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Effect of Crescent Wears on Tubing Burst Pressure Rating

Mesfin Belayneh and Therese Vu
[1]*University of Stavanger, Norway.*
[2]*ConocoPhillips Tananger, Norway.*

Abstract

This paper presents finite element method (FEM) and API-Barlow's model for burst pressure rating of crescent type-damage included tubing. FEM based modeling considers local wear as a part of the analysis, but API Barlow modeling does not.

Analysis of stress concentration and derated burst pressure results show quite significant differences between the two modeling approaches.

Result from the single crescent shaped worn out tubing shows that as the wear depth increases from 0% to 50% of the wall thickness, the API model prediction deviates from the FEM by overestimating the burst derated pressure in the range of 1% to 40%. For double crescent, the maximum deviation reaches up to 46%. On the other hand, for undamaged uniform wall thickness, the FEM and Barlow's prediction are the same.

In the oil and gas industry, commercial tubular design and analysis tools assume a uniform wall thickness cylinder and do not consider the effect of damage on the tubular strength. Therefore, the analysis presented in this paper indicated that FEM based modeling is useful tool for burst/collapse pressure derating of damaged tubulars. Proper design of safe operational window for casing/tubing is very important to handle shut-in, overpull, gas lift, bullheading, production and stimulation loadings during the life of a well and minimize integrity issues.

1 INTRODUCTION

Petroleum safety authority of Norway has developed a guideline for the Norwegian Continental Shelf (NCS) (NORSOK D-010 , 2013). The standard defines requirements for well integrity in drilling and well activities. Well integrity is defined as:

"*the application of technical, operational, and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of the well.*"

NORSOK D-10 standard defines production tubing as a primary barrier element. It is exposed to high pressure, temperature, corrosive gases, chemicals, mechanical loading during production and intervention operations. Barrier integrity problem associated with production tubing has been reported to be an issue on the NCS and other parts of the world. To minimize the risk of well integrity problems, NORSOK D-10's design criteria require two issues. (a) Casing shall be of a higher quality that they can withstand particularly corrosive media in the well (H_2S, CO_2, etc…), if they will be exposed to such environments. (b) Casing shall be designed with respect to realistic load conditions during the lifetime of the well. The loads shall be corrected for additional loads and effects: (NORSOK D-010 , 2013).

- *"Casing wear*
- *Bending in a deviated hole section*
- *Temperature effects*
- *Corrosion*
- *Plastic formations and reservoir compaction*
- *Pressure during completion, workover and kill operation"*

Petroleum safety authority of Norway performed well integrity survey on 75 wells (Injection and Production). As shown in **Figure 1**, production tubing recorded 39% of integrity problems, which was the highest. Cement and casing related failures recorded about 11% each.

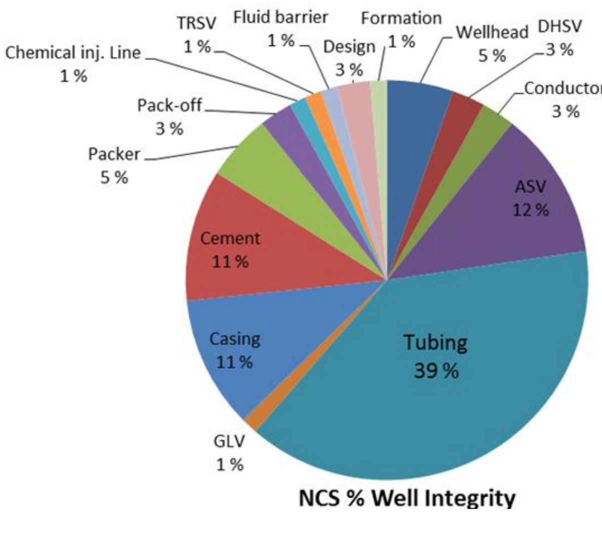

Figure 1: Wells categorized by type of element-barrier failure (Vignes et al, 2010).

During production phase, it is common practice to re-enter the well to perform downhole servicing. The collective term for these operations is well intervention. The purpose of well intervention is to alter the state or geometry of the well, to perform measurements and tests, to provide well diagnostics, or manage production. However, intervention tools and tubing mechanical interaction, high flow rate (erosion) and electrochemical process (corrosion) cause damage on tubular.

