Effect of wear on the burst strength of L-80 steel casing

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Abstract. Casing wear has recently become one of the areas of research interest in the oil and gas industry especially in extended reach well drilling. The burst strength of a worn out casing is one of the significantly affected mechanical properties and is yet an area where less research is done. The most commonly used equations to calculate the resulting burst strength after wear are Barlow, the initial yield burst, the full yield burst and the rupture burst equations. The objective of this study was to estimate casing burst strength after wear through Finite Element Analysis (FEA). It included calculation and comparison of the different theoretical burst pressures with the simulation results along with effect of different wear shapes on L-80 casing material. The von Misses stress was used in the estimation of the burst pressure. The result obtained shows that the casing burst strength decreases as the wear percentage increases. Moreover, the burst strength value of the casing obtained from the FEA has a higher value compared to the theoretical burst strength values. Casing with crescent shaped wear give the highest burst strength value when simulated under nonlinear analysis.

1. Introduction
The deep wells or extended reach wells have seen an increasing problem of casing wear [1]. These wells often follow highly-deviated, horizontal, and multilateral well path trajectories leading to the drill string coming in contact with the casing leading to wear. Wear is the removal of material from a surface as a result of dynamic conditions [2]. It can be caused due to the rotational effect of the drill string or due to the contact force in a dogleg section when a directional drilling is conducted. In the years prior to 1980s, casing wear was not considered as a big problem in oil and gas industry [3]. However, recently more emphasis has been given on the investigation and monitoring of casing wear given that wear has significant effect on the strength of the casing. This is achieved by considering the various loads, specifically the burst and collapse loads, which the casing needs to resist during its life time. The burst strength of a casing is the ability of a casing to resist the internal pressure exerted on the casing before failure [4]. If a thorough analysis of the burst strength of casing is not performed, well control problem such as casing leakage, kick or blow out might occur. Thus, the resulting burst strength analysis is significant to overcome such undesirable scenarios and ensure good casing design.

This study estimates the casing burst strength after wear using Finite Element Analysis (FEA). Findings were compared with the theoretical values obtained from equations in literature. The scope of this work mainly focused on analyzing the mathematical equations developed to compute the
allowable internal pressure for a worn out casing and to generate various models using FEA to estimate the burst strength after wear. The initial, full and rupture yield strengths are estimated and compared with each other. The shape of the wear, as a factor impacting the magnitude of burst strength, is also studied in this work.

2. Literature Review

Casing wear has a significant impact in the performance of a casing in the life of a well especially for future plans in operations such as artificial lift. The oil and gas industry allocates additional investment per year on additional well thickness to allow for wear [3]. One of the main responsibilities of a well engineer is to design a casing that has the strength to withstand the various forces it may face in its life time. The three important mechanical properties that are used to describe the strength of a casing are collapse, burst and tensile strength. The customary practice to estimate the burst strength of a casing is by using the American Petroleum Institute (API) standard equation which is also known as Barlow’s equation as equation (1). Barlow’s equation related the internal pressure with the tensile strength of the pipe and its dimensions. In addition to Barlow’s equation, there are three other casing burst strength estimation equations which Wu and Zhang [1] had briefly discussed in their paper. The initial yield burst equation as equation (2) calculates the burst pressure as the casing yields at the inner diameter before reaching the entire wall thickness. The full yield burst equation as equation (3) is related to the pressure as casing yield throughout its entire wall thickness and the casing rupture burst equation as equation (4) refers to the pressure where ductile failure of the casing takes place [1].

Bradley [5] performed a theoretical analysis to determine the effects of wear on the burst strength of casing and showed that the API methods for determining burst resistance may result in burst values that have very low probabilities of failure.

Song, Bowen [6] conducted a study focusing on the burst strength of a casing after wear. An analytical solution for the hoop stress of worn casing was developed by dividing the entire worn casing into three shapes that are mirror to one another. This superimposition principle was used to obtain the induced hoop stress of the worn casing. Other studies were conducted to show assumptions of slotted ring in a casing wall can be used to create a more simplified casing wear models [1]. The research conducted by Wu and Zhang [1] reflects the relationship between casing wear, hoop stress and burst strength. They performed FEA modeling to study the effect of internal pressure on the hoop stress. They observed the casing is deformed into an oval shape when exposed to an internal pressure loading and zero external pressure [1].

Researchers studied the wear depth caused by the contact pressure applied to the inner wall of casing. They utilized different sizes of drill string to find the wear depth as a function of time [7]. Field studies have revealed the different parameters that affect the intensity of wear. The most common parameters are side loads, dogleg severity, chemical composition of drilling mud, ability of drill pipe to cause wear, resistance of casing to wear, rotation time and revolution per minute [8]. In directional wells, the rotating tool joint is forced by the drill string against the inner wall of the casing for a longer period of time. As a result, it grinds against the casing wall, creating material erosion in both the rotating tool and casing surfaces i.e. wear. The decrease in the thickness of a casing wall affects the geometry and load distribution on the casing.

