3D Non-Linear FEA to Determine Burst and Collapse Capacity of Eccentrically Worn Casing

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Abstract

Deviated and deep wells introduce new challenges, and necessitates focus on well casing design. A characteristic problem when drilling deviated wells is the wear caused by the drill string damaging the inside wall of the well casing. When the well casing is bent, long exposure to a rotating drill string creates large contact forces that cause eccentricity of the well casing. Modelling the eccentricity for burst and collapse capacity is important for providing an improved perspective into reaching a more robust understanding of well integrity. The nature of this project is to investigate the effects on burst and collapse capacity caused by eccentricity, by evaluating numerous analytical solutions providing comparisons to a finite element analysis (FEA) created with ABAQUS. The investigation shows that the American Petroleum Institution Bulletin 5C3 (API 5C3) standards solutions are the most conservative whereas the International Organisation for Standardization Technical Report 10400 (ISO 10400) recommendations were of Klever-Tomano Collapse Theory and Klever-Steward Burst Theory which are more comparable to the true collapse and burst failures.

1. Introduction

Within the oil and gas industry well casing is widely used as a protective conduit thoughout drilling operations and production. The primary sources of well casing wear are the contact load, tool joint hard facing condition, contact time and wear track length. The main issue is the contact between the rotating drill string and the inner wall of the well casing. The rotational wear creates a crescent indent in the wall of the well casing. The indent thins the well casing at a localised area and hence there is a reduction in the casing integrity. The reduction of well casing wall has become an important issue in the oil and gas industry has more challenge well target are being perused and the safety of designing well casing strings for these comes into question.

The current stress analysis practice conservatively accounts for concentric wear to estimate wall reduction as a uniformly worn model and then evaluate this wall reduction using the API 5C3 burst/collapse capacity. Although this provides a larger operating window, past constructions are helping to quantify “as built wear” which will update future design envelopes. This generally results in an over-conservative design and higher well casing cost.

To modernize the API 5C3, a work group between API/ISO created a new set of standards for well casing design called ISO 10400. This set of standards defined new analytical solutions for industry use, based on their comparison to updated experimental analysis. ISO 10400 recommended that for collapse capacity, the rational formulation of the analytical solution Klever-Tamano Collapse Theory presented in ‘A New OCTG Strength Equation for Collapse under Combined Load' (SPE 90904), was appropriate. Eccentricity is described by Klever-Tamano by a decrement function. The decrement function accounts for imperfection empirically and ISO 10400 describes a linear function to characterise imperfections such as ovality, stress/strain curve, eccentricity, and residual stresses. For burst capacity, ISO 10400 recommended Klever-Stewarts solution presented in 'Formulas for rupture, necking and wrinkling of OCTG under combine loads' (SPE 102585). It is important to note that for this investigation, for no axial load, the solution shown in the previous works by Klever and Stewart, in 'Analytical Burst Strength Prediction of OCTG With and Without Defects' (SPE 48329) is the same solution as in SPE 102585. Great accuracy was shown for both analytical solutions against an extensive experimental dataset that was used to modernized the API 5C3 in ISO 10400.

From this investigation, it is intended that analysis will provide insight into a more sustainable use of resources and optimized well casing design. Improved information could result in a more robust well integrity envelope for the expansions in the North West Shelf or indeed globally.

2. Methodology

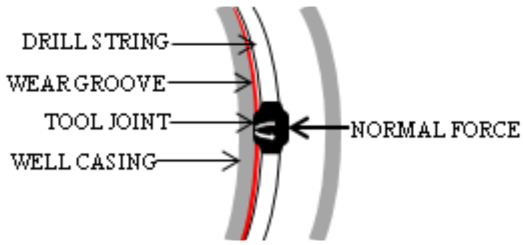

Figure 1 Internal well casing wall wear caused during rotation of drill string

The main mechanism of failure for well casing is the well casing material being unable to withstand the applied pressure, internally or externally, which results in an oval like deformation. Figure 1 shows the normal force of the drill string influencing well casing, producing a wear groove and hence eccentricity occurs. Within the wear groove (worn portion), localisation of forces occurs, which promotes oval deformation earlier than in the non-worn portion. This failure is an unstable mechanism and the transition from where the external pressure capacity reaches a maximum, and a round pipe starts to ovalise, can happen swiftly. The mechanisms of failure are described differently for each analytical solution. Solutions are described as either an analytical solution for an eccentric cylinder or an empirical formula in comparison to ideal well casing.

