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LIFETIME ASSESSMENT OF HYDROGEN PIPELINES: MODELING HYDROGEN-INDUCED FATIGUE USING FRACTURE MECHANICS APPROACHES

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ABSTRACT: Hydrogen pipelines are a critical infrastructure for the transition toward a sustainable energy future. However, hydrogen embrittlement (HE) poses significant challenges to the integrity of pipeline steels, leading to accelerated fatigue crack growth and potential failures. In this study, a comprehensive lifetime prediction model for hydrogen pipelines was developed based on fracture mechanics principles outlined in ASME B31.12 and API 579-1/ASME FFS-1. The model simulates crack propagation under cyclic internal pressures using a cycle-by-cycle computational approach, incorporating material properties, crack geometry, and fatigue crack growth laws specific to hydrogen environments. Validation against literature models reveals strong agreement, with noticeable variations in some cases that are likely attributed to differences in stress intensity factor (SIF) solutions. A case study on API 5L X52 steel pipelines revealed the influence of initial crack depth and pressure fluctuation range on predicted allowable number of load cycles. The developed model offers a reliable framework for assessing hydrogen pipeline integrity to ensure safe design and operation.

KEYWORDS: *Hydrogen Embrittlement, Pipeline Steel, Lifetime Modeling.*

1. INTRODUCTION

Hydrogen is increasingly regarded as a central energy carrier for achieving a sustainable, low-carbon future [1-2]. Pipelines offer the most cost-effective means of transporting hydrogen at scale, but their long-term reliability is challenged by hydrogen embrittlement (HE), a degradation process that accelerates crack initiation and growth in pipeline steels [3]. This phenomenon compromises ductility, fracture toughness, and fatigue resistance, raising concerns about premature failures under cyclic operating pressures. Conventional pipeline design methods, largely developed for natural gas, do not fully account for the accelerated crack growth mechanisms unique to hydrogen service [2]. As a result, there is a critical need for physics-based models that can predict the remaining service life of hydrogen pipelines with sufficient accuracy and conservatism. This study develops a fracture mechanics-based lifetime prediction model, following ASME B31.12 and API 579-1/ASME FFS-1 guidelines. The model simulates fatigue crack propagation under hydrogen environments and provides insights into how initial flaw size and pressure fluctuations influence the allowable number of operating cycles.

2. LIFETIME ASSESSMENT OF PIPELINES

Hydrogen pipelines experience dynamic loading from frequent pressure cycles, which, when combined with hydrogen embrittlement, accelerate fatigue crack initiation and growth. Small flaws (Fig. 1) from welding, corrosion, or material inhomogeneities can serve as crack

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initiation sites, making accurate lifetime prediction critical for safe operation. Traditional non-destructive testing has limited resolution, so fracture mechanics-based assessment methods provide a more reliable framework. The ASME B31.12 code, supported by API 579-1/ASME FFS-1, requires fracture mechanics evaluations when hoop stresses exceed 40% of the specified minimum yield strength, emphasizing fatigue crack growth laws and hydrogen-assisted cracking thresholds.

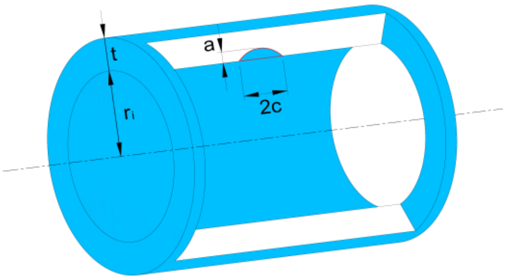

Fig. 1. Crack geometry assumed in ASME B31.12—an axially oriented, semicircular surface crack located on the inner wall of the pipe (Adapted from [4]).

In this study, a cycle-by-cycle lifetime prediction model was developed following ASME B31.12 guidelines. The model incorporates pipeline dimensions, material properties, initial crack size, and internal pressure fluctuations to calculate stress intensity factor (K). The crack growth rate (da/dN), represents the increase in crack depth a per loading cycle N, which is the standard way fatigue crack propagation is quantified in fracture mechanics. Hydrogen-specific fatigue crack growth laws are used to evaluate da/dN, and the crack depth is updated iteratively per load cycle [5]. Failure is assumed once either the critical crack depth (acrit = 0.25t) is reached or the maximum SIF exceeds the hydrogen-assisted The crack growth rate (da/dN) The procedure outputs the number of allowable cycles, representing the predicted service life of the pipeline under specified conditions.

