPONSE

The simulation involves the elastic-plastic material response and progressive ductile and shear damages of the drill pipe and therefore, appropriate damage and material models are used. The elastic-plastic material response data without damage is obtained by employing a Ramberg-Osgood (R-O) fit to the material test data for S-135 material. Reference 6 provides the material strength parameters.

The following criteria are specified for material response:

- Undamaged elastic-plastic response (classical metal plasticity)
- Damage initiation criterion
- Damage evolution response, including element removal criteria

<u>Undamaged Elastic-Plastic Response [10]</u>

Undamaged elastic-plastic response is modelled using R-O fit to the material strength parameters such as yield and ultimate stresses. R-O equation can be written as

$$\varepsilon = \frac{\sigma}{E} + \alpha \frac{\sigma_0}{E} \left(\frac{\sigma}{\sigma_0} \right)^n$$

Where, ϵ is strain

σ is stress

σ_0 is yield strength

E is Young's modulus

$\alpha = K \left(\frac{\sigma_0}{E} \right)^{n-1}$

n is a constant describing the hardening behavior of the material

<u>Damage Initiation Criteria [10]</u>

Two mechanisms can cause the fracture of a ductile metal:

- Ductile fracture due to nucleation, growth, and coalescence of voids
- Shear fracture due to shear band localization

Ductile Criterion: This is a phenomenological model for predicting the onset of damage due to nucleation, growth, and coalescence of voids. The model assumes that the equivalent plastic strain at the onset of damage ε_D^{-pl} is a function of stress triaxiality and strain rate:

$$\epsilon_D^{-pl}\ (\eta, \epsilon^{\cdot -pl}),$$

where, *η= -p/q* is the stress triaxiality, *p* is the pressure stress, *q* is the Von Mises equivalent stress, and $\varepsilon^{\cdot -pl}$ is the equivalent plastic strain rate. The criterion for damage initiation is met when the following condition is satisfied:

$$\omega_D = \int \frac{d\varepsilon^{-pl}}{\varepsilon_D^{-pl}(\eta, \varepsilon^{\cdot -pl})} = 1,$$

where, ω_D is a state variable that increases monotonically with plastic deformation.

Shear Criterion: This is a phenomenological model for predicting the onset of damage due to shear band localization. The model assumes that the equivalent plastic strain at the onset of damage, ε_S^{-pl}, is a function of the shear stress ratio and strain rate:

$$\epsilon_s^{-pl}\ (\theta_s, \epsilon^{\cdot -pl}),$$

where, $\theta_s = (q + k_s p)/\tau_{max}$ is the shear stress ratio, τ_{max}, is the maximum shear stress, and k_s is a material parameter. The criterion for damage initiation is met when the following condition is satisfied:

$$\omega_s = \int \frac{d\varepsilon^{-pl}}{\varepsilon_s^{-pl}(\theta_s, \varepsilon^{\cdot -pl})} = 1,$$

where, ω_s is a state variable that increases monotonically with plastic deformation proportional to the incremental change in equivalent plastic strain.

Damage Evolution Response [10]

This describes the rate of degradation of the material stiffness once the corresponding initiation criterion has been reached. For damage in ductile materials, Abaqus assumes that the degradation of the stiffness associated with each active failure mechanism can be modeled using a scalar damage variable,$d_i\ (i \in N_{act})$, where N_{act} represents the set of active mechanisms. At any given time during the analysis the stress tensor in the material is given by the scalar damage equation.

$$\sigma = (1 - D)\bar{\sigma},$$

where, D is the overall damage variable and $\bar{\sigma}$ is the effective (or undamaged) stress tensor computed in the current increment $\bar{\sigma}$ represents the stresses that would exist in the material in the absence of damage. The material will lose its load carrying capacity when *D=1*. By default, an element is removed from the mesh if all of the section points at any one integration location have lost their load-carrying capacity.

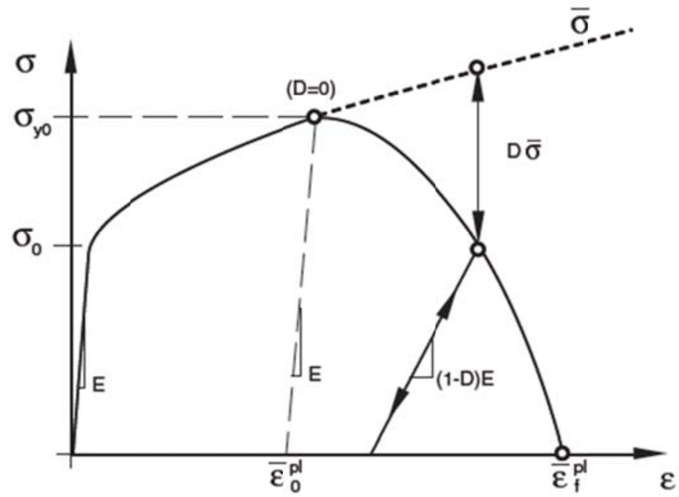


Figure 6.22: Stress-Strain Curve with Progressive Damage Degradation [10]

6.3.3.2 CONTACT FORMULATION

The contact interaction between the shear rams and drill pipe is modeled using the *General Contact method* considering the normal and tangential behaviors. The normal behavior is modeled using *Scale Factor (General Contact, Explicit)* Pressure-Overclosure with an Overclosure factor of 0.1 and contact stiffness scale factor of 10. The tangential behavior is modeled using *Penalty* formulation with a coefficient of friction of 0.7 which is typical for steel-steel contact.

6.3.4 FEA Model

The finite element (FE) model is built using Abaqus CAE. The overall assembly, material properties, mesh size and types, loads and boundary conditions are discussed in detail in this section.

The FE assembly for the centralized drill pipe is depicted in Figure 6.23. The total length of the drill pipe is 9.84 ft out of which 7.5 ft is above the shear rams shearing plane to the top of the overhead crane and the remaining 2.35 ft is below the shear ram shearing plane. The positioning of the shear rams represents the experimental set up where the drill pipe is hanged from an overhead crane. The rams are placed 3.81” apart and are 0.157" away from the drill pipe outer surface. Figure 6.23 and Figure 6.24 depicts the front and top views of the shear ram assembly.

In the physical test the initial positions of the shear rams is at the edge of the BOP bore. As the focus of FE simulation, is on shearing the drill pipe, the initial positions of the shear rams is close to the drill pipe outer surface. Modeling of entire stroke of shear ram is not required and it does not add any value and is computationally expensive. The ram motion is modeled by providing a pseudo velocity (constant rate of change in position with time). This replicates the actual boundary condition where displacement controlled motion of the shear rams occurs due to the force applied by the pistons.

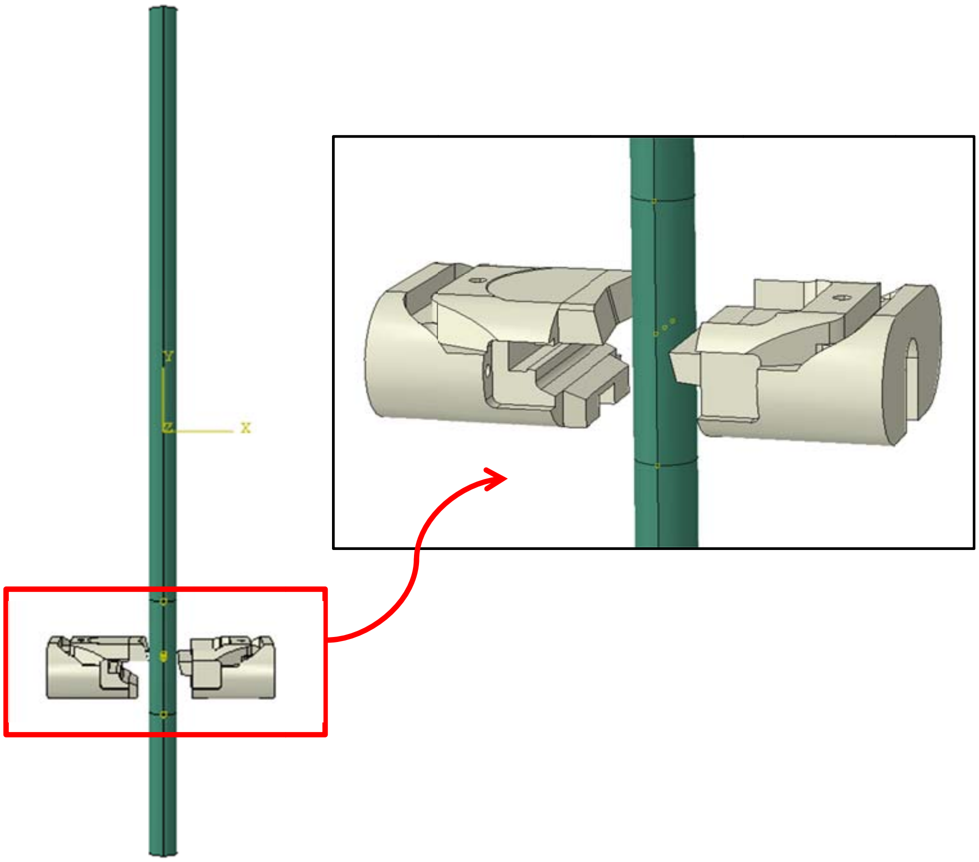


Figure 6.23: Typical FE Configuration - Front View of Assembly

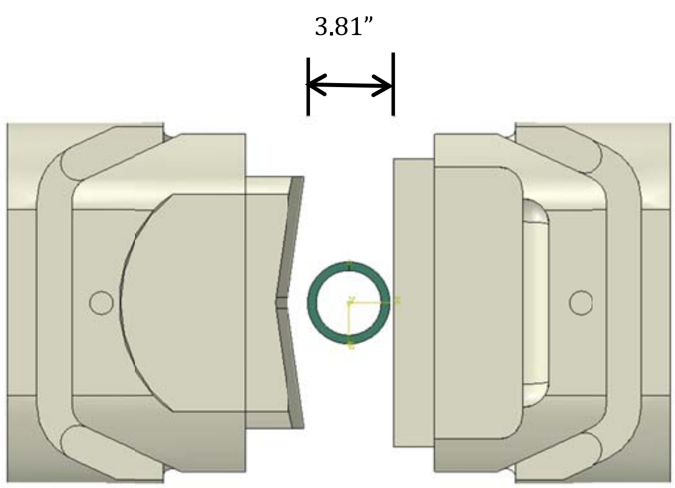


Figure 6.24: Typical FE Configuration - Top View of Assembly

6.3.4.1 ELEMENT SELECTION AND MESH SIZE

The drill pipe is meshed using 3D solid elements with four elements through the pipe thickness. The mesh density near the shearing region of drill pipe is refined to capture the displacement field accurately and the mesh density away from it is coarsened for computational efficiency without compromising on the accuracy of the solution of interest [Figure 6.25]. Also, it can be noted that the implementation of the damage formulation in Abaqus has minimal mesh dependency [10]. The drill pipe has 8-node linear brick elements with reduced integration and stiffness hourglass control (C3D8R). To check the dependency of the solution on the choice of integration scheme, simulations were also performed with full integration and it was found that with the maximum shearing force obtained was not realistic and it also led to contact problems.

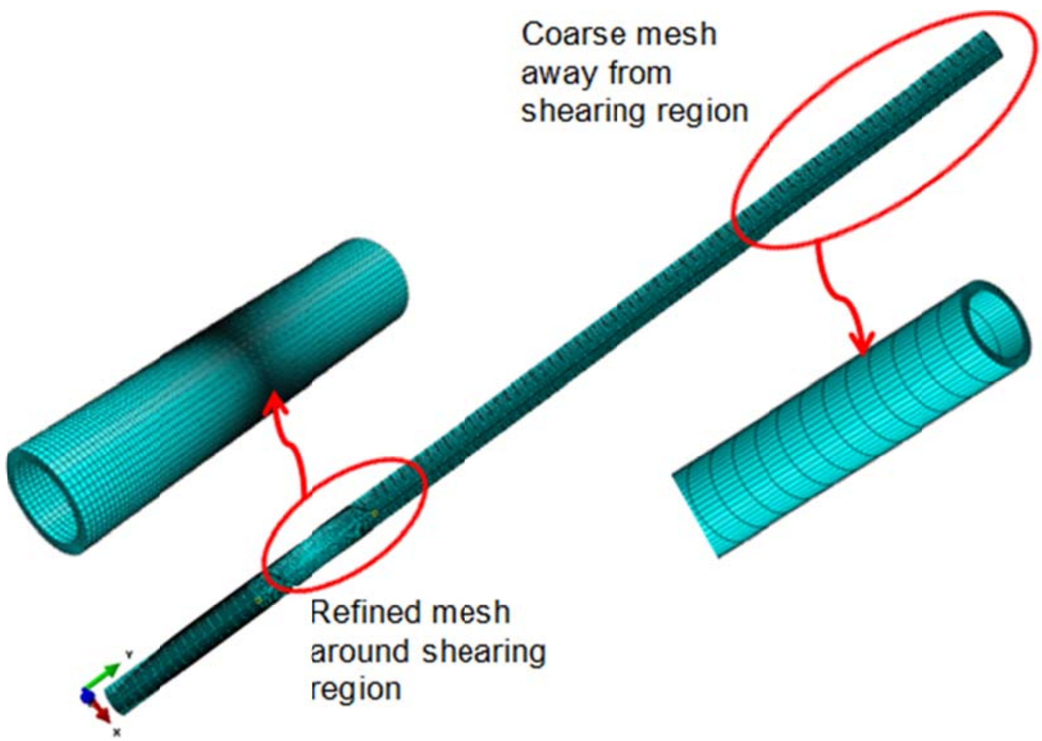


Figure 6.25: Drill Pipe Structural Mesh

A structured mesh with hexahedral brick elements is not required for the shear rams as they are modeled with high stiffness and are undeformable. The shear rams were meshed with tetrahedral elements (C3D4). The mesh density on the regions of the rams that comes in contact with drill pipe is refined and other regions are coarser for computational efficiency

(Figure 6.26). A finer mesh size of 0.39” is used for the blades and a coarser mesh size of 3.93” is used for other regions of shear rams.

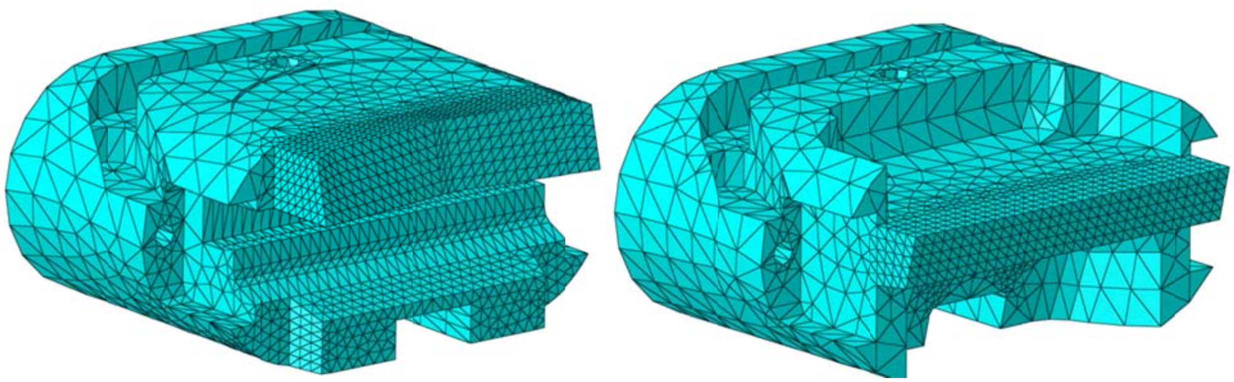


Figure 6.26: Shear Rams with Mesh

6.3.4.2 MATERIAL PROPERTIES

Compared to pipe deformation, the deformation of the shear ram is negligible except at the very small region that comes in direct contact with the drill pipe. Thus, the shear rams are modeled as elastic material with very high Young’s modulus (rigid like material property). Simulations are run using deformable elastic-plastic material properties with progressive damage degradation for the drill pipe. No damage model is considered for the shear rams since the damage in the shear rams are very localized and small compared to the damage in pipe and has negligible effect on the maximum shearing force.

The drill pipe mechanical properties used for the simulation are listed below in Table 6.3.

Table 6.3: Drill Pipe Mechanical Properties [6]

Property	Value
Young’s Modulus	29E6 psi (assumed)
Poisson’s Ratio	0.3 (assumed)
Yield Stress	155,400 psi
Tensile (Ultimate) Stress	161,500 psi
Maximum Elongation	19.5%
Stress-Strain Curve	R-O Fit

The yield strength, ultimate strength, and elongation data provided in the above table are obtained from Reference 6. Two sets of material strength data were available in the reference. However, the properties with higher yield and ultimate strength values are used for the simulation. The true stress versus true strain plot used for the simulation is depicted in Figure 6.27. The data is strain rate independent.

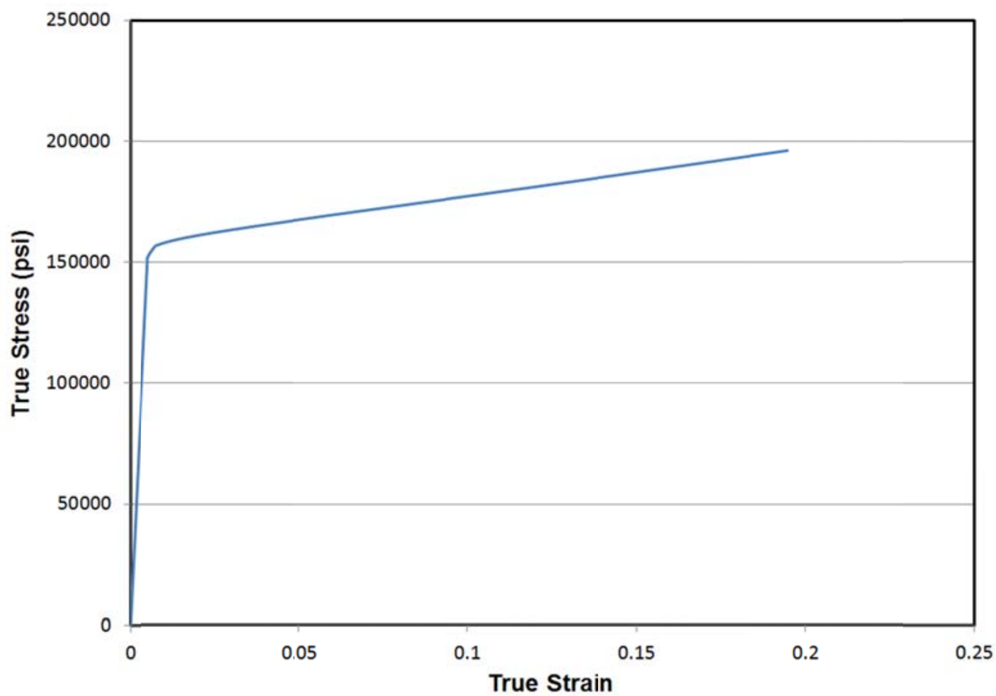


Figure 6.27: True Stress Versus Strain

The ductile damage initiation data for high strength steel (representative of S-135 material) is obtained from a peer reviewed journal article [14], Figure 16. Figure 6.28 shows the Fracture Strain (ε_S^{-pl}) versus Stress Triaxiality (η) data independent of the strain rate ($\dot{\varepsilon}^{-pl}$) .

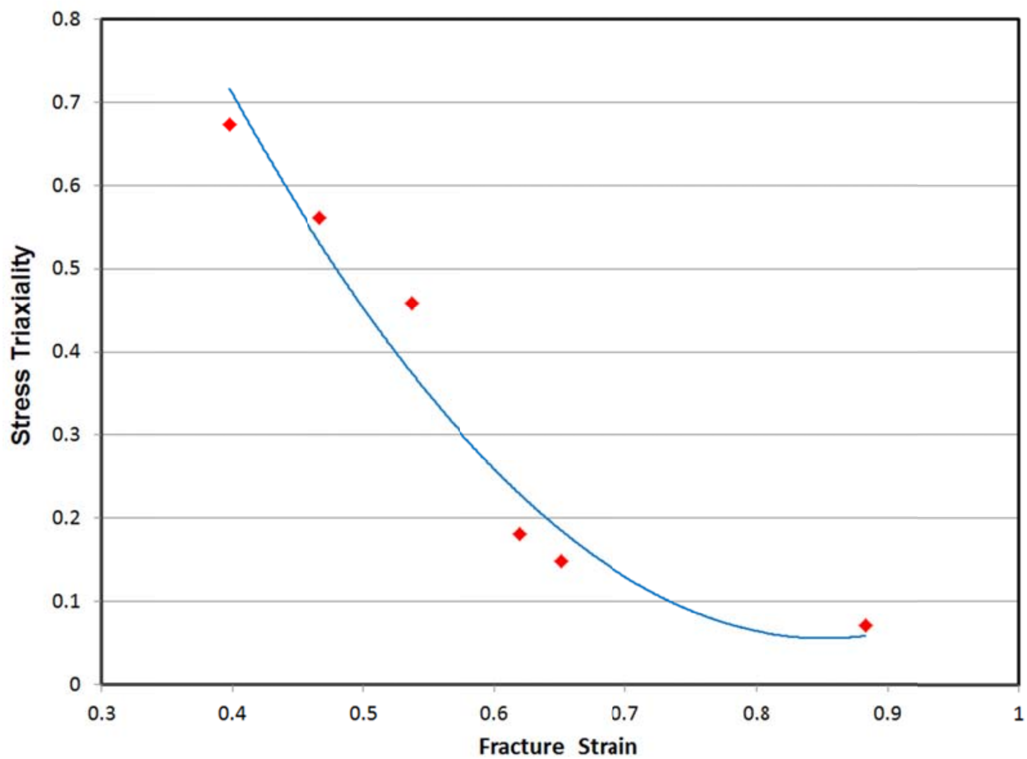


Figure 6.28: Stress Triaxiality Versus Fracture Strain

No published data was found for the shear damage initiation parameters of high strength steel. Aluminum shear damage data was used from a peer reviewed journal article [15], Figure 8, and the trend in the curve was used to scale the data for high strength steel. For a given shear stress ratio, this is achieved by increasing or decreasing the fracture strain by a constant factor. Sensitivity studies were performed to evaluate the effect of shear damage data on the maximum shearing force and it was found that there is considerable effect [refer Section 6.3.5]. Strain rate independent shear stress ratio (θ_s) versus Fracture strain ($\bar{\varepsilon}_S^{pl}$) curve is used for the simulation as shown in Figure 6.29. The fracture strain is scaled up by 30% than that for aluminum since it showed results comparable to the experiment. This is discussed in details in Section 6.3.5.

Strain rate independent material data is used since the shearing process does not represent a high-strain rate scenario. Also, all material data used are temperature independent. High temperature would degrade material properties and aid in the shearing process so it is conservative for shear force calculation perspective to consider temperature independent material properties.

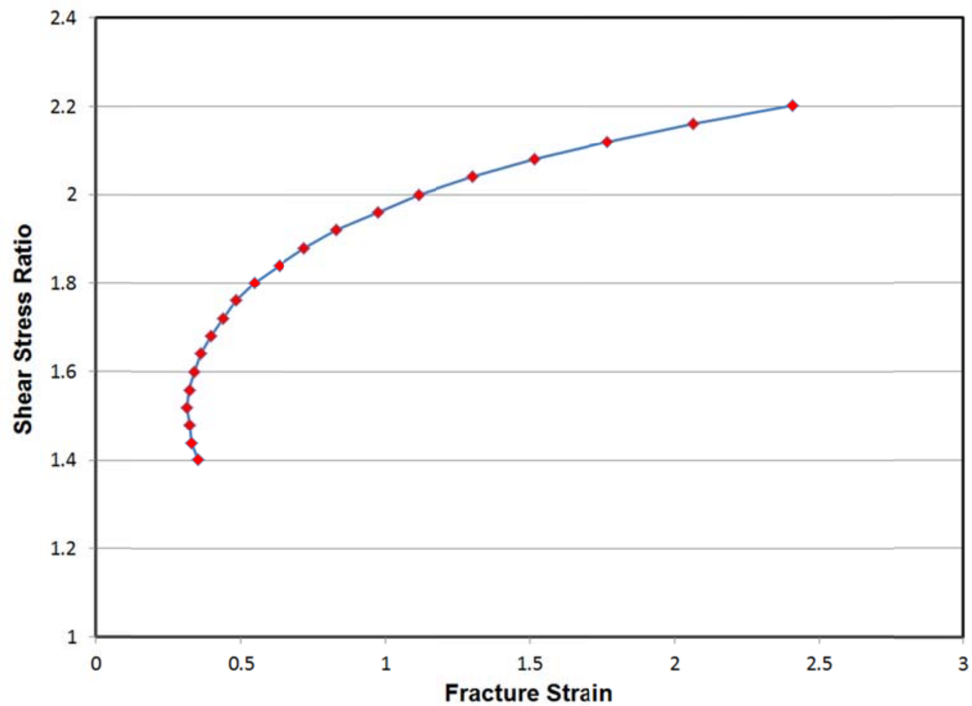


Figure 6.29: Shear Stress Ratio Versus Fracture Strain

Table 6.4: Damage Evolution Parameters

Damage Evolution Parameter	**Value**
Type	Displacement
Softening	Linear
Degradation	Maximum
Ductile damage displacement at failure	0.291 mm (refer to Ref. 20, Table 2)
Shear damage displacement at failure	0.415 mm (refer to Ref. 20, Table 4)

6.3.4.3 LOADS AND BOUNDARY CONDITIONS

In the subsea environment, high pressure from the accumulators is used to activate the shear rams and shear the drill pipe. Generally the entire process from activation of shear rams to the shearing of the drill pipe takes less than about 45 seconds. In the physical test conducted using the surface BOP, the drill pipe is sheared in about 30 seconds. However, the time it took for the rams to shear the pipe from the moment the rams touch the pipe was about 7 seconds. In the computer model the motion of shear ram is modeled using a velocity such that the shearing process takes place about 20 seconds from the moment the rams touch the pipe. It can be noted that in the simulation, rams are initially set close to the pipe outer surface and is then provided a constant velocity. A lower ram velocity (longer time to shear) was used in the simulation to be conservative as study (refer to section 6.3.5) showed decrease in the shearing force for higher ram velocity.

During the motion of the rams the corresponding shearing force is computed from the blade region in contact with the pipe surface. The translational degrees of freedom for the top and bottom of the drill pipe are fixed. This is different than the test set-up. However, the effect of boundary conditions at top and bottom of the pipe were found to be negligible since they are remote from the shearing area.

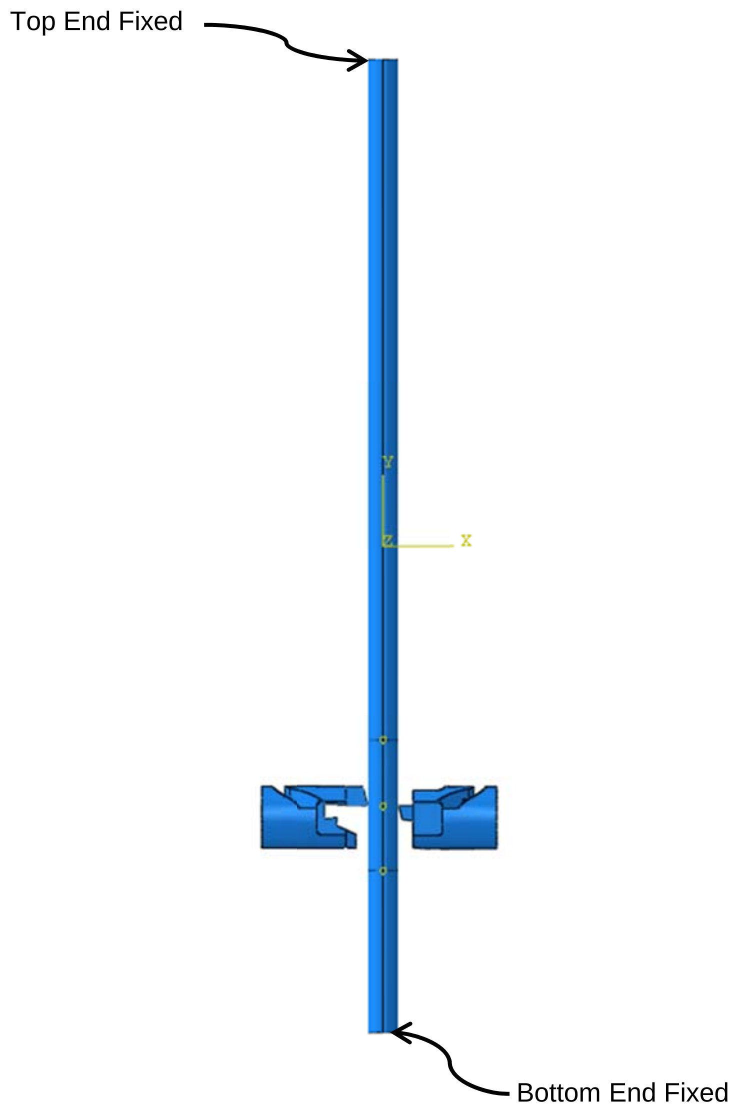


Figure 6.30: Boundary Conditions for Drill Pipe

6.3.5 Determination of FE Model Parameters

In order to ascertain the sensitivity of different simulation parameters on the maximum shearing force, several parametric studies were performed. They are listed below.

- Reduced integration versus full Integration elements
- Effect of ram velocity
- Effect of load and displacement controlled motion of the shear rams
- Sensitivity of various damage parameters

6.3.5.1 REDUCED INTEGRATION VERSUS FULL INTEGRATION

All elements in Abaqus are integrated numerically. Abaqus uses either the full or reduced integration depending on the type of elements. By default, full integration is used for all triangular and tetrahedral elements and reduced integration is used for quadrilateral and hexahedral elements. The advantage of reduced integration is that the stresses and strains are calculated at the locations that provide optimal accuracy and the reduced number of integration points decreases CPU time and storage requirements. On the other hand, the disadvantage is that the reduced integration procedure can admit deformation modes that cause no straining at the integration points. These zero energy modes cause the phenomenon called hourglassing, where the zero energy mode starts propagating through the mesh leading to inaccurate solutions. To prevent these excessive deformations, an additional artificial stiffness is added to the element.

Simulations are performed using both type of elements and it was found that the simulation using the reduced integration gave closer results to those from the physical shearing tests. Therefore, reduced integration elements were used for the final runs.

6.3.5.2 EFFECT OF RAM VELOCITY

To verify the sensitivity of the shear ram velocity on the results, simulations were performed by increasing the velocity used in the benchmark simulation by five times. It was observed that with the increase in velocity of the shear rams, there is a reduction in the maximum shearing force. From Figure 6.31, a reduction of 16.7% is seen by increasing the velocity by 5 folds.

A velocity of 0.197 inch/sec, half the velocity of the rams in the physical test, is used for all simulations.

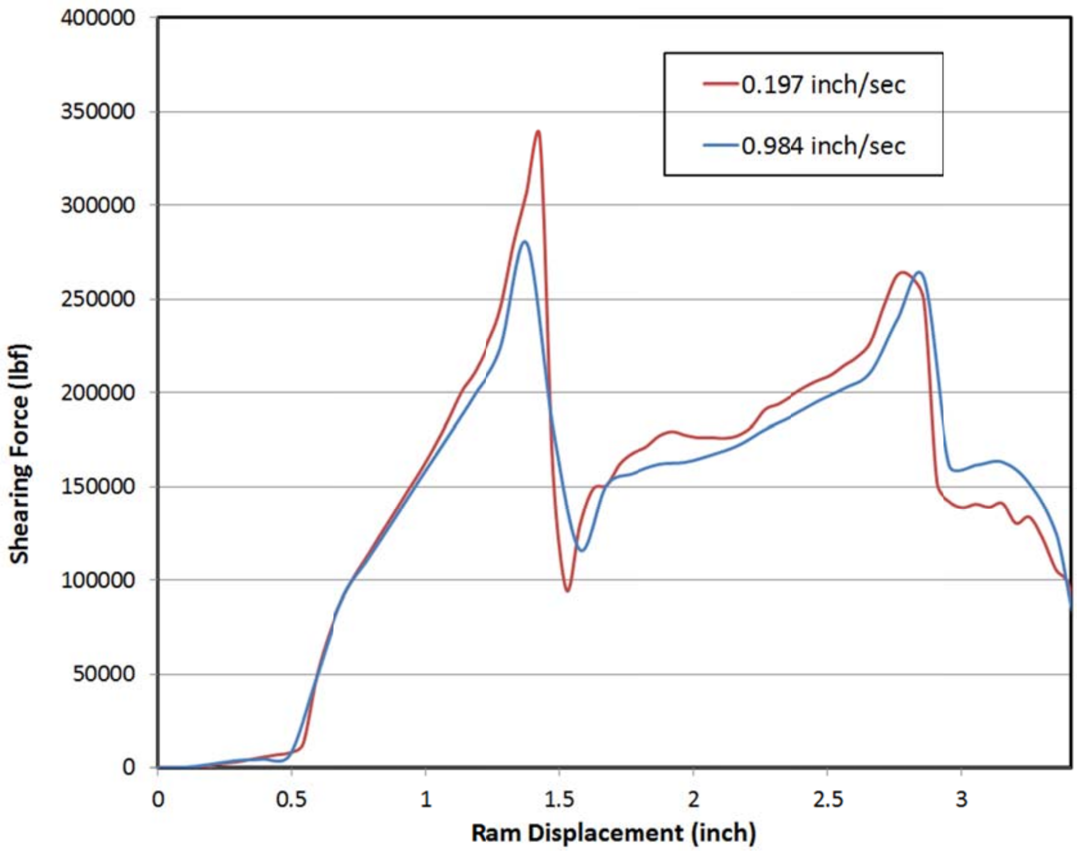


Figure 6.31: Effect of Ram Velocity on Max Shearing Force

6.3.5.3 EFFECT OF LOAD AND DISPLACEMENT CONTROLLED MOTION OF THE RAMS

In the physical test, the shear rams are activated due to the high pressure from accumulators acting on the shear ram piston. The application of pressure is difficult to model in the computer simulation due to the convergence issues and computational demand for larger CPU time. Therefore a constant velocity boundary condition is used in the computer model to replicate the motion of the shear ram motion due to high pressure from the accumulators.

It is observed that the difference in maximum shearing force between the two simulations (applying pressure on the ram and using a constant ram velocity) is around 2%, which is small. In addition, it is found that using the velocity boundary condition for the simulation is computationally more efficient. The final sets of runs are performed by providing a constant velocity for the shear rams. The plot of shearing force with respect to time is shown in Figure 6.32 for the pressure boundary condition applied to shear rams.

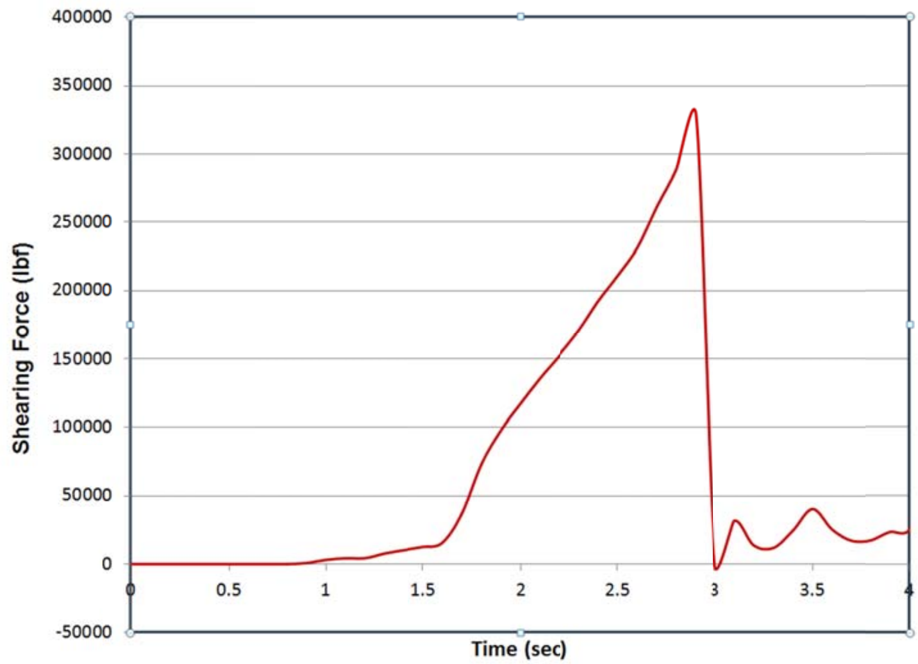


Figure 6.32: Shearing Force Versus Time Plot for Pressure Boundary Condition Applied to Shear Rams

6.3.5.4 SENSITIVITY OF DAMAGE PARAMETERS

As mentioned earlier, the ductile and shear damage parameters are obtained from References 14 and 15. The trend of shear damage initiation data for aluminum material is used as no published data is found for S-135 material. Therefore, the sensitivity of shear damage initiation data on the required maximum shearing force is computed and plotted in Figure 6.33. Based on the difference in damage response of S-135 and aluminum (different fracture strain for a given loading), it is assumed that the S-135 shear damage parameter (fracture strain for a given loading) should be different than aluminum. Therefore two simulations are performed by reducing and increasing the aluminum fracture strain for a given loading by a constant factor of 30%. Figure 6.33 shows the difference in shear force for the two damage data sets. It is observed that increasing the fracture strain by 30%, increases the force required to shear the drill pipe. A 30% higher strain than aluminum is used for the final runs as shown in Figure 6.29. All these sensitivity cases are performed using a higher ram velocity of 0.98 inch/sec to reduce the CPU time. However, this does not affect the relative change in shearing force with respect to variation in shear damage initiation parameter.