Mark Haning, James Doherty [9] performed FEA modeling of an eccentrically worn casing to determine the burst capacity of a worn out casing. They analyzed the various casing burst strength equations i.e. API burst capacity equation, rupture burst strength equation and Klever Stewart’s burst capacity. Their research concluded as Barlow equation is more stringent compared to the rest of the existing burst strength equations.
3. Methodology

3.1. Material Properties
L-80 steel is used as the casing material in this project. The reasons for choosing L-80 casing are: (a) it is suitable for sour drilling environment, (b) it is widely available and (c) it is suitable for effective steam injection in shallow wells. The mechanical and physical properties of the casing material are summarized in table 1.

| Parameter                          | Value          |
|------------------------------------|----------------|
| Material Grade                     | L-80 Steel     |
| Length, L (mm)                     | 2000           |
| Nominal Outer Diameter, OD (mm)    | 244.475        |
| Nominal Wall Thickness, t (mm)     | 11.9888        |
| API Minimum yield strength (MPa)   | 552            |
| API Minimum Tensile strength (MPa) | 655            |
| Poisson ratio                      | 0.3            |
| Modulus of elasticity (MPa)        | 200,000        |

3.2. Theoretical Solution
The four equations used to estimate the theoretical values of burst strength of a worn out casing are mentioned in equation (1) – (4).

\[ P_{API} = \frac{1.75\sigma_y t}{D} \]  \hspace{1cm} (1)
\[ P_{API} = \frac{1.75\sigma_y 2t}{\sqrt{3} D} \left( 1 - \frac{t}{D} \right) \] \hspace{1cm} (2)
\[ P_{API} = \frac{1.75\sigma_y 2t}{\sqrt{3} D} \left( 1 + \frac{t}{D} \right) \] \hspace{1cm} (3)
\[ P_{API} = \frac{1.75\sigma_{ult} t}{D - t} \] \hspace{1cm} (4)

where, \( P_{API} \) is the burst strength of the casing under API standards, \( \sigma_y \) is the yield strength of the casing material, \( t \) is the casing wall thickness, \( D \) is the casing outer diameter, \( \sigma_{ult} \) is the ultimate tensile strength of the casing material.

3.3. Finite Element Modeling
The model involves a casing pipe of the required dimension and placing the defector wear accurately. Since the actual shape of a wear is irregular, three different wear models are used to represent the idealized model i.e. to represent the wear shape using regular geometric shapes. These wear models have varying depth and shape.

**Case 1**- Rectangular shaped wear

The first case represents a casing with a rectangular shaped wear as shown in figure 1.
The dimensional parameters for modelling case 1 are shown in table 2.

**Table 2. Dimensions for the models in case 1.**

| Wear depth (%) | Wear depth, d (mm) | Wear length, l (mm) |
|----------------|--------------------|---------------------|
| 20             | 2.39776            | 200                 |
| 40             | 4.79552            | 200                 |
| 60             | 7.19328            | 200                 |
| 80             | 9.59104            | 200                 |

**Case 2 - Crescent shaped wear**

The second case is developed by assuming that a crescent shaped wear is formed. The geometry of such wear is represented by figure 2.

**Figure 2. Geometry of cresent wear.**

The depth and length of the wear case is presented in table 3.

**Table 3. Dimensions for the models of case 2.**

| Wear depth (%) | Wear depth, d (mm) | Wear length, l (mm) |
|----------------|--------------------|---------------------|
| 20             | 2.39776            | 200                 |
| 40             | 4.79552            | 200                 |
| 60             | 7.19328            | 200                 |
| 80             | 9.59104            | 200                 |

**Case 3 - Multiple wear**

The third geometric model considers the possibility of multiple wear located on the casing. Figure 3 illustrates this case.
The data tabulated in table 4 show the wear depth in percentage as well as the length for major and minor wear on the casing.

**Table 4. Dimensions for the models of case 3.**

| Wear depth (%) | Wear depth, d (mm) | Minor Wear length, $l_1$ (mm) | Major Wear length, $l_2$ (mm) |
|----------------|--------------------|-------------------------------|-------------------------------|
| 20             | 2.39776            | 100                           | 200                           |
| 40             | 4.79552            | 100                           | 300                           |
| 60             | 7.19328            | 100                           | 400                           |
| 80             | 9.59104            | 100                           | 500                           |

Hexahedron mesh is used for the Finite Element Analysis. Figure 4 represents the FE model along with the meshing and a couple of boundary conditions. The meshing properties for each model described in above are presented in table 5.

3.4. Boundary conditions and Load applications

A symmetric boundary condition is applied on three edges of the casing model in order to be able to simulate a quarter of the casing pipe. Also at the end faces of the model all degrees of freedom are
fixed. The major loads applied are the internal pressure and axial load on the model. The internal pressure applied is increased until the casing equivalent Von Mises stress equals to the minimum tensile strength of the casing i.e. when the casing bursts. An axial load is applied at the ends of the pipe to represent the closed end of the pipe during a burst test. A displacement vector equivalent to zero is applied at the end of the pipes to constrain the pipe from moving.