2.1. Case Study

In developing the lifetime prediction model, the methodology applied in [4], [5] has been adopted. This approach ensures a standardized basis for comparison, which will be thoroughly discussed in the results section. The X52 pipeline, as modeled in previous studies [4-5], had an outer diameter, D0 = 323.9 mm, and a wall thickness of t = 16 mm, with a maximum operating pressure, P_{max} = 20 MPa across all cases. External factors such as secondary bending stresses and residual stresses affecting the pipeline tubes were considered negligible. The yield strength ($\square_{YS}$) and ultimate tensile strength ($\square_{UTS}$) were found to be 468 and 531 MPa, respectively, based on measurements.

3. RESULTS AND DISCUSSION

In this section, the results of the developed lifetime assessment model will be presented, analyzed, and compared with the predictions of existing models as documented in recent studies [4-5]. Before discussing the results, it is important to note that the notation a_0/t represents the initial crack depth (a_0) normalized by the pipe wall thickness (t). This ratio expresses the flaw size as a fraction of the wall thickness, which allows direct comparison of different initial defect sizes. As shown in Fig. 2, the Number of Allowable Cycles (NAC) for the developed model, based on ASME B31.12, yields 49,650 allowable cycles, compared to the 43,115 cycles reported in [4] for the same initial crack depth (a_0/t = 5 %) and pressure range (5–20 MPa). In both cases, the initial crack depth was assumed to be 5% of the wall thickness, with minimum and maximum pressures of 5 and 20 MPa, respectively. The fatigue crack

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growth (FCG) law from the ASME B31.12 standard, as applied in both models, plays a critical role in these predictions. The higher NAC observed in the current model suggests a marginally less conservative approach compared to the solution referenced in the literature. The difference in predicted cycles (49,650 in this work versus 43,115 in [4]) likely results from the different SIF solutions used, which produce different SIF ranges.

As the initial crack depth increases, the number of allowable cycles decreases sharply (Fig. 3). The model developed in this study predicts approximately 267,700 cycles for a_0/t = 2.5 %, 49,650 cycles for 5 %, and about 7,850 cycles for 10%., confirming that larger initial flaws significantly shorten pipeline fatigue life. Differences in predicted cycles compared to literature arise from the SIF solutions used. The reference model applies to a plate-based SIF solution (KPSE1), while this work uses a cylinder-based SIF solution (KCTCL). These assumptions alter stress distribution, leading to variations in fatigue life. Both the new model predictions and the one reported in literature show that higher pressure fluctuations reduce fatigue life.

At low pressure ranges (Fig. 4), the model predicts more cycles, while at high pressure ranges it becomes more conservative such as 116,350 vs. 52,800. These differences could be attributed to the variation in SIF solutions used, which affect considerably the NAC due to its cumulative effect. For a_0/t = 5%, the model predicts slightly fewer cycles than literature at low pressure (Fig. 5), but at higher pressures, the results converge, showing close agreement. This indicates similar performance across pressure ranges, with only minor variations due to stress intensity assumptions.

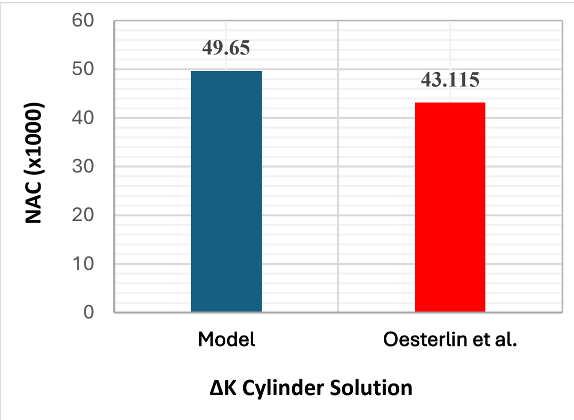

Fig. 2. Comparison of NAC for ΔK cylinder solution with literature using: B31.12 with API 579-1

