Damage Tolerance Analysis with Boundary Elements

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Abstract

Hamilton Sundstrand utilizes the 3-D fracture growth analysis capabilities in the commercial boundary element software product, BEASY, to study crack growth rates and directions in many of our aerospace flight components. The outcome has been assessed to be a significant improvement over previous, less sophisticated methods used in fracture mechanics.

BEASY enables these fracture mechanics studies to be performed on the actual 3-D hardware, thereby, eliminating the need for crude 2-D approximations. This paper will discuss specific study details, which include correlation/calibration to test data as well as actual field data. It will also describe the various geometries of hardware, the nature and simulation of the spectral loading, the results of the BEASY fracture analysis, and the overall usage of fracture mechanics life prediction for aerospace components at Hamilton Sundstrand.

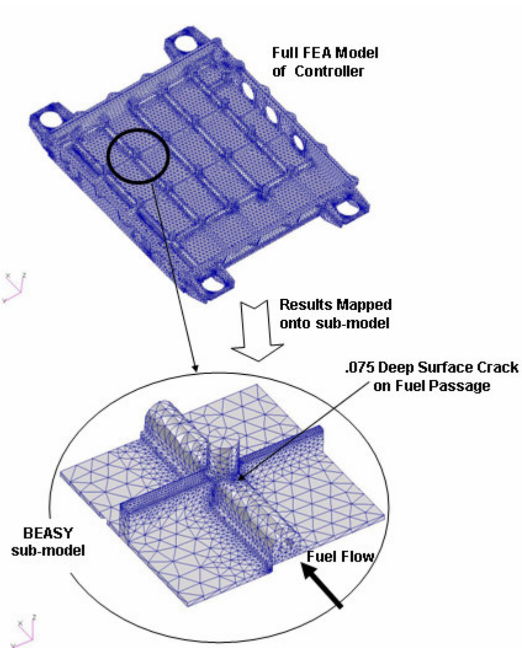

Figure 1 FEA of Controller and BEASY sub Model

1 Damage Tolerance Design Approach

The analysis procedure for Damage Tolerant parts during design is a stepwise approach, which proceeds from the very conservative to the least conservative. The goal is to show that the largest flaw that may exist in the part, after a specified level of inspection, does not grow during the service life of the part. This involves a first cut stress analysis, an assumed flaw size, and a hand calculation of the form

$$K \approx \sigma\sqrt{\pi a}\, C_f$$

The stress Intensity K is calculated with this closed form estimation and is compared to the threshold value for crack propagation for the specific material. If the stress intensity value is below threshold, the design is accepted and the level of inspection specified on the drawing. It is assumed that the stress analysis and the correction factor, C_f, are conservative and lead to a safe design. If the stress intensity is found to be above the threshold, a less conservative approach is taken. This may involve a refined stress analysis through finite elements or boundary elements, and/or the use of a fracture mechanics code, which has better approximations for the correction factors.

One such example of a fracture mechanics code is the commercial code NASGRO, which provides a variety of example cases in which the user can better approximate their specific geometry. If these results show that the crack will propagate during service life, the designer has two options: improve the level of inspection to reduce the crack size assumed, or remove any remaining conservatism in the stress intensity calculation. As improving the inspection level can be expensive as well as time consuming, the preferred choice is often to use the boundary element method that combines detailed stress analysis with exact crack geometry modelling to predict the most accurate stress intensity calculation possible. Of course, this type of study is predicated on the assumption that the da/dN data is an accurate representation of fracture properties of the material.

