Crack Damage Tolerance Assessment and Leak-before-break Flow Simulation of Aircraft Bleed Air System Ducts

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Abstract: *In aircraft bleed air system ducts, cracks may exist or initiate from manufacturing defects in areas of high stress concentration in particular at welds. The initial minor cracks may grow into two possible failures: either the crack grows steadily through the wall to form a stable "through-crack" (leak-before-break), or it becomes unstable before or after it has reached the opposite surface of the duct wall and spreads rapidly over a large portion of the duct (break-before-leak), depending on the pressurized hot-air load and the toughness of material. For the safe design of bleed air system ducts and assessment of ducts with minor cracks found in the quality inspection, it is required to understand and predict the crack behavior and leak-before-break leakage rate. A leak before break is desired so a leak can be detected and a repair made before a structural failure. In this study, the Extended Finite Element Method (XFEM) is used to evaluate if an initial crack will grow into unstable failure. Abaqus CFD is used to calculate the leak-before-break crack leakage rate in the case of a stable through-crack, utilizing the crack dimensions obtained from crack propagation simulation. The leakage rate result compares well with an existing explicit equation that describes the idealized zig-zag crack flow channel.*

Keywords: *Aircraft Bleed Air System, Duct, Leak-before-break, Crack Damage Tolerance, Leakage Flow Rate, Extended Finite Element Method, XFEM*

1. Introduction

The aircraft bleed air system is used for conveyance of high pressure, hot air from the main engine or auxiliary power unit to other applications throughout the aircraft, such as anti-icing system, environment control system, etc. The system consists of ducts, control valves, and heat exchangers. For a large number of aircraft bleed air systems, the duct assemblies are Inconel 718 weldments. Because of its properties of readily fabricated, good tensile, fatigue, creep, and rupture strength, Inconel 718 has been widely used for aircraft air and liquid duct applications. However in the case of Inconel 718 weldments, crack initiation during conventional welding processes is not uncommon. As such, cracks may initiate or exist in areas of high stress concentration or from material/manufacturing defects.

The initial minor cracks may or may not grow, depending on many factors, such as initial crack size, loading, material strength, etc. If propagation does occur, the cracks may grow resulting in two possible failures: either the crack grows steadily through the wall to form a stable "through-crack" (leak-before-break), or it becomes unstable before or after it has reached the external surface and spreads rapidly over a large portion of the duct (break-before-leak). For the safe design and assessment of these ducts for which minor cracks are identified during quality inspection, it is required to understand and predict the crack behavior and leak-before-break leakage rate in order to determine if a crack can be detected before it reaches a critical size and leads to structural failure.

2. Duct Damage Tolerance Assessment

Crack damage tolerance approach, introduced by the United States Air Force in 1985, requires the aircraft system/component manufacturers to account for the intrinsic material flaws in their design and screen out any components which contained flaws exceeding analytically determined maximums. In this study, the damage tolerance assessment procedure is based on military standards and aircraft manufacturing customer's specifications.

For the purpose of the analysis, an initial crack size is assumed to be located at the most unfavorable position and orientation with respect to fatigue crack growth potential. The maximum flaw size allowable is determined by a damage tolerance analysis utilizing finite element analysis (FEA) in conjunction with simulated operational loads in a test lab environment.

Non-destructive inspection in the form of dye penetrant, ultrasonic and radiographic testing is performed on the duct assemblies as part of the manufacturing process. As some level of cracking is anticipated considering the given material, the measured crack size is compared with the maximum allowable initial crack size as determined by analysis.

In the case of aircraft engine systems, ducting is typically designed for full life based on the components duty cycle. Typically, the first major inspection is targeted around mid-life. Depending on the ability to inspect and detect crack growth or leakage, a margin on loading or a scatter factor on life may be required to account for statistical variation.

Micro-cracks found during the quality inspection are a combination of material flaws, such as a lamination or inclusion, and post-weld cracks. The post-weld cracks are largely located at the weld toe region and along the axial direction. Figure 1 shows the duct geometry and crack considered in the study. Both partial-through and through cracks are considered. The partial-through crack may or may not break through the wall thickness depending on initial crack size, material strength, and load condition. The initial maximum size of a partial-through crack should be determined so the crack does not propagate through the wall to produce a leak during the life of the aircraft. An assessment is required to ensure that if a crack does propagate through the wall a leak-before-failure condition exists versus a break-break-leak condition. The leakage rate should be determined to ensure that it can be detected by the inspection or onboard aircraft systems to ensure the part can be repaired or replaced before a structural failure occurs.