2.1 Burst Capacity Mechanism

Burst capacity deals with a pressure differential where internal pressure is larger than external pressure. When excessive internal pressures are applied to the well casing wall, failure can be characterised initially as yielding of the internal wall. When yielding occurs, oval like deformation follows and thus failure occurs due to well casing material being unable to withstand additional internal pressure.

The API 5C3 adopted Barlow's formula to represent well casing burst strength. Barlow's formula describes hoop stress at the inner wall with its failure criteria at the yield stress. API uses the equation with 87.5% of the nominal wall depth for manufacturing processes tolerance. With modelling eccentric wear, concentric wear is considered and the inner wall of the worn portion becomes the critical section. This is a purely elastic equation and modern well casing can currently withstand increased pressure passing the elastic region. Therefore is equation is a very conservative solution for predicting well casing burst capacity.

Klever-Stewart's Burst Theory characterised burst capacity through the von Mises yield criterion and Tresca yield criterion. Klever generalised Stewart's previous work that involved analysis of the mechanism of failure by examining the hoop stress. The solution is characterised by predicting the behaviour of the material at large strains using a logarithmic strain ratio. This is important when considering the worn portion of the pipe, where there is localisation of forces in which large strains will occur. The model accounts for material differences within the non-elastic region by using a correction factor for the material-hardening index.

Contrasting Klever-Stewart's solution, Dr Wu burst capacity presented in 'Casing Burst Strength after Casing Wear' (SPE 94304) which also models burst capacity by investigating hoop stress. Conservatively Dr Wu ignored well casing deformation and showed that due to the worn section addition forces and moments within the worn section cause an increase in hoop stress in the worn section. Dr Wu detailed three methods of failure; initial yield at the inner diameter, full yield at the middle of the worn section and tensile ductile rupture at the middle of the worn section. Since other investigations have detailed API 5C3 as conservative, this investigation looked only at Dr Wu's full yield and tensile ductile rupture as to compare to Klever-Stewart's Burst Theory.

2.2 Collapse Capacity Mechanism

Collapse capacity is detailed similar to burst capacity as it deals with a pressure differential where external pressure is larger than internal pressure. Collapse failure mechanism is quite similar to the burst failure mechanism, but instead of expanding deformation, the well casing flattens. The flattening deformation can occur differently for the extremes of well casing dimensions (i.e. thick or thin walled well casing). The reason for this is that thick walled well casing collapse will occur sometime after yielding, whereas for a thin walled well casing yields near collapse capacity. For this reason, thick walled well casing is detailed as yield region collapse and thin walled well casing is detailed as elastic region collapse. Describing the region between these extremes is problematic and thus this investigation has presented an empirical solution, which is a common solution to predict transitional well casing collapse capacity (the area between yield region and elastic region failure).

Klever-Tamano Collapse Theory (SPE 90904) explains an analytical solution that depicts the three main interlinked concepts, which are: (1) elastic region collapse of a very thin walled ideal well casing, as described initially by Timoshenko in 1936; (2) through-wall yield region collapse of an very thick walled ideal well casing; (3) transitional region between elastic region and yield region collapse, relevant for the collapse strength of all well casing dimensions by Tamano in 1983. These original derivations were used to create an analytical solution that describes a quadratic solution to solve for all ranges of well casing dimensions. Klever-Tamano solution characterised a decrement function as described in the introduction that accounted for imperfections such as eccentricity.