2 Example of Basic Stress Intensity Calculation with BEASY

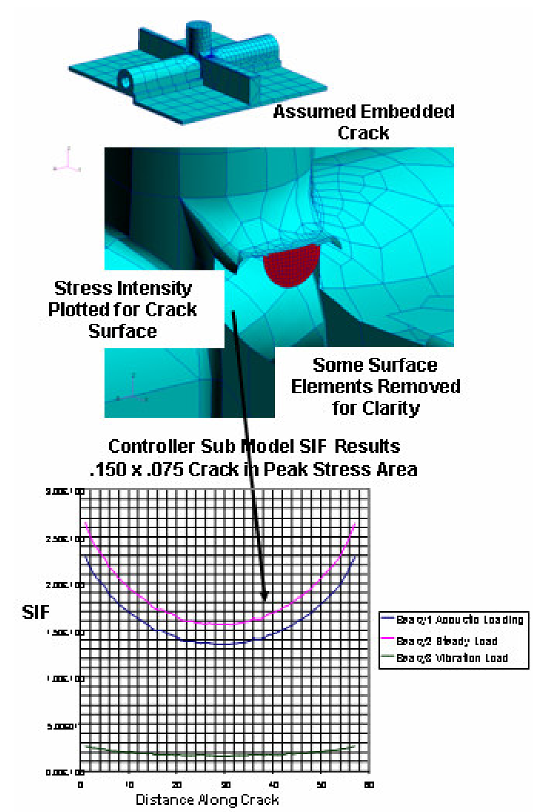

Figure 2 Results of BEASY sub model

One example of using the stress intensity calculation capability within BEASY comes in the form of a Finite Element Analysis (FEA) of an Electronic Controller. This controller used fuel as a coolant within the primary structure and it was vital to show that any pre-existing crack that may have been missed during inspection would not grow to a condition where fuel was leaked into the controller. Using the stress results from a detailed FEA, and the hand calculation of stress intensity factor shown in Formula 1, the assumed crack was shown to be above the threshold of the material.

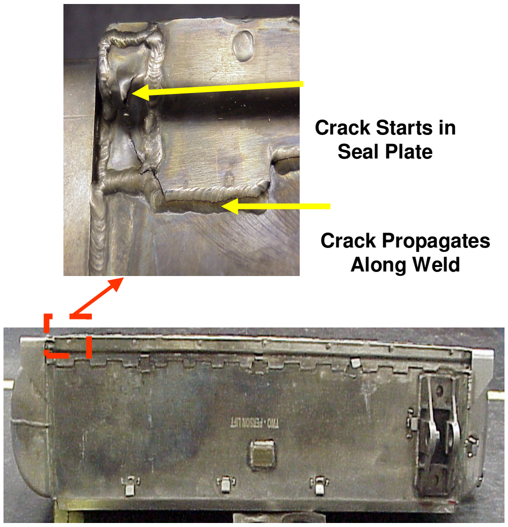

Figure 3 Heat Exchanger with Inset sowing Cracks

When a further attempt to reduce conservatism through the use of NASGRO also showed growth, BEASY was used to create a sub-model for a more accurate stress intensity calculation. The overall deflections of the FEA were used to create boundary conditions for the sub-model and the BEASY model calculated the stress intensities of the specific crack geometry. Through the use of the model, several flaw assumptions were made and analysed, and each was shown to be below the threshold of the material, thereby removing the need for a higher level of inspection or redesign to reduce stress. Figure 1 shows the FEA model and the sub model made with boundary elements. The resulting stress intensity plots for one of the cracks investigated is shown in Figure 2.

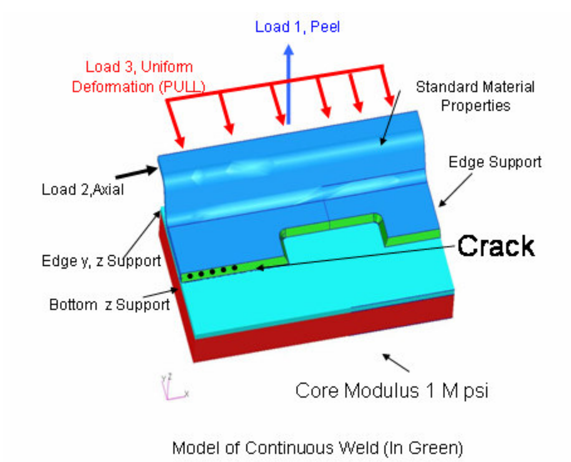

Figure 4 BEASY Model of Cracked Area of Heat Exchanger

3 Use of BEASY as a Problem Solving Tool

Trouble-shooting existing cracks that have been found on hardware in the field is another application of the stress intensity capability within BEASY. Existing cracks on hardware in the field may point to unexpected service loads or cycles that the design was not created to withstand. Attempting to evaluate if a proposed design solution will retard crack growth rate is premised upon knowing the exact nature of the loads inducing growth. In the following example BEASY was used to predict a reduction in stress intensity factor for a proposed design solution without the details of the service loading being fully defined.