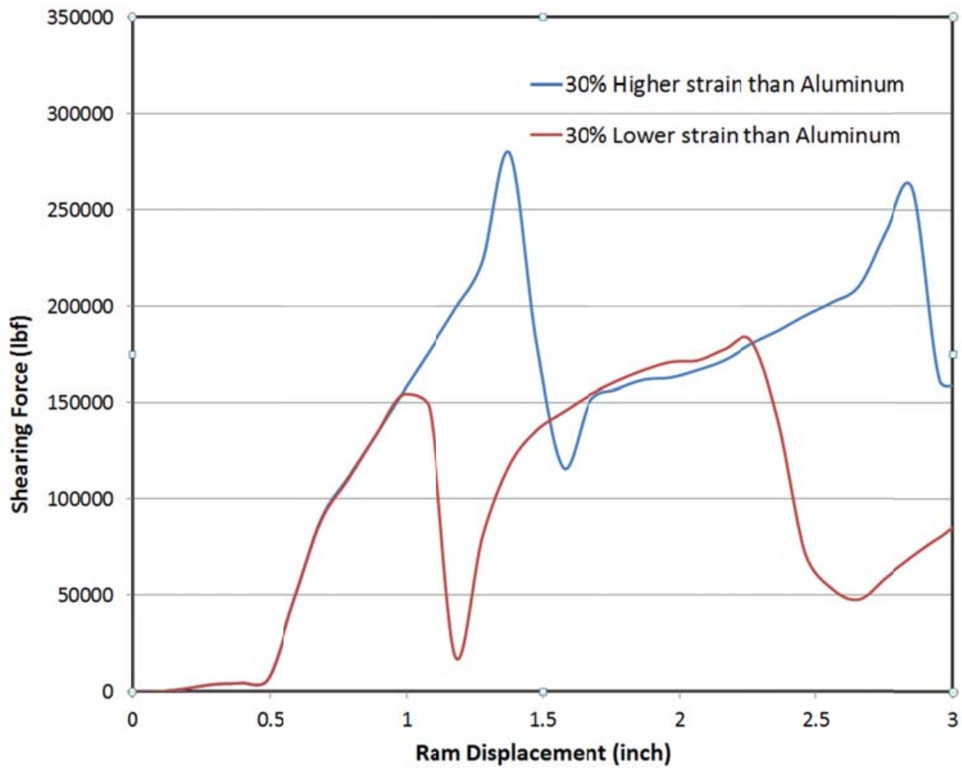


Figure 6.33: Influence of Shear Damage Data on Max Shearing Force

6.3.6 FE Model Validation Results

Simulation is performed for a physical time of about 20 seconds. The drill pipe shows plastic deformation till cracks appear and grow through wall to completely shear the pipe. Thereafter, the upper and lower drill pipe fish are separated and the lower drill pipe fish is further flattened due to the fold-over pocket located between the two shear rams.

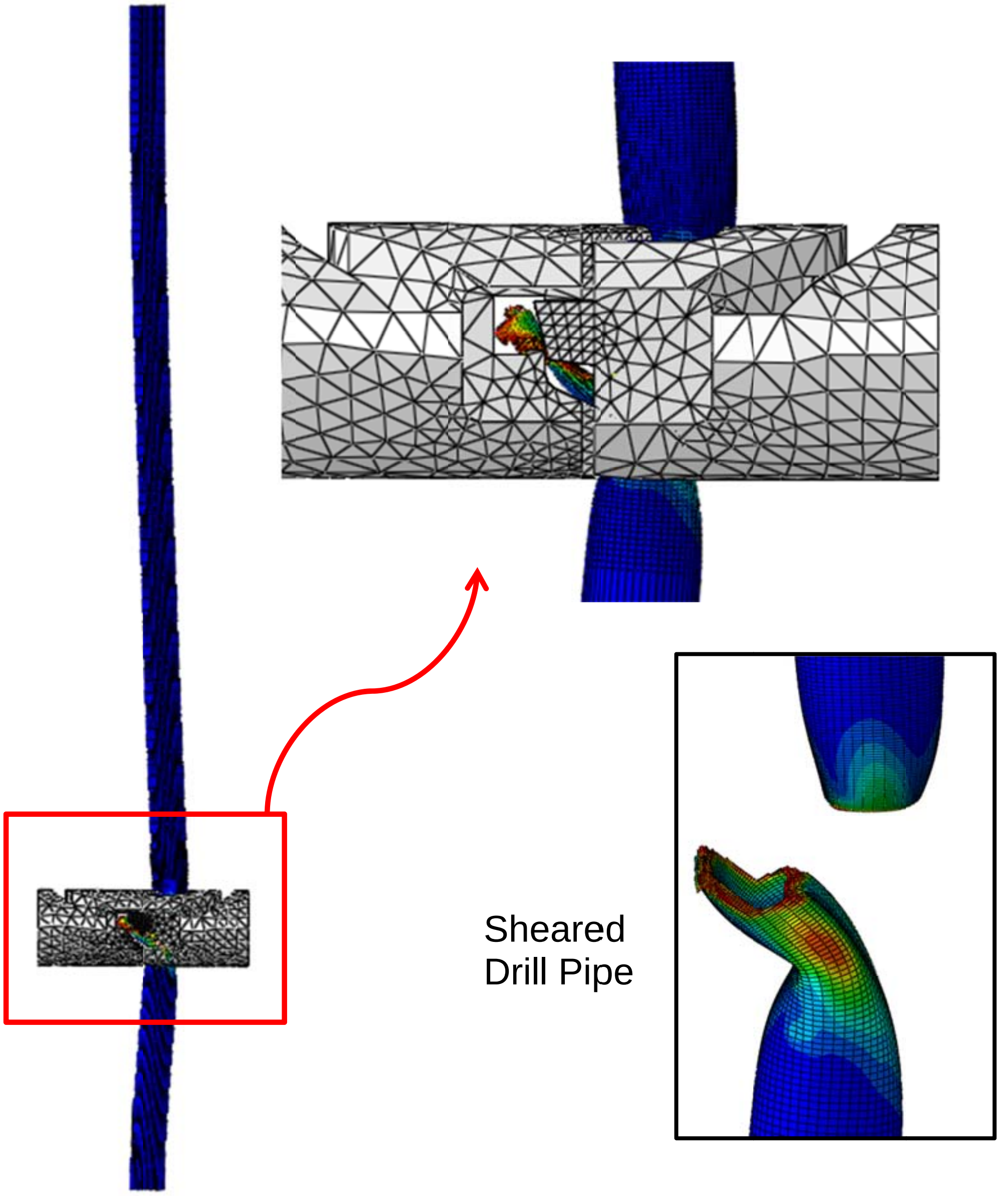


Figure 6.34: Drill Pipe in Sheared Condition

Figure 6.34 shows the shear rams in closed position with the drill pipe. It is observed that, after shearing the upper drill pipe fish is free except being hold on top, while the lower drill pipe fish is stuck between the rams and gets flattened as the rams move further. The lower fish is bent to an angle due to the fold over pocket between the two shear rams (Figure 6.35).

The position of the shear rams and the deformation of the drill pipe for different ram displacements are depicted in Figure 6.36. The drill pipe is centered and its initial position in the

BOP bore as shown in Figure 6.36 (a). The shear rams motion is actuated causing the drill pipe to be deformed initially and sheared as shown in Figure 6.36 (b), (c) and (d). For the same displacements of the shear rams Figure 6.35 provides the deformations of the drill pipe in front view.

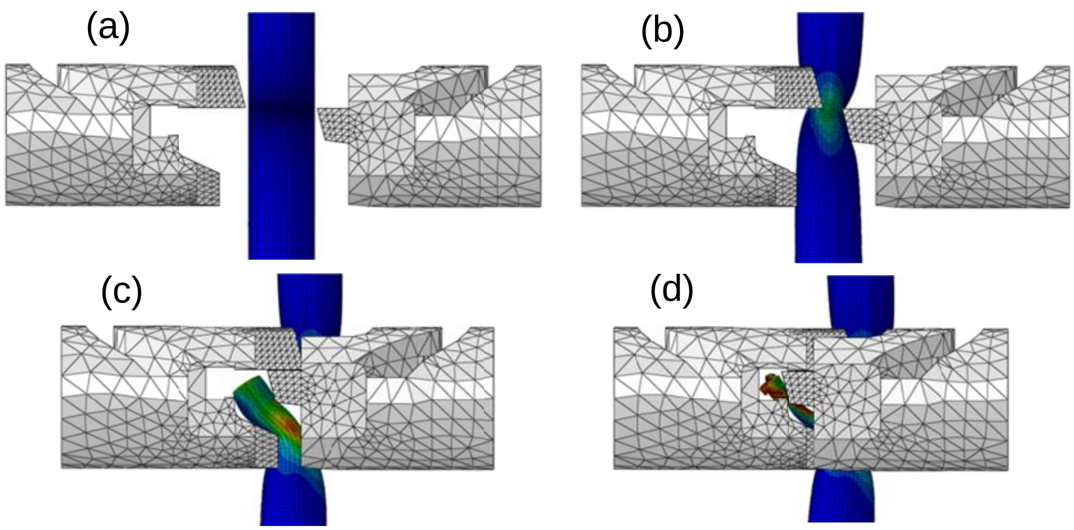


Figure 6.35: Front view, 3.5" Drill Pipe Centered in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 1.38", (c) Ram Displacement = 2.85", (d) Ram Displacement = 3.93"

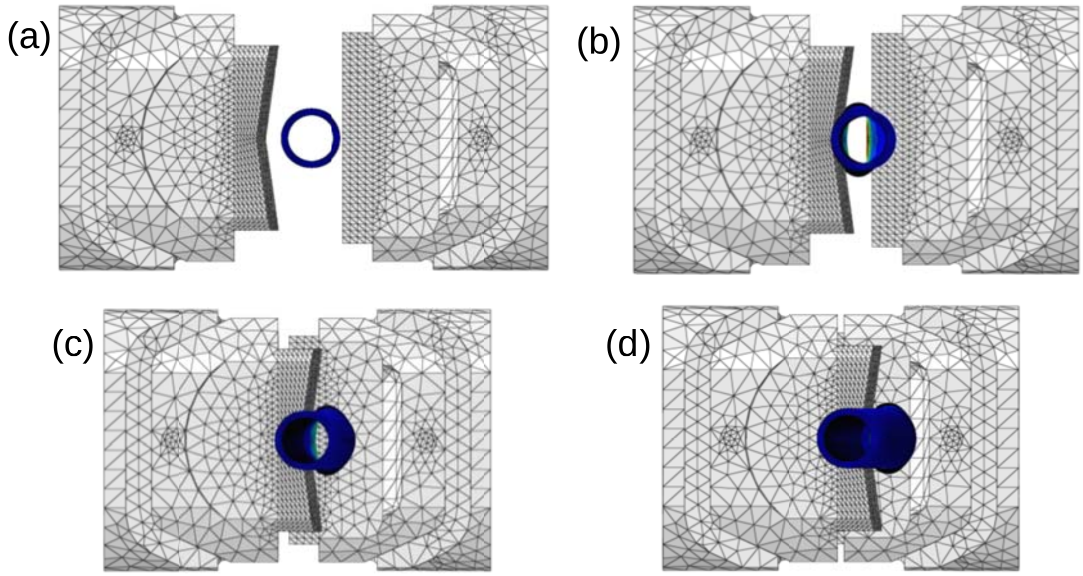


Figure 6.36: Top View, 3.5" Drill Pipe Centered in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 1.38", (c) Ram Displacement = 2.85", (d) Ram Displacement = 3.93"

The cross section of the sheared drill pipe fish from the computer model is shown in Figure 6.37

The dimensions of the upper fish are measured to be 4.17" x 2.16". The dimensions of the upper fish in the physical tests are found to be 4.5" x 2.06". The cross sections of the sheared drill pipe fish from physical test are shown in Figure 6.38 for Test 1 and Figure 6.39 for Test 2. The actual pipe shapes are comparable with that from the simulation. The lower fish is flattened and looks similar to Test 2 (Figure 6.39). The final deformed shape of the bottom drill pipe fish may have slightly varied compared to shop test as elastomers are not provided in the simulation model. The elastomers provide some degree of guidance during deformation and hence influence the deformed shape.

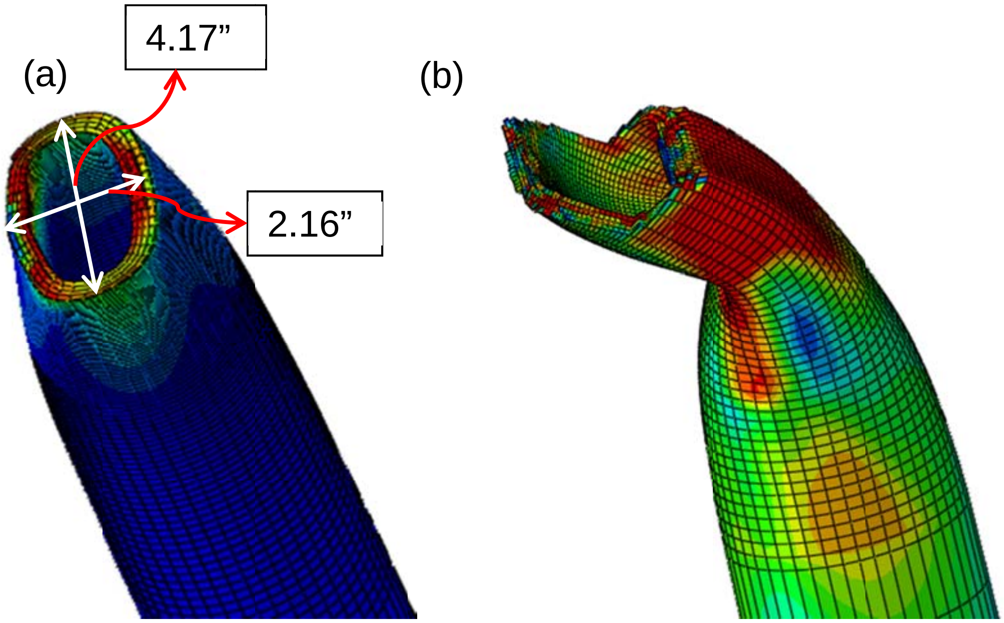


Figure 6.37: Sheared Drill Pipe Cross Sections: (a) Top Fish (b) Bottom Fish

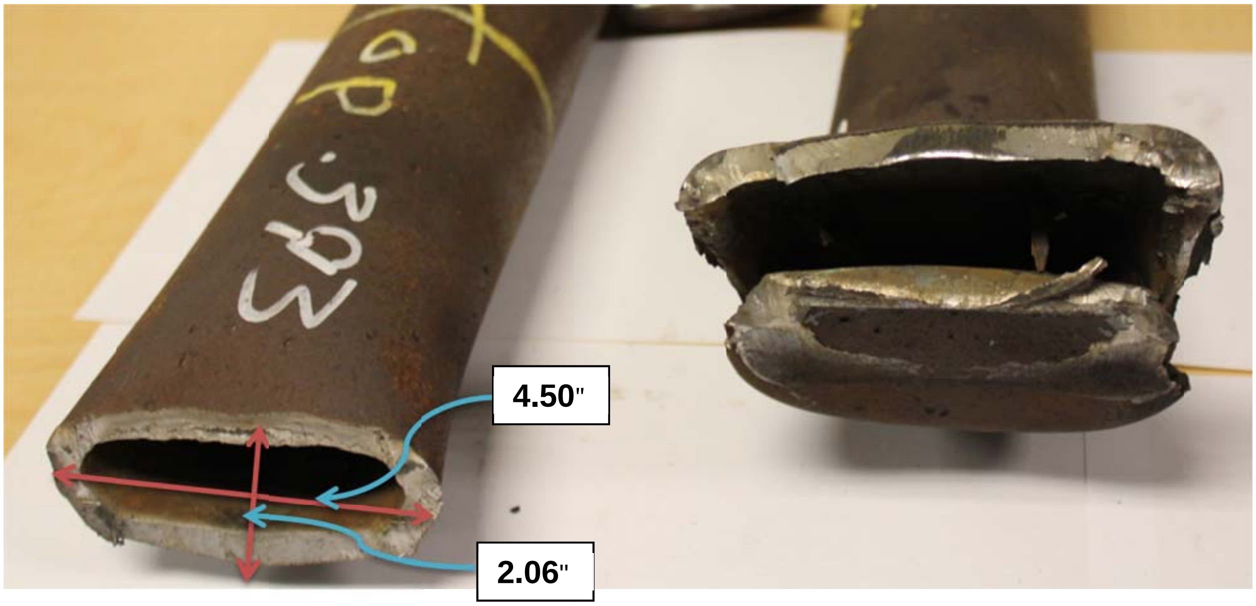


Figure 6.38: Sheared Drill Pipe in Test 1: Left Photo is Top Fish and Right Photo is Bottom Fish

Figure 6.39: Sheared Drill Pipe in Test 2: Bottom Fish

The force required to shear the drill pipe is plotted with respect to the displacement of the ram from its initial position in the simulation model as shown in Figure 6.40. It is observed that the shearing force increases with ram displacement until the drill pipe is sheared and then the force drops abruptly. After shearing the drill pipe, the load on the shear rams was very small until the lower fish gets pinned between the rams. A high force is then required to flatten the lower fish which indicates the second rise in shear force as depicted in Figure 6.40. The maximum shearing force needed to shear the drill pipe is 336,160 lbf which is higher than the maximum shearing force recorded in both the shearing tests (Table 6.5). This in part can be attributed to the lower ram velocity used in the simulation compared to the actual test.

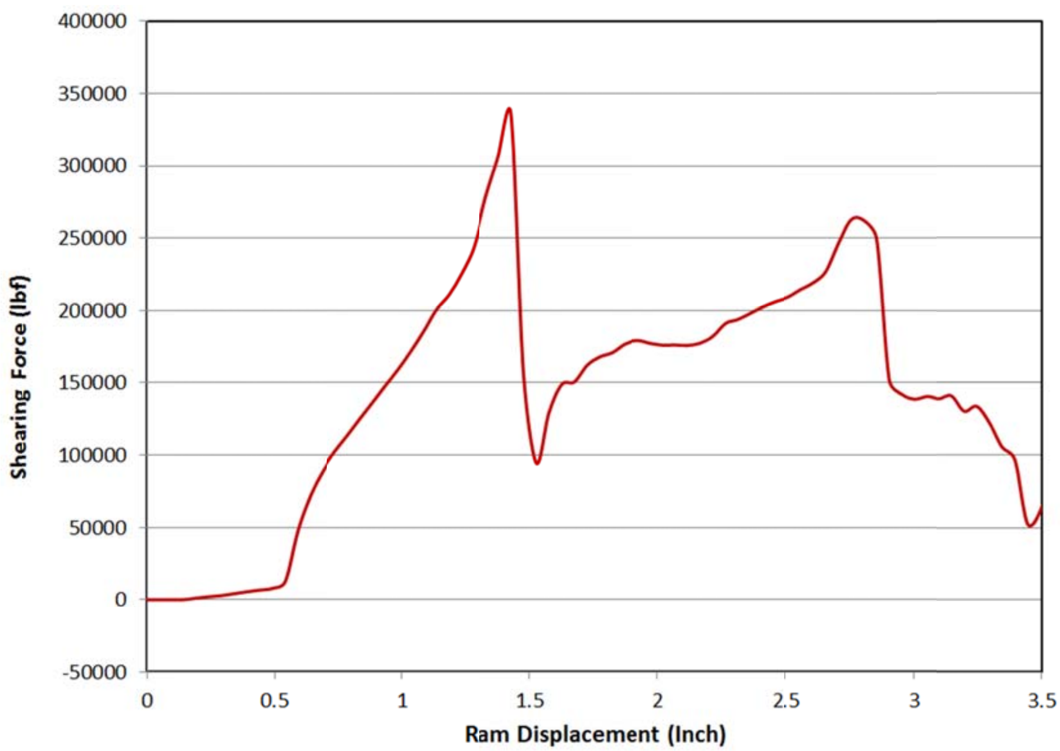


Figure 6.40: Shearing Force vs. Ram Displacement

Table 6.5: Maximum Shear Force from Shop Test and Computer Simulation – 3.5" Pipe

Drill Pipe Outer Diameter OD (Inch)	Shop Test Average of Maximum Shearing force (lbf)	Computer Simulation Maximum Shearing Force (lbf)	OEM Formula (lbf)	% Difference (Test to Computer Simulation)
3.5	296800	336,160	417,984	13.25%

6.3.7 Model Sensitivity to Drill Pipe Size

Computer simulations are also performed with 5.5” and 6.625” drill pipe which are more common in deepwater drilling applications.

A 5.5” S-135 drill pipe having a thickness of 0.361” and 23.9 lb/ft is modeled by centralizing it in the BOP bore. The 9.84 ft drill pipe is positioned in the BOP bore with 7.55 ft above the shear rams as shown in Figure 6.41 (a) which is similar to the validated computer model. The material properties, damage data, contact conditions, boundary conditions used for the drill pipe are the same as the ones used in the validation study (refer to Section 6.3.4). An 8-node linear brick element with reduced integration and stiffness hourglass control is used to mesh the drill pipe. Element deletion feature is turned On and maximum degradation is set to 1. A global mesh size of 3.93” is specified with 4 layers of elements are provided along the thickness and 64 elements across the circumference of the pipe. A finer mesh (0.035”) is generated in the region of shearing and is gradually coarsened (1.18”) towards either side of the drill pipe. The translational degrees of freedom for the top and bottom of the drill pipe are fixed. Figure 6.41 (a) and (c) shows the front and top views of 5.5” drill pipe centralized in the BOP bore.

The shear rams used in the validating study (refer to Section 6.3) is used for the simulation. The material properties, contact and boundary conditions are also the same as in the validation study. A 4-node linear tetrahedron with a finer mesh size of 0.39” is used for the blades and a coarser mesh size of 3.93” is used for other regions of shear rams. Instead of placing the shear rams outside of the BOP bore as in shop test, the initial position is close to the drill pipe as the major focus is to compute the force required to shear the drill pipe. This will reduce the stroke of the shear ram and computational time for the simulation without having any impact on the solution. The shear rams are allowed to move only in the x-direction with a velocity of 0.197 inch/sec similar to the test.

A 6.625” S-135 drill pipe having a thickness of 0.362” and 27.7 lb/ft is modeled by centralizing in the BOP bore. The model set up is very similar to that of the 5.5” case, with the same meshing parameters, boundary and contact conditions. Initially the rams are placed close to the drill pipe as shown in Figure 6.41 (d).

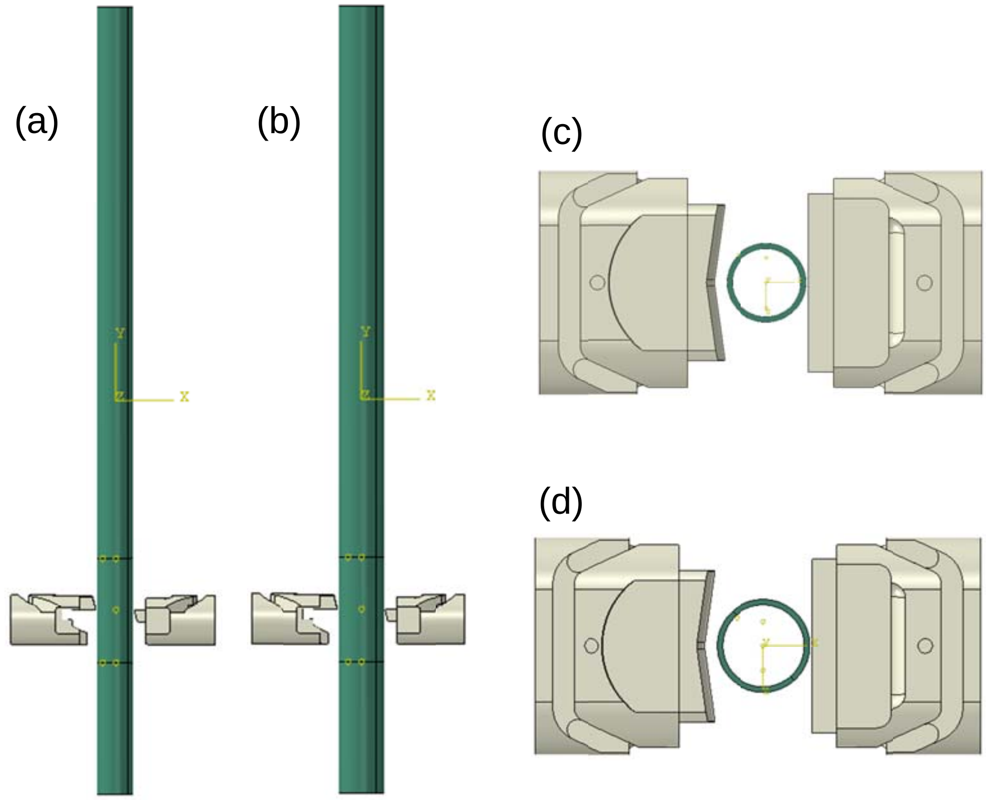


Figure 6.41: Drill Pipe Centralized in 13.625" BOP Bore (a) Front View 5.5" Drill Pipe, (b) Front View 6.625" Drill Pipe, (c) Top View 5.5" Drill Pipe, (d) Top View 6.625" Drill Pipe

Stroke length is the distance travelled by each ram during the shearing process. Compared to the shop test, the computer model has shorter stroke lengths as the shear rams are placed close to the drill pipe. Simulations are performed for each drill pipe until the shear rams complete the entire stroke. The stroke length is based on the diameter of drill pipe, as larger diameter drill pipe have larger stroke length.

The position of the shear rams and shape of 5.5" drill pipe at different time intervals during the shearing process is captured in front and top views as shown in Figure 6.42 and Figure 6.43 respectively. Initially the drill pipe is deformed and then the shearing process takes place separating the top and bottom parts of drill pipe as shown in Figure 6.42 (b). The sheared bottom part is further bent as shown in Figure 6.42 (c) and finally gets stuck between the shear ram blades.

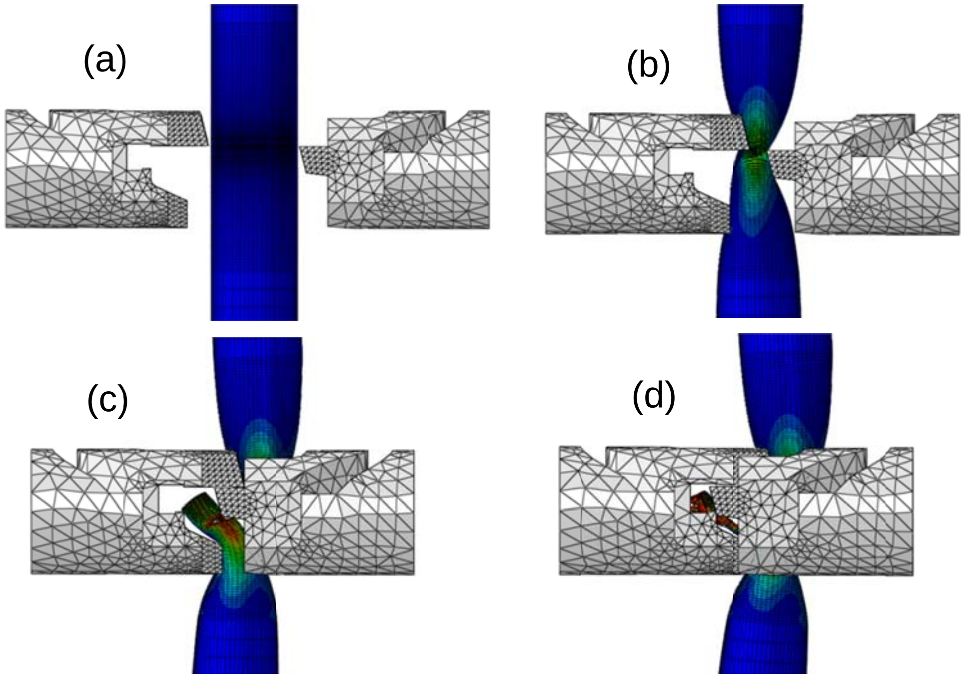


Figure 6.42: Front View, 5.5" Drill Pipe Centered in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.36", (c) Ram Displacement = 3.83", (d) Ram Displacement = 5.0"

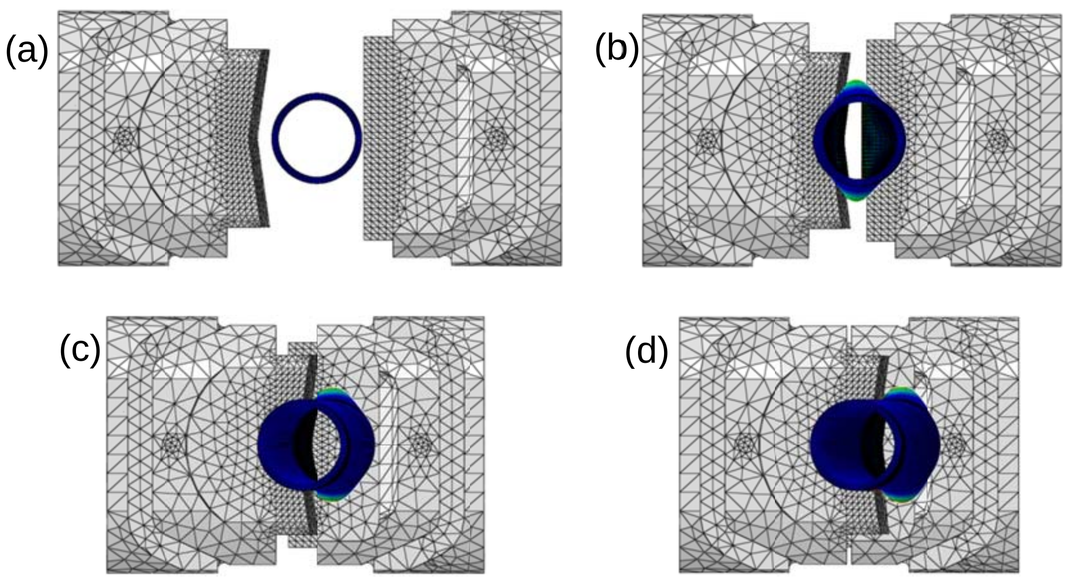


Figure 6.43: Top View, 5.5" Drill Pipe Centered in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.36", (c) Ram Displacement = 3.83", (d) Ram Displacement = 5.0"

The final shape of the sheared drill pipes are shown in Figure 6.44. It is observed that the bottom drill pipe have a piece broken at the region where the lower ram touches the drill pipe. The top drill pipe cross section is elliptical in shape and the measurements are shown in Figure 6.44 (c).

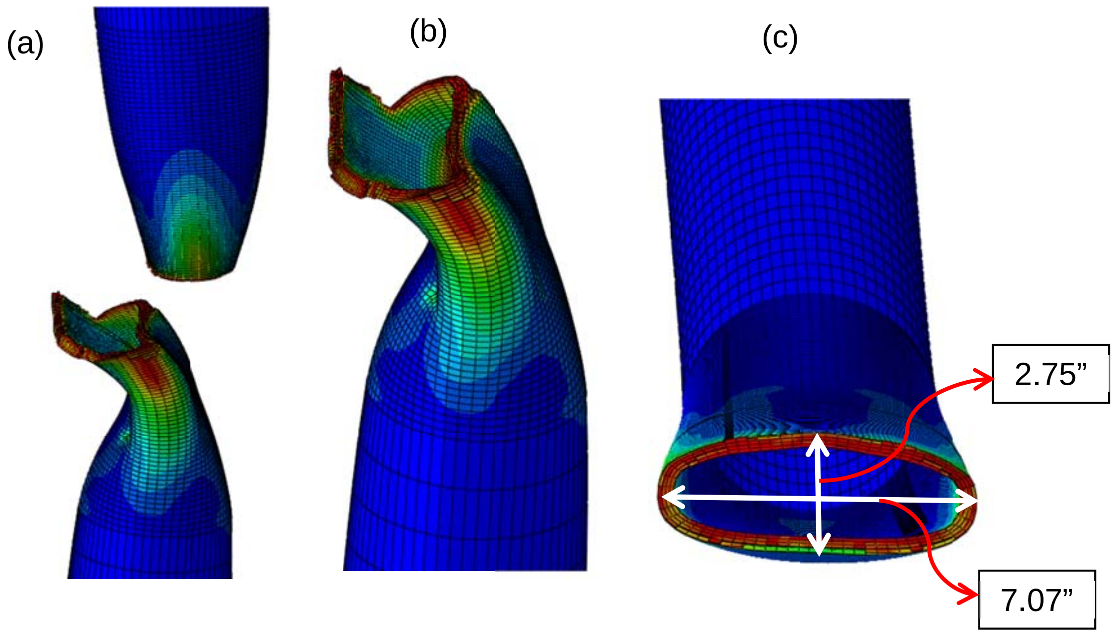


Figure 6.44: Sheared 5.5” Drill Pipe (a) Top and Bottom Pipe, (b) Bottom Drill Pipe, (c) Top Drill Pipe with Sheared Cross Section

The position of the shear rams and shape of 6.625” drill pipe at different time intervals during the shearing process is captured in front and top views as shown in Figure 6.45 and Figure 6.46 respectively. Similar to the 5.5” drill pipe the drill pipe initially deforms and the shearing occurs. The deformed top drill pipe section undergoes very little additional deformation while the bottom pipe is bent and flattened as it gets stuck between the lower lip of upper ram and blade of the lower ram as shown in Figure 6.45 (c) and (d).

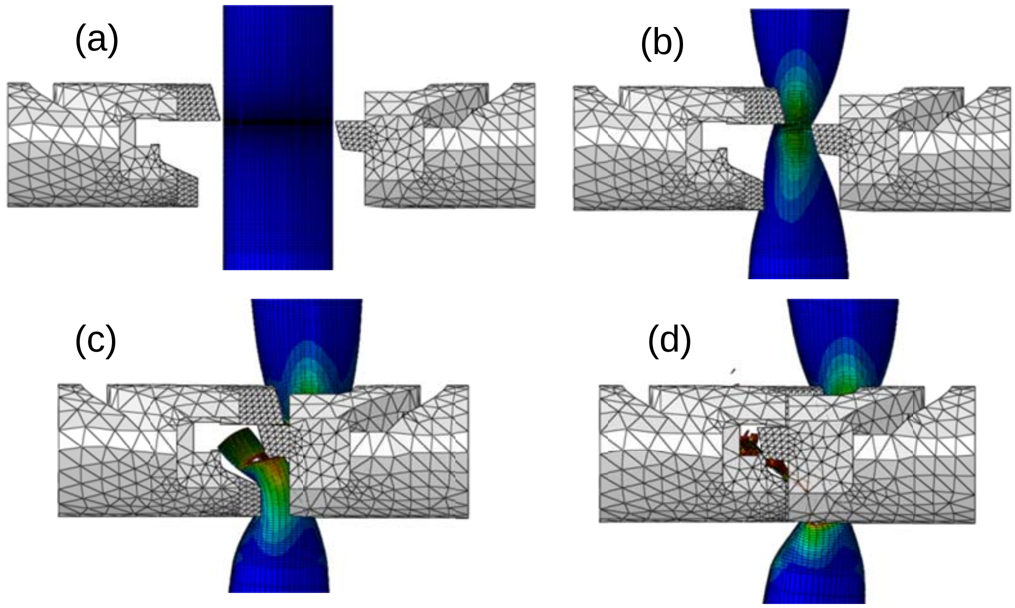


Figure 6.45: Front View, 6.625" Drill Pipe Centralized in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.75", (c) Ram Displacement = 4.33", (d) Ram Displacement = 6.05"

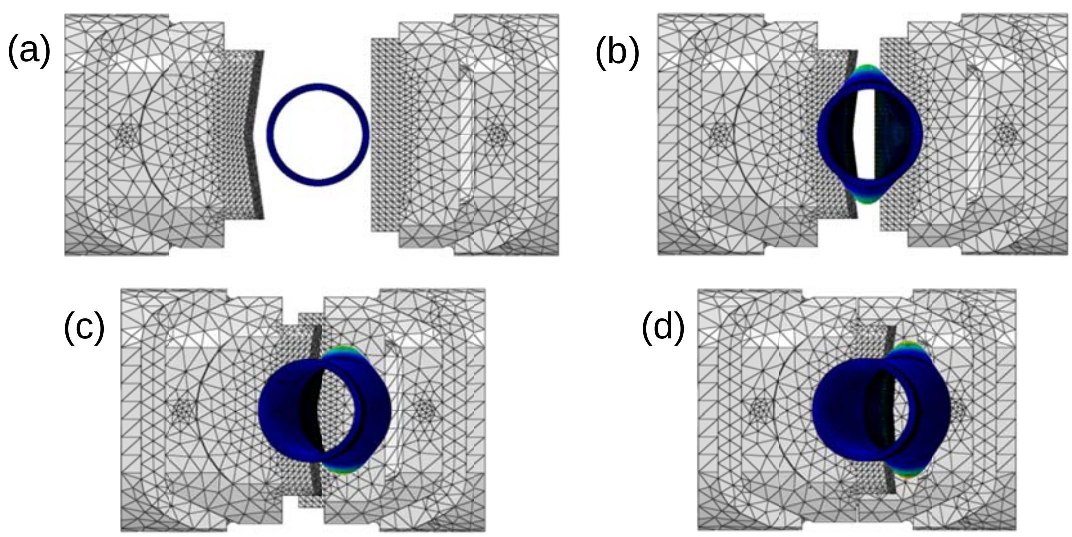


Figure 6.46: Top View, 6.625" Drill Pipe Centralized in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.75", (c) Ram Displacement = 4.33", (d) Ram Displacement = 6.05"

The sheared drill pipes are shown in Figure 6.47. It is observed that a piece of the bottom drill pipe gets separated during the bending process and a crack is found to be propagating along the circumference as shown in Figure 6.47 (b). Top drill fish is deformed to an elliptical shape and the dimensions of the sheared cross section are provided in Figure 6.47 (c).

