# Damaged welded pipes for oil and gas rigs exposed to internal pressure - failure estimation

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**Abstract.** The paper deals with the integrity assessment of API J55 steel casing pipes for drilling rigs, manufactured by high frequency contact welding procedure. The influence of corrosion defects on the pipeline load carrying capacity is determined through pressure test of a pipe with corrosion damages simulated by machining the circular holes. Finite element analysis of the damaged pipe subjected to internal pressure is used for determining the stress/strain conditions in the damaged area of the pipe. Also, numerical model was used for establishing the load carrying capacity of the pipe with different damage levels (i.e. defect depth and length). Several expressions from the literature are used for estimation of the maximum pressure in the damaged section of the pipe, and the solutions are compared with the predictions of finite element models and experimental results.

## Introduction

During the exploitation, pipes in the oil and gas drilling rigs are typically subjected to a corrosive atmosphere, high pressures and elevated temperatures. Having in mind that reliability of drilling rig systems is crucial for efficient production and that their failure can cause environmental hazard, a large amount of research activities has been conducted on the pipes with corroded areas [1-8]. One of the solutions for assessment of the corrosion defect influence to the pipe integrity is ASME B31G code [1]. Since it is often regarded as too conservative, other procedures have been derived in order to improve its predictions, e.g. a modification by Kiefner and Vieth [2,3] (often denoted as modified ASME B31G). Det Norske Veritas (DNV) developed procedure [4] for estimating the load carrying capacity of corroded pipelines which takes into account the internal pressure and axial compressive loading. European FITNET project [5] also dealt with such problems, and the pipes with corrosion defects are included in the resulting integrity assessment procedures. Adib-Ramezani et al. [6] derived an approach for determining the remaining strength of the corrosion damaged pipes through modification of SINTAP procedure [9] (typically used for analysis of cracked geometries, including cracked pipes [10]).

In this work, criteria for estimation of maximum pressure for casing pipes used in the oil and gas drilling rigs are discussed. The pipes were manufactured by high frequency contact welding (HF) of API J55 steel, and the influence of local corrosion is examined on a pipe with different damage levels simulated by machining the circular notches at the outer surface. The vessel, produced by welding the dished ends to the pipe segment, was subjected to hydrostatic pressure, to determine the development of plasticity around the machined defects. Finite element analysis is conducted with the aim to determine the stress state in the pipe and to establish the failure criterion. Also, four analytical-empirical limit load solutions from the literature are applied for calculation of the maximum pressure: ASME B31G code, modified ASME B31G, FITNET and the solution of Choi et al. [7].

**Experimental procedure**

Tensile properties of API J55 steel in the presented analysis are determined on specimens taken from the examined casing pipe. The yield stress is 380 MPa and the ultimate tensile strength is 562 MPa; chemical composition and more material properties are given in [11].

The experimental test is performed on the vessel (made from a part of the examined pipe by welding the dished ends) with simulated defects of the circular shape, Fig. 1. Nominal dimensions of the pipe are: diameter $\phi$139.7 mm, wall thickness 6.98 mm. The corrosion defects were simulated by machining circular holes with different depth at the outer surface (Fig. 1). Strain gauges were mounted at the bottom of each defect, in hoop and axial direction.