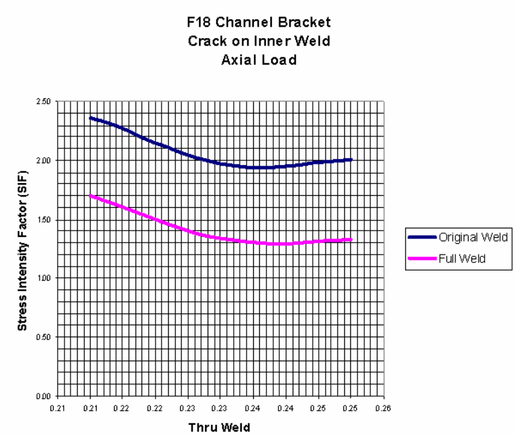

Figure 5 Reduction in Stress Intensity factor Based on Proposed Design Fix

Figure 3 shows a crack in a heat exchanger (HX) sealing support bracket. The loading for this device is a complicated transient thermal and vibration environment in which not all loading conditions are fully defined. Many design solutions were proposed to retard the crack growth rate and increase the overall life of the part. To evaluate the effectiveness of the various design proposals a boundary element analysis model was created. This model was used to predict the reduction in stress intensity at the tip of an existing crack based on each of the proposed solutions under a variety of loads thought to exist in the service life of the part. The most promising of these solutions was creating a continuous weld along the entire joint.

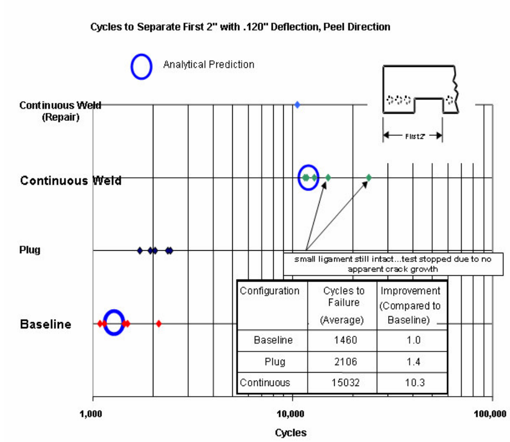

Figure 6 Test Results Compare Well with Analysis Prediction Shown in Blue

Figure 4 shows one of the two models created. One model was a representation of the original design with the stepped weld attachment. The other was the continuous weld configuration (see Figure 4). The reduction in stress intensity based on one of the expected loads was calculated and is shown in Figure 5.

An inexpensive test program was conducted to test a simple peel load condition on the original and improved design. The model, through the use of material crack growth rate data, achieved good correlation to test. This removed the need for more complicated testing and increased confidence in the design solution. The test-to-analysis comparison is shown in Figure 6.

4 Use of BEASY to Predict Crack Direction

As important as whether or not a crack will grow is the direction a crack may take. Some types of hardware, like the electronic controller with a fuel line in it, have certain areas very intolerant to cracks. A 2-D boundary element model of a support bracket attached to a heat exchanger is shown in Figure 7. At the base of the weld, a crack was found during a routine inspection. If the crack were to propagate in a downward direction, into the heat exchanger, hot gases would be released and cause severe reduction in performance for the hardware. Many units with this configuration were already deployed in the field and the cost to immediately remove and repair them would have been prohibitive and impractical. It was shown by analysis, through a variety of assumed crack starting sizes and orientations, that the crack would propagate outward, away from the heat exchanger core. This was a tremendous savings and took only two days to complete. This allowed the field repairs to proceed at an acceptable pace in terms of customer convenience and cost.

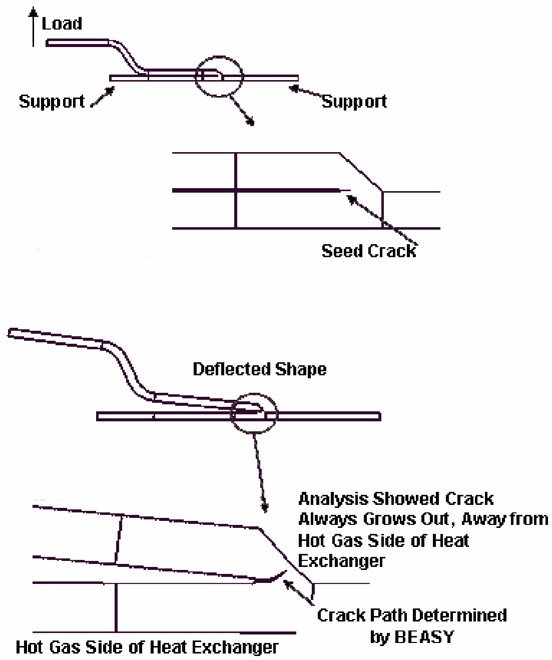

Figure 7 Two Dimensional Analysis of Bracket That Predicted Direction of Assumed Crack

5 Predicting Total Crack Growth Life

Cracking was found in a propeller tulip and this posed a tremendous challenge in a variety of crack analysis areas. Figure 8 shows a 3-D model of a propeller retention area.