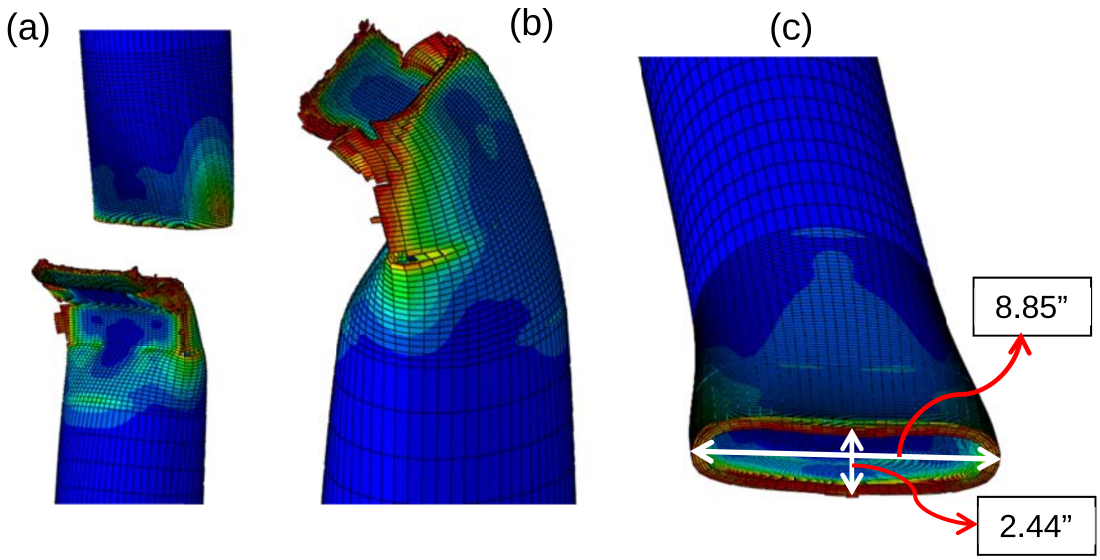


Figure 6.47: Sheared 6.625” Centralized Drill Pipe (a) Top and Bottom Pipe, (b) Bottom Drill Pipe, (c) Top Drill Pipe with Sheared Cross Section

Figure 6.48 shows the plot of average shearing force versus ram displacement for 3.5”, 5.5” and 6.625” drill pipes centralized in the BOP bore. The force data for 3.5” drill pipe is taken from the validation study (refer to Section 6.3.6). It is observed that the force rises with respect to ram displacement during the deformation of drill pipe and the force is a maximum when shearing occurs. After shearing, force drops abruptly to a lower value and again rises during the bending of bottom drill pipe. This trend is observed for all three drill pipes under consideration and the maximum shearing force increases with respect to drill pipe diameter. Figure 6.48 also shows the maximum shearing force obtained from OEM formula for each of the drill pipes. Based on the input available, either of the two formulas is used. If both equations are used, the one that provides higher shear force is considered to be conservative.

PPF Method: Used for maximum shear force computation if nominal weight of the tubular is known

$$P_{shear} = \frac{[C_3 * ppf * \sigma_{yield}]}{C_1} \qquad \text{(No well bore pressure)}$$

$$P_{shear} = \frac{[C_3 * ppf * \sigma_{yield}] + [P_w * C_2]}{C_1}$$ (Including well bore pressure (psi))

Dimensional Method: Used for maximum shear force computation if drill pipe inner and outer diameter are known.

$$P_{shear} = \frac{[(C_3 * \sigma_{yield})(OD^2 - ID^2) * 2.92]}{C_1}$$ (No well bore pressure)

$$P_{shear} = \frac{[(C_3 * \sigma_{yield})(OD^2 - ID^2) * 2.92 + P_w * C_2}{C_1}$$ (Including well bore pressure (psi))

Where,

C_1 is the BOP/Operator constant. This corresponds to the piston closing area (in^2)

C_2 is the BOP/Operator constant. This corresponds to the operator piston rod cross sectional area (in^2)

C_3 is the shear ram type/pipe grade constant. This is an empirical constant obtained from laboratory testing with various pipe grades and ram types.

σ_{yield} is the minimum yield strength of the tubular material

ppf is the nominal weight of the tubular (pounds per foot)

OD is the pipe outside diameter (in)

ID is the pipe inside diameter (in)

For the three drill pipe sizes considered, maximum shearing force computed using OEM formulae is higher than the simulation model. The OEM formulae are believed to be conservative. The percentage difference in shear force between the OEM and simulation model is provided in Table 6.6.

Table 6.6: Comparison of FEA Max. shearing force with OEM Max. shearing force

Drill Pipe Diameter OD (inch)	FE Analysis Max. Shearing Force (lbf)	OEM Formula Max. Shearing Force (lbf)	% Difference
3-1/2	336,160	417,984	24.34
5-1/2	584,255	702,338	20.21
6-5/8	668,842	886,016	32.47

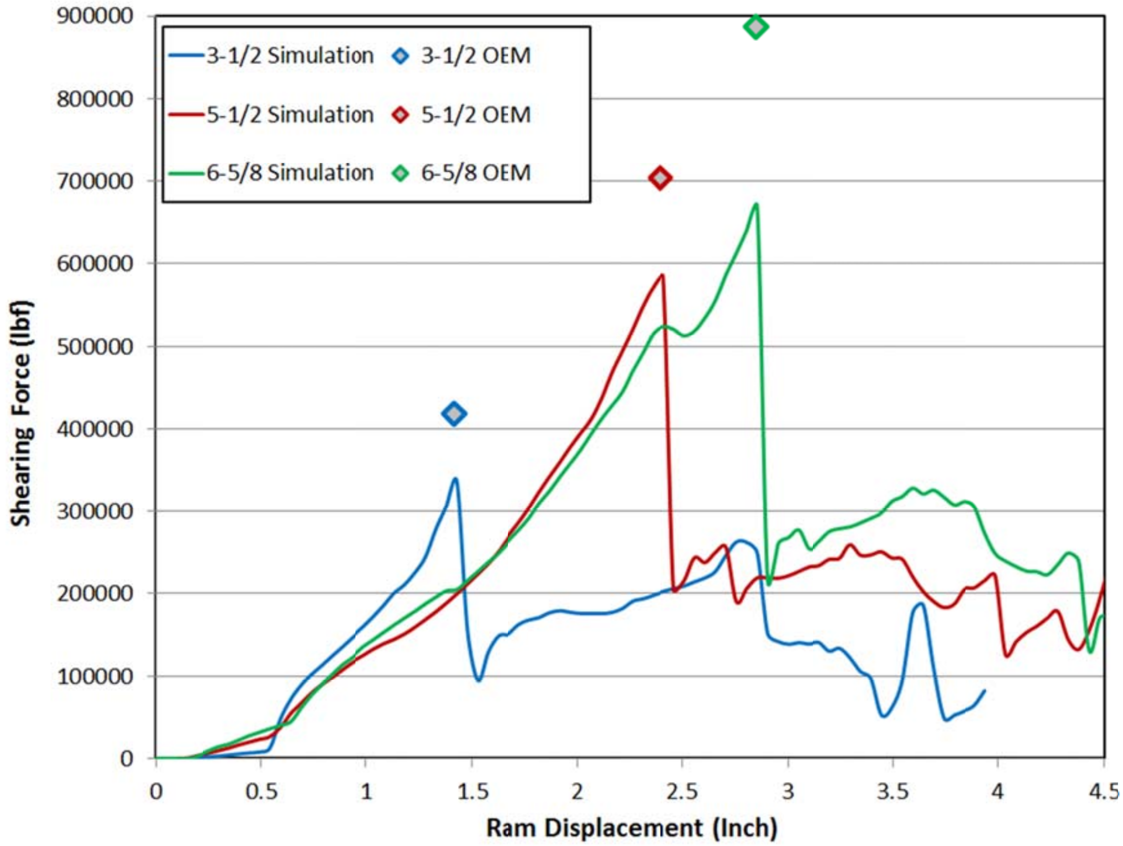


Figure 6.48: Shearing Force Versus Ram Displacement for Different Drill Pipe sizes and Comparison with OEM Max. Shearing Force

7.0 SHEAR RAM PERFORMANCE EVALUATION

7.1 INTRODUCTION

The developed benchmark model is used as a base case for running additional studies to understand the effect of the following parameters on the shearing process:

- Drill pipe position
- Effect of pre-load
- Flowing well condition / Effect of well bore pressure

Each case is evaluated by comparing the shear force with the benchmark (centralized with no pre-load and no fluid flow). Throughout this study, 13-5/8” BOP model is used.

7.2 DRILL PIPE POSITIONING WITHIN WELL BORE

This section focusses on various possible positions of the drill pipe within the BOP bore and its effect on the shearing process. Three different drill pipe positions within the well bore are considered and listed below.

1. Non-centralized drill pipe parallel to shear ram blades
2. Non-centralized drill pipe positioned towards upper (or) lower ram
3. Drill pipe oriented at an angle with respect to well bore

Simulations are performed to assess the shearing performance and maximum shearing force requirements. In the first case, the drill pipe is positioned to the extreme end of the BOP bore (touching the wall of BOP) parallel to the lower ram blade as shown in Figure 7.1(a). In the second case again the drill pipe is positioned to the extreme end of the BOP bore (touching the wall of BOP) towards the shear rams shown in Figure 7.1 (b). In the third case the drill pipe is positioned at an angle with respect to the BOP bore to study its effect on the shearing process (Figure 7.1(c) and (d)).

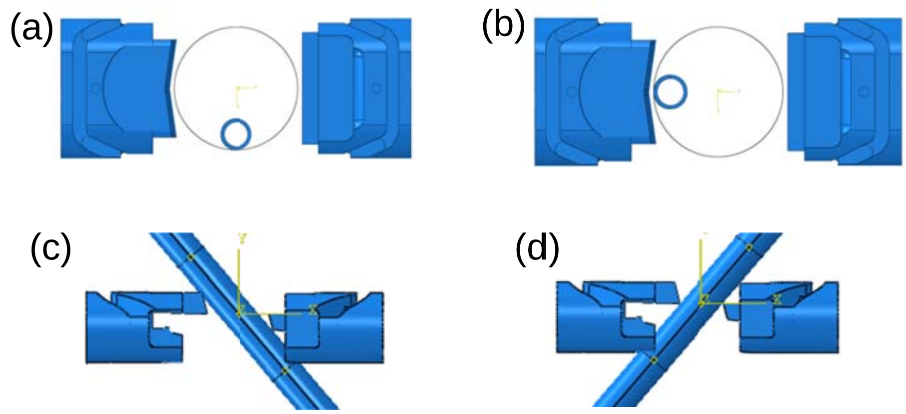


Figure 7.1: Drill pipe positioning within well bore, (a) Non-centralized drill pipe parallel to shear ram blades, (b) Non-centralized drill pipe positioned towards upper ram, (c) Drill pipe oriented 40 degrees anti-clockwise with respect to well bore, (d) Drill pipe oriented 40 degrees clockwise with respect to well bore

The material properties, boundary conditions, contact conditions are the same as the centralized cases. The element size and type are the same as used for the Centralized drill pipe under no-flow condition. A constant velocity of 0.197 inch/sec is provided to the shear rams. This velocity is used to represent the same speed of the rams as in the shear test.

7.2.1 Non-Centralization of Drill Pipe Parallel to Shear Ram Blades

The methodology and model set up are similar to the centralized no-flow cases except the drill pipe is positioned to the extreme end of the BOP bore and parallel to the Lower Ram blade as shown in Figure 7.2. The effect of non-centralization of the drill pipe on the shearing process and maximum shearing force requirements are analyzed.

Figure 7.2 shows the assembly of model in front and top views for 3.5", 5.5" and 6.625" non-centralized cases. For all the cases, the drill pipe is positioned such that it touches the wall of the BOP bore. In the simulation only the drill pipe and shear rams are modeled, BOP bore is not considered. Therefore no contact modeling is required between the drill pipe and BOP bore. Similar to the centralized cases, the shear rams are initially positioned close to the drill pipe. The top and bottom of the drill pipe are fixed and the shear rams are allowed to move only in the x-direction and all other degrees of freedom are fixed.

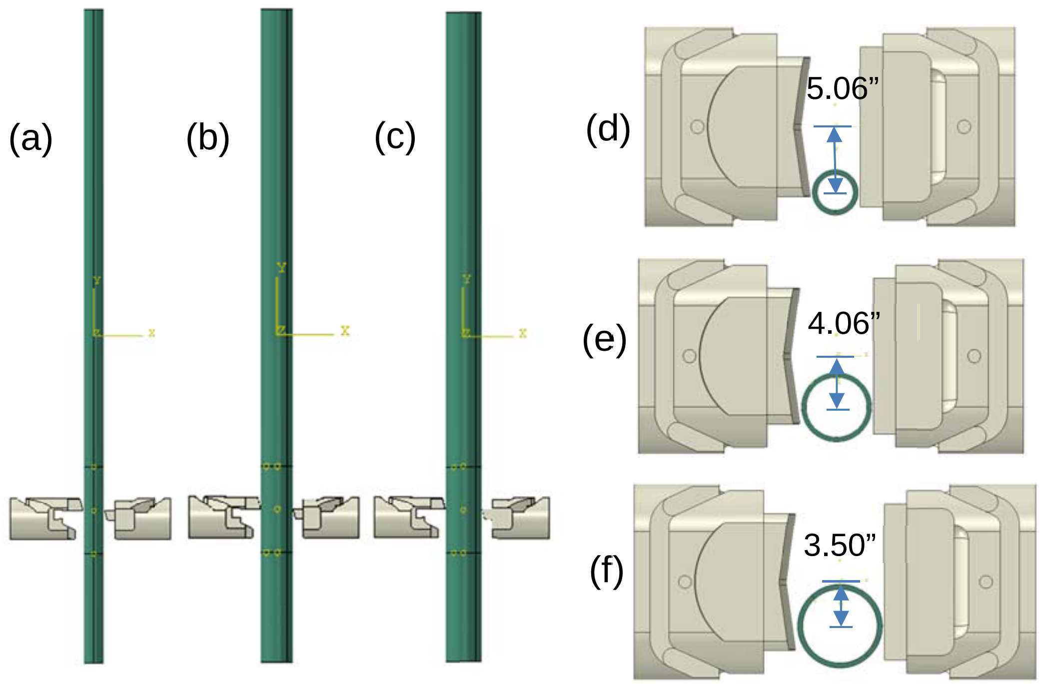


Figure 7.2: Non-centralized Drill Pipe Shear Ram Assembly (a) Front View 3.5” Drill Pipe, (b) Front View 5.5” Drill Pipe, (c) Front View 6.625” Drill Pipe, (d) Top View 3.5” Drill Pipe, (e) Top View 5.5” Drill Pipe, (f) Top View 6.625” Drill Pipe

The position of the shear rams and the shape of 3.5” drill pipe non-centralized in the BOP bore at different time intervals during the shearing process is captured in front and top views as shown in Figure 7.3 and Figure 7.4. The upper ram V-blade width is less than the BOP bore diameter and it does not cover the entire bore. Therefore the upper ram comes in contact with only a part of the drill pipe making it difficult to shear. Most of the time a crack propagates through the remaining cross section of drill pipe to separate the top and bottom drill pipe surfaces.

During the shearing process the corner of upper ram and flat blade of the lower ram comes in contact with the drill pipe. After initial deformation, the upper ram pierces through the drill pipe causing the shearing. After shearing the top drill pipe comes in contact with other features of the shear rams causing it to deform further as shown in Figure 7.4 (c), (d) and Figure 7.5 (a).

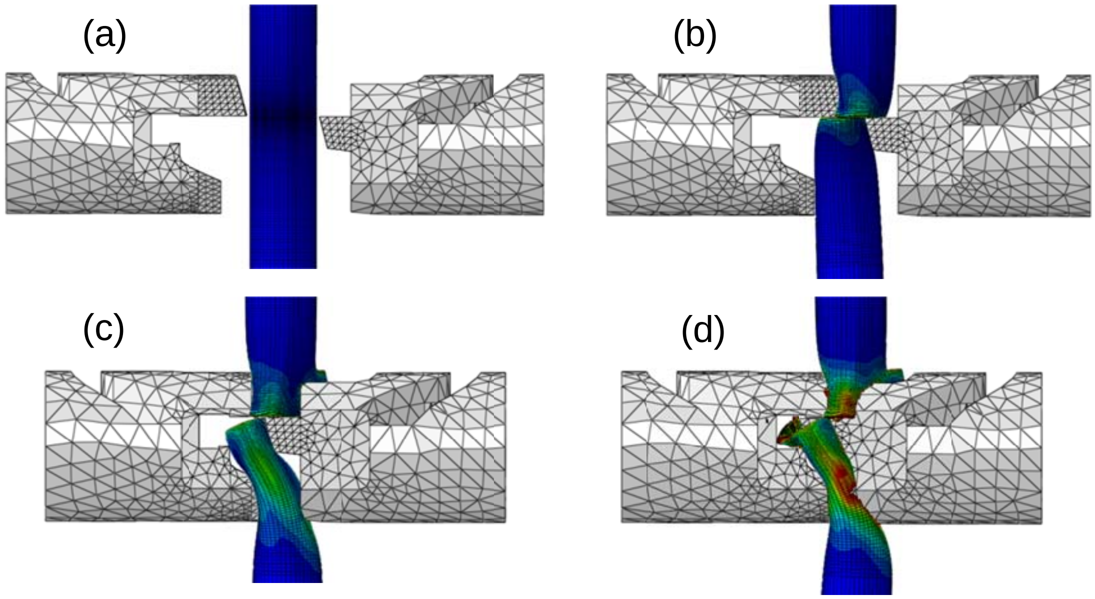


Figure 7.3: Front View, 3.5” Drill Pipe 5.06” Away from Center of BOP (a) Ram Displacement = 0, (b) Ram Displacement = 1.38”, (c) Ram Displacement = 2.85”, (d) Ram Displacement = 3.93”

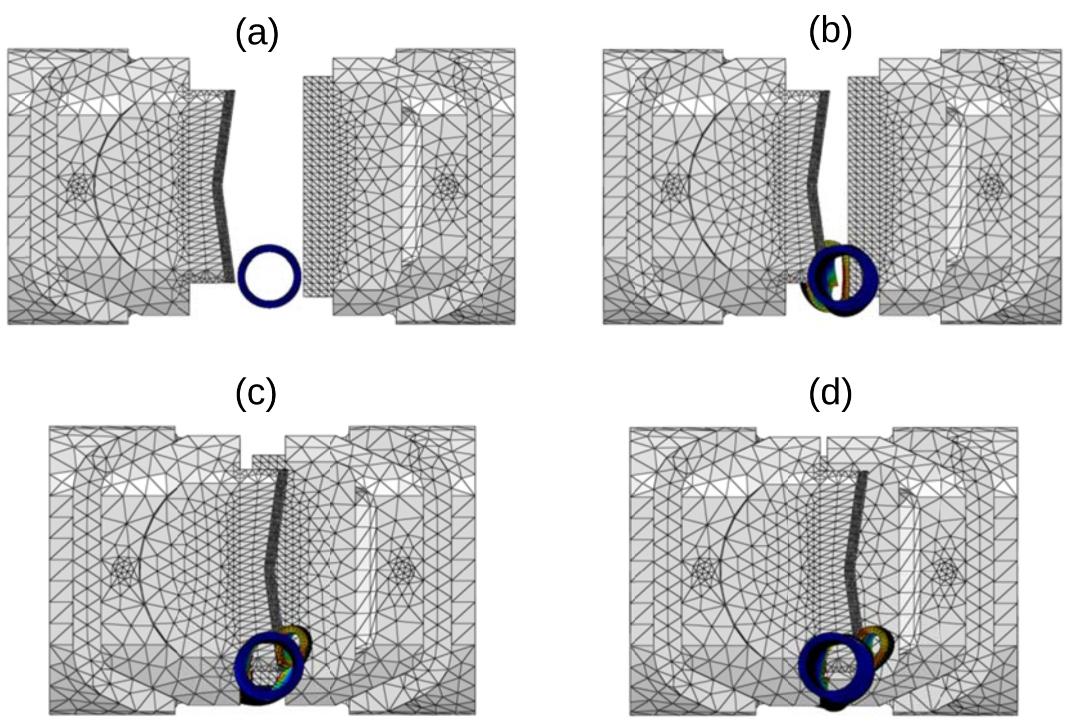


Figure 7.4: Top View, 3.5” Drill Pipe 5.04” Away from Center of BOP (a) Ram Displacement = 0, (b) Ram Displacement = 1.38”, (c) Ram Displacement = 2.85”, (d) Ram Displacement = 3.93”

Figure 7.5 shows the final deformed shapes of the top and bottom drill pipes. The sheared drill pipes are deformed based on the shear ram features that come in contact with the drill pipe.

The position of the shear rams and the shape of 5.5" drill pipe non-centralized in the BOP bore at different time intervals during the shearing process is captured in front and top views as shown in Figure 7.6 and Figure 7.7 respectively.

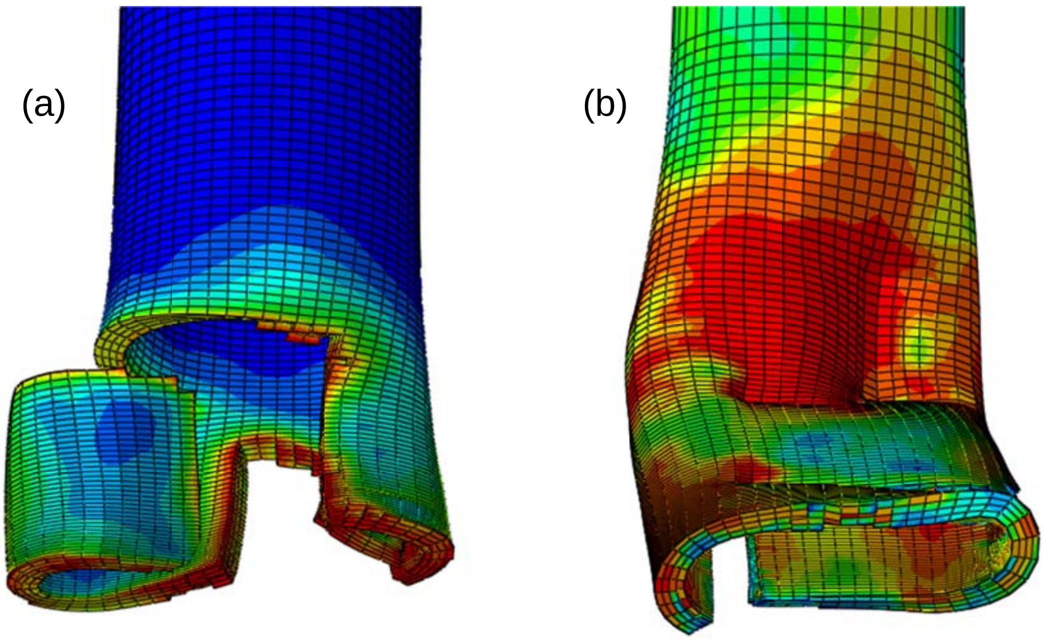


Figure 7.5: Sheared of 3.5" Drill Pipe Fish for Non-Centralized Pipe (5.04" from BOP Center) (a) Top Fish (b) Bottom Fish

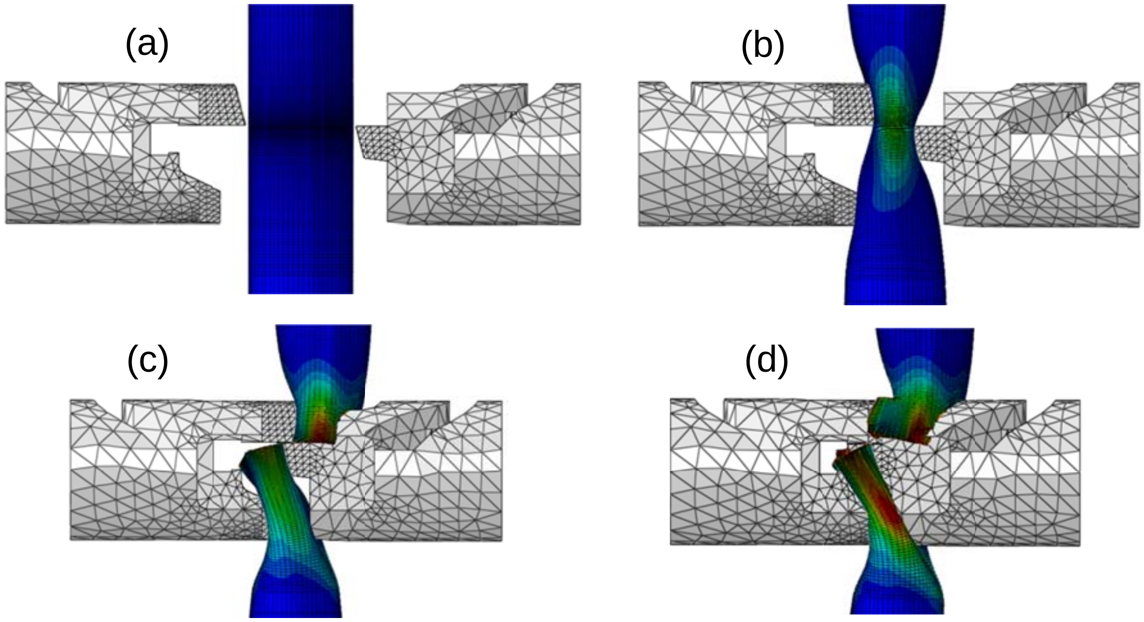


Figure 7.6: Front View, 5.5" Drill Pipe Non-Centered in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.16", (c) Ram Displacement = 3.84", (d) Ram Displacement = 4.82"

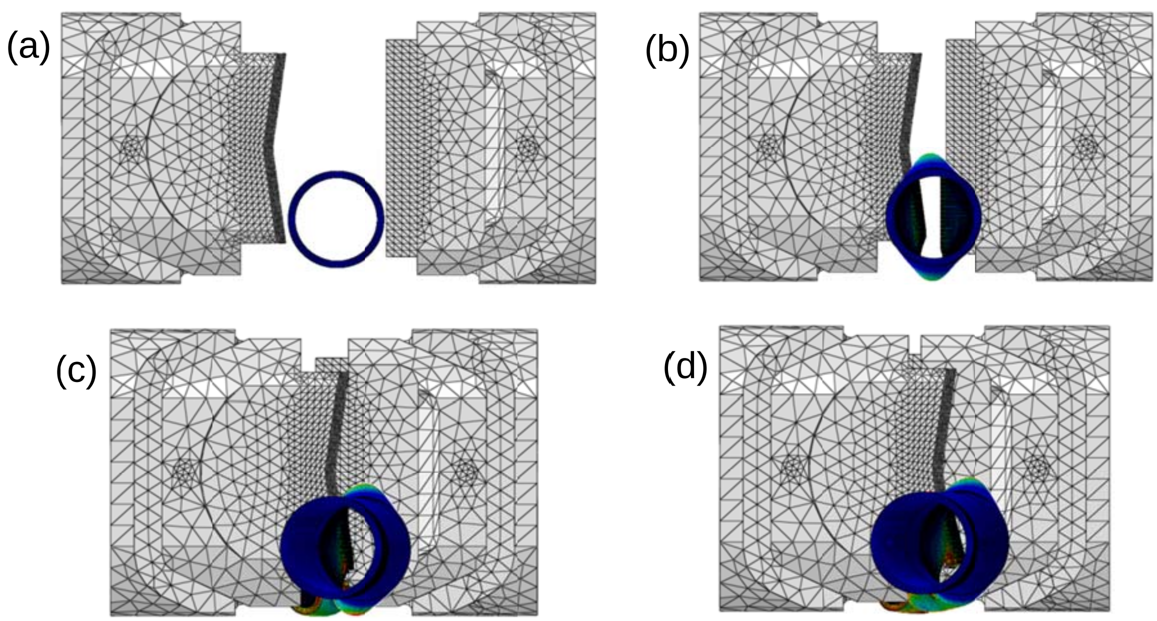


Figure 7.7: Top View, 5.5" Drill Pipe Non-Centered in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.16", (c) Ram Displacement = 3.84", (d) Ram Displacement = 4.82"

Figure 7.8 shows the final deformed shape of top and bottom drill pipes. There is an impression of the upper ram on the bottom part of the pipe. The remaining area (without shear ram impression) gets sheared based due to crack propagation. The sheared top pipe gets further deformed due to the obstruction of other shear ram features.

The position of the shear rams and the shape of 6.625" drill pipe non-centralized in the BOP bore at different time intervals during the shearing process is captured in front and top views as shown in Figure 7.9 and Figure 7.10 respectively.

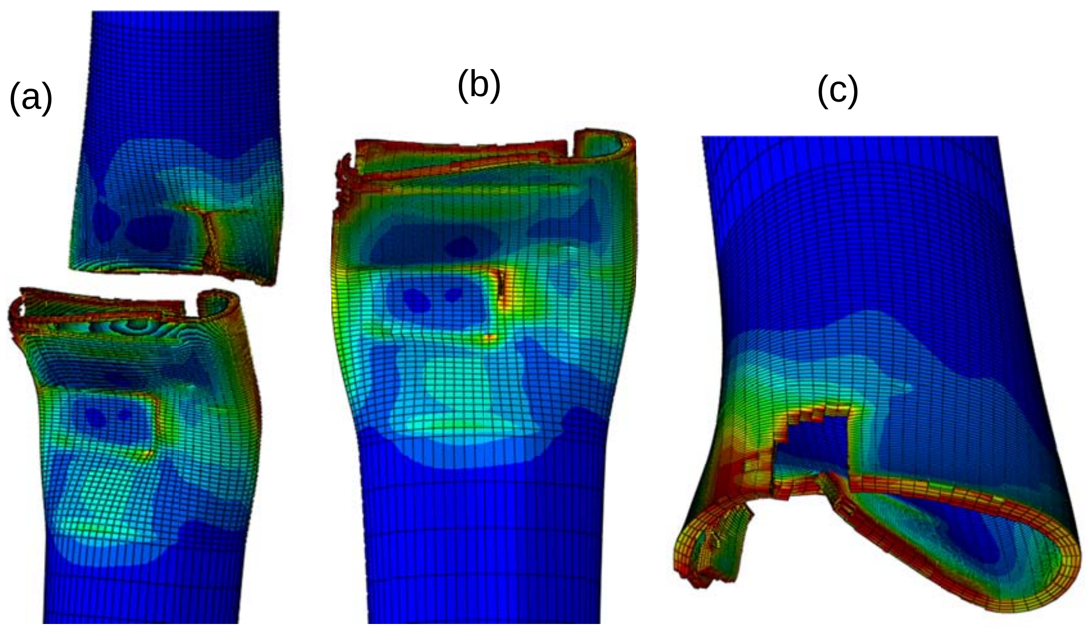


Figure 7.8: Sheared 5.5" Drill Pipe (a) Top and Bottom Pipe, (b) Bottom Drill Pipe, (c) Top Drill Pipe with Sheared Cross Section

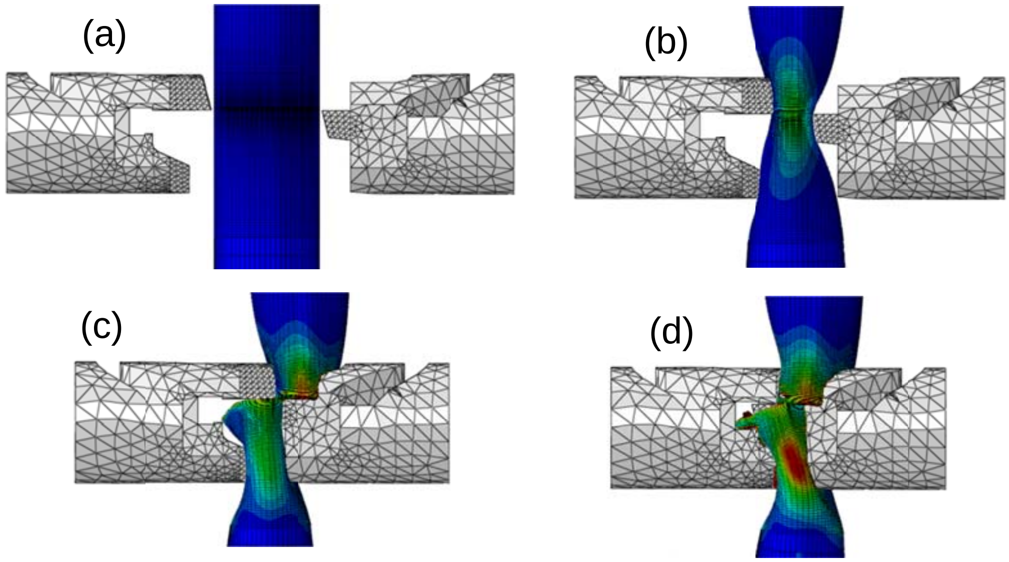


Figure 7.9: Front View, 6.625" Drill Pipe Non-Centralized in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.66", (c) Ram Displacement = 4.33", (d) Ram Displacement = 5.70"

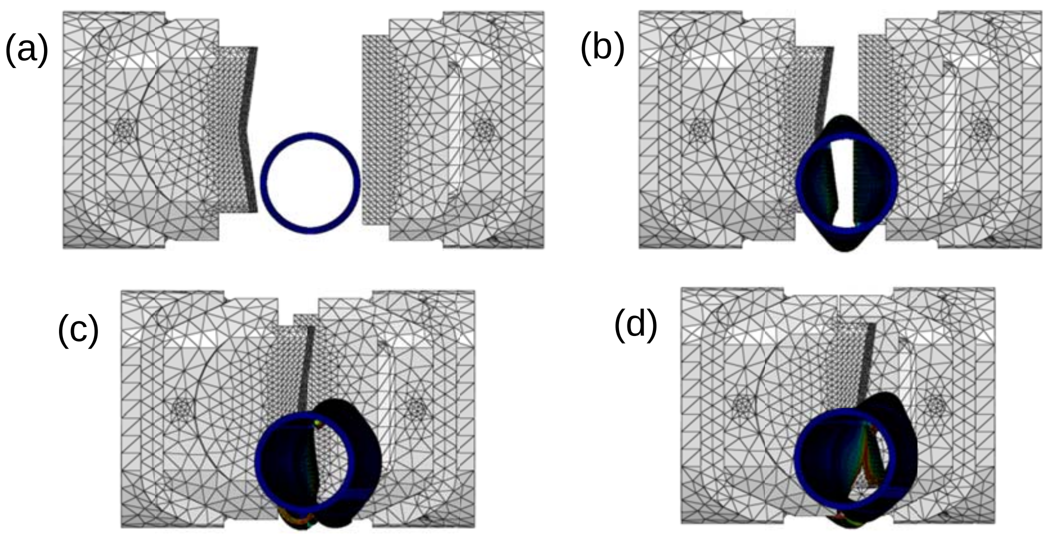


Figure 7.10: Top View, 6.625" Drill Pipe Non-Centralized in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.66", (c) Ram Displacement = 4.33", (d) Ram Displacement = 5.70"

Figure 7.11 shows the sheared 6.625" drill pipes. The bottom pipe gets deformed further and a piece is broken as in Figure 7.11 (b). The top pipe is also broken and deformed due the obstruction of shear ram surfaces other than the blades.

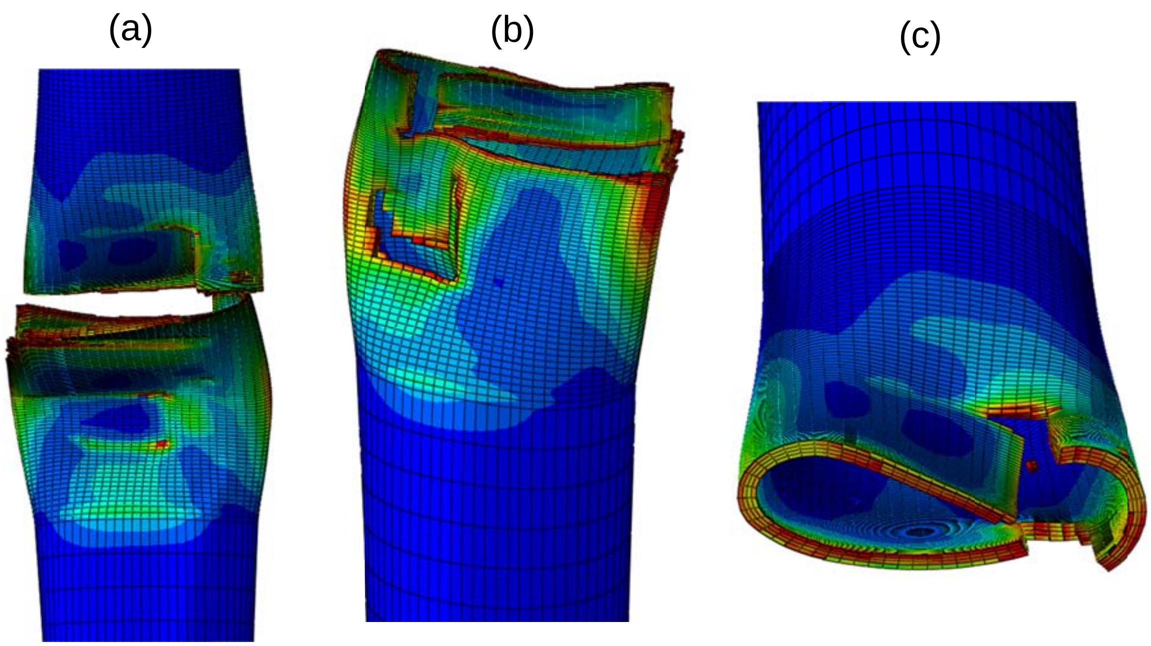


Figure 7.11: Sheared 6.625" Non-Centralized Drill Pipe (a) Top and Bottom Pipe, (b) Bottom Drill Pipe, (c) Top Drill Pipe with Sheared Cross Section

The same phenomenon is observed for three pipe sizes and the deformed shapes are also similar. The total force required to shear the pipe is computed by extracting the force data with respect to ram motion. Figure 7.12 shows the shearing force versus ram displacements for the 3.5", 5.5", and 6.625" respectively. Initially the force required increases during the deformation phase of the drill pipe and the maximum shearing force is observed at the time of shearing. After shearing, shearing force abruptly drops and rises again when the drill pipe gets stuck between the ram blades making it difficult for the shear rams to close. It is also observed that for the cases under consideration shearing force increases with respect to the diameter of the drill pipe.

