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On the Load Ratio Equation in API TR 5C3 for Pipe Body Fracture Performance Evaluation

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ABSTRACT

Pipe fracture performance often becomes one of the governing factors in the tubular design and material selection for OCTG (Oil Country Tubular Goods) steel pipes used in the sour (H_2S) service environments. API TR 5C3 Annex D [1] provides equations for calculating pipe internal pressure at which a pipe will fail due to crack propagation of existing crack-like flaws. The fracture pressure equations in API TR 5C3 was derived based on API 579 [2] Failure Assessment Diagram (FAD) methodology.

The load ratio equation in API TR 5C3 Annex D uses the combined von Mises equivalent stress as reference stress and includes the crack depth (a) in the calculations of the hoop and axial stresses, which are inconsistent with the API 579. In contrast, API 579 uses the component stress distribution normal to the crack face (e.g., hoop stress due to internal pressure for a longitudinal crack) for the un-cracked geometry. The crack depth (a) is then incorporated in the reference stress (σ_{ref}), which is then used in the load ratio equation.

In this paper, a general load ratio equation is first derived and then compared to the API TR 5C3 load ratio equation. It is found that the API TR 5C3 equation underestimates the load ratio by approximately 15% to 25% depending on the pipe OD to wall thickness ratio (i.e. D_o/t) as well as the crack depth to pipe wall thickness ratio (i.e. a/t). This can potentially lead to an over-prediction of pipe internal pressure at fracture.

Key words: OCTG Pipe, Fracture, Failure Assessment Diagram (FAD), Load Ratio, Sour Service.

INTRODUCTION

API TR 5C3 (7th Edition, June 2018 with October 2019 Addendum) [1] provides equations for pipe body fracture performance in Annex D (informative). The API 579 [2] level-2 FAD curve is utilized to obtain the elastic-plastic fracture pressure equations. The equations address the protection against failure through fracture (brittle or ductile) and are applicable to brittle, ductile, or somewhere between the two extremes for a pipe body containing an infinitely long, internal axial surface crack-like flaw subjected to internal pressure.

The fracture equations provided in Annex D of API TR 5C3 are particularly useful for a pipe to be used in a sour (H₂S) service environment where the environmental fracture toughness (K_{Imat}) of the material becomes significantly lower than that in a sweet environment (such as in water and air). For instance, for an OCTG grade, its material fracture toughness can drop from above $150 \text{ ksi} \sqrt{\text{in}}$ in air to around $30 \text{ to } 40 \text{ ksi} \sqrt{\text{in}}$ in a mild sour environment. A variety of fracture mechanics test methods have been used to develop K_{Imat} data. The standard double cantilever beam (DCB) test method in NACE TM0177-2016 [3] has been widely used to develop K_{Imat} data for sulfide stress cracking (SSC) under different H₂S environments.

FAD curve is a plot of toughness ratio (K_r) versus load ratio (L_r). The toughness ratio (K_r) not only depends on primary stress (e.g. stress due to internal pressure) but also depends on secondary stress (e.g. residual stress exists in the as-manufactured OCTG pipes). On the other hand, load ratio (L_r) depends on primary stress but not on secondary stress. Moreover, the reference stress based on the secondary residual stress distributions is also required to determine the plasticity interaction factor in the toughness ratio (K_r) calculations. According to ASME BPVC VIII-2 [4], there are two categories of stresses: (i) primary stress – the stress distribution resulted from the load-controlled loading that is necessary to satisfy laws of force equilibrium and moment equilibrium. (ii) Secondary stress – the stress distribution that is developed by self-constraint of a component or by the constraint of adjacent parts. The secondary stress is strain-limited and is self-equilibrating. For more information and discussions on stress classification, linearization, and categorization, please refer to ASME BPVC VIII-2, Part-5.