For the purpose of this analysis, the modeled cracks are considered to be pre-existing or initiated at the inner wall surface, along the duct axis direction. This orientation is similar to many cracks found in the quality detection. Only a single defect at the location is considered.

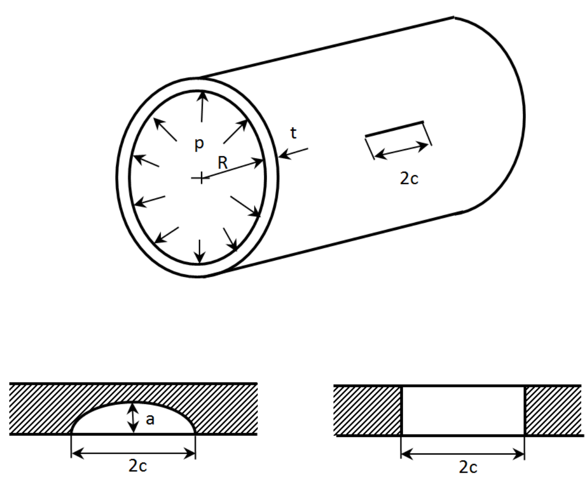


Figure 1. Axial crack considered in a duct (initiate from inside and crack through the thickness).

The crack length and depth can be found from the quality inspection. For analysis, the weld defect crack is assumed to have a semi-elliptical profile (see Figure 2).

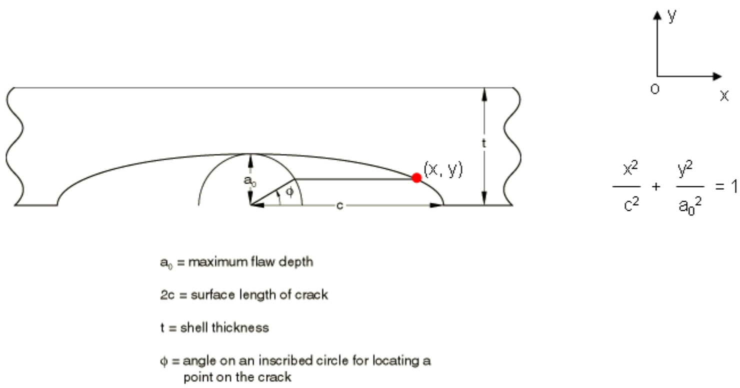


Figure 2. Representation of the weld defect crack with a semi-elliptical profile.

Considering symmetry and crack geometry, one-half segment of the duct is modeled for the finite element analysis (see Figure 3). Abaqus' quadratic structural elements, C3D8R, are used in the duct modeling. A finer mesh is used for elements surrounding the initial crack site. The equivalent operating pressure that factors in the known material response to the temperature is applied on the inner surface of the duct. The plug load, $p*0.25*d^2$, is applied at one end of the duct model.

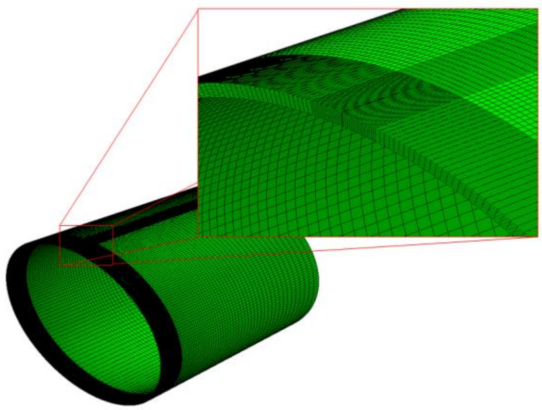


Figure 3. Finite element mesh and initial crack.