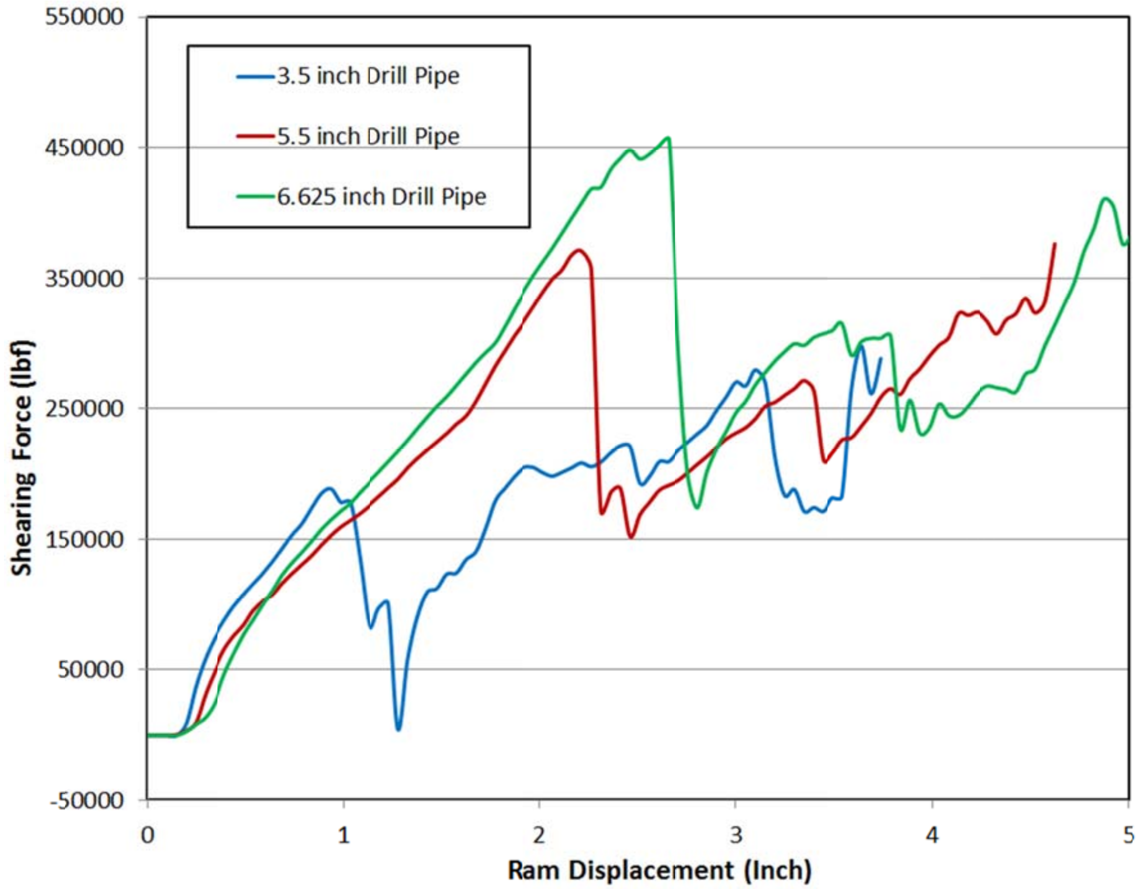


Figure 7.12: Shearing Force vs. Ram Displacement for 3.5", 5.5" and 6.625" Non-Centralized Drill Pipe

The force required for shearing and the final shape of the sheared drill pipe fish are different for the centralized and non-centralized cases. This is because when the drill pipe is non-centralized (drill pipe close to the BOP wall), the V-shape blade of the upper ram punctures the drill pipe with its sharp edge. Figure 7.13 shows the shearing force versus ram displacement for the 3.5" drill pipe centralized and non-centralized cases. It is observed that the maximum shearing force is lower for the non-centralized case and this is due to the piercing of the drill pipe by the upper ram blade corner which makes it easy to shear with less force.

After shearing the drill pipe, both the cases show nearly the same amount of force for bending the sheared drill pipe. When the rams are about to close the well bore the sheared non-centralized drill pipes get stuck between the blades of the shear rams, making it difficult to close and requiring higher force compared to the centralized pipe case.

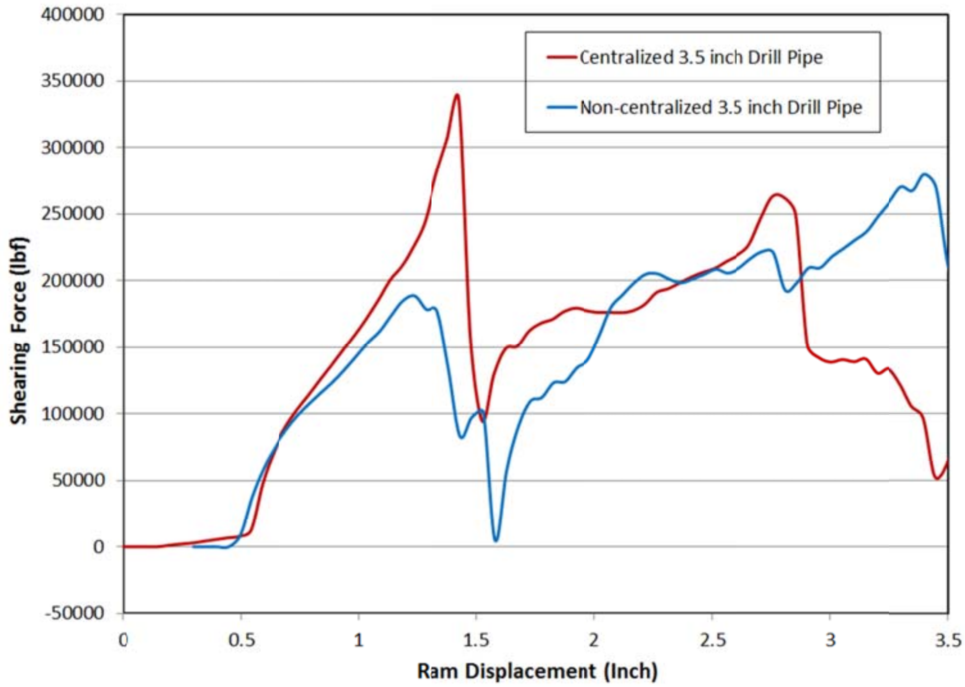


Figure 7.13: Comparison of Shearing Force versus Ram Displacement for Centralized and Non-centralized 3.5" Drill pipe

A similar phenomenon is observed in 5.5" and 6.625" drill pipes as shown in Figure 7.14 and Figure 7.15 respectively.

Although the non-centralized drill pipe cases requires less maximum shearing force for this type of shear rams it is not recommended due to the metal which may be trapped within the seal areas leading to seal damage and loss of seal capability. In addition the final deformed shapes of the drill pipes are unpredictable and can cause difficulty while removing the sheared bottom drill pipe fish and to open the well for production. Both the negative effects of not having full bore coverage and the benefits of puncturing the drill pipe are noted from this simulation.

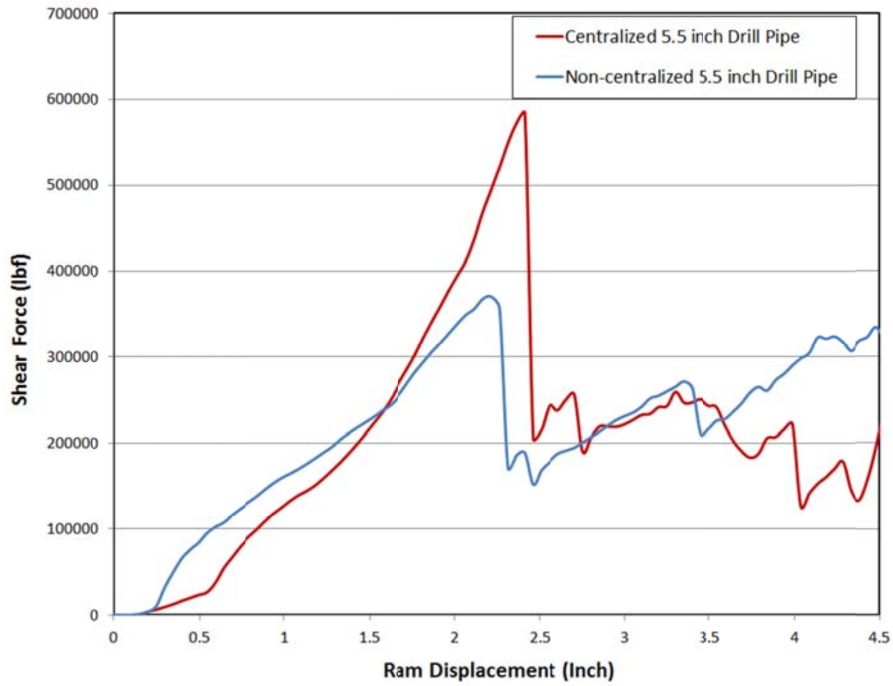


Figure 7.14: Comparison of Shearing Force versus Ram Displacement for Centralized and Non-Centralized 5.5" Drill pipe

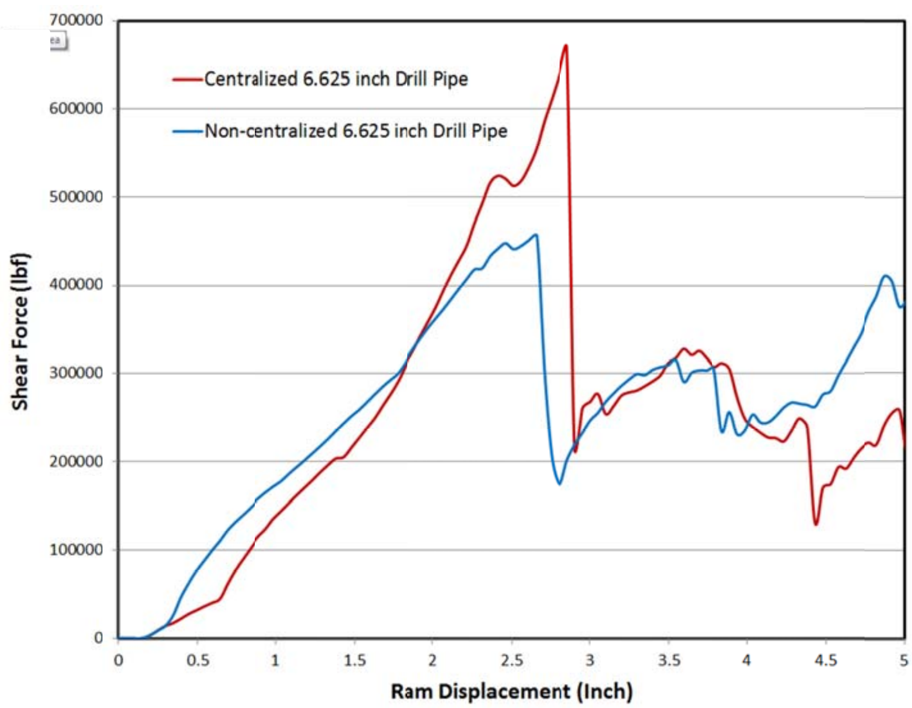


Figure 7.15: Comparison of Shearing Force versus Ram Displacement for Centralized and Non-Centralized 6.625" Drill pipe

Figure 7.16 shows the shear force versus ram displacement plots for 3.5", 5.5" and 6.625" drill pipe centralized and non-centralized scenarios.

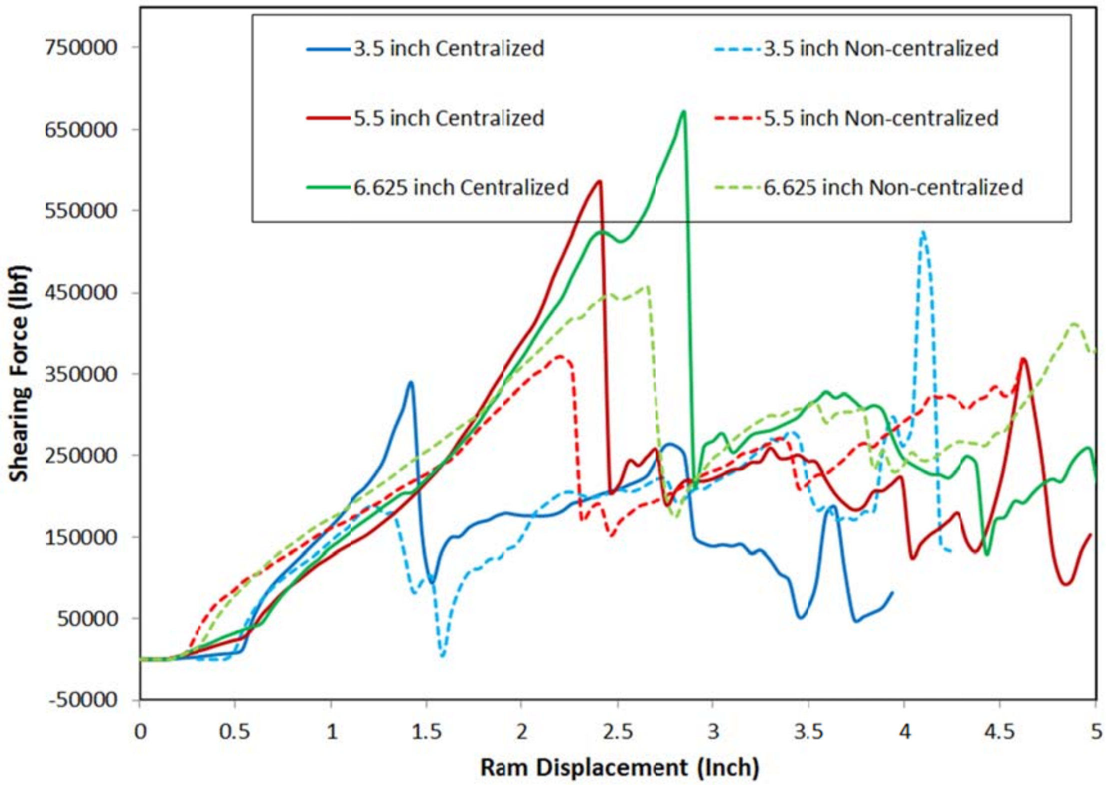


Figure 7.16: Comparison of Shearing Force vs. Ram Displacement for Centralized and Non-Centralized 3.5", 5.5" and 6.625" Drill Pipes

7.2.2 Non-centralization of Drill Pipe Positioned towards Upper Ram Side

In Section 7.2.1, the shearing of non-centralized drill pipe where the entire cross section of drill pipe does not come in contact with the shear ram blades is evaluated. In this section, shearing process is evaluated for drill pipe placed away from the BOP center but towards the upper ram side end of the BOP bore as shown in Figure 7.17. This case is evaluated with only one drill pipe size as the effect is expected to be similar for other drill pipe sizes.

A 9.84 ft long, 3.5" OD S-135 drill pipe with a thickness of 0.368" is used for the analysis. The drill pipe is centered such that it has the same length of pipe above and below the shear rams as shown in Figure 7.18. The drill pipe is positioned such that it touches the BOP wall towards the upper ram side.

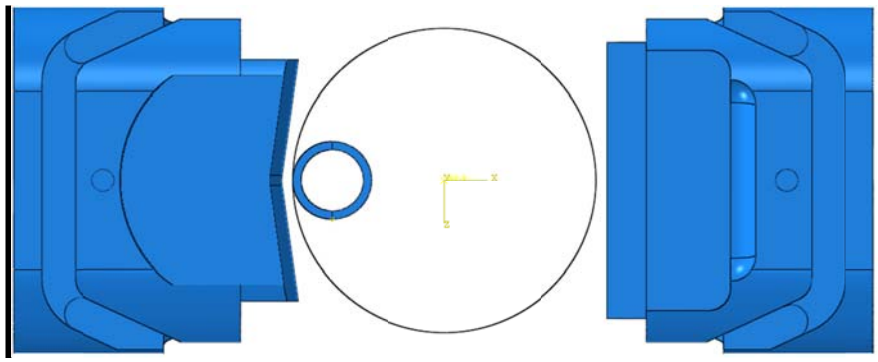


Figure 7.17: Schematic of Non-Centralized Drill Pipe towards Upper Ram

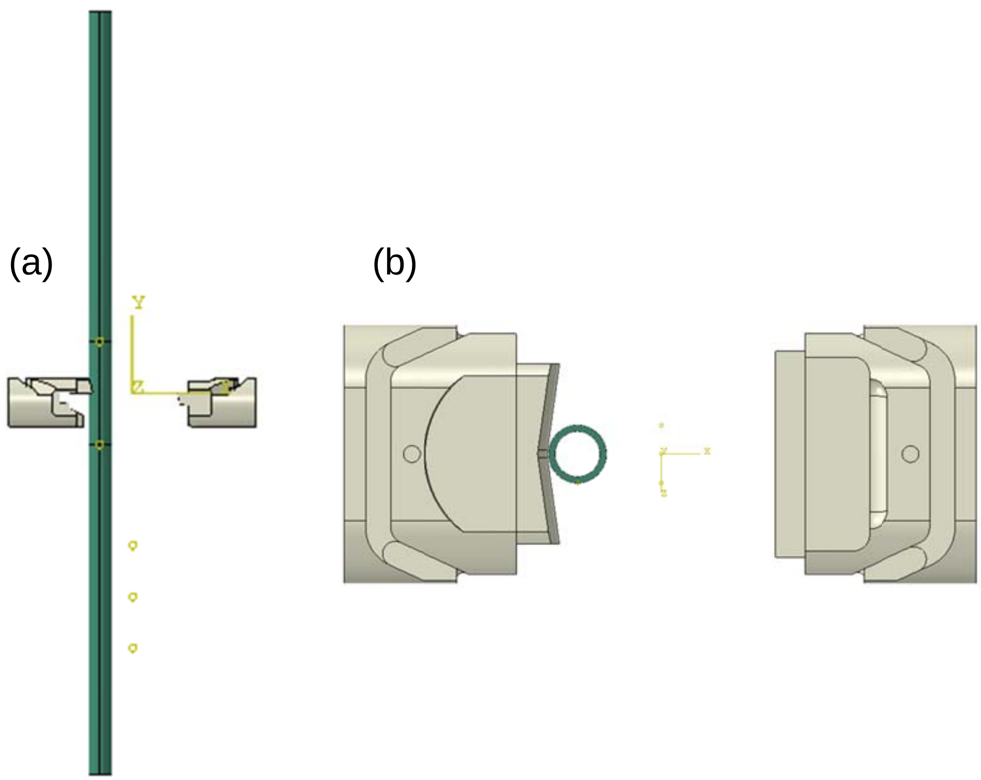


Figure 7.18: Drill Pipe 5.04" towards Upper Ram from the Center of BOP Bore (a) Front View, (b) Top View

The initial position of the shear rams is outside the BOP bore and both the rams are moved with a constant speed. Simulation is performed for the full stroke length and it is observed that the upper shear ram deforms the pipe until it reaches the center of BOP. The deformed drill pipe is sheared and the bottom drill pipe is bent as shown in Figure 7.19.

The force required to shear the drill pipe is plotted as shown in Figure 7.20. It is observed that the shearing forces increases with ram displacement and the pipe is being deformed towards the center of

BOP. After shearing, the upper ram continues to deform the top drill pipe and requires a higher force than the force during shearing as shown in Figure 7.20. The maximum shearing force is less compared to force required for shearing the drill pipe under no load. This is due to the drill pipe being bent towards the center of the BOP, which increased the stresses acting on the drill pipe making it easier to shear.

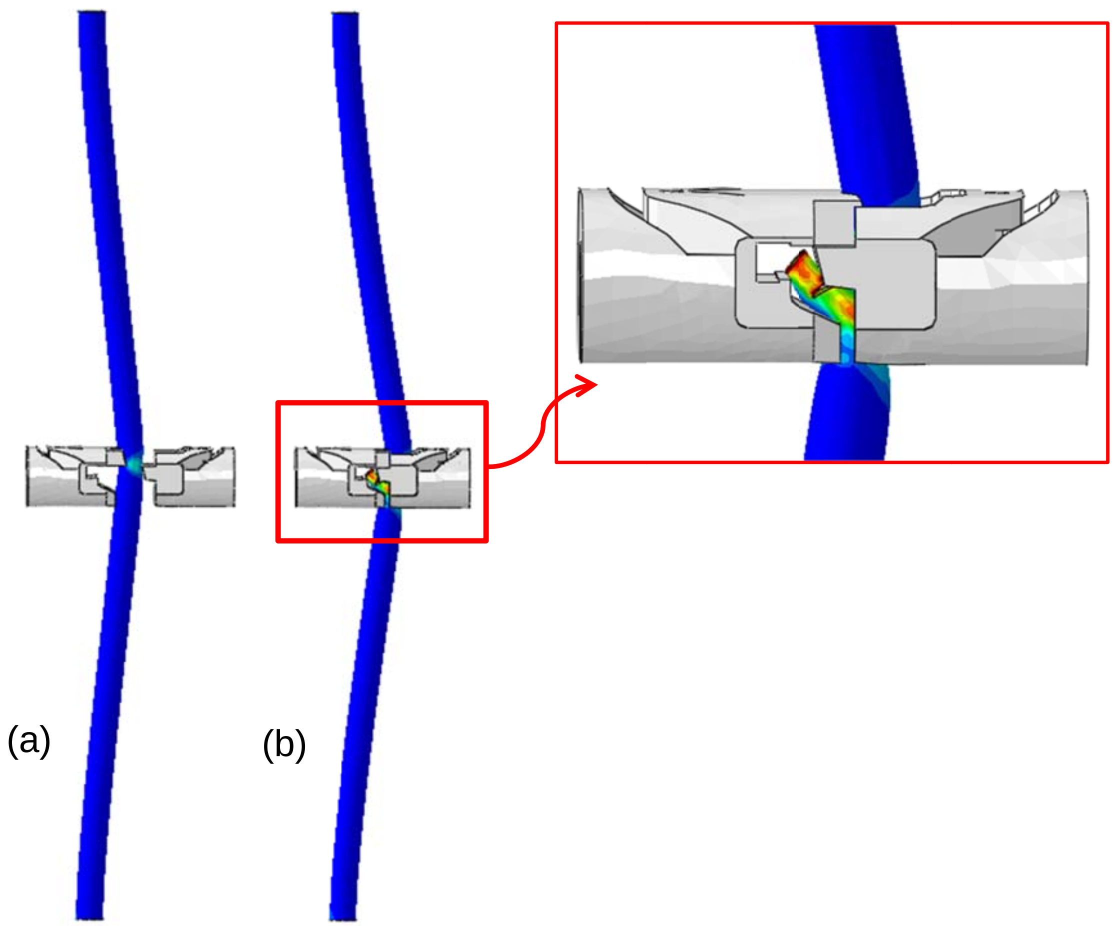


Figure 7.19: Drill Pipe Positioned Close to Upper Ram (a) Front View at Ram Displacement = 5.51", (b) Front View at Ram Displacement = 7.5"

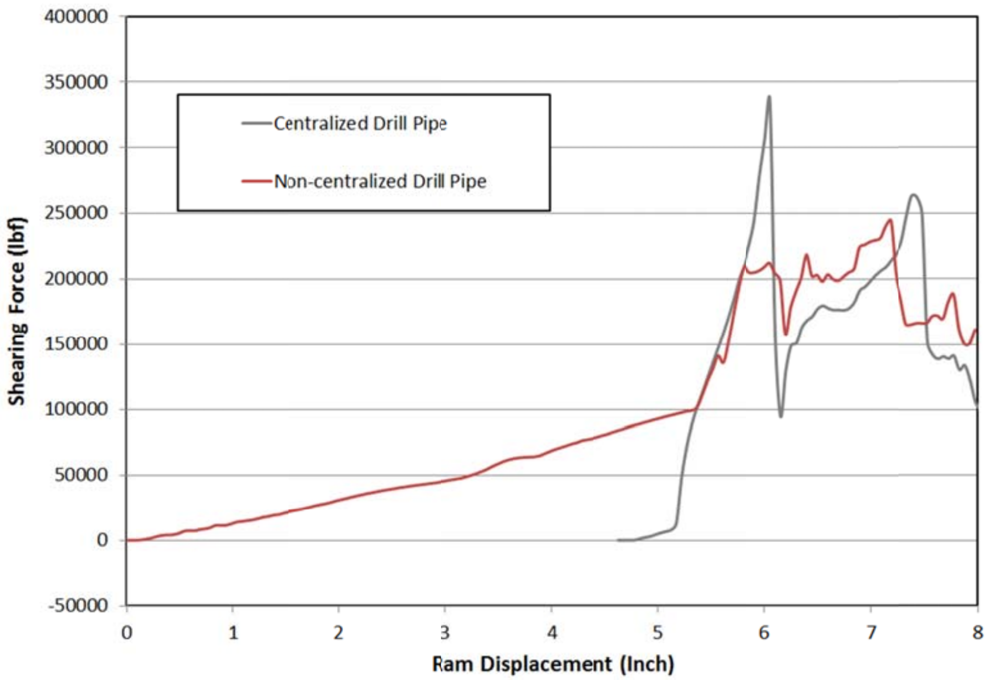


Figure 7.20: Comparison of Shearing Force versus Ram Displacement for Non-Centralized 3.5" Drill Pipe Positioned Close to Upper Ram Side of BOP Bore with Centralized 3.5" Drill Pipe

7.2.3 Orientation of Drill Pipe at an Angle to the Well Bore

This section discusses the effects of shearing a drill pipe positioned at an angle to the axis of the BOP bore. A 9.84 ft long, 3.5" OD S-135 drill pipe with a thickness of 0.392" is used for the analysis. The drill pipe is centered such that it has the same length of pipe above and below the shear rams as shown in Figure 7.21. Two different positions of the drill pipe are considered by orienting the drill pipe 40 degrees clockwise and counter clockwise.

The goal of this study is to evaluate if the drill pipe can shear a locally deformed drill pipe inclined at a steep angle to the well bore. Therefore the drill pipe is positioned at an angle to simplify and replicate the localized steep angle of a buckled pipe. The top and bottom of the drill pipe are fixed and the shear rams are initially positioned such that they are close to the drill pipe as shown in Figure 7.21.

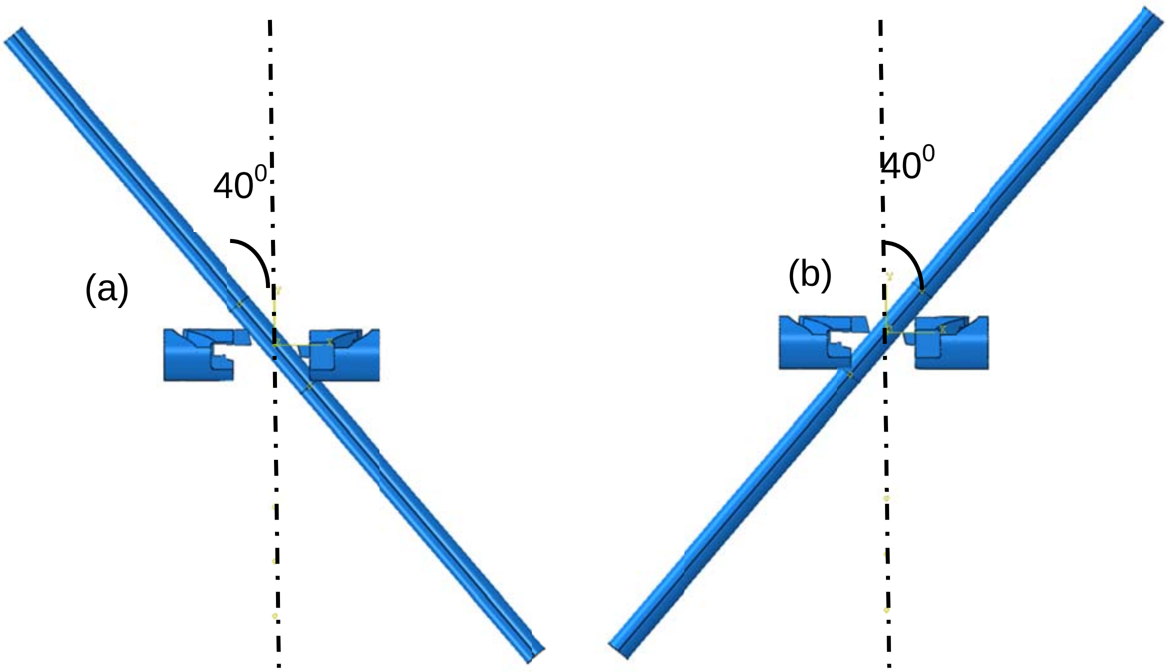


Figure 7.21: Assembly of 3.5" Drill Pipe Inclined at 40 Degrees; (a) Counter Clockwise from Vertical, (b) Clockwise from Vertical

The position of the shear rams and the shape of 3.5" drill pipe inclined 40 degrees counter clockwise to the BOP bore at different time intervals during the shearing process is captured as shown in Figure 7.22. As the shear rams move, they come in contact with the drill pipe and start deforming the pipe. The drill pipe is fixed on the top and bottom end and the motion of shear rams creates a tensile force in the drill pipe making it easier to shear. It can also be clearly seen based on the contact between the drill pipe and shear rams. Initially the drill pipe come in contact with the edge of the shear ram blades (Figure 7.22(b)) and as the shear ram progresses; the drill pipe deforms and contacts the entire inclined face of the blade (Figure 7.22(c)). This tries to stretch the drill pipe and generates tension which helps in the shearing of the drill pipe.

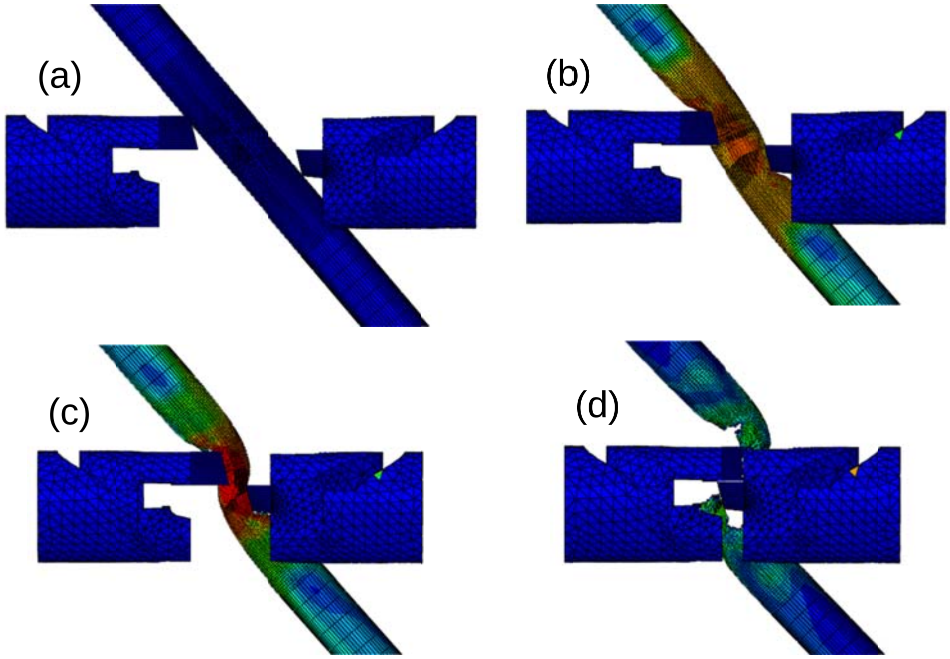


Figure 7.22: Front View, Shearing of Drill Pipe Oriented 40 Degrees Counter Clockwise from Vertical. (a) Ram Displacement = 0, (b) Ram Displacement = 1.77", (c) Ram Displacement = 2.76", (d) Ram Displacement = 4.87"

The position of the shear rams and the shape of 3.5" drill pipe inclined 40 degrees clockwise to the BOP bore at different time intervals during the shearing process is captured as shown in Figure 7.23. In this case, as the shear rams move, a compressive force is generated in the drill pipe making it difficult to shear. After shearing the top drill pipe is also under compression and the upper ram requires a very large force to seal the well.

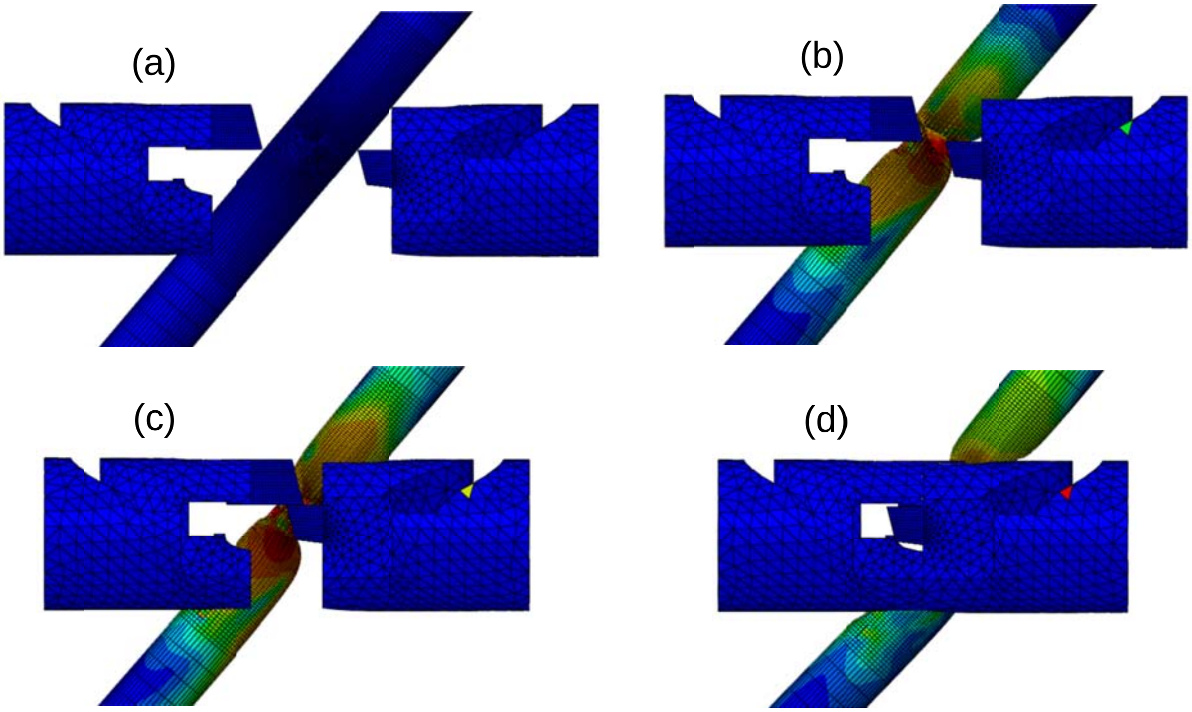


Figure 7.23: Front View, Shearing of Drill Pipe Oriented 40 Degrees Clockwise from Vertical. (a) Ram Displacement = 0, (b) Ram Displacement = 1.77", (c) Ram Displacement = 2.76", (d) Ram displacement = 4.87"

The shearing force required for the drill pipe inclined 40 degrees clockwise is higher than the other case due to the drill pipe subjected to compressive force. This is observed even after shearing as the top drill pipe is still under compression and requires large force for the shear rams to complete the stroke and close the BOP bore. Figure 7.24 shows the shearing force versus ram displacement

For the case where the drill pipe is inclined 40 degrees counter clockwise, the shearing force is low compared to the other due to the drill pipe in tension. After shearing, the force required is nearly zero as the sheared drill pipes are not bent or flattened. Figure 7.25 shows the deformed shapes of the sheared drill pipes for both the cases.

