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On the failure pressure of pipelines containing wall reduction and isolated pit corrosion defects

J.E. Abdalla Filho [a,b,*], R.D. Machado [a], R.J. Bertin [a], M.D. Valentini [a]

[a] *Graduate Program in Mechanical Engineering, Pontifical Catholic University of Paraná, Rua Imaculada Conceição, 1155, CEP: 80.215-901 Curitiba, PR, Brazil*
[b] *Graduate Program in Civil Engineering, Federal Technological University of Paraná, Rua Dep. Heitor Alencar Furtado, 4900, CEP: 81.280-340 Curitiba, PR, Brazil*

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ABSTRACT

Corrosion defects which occur in oil and gas pipelines may compromise the safety of such structures. This paper makes an assessment of the accuracy of some of the analytical procedures commonly employed by industry to calculate the failure pressure of corroded pipelines via finite element analyses (FEA). Second, this paper studies the stress distribution on isolated pit corrosion defects also via FEA. Analytical procedures to calculate the failure pressure associated to isolated pits are not available yet. Thus, based on the stress analysis results, such a procedure is devised and proposed here.

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1. Introduction

Safety and reliability of structural systems involve planning, careful design, proper selection of materials, consideration of all forces involved and appraisal of possible defects and limits of failure. Among the multitude of possible defects, corrosion has been recognized as one of the most detrimental, mostly to steel structures, since it may grow to a degree which might be sufficient to compromise the safety of such structures. Particularly, the failure of oil exploration, distribution and storing structures can lead to huge environmental disasters and financial loss, always very well documented and covered by the press.

This paper is concerned specifically with the issue of oil and gas pipelines failure due to the presence of corrosion defects. According to Chouchaoui and Pick [1], corrosion occurs as wall thickness reduction, individual pits or colonies of pits, or a combination of both types.

Several analytical methods are available to assess the failure pressure of pipelines containing corrosion defects in the form of wall thickness reduction. Among these methods, the authors cite ASME B31G [2], Rstreng 085 dL, proposed by Kiefner and Vieth [3], RPA, proposed by Benjamin and Andrade [4], and DNV RP-F101 [5], which will be investigated here. Such procedures are semi-empirical solution methods which are derived from solid mechanics principles, physical experiments up to rupture, and also via finite element simulations. Analytical (or semi-empirical) procedures are easy-to-use and they are routinely applied by oil and gas engineers in order to decide whether a corrosion defect is critical.

Finite element analysis has also been used as a tool in the development of accurate limit load solutions for pipelines containing corrosion defects. The understanding is that procedures which are more accurate than the semi-empirical methods could be devised. Further, the use of finite element analysis allows for evaluating more complex situations such as those of multiple corrosion defects.

The current practice in pipeline engineering is to employ semi-empirical methods in the assessment of corroded pipeline integrity either because these are coded methods or because they are inserted into well-established company methodologies. Thus, it is important to assess the accuracy of semi-empirical methods further in order to increase engineers' confidence in applying them routinely in the field. This work aims at giving a contribution in this issue by evaluating the accuracy of the aforementioned semi-empirical methods; namely, ASME B31G [2], Rstreng 085 dL [3], RPA [4], and DNV RP-F101 [5], via comparison to numerical results provided by finite element analyses.

The present work also assesses the effects of a very specific type of corrosion defect known as pit corrosion. Analytical procedures to estimate failure of pipes due to pit corrosion defects are not

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[*] Corresponding author. Address: Programa de Pós-Graduação em Engenharia Mecânica, Pontifícia Universidade Católica do Paraná, Rua Imaculada Conceição, 1155, CEP: 80.215-901 Curitiba, PR, Brazil. Tel.: +55 (41) 3271 1337; fax: +55 (41) 3271 1349.

E-mail addresses: joao.abdalla@pucpr.br, joaofilho@utfpr.edu.br (J.E. Abdalla Filho).

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available. This paper investigates the stress distribution on pits due to pipes internal pressure alone using finite element analyses and proposes an analytical procedure derived from such results.

This paper is an updated and revised version of the conference paper [6] and it is organized as follows. Section 2 describes semi-empirical methods in an overall manner, and then focuses on four methods which are investigated in this research work. Section 3 presents a brief review of important works on finite element analysis applied to pipeline corrosion defect assessment. Section 4 performs a numerical assessment of the four semi-empirical methods selected using finite element analyses. Regarding the previous work [6], further finite element analyses have been performed to increase the sets of results allowing the authors to strengthen their conclusions on the accuracy of these semi-empirical methods. Further, Section 5 addresses the issue of pit corrosion defects via finite element analyses (again, regarding the previous work [6], further analyses have been performed). An analytical procedure is proposed to estimate failure pressure of pipelines containing a single pit defect. Finally, Section 6 presents the conclusions drawn.