Table 5. Mesh Property.

| Model | Wear Depth (%) | Number of nodes | Number of Elements |
|-------|----------------|-----------------|--------------------|
| Case 1 | 20             | 23566           | 11843              |
|       | 40             | 26194           | 13751              |
|       | 60             | 26497           | 13619              |
|       | 80             | 26828           | 13790              |
| Case 2 | 20             | 27022           | 14053              |
|       | 40             | 26491           | 13674              |
|       | 60             | 26295           | 13481              |
|       | 80             | 27386           | 14128              |
| Case 3 | 20             | 16684           | 8410               |
|       | 40             | 18566           | 9636               |
|       | 60             | 21428           | 11706              |
|       | 80             | 16686           | 8799               |

4. Result and discussion

4.1. Type of analysis
Both linear and nonlinear analyses are considered in this work. A linear analysis demonstrates a direct relationship between stress and strain. On the other hand nonlinear analysis allows for a nonlinear relationship between stress and strain beyond the yielding point and it takes into account the effect of temperature on material properties. The stress-strain curve for L-80 steel casing is shown below in figure 5.

![Stress-Strain Curve for L-80 steel casing.](image)
The models are simulated with increasing internal pressure loading (P) until the Von Mises Stress, $\sigma_{\text{Von Mises}}$, of the entire nodes ligament values is equal to the specific yield strength of the casing, i.e. 552 MPa. Figure 6 shows a sample output result of how the casing with a 40% wear depth percentage under nonlinear analysis looks like when exposed to an internal pressure.

**Figure 6.** Von Mises stress distribution for non-linear analysis of 40% crescent shaped wear depth.

The theoretical values plotted in figure 7 shows that Barlow’s equation gives the lowest value of burst strength whereas the rupture burst equation gives the highest value amongst the four theoretical equations. This is reasonable considering that the rupture strength model assumes burst after the casing string has completely failed or ruptured. Therefore, Barlow’s equation should be used in the casing design. As the burst strength is extremely crucial in well operations, the equation providing the lowest failure point is always noteworthy. The burst strength decreases as the wear depth percentage increases which is naturally expected [1]. It is also seen that all theoretical results tend to converge with increase in wear depth. This is because all the theoretical models depend on the t/D ratio. At higher wear depth, the ratio approaches zero and hence, the values begin to converge.

**Figure 7.** Theoretical casing burst strength values.
Figure 8 shows the graphical representation of the linear and non-linear FE analysis of a worn out casing with varying wear depth and shape respectively. The values for linear analysis of the casing shows similar trend as the analytical solution i.e. the burst strength values decrease in a similar trend with increase in wear depth percentage showing that the FE analysis validates the theoretical analysis. However, the linear and the theoretical results underestimate the burst strength of the casing material. This can be seen through the result for the nonlinear analysis which provides a higher burst strength value. The flattened trend between 40% wear depth and 60% wear depth as seen in figure 8 indicates that the material is able to absorb some of the stresses developed. This is related with the nonlinear response of the L-80 steel. Therefore, non-linear analysis is important to have a realistic estimate of the burst strength. Different shapes have different impact from the analysis and it is seen that the casing bearing crescent shaped wear has higher burst strength than rectangle or multiple wear. This is primarily due to the lower volume of material being lost through wear in crescent shape as compared to rectangular. Larger volume of wear results in lower burst strength and less than 10 MPa difference in burst strength is noted for the given wear geometry mentioned above.

**Figure 8.** Linear and Non-Linear FEA results for casing burst strength with wear.

The result from nonlinear analysis for a crescent shaped wear is selected to be the most representative of the actual burst strength condition for a worn out casing. The reason is that it takes into consideration the nonlinear material property of steel and the shape of the tool joint causing the wear. The values of burst strength obtained using this case are the highest among the other two cases. Barlow’s equation gives a smaller burst pressure value compared to the result from FEA as shown in figure 9. This comparison is crucial for the drilling engineers to estimate the onset of casing failure post Barlow’s burst strength estimation. It will enable the engineers to take the necessary steps in managing the pressures inside the wellbore.
5. Conclusion

The comparison between the existing theoretical burst strength results for L-80 steel are shown in this paper. It is seen that the rupture burst equation provides the highest burst strength while the Barlow’s equation provides the lowest value of burst strength. This suggests that using Barlow’s equation for initial prediction of casing burst strength is a better option as casing failure would occur around 10 MPa from that value. Linear and non-linear finite element analysis results for different wear shapes and depths are obtained and compared. Non-linear finite element results provide more realistic burst strength as compared to the linear or theoretical values. The non-linear analysis of the crescent shape wear seems to best predict the general type of wear in the extended reach wells. It is also seen that casing with crescent shape wear tends to have higher burst strength as compared to rectangular wear. The results of non-linear crescent shaped casing wear (highest value) are plotted with the results of Barlow’s equation (lowest value) to obtain an indication of onset of casing failure. With this result drilling engineers can perform accurate pressure management in the wellbore and prevent mishaps such as kick, blow out or casing leakage from occurring. A future study on buckling and bending stresses at the worn section can help in estimating the life of the casing.

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