During drilling process, the measured casing wear in Gullfaks A-42 recorded about 30% wall thickness reduction (Jiang et al, 2005). The casing wear damage was due to drill string connection and casing mechanical and hydraulic interaction. In North Sea, caliper log measurement in production tubing indicates that about 47% wall thickness has been removed (Oijord et. al, 2010). Tubing has been exposed to a higher bend section, where the contact force is higher. The examples presented illustrate how tubular wear is critical issue in drilling and production wells.

During well stimulation, gas lift, and integrity pressure testing operations, worn out tubular experience excessive loads. To avoid or to minimize the risk of tubular integrity problem, it is important to continuously monitor and perform damage included tubing burst/collapse derated pressure calculation. The main objective of this paper is to analyze the applicability and the limitation of Barlow's API burst model for crescent shape damage included tubing design.

2. THEORY

Casing and tubing design is a key engineering work during well construction process. Selection of the right material with respect to loading and corrosion resistance prolong the life of the well. In the oil and gas industry, there are API burst and collapse tubular design models (API-Bulletin 5C3, 1994). Moreover, there are tri-axial and bi-axial analytical burst and collapse analytical solution (Aasen et al, 2007, Aadnøy, 2010). These are derived based on uniform wall-thickness cylinder theory and experimental data. However, in the presence of local damage on tubing, the current practice for burst pressure derating calculation is by removing the defect parts and applying the API burst model.

The API burst model is derived based on thin-walled cylinder theory and the model is known as Barlow equation (API-Bulletin 5C3, 1994):

$$P_y = Tol.\frac{2\sigma_y.t}{OD} \tag{1}$$

Where, t, and OD are the wall thickness, and outer diameter, respectively. σ_y is the yield strength. The model includes 87.5% tolerance (Tol.) factor or safety factor of 8/7 (API-Bulletin 5C3, 1994). [Tol. = 1/SF].

For thick-walled cylinder theory, the tri-axial burst model is derived based on thick-walled cylinder theory and the model reads (Aasen et al, 2007, Aadnøy, 2010):

$$P_i = \frac{\beta\sigma_a - 2\sigma_a + 2\beta^2 P_o - \beta P_o \pm \sqrt{-3\beta^2\sigma_a^2 - 6\beta^2\sigma_a P_o - 3\beta^2 P_o^2 + 4(\beta^2 - \beta + 1)\sigma_y^2}}{2(\beta^2 - \beta + 1)} \tag{2a}$$

Where, P_i, P_o and σ_a are internal pressure, outer pressure and axial stress, respectively. The geometrical factor, β, is defined based on the outer (d_o) and inner (d_i) diameters of the tube as:

$$\beta = \frac{2d_o^2}{d_o^2 - d_i^2} \tag{2b}$$

3. API-BURST AND FEM BASED-MODELLING

Three simulation setups were designed to study the single- and double crescents wear effect on tubing burst pressure rating. The results are compared with the API-burst model. The assumption is that tubing is under an isothermal and no bending effect condition.

3.1 Simulation setup

Based on the tubing damage profile reported in reference (Oijord et. al, 2010), up to 50% worn out tubular was modeled. Please note that the term ''percentile wear'' we mean the wear depth relative to the nominal wall thickness of the tubing.

For the simulation, L-80 tubing has been considered. Due to 8.6 ppg completion fluid, tubing has been loaded externally with 727-psi hydrostatic pressure at the point where the maximum wear was observed. During simulation, the external pressure was kept constant as we varied the internal pressures to determine the burst pressure.

The internal loads could be due to production /injection fluids and downhole service operations such as bullheading or stimulation. External pressure loading in A-annulus may be increased during a gas lift operation, annulus pressure testing and if tubing/packer leak occurs.

3.2 Results and analysis

3.2.1 Base case- uniform wall thickness effect on tubing pressure

In an oilfield, it is common practice to perform downhole acid treatment to improve productivity or to remove scale deposits. After acid treatment, it is possible that the corrosive protecting layer of tubing will be attacked and removed. In addition, oxygen aerated water injection or CO_2 localized corrosion may change from localized corrosion to uniform corrosion or general corrosion with the increase of temperature (Li et al, 2013). Since tubing will have uniform wall thickness reduction, API burst, and collapse models can be applied.

Considering a uniform corrosion scenario, the base case model was designed to compare the analytical API Barlow's equation (Eq.1) with FEM numerical model computation. **Figure 2** illustrates a tube with initial radius, r_i and the final radius r_f, where 50% of the wall thickness has been removed uniformly. **Figure 3** shows the derated burst pressure simulation results obtained from API Barlow equation and finite element method.