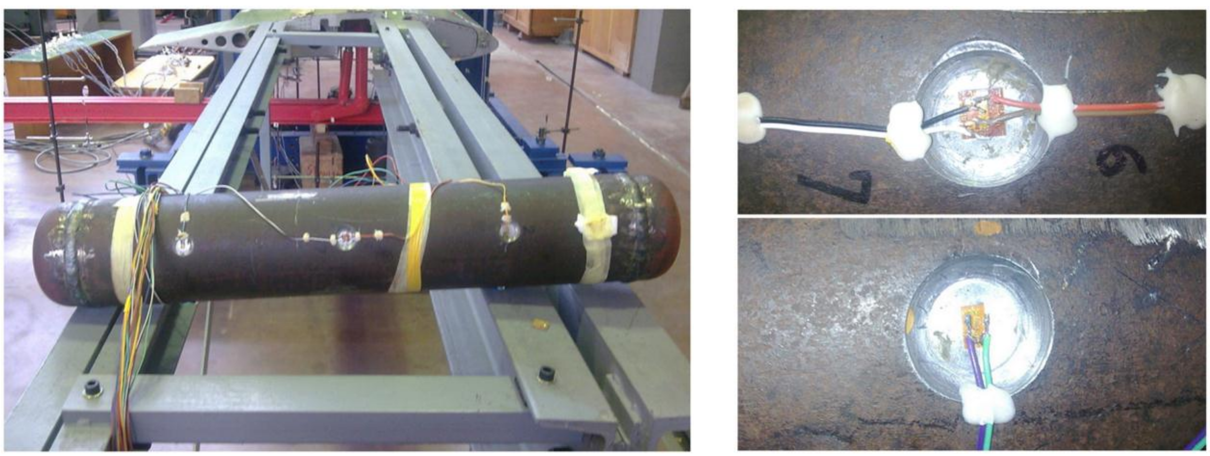

Fig. 1. Experimental setup - pipe with machined defects and strain gauges

**Maximum pressure of the corroded pipe**

Four solutions from the literature are applied for calculation of the maximum pressure of the analysed API J55 steel casing pipe: ASME B31G code, modified ASME B31G, FITNET and the solution of Choi et al. (in the remainder of the paper - Choi's solution/equation), see Table 1.

In Table 1, $a$ and $L$ are defect depth and length, $M$ is geometry correction factor, while $C_j$ ($j$ = 0..2) are coefficients in Choi's equation. $D_e$ and $D_i$ represent the external and internal diameter of the pipe, while the mean radius of the pipe is $R$.

Table 1. Expressions for determining the maximum pressure

| | | |
|---|---|---|
| ASME B31G [1]: | | |
| $L \le \sqrt{20 \cdot D_e t}$ | $p_{max} = 1.1 \cdot \sigma_Y \dfrac{2t}{D_e} \left[ \dfrac{1 - \frac{2a}{3t}}{1 - \frac{2a}{3t} \cdot \frac{1}{M}} \right]$ | $M = \sqrt{1 + 0.8 \dfrac{L^2}{D_e t}}$ |
| $L > \sqrt{20 \cdot D_e t}$ | $p_{max} = 1.1 \cdot \sigma_Y T \dfrac{2t}{D_e} \left( 1 - \dfrac{a}{t} \right)$ | $M = \infty$ |
| Modified ASME B31G [2]: | | |
| $L \le \sqrt{50 \cdot D_e t}$ | $p_{max} = \left( 1.1 \cdot \sigma_Y + 69 \cdot 10^6 \right) \dfrac{2t}{D_e} \left( \dfrac{1 - 0.85 \frac{a}{t}}{1 - 0.85 \frac{a}{t} \cdot \frac{1}{M}} \right)$ | $M = \sqrt{1 + 0.6275 \dfrac{L^2}{D_e t} - 0.003375 \left( \dfrac{L^2}{D_e t} \right)^2}$ |
| $L > \sqrt{50 \cdot D_e t}$ | | $M = 3.3 + 0.032 \dfrac{L^2}{D_e t}$ |
| Choi et al. [7]: | | |
| $L < 6\sqrt{Rt}$ | $p_{max} = 0.9 \cdot \sigma_m \dfrac{2t}{D_i} \left[ C_2 \left( \dfrac{L}{\sqrt{Rt}} \right)^2 + C_1 \left( \dfrac{L}{\sqrt{Rt}} \right) + C_0 \right]$ | $C_2 = 0.1163 \left( \dfrac{a}{t} \right)^2 - 0.1053 \left( \dfrac{a}{t} \right) + 0.0292$ <br> $C_1 = -0.6913 \left( \dfrac{a}{t} \right)^2 + 0.4548 \left( \dfrac{a}{t} \right) - 0.1447$ <br> $C_0 = 0.06 \left( \dfrac{a}{t} \right)^2 - 0.1035 \left( \dfrac{a}{t} \right) + 1.0$ |
| $L \ge 6\sqrt{Rt}$ | $p_{max} = \sigma_m \dfrac{2t}{D_i} \left[ C_1 \left( \dfrac{L}{\sqrt{Rt}} \right) + C_0 \right]$ | $C_1 = 0.0071 \left( \dfrac{a}{t} \right) - 0.0126$ <br> $C_0 = -0.9847 \left( \dfrac{a}{t} \right) + 1.1101$ |
| FITNET [5]: | | |
| | $p_{max} = \dfrac{2 \cdot t \cdot \sigma_{cyl}}{(D_e - t)} \left[ \dfrac{\frac{t_{mm}}{t}}{1 - \left( 1 - \frac{t_{mm}}{t} \right) \frac{1}{M}} \right]$ | $M = \sqrt{1 + 0.8 \dfrac{L^2}{D_e t}}$ <br> $t_{mm} = t - a$ <br> $\sigma_{cyl} = \left( \dfrac{1}{2} \right)^n \sigma_m$ |