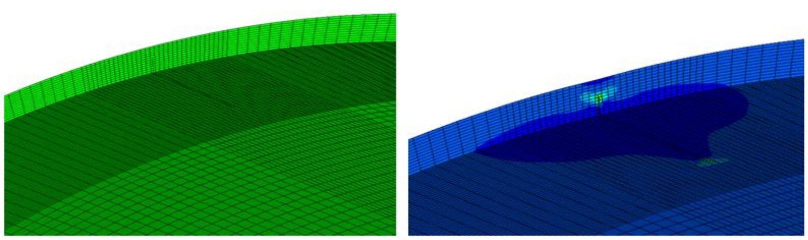


Figure 4. Example of non-through crack and stress distribution.

The stress intensity factor is calculated in FEA at the crack defect. If the stress intensity factor, ΔK, is smaller than the threshold intensity factor, K_{th}, or $\Delta K < K_{th}$, no crack growth occurs and no crack propagation calculation is needed. If the stress intensity factor is greater than the threshold, $\Delta K > K_{th}$, the crack will begin to propagate.

In the case of $\Delta K > K_{th}$, the crack propagation calculations can be performed using the Paris equation (Paris et al, 1961):

$$da/dN = c\,(\Delta K)^m$$

Where,

da/dN, is the change in crack length per cycle
c, is the Paris Coefficient ($ksi^{-m}\ in^{(1-0.5m)}$)
ΔK, is the change in stress intensity factor ($ksi\ in^{1/2}$)
m, is the Paris exponent

The pressure load cycle is defined as the bleed air system is turned on (0 to operating pressure), hold-on at the operating pressure, and then turned off (operating pressure to 0 psi). The loadings, the pressure and plug loads, used in the FEA crack assessment analysis were simply related to pressure loading. The resulting ΔK is therefore equal to K_I for each pressure load cycle.

The K factors at different crack depths were calculated in the finite element model. A best-fit curve function $\Delta K = f(a)$ was used for integration of the Paris equation to get the life cycle vs. crack depth relationship.

$$N = \int_{a_0}^{a_c} \frac{da}{c(\Delta K)^m}$$

Where,

N is the number of life cycle
a_0 is the initial crack depth
a_c is the critical crack depth

The critical crack depth (one component of the maximum allowable flaw size) is the crack depth at which one more load cycle will cause the crack to propagate through the thickness and allow the internal air to escape.

3. Leakage Analysis Approach

In addition to the leak-before-break requirement, the resulting through-thickness crack must demonstrate a sufficient leak rate able to be detected. In other words, the aircraft maintenance team must be able to notice the leak at inspection to initiate a replacement. As such, there is a need to calculate the leakage flow of gases through the crack after the calculation of through-the-thickness crack opening. The initial through-crack length may be assumed as two-times wall thickness or based on quality control measured data.

The leak flow rate through a narrow crack can be obtained by the following methods:

- Experiment measurement (Narabayashi et al, 1991);
- CFD modeling (ex. 2-D idealized crack);
- Analytical equations (Beck et al, 2005) .

Beck et al proposed an analytical approach to calculate the leak flow. Figure 5 shows the idealized crack geometry. The zig-zag shape represents the effect of wall roughness. The assumption is that the angle between metal grain faces is exactly 90 degrees. It was demonstrated that the analytical results have a good agreement with lab test data.

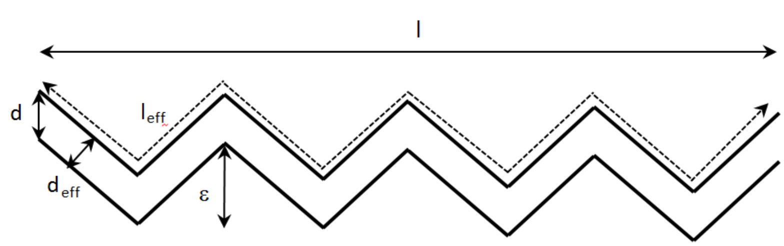


Figure 5. Idealized crack geometry.