As shown in the **Figure,** the FEM modeling captures the API model result. The base case simulation result clearly illustrates the trustworthy of FEM and the applicability of the API Barlow's model for a uniform wall thickness tube. As mentioned, the API model is derived based on a uniform wall thickness cylinder. In the presence of crescent shaped defects in a structure, the stress concentration varies. The following section will explore the effect of defects on the tubing.

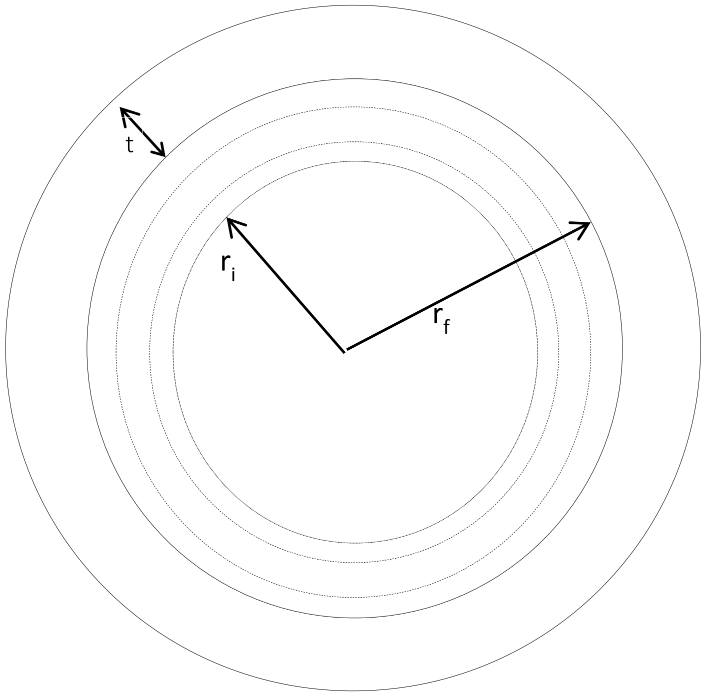

Figure 2: Illustration of uniformly removed tube model.

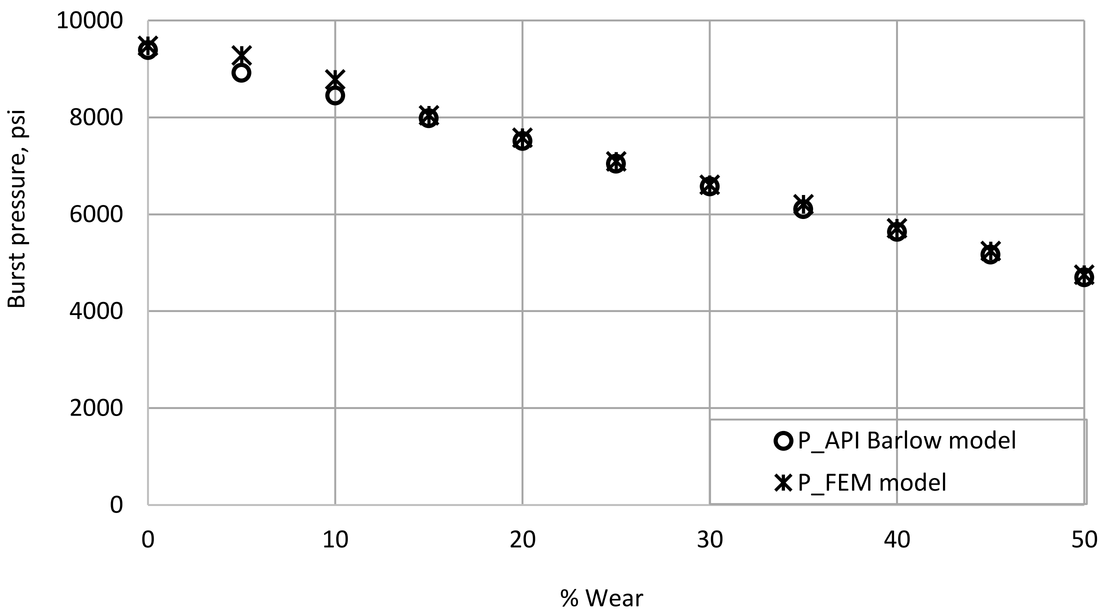

Figure 3: Comparison between API Barlow and FEM derated burst pressures.