$n = \frac{65}{\sigma_Y}$

**Finite element model**

Numerical analysis is conducted using the software package Abaqus. The meshes consist of 20-node reduced integration elements, and due to the symmetry only one quarter of the pipe is modelled. Axial loading is introduced at one side of the model to replace the influence of the dished end. Cases with increased defect length are also investigated (lower right corner of Fig. 2), in order to formulate the dependence of maximum pressure on defect length.

The strains in hoop and axial direction are determined in the in the finite element nearest to middle of the defect, which resembles the position of the strain gauges; this element is marked in Fig. 2. Both numerical analysis and experimental testing gave a very large difference in values for the two directions; hoop strain values are up to 10 times higher in comparison with the axial ones.

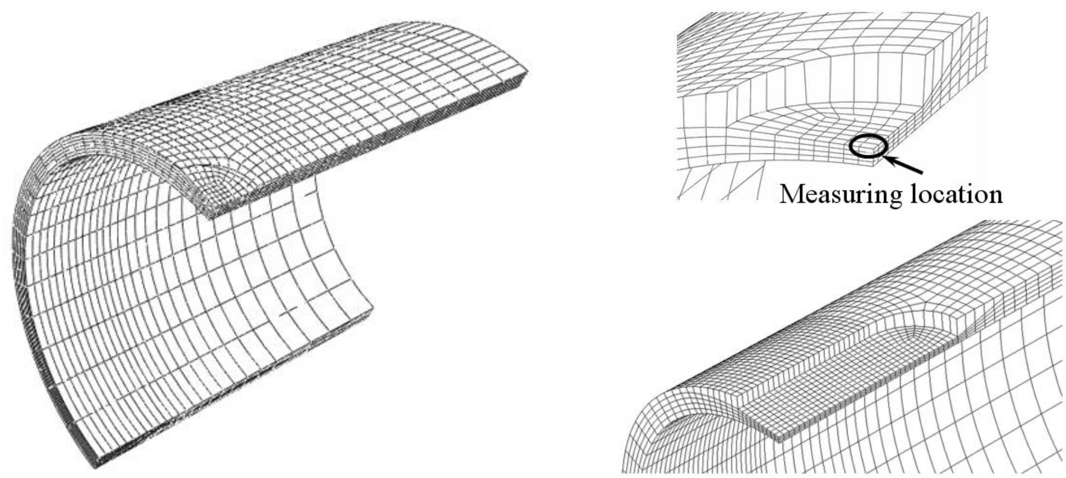


Fig. 2. Finite element meshes of the pipe with a defect

**Failure criteria - comparison**

Fig. 3 shows the comparison between the results obtained by the used limit load criteria for the three damage levels.

