# PROBABILISTIC CRITICAL FLAW SIZE ASSESSMENTS IN THE CIRCUMFERENTIAL WELDS OF LAYERED PRESSURE VESSELS

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## Abstract

The National Aeronautics and Space Administration (NASA) operates approximately 300 aging, carbon steel, layered pressure vessels (LPVs) that were designed and manufactured prior to ASME Boiler and Pressure Vessel (B&PV) code requirements. Fitness-for-service assessments and traditional evaluations of these non-code vessels is a challenge due to unique uncertainties that are not present in code vessels, such as missing construction records and the use of proprietary materials in construction. Furthermore, many of the steels used in these non-code vessels are at a risk of cleavage fracture at low temperatures within the operating temperature ranges of the NASA sites where these vessels are installed. Additionally, the stress state in critical regions of the LPVs, such as the longitudinal seam welds and circumferential welds, is uncertain due to weld residual stresses (WRS), geometric discontinuities, and stress concentrations in weld connections. In order to guide non-destructive evaluation (NDE) and assessment of the circumferential welds and account for uncertainties in these non-code LPVs, probabilistic critical initial flaw size (CIFS) and critical crack size (CCS) analyses were performed for eleven locations of interest within the head-to-shell and shell-to-shell circumferential welds of three demonstration LPVs.

## 1. Introduction

Figure 1 shows the eleven semi-elliptical surface flaws (six circumferentially-oriented and five axially-oriented) in the head-to-shell and shell-to-shell circumferential welds analyzed in this study. The service stresses in the circumferential welds as a result of the internal pressure in the vessel were predicted using a linear elastic, axisymmetric finite element model of the vessel. An elastic-plastic finite element weld simulation, which involved sequentially coupled thermal and mechanical analyses, was performed to predict the WRS in the circumferential welds after welding and the subsequent hydrostatic test. Linear superposition was employed to estimate the stress field (service stresses + WRS) in the weld, and the stresses were input to the NASGRO fatigue and fracture control software to compute the CIFS and CCS using an innovative approach for cleavage fracture toughness. The modeling framework is described in more detail in [1]. The NESSUS probabilistic analysis software was used to change deterministic model inputs into random variables, sample the random variables, and propagate uncertainty through the models to predict the sensitivities and empirical cumulative distribution function of the CIFS and CCS.

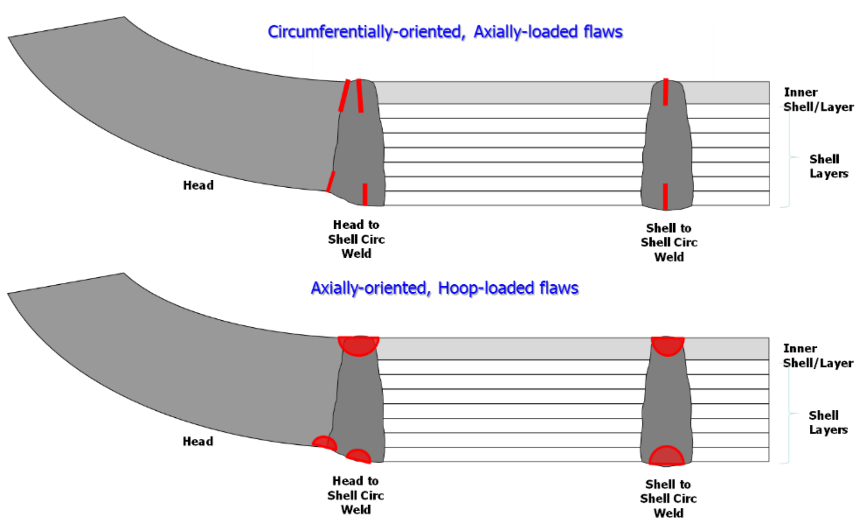


Fig. 1 - The circumferentially- and axially-oriented, semi-elliptical surface flaws investigated in the study.