3.2.2 Stress field in worn out and uniform tubing

The second simulation scenario is designed to investigate if the API Barlow uniform wall thickness modeling approach can be applicable for locally worn-out tubing. **Figure 4** illustrates crescent shaped type local wear damage to be modelled with FEM. **Figure 5** is going to be modelled after removing the worn-out part (i.e., the red shaded region), which will then have a uniform and reduced wall thickness. Both tubulars were internally and externally loaded with 3200 - and 727 psi, respectively.

The Finite element stress analysis results showed that maximum von Mises stress concentrated at the local damage region. In **Figure 4**, the von Mises stress is found out to be 81350 psi and exceeded the yield limit. Similarly, in the uniform wall thickness model (Figure 5), the maximum value was 41370 psi, and the stresses are uniformly distributed throughout the surfaces.

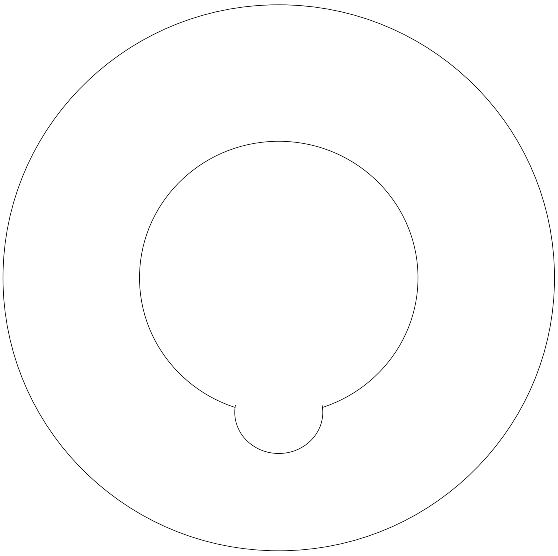

Figure 4: Local wear

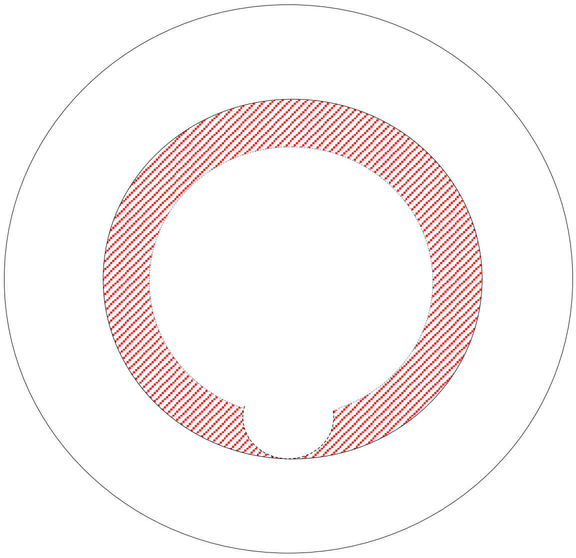

Figure 5: Local wear removed

Based on the stress analysis results, the assumption of uniform wear for locally damaged tube used by Barlow's equation overpredict burst pressure. Simulation results therefore suggest that Barlow's equation cannot be used to calculate burst derated pressure for locally worn thick/thin-walled tubing. This led us to analyze further the effect of a single- and two crescents on tubular derating burst pressure.

On the other hand, for the uniform wall thickness tubular and thin-walled cylinder, Barlow's model derated burst pressure matches with FEM simulation result (See **Figure 3**). However, for the thick-walled cylinder, the model derived in reference (Aasen et al, 2007, Aadnøy, 2010) believed to be better than Barlow's equation since the models consider the axial and bending stress effects.

3.2.3 Effect of one crescent wear on tubing burst pressure

The assumption for the one crescent damage scenario is that during intervention operation, tubing has been damaged along one side as illustrated in **Figure 4**. The depth of indentation increased from 5% to 50% of the wall thickness. The simulation result is displayed in **Figure 6.** The wear depth increases result in reduction of tubular burst pressure. The FEM simulated data is modeled as quadratic polynomial curve fitting, which relates the internal pressure with percentile wear. The model reads:

$$P_{internal} = 22487*Wear\%^2 - 24008*Wear\% + 9506.1 \qquad (3)$$

Please note that in **Figure 6** and Eq.3, tolerance (or safety factor) is not included. Internal pressure in the regions above the curve causes tubing failure and below the curve is safe region. Including 87.5% tolerance (Tol.), the results are plotted in **Figure 7.** As can be seen, for the unworn tubing (i.e., 0% wear), both the API and FEM show the same prediction.

