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Model error assessment of burst capacity models for energy pipelines containing surface cracks

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ABSTRACT

This paper develops the probabilistic characteristics of the model errors associated with five well-known burst capacity models/methodologies for pipelines containing longitudinally-oriented external surface cracks, namely the Battelle and CorLAS™ models as well as the failure assessment diagram (FAD) methodologies recommended in the BS 7910 (2005), API RP579 (2007) and R6 (Rev 4, Amendment 10). A total of 112 full-scale burst test data for cracked pipes subjected internal pressure only were collected from the literature. The model error for a given burst capacity model is evaluated based on the ratios of the test to predicted burst pressures for the collected data. Analysis results suggest that the CorLAS™ model is the most accurate model among the five models considered and the Battelle, BS 7910, API RP579 and R6 models are in general conservative; furthermore, the API RP579 and R6 models are markedly more accurate than the Battelle and BS 7910 models. The results will facilitate the development of reliability-based structural integrity management of pipelines.

1. Introduction

Mechanical defects, such as metal-loss corrosion, gouges and stress corrosion cracking, are major threats to the safety and structural integrity of oil and gas transmission pipelines. Reliability-based integrity management program has been increasingly adopted by pipeline operators to ensure the safe operation of pipelines [1,2]. Central to this program is to evaluate the failure probability of the pipeline with respect to various limit states, such as bursts of pristine pipes, corroded pipes, cracked pipes and pipes containing stress corrosion cracking under internal pressure, and to ensure that the maximum allowable failure probability is met for a reference length (e.g. 1 km) over a reference period of time (e.g. one year). Therefore, it is of great importance to accurately evaluate the model errors of the deterministic pipe capacity models and incorporate these model errors in the reliability analysis.

Various models and methodologies are available to predict the burst capacities of pipes containing cracks (i.e. planar defects), e.g. the Battelle model [3–5], CorLAS™ model [6–8] and the failure assessment diagram (FAD) methodologies [9–11]. A number of experimental studies have been reported in the context of investigating fracture-based burst capacity models for pipes and vessels containing cracks [e.g. [3–5,12,13]]. For example, Kiefner et al. [3] conducted 140 tests for thin-walled pipes, including 92 tests for pipes with through-wall flaws and 48 tests for pipes with part-through-wall (surface) flaws, for the purpose of developing semi-empirical equations to predict the ductile failure stress levels of through-wall and surface flaws. Stoppler et al. [12] employed four engineering approaches, namely the local collapse loads based on the flow stress, toughness, plastic instability and ligament stress criteria, respectively, to predict the burst pressures for 134 pipes and vessels containing longitudinally oriented cracks. Large deviations were observed between the predicted and test burst capacities, especially for deeply-cracked specimens. Motivated by the study in Stoppler et al. [12], Staat [13] collected a total of 293 full-scale tests mostly carried out in Germany and improved the formulas for local and global collapse loads of thick-walled pipes and vessels containing cracks. Furthermore, studies involving a limited number of burst tests for pipes with external surface cracks have also been reported in the literature [14–21].

The model errors associated with the burst capacity of pristine pipes and pipes containing metal-loss corrosion defects (i.e. volumetric defects) have been investigated and reported in the literature [22,23]. However, reports of model errors associated with the burst capacity models for pipes containing cracks (referred to as cracked pipes) are scarce in the literature. The objective of the work reported in this paper was therefore to evaluate the model errors

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associated with the burst capacity models for cracked pipes. We focused on thin-walled pipes containing longitudinally-oriented external surface cracks, which is of direct relevance to the integrity management of oil and gas pipelines [24,25]. We considered five widely used models/methodologies in this study, namely the Battelle and CorLAS™ models, as well as the FAD methodologies recommended in the British Standard 7910 (BS 7910) [9], American Petroleum Institute Recommended Practice 579 (API RP579) [10] and R6 [11]. A total of 112 full-scale burst test data for cracked pipes were collected from the literature. The model error for a given burst capacity model/methodology was evaluated based on the ratios of the test to predicted burst pressures for the collected data.

The organization of this paper is as follows: Section 2 presents a brief description of the models and methodologies considered in this study; Section 3 describes the full-scale test data collected from the literature; the analysis results are presented in Section 4, followed by the conclusions in Section 5. The equations to evaluate the applied J-integral associated with the CorLAS™ model and calculate the parameters involved in the FAD methodologies are given in Appendixes A and B, respectively.