Another analytical solution, presented by Kuriyama et al. in 'Effect of Wear and Bending on Casing Collapse Strength' (SPE24597), developed an empirical derivation of the ideal well casing collapse pressure and compared that to the onset yield strength at the inner diameter of worn well casing. The relationship was developed by testing numerous worn samples of thick walled well casing to investigate yield region collapse. An equation was derived from yield onset of thick walled well casing that compared worn collapse pressure with the ideal collapse pressure. The mechanism of this failure is yield onset occurring first in the worn part of the well casing, which then becomes a plastic hinge, following which, collapse occurs. The ideal collapse capacity was determine by evaluating Tomano's equation that was presented in 'A New Empirical Formula for Collapse Resistance of Commercial Casing' in 1983.

In 1994, API bulletin 5C3 detailed a series of collapse testing to investigate the methods of failure for a range of diameter/thickness ratios (D/t). It was found that collapse pressure could be modelled over four regions: internal yield failure, plastic yield failure, elastic yield failure, and the transitional zone. Multiple formulas were used to curve fit well casing dimensions to experimental capacity results. For worn well casing, industry uses an extremely conservative approach in taking the wear percentage as overall concentric wear and thus increases the D/t in which decrease collapse capacity. SPE 90904 stated that the API 5C3 gives highly non-uniform failure probability over D/t and provides a relatively poor prediction of true collapse failure. Thus, SPE 90904 suggests that there is no compelling case to uses this solution for anything other than API grade well casing.

3. Finite Element Modelling

The software that will be used to model the capacity of well casing is ABAQUS. The failure criterion for collapse/burst capacity will be the point which integration strain increments have increased pasted fifty times the initial yield point. Thus integration points can no longer withstand incremental increases in internal or external pressure.

The results of the Finite Element Analysis are not included in this seminar proceeding. This section details the main procedures that will be required to complete the FEA.

API grade T-95 well casing was selected to access the accuracy of the analytical solutions. Analysis is guided by the profile of 13-5/8" 88.2 ppf 95 ksi well casing worn by a 7" tool joint.

3.1 Model Setup

Figure 2 is a meshed model that was created in ABAQUS. This was one of several models in the analysis. The model was constructed by creating a 2D shape that illustrates worn well casing and then extruded to simulate an infinitely small portion of well casing.

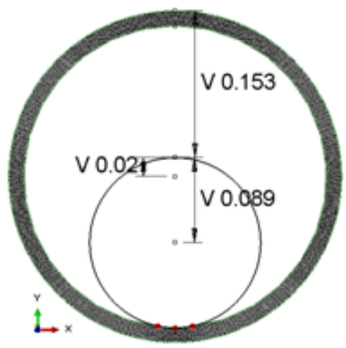

Figure 2 2-D meshed model setup: black area is the meshed casing wall and the smaller circle is the wearing tool joint

The model uses tetrahedra elements to simulate strain. Tetrahedra elements are useful when meshing technique requires large variation in element size, which occurs when refining only certain parts of the mesh. For this model, it is important to generate a concentrated meshed area around the worn section to accurately predict well casing capacities. The following assumptions were also made for the model: (1) the model has only external/internal loaded for collapse/burst capacity; (2) the model does not account for manufacturing defects and thus assumes a perfectly round and defect free well casing surface.

3.2 Material Properties

Fitting the stress strain curve is an important material property that's required for an accurate investigation into well casing capacity. It is important for the burst and collapse capacity that true stress is modelled rather than engineering stress because it correctly emulates the material properties in reality. Using a generalised material response for finite element modelling of uniaxial testing provides equivalent parameters to use for modelling well casing capacity. The Ludwik power law provides a good representation between true and engineering stress/strain and is used for this analysis.