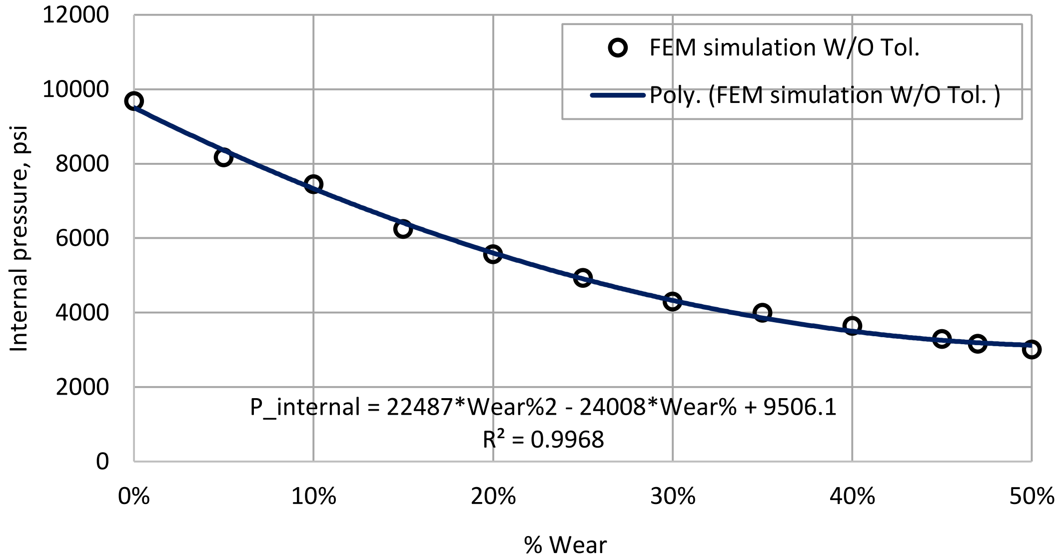

Figure 6: FEM derated tubular burst pressure of single crescent damage model without tolerance factor.

As the wear depth increases, we can observe a significant difference between the API Barlow's model and the FEM simulation-based model results. The API Barlow's model shows a linear derated burst pressure curve, whereas the FEM model shows a nonlinear curve. For instance, for 20% of wall thickness worn out tubing, according to API Barlow model, the 6000psi internal pressure does not burst tubing, but the FEM model indicates that tubing burst. The result analysis clearly shows that the application of API burst equation for worn out tubular is not reliable.

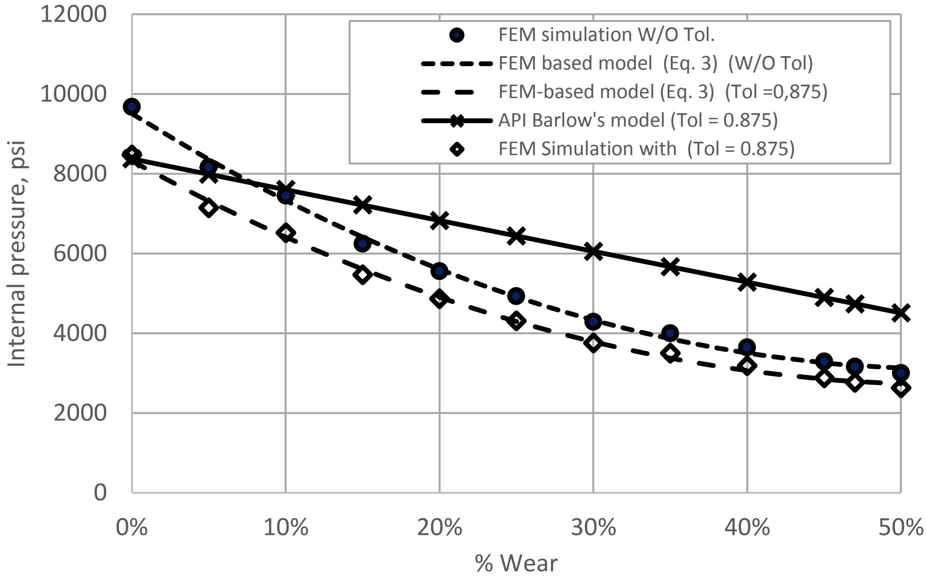

Figure 7: Comparison of FEM and API Barlow's model derated burst pressures with and without (W/O) tolerance (Tol.) factor.