2. Models and methodologies for predicting burst capacity

2.1. Battelle model

The Battelle model, also known as the log-secant approach or NG-18 Equation, is a semi-empirical model developed at the Battelle Memorial Institute to predict the burst pressure of pipes containing longitudinally-oriented surface cracks subjected to internal pressure only [3–5]. The model assumes a rectangular crack profile in the through-wall thickness direction defined by the maximum crack depth and length and employs two criteria, namely the flow stress- and fracture toughness-based criteria, to determine the burst pressure. The flow stress-based criterion addresses the plastic collapse failure mode, whereas the toughness-based criterion addresses the fracture failure mode. According to the Battelle model, the burst pressure, P_{b1}, is given by

$$P_{b1} = \min\left\{ \frac{2t\sigma_f}{D}\frac{1-\frac{a}{t}}{1-\frac{a}{Mt}},\ \frac{4t\sigma_f}{\pi D}\frac{1-\frac{a}{t}}{1-\frac{a}{Mt}}\arccos\left(\exp\left(-\frac{\pi K_{mat}^2}{8c\sigma_f^2}\right)\right)\right\} \tag{1}$$

where t and D denote the pipe wall thickness and outside diameter, respectively; σ_f is the flow stress of pipe steel and equals $\sigma_y + 68.95$ MPa with σ_y being the yield strength of the pipe steel; a and $2c$ denote the crack depth (i.e. in the through pipe wall thickness direction) and length (i.e. in the longitudinal direction of the pipeline), respectively; K_{mat} denotes the fracture toughness of pipe steel in terms of the stress intensity factor, and M is the so-called Folias factor and calculated by

$$M = \begin{cases} \sqrt{1+0.6275\frac{(2c)^2}{Dt} - 0.003375\frac{(2c)^4}{(Dt)^2}} & \frac{(2c)^2}{Dt} \le 50 \\ 3.3+0.032\frac{(2c)^2}{Dt} & \frac{(2c)^2}{Dt} > 50 \end{cases} \tag{2}$$

If direct measurement of K_{mat} is not available, it is suggested to be evaluated by an empirical equation, i.e. $K_{mat} = (C_v E/A_c)^{0.5}$, with C_v, Ac and E denoting the upper shelf Charpy V-notch (CVN) impact energy, net cross-sectional area of the Charpy impact specimen (i.e. 80 mm^2 for full-size and 53.33 mm^2 for 2/3-size specimens) and Young's modulus of steel, respectively.

Note that the two terms in the curly brackets in Eq. (1) are the burst pressures corresponding to the plastic collapse and fracture failure modes, respectively.

2.2. CorLAS™ model

CorLAS™ is a widely used tool in the pipeline industry to assess the integrity of cracked pipes [20]. Similar to the Battelle model, the burst capacity model incorporated in this tool also considers two independent failure criteria: the flow stress- and toughness-based criteria. For simplicity, we refer to the corresponding burst capacity model as the CorLAS™ model. If the detailed crack depth profile is available, the CorLAS™ model uses the so-called effective area method [8] to evaluate the burst capacity (i.e. an iterative procedure to find the critical portion of the defect profile that leads to the lowest predicted burst pressure); otherwise, a semi-elliptical crack profile is assumed in the model, with the length and depth of the semi-ellipse equal to the crack length and maximum depth, respectively. The latter was considered in this study given that the actual crack profiles are, more often than not, unavailable in practice.

The burst pressure, P_{b2}, according to the CorLAS™ model is given by

$$P_{b2} = \frac{2t}{D}\sigma_{crit}\left(\frac{1-\frac{\pi a}{4t}}{1-\frac{\pi a}{4tM}}\right) \tag{3a}$$

$$\sigma_{crit} = \min\left\{\sigma_f, \sigma_l\right\} \tag{3b}$$

where the flow stress σ_f is defined as $(\sigma_y + \sigma_u)/2$ (as opposed to $\sigma_f = \sigma_y + 68.95$ MPa in Eq. (1)) with σ_u denoting the tensile strength of the pipe steel, and σ_l is the local failure stress at the crack determined by the toughness-based criterion. The value of σ_l is obtained by solving $J_c = J$, where J is the applied J-integral, i.e. the cracking driving force, and J_c is the fracture toughness of the pipe steel. Detailed formulations to evaluate J [6,8] are given in Appendix A. An empirical equation, i.e. $J_c = C_v/A_c$, which is equivalent to the one used for the Battelle model in terms of K_{mat}, is suggested to estimate J_c from the CVN impact energy, if more accurate information about J_c (e.g. from fracture toughness tests) is unavailable. This empirical equation was adopted in this study.

2.3. Failure assessment diagram (FAD) methodologies

2.3.1. Overview

The failure assessment diagram (FAD) was proposed by Dowling and Townley [26] based on fracture mechanics and involves two key parameters, namely the brittle fracture parameter, K_r, and plastic collapse parameter, L_r. The use of FAD to carry out the integrity assessment of cracked pipes involves three components, namely evaluating the assessment point (L_r, K_r), establishing the assessment line and checking the relative position of the assessment point with respect to the assessment line (or cut-off line) (see Fig. 1). The integrity of a cracked pipe under a given pressure and/or other loading conditions is acceptable if the assessment point falls within the region bounded by the assessment and cut-off lines as well as the two axes, and unacceptable otherwise.

To predict the burst pressure of a cracked pipe based on FAD is to evaluate the pressure that causes the assessment point to fall on the assessment or cut-off line. Note that the FAD-based burst pressure prediction can account for the interaction between the plastic collapse and fracture failure modes, whereas the Battelle and