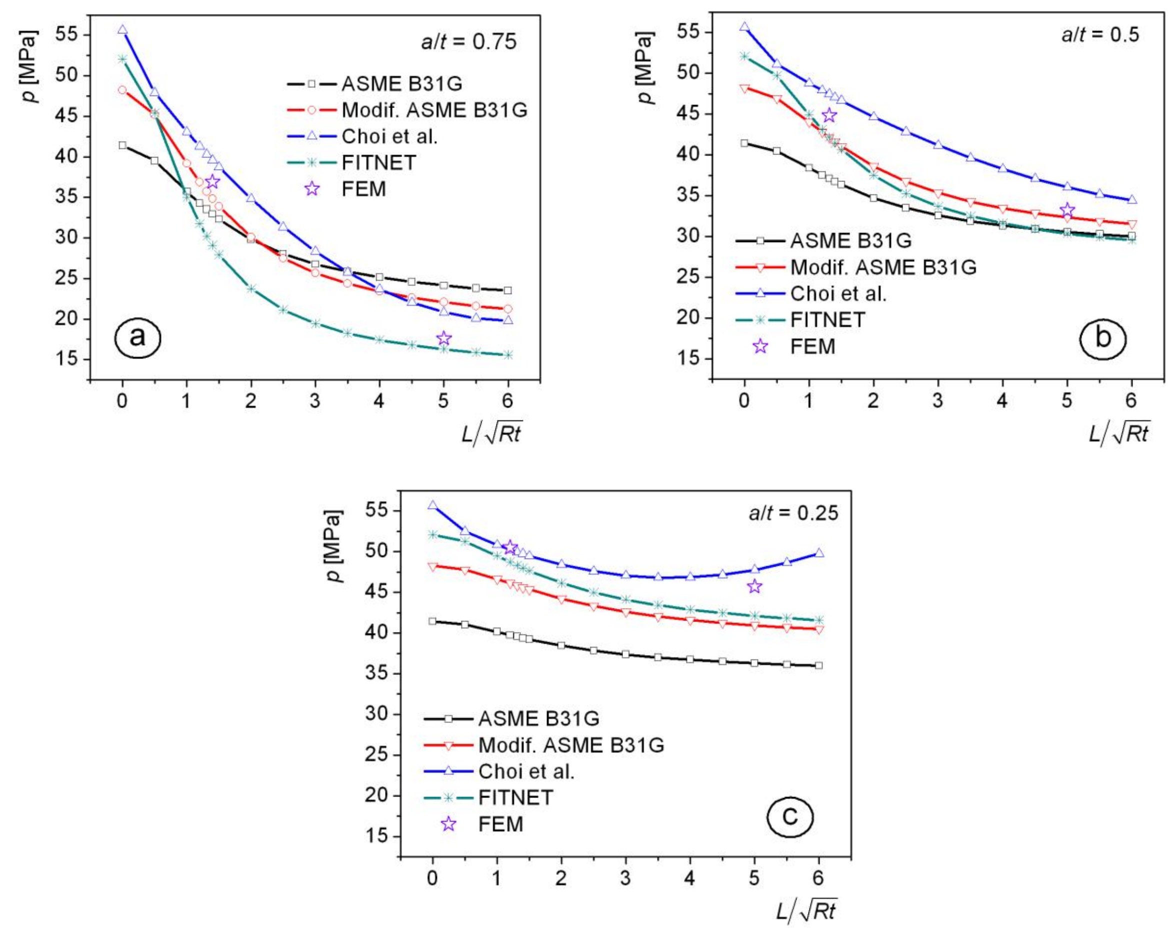


Fig. 3. Dependence of the load carrying capacity on the defect length, for three damage levels - 75% (a), 50% (b) and 25% (c) of the pipe wall thickness

The maximum pressure in the finite element analysis is determined as the pressure value at the moment when von Mises stress reaches the reference stress value through the ligament in the middle of the defect [7, 12]. The reference stress is varied: 80%, 85 % and 90 % of the ultimate tensile strength $\sigma_m$; it is set to 85 % of $\sigma_m$, as a moderately conservative solution for this material [13]. This solution gives results between modified ASME B31G, still regarded as conservative, and Choi's solution.

Choi's equation and FITNET solution give more conservative results for long and deep defects (in comparison with the prediction of modified ASME B31G), and therefore can be more suitable in that case. On the other hand, for long and shallow defects it seems that modified ASME B31G and FITNET are more appropriate, because Choi's equation not only gives non-conservative solutions in that case, but also predicts an increase of the maximum pressure with the increase of defect length for very shallow defects (25% in the analysed case, Fig. 3c). However, the mentioned increase in maximum pressure does not exist for slightly deeper defects (more than 35% of the pipe wall thickness). When considering the short defects of any depth, modified ASME B31G and FITNET are more conservative in comparison with Choi's equation.

Fig. 4 shows the dependence of the load carrying capacity of the damaged pipes with the increase of defect depth. The results are given for two fixed defect lengths - $L/\sqrt{Rt}$ equal to 1 and 5. It can be seen that much steeper decrease of maximum pressure with increase of depth has been obtained for long defects.