4. Results and Discussion

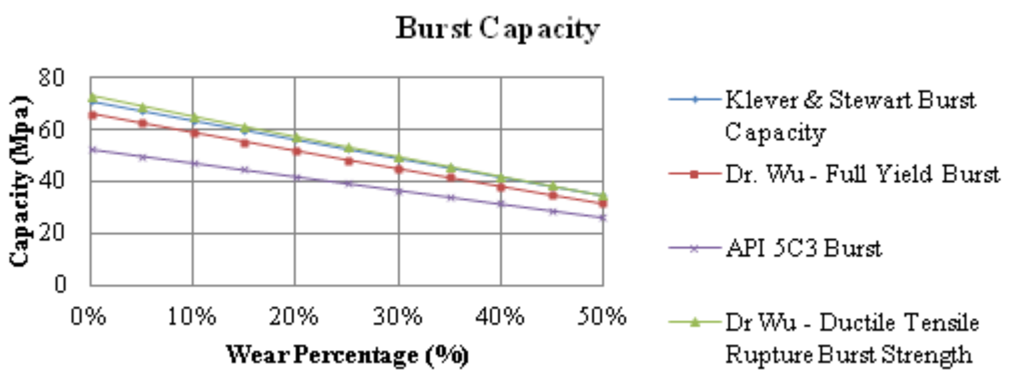

Figure 3 Burst Capacity of 13 5/8" eccentrically worn well casing(MPa) vs Wear Percentage (%)

Figure 3 underlies the differences between each analytical solution's burst capacity. From the above graph, the API 5C3 burst curve is the most conservative capacity and all curves act linearly in comparison to wear percentage. The two uppermost curves Dr. Wu – Ductile Tensile Rupture Burst Strength and Klever & Stewart Burst Capacity, are both determined by the use of the ultimate tensile strength instead of the yield strength and hence this is the reason behind their higher capacity values.

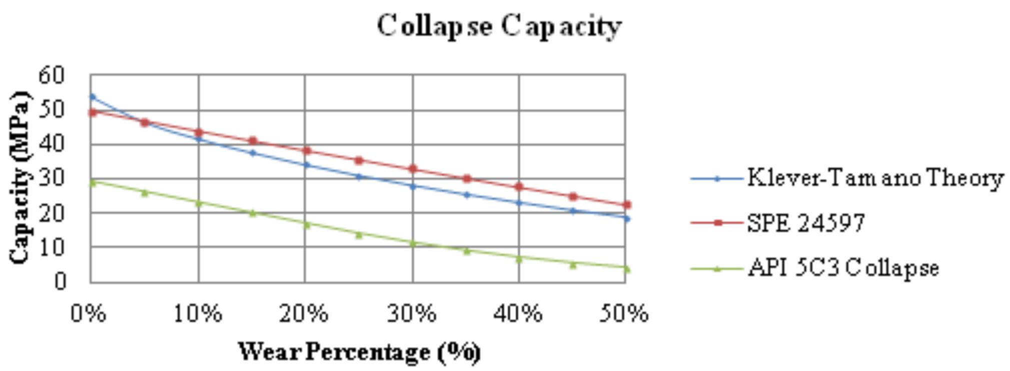

Figure 4 Collapse Capacity of 13 5/8" eccentrically worn well casing (MPa) vs. Wear Percentage (%)

Figure 4 underlies the differences between each analytical solution's collapse capacity. Similar to the burst capacity, the solution defined by API 5C3 is the most conservative prediction. The API and the Klever-Tamano theory collapse capacities are determined by quadratic formulas and hence decrease quadratically when graphed against wear percentage. The SPE 24597 collapse capacity acts linearly when graphed against wear percentage. The two uppermost curves, Klever-Tamano Theory and SPE 24597, are both determined by the use of the eccentrically worn well casing instead of concentrically worn well casing, as in API 5C3, and hence this is the reason behind their higher capacity values

5. Conclusions and Future Work

The investigation shows that API 5C3 details the most conservative solution for determining either collapse or burst capacity. The ISO 10400 has published updated industry standards and determines higher capacities than API 5C3. Thus for worn well casing capacity, usage of the ISO 10400 recommended models generates a more robust design window for considering worn well casing. Once FEA is justified and complete, this will provide comparisons to the true performance of the analytical solutions present within this investigation.

Further investigation into stress-strain properties and plastic deformation is required to gain further understanding into its relation when analysing well casing capacities. Thus, further testing into the material properties and average manufacturing defects would allow for a more accurate prediction of well casing capacity.

6. Acknowledgements

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7. References

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