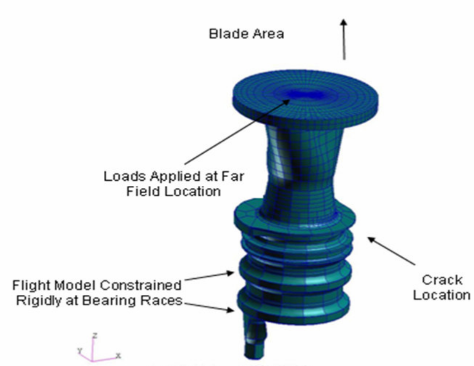

Figure 8 3D Boundary Element Model of Blade Tulip with Crack Site

The propeller was known to have a possible crack initiation site just within the on-wing inspectability area. What was unknown was whether or not an initiation crack, whose presence may have been shielded by a fibreglass over wrap, would grow into an area that was out of the on-wing detectable range. If this were so, the normal inspection interval that all blades receive would have to be highly accelerated. This would have been a high impact requirement, as the planes associated with these propellers would have been temporarily out of service prematurely. A 3-D analysis was able to show that the crack would not turn to a location that was not accessible for inspection on the wing of the aircraft. Figure 9 shows results from the stress analysis portion of the fracture analysis. The analysis predicted a fracture path that would allow for on-wing inspections; this is shown in Figure 10. This same model was used to predict the remaining life in a blade if an unseen crack did exist in the blade. This is an important prediction as it sets the inspection interval for safe operation of the aircraft.

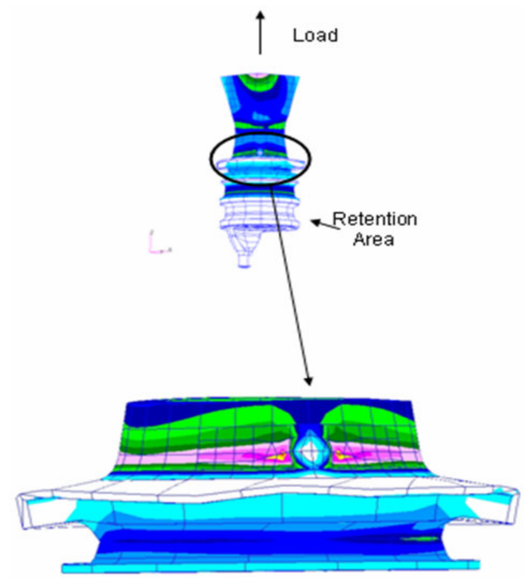

Figure 9 Results of BEASY Stress Analysis Note Redistribution of Stress Around Crack Location

To correlate the model, a test was run in which a known load was applied on a blade stump with a crack that was mechanically induced. After an adjustment to the threshold value for crack growth data was input into the model, the test results were well represented by the analysis. This is shown in Figure 11. Once calibrated this model was used to predict life to failure under known flight conditions. This prediction is shown in Figure 12, along with the one service life failure that was observed in the field.

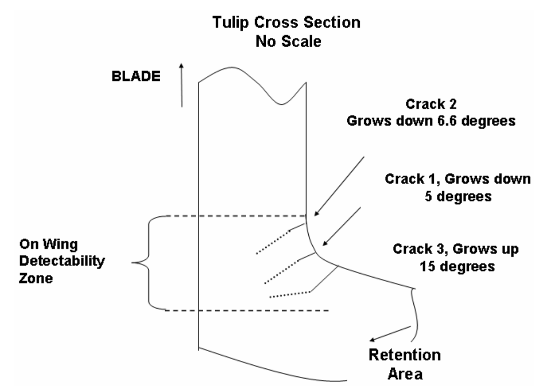

Figure 10 Cross Section of Tulip Results of Crack Direction Analysis

The ability of a 3-D boundary element analysis to remove the need for approximation is seen most clearly in the following example. Figure 13 shows a model, which is a full representation of an 80" propeller. In order to conduct a fracture analysis on a blade in the past, many steps were required. First the overall operation aerodynamic loads on the blade would be reduced to a series of moments and forces resolved to a certain station above the highly stressed root region. These forces would then be used in a finite element stress analysis of the root area to recover operational stresses. These stresses would then be used in an approximated NASGRO fracture analysis.

