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A Statistical Analysis of the Gamma Exponent Model; a New Methodology for Corrosion Assessment of Localized Metal Loss Flaws and Stress Corrosion Cracking in Oil and Gas Pipelines

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ABSTRACT

The Gamma Exponent Model ("GEM") is a recently developed methodology for failure pressure prediction of flaws in oil and gas pipelines. The model has already shown varied applicability for different flaw types.

The focus of this work is axial metal loss flaws and axial stress corrosion cracking (SCC). The basic model is applicable to axial metal loss. The model is then modified to address issues associated with SCC. Specifically, this work demonstrates that a stress intensity factor relevant to periodic crack arrays, as observed in SCC colonies, can be used to account for crack-shielding. This results in more accurate failure predictions.

The model is validated against available laboratory, hydrotest and in-service failure data. Statistical analyses are performed to demonstrate the mathematical form of the new model are valid. Failure pressure predictions are shown to be comparable or better than current industry models.

Keywords: fracture, corrosion management, stress corrosion cracking, risk

INTRODUCTION

Failure pressure calculations are an important part of all oil and gas pipeline operators' integrity management programs. Analysts must be able to predict the maximum pressure a pipeline can sustain in service and apply a suitable safety factor to account for uncertainties. Pipelines in service will have known (or unknown) distributions of flaws that must be included in these failure pressure predictions. Flaws may be crack-like, such as long seam or stress corrosion cracks (SCC), metal loss, such as corrosion or gouges, or deformation, such as dents or ovality. The focus of this work is axial corrosion and SCC crack-like flaws.

The failure pressure predictions, and their reliability, have a direct impact on the effectiveness and efficiency of the operators' integrity management programs. If failure pressure predictions are non-conservative, the operator may excavate and repair fewer features than are necessary to maintain pipeline integrity and this could result in an ineffective and unsafe integrity program. However, if failure pressure predictions are overly-conservative, the operator may excavate and repair more features than are necessary and this could result in an inefficient and financially costly integrity program.

Several failure pressure prediction models are available to industry to assess corrosion, including the original and modified ASME B31G models, RSTRENG, ASME FFS-1 / API 579, BS 7910 and DNVGL RP F101.¹⁻⁵ SCC

crack-like flaw assessment can be performed using the original and modified log-secant models, ASME FFS-1 / API 579, BS 7910, CorLAS™ and PRCI MAT-8.⁶⁻⁹ These models have been studied extensively and their failure pressure predictions compared to laboratory tests and in-service failure data.¹⁰⁻²⁰

The quality of each failure prediction model can be gauged in terms of both accuracy and precision. The accuracy and precision of the models reported in the literature tend to be dependent on the shape of flaws and material property approximations assumed by the analyst, and in some cases, the relative depth of the flaws with respect to wall thickness. Each model has its own characteristics, and some models may be more applicable than other models under various conditions. It is the responsibility of the analyst to select a suitable model to ensure pipeline integrity.

The focus of this work is validation of the recently developed Gamma Exponent Model (“GEM”).¹⁹ The GEM was initially developed for assessment of axial crack-like flaws, but the methodology has also been adapted for assessment of axial corrosion.^{12 - 13} This is similar to the original Battelle Institute NG-18 equations (used in the ASME B31G and original log-secant models^{6,10}), which have varied applicability for both cracks and corrosion flaws.

The GEM was derived following a similar methodology to the original NG-18 log-secant equation, but with one key difference. The original log-secant equation was based on the behavior of a through-wall flaw and then empirically corrected for finite flaw depth. The new GEM was based on the behavior of an infinitely long part through-wall and then empirically corrected for finite length. The result is a model that is mathematically more focused on flaw depth than it is on flaw length. The details of the derivation are described in Reference 18.

The GEM has been validated previously for axial crack-like flaws against available industry data.^{19,20} Preliminary studies have also shown the GEM to be applicable to axial corrosion flaws.^{12,13,19} In this paper, the preliminary corrosion work is built upon to account for flaw profile, rather than using a simple Level 1 “maximum depth and length” approach. In addition, this work describes the development of a depth correction factor that can be applied to SCC flaws to account for crack shielding. Previous analysts have acknowledged the role of crack shielding,^{14,21,22} but to the author’s knowledge, no theory has been applied to the available industry failure pressure models.

GAMMA EXPONENT MODEL

The basic form of the new GEM is given by:

$$\frac{S_{pred}}{S_{flow}} = \left(1 - \frac{a}{t}\right)^{\gamma} \cdot \frac{2}{\pi} \cdot \arccos \left[\exp \left(-\frac{\pi \cdot K_{mat}^2}{10 \cdot a \cdot S_{flow}^2} \right) \right] \quad (1)$$

Where S_{pred} is the predicted failure stress, S_{flow} the flow stress, a the flaw depth, t the pipeline wall thickness, γ the gamma exponent and K_{mat} the material toughness. The flow stress is defined as the “yield stress + 69 MPa (or +10 ksi).