The leak flow is divided into 4 regions:

1) Narrow crack, the flow is dominated by the viscosity:

$$u\left[\frac{12\mu l_{eff}}{d_{eff}^2}\right]-\Delta P=0$$

2) A larger crack, the inertia pressure becomes more important:

$$\frac{\rho u^2}{2}\left[N2\theta\frac{d_{eff}}{d}\right]+u\left[\frac{12\mu l_{eff}}{d_{eff}^2}\right]-\Delta P=0$$

3) A further larger crack, the inertia forces are now minor:

$$\frac{\rho u^2}{2}\left[N\left[1-\left(\frac{d_{eff}}{d}\right)^2\right]\right]+u\left[\frac{12\mu l_{eff}}{d_{eff}^2}\right]-\Delta P=0$$

4) The flow becomes turbulent, the expansion and contraction losses are dominant:

$$\frac{\rho u^2}{2}\left[N\left[1-\left(\frac{d_{eff}}{d}\right)^2\right]\right]-\Delta P=0$$

In this study, a simple 2-D model is created using Abaqus CFD for leakage flow simulation. The simulated leakage flow is compared with the analytical solution.

Figure 6 is a cross-sectional view of a duct crack path. The metallurgy micrograph picture (Figure 7) shows that the mean grain size of the duct material, Inconel 718, is about 0.001” (25.4 micrometer).

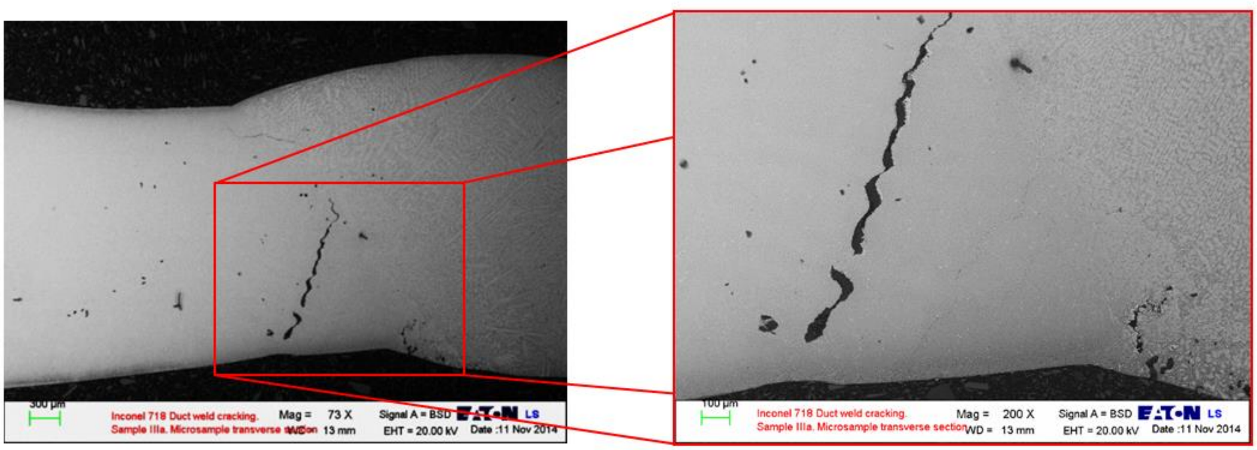


Figure 6. Sectional view of the crack path.

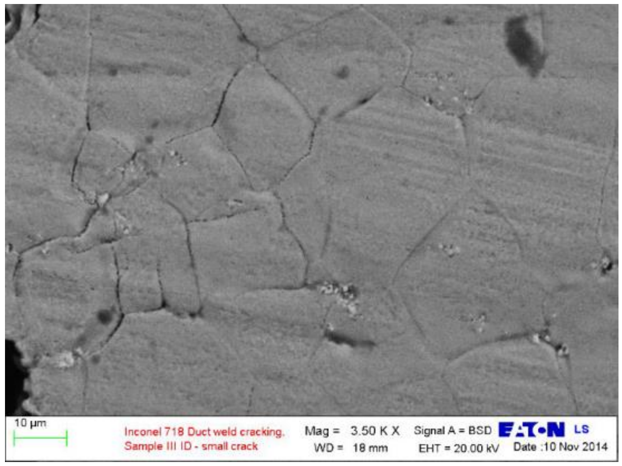


Figure 7. Micrograph of Inconel 718 material.