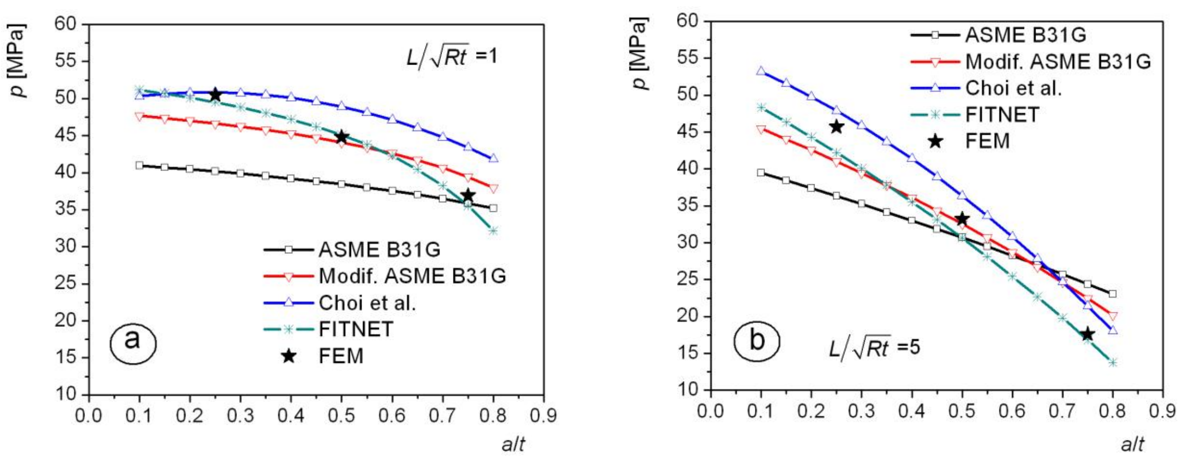


Fig. 4. Dependence of the load carrying capacity on the defect depth, for two defect lengths - $L/\sqrt{Rt}$ = 1 (a) and $L/\sqrt{Rt}$ = 5 (b)

Solutions obtained by the four used expressions are also compared with the results of experimental investigations on pipes with much larger defect length (ratio $L/\sqrt{Rt}$ ranging from 6.2 - 13), presented in [14] and [15]. These pipes were produced from API X60 steel (yield strength 452 MPa, ultimate tensile strength 542 MPa, nominal pipe diameter 323.9 mm, ratio $a/t \approx 0.75$). The results, given in Fig. 5, confirmed that Choi's solution is more conservative than modified ASME B31G for long damages. Also, the experimental values are between the two corresponding lines, which is in agreement with the adopted failure criterion for FEM analysis. Concerning the ASME B31G, it gives the most conservative results, except for the first point, lying very close to the limit between the two equations given in Table 1 ( $L = \sqrt{20 \cdot D_e t}$ ). This limit is the cause of the sudden decrease of the maximum pressure for ASME B31G in Fig. 5.

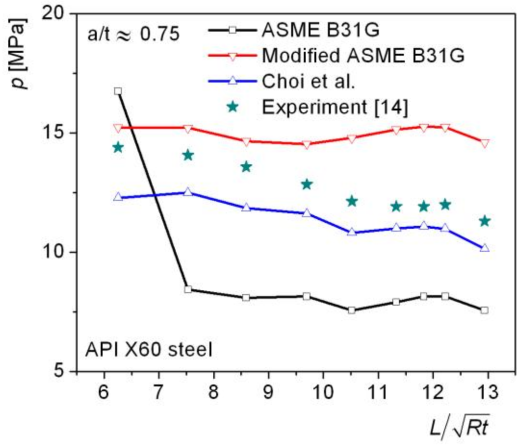


Fig. 5. Comparison of the maximum pressure for defects with depth around 75% of the pipe wall thickness - API X60 steel

In addition to the corrosion damages, crack-like defects are also often encountered in exploitation of the drilling rig equipment. The fracture resistance of API J55 steel specimens is analysed in [11], while the behaviour of a surface-cracked pipe manufactured from this material is treated in [16].

**Conclusions**

Criteria for determining the remaining strength of the corroded pipes manufactured from API J55 steel are discussed in this paper. The maximum pressure in numerical analysis is determined as the pressure value at the moment when plasticity spreads through the ligament, and von Mises stress reaches the reference stress value through the ligament in the middle of the defect. The reference stress is varied and the following values are used: 80%, 85 % and 90 % of the ultimate tensile strength $\sigma_m$. The reference stress is set to 85 % of $\sigma_m$, as a moderately conservative solution for this material. This criterion correctly predicts the decrease of the maximum pressure with the increase of defect length and depth. Its validity for very long defects has been verified by comparing the obtained values with the literature results. The dependence of the maximum pressure on defect length and depth has been established. It can be said that the Choi's solution and FITNET give conservative predictions for long and deep defects at the outer surface of API J55 steel pipe. On the other hand, both ASME solutions are found to be conservative for long and shallow defects. Also, it gives more conservative results in comparison with Choi's equation and FITNET for short defects.


**Acknowledgements**

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