3.2.4 Effect of two crescents wear on tubing burst pressure

During the life of the well, tubing may experience several intervention operations. During tripping in/out of the well, production tubing is assumed to be scratched at the lower -and at the opposite upper sides, respectively. This type of damage is expected in bended section of tubing, where a higher contact force exists. In order to investigate the effect of more defects on tubing, two crescents have been introduced in the model.

Figure 8 shows the two-crescents based FEM generated burst derated pressure. The burst pressure as a function of percentile wear is correlated as:

$$P_{internal} = 20513*Wear\%^2 - 23969*Wear\% + 9502.5 \quad (4)$$

For comparison purpose, the single crescent (Eq. 3) and the double crescents (Eq. 4) burst derated models are plotted along with the API Barlow model (Eq. 1). As shown in **Figure 9**, the one- and the two crescent models show nearly the same prediction in the ranges of 0-25% wear. At 50% wear, about 300-psi difference between the two damages can be observed.

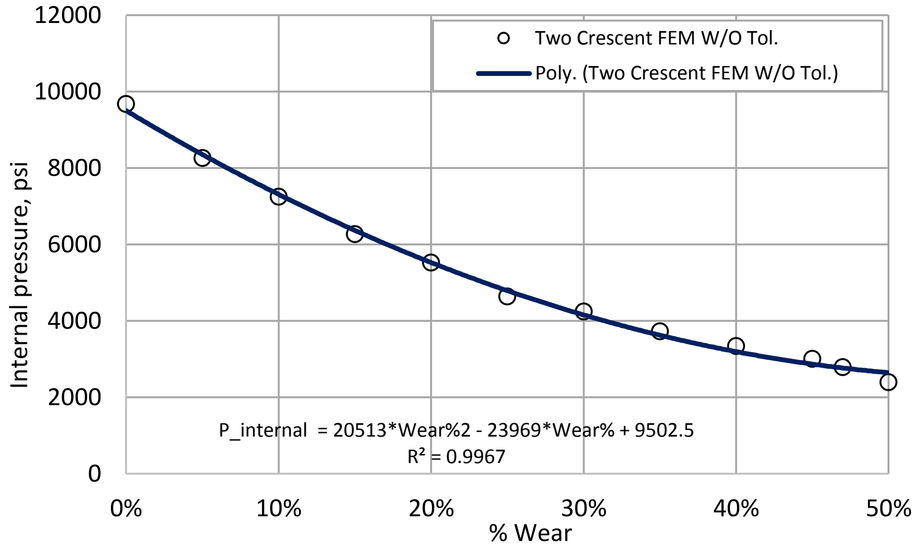

Figure 8: FEM simulated derated burst pressure of double crescent model without tolerance factor.

Figure 10 shows the pressure difference between the Barlow's model and the FEM based model displayed in **Figure 9.** As the tubing wear increases from 0% to 50%, the burst derated pressure prediction of Barlow's model deviates from the one crescent FEM pressure in the range of 56-2290 psi (4-158bar). Similarly, from the two crescents, the deviation varies from 60 to 2492 psi (4-172bar).