Using the crack length and opening calculated in XFEM crack modeling together with the assumption of through crack, the leakage flow rate can be simulated. Figure 8 demonstrates the CFD model of the idealized crack and velocity magnitude plot. Figure 9 shows the initial through-crack under no load condition and the crack size (with a magnification factor of 10) under pressure load. The crack opening area may be different at the inner diameter (ID) and outer diameter (OD). The averaged crack width, calculated by dividing the averaged crack opening area with the crack length, is used for the leakage flow rate calculation.

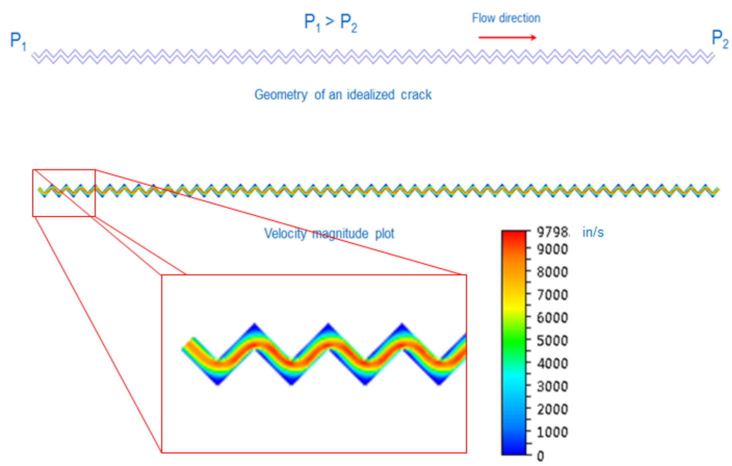
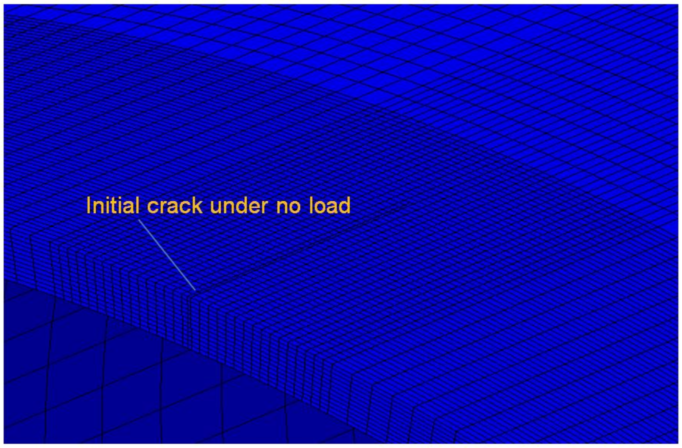
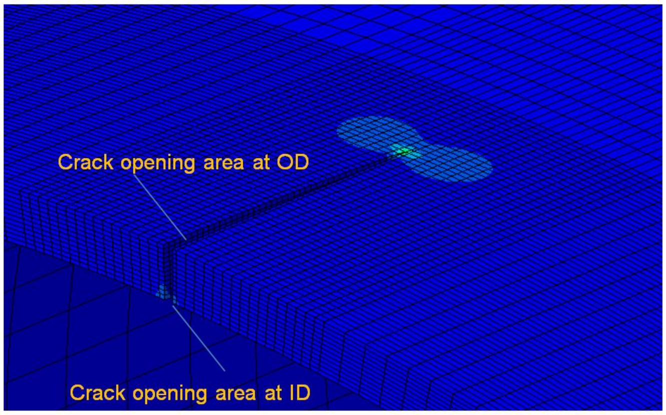


Figure 8. CFD Model of an idealized crack.



(a) Without pressure load



(b) With pressure load

Figure 9. Initial crack and crack size under load.

4. Results and Discussion

During the flight, the bleed air system may endure different load conditions. A worst scenario simulation is carried out for a specific duct with given initial through-crack lengths. Four cases are studied:

Case 1: System on and at sea level, $T = 700^oF$, $P_1 = 130$ psia, $P_2 = 14.7$ psia;

Case 2: System on and at 41000 ft, $T = 700^oF$, $P_1 = 130$ psia, $P_2 = 2.6$ psia;

Case 3: System off and at sea level, $T = 1200^oF$, $P_1 = 400$ psia, $P_2 = 14.7$ psia;

Case 4: System off and at 41000 ft, $T = 1200^oF$, $P_1 = 400$ psia, $P_2 = 2.6$ psia.