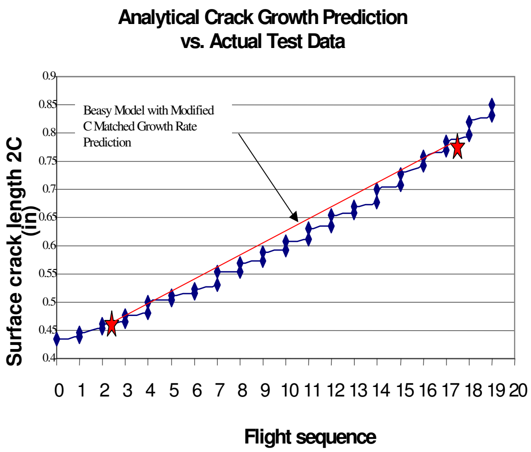

Figure 11 Calibration of Test Data (BLUE) to Analytical Prediction (RED)

While accurate predictions could be made, the process would involve many iterations and tuning to assure that no approximation assumption was falsely impacting the life prediction. The 3-D boundary element process reduces the process to one analysis with less room for error because fewer approximations are being made.

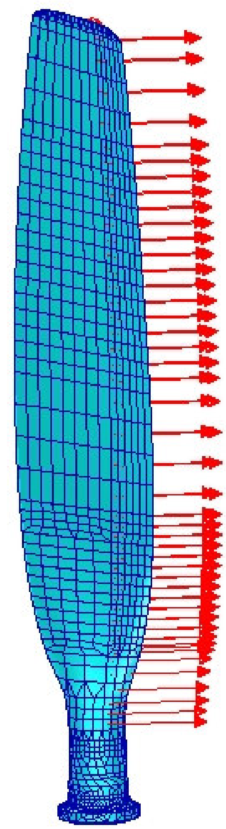

Figure 13 Full Blade Model in BEASY with Aerodynamic Load Shown

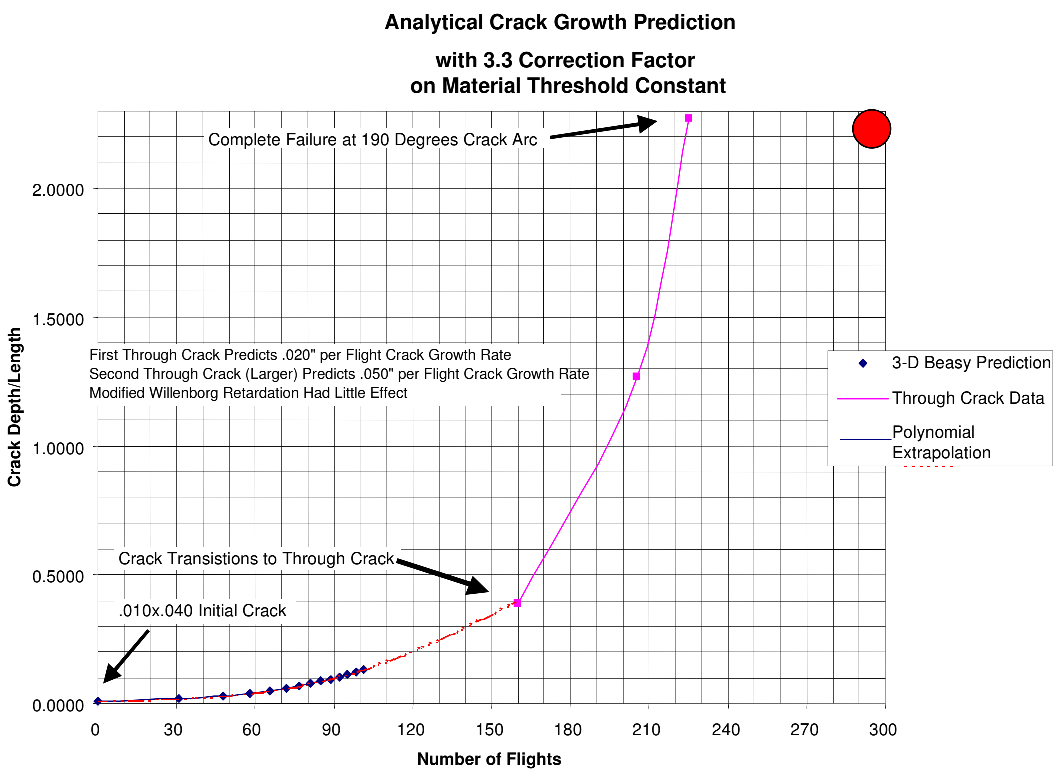

Figure 12 Life Prediction of Blade with Assumed Flaw