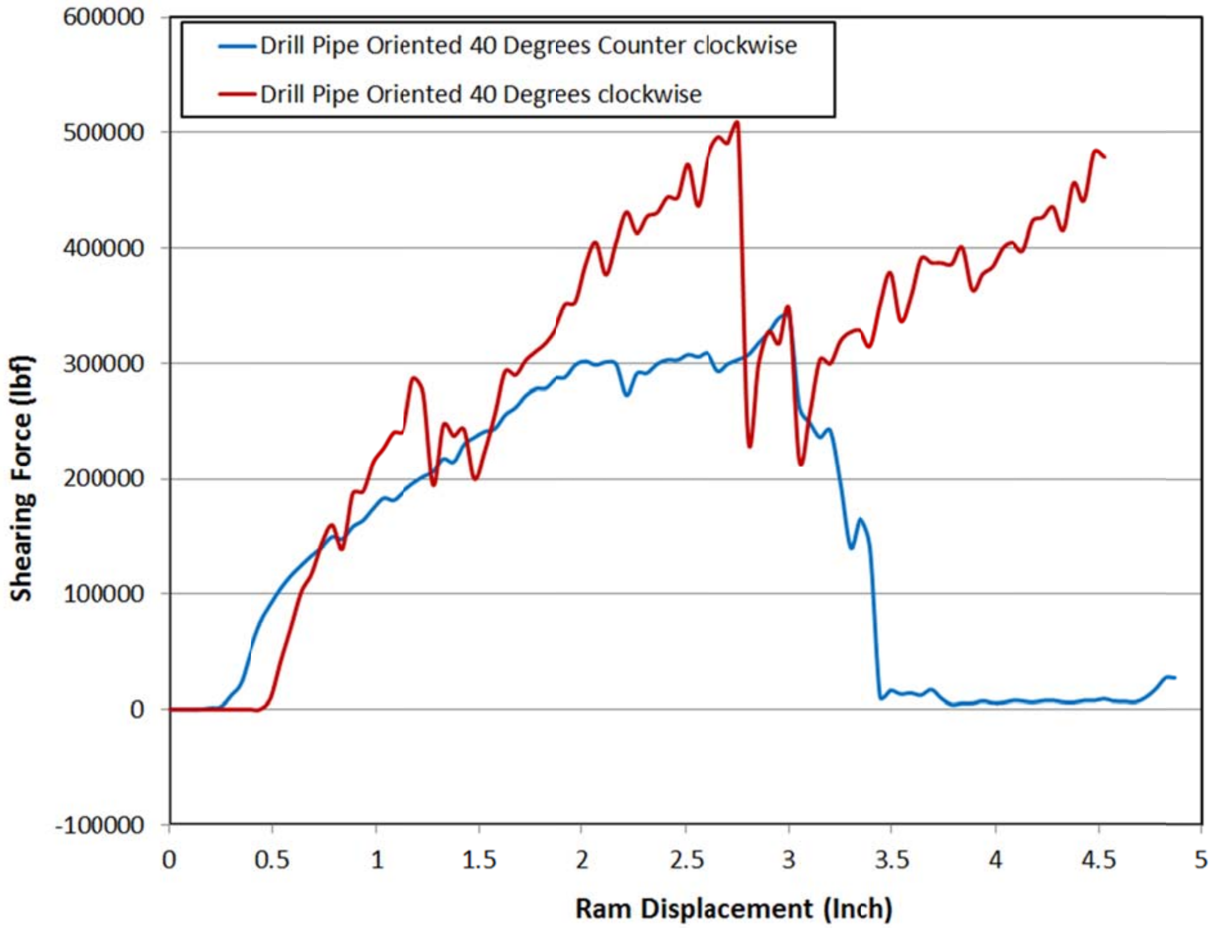


Figure 7.24: Shearing Force vs. Ram Displacement for 3.5" Drill Pipe Oriented 40 Degrees Counter Clockwise and Clockwise

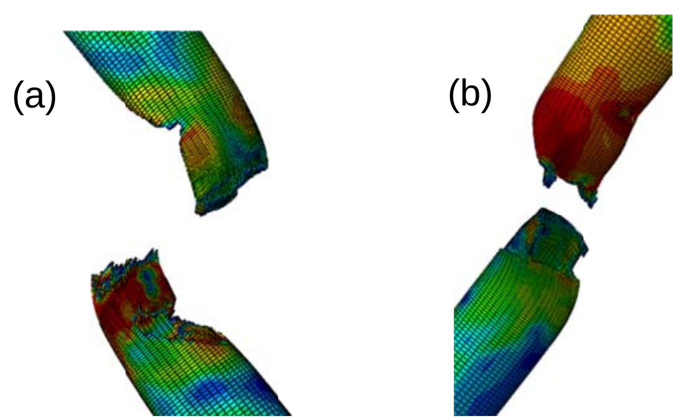


Figure 7.25: Sheared Drill Pipes. (a) Drill Pipe Oriented 40 Degrees Counter Clockwise; (b) Drill Pipe Oriented 40 Degrees Clockwise

7.3 EFFECT OF PRE-LOAD ON DRILL PIPE DURING SHEARING PROCESS

This section studies the effect of various loading parameters on the shearing process and the shearing force requirements. The shearing process is evaluated for the following scenarios.

- Drill Pipe under tension
- Drill pipe under compression
- Drill pipe subject to buckling

A 9.84 ft long, 3.5" OD S-135 drill pipe with a thickness of 0.368" is used for the analysis. The drill pipe is positioned such that 7.55 ft is above the shear ram blades similar to the validated model as shown in Figure 7.26.

7.3.1 Drill Pipe under Tension

In this case the effect of tensile load acting on the drill pipe during the shearing process is assessed. A tensile force of 100 kips is applied to the top end of the drill pipe where the bottom end of the drill pipe is fixed. As expected, it is observed that the force required to shear the drill pipe during tension is less compared to the drill pipe without any initial load and is shown in Figure 7.27. It is found that for a tensile force of 100 kips, the shearing force required is 301,714 lbf which is 10.25% lower than the benchmark case.

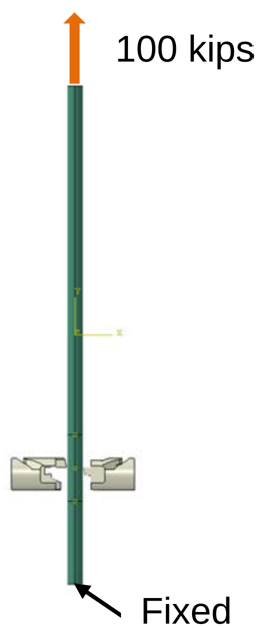


Figure 7.26: Drill Pipe in Tension

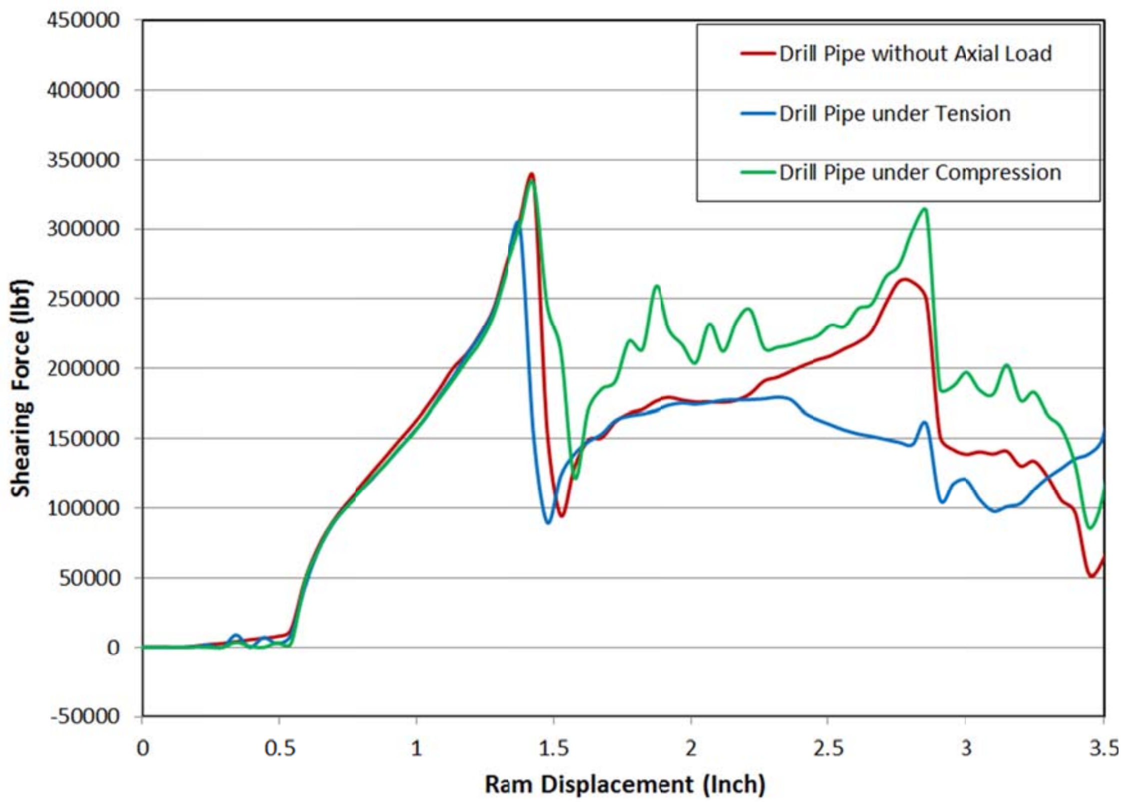


Figure 7.27: Shearing Force versus Ram Displacement for undeformed Drill Pipe under axial load

7.3.2 Drill Pipe in Compression

The model in Section 7.3.1 is used except the 100 kips tension force is replaced by a compressive force of the same magnitude. It is observed that the force required for shearing the drill pipe is nearly the same as for the drill pipe under no load. Therefore the compressive load has a smaller effect on the maximum shearing force compared to the tensile load. After shearing, the compressive load case requires higher force to complete the stroke of the shear rams as the compressive load is acting on the shear rams through the top drill pipe section.

Figure 7.28: Drill Pipe in Compression

7.3.3 Buckled Drill Pipe

This section studies the effect of shearing a buckled drill pipe under compression. The drill pipe is centered such that it has the same length of pipe above and below the shear rams. The BOP bore is modeled using discrete rigid shell elements to prevent the buckling of the drill pipe outside of the bore. A circular plate with shell elements is modeled on the top of the drill pipe for applying a compressive load and cylindrical shell elements are generated around the drill pipe to model the BOP annulus as shown in Figure 7.29. The simulation consists of two stages:

1. Buckling of the drill pipe
2. Shearing of the buckled drill pipe

Initially the drill pipe is buckled by applying a displacement controlled motion of the upper plate which is tied to the top of the drill pipe. A small magnitude of lateral force is applied on the drill pipe surface close to the center of the drill pipe to introduce an imperfection and initiate buckling.

After buckling, the drill pipe is held under the compressive load and the shear rams are activated. As the initial position of the buckled drill pipe is close to the upper ram, it comes in contact and moves the drill pipe towards the center of the bore. Shearing occurs when the upper and lower rams come in contact and deform the buckled drill pipe.

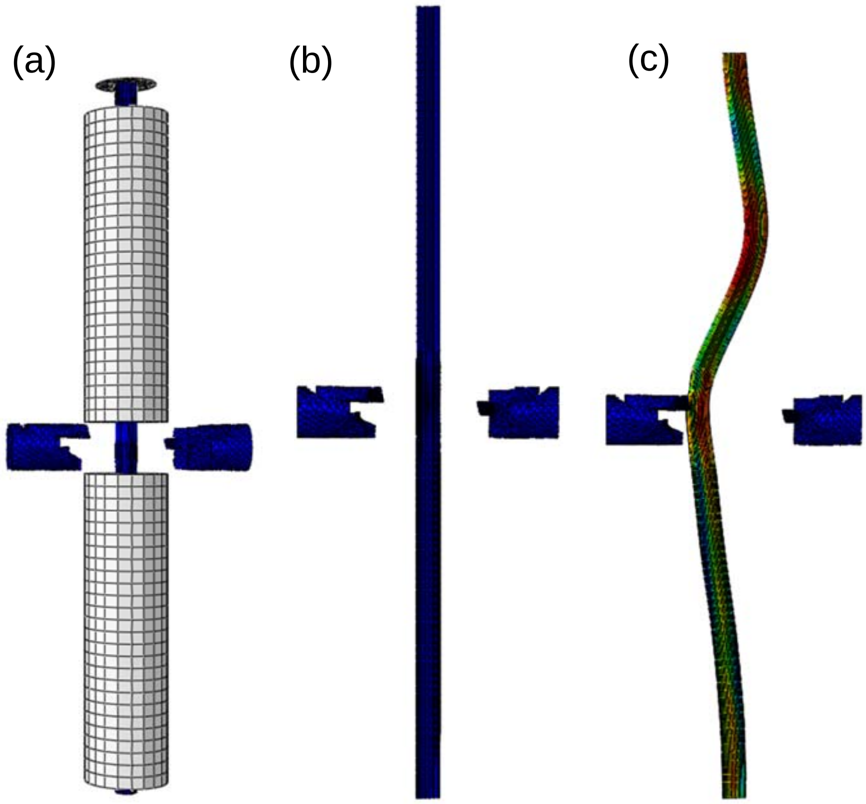


Figure 7.29: Buckled Case (a) Assembled Model (b) Undeformed Pipe (c) Buckled Pipe

The position of the shear rams and the shape of the buckled drill pipe at different time intervals during the shearing process is captured as shown in Figure 7.30.

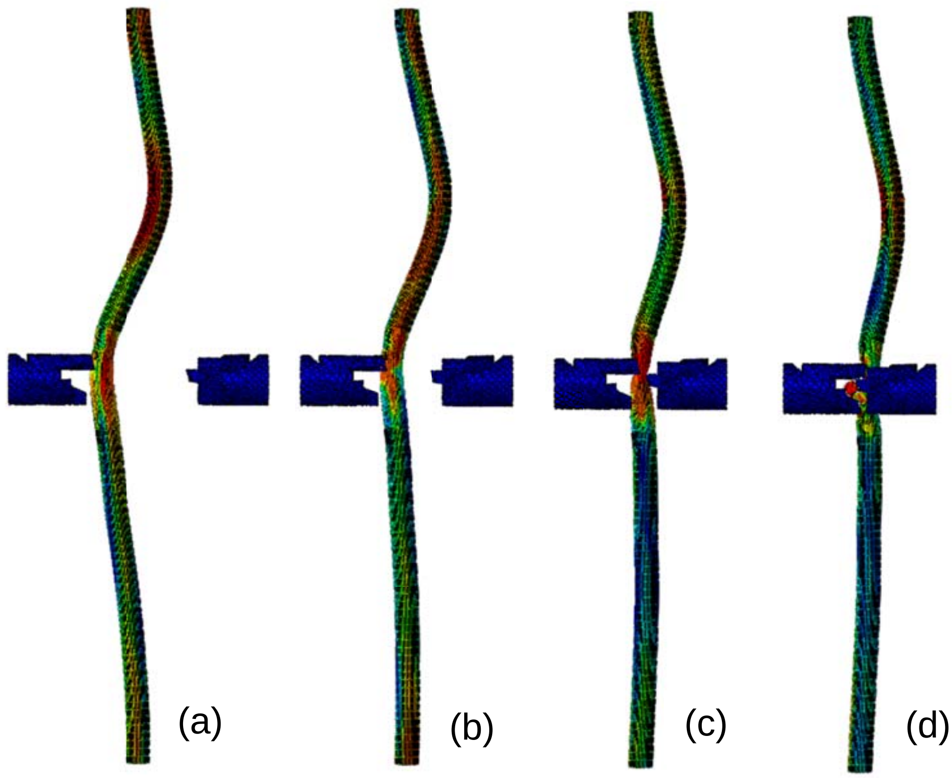


Figure 7.30: Front View, Shearing of Deformed Drill pipe (a) Ram Displacement = 0, (b) Ram Displacement = 3.54", (c) Ram Displacement = 6.6", (d) Ram Displacement = 7.87"

The force required for shearing the buckled drill pipe is shown in Figure 7.31. As the shear rams move, there is an increase in force due to the centering of the drill pipe in well bore. The force is a maximum during shearing and drops abruptly after the top and bottom drill pipes are separated. The force increases again during the bending of sheared lower drill pipe. Figure 7.31 also shows the force required to shear a centralized drill pipe under no external loads. It is observed that the buckled drill pipe requires higher shearing force compared to a drill pipe under no load. For the modeled scenario, the buckled model required 41.48% higher force compared to the centralized case. A high force is required to deform the lower drill pipe fish and seal the well. The maximum shear force required to shear the buckled pipe exceeded the OEM calculated shear force by approximately 13.7% (Table 7.1). It is recommended that the OEM calculation consider the buckled pipe case in its shear force operator and shear ram design.

Table 7.1: Comparison of FEA Max. Shearing force with OEM Max. Shearing force for Centralized and Buckled Pipe Cases

3-1/2 Drill Pipe Diameter OD (inch)	FE Analysis Max. Shearing Force (lbf)	OEM Formula Max. Shearing Force (lbf)	% Difference
Centralized – No Pre-load	336,160	417,984	- 24.34 %
Buckled Pipe	475,619	417,984**	+ 13.7 %

** The OEM formulation does not consider buckled pipe conditions; the force calculated by the standard formula is used.

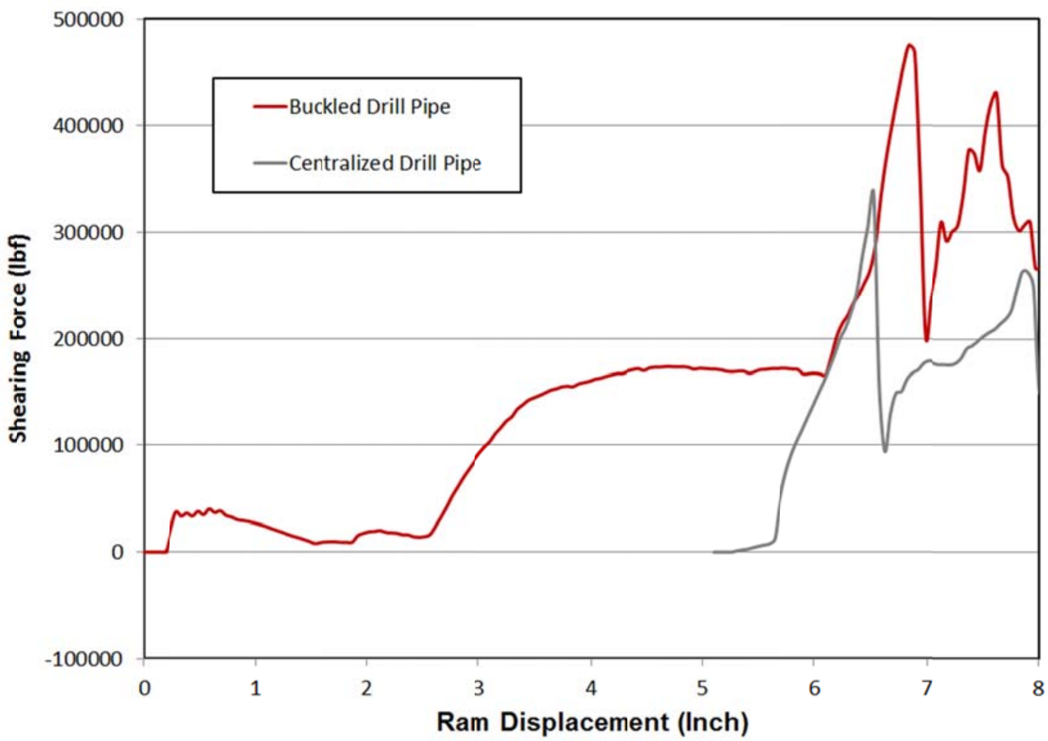


Figure 7.31: Shearing force vs. Ram Displacement for 3.5" Buckled and Centralized Drill Pipe

7.4 Simulated Flowing Well Conditions

In this section the effects of a flowing well on the shear force requirements are assessed. A series of simulated flowing well cases are analyzed. These analyses provide the effect of flowing well on the shearing process and the required maximum shearing force.

The high velocity fluid flowing through the drill pipe (and annulus) can pose a resistance to the motion of shear rams. In this study, a de-coupled methodology is chosen by performing a series of steady state simulations for different positions of the shear ram in the annulus. This solution is less computationally intensive and more efficient compared to a fully coupled simulation methodology.

During a well control event, formation fluid flows through the annulus and drill pipe with a very high velocity. The shear rams move from the wall of the well bore and seal the well. During the motion, the shear rams blade has to overcome any resistance offered by the flowing fluid in the annulus and as they deform and shear the drill pipe there can be an effect of fluid inside the drill pipe. The effect of flowing fluid through the well bore (or annulus) and drill pipe on the moving shear rams during a well control event are assessed.

The initial position of the shear rams is at the wall of annulus and does not obstruct the flow. The shear rams are pressure balanced and the back of the ram sees almost the well bore pressure. The only loss of area is for the piston rod which is accounted in the OEM formula. Therefore all the simulations are performed with a constant operating pressure and the rise in pressure due to the blockage of shear rams is used to compute the net increase in force on shear rams.

The motion of the shear rams through the well bore is a transient process as the shear rams velocity may vary depending on the net actual force acting on it. This depends on the accumulator pressure acting on the piston of the rams and the resistance force opposing it. The motion of the shear rams is modeled through a series of steady state simulations by placing the shear rams at different positions in the well bore. All the simulations are performed using AcuSolve commercial CFD software. AcuSolve is general purpose finite element based CFD software capable of performing steady RANS to complex transient, multiphysics simulations.

As the shear rams progress through the well bore, the cross sectional area of flow in the region of shearing gets constricted which increases the pressure exerted by the fluid on the shear rams. Figure 7.32 shows 4 different positions of the shear rams from its initial position until it contacts the drill pipe.

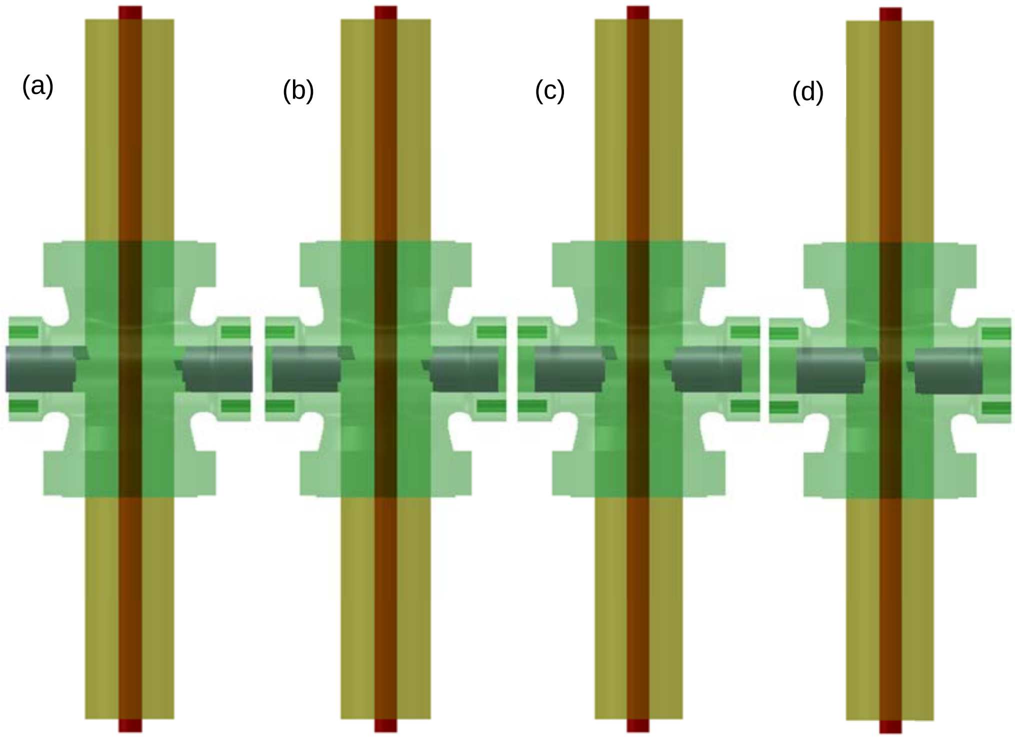


Figure 7.32: Geometry of the Flow Model (a) Rams 13.5" Apart, (b) Rams 10.5" Apart, (c) Rams 7.5" Apart, (d) Rams 4.5" Apart

7.4.1 FE Model

Four BOP models consisting of a bonnet, well bore (annulus), upper and lower set of shear rams are developed. The shear rams are positioned at various distances from the drill pipe:

(A) Rams 13.5" apart

(B) Rams 10.5" apart

(C) Rams 7.5" apart

(D) Rams 4.5" apart (2.25" from center of BOP bore)

The flow is most restricted just prior to contact with the drill pipe (Figure 7.32 (d)). This condition is the primary analysis case. The same BOP (13-5/8) and shear rams used in the physical and bench mark FE models are used in the flowing well simulations. The upper ram is a V-blade and the lower ram is a flat blade with a constant rake angle. A 3.5" drill pipe is modeled with an assumed length of 9.84 ft as shown in Figure 7.33.

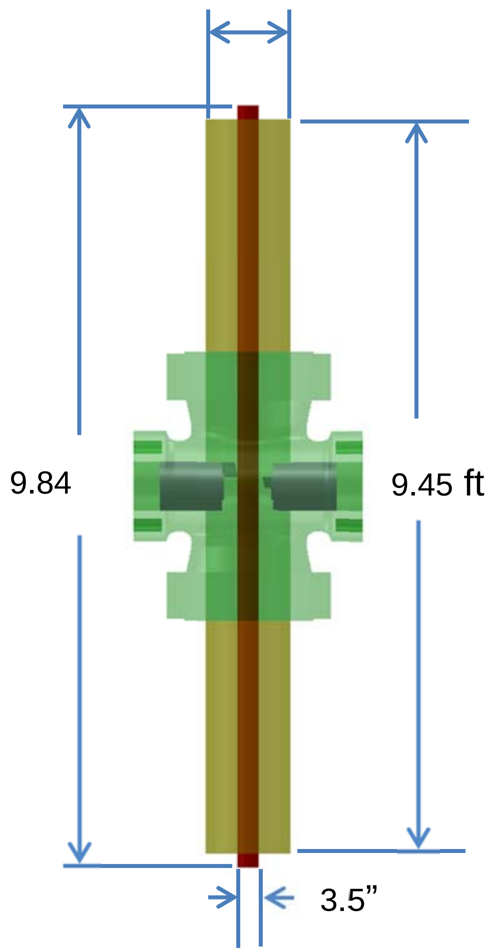


Figure 7.33: Dimensional Details of Flow Model

The shear rams used for the flow analysis are modified to reduce the complexity of the geometry and to ensure no leak between the shear ram slots in the bonnet and the shear rams. The elastomer grooves on the shear rams are filled with material and smoothed as shown in Figure 7.34. These changes do not have any impact on the flow solution as they do not affect the regions where the fluid will come in contact with ram surface and no changes have been made to the blade surface.

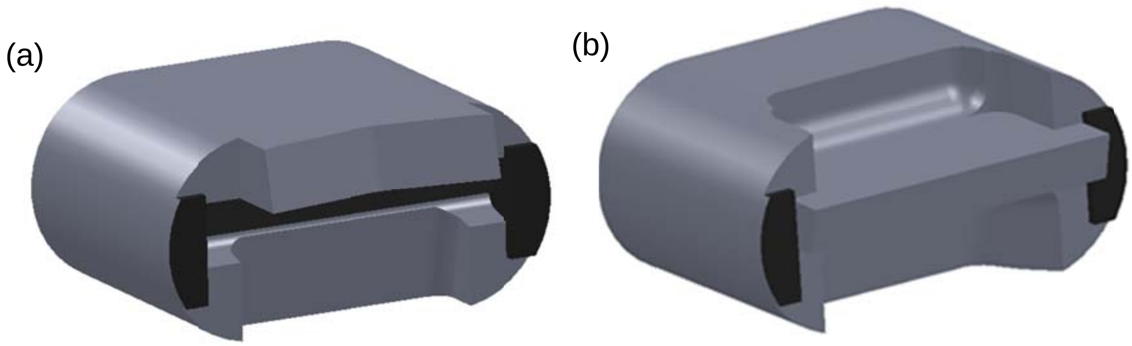


Figure 7.34: Modified Shear Rams for Flow Analysis (a) Upper Ram, (b) Lower Ram

Due to the high velocity of fluid in the well bore, the flow is modeled as turbulent using steady state one equation Spalart-Allmaras (SA) turbulence model. The following assumptions are considered for the flow analysis:

- The pressure on either side of the BOP rams is assumed to be the same i.e. a stabilization of pressure is assumed to have occurred when the rams are activated.
- Formation fluid is replaced by water as it is conservative due to higher density of water
- Compressibility effects are neglected
- Length of the drill pipe and well bore is limited.

A series of CFD simulations are performed for the various ram positional models for a range of inlet volume flow rates (50,000 BPD to 200,000 BPD) and for a range of pressure outflow boundary conditions (1000psi to 10,000psi). The pressure drop from inlet to outlet will be small as the length (9.84 ft) is short. All other surfaces are modeled as walls with zero roughness and with wall function turned on to resolve the boundary layers at the wall.

7.4.2 Analysis Results

A summary of the main flow simulation results is presented in Table 7.2. The largest pressure rise observed for all the cases analyzed is <2 psi with a volume flow rate at the inlet of 200,000 BPD. This effect of fluid flow through the annulus on the shearing process is very small (less than 1%). For the 200,000 BPD cases the fluid velocity increases by a factor of 2.7 between inlet and constricted area (case D) from 15.4ft/s to 42.1ft/s.

Table 7.2: Flowing Well Simulation Results

Config	Volume Flow Rate (BPD)	Inlet Velocity (ft/s)	Max Velocity (ft/s)[3]	P_{inlet} (psi)	P_{outlet} (psi)	Max Pressure At Ram (psi)[1]	Pressure increase (psi)	Force Increase on Ram (lbf)[2]	% Force Increase on Ram (lbf)[4]
D1	50,000	3.89	10.5	1000.3	1000	1000.4	0.1	10.32	0.003%
D2	100,000	7.73	20.3	1002	1000	1002.25	0.25	25.8	0.008%
D3	200,000	15.4	42.1	1008.7	1000	1009.8	1.1	113.52	0.034%
D4	200,000	15.4	42.1	10006.4	10,000	10007.5	1.1	113.52	0.034%
D5	200,000	15.4	40.6	20003.8	20,000	20004.8	1	103.2	0.031%
B5	200,000	15.4	19.4	19995.7	20,000	19996.9	1.2	123.84	0.037%
C5	200,000	15.4	26	19997	20,000	19998.2	1.2	123.84	0.037%

Note:

1. Max pressure is conservatively assumed.
2. Projected area of shear ram is blade is 103.2 in^2
3. Max velocity occurs at the shear rams.
4. Ram force = 336,160 lbf (Table 6.5)

The observed drop in pressure and rise in velocity due to the narrow flow region between the drill pipe and shear ram blades are illustrated in Figure 6.36. The pressure profile on the shear ram blades is shown in Figure 6.37. The higher pressure on the underside of each ram is consistent with the fluid flow direction.

Figure 7.35 (a) shows the contour of pressure within the simulated BOP bore for a 5psi differential pressure. There is a pressure change upstream and downstream of the shear rams, due to constriction of the flow region by the shear rams. Recirculation of the fluid flow is also observed due to the shape of the shear rams. This is illustrated by the velocity vector shown in Figure 7.35 (b).

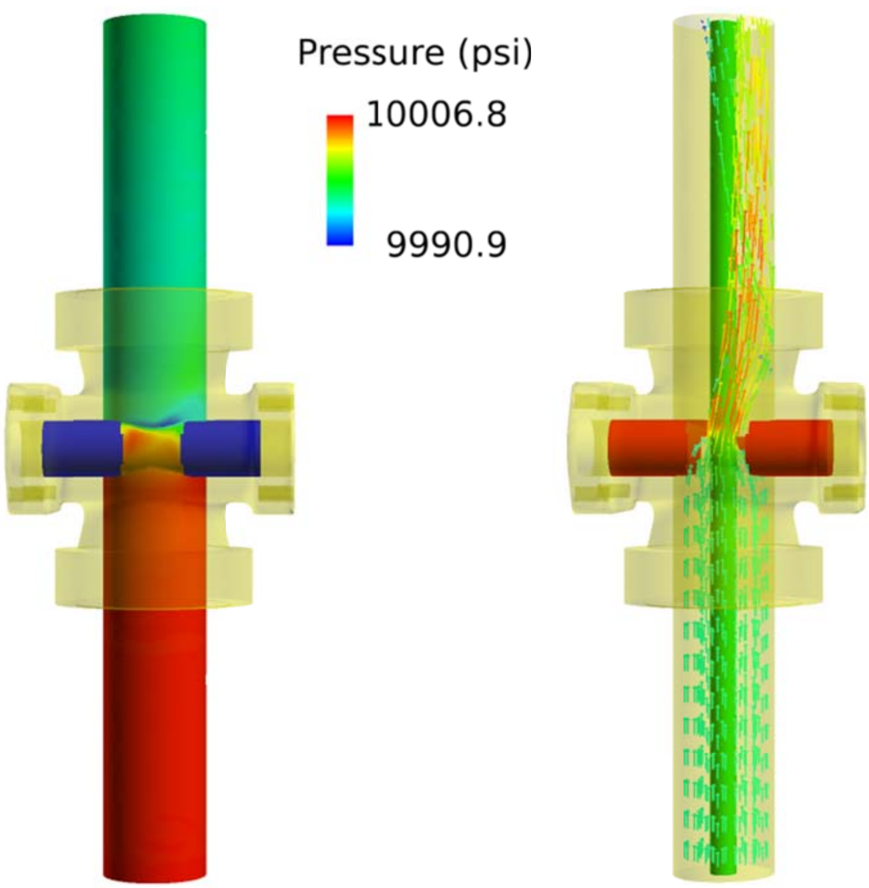


Figure 7.35: Shear Ram Assembly Model-D4. (a) Pressure Contour (b) Velocity Vector

The observed drop in pressure and rise in velocity due to the narrow flow region between the drill pipe and shear ram blades are illustrated in Figure 7.36.

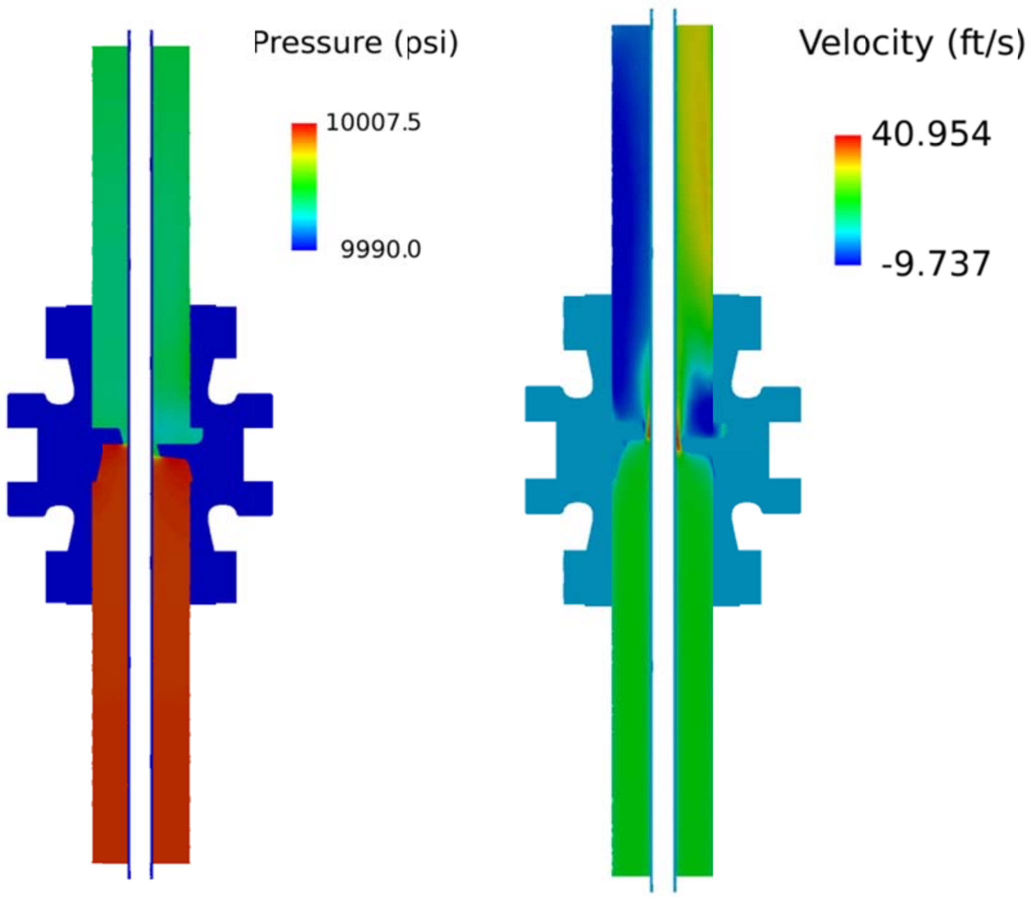


Figure 7.36: Contours on a Coordinate X-Y Plane (a) Pressure (b) Velocity

The pressure profile on the shear ram blades is shown in Figure 7.37.