Where: P_1 – pressure inside of duct, P_2 – pressure outside of duct, T – hot air temperature

The wall thickness is the nominal part dimension. The crack size under load condition is analyzed with XFEM. The mean grain size, crack length, and averaged width along the length are used in the leakage calculation. The averaged crack width is determined by dividing the crack opening area by the crack length.

Figure 10 shows a leak-before-break situation analysis result of the duct component. Normalized flow rate is the leakage flow per unit surface crack length. The results show that the effect of pressure at the outside of the duct is small. The curvature and slope variation reflect the leakage flow characteristics as the crack size increases.

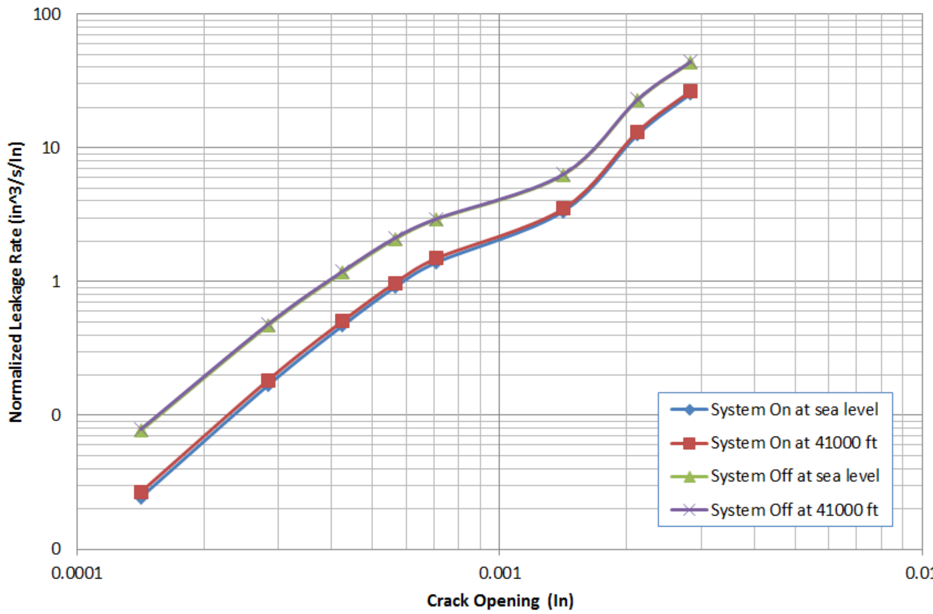


Figure 10. Normalized leakage rates at various operating conditions.