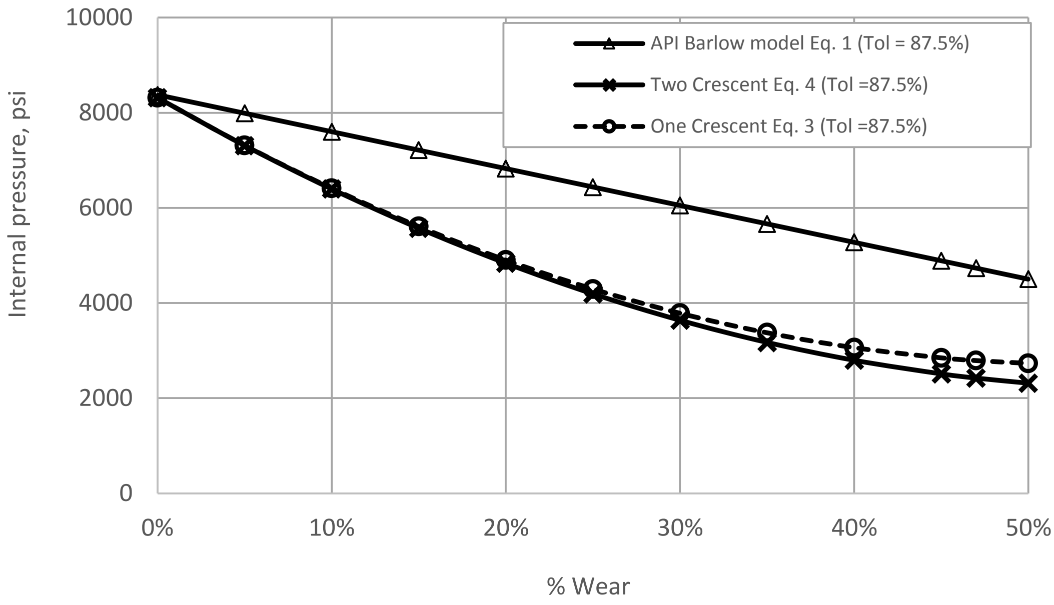

Figure 9: Comparison of tubing burst derated pressures.

Further, the pressure differences presented in **Figure 10** are converted to percentile. As shown in **Figure 11,** Barlow's model prediction deviates from the single and the double crescents FEM result in the range of 1% - 40% and 1% -46%, respectively.

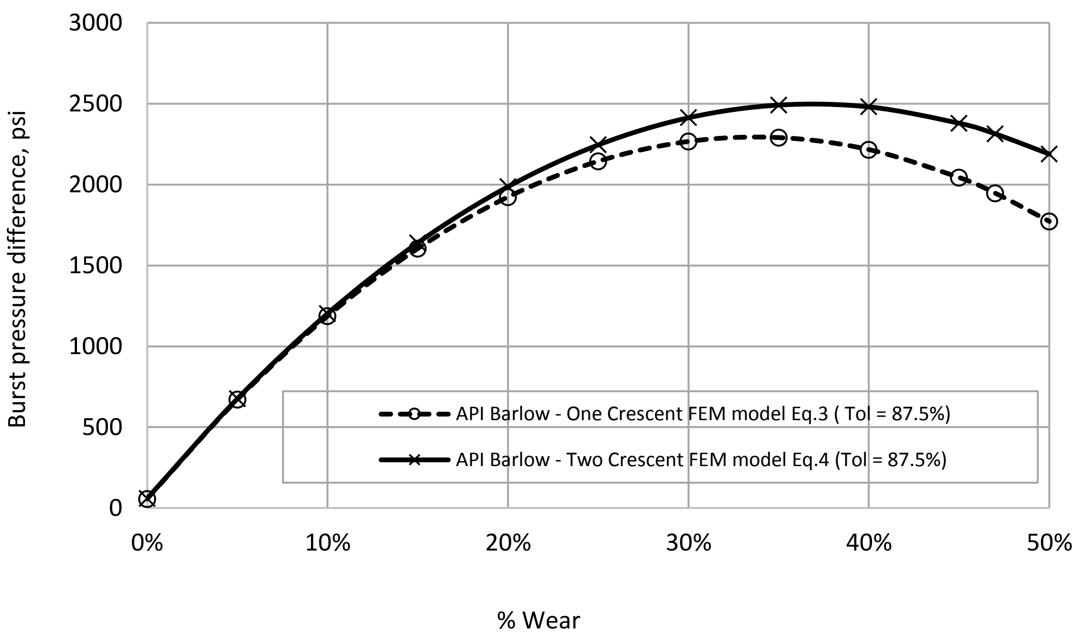

Figure 10: Tube burst derated pressure difference between Barlow's model- and FEM model predictions.