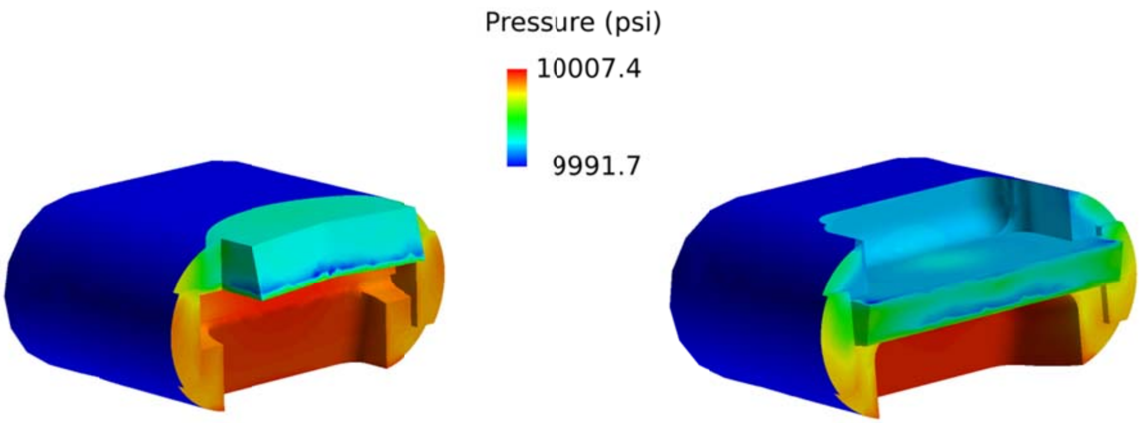


Figure 7.37: Pressure on Shear Rams Faces Exposed to Flow

The effect of flowing fluid inside the drill pipe on the shearing process will be similar to that in the annulus. As the shear rams continue to close, they come in contact with the drill pipe. Initially the drill pipe is deformed and the flow cross section inside the drill pipe is changed. The deformed cross section represents a nozzle and changes the force acting on the drill pipe. After certain deformation, the drill pipe is sheared and the lower drill pipe fish is bent. The deformation and shearing of the drill pipe is not modeled as the phenomenon is similar to that in the annulus (flow cross section reduces which eventually increases the force acting on the shear rams). The effect of flow through the drill pipe is expected to be minimal.

It should also be noted that the dynamic fluid flow conditions such as fluid hammer effect are not considered in this study. Moreover any abrupt pressure drop above the BOP rams is not considered. Such a drop would result in a steep pressure gradient across the rams during their shearing action. Additionally, it is assumed that an equalization of pressure on either side of the rams has occurred. The results of the flow simulations should be seen as a precursor to further investigation on the effects of these flow uncertainties on the shearing process. The feasibility of occurrence of these uncertainties during shearing ram activation should also be taken into account during this investigation.

Wellbore pressure is included in standard OEM shear calculations. Figure 7.38 shows the increase in required shear pressure with well bore pressure for one set of shear test variables (BOP type, shear ram type, actuator type, drill pipe yield strength). A linear increase in required pressure is observed for increasing wellbore pressure. For 10,000psi bore pressure the required shear pressure has increased 32%, equivalent to approximately 130,000 lbf of additional shear force. While this force, calculated and accounted in OEM shear force requirements, is not insignificant, it is worth noting that the force exerted by the wellbore on the ram face (projected area) would be much larger than this. It is believed that shear ram design minimizes the pressure differential between the front and back of the ram and hence a less significant shear pressure increase is required. However, due to the large number of variables in the design of BOP shear ram systems it is recommended that a thorough review of different designs and how they compensate for wellbore pressure be performed. Particularly as significant pressure may be in the bore when the shear operation is performed, especially if the annular(s) have been closed.

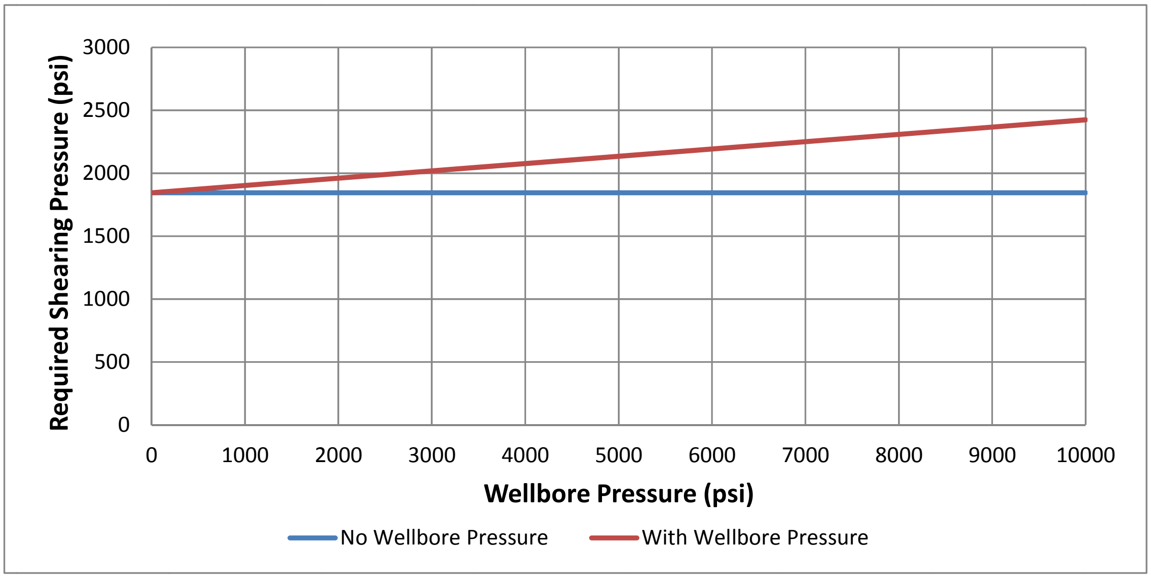


Figure 7.38: OEM Increase in Shear Pressure with Wellbore Pressure

8.0 NEW SHEAR RAM DESIGNS

8.1 INTRODUCTION

Chapter 7.0 identified a number of the challenges facing some of the older v-blade shear ram designs. These included full bore coverage, high shear force requirements, low/moderate centralization capabilities, high force required post shearing. The beneficial effect that puncturing of the drill pipe has on lowering the required shearing force has also been identified.

Many of the BOP equipment manufacturers have developing new shear ram designs targeting many of these issues. Some of these new technologies are presented in this chapter.

8.2 NOV'S LOW FORCE SHEAR RAM

NOV has developed the Shear Max Low Force Shear Rams which need less force to shear the pipe than “standard shear ram”. Compared to the conventional rams, the low force ram is smaller and more efficient which in turn leads to requiring around two times less shear force.

The principle behind low force shear ram is that it is shearing the drill pipe instead of crushing the entire pipe to initiate brittle fracture, the improved blade profile raises stress in a limited region and allows the crack to then propagate hence reducing the required shear force. This design can significantly reduce required shear force which would reduce the size and weight of rams [24].

The efficiency of the low-force shear is credited to the design and geometry of the blade. To ensure that the tubular is in the center to take advantage of that efficiency, NOV has developed an integrated centralizer with plates that sit at the bottom of the ram.

Multiple tests have been conducted to validate this design. NOV has sheared a range of tool joints up to XT-69 connection without exceeding the BOP operator’s safe working design envelope [25].

One drilling contractor has placed an order for the low force shear ram technology for their new build drill ships.

Figure 8-1: NOV Low Force Shear Ram [25]

8.3 T3 SHEAR ALL RAM

This system developed by T3 Energy (now owned by NOV) could shear offset pipe and casing in the BOP. It claims to shear multiple times without damaging the blades and compromising the ram block integrity. New design of the ram bonnets helps in reducing the closing force by 30-50% which in turn allows the BOP bonnets to handle any situation at low hydraulic operating pressures. It can shear an offset pipe which has been buckled or positioned such that it is lying to the side of the BOP. It has a near vertical rake angle, curved shearing blades which help in creating an even stress distribution and reducing stress concentrators. There is no information confirming if this technology has being commercialized yet.

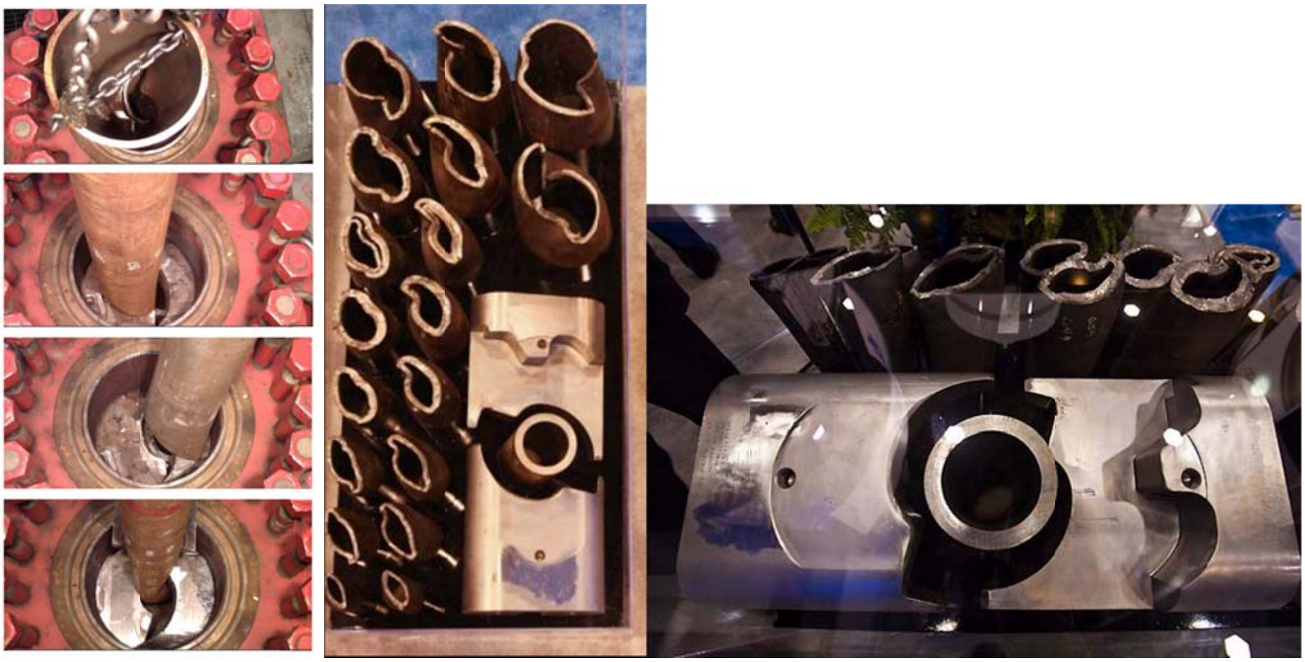


Figure 8-2: T3 Shear All Ram (SAR) [27]

8.4 GE's 5K Blind Shear Ram

This new system from GE will be used in the 5,000 psi, 22" actuator shear ram to shear drill pipe tool joints and casings. With 1.9 million lbf the rams have the ability to shear tool joints and then seal the well. The shear rams has centralizing arms that allow for shearing of buckled or offset pipe. Shop tests involved simulating shearing and sealing a buckled pipe against the wall of the BOP. The system can shear and seal after shearing up to 6-5/8" tool joints and 10-3/4" casing. They are developing shear rams to work at 250°F and will be performing testing on 11-3/4", 13-5/8" and 13-34" to demonstrate its shearing and sealing capability.

Figure 8-3: GE 5k Blind Shear Ram [33]

The upper ram has a pair of guide arms which protrude a greater distance than the blade. Each of the arms has an inboard wedge surface for guiding the pipe string towards the cutting zone of the shear rams (Figure 10.7). A pair of recesses is located on the second ram block for receiving the guide arms when the rams close.

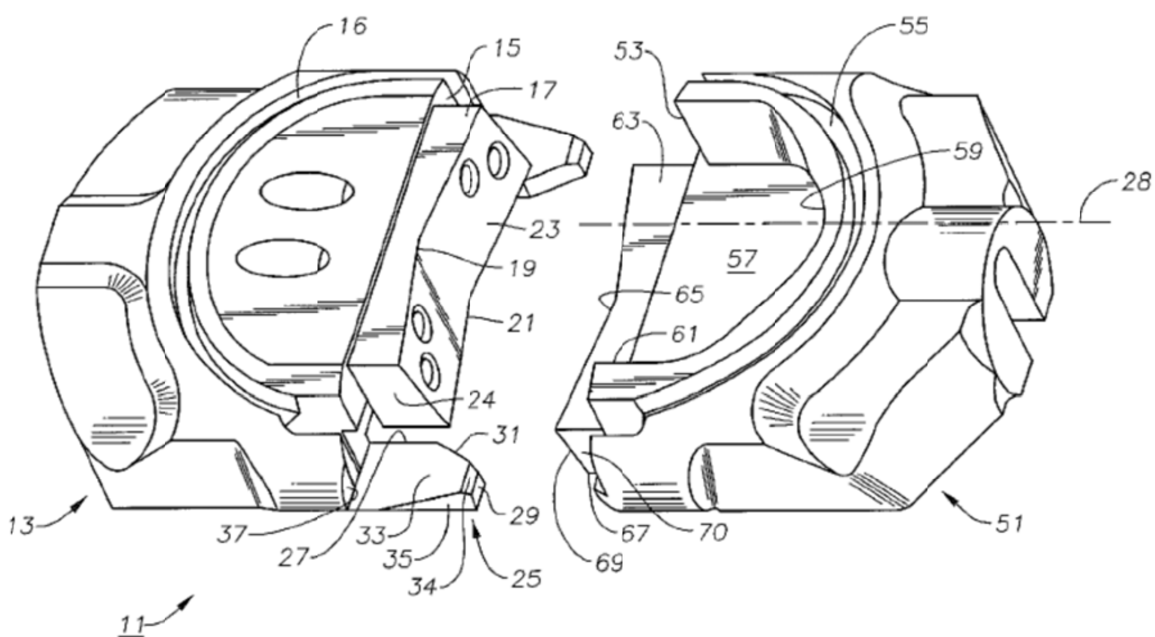


Figure 8-4: GE 5k Blind Shear Ram [19]

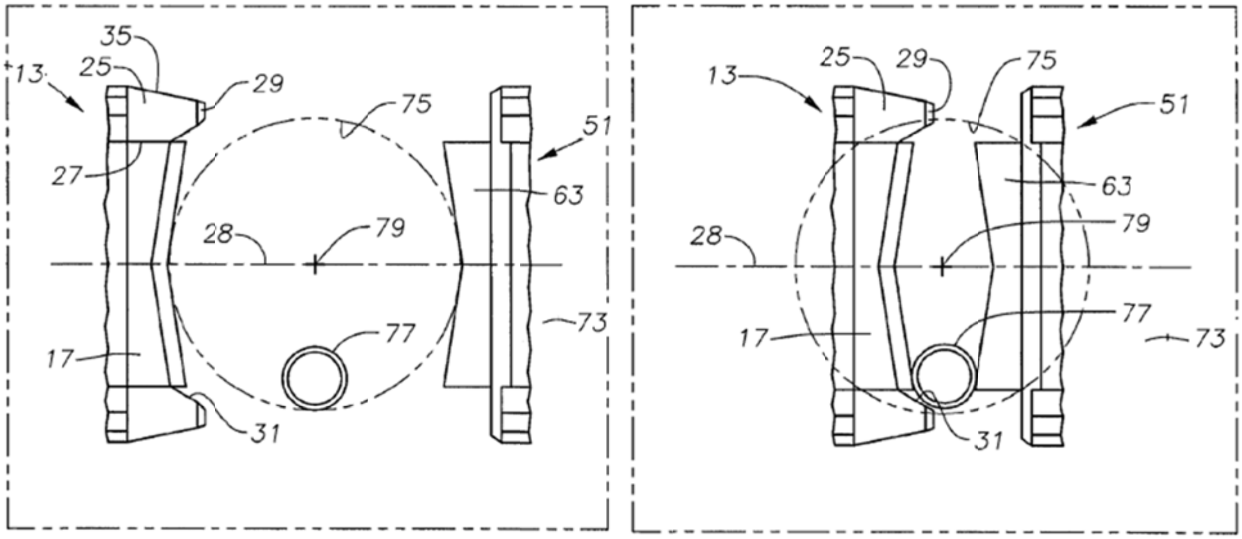


Figure 8-5: GE 5k Blind Shear Ram (a) Top View – Open position (b) Top View – Close Position [19]

9.0 EVALUATION OF DIFFERENT SHEAR RAM DESIGN FEATURES

9.1 INTRODUCTION

In this section an assessment of some of the features of different BOP ram designs is made. This evaluation includes the following designs.

- Ram Design 1 – Increased width of upper V-blade and Removal of Lower Lip (some of the features of the Cameron Type U Shearing Blind Ram)
- Ram Design 2 – Full bore coverage and curved blade profile (some of the features of the T3 Shear All Ram)
- Ram Design 3 – Pipe puncturing and centralizing (qualitative assessment only of some of the features of the NOV low force shear ram)
- Ram Design 4 – Upper and Lower V shaped Rams with Centralizing Guide Arms (some of the features of the GE 5k Blind Shear Ram)

It should be noted that the authors were not privy to the OEM proprietary dimensions of many of these designs, and used publicly available information to capture some of the key features of these designs. Many of the patented designs include a range of design variations [18,19,34]. Some of these features include increased well bore coverage, pipe centralization and the ability to shear a range of pipe sizes. In all cases the rams have been scaled to fit the same 13-5/8" BOP used throughout the study. A comparison to the benchmark models (Section 6.3.6) is made for each design.

9.2 RAM DESIGN 1 – LOWER WIDTH OF UPPER RAM V-BLADE AND REMOVAL OF LOWER LIP

This first design is not too dissimilar to the shearing blind rams used throughout this study. Figure 9.1 and Figure 9.4 compares the base case ram used for physical testing, validation of simulation model and FEA studies to Ram Design 1. The main differences between the two designs are the V-blade width and the lower lip.

9.2.1 Geometry

Ram Design 1 has a smaller V-blade width for the upper ram and does not have a lower lip as shown in Figure 9.1 (b). The lower shear rams used in the two cases have the same blade width and shape. The same rake angle (3deg) is also considered.

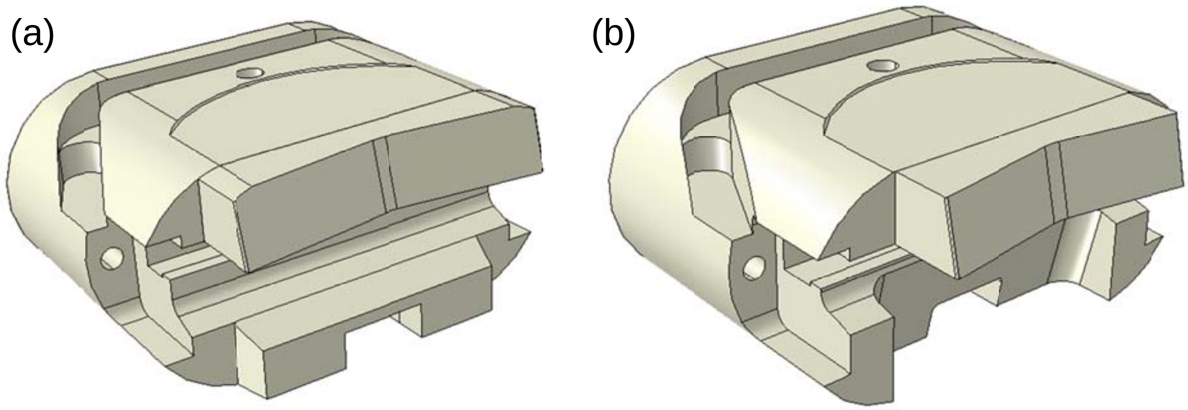


Figure 9.1: Cameron Type U (a) Base Case – Shearing Blind Ram (b) Ram Design 1

9.2.2 Model Setup

A 9.84 ft long, 3.5" OD S-135 drill pipe with a thickness of 0.368" is used for the analysis. As per the benchmark model the drill pipe is positioned such that 7.55 ft is above the shear ram blades (Figure 9.2). The material properties, damage data, contact conditions, boundary conditions used for the drill pipe are the same as the ones used in the validation study (refer to Section 6.3.4).

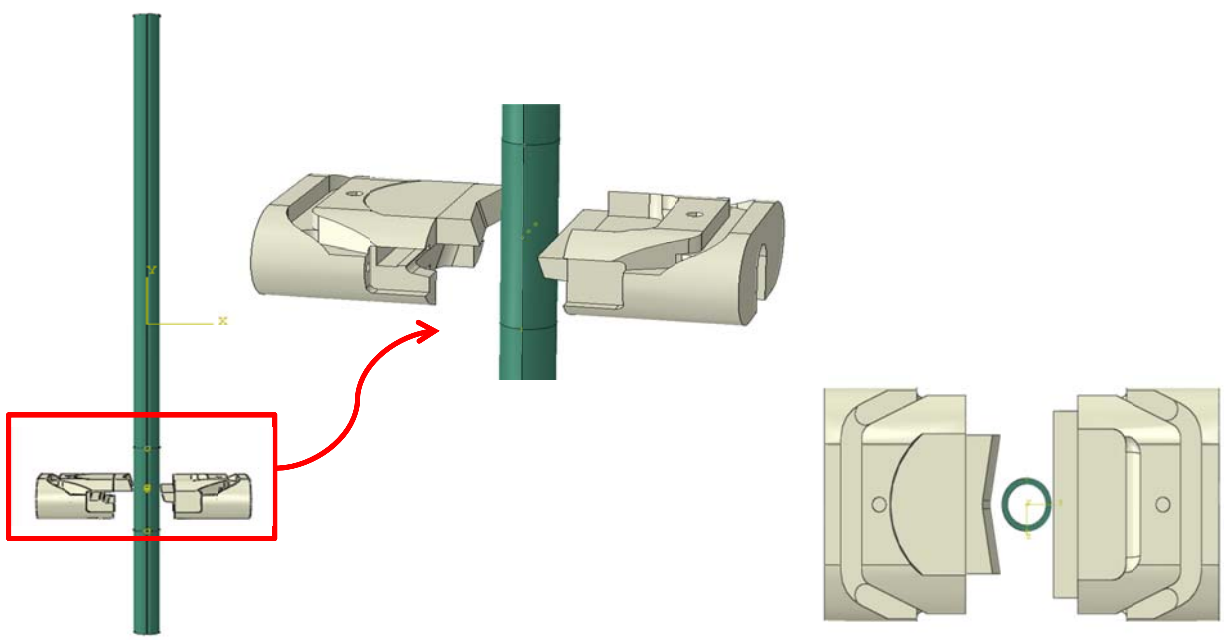


Figure 9.2: Typical FE Configuration - Front View of Assembly

9.2.3 Centralized Drill Pipe Results

The force required to shear the drill pipe is plotted with respect to the displacement of the ram for both the base case and ram design 1 and presented in Figure 9.5. The maximum shearing force is similar to the benchmark model however there is a noticeable difference in the force post shearing, after 1.5inch displacement. The force for Ram Design 1 drops immediately to zero while the benchmark model force remains high. This is because in the benchmark model the lower lip of the ram is still in contact with the pipe. As the rams close further the force on the rams starts to increase again. For the benchmark model the force does not increase above the maximum force required to shear. However for Ram Design 1 the force to shear approaches 390,000 lbf, higher than the force to shear. It is taking a considerable force to squash the lower fish into the packer groove. While the constraints of the model are such that they prevent the lower pipe from falling after it has sheared the process and force required to form the lower fish can potentially impact the ability of the rams to close and seal. Further evaluation of the fish forming process is recommended.

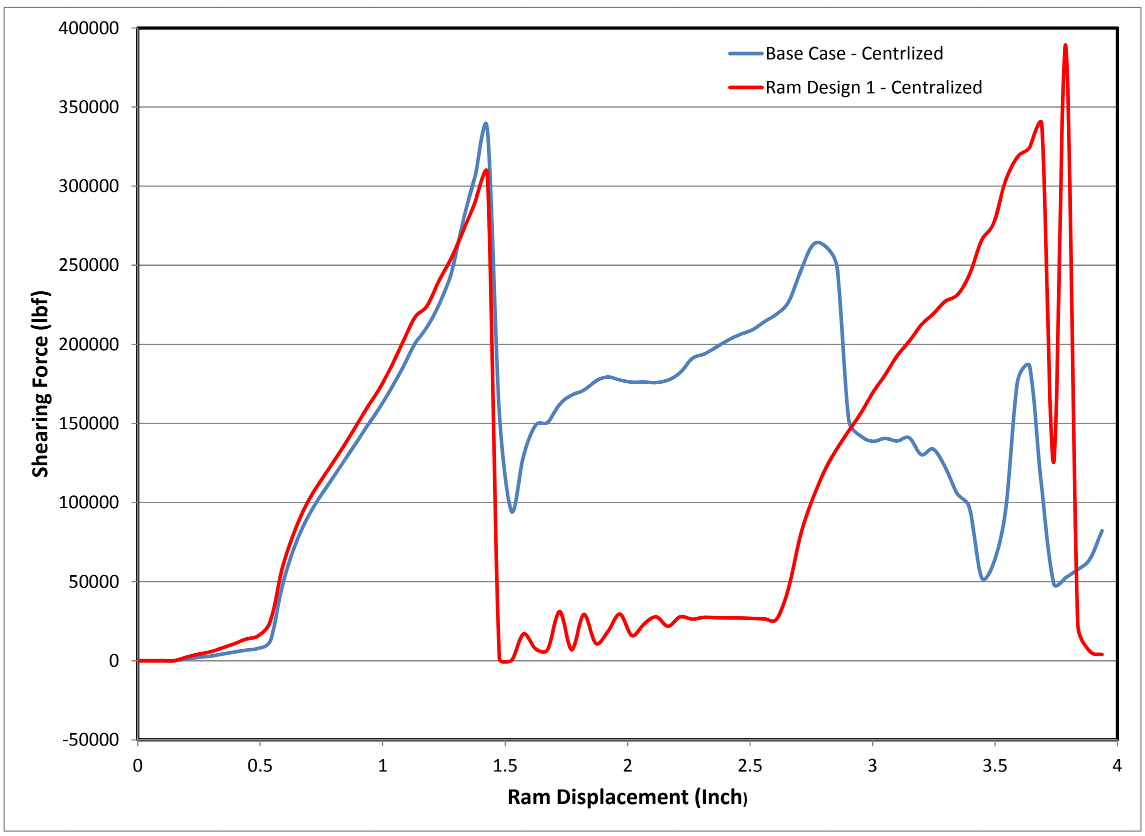


Figure 9.3: Shearing Force vs Ram Displacement (Base Case vs. Ram Design 1)

9.2.4 Non-Centralized Drill Pipe Results

A 5.5" S-135 drill pipe having a thickness of 0.361" and 23.9 lb/ft is modeled by positioning it to the wall of the BOP bore as shown in Figure 9.4.

The material properties, damage data, contact conditions, mesh, boundary conditions used for the drill pipe are the same as the ones used in the validation study (refer to Section 6.3.4).

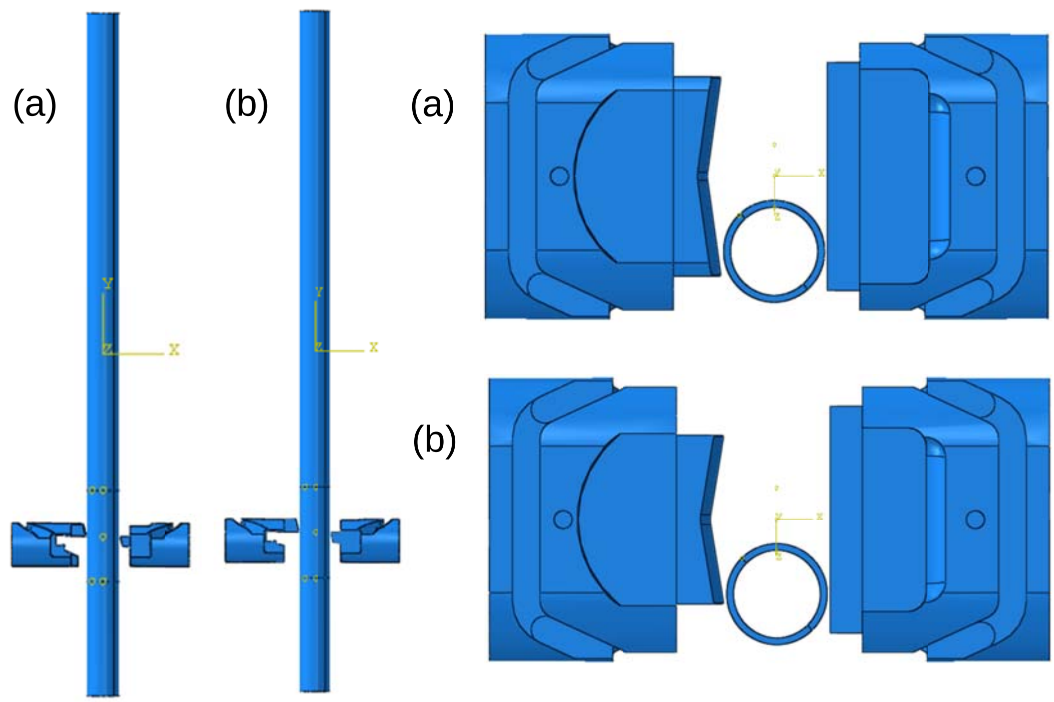


Figure 9.4: Assembly in Front and Top View (a) Base Case – Shearing Blind Ram (b) Ram Design 1

Simulations are performed using both sets of shear rams and it is observed that Ram Design 1 is not able to completely shear the drill pipe. This is due to the smaller width of the upper ram blade which doesn't come in contact with the entire surface of the drill pipe making it harder to shear. Initially the sharp corner of the blade pierces through the pipe and a crack propagates to the remaining pipe surface trying to shear the drill pipe. Base case is able to shear the drill pipe as the V-blade is wider and contacts a larger portion of the drill pipe compared to Ram design 1.

Non-centralization can cause the unsheared portion of drill pipe to get in stuck between the rams making them difficult to move and close the well as shown in Figure 9.5 and Figure 9.6. This is consistent with the observations made in Section 7.2.1 which indicates that full bore coverage with the shearing rams is required to guarantee successful shearing and sealing. If full bore shearing is not achievable then some method of centralization to move the pipe within the shearing zone is essential.

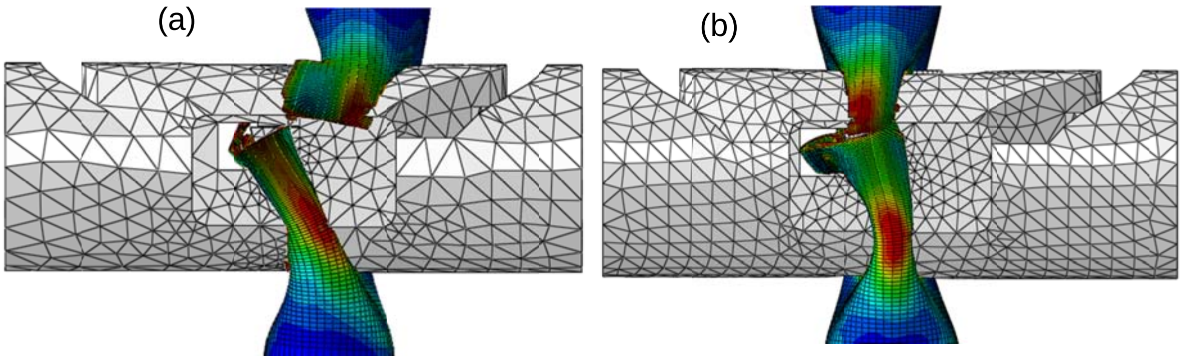


Figure 9.5: Assembly of sheared drill pipes (a) Base Case – SBR (b) Ram Design 1

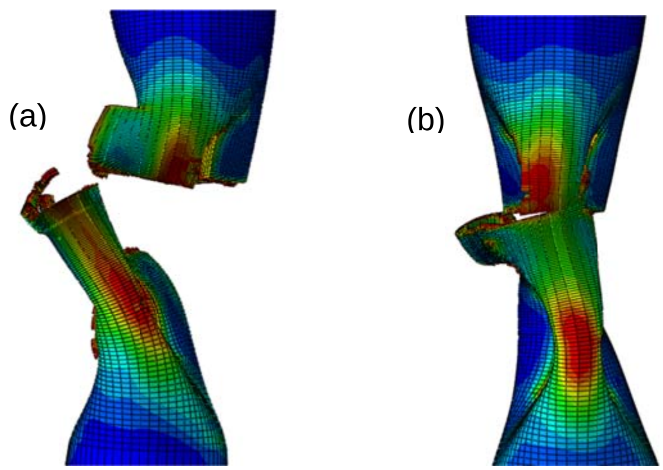


Figure 9.6: Sheared drill pipes (a) Base Case – SBR (b) Ram Design 1

9.3 RAM DESIGN 2 – FULL BORE COVERAGE AND CURVED BLADE PROFILE

Ram Design 2 has curved blades and covers the entire well bore and has some of the features of the T3 Shear All Ram discussed in Section 8.3. These rams are selected as they can be more efficient in centralizing the drill pipe. The sealing of the well bore is not considered and therefore no elastomers are modelled. The major focus is on the efficiency of shearing the drill pipes under different loads and positions in the well bore.

9.3.1 Geometry

The cad geometry is developed based on the patented drawings without dimensions. The upper and lower ram blade profiles are the same except they are inverted as shown in Figure

9.7 and a rake angle of 3 degrees is provided to the shear ram blades. A curved profile is also provided for the ram surface that helps in sealing the well and holding the sheared drill pipes without much deformation.

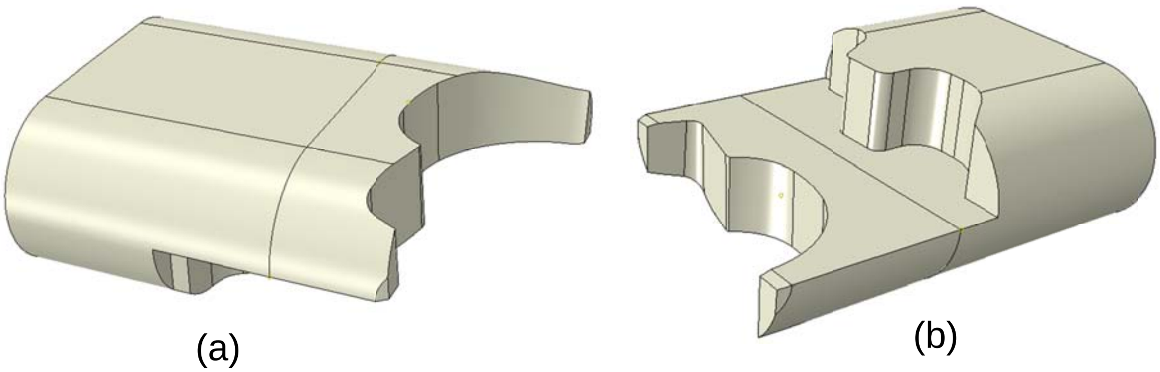


Figure 9.7: Ram Design 2 – Upper and Lower Shear Rams

9.3.2 Model Setup

A 9.84 ft long, 3.5” OD S-135 drill pipe with a thickness of 0.368” is used for the analysis. The drill pipe is positioned such that 7.55 ft is above the shear ram blades similar to the validated model as shown in Figure 9.8. The material properties, damage data, contact conditions, boundary conditions used for the drill pipe are the same as the ones used in the validation study (refer to Section 6.3.4).

Figure 9.9 shows the meshed upper and lower rams. The shear rams are allowed to move only in the x-direction with a velocity of 0.197 inch/sec similar to the validated model.