2. Overall description of semi-empirical methods

Semi-empirical methods are based on the assumption of a simplified region of the corrosion defects. That is, the surface roughness due to corrosion is disregarded and the defect is considered as having a regular smooth geometry. This simplifies analysis procedures and provides results which are usually conservative. In the present context, semi-empirical methods estimate the failure pressure of pipes containing wall thickness reduction corrosion defects. The general expressions which govern every procedure are given below:

$$P_f = P_0\left[\frac{1-\left(\frac{A}{A_0}\right)}{1-\left(\frac{A}{A_0}\right)M^{-1}}\right] \tag{1}$$

$$A = \alpha a d \tag{2}$$

$$A_0 = a t \tag{3}$$

$$P_0 = \frac{\sigma_{flow} 2t}{D} \tag{4}$$

where P_f is the failure pressure of the corroded pipe; P_0 is the failure pressure of the intact pipe; A is the longitudinal area loss due to corrosion; A_0 is longitudinal area of the intact pipe; M is Folias bulging factor (non-dimensional factor which accounts for the defect length); a is the defect length; d is the defect depth; t is the pipe wall thickness; α is an empirical factor which accounts for the corrosion defect shape ($\alpha = 1$ if rectangular shape; $\alpha = 2/3$ if parabolic shape; $\alpha = 0.85$ if intermediate shape between rectangular and parabolic); and σ_{flow} is the material's flow stress.

One of the pioneering semi-empirical methods, the ASME B31G method [2], is fairly simple as it represents long corrosion defects as rectangular shaped profiles and short corrosion defects as parabolic shaped profiles, providing conservative results, mostly for long corrosion defects. Due to this conservatism, the B31G method has been widely used in practice. For the same reason, it was later modified by Kiefner and Vieth into the Rstreng 085 dL method [3] (also known as Modified B31G method) aiming at devising a method which could provide more realistic results. The Rstreng 085 dL method considers the geometry of the defect profile as half depth rectangular and half depth parabolic. Experimental studies demonstrated that the Rstreng 085 dL method gives non-conservative results for long defects, which is the reason the method did not become popular among pipeline engineers. Therefore, Benjamin and Andrade have proposed the RPA (rectangular parabolic area) method [4] which claims to provide adequately conservative results for short and long corrosion defects as well. Further, from experimental tests and finite element analyses, the DNV RP-F101 method [5] was developed. It is intended to be used for defects that fail through plastic collapse and applies only to pipe materials with Charpy energy greater than 61 J (ductile materials). Charpy energy, which is determined by the Charpy impact test, is the energy absorbed by a material during fracture and it is a measure of the material's toughness [7].

3. Finite element analysis in the assessment of corrosion defects

Finite element analysis has been used as an important tool in the development of accurate limit load solutions for pipelines containing corrosion defects. This section presents a brief review of the subject. Saldanha and Bucherie [8] employed three-dimensional finite element analysis to evaluate pipes with internal or external corrosion defects. They have defined failure pressure as the pressure that causes the averaged Von Mises stress through the minimum ligament of the defect to be equal to the material tensile strength. Choi et al. [9] have developed a specific limit load solution for corrosion defects assessment in API X65 gas pipelines by comparing experimental data with finite element analysis results. The limit load solution derived provides the maximum allowable pressure as a function of corrosion defect geometry. Silva et al. [10] have employed finite element analysis to address the issues of the reduction in failure pressure due to defects interaction and of the minimum distance between defects at which no interaction occurs. Machado et al. [11] have compared semi-empirical methods results to finite element analysis results using experimental results as references. They have concluded that finite element analysis results are more accurate. Further, they have investigated the interaction between longitudinally aligned and circumferentially aligned defects, and have prescribed distances at which defects may be considered as isolated.

These works involving finite element analyses are examples of attempts to devise procedures which can be more accurate than semi-empirical methods, or which cover more complex situations such as those of multiple corrosion defects.

4. Assessment of semi-empirical methods

The effectiveness of the aforementioned semi-empirical methods for the estimation of failure pressures of corroded pipes is assessed in this section relating results provided by those methods to experimental results and to numerical results provided by finite element analyses. Experimental results are those provided by Choi et al. [9] and they are valid for short defects. ANSYS® program is used to perform finite element analyses. Four-node shell elements (Shell 43) and eight-node shell elements (Shell 281) are employed to model the problem. Shell 43 is a flat four-node, plastic, large strain shell element. It has six degrees of freedom per node: translations in the x, y and z axes, and rotations about the x, y and z axes (z is the out-of-plane axis). The deformation shapes are linear in both in-plane directions. For the out-of-plane motion, it uses a mixed interpolation of tensorial components. Allman rotations may be employed for rotation stiffness definition of the Shell 43 finite element. According to Wisniewski [12], Allman rotation is a drilling rotation, which is defined as a rotation vector normal to the tangent plane of the shell finite element. Allman shape functions may be employed to approximate the finite element's displacements in terms of nodal displacements and nodal drilling rotations. Although Allman rotations certainly enhance the performance of the four-node flat shell finite element, they have not been

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