## 2. Results

Model parameters for vessel geometry (inner layer thickness, wrapper layer thickness, LPV efficiency, and weld geometry), weld thermo-mechanical properties (yield strength and coefficient of thermal expansion), and fracture properties (upper shelf toughness, lower shelf toughness, and transition temperature) were treated as uncertain variables. Cleavage fracture toughness was determined according to ASTM E1921 and experimental data was used to fit probability distributions for the input random variables when available. In addition, laboratory $da/dN\ vs.\ \Delta K$ data was obtained for A225 Grade B head, weld, and heat affected zone steel. The cyclic loading schedule for 40 years of vessel service was conservatively estimated assuming minor hourly depressurizations from 90% to 100% of the maximum internal pressure, one depressurization to 30% daily, one depressurization to 10% weekly, and one depressurization to 0 monthly.

Global sensitivity analysis was performed to understand the impact of uncertainty in the model inputs on uncertainty in the predicted CIFS and CCS. According to the sensitivity analysis, the choice of cleavage fracture toughness used in the analysis is arguably the most important value, having a significant impact on the predicted CIFS and CCS values. After the sensitivity analysis, full cumulative distribution function analysis of the CIFS and CCS was performed as a function of deterministic minimum operational temperatures to understand the critical flaw sizes for each of the eleven flaw locations in the circumferential weld and how the critical flaw sizes change with temperature. Figure 2 shows the left tail of the predicted cumulative distribution function of CIFS for the axially-loaded flaw originating from the inner diameter of the shell-to-shell weld in a 9-layer demonstration vessel. The results show that the CIFS at 0.05 cumulative probability ranges from 0.15 inch to 0.32 inch from a temperature of -20°F to 40°F.

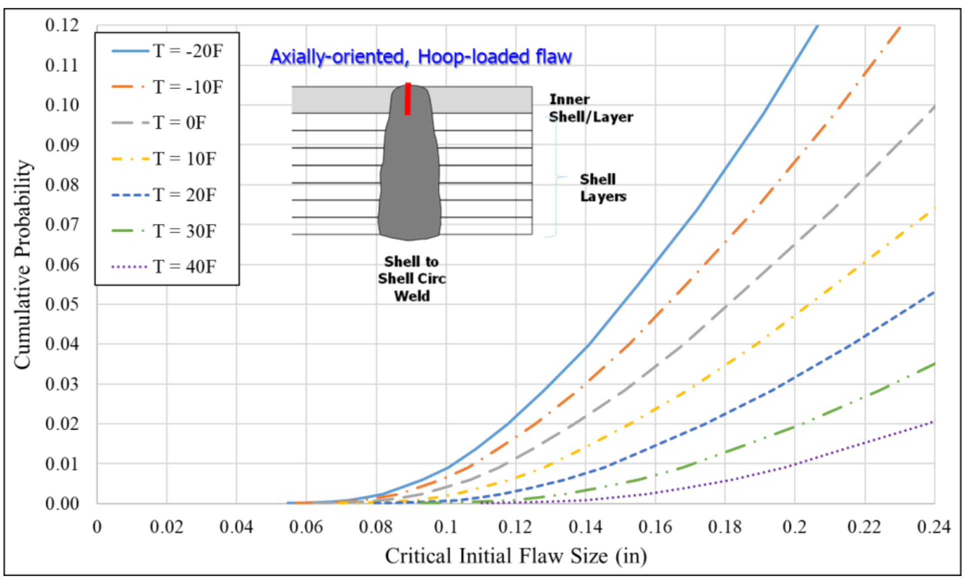


Fig. 2 - Left-tail of the predicted cumulative distribution functions of CIFS in a 9-layer vessel.

## 3. Conclusions

The global sensitivity analysis results provide insight as to what additional data is needed to reduce uncertainty in the CIFS and CCS predictions. The cumulative distribution results provide information about the relative risk of a critical flaw size and give guidance for NDE inspections regarding the flaw sizes that need to be detected. This presentation will discuss the innovative approach being used for CIFS and CCS calculations in NASGRO using cleavage fracture toughness and show an example of the probabilistic fracture assessments that are being performed to evaluate NASA's non-code LPVs.

## 4. References

[1] Riha, D., et al. *Probabilistic Risk Assessment of Aging Layered Pressure Vessels*. in *Pressure Vessels and Piping Conference*. 2019. American Society of Mechanical Engineers.