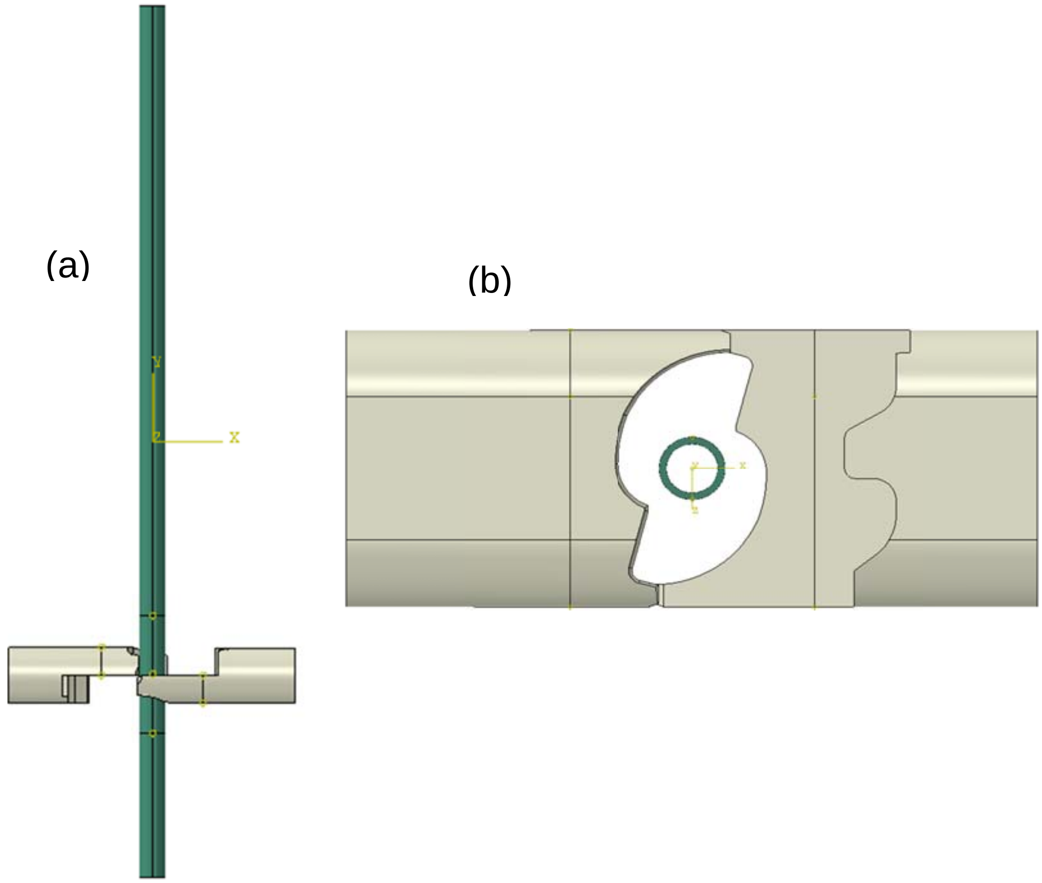


Figure 9.8: Drill Pipe and Shear Ram Assembly

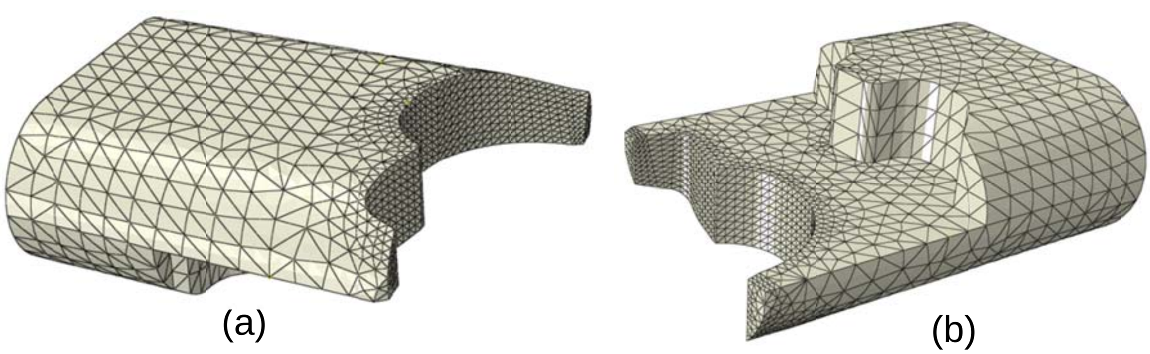


Figure 9.9: Meshed Shear Rams

9.3.3 Centralized Drill Pipe Results

The position of shear rams and the shape of the 3.5" drill pipe at different time intervals during the shearing process are captured in isometric and top views as shown in Figure 9.10 and Figure 9.11. Initially the drill pipe is deformed and the shearing takes place separating the top and bottom parts of drill pipe. The separated top and bottom drill pipes are stuck between the blade and the other shear ram curved face.

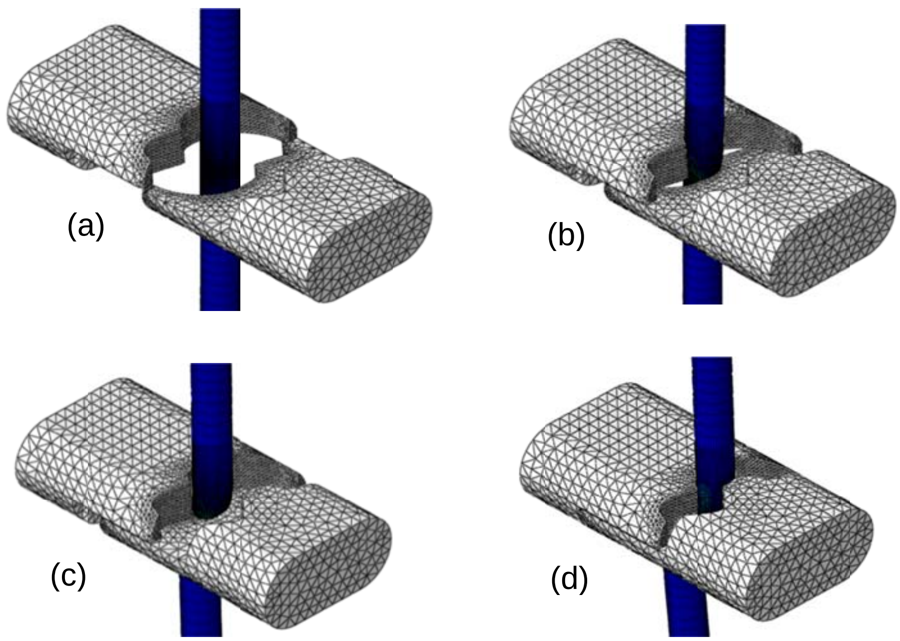


Figure 9.10: Isometric View, 3.5" Drill Pipe Centralized in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.55", (c) Ram Displacement = 3.15", (d) Ram Displacement = 4.97"

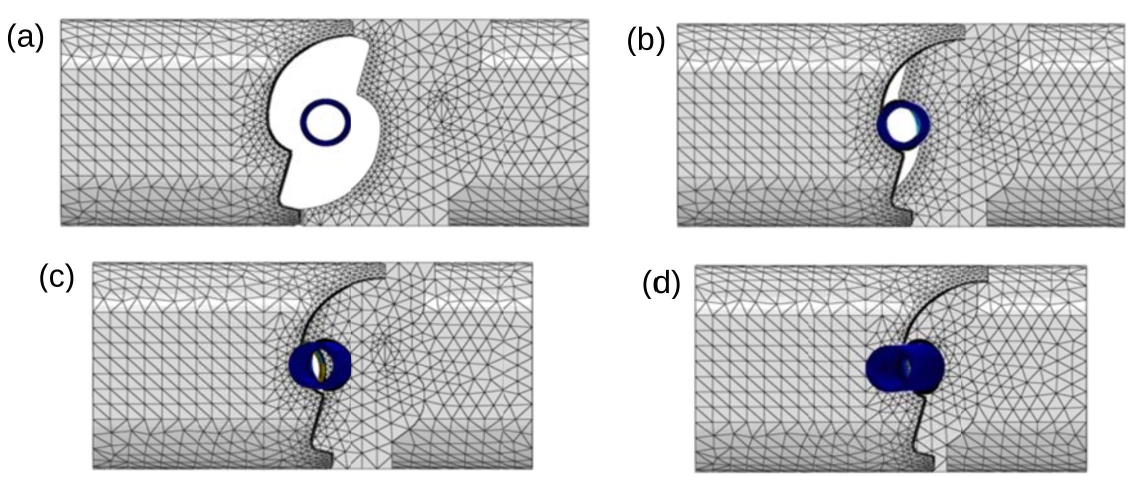


Figure 9.11: Top View, 3.5" Drill Pipe Centralized in the BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.55", (c) Ram Displacement = 3.15", (d) Ram Displacement = 4.97"

Figure 9.12 provides the shearing force versus ram displacement curve and it is observed that the shearing force increases during the deformation phase of drill pipe and the maximum shearing force is observed during shearing. After shearing, the shearing force is close to zero as there is no bending or flattening of the sheared drill pipes. The maximum shearing force is 244,643 lbf. This is a drop of 27% compared to the base case validated shear ram model (336,160 lbf). This is also a lower force than that observed during the physical test (296,800 lbf). This reduction in forces is believed to be a result of the higher contact area between the shear ram and drill pipe due to the curved blade profile.

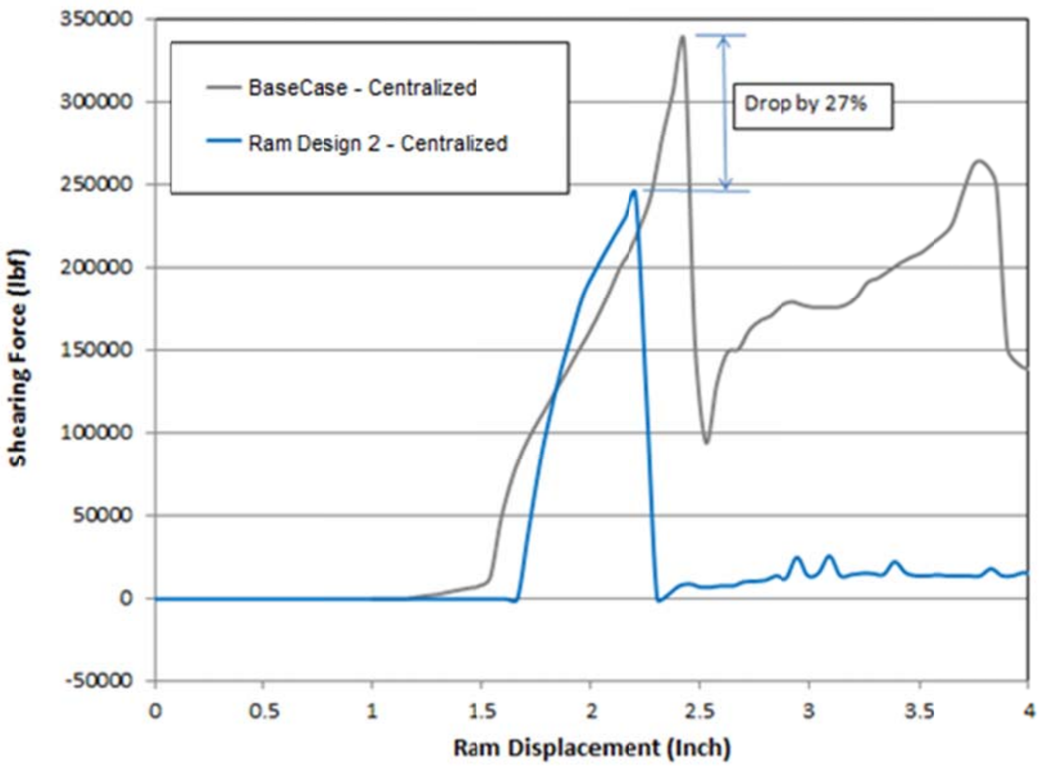


Figure 9.12: Shear Force vs. Ram Displacement (Ram Design 2 - Centralized Drill Pipe and Validated Model)

9.3.4 Non-Centralized Drill Pipe Results

Two non-centralized drill pipe cases are considered.

- Case 1 – In the first case, the drill pipe is positioned 4.55" from the center of BOP (Figure 9.13 (a)). At this position the drill pipe comes in contact with the steep angle of the shear ram blade.
- Case 2 – In the second case the drill pipe is placed against the inner wall of the BOP (Figure 9.13 (b)).

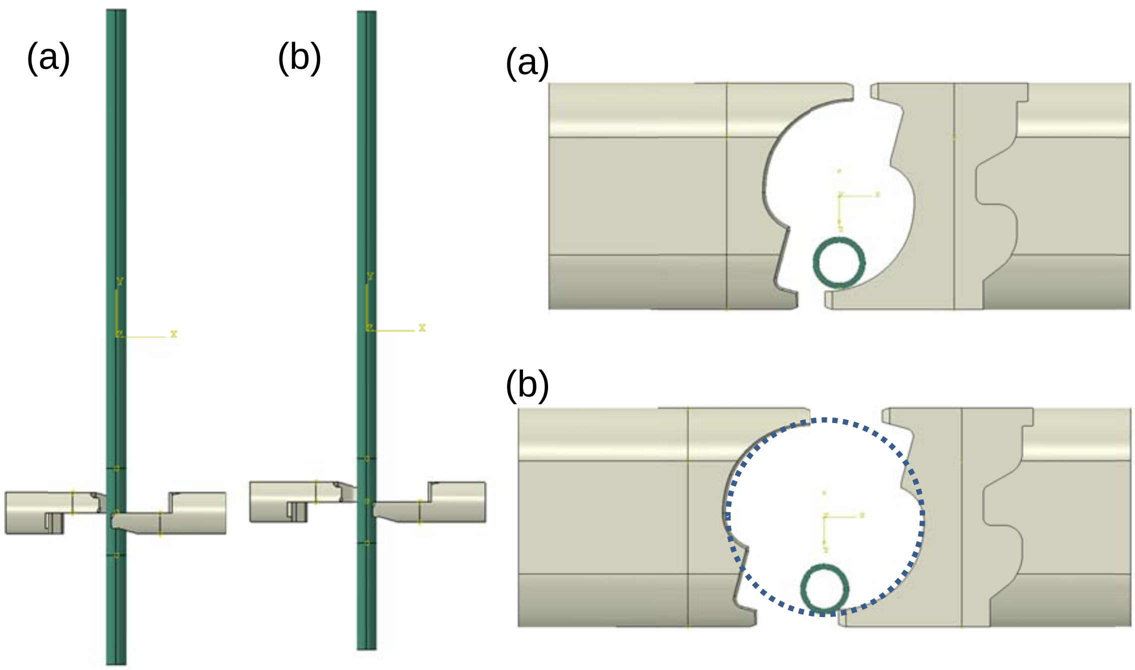


Figure 9.13: Non-centralized Drill Pipe Shear Ram Assembly (a) Drill pipe positioned on the curved blade profile, (b) Drill pipe positioned against the inner wall of the BOP

For case 1, the position of the shear rams and the shape of the 3.5" drill pipe at different time intervals during the shearing process are captured in front and top views as shown in Figure 9.14 and Figure 9.15. As the ram starts moving, the drill pipe comes in contact with the steep curvature of the lower ram blade and slides inwards as shown in Figure 9.15 (b) and (c), highlighting the centralizing feature of this shear ram.

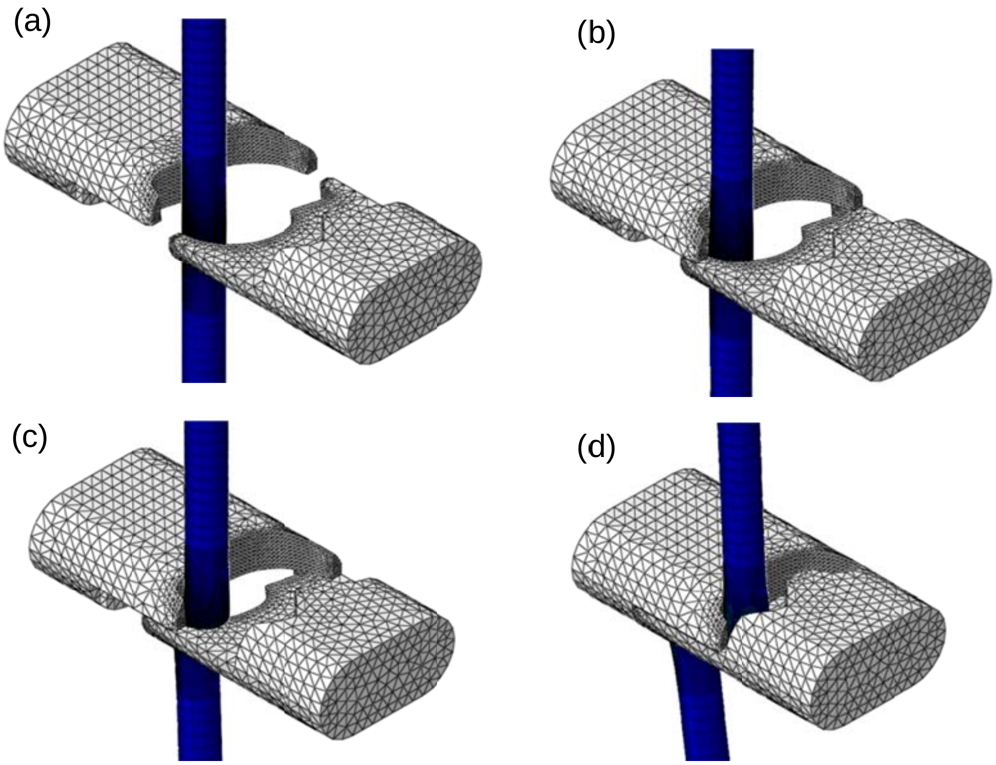


Figure 9.14: Isometric View, 3.5" Drill Pipe Non-Centralized by 4.55" from Center of BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 1.96", (c) Ram Displacement = 2.95", (d) Ram Displacement = 6.3"

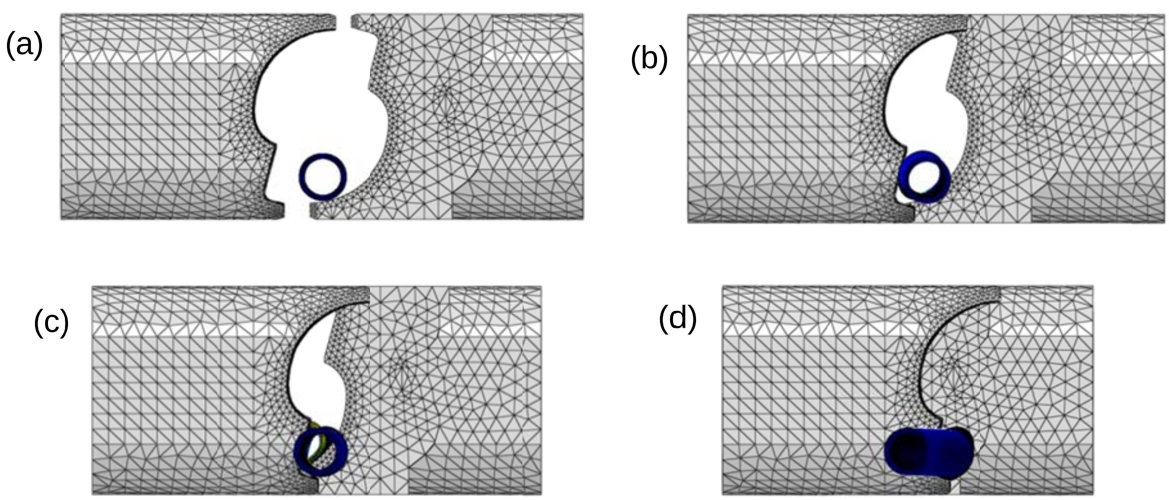


Figure 9.15: Top View, 3.5" Drill Pipe Non-Centralized by 4.55" from Center of BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 1.96", (c) Ram Displacement = 2.95", (d) Ram Displacement = 6.3"

For case 2, the drill pipe against the BOP wall, the position of shear rams and the shape of 3.5" drill pipe at different time intervals during the shearing process are captured in front and top views as shown in Figure 9.16 and Figure 9.17. As the ram starts moving, the drill pipe comes in contact with the lower ram and is initially bent as shown in Figure 9.16 (b) and deforms in the region of contact before shearing completely as in Figure 9.16 (c).

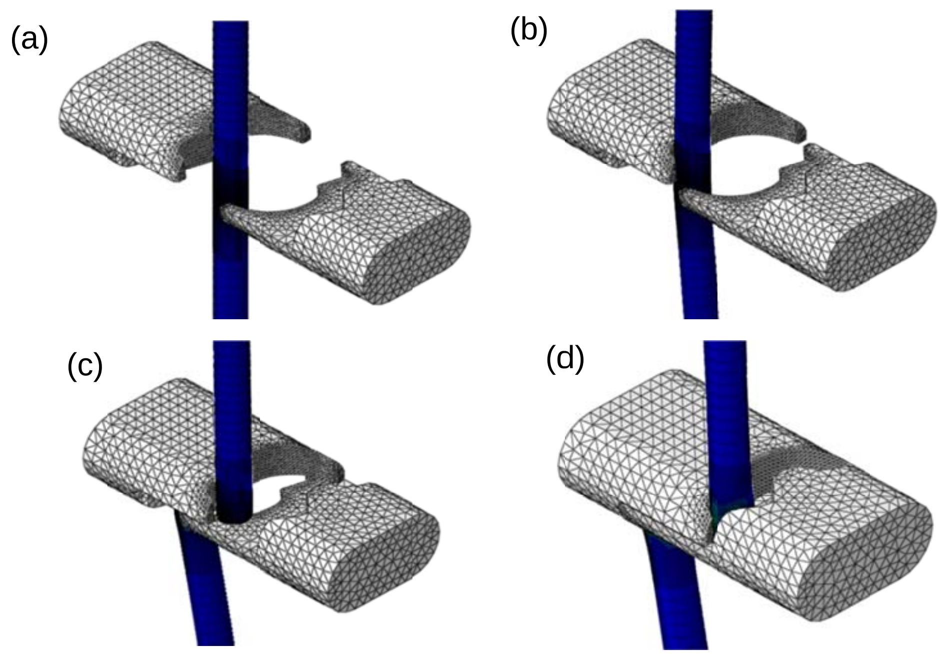


Figure 9.16: Isometric View, 3.5" Drill Pipe Non-Centralized by 5.06" from the Center of BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.36", (c) Ram Displacement = 4.92", (d) Ram Displacement = 8.7"

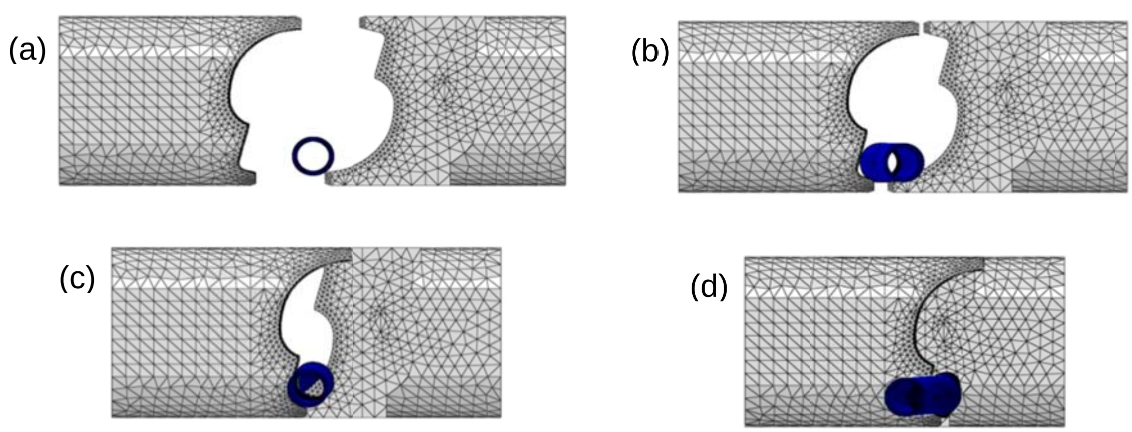


Figure 9.17: Top View, 3.5" Drill Pipe Non-Centralized by 5.06" from the Center of BOP Bore (a) Ram Displacement = 0, (b) Ram Displacement = 2.36", (c) Ram Displacement = 4.92", (d) Ram Displacement = 8.7"

The force required to shear the drill pipe in both positions are shown in Figure 9.18. It is observed that for the case where the drill pipe positioned on steep curved blade profile, the force increases with respect to ram displacement until the shearing happens and drops to nearly zero. After that the sheared drill pipes are bent as the rams propagate to close the well and this requires a small magnitude of force. For the case where the drill pipe is positioned against the BOP wall two peaks are observed as shown in Figure 9.18 (green). The first peak occurs when the crack is initiated due to the contact between the front corner of the lower ram and the second peak is when the drill pipe is completely sheared. After shearing the force abruptly drops close to zero and thereafter a small amount of force is required for the shear rams to close the well. The shearing force from both non-centralized cases is lower than that for the centralized case (Figure 9.12). In the non-centralized positions the rams cause an initial bending of the pipe and the knife like action of the curved blades help in the shearing process.

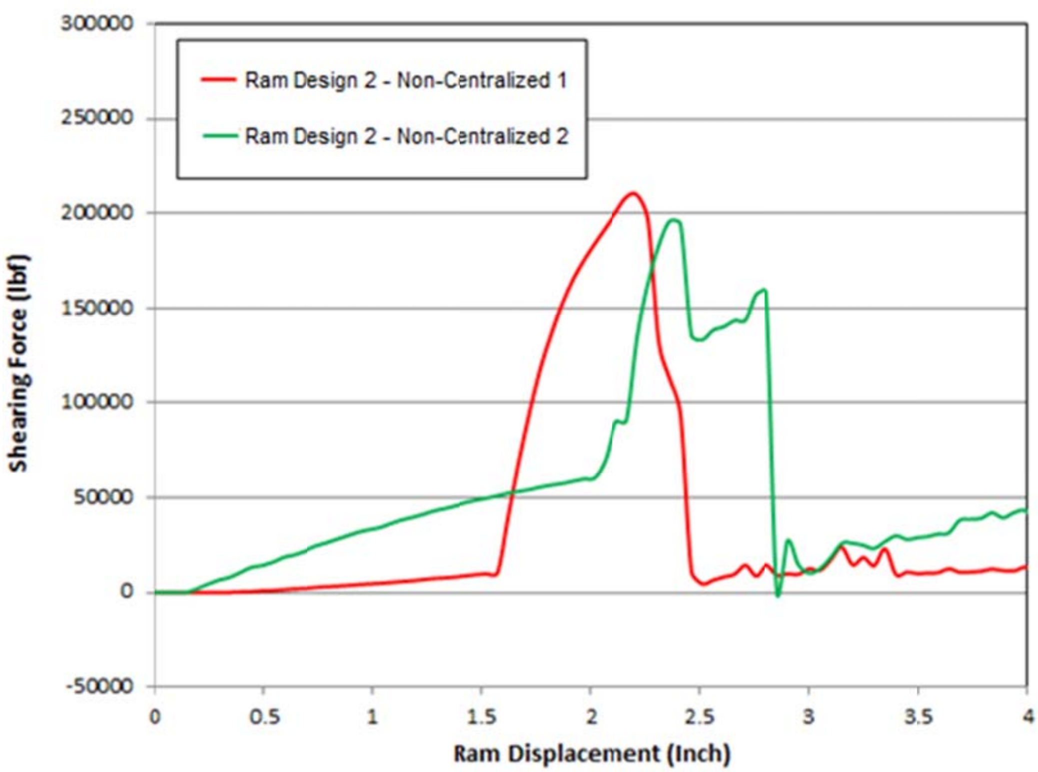


Figure 9.18: Shearing Force vs. Ram Displacement for Different Positions of Drill Pipe for Ram Design 2

Figure 9.19 and Figure 9.20 illustrate the clean cut of the upper and lower drill pipe sections for both non-centralized cases.

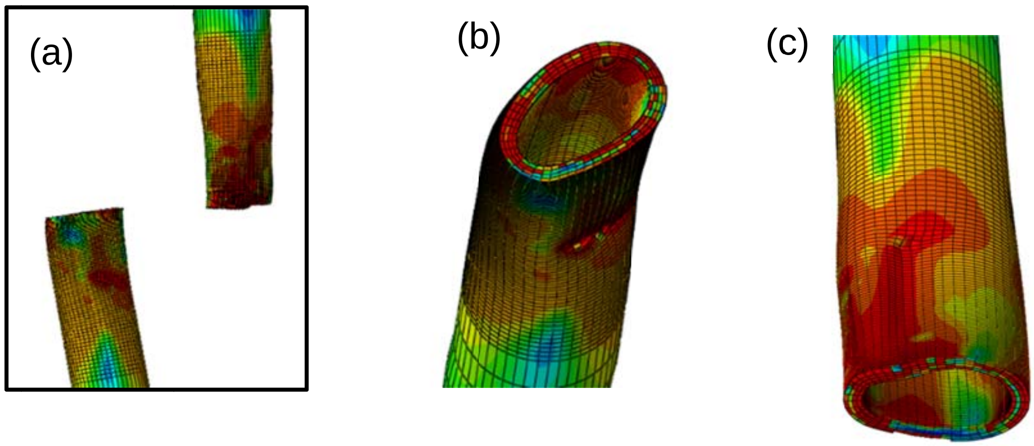


Figure 9.19: Sheared 3.5" Drill Pipe positioned on steep curved blade profile (Non-Centralized 4.55" from BOP Center) (a) Top and Bottom Pipe, (b) Bottom Drill Pipe, (c) Top Drill Pipe with Sheared Cross Section

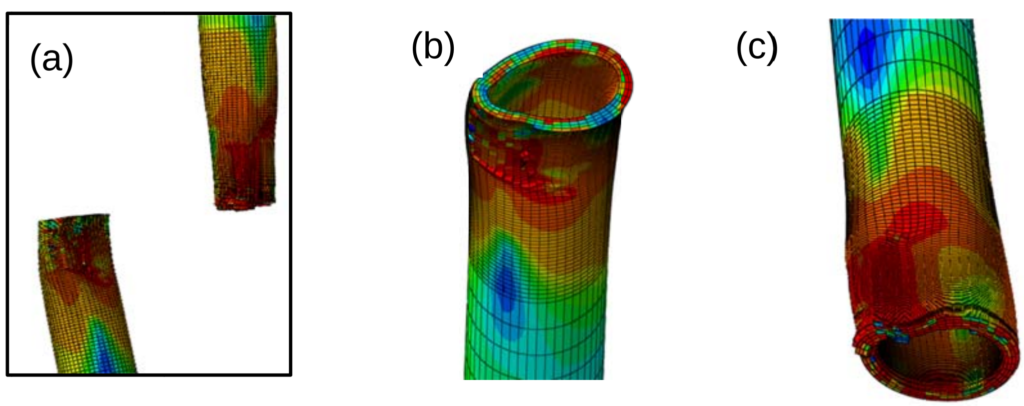
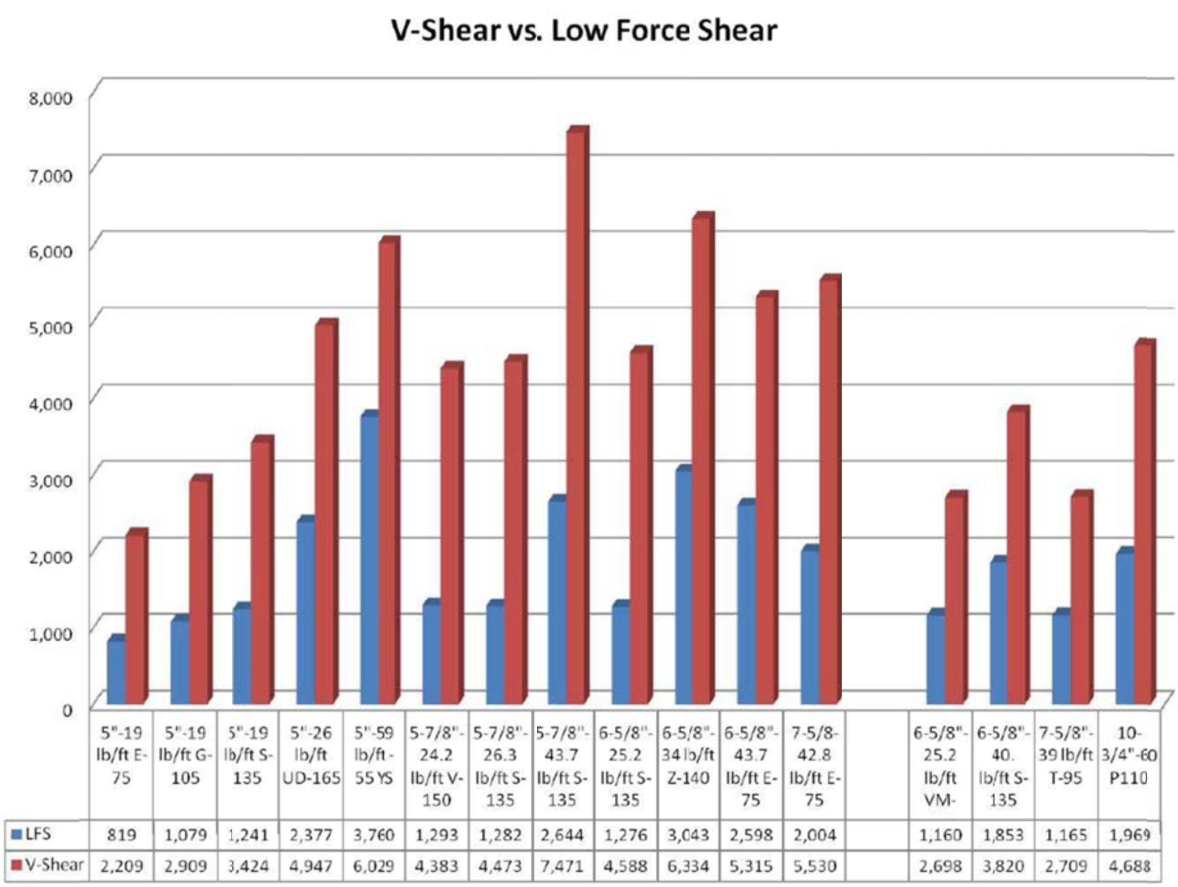


Figure 9.20: Sheared 3.5" Drill Pipe positioned against BOP wall (Non-Centralized 5.06" from BOP Center) (a) Top and Bottom Pipe, (b) Bottom Drill Pipe, (c) Top Drill Pipe with Sheared Cross Section

9.4 RAM DESIGN 3 – PIPE PUNCTURING AND CENTRALIZING

The third shear ram design has similar features to the NOV Low Force Shear Ram discussed in Section 8.2. No analysis has been performed on this ram type but some key lessons from earlier in this study can be applied to its features. By raising stress in a limited region and allowing crack propagation through the drill pipe the ram requires lower force than a more traditional v-blade ram design. This puncturing effect was also observed in Section 7.2.1 where the corner of the shear ram punctured the drill pipe. The force required to shear the pipe was much less as a result of the puncturing. Figure 9-21 presents a comparison of the NOV low force shear ram performance vs. the V-Shear systems. All testing was performed by NOV. The LFS ram requires much lower shear force compared to the v-shear systems used in the test.



	5"-19 lb/ft E-75	5"-19 lb/ft G-105	5"-19 lb/ft S-135	5"-26 lb/ft UD-165	5"-59 lb/ft - 55 YS	5-7/8"-24.2 lb/ft V-150	5-7/8"-26.3 lb/ft S-135	5-7/8"-43.7 lb/ft S-135	6-5/8"-25.2 lb/ft S-135	6-5/8"-34 lb/ft Z-140	6-5/8"-43.7 lb/ft E-75	7-5/8-42.8 lb/ft E-75		6-5/8"-25.2 lb/ft VM-	6-5/8"-40. lb/ft S-135	7-5/8"-39 lb/ft T-95	10-3/4"-60 P110
LFS	819	1,079	1,241	2,377	3,760	1,293	1,282	2,644	1,276	3,043	2,598	2,004		1,160	1,853	1,165	1,969
V-Shear	2,209	2,909	3,424	4,947	6,029	4,383	4,473	7,471	4,588	6,334	5,315	5,530		2,698	3,820	2,709	4,688

Figure 9-21: NOV Low Force Shear Ram Performance vs. V-Shear [26]

9.5 RAM DESIGN 4 – UPPER AND LOWER V SHAPED RAMS WITH CENTRALIZING ARMS

The fourth shear ram design has similar features to the GE 5k Blind Shear Ram discussed in Section 8.4. This design has V-blades for both the upper and lower shear rams and guide arms on either end of the upper ram to move the drill pipe within the shearing zone. The lower ram has slots on either side of the blade to seat the guides in the closed position.

A review of [19] highlights some of the key features of this design (Figure 9.22):

- The distance between guide arm tips, measured from the inside surface of each arm tip is approximately equivalent to the BOP bore diameter, facilitating full bore coverage.
- The tip of the guide arm extends further forward than the shearing blade leading edge.
- The wedge surface is vertical and makes an acute angle (15 to 30 degrees) with respect to the shear ram longitudinal axis, helping to move the drill pipe within the shearing zone.
- The outboard surface of the guide arm can be at an acute angle (15 degrees) with respect to the shear ram longitudinal axis.

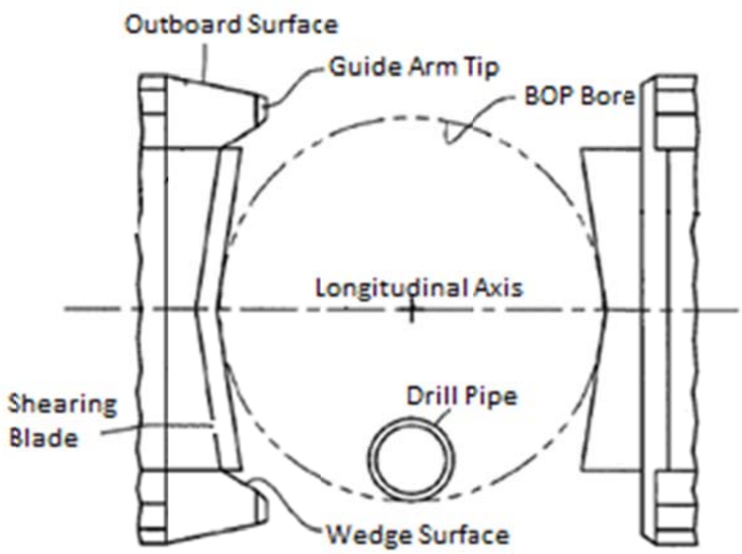


Figure 9.22: Key Features of Ram Design 4

10.0 OTHER ADVANCES IN SHEARING TECHNOLOGY

10.1 GENERAL

There are many other advances in shearing technology. Some of these are discussed in this section.

10.2 ENOVATE EN-TEGRITY SHEAR SEAL VALVE

The En-Tegrity Shear Seal Valve system [21] replaces the ram-type valves in conventional BOPs by utilizing gate valves to allow for greater shearing force. The design features a two-stage piston operation, with the first piston generating the shearing force and the second moving the gate valves into the closed position. The testing with the 7 3/8-in. size, has been validated by several major operators. The 3/8-in can generate 1 million lbs of force.

7-3/8" En-Tegrity is capable of shearing 3-1/2" S-135 Drill collar tool joints and the 13-5/8" En-Tegrity is capable of shearing 6-5/8: S-135 Drill collar tool joints (Figure 10-1).

