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Evaluating Appropriateness of LEFM Tools for COPV and Metal Pressure Vessel Damage Tolerance Life Verification

Human spaceflight composite overwrapped pressure vessels (COPVs) and metal pressure vessels can use linear elastic fracture mechanics (LEFM) analysis to demonstrate damage tolerance life in some cases per ANSI/AIAA-S-081 for COPVs and ANSI/AIAA-S-080 for metal pressure vessels. LEFM analysis assumptions require that the crack tip plastic zone is small relative to the crack size and is completely surrounded by elastically responding material. Test and analysis have shown that LEFM tools (e.g., NASGRO*) can provide unconservative crack growth predictions for cracks in COPV liners that violate LEFM assumptions. COPV and metal pressure vessel designers should evaluate and address the violation of LEFM plasticity assumptions before using LEFM analysis tools for damage tolerance life verification.

Background

LEFM methods have traditionally been used to successfully characterize the damage tolerance life of elastically responding components that contain cracks that are small relative to the thickness or other structural features. However, prediction of part-through cracks in thin metallic materials, where break-through is an end-of-life condition (e.g., COPV liners or thin metal pressure vessels), presents a unique problem. For example, traditional plastic zone limits that bound the use of LEFM (e.g., Irwin plastic zone model) are based on cracks in semi-infinite bodies and can be unconservative for a part-through crack approaching the back surface of a thin component. Furthermore, existing standards (e.g., ANSI/AIAA S-081 and S-080) do not provide guidelines for end-of-life limits in damage tolerance life analysis with LEFM tools such as NASGRO.

Discussion

In addressing the impact of LEFM plasticity assumptions on conservatism of damage tolerance life predictions, the NESC assessment team:

- Performed testing to generate crack growth and crack mouth opening displacement (CMOD) data.
- Performed LEFM analyses using NASGRO v8.2 as an exemplar LEFM tool to compare against crack growth test data.
- Developed a validated finite element model (FEM) to compare predicted crack behavior using elastic and elastic-plastic material models (Figure 1).
- Experimentally and numerically demonstrated that the divergence between elastic and elastic-plastic predictions is gradual.

The validated FEM considered various crack sizes, liner thicknesses, stress levels, and materials. Analysis data demonstrated a gradual divergence in predicted elastic-plastic and elastic crack behavior. As a result, the NESC assessment team:

- Developed criteria that expands on the concepts developed in ASTM E2899 to determine when LEFM plasticity assumptions are invalid (i.e., LEFM limit, a_L).
- Provided a modified failure criterion, a_i*, to be considered when LEFM analyses are used beyond the LEFM limit.

As illustrated in Figure 2, a_i* is a knockdown on the LEFM damage tolerance life state-of-practice limit (i.e., the Irwin plastic zone limit, a_i), meaning a_i* is as or more conservative than a_i. To account for the aforementioned gradual divergence between elastic and elastic-plastic predictions, the knockdown is only applied when the analysis shows exceedance of the LEFM limit, a_L. The magnitude of the knockdown depends on the degree of exceedance, elastic-plastic finite element analysis, and applicable test data.

LEFM Evaluation Approach

When LEFM-based fatigue crack growth predictions are made for damage tolerance life (e.g., with a LEFM tool such as NASGRO), COPV and metal pressure vessel designers should use the following analysis procedure to address the potential violation of LEFM plasticity assumptions:

- Simulate crack growth to failure (i.e., breakthrough).
- Identify the predicted crack depth after 4-lifetimes, a_F.
- Identify the limits a_i, a_L, and a_i*.
- Verify that $a_F < a_i*$, otherwise the design does not meet recommended requirement for damage tolerance life by analysis.
- Report a_F, a_i, a_L, and a_i* to fracture control engineering technical authority.

References

1. ANSI/AIAA-S-081 and ANSI/AIAA-S-080, Space Systems – Composite Overwrapped Pressure Vessels, Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
2. COPV Damage Tolerance Life Analysis and Test Best Practices, NASA/TM-2020-5006765
3. Damage Tolerance Life Issues in COPVs with Thin Liners, NESC-TB-16-02

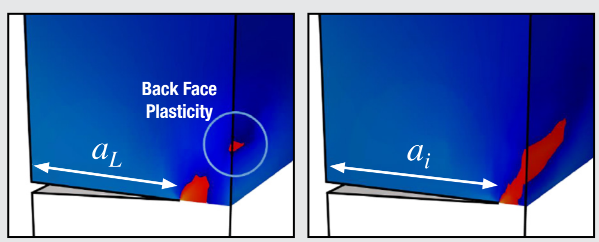

Figure 1. Plastic zone size from FEM comparing LEFM limit calculated according to ASTM E2899-15 and the Irwin limit. The crack tip plastic zone is highlighted in red.

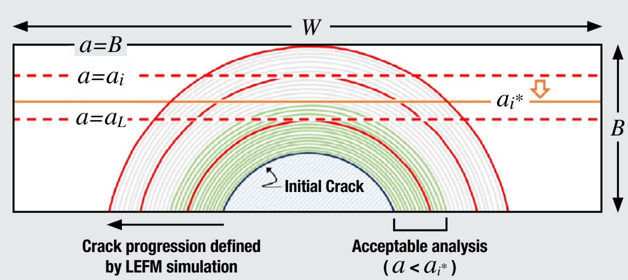

Figure 2. Schematic of a surface crack growth simulation and applicable limits on a, including the Irwin limit, a_i, the LEFM limit, a_L, and the modification limit, a_i*.

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