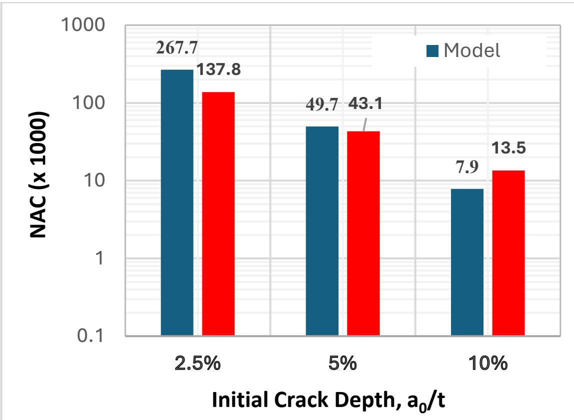

Fig. 3. Model comparison of the effect of a_0 on NAC at Pmin/Pmax = 5/20

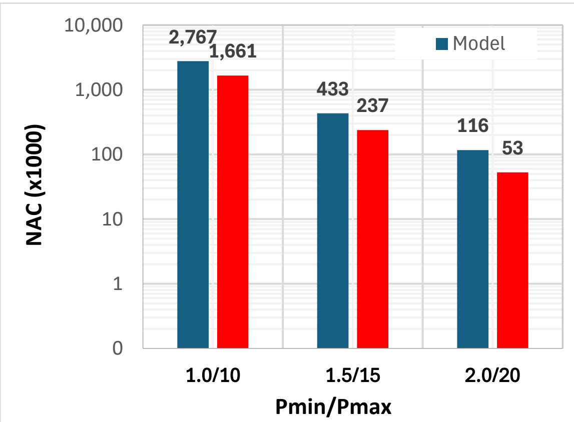

Fig. 4. Comparison of the effect of pressure range on NAC at a_0/t = 2.5% & R = 0.1

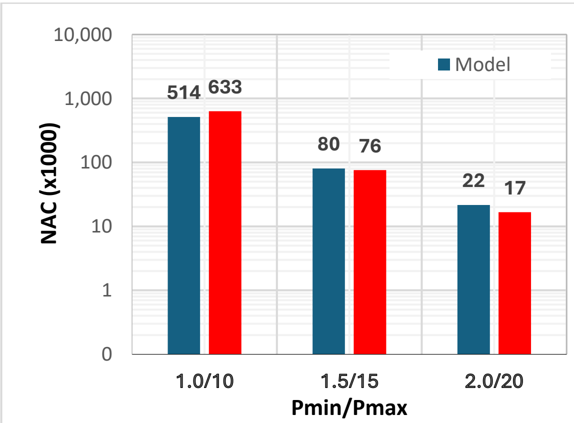

Fig. 5. Comparison of the effect of pressure range on NAC at a_0/t = 5% & R = 0.1

Overall, the comparison shows that the model aligns closely with reference literature for moderate initial crack depths and moderate pressure ranges. However, for larger cracks and higher-pressure fluctuations, the model predicts more conservative values, indicating a greater sensitivity to initial defect size and pressure fluctuations. This trend is consistent with the known relationship between crack depth, pressure-induced stress intensities, and fatigue life predictions. These differences highlight the influence of the SIF solutions used, where the cylinder through-wall crack model may predict faster crack growth compared to other solutions, such as the surface cracked plate with semielliptical cracks used in [4, 5].

4. CONCLUSIONS

A fracture mechanics-based lifetime prediction model was developed for hydrogen pipelines using ASME B31.12 and API 579-1/ASME FFS-1 guidelines. The model simulates cycle-by-cycle crack growth and provides a conservative framework for assessing pipeline integrity. Key findings are:

- The model captures hydrogen-assisted fatigue crack growth and agrees well with [4,5], with differences tied to stress intensity assumptions.
- Initial crack depth strongly affects fatigue life; increasing from 2.5% to 10% of wall thickness reduces allowable cycles by over an order of magnitude.
- Pressure fluctuations accelerate crack growth, with higher differentials leading to shorter lifetimes.
- The model shows heightened sensitivity at larger crack depths and high pressures, emphasizing the need to minimize initial defects and pressure swings.
- Hydrogen significantly increases crack growth rates even at low stress intensities, underscoring the need to account for HE in design and requalification.

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