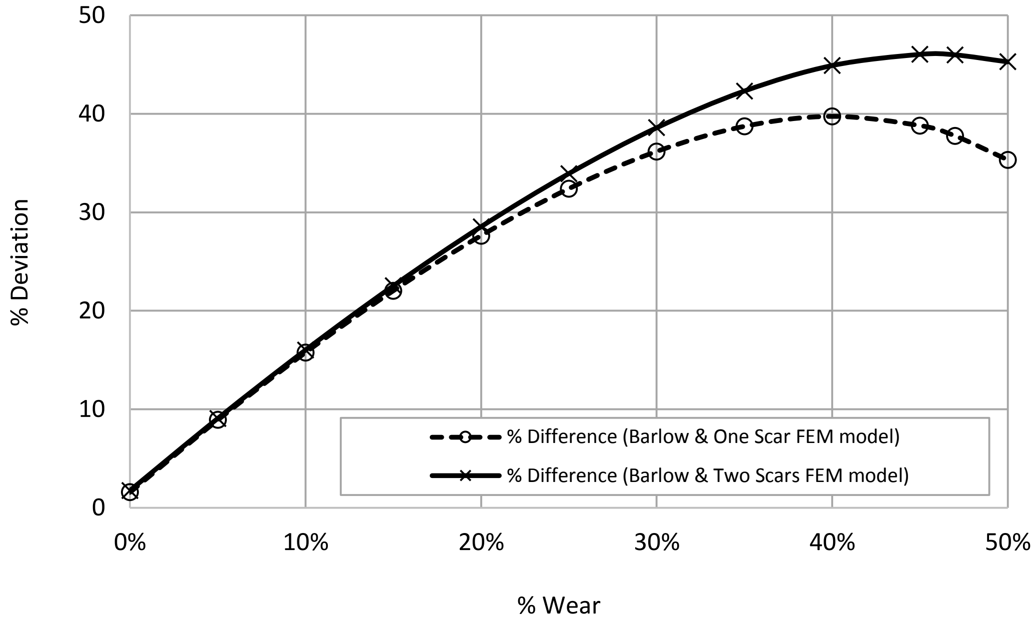

Figure 11: Percentile deviation between Barlow's model - and FEM prediction.

3.3 Limitation and application of this work

The results presented in this paper are valid for the considered external pressure loading, and 5.5″ (OD) x 4.892″ (ID) L-80 grade tubing. As the external pressure increases, the burst pressure is also increasing. However, the differential pressure across tubing remains the same. In this respect, the simulation results presented in this paper are valid for any other external pressure loading since the differential pressure is the one that determine tubular failure.

The correlation equations are valid for the single -and double crescents local damages. For other damage types, the stress field is different from the crescent shaped. It is therefore important to model the right defect shapes and sizes.

Results presented in this paper do not consider the effects of temperature and bending. However, these effects need to be coupled for better prediction and understanding.

The FEM modelling procedure outlined in this paper can be applied for casing/coil tubing and other structures.

4. CONCLUSIONS

In order to maintain well integrity, the accurate prediction of safe operational tubing pressure before and after being deteriorated is crucial. The primary objective of the paper was to evaluate the application of FEM and API modeling for locally damaged tubular.

Results obtained from the three case modeling setups can be summarized as:

- For the single crescent, as the wear depth increases from 0% - 50%, the Barlow's model prediction deviates from the FEM by overestimating in the range of 1% - 40%. For the double crescents, the deviation varies from 1% to 46%.
- Since the stress concentration at local damage is higher than the uniform surface tube, the applicability of Barlow's model needs to be revisited for worn out tubing.
- For the wear depth in the range of 0-25%, the single - and the double crescent damages show nearly equal tubing burst pressure.
- The FEM burst derating pressure modeling shows a nonlinear relationship with the wear depth.
- For undamaged uniform wall thickness tubular, both FEM and Barlow's burst pressure predictions are the same.

The advantage of FEM is that it allows modeling any type of wear along with its size. Since commercial software assumes a uniform wall thickness cylinder, the analysis in the paper suggests the importance of continuously monitoring the condition of tubulars and perform pressure-derating computation based on FEM modeling approach.

LIST OF SYMBOLS

r_i = Inner radius

r_o = Outer radius

$_{di}$ = Inner diameter

$_{do}$ = Outer diameter

t = Wall thickness

P_i = Inner pressure

P_o = Outer pressure

σ_h = Hoop stress

σ_r = Radial stress

σ_a = Axial stress

σ_{von} = Von Mises stress

ABBREVIATIONS

API = American Petroleum Institute

FEM = Finite element method

ID = Inner diameter

NCS = Norwegian Continental Shelf

OD = Outer diameter

PSA = Petroleum Safety Authority

SF =Safety factor

Tol =Tolerance

UNIT CONVERSION

1 psi = 6.89475729 kpa

1 psi = 0.0689475729 bar

1 in = 0.0254 m

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