Each valve has two independent barrier elements that provide metal-to-metal seals throughout the operation. The process is very simple, using conventional gate valves in a new way as the gate valves provide a bi-directional sealing capability that protects the critical sealing areas during the close/shearing operations.

The metal-to-metal sealing (Figure 10-3) also provides an extended temperature envelope, improved chemical compatibility and a more rugged sealing environment that is resistant to erosion, all of which results in reduced maintenance. The En-Tegrity system enhances safety by separating the shearing and sealing functions, ensuring that the sealing area of the gates is unaffected by any metallic fragments.

Enovate is also working on ways of integrating components of the En-Tegrity system into existing BOP designs.

A 7-3/8” version of the En-Tegrity system is scheduled to be deployed for a major operator on Australia’s North West Shelf, with delivery of the first unit planned for May 2013 and an additional 10 to 14 units delivered later in the year. A 13-5/8” model has undergone extensive testing, and the company hopes to introduce the first unit in early 2014.

Figure 10-1: Qualification Summary Shearing [22]

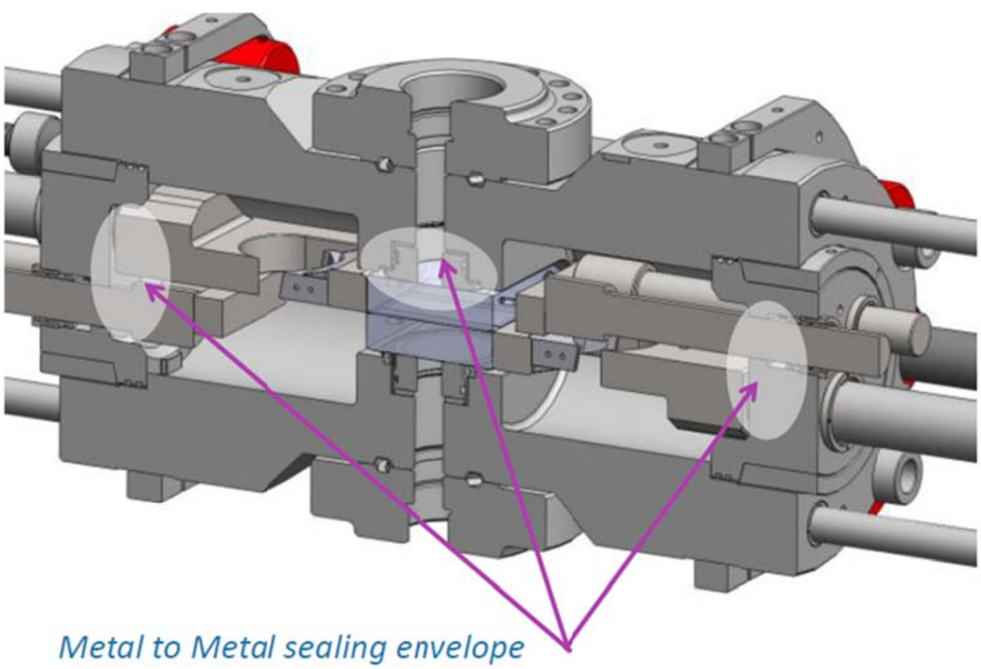


Figure 10-2: Metal to Metal Sealing Envelope [22]

10.3 GE Hydrostatic Pressure Assisted Shearing (HPAS) System

This system from GE is under development, it uses hydrostatic pressure of the sea water to significantly increase the shearing force without requiring additional accumulator bottles. The accumulators are used for storage for supplying hydraulic pressure during shearing. The HPAS can reduce the accumulator bottle count by up to 90 percent and can be reset for multiple uses without requiring any subsea intervention [4].

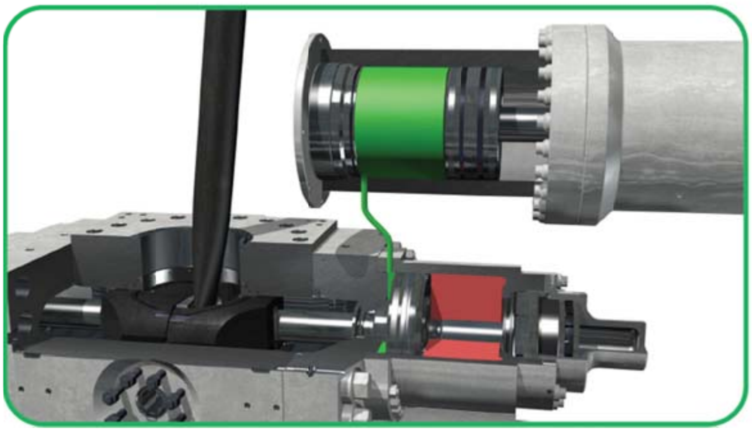


Figure 10-3: GE Hydrostatic Pressure Assisted Shearing [28]

10.4 Explosive Shearing

Shell is developing multiple technologies which use explosives to handle unplanned well control issues. These technologies are designed to take control of the well from the surface or subsea. Some of the technologies are:

10.4.1 Collapsible Insert Device (CID)

Collapsible Insert Device is a well control device which uses charges inside a double walled pipe to crimp and restrict the pipe to stop the flowing well. CID is included in the casing design and the explosions push the casing to create a restriction. Once it is activated, an explosion pushes in the inner walls, filling the space inside the pipe to reduce the flow (Figure 10.5). The addition of the insert adds half of an inch to the diameter of the pipe. The force from the explosion does not damage the outer casing and the blockage in the inner casing can be drilled out later to open the well bore without any damage to the outer casing.

The CID is activated from the surface using acoustic signals. The acoustic signal equipment sends vibrations downhole along the pipe. Battery powered relays would be needed along the casing to sustain the acoustic signals. The acoustic signal can operate on multiple frequencies and tune itself to cope with a dynamic environment.

So far testing has been done using 4-1/2”, 6-5/8”, 8-3/4” and 10-3/4” test casing samples which have yielded the results shown in Figure 10.6. The CID is being designed to be run as part of casing string in sizes from 7-5/8” through 14”.

Shell is planning on conducting a field trial of the CID in the uncemented portion of the primary protective casing. Shell foresees multiple CID installed above the reservoir [40].

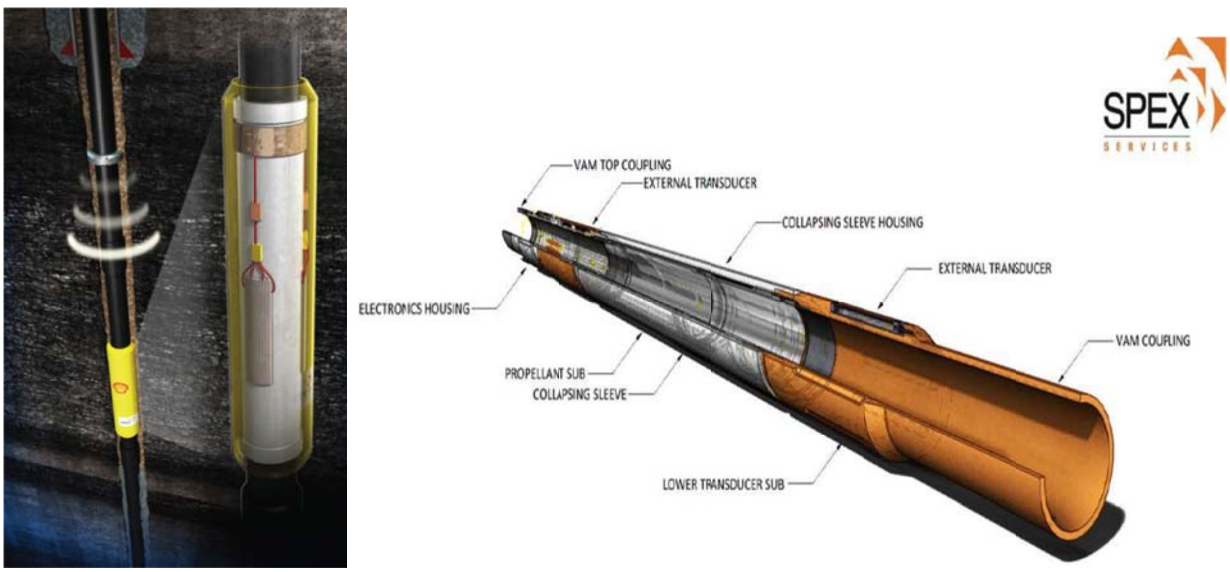


Figure 10.4: CID [40]

Figure 10.5: Restricting the Well Flow [40]

Figure 10.6: Results from Testing on 4-1/2", 6-5/8", 8-3/4" and 10-3/4" Casing [40]

10.4.2 Emergency Separation Tool (EST)

Emergency Separation Tool is designed to cut the pipe in well control situations where the BOP cannot shear the pipe. EST will be installed in the riser above the BOP and is controlled independently from the BOP. EST uses shape charges placed in the riser to cut the pipe even if the pipe is moving. The cut drill pipe drops into the well bore and the BOP can be closed to secure the well.

The shaped charges used in the EST are similar to the ones used in perforating casing. The amount of charges used on perforating casing during well completion operation is far higher than the amount of charges used on EST. The EST has rings of charges which are doubled for redundancy and has cut through a 9-1/4" drill collar during a test. This polyurethane holder on the other side of circle was not damaged during this test.

Shell was planning on doing subsea testing of the EST in November 2012 in the GOM. The test was planned in 6,000 ft to 8,000 ft of water from an anchor handling vessel to a suction pile on the sea floor. A 9-in drill collar and 16-in casing would be included in the test setup. The activation of the EST can be done from the surface using acoustic signals and requires multiple key operation where three switches must be armed before the EST can be fired to avoid any accidental firing [39].

There are three wireless ways to activate the EST. The primary system which will be used from the rig is the direct sight sonar where an encrypted signal is sent to a sonar beacon which is transferred to a receiver on the EST which activates the detonator. The second system to activate is from a boat near the well. The boat will drop the dunker in the water which will be used to pick up the signal and transmit it to the EST. The third system will be activated from an offsite location [41].

Figure 10.7: Components of Emergency Separation Tool [39]

10.4.3 Riser Separation/Severance Tool (RST)

Riser Separation Tool is designed to cut the riser in an emergency situation such as DP loss or drift off. It has a clamp which is retrofitted externally on any size or type of riser above the BOP. The clamp could be installed in the rig when the riser is being run in the water or can be installed by an ROV subsea.

RST contains explosive shaped charges which surround circumferentially the riser, choke and kill lines, hydraulic lines and other auxiliary lines. The RST is activated acoustically from the surface. After activation, all the shaped charges fire simultaneously to cut through all the pipe in its way. The riser and all the auxiliary lines are completely severed which allows the rig to disconnect permanently from the riser.

Shell was planning on doing subsea testing of the RST in November 2012 [39].

Figure 10.8: RST Clamps [40]

Figure 10.9: Sheared Pipe Using RST & RST Assembled on the Riser and Auxiliary Lines [40]

10.5 LASER SHEARING

A patent was granted in 2012 to Chevron and Foro Energy for a laser assisted BOP technology [42]. This new technology uses high power laser energy to shear pipe within the BOP to increase chances of sealing the well.

10.6 SHEARABLE DRILL COLLAR

During drilling with subsea BOP, if there is a well control situation which cannot be controlled then the driller could shear the pipe in the wellbore so the rig can be disconnected from the well head. If the drill collars are being used in the wellbore at that time then the drill collars cannot be sheared using existing BOP systems.

Radoil has developed a new style of drill collar which can be sheared and sealed using regular BSR. This drill collar is called a shearable drill collar and has an outer diameter of 6.75” with 0.5” wall shell, and an inner internal diameter of 2.157” with 0.109” wall bore thickness. The hollow space between the outer shell and the inner shell is filled with lead.

Compared with the weight of solid steel drill collars of 108.3 lb-ft the shearable drill collar has a weight of 141.9 lb-ft. As the drill collar is filled with lead the drill collar is shearable and provides the required weight and stiffness needed for normal drilling operations.

In June 2011, Cameron shear ram with 22” actuator was used to shear a shearable drill collar at 963 psi and consequently followed with a low (250 psi) and high (10,000 psi) wellbore pressure test to make sure that the BOP is sealing after the test. There was also a similar successful drill collar shearing test conducted using the Hydril shear rams.

Figure 10.10: Sheared Drill Collar and Shear Ram Used for Testing [43]

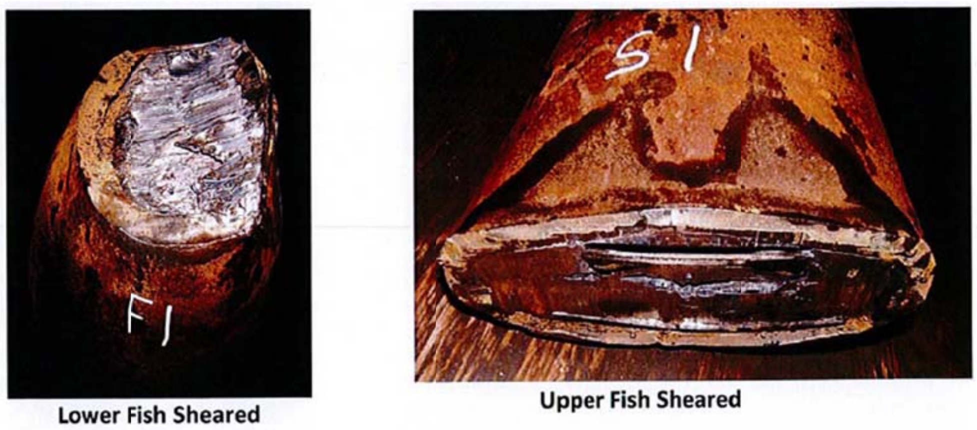


Figure 10.11: Sheared Drill Collar Using Shear Ram [43]

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Appendix A:

13-5/8” BOP Shear Tests

APPENDIX A 13-5/8" BOP SHEAR TESTS

The primary objective of the shear test was to shear 3-1/2" drill pipe using the 13-5/8" BOP and capture relevant information such as shearing force, shearing time, and deformed shape of the sheared pipes, which would then be used to validate a computer simulation model. Two pipe specimens were tested which were obtained from the same drill pipe.

A.1 TEST OBJECTIVE

The following tasks were performed to meet the objective of the test.

- Shear 3-1/2", 13.3 lbs/ft, S-135 Drill pipe in a 13-5/8" BOP in the following condition:
  - The drill pipe is centralized inside the bore
  - Non flowing well
- Obtain the maximum pressure needed to shear the pipe
- Measure the total time to shear the pipe
- Obtain snap-shots and physical samples of the sheared drill pipe
- Measurements of the sheared pipe cross section

A.2 TEST EQUIPMENT DETAILS

The shear test was performed on May 31, 2013 at Archer's facility in Amelia, LA.

The BOP Assembly is of type U BOP 13-5/8" - 5,000 psi Ram BOP PN S6113. The other details are shown in the tables below.

Table 11.1: Bonnet Details

Item	Value
Manufacture Date	April 2010
Product Description Code	CCP
Type	DBCE U
Temperature	T-20
Working Pressure	5,000 psi
Serial No.	SRT - 6113

Table 11.2: Ram Details

Ram Components	Material	Serial No.
Upper Shear Ram	4140 - 235 Min, 258 Max Hardness	OGR 13183
Lower Shear Ram	4140 - 235 Min, 258 Max Hardness	OGR 13183
Bonnet	N/A	OGR 4661
Large Bore Tandem Booster	N/A	AC 27723

A.3 PRE-JOB INSPECTION

The following are confirmed before the test:

- The procured drill pipe was measured and the material properties were documented (Table 11.3 through Table 11.6).
- It was confirmed that the pipe used for shearing was not damaged. See Figure 11.2.
- The shear rams and bonnet were visually inspected to confirm there was no damage. The BOP information was documented in Table 11.7.
- The drill pipe length was measured as 130" and the length of the pipe inside the BOP was 55.75".

Table 11.3: Pipe Information

Test	Pipe Diameter (in)	Measured Wall Thickness (In)	Density (lbs/ft)	Material Grade
1	3.5	0.393" Top part of the sheared pipe 0.393" Bottom part of the sheared pipe	13.3	S-135
2	3.5	0.385" Top part of the sheared pipe 0.390" Bottom part of the sheared pipe	13.3	S-135

*Note: Wall thickness of 0.368" is stated in the Quality Documentation Package [6] provided by Archer

Table 11.4: Pipe - Mechanical Test Data [2]

Specimen	Position	Size (in)	Heat No.	Tensile Strength (Psi)	Yield Strength (Psi)	Elongation %
Tube	2,707	1.000	458,898	161,500	155,400	19.5

Tube	2,706	1.000	458,898	157,500	150,100	21.5

Table 11.5: Pipe - Longitudinal Charpy-V Notch Impact Data (Ft-lbs) [2]

Size (mm)	Temp (F)	Heat No.	Position	A	B	C	Avg	Shear (%)
10 X 7.5	72	458,898	2,707	65	65	62	64	90
10 X 7.5	72	458,898	2,706	65	63	61	63	90

Table 11.6: Serialization Log [2]

Test No.	Pipe Serial No.	Box Heat Code	Pin Heat Code
1	NZ78620	85P	85G

Table 11.7: BOP Information

BOP Type	BOP Bore (In)	Working Pressure (psi)	BOP Type	BOP Close/Piston Area (in^2)	Shear Ram Type	Operator Type	Regulator Set Pressure (psi)
U BOP SBR	13.625	5,000	U	224	Blind Shear and V Shear	Large Bore Tandem Booster	3,000

- The pressure gauges and chart recorders used were inspected to make sure they were within calibration and met requirements of API Specification 16A Section 8.2.2 that states:

  "*Pressure-measuring devices - Test pressure-measuring devices shall be either pressure gauges or pressure transducers and shall be accurate to at least + 0.5 % of full-scale range. Pressure gauges shall have a minimum face diameter of 100 mm (4 in). Pressure measurements shall be made at not less than 25 % or more than 75 % of the full-pressure span of the gauge. Pressure-measuring devices shall be periodically recalibrated with a master pressure-measuring device or a deadweight tester at 25 %, 50 % and 75 % of full scale*". The pressure gauge used for the shear tests was a 0-5,000 psi range gauge. The chart pressure recorder used for the shear tests was a 0-5,000 psi range recorder.

Figure 11.1: Condition of the Bonnet and Shear Rams Before the Test

Figure 11.2: Drill Pipe Before Shearing

A.4 TEST SCHEMATIC

The schematic in Figure 6.3 shows the BOP shearing test setup. The BOP was connected to a control panel to control the opening and closing of the shear ram. The pressure chart recorder was also connected to the BOP and measured the pressure needed to close and open the ram.

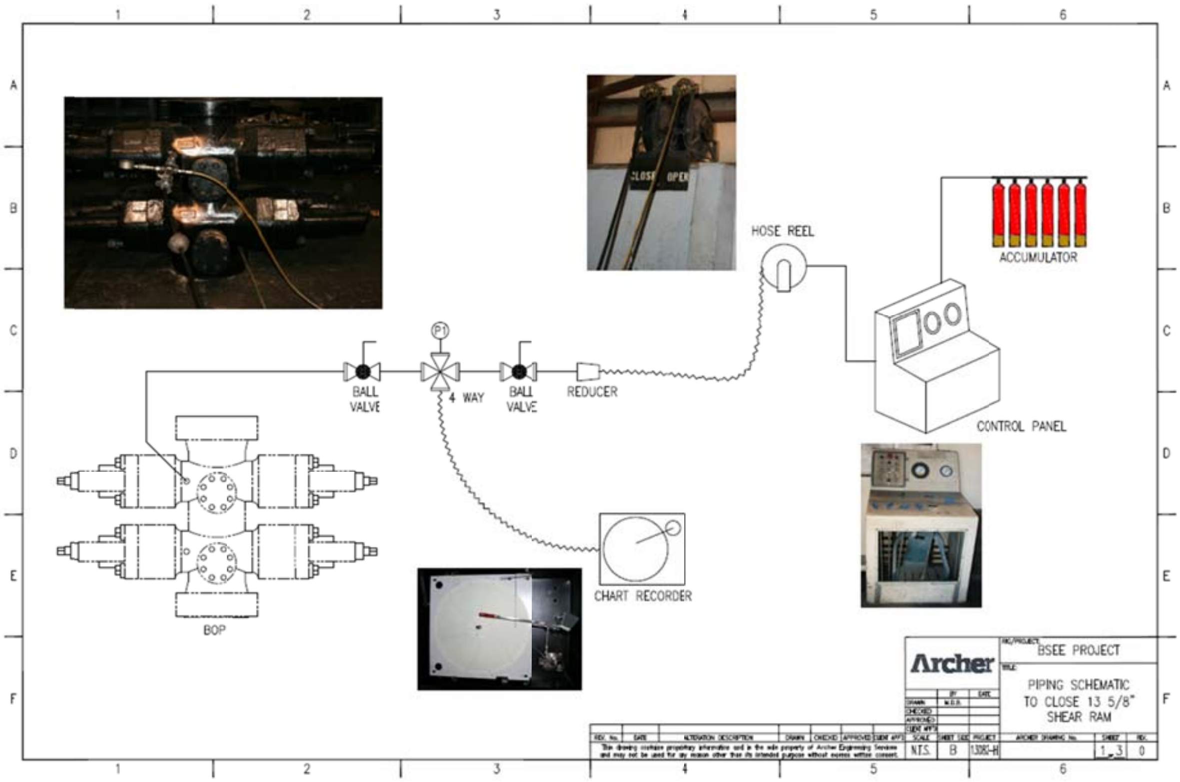

Figure 11.3: Shearing Test Schematic - 13-5/8" - To Close Shear Ram

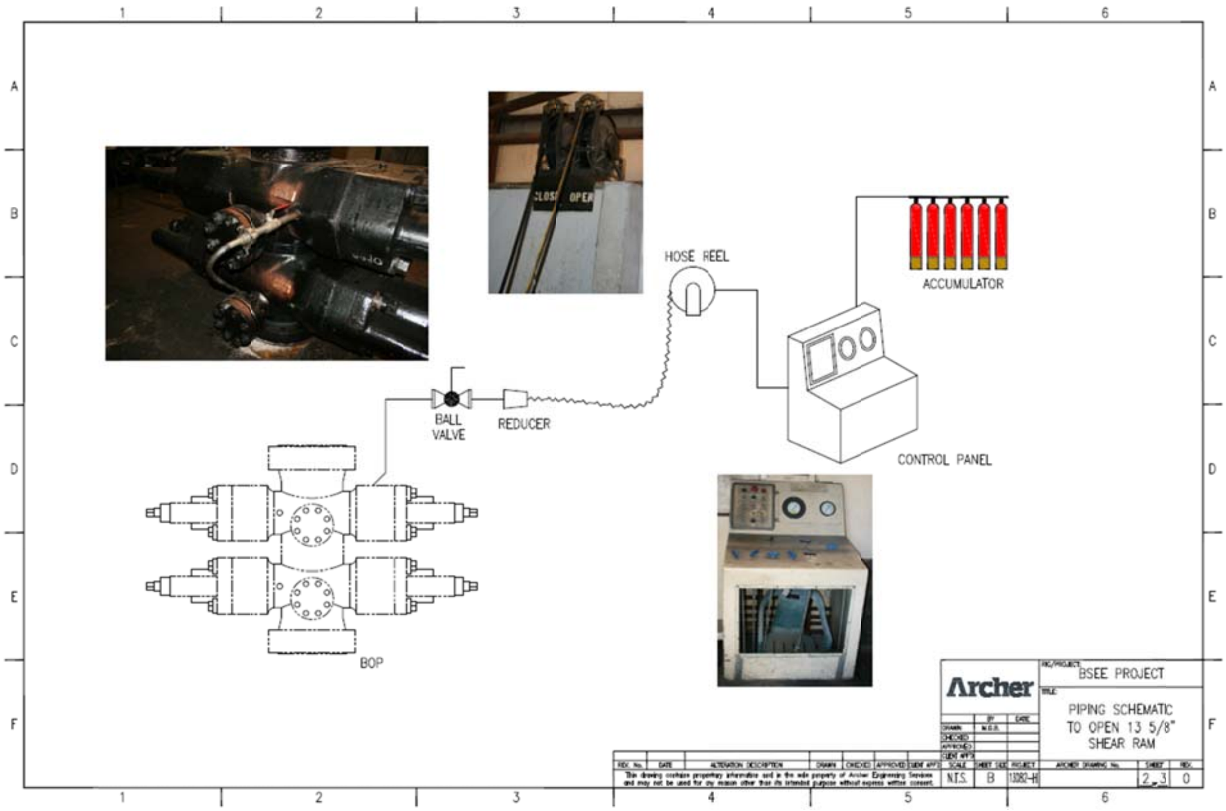

Figure 11.4: Shearing Test Schematic - 13-5/8" - To Open Shear Ram

A.5 PRE-TEST SETUP [5]

The following procedures were performed chronologically before the test.

- Installed new rubber seals into Shear rams
- Installed Shear rams into blowout preventer
- Installed new bonnet seals into each Blow Preventer bonnet seal groove
- Closed bonnets and torque bonnet bolts to manufacture's recommended torque
- Connected opening line to the Blowout preventer
- Connected closing line along with manifold, pressure gauge and pressure transducer to Blowout preventer
- Connected the line from transducer on closing line manifold to chart pressure recorder
- Connected high pressure test line with gauge to Blowout preventer and to test pump
- Checked the calibration stickers on pressure recorder for closing line and pressure recorder in test pump control panel
- Made sure that the rams are in full open position

A.6 TEST PROCEDURE

Two pipe specimens were tested. Procedure set by Archer [5] was followed during the test and is listed below.

3. Suspended drill pipe from the shop crane to be sheared vertically over the BOP and lowered it into the well bore until lower end touches the top of the test stump, then lift the pipe 2". This will insure sufficient pipe length is below the rams (Figure 11.5). The drill pipe was centered in the Ram Bore. The total length of the pipe in the ram bore was 130".
4. Set the closing unit manifold pressure to manufacturers recommended closing pressure.
5. Closed the rams and sheared the pipe in a single location
6. Opened the bonnets and removed the upper and lower fish. The first shear test is complete
7. The drill pipe was placed again in the Blowout preventer as per procedure step 1 and the rams were closed to shear the pipe.
8. The bonnets were opened and the upper and lower fish were removed. The second shear test is complete.
9. The shear rams were disassembled from the BOP and inspected. There was no damage on the shear ram blades observed (Figure 6.12).

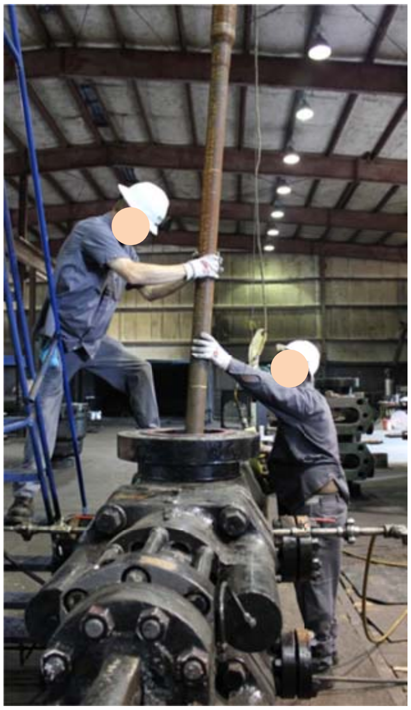

Figure 11.5: Pipe Centered in the BOP

Figure 11.6: Test Setup

A.7 TEST OUTPUT

The highest pressure which was recorded to shear the pipe for Test 1 is 1,400 psi and that for Test 2 is 1,250 psi (Figure 6.5 and Figure 6.6, respectively).

The shearing process for the two tests was recorded and the time taken to shear the pipe in the first and second test was found to be about 7 seconds and 6 seconds, respectively (Table 6.1). The time count starts when the shear ram touches the pipe and ends when the shearing process is complete.

The shear force (Table 6.1) needed to shear the pipe was calculated by multiplying the area of the large bore tandem piston (224 sq. in) to the maximum pressure needed to shear the pipe.

Table 11.8: Test Output

Test	Measured Shear Pressure (psi)	Calculated Shear force (lbs)
1	1,400	1400 psi X 224 sq. in = 313,600
2	1,250	1250 psi X 224 sq. in = 280,000

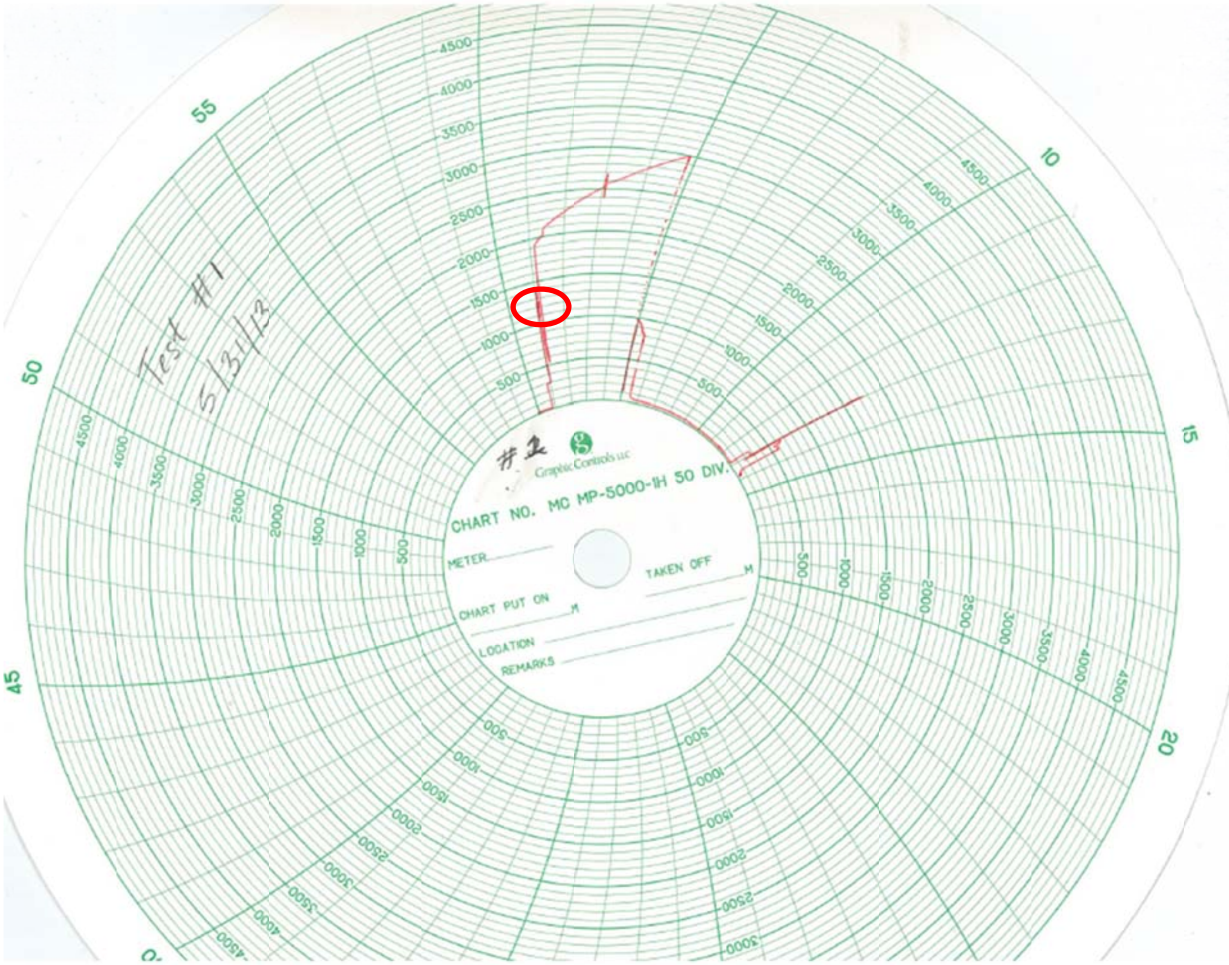

Figure 11.7: Shear Test 1 - Time (Minutes, Radially) Versus Pressure (psi, Vertically)

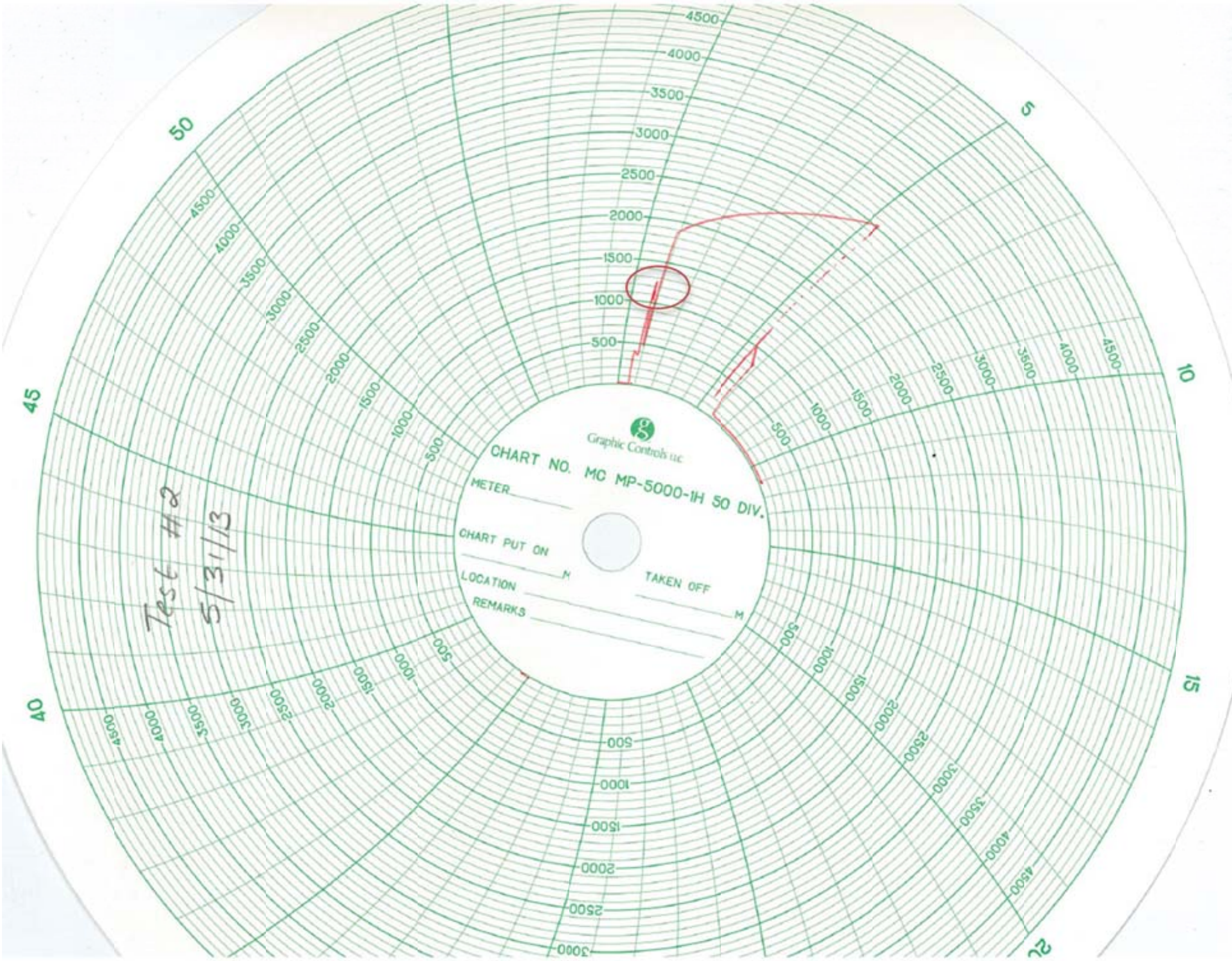

Figure 11.8: Shear Test 2 - Time (Minutes, Radially) Versus Pressure (psi, Vertically)

Further, the pressure needed to shear the pipe was calculated using the OEM shearing formulas (Figure 6.7) and crosschecked using the OEM spreadsheet and the value is found to be 1,844 psi (Figure 11.9). The actual shearing pressures observed during the test are lower than the calculated pressures from OEM shearing formulas. The calculated shearing pressure values used by OEM are conservative and can be considered as the upper bound pressure which may be seen during the shearing operation.

Required Shear Pressure Calculation Worksheet for Equation 1
(No Wellbore Pressure Effects)

IMPORTANT: ENSURE TUBULAR MEETS THE RERQUIREMENTS OF STEP 1 (PAGE 3) BEFORE PROCEEDING TO THE CALCULATIONS.

BOP TYPE 13-3M/10M U e.g 18-10M UBOP (REF. Table 2)

OPERATOR TYPE LBT e.g SBT (REF. Table 2)

MAXIMUM ALLOWABLE OPERATING PRESSURE OF OPERATOR 3,000 e.g 3000 psi

TUBULAR TYPE 3.5" 13.3ppf S135 e.g 5" 19.5 ppf S135

C_1 = 224 From Table 2 on page 6

C_3 = 0.23 From Table 3 on page 7

ppf = 13.3 Specified (lbf/ft)

σ_{yield} = 135,000 Minimum yield strength (psi) (reference section 3 on page 2)

Calculated Shear Pressure, P_{shear} is given by :

$$P_{shear} := \left[\frac{\left(C_3 \cdot ppf \cdot \sigma_{yield}\right)}{C_1}\right]$$

P_{shear} = 1844 Operator shear pressure (psi)

Note: P_{shear} required to be less than the maximum allowable operator pressure

Figure 11.9: Hand Calculations using Shear Formula [7]