Experienced analysts will recognize the form of the GEM is similar to the original NG-18 log-secant equation, but with three key differences. The NG-18 “effective area” term is replaced with the remaining ligament term to the gamma exponent. The typical “8” factor in the denominator of the arccos – exponent term is replaced with a “10” factor. Finally, the typical crack half length “c” in the arccos-exponent term is replaced with the crack depth “a”.

For localized corrosion flaws, the only applicable term is the “front term” of Equation (1), that is;

$$\frac{S_{pred}}{S_{flow}} = \left(1 - \frac{a}{t}\right)^{\gamma} \quad (2)$$

This is analogous to the ASME B31G equation. The gamma exponent for localized corrosion is defined as:

$$\gamma = \min \left[\left(\frac{2c}{D/2} \right), \frac{1}{2} \right] \quad (3)$$

Where $2c$ is the full flaw length and D is the pipeline diameter. The gamma term was determined in part theoretically and in part empirically from the validation data.

Note that the upper limit of one-half is unusual; it indicates that the failure pressure of a corrosion flaw converges to the square root of the remaining ligament with increasing flaw length. This is not intuitive. The technical rationale is discussed in Reference 19. Note that this limit is applicable to localized corrosion flaws, but not general wall thinning.

For crack-like flaws, the full model provided as Equation (1) is applicable. The gamma exponent for crack-like flaws is defined as:

$$\gamma = \min \left[\left(\frac{2c}{D/2} \right), 1 \right] \quad (4)$$

The flaw depth “ a ” and relative depth “ a/t ” can be modified, and have been as part of this development work. For example, multiplying the depth by a $(\pi/4)$ factor simulates the shape of a semi-elliptical flaw and results in a higher failure stress prediction. Depth correction factors will be discussed in later sections of this paper.

The toughness for crack-like flaws is calculated from Young’s modulus of elasticity and laboratory test J-integral toughness measurements.²⁵

$$K_{mat}^2 = E \cdot J \quad (5)$$

Where E is Young’s modulus of elasticity and J is the material toughness test measurement. The validation work for the crack-like flaws was completed using the Charpy impact energy to Wallin J-integral correlation described in API 579.^{3, 23} The 5% lower bound Wallin correlation showed the best agreement during the preliminary work. It has been confirmed as the most appropriate during the ongoing development work. Other correlations may provide more or less conservative failure stress predictions.

INDUSTRY DATA

Corrosion Data

The corrosion data compiled for the model validation are summarized in Table 1. The data consists of results of eighty-five laboratory hydrotests on ex-service pipeline sections containing external corrosion flaws. Test cases with (D/t) ratios of less than twenty were not considered. The GEM derivation assumes thin-walled pipe and any thick-walled conditions may result in overly-conservative failure stress predictions that skew the validation results.

Table 1: Summary of laboratory test data.

Reference	Data Sets	Data Ranges
AGA ¹⁶	45	D = 406-672 mm t = 7.8 – 10.5 mm YS = 196 - 508 MPa a = 2.9 – 9.7 mm 2c = 41 – 381 mm
Cronin ¹¹	40	D = 273-864 mm t = 4.5 – 9.7 mm YS = 350 - 462 MPa a = 0 – 4.6 mm 2c = 0 – 1433 mm

Stress Corrosion Cracking Data

The SCC failure data compiled are summarized in Table 2. The data consists of results of one in-service and eight hydrotest failures. The author is aware that there are other SCC failures reported in the literature, however, the raw data from these failures are not necessarily publicly available. Although the data set is limited, it is sufficient to demonstrate some interesting trends and support the GEM development.

GEM VALIDATION

The model validation consisted of using the GEM to predict a failure stress based on the literature data, and then comparing to the reported in-service or hydrotest “true” failure stress. Predicted and true failure stresses were plotted against each other and compared to a unity line. Stresses were normalized to the reported yield strengths of the pipes, or to SMYS if the measured yield strength was not reported in the source.

Basic GEM Analysis for Corrosion

Figure 1 is a validation plot for the eighty-five corrosion data sets. The reported true stress is plotted on the X-axis. The GEM predicted failure stress is plotted on the Y-axis. These predictions assumed a semi-elliptical flaw shape and included a ($\pi/4$) factor applied to the flaw depths. Data above and left of the unity line are considered non-conservative and could result in ineffective and unsafe pipeline integrity programs. Data below and right of the unity line are considered conservative and could result in inefficient and cost prohibitive pipeline integrity programs.