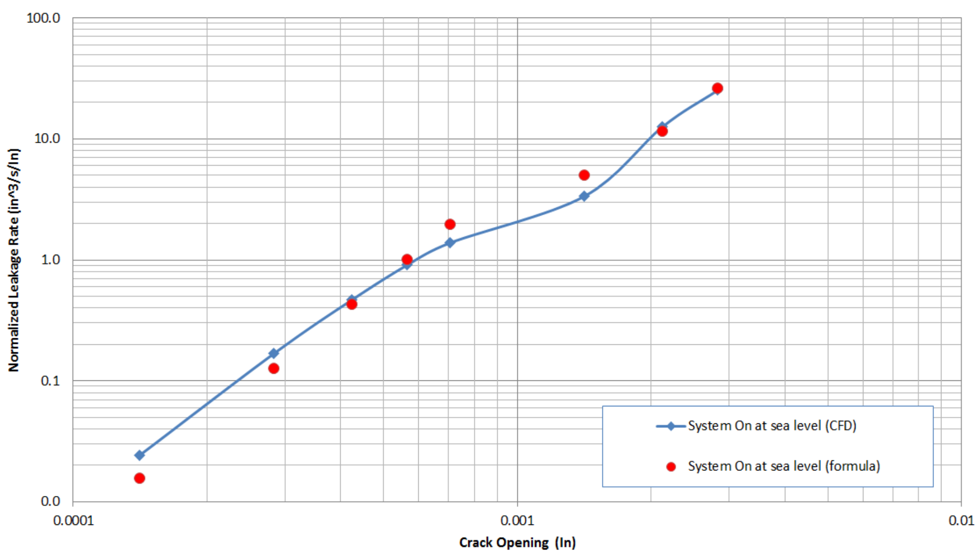
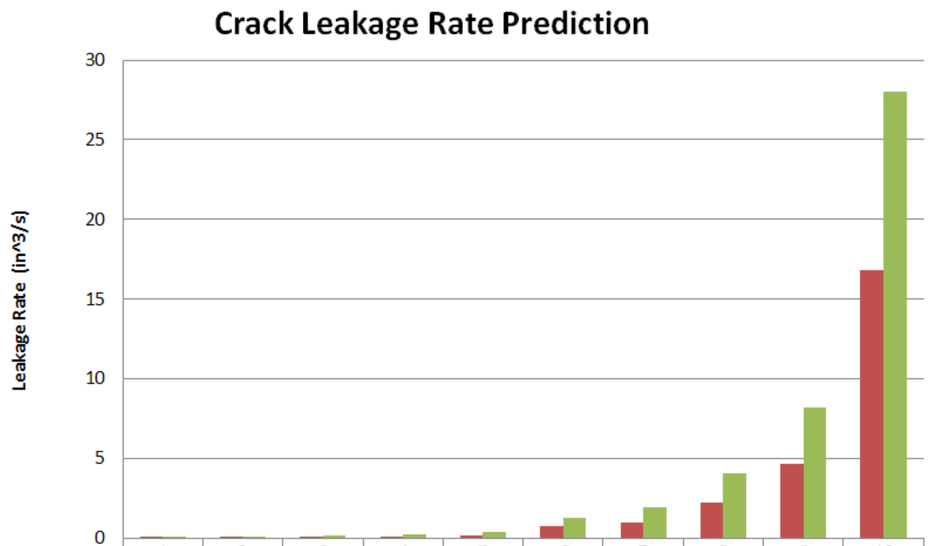


Figure 11. Comparison between CFD results and analytical calculation.

Figure 11 shows a comparison of the CFD simulated leakage flow rate with the analytical calculation method proposed by Beck et al. Both methods predict a similar trend and are quantitatively close.

Ten cases with crack length varying from 0.186 to 0.673 inches (4.72 to 17 mm), were simulated and the results are summarized in Figure 12. It covers the two-times of wall thickness to just approching the critical crack length. In the cases of the crack length less than 0.3 inch, the leakage rate is small (0.15 to 0.36 in^3/s). As the crack size further increases the leakage rate grows in an exponential manner.

The aircraft ground maintenance team uses techniques, such as hand, hearing, thermal imaging, temperature probe, ultrasonic leak detector, etc. to detect the bleed air leakage. There are also on-aircraft detection systems. Through the use of leakage flow estimation, a prediction of the heat loss through the crack can be performed. A comparison between the measured temperature/thermal results with the simulated temperature field may serve as an indirect measurement of the leakage flow rate.



	1	2	3	4	5	6	7	8	9	10
System On, 41000 ft	0.0188	0.0366	0.0640	0.1071	0.1506	0.7122	0.9826	2.1873	4.6235	16.8141
System Off, 41000 ft	0.0509	0.0957	0.1623	0.2623	0.3594	1.2864	1.9457	4.0746	8.2010	28.0283

Figure 12. Leakage rate prediction.

5. Conclusion

For safe aircraft operation, the maximum initial flaw size should be determined so a crack will not propagate into a catastrophic failure during operation. This maximum initial flaw size should not be smaller than the non-destructive test method can detect. Any crack found larger than the determined maximum flaw size should be repaired or rejected. Additionally, an assessment should be made that if a crack does propagate through the wall, a leak-before-break scenario is necessary. The flow rates need to be assessed against the capability of the detection system to determine if the leakage rates are high enough to be detected so a repair or replacement can happen before a structural failure.

The Abaqus XFEM simulation provides a validated, reliable tool for the assessment of allowable preexisting defect size and predicting the crack size under load. The combination of through-crack size prediction and CFD crack leakage flow simulation makes it possible to predict the leakage flow rate through a simple or complex crack path with a reasonably good accuracy. The simulated leakage rate result compared well with an existing explicit equation that describes the idealized zig-zag crack flow channel.

6. References

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