In this paper, we will focus on the load ratio (L_r) equation for an infinitely long, internal axial surface crack for a pipe subjected to internal pressure, which is the same configuration as considered in API TR 5C3 Annex D. First, the load ratio equation is derived based on Lamé stress solutions, stress linearization and categorization, and reference stress equation in terms of linearized primary membrane and primary bending stress. Second, comparisons between different load ratio equations, including the general equation and thin-wall approximation derived in this paper, current API TR 5C3 equation, and API 579 equation, are made. Third, a discussion of an external axial surface crack is also considered. Finally, the general load ratio equation is recommended for use in the pipe body internal fracture pressure calculation.

DERIVATION OF GENERAL LOAD RATIO EQUATION

We consider a pipe with an infinitely long, internal axial surface crack that is subjected to internal pressure, which is the same configuration considered in API TR 5C3 Annex D. Component stress perpendicular to the crack face is the hoop stress (σ_h) (i.e., driving stress for an axial crack). For a pipe (or cylinder), the general Lamé solution [5] for hoop stress is

$$\sigma_h = \sigma_h(r) = \left(\frac{R_i^2}{R_o^2 - R_i^2} \right) \left(1 + \frac{R_o^2}{r^2} \right) P_i \quad (1)$$

in which, R_o and R_i are pipe inner and outer radius, respectively. P_i is internal pressure. The through-wall hoop stress distribution is a nonlinear function of radial position (r , where, $R_i \leq r \leq R_o$). In other words, it varies from pipe inner surface (ID) to outer surface (OD).

For a general through-wall stress distribution ($\sigma(r)$), the statically equivalent, linearized membrane (σ_m) and bending (σ_b) stresses can be determined using equations (2) and (3), respectively [2, 4].

$$\sigma_m = \frac{1}{t} \int_{R_i}^{R_o} \sigma(r) dr \quad (2)$$

$$\sigma_b = \frac{6}{t^2} \int_{R_i}^{R_o} \sigma(r) \left(\frac{R_i + R_o}{2} - r \right) dr \quad (3)$$

in which, t is the pipe wall thickness. By applying the linearization equations (2) and (3) to hoop stress distribution, i.e. equation (1), the linearized membrane stress is then obtained as

$$\sigma_{m_h} = P_i \left(\frac{R_i}{t} \right) \quad (4)$$

while the linearized bending stress is

$$\sigma_{b_h} = P_i \left(\frac{3R_o R_i}{t^2} \right) C \quad (5)$$

where,

$$C = 1 - \left(\frac{2R_o R_i}{R_o^2 - R_i^2} \right) \ln \left(\frac{R_o}{R_i} \right) \quad (6)$$

According to API 579, reference stress (σ_{ref}) [2, 6] for a cylinder containing an infinitely long, internal axial surface crack with crack depth (a) is defined as

$$\sigma_{ref} = \frac{\sigma_{b_h} + \sqrt{\sigma_{b_h}^2 + [3(1 - \frac{a}{t})\sigma_{m_h}]^2}}{3(1 - \frac{a}{t})^2} \quad (7)$$

Next, by replacing σ_{m_h} and σ_{b_h} with equations (4) and (5), respectively, in equation (7), reference stress can then be obtained as

$$\sigma_{ref} = \left(P_i \frac{R_i}{t} \right) \frac{\left(\frac{R_o}{t} \right) C + \sqrt{\left[\left(\frac{R_o}{t} \right) C \right]^2 + \left(1 - \frac{a}{t} \right)^2}}{\left(1 - \frac{a}{t} \right)^2} \quad (8)$$

According to API 579, load ratio (L_r), i.e. the abscissa of the FAD, is defined as

$$L_r = \frac{\sigma_{ref}}{\sigma_y} \quad (9)$$

where, σ_y is the material yield strength. By substituting σ_{ref} with equation (8), load ratio equation (9) can then be written as

$$L_{r_Lame} = \left(\frac{P_i}{\sigma_y} \right) \left(\frac{R_i}{t} \right) \frac{\left(\frac{R_o}{t} \right) C + \sqrt{\left[\left(\frac{R_o}{t} \right) C \right]^2 + \left(1 - \frac{a}{t} \right)^2}}{\left(1 - \frac{a}{t} \right)^2} \quad (10)$$

Alternatively, load ratio equation (10) can also be written in terms of D_o/t and a/t