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THE A-10 WARTHOG: DAMAGE TOLERANCE AND RESIDUAL STRESSES IN TRANSITION

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Abstract: For over 15 years, the A-10 Aircraft Structural Integrity Program (ASIP) team within the US Air Force (USAF) has facilitated the advancement of fatigue crack growth analytical methods for residual stresses at cold expanded holes through numerous research studies and test programs. These many years of research and test validation have consistently shown that fatigue crack growth analyses that incorporate residual stress can dramatically improve aircraft availability by extending inspection intervals, simultaneously increasing safety by accurately predicting scenarios that legacy methods (such as using a reduced initial crack size) have shown to overpredict.

In a breakthrough this last year, the USAF has released new guidance on analytical methods to account for residual stresses in fatigue crack growth analyses in the form of a Structures Bulletin, permitting the explicit use of residual stresses in a Damage Tolerance Analysis (DTA) to justify an extension (or elimination) of recurring inspections. The development and completion of this bulletin was a culmination of many contributions from A-10 ASIP, the Engineered Residual Stress Implementation (ERSI) working group, and Air Force Research Laboratories partners.

Leveraging the guidance provided in the new structures bulletin, the A-10 ASIP team has now analyzed multiple fatigue critical locations, explicitly incorporating residual stresses in fatigue crack growth analyses with multi-point fracture mechanics models. Analyses are validated by spectrum crack growth test data.

A review of major milestones that have contributed to the introduction of residual stresses in A-10 DTAs is provided, including advancements in applying residual stresses, multi-point fracture mechanics, shortfalls of reduced initial crack size methods, and test validation. Test validation results are compared with multi-point and traditional two-point linear elastic fracture mechanics predictions. For comparison purposes, reduced initial crack size predictions are also shown. Including residual stresses directly in DTAs empowers more accurate predictions and inspection intervals while simultaneously increasing aircraft safety and airworthiness.

Keywords: residual stress, damage tolerance, fatigue, crack growth

INTRODUCTION

Early efforts by the USAF to account for the effects of cold expansion (Cx) led to the reduced initial flaw size (IFS) approach described by Dr. Lincoln [1] and formally published in the US Joint Services Specification Guide [2]. That reduced initial flaw size approach has served numerous programs and services very well, especially for the simplicity of the approach. However, more recent research has demonstrated that in most cases the reduced initial flaw size approach significantly under predicts the damage tolerant life benefits, while in extreme cases it can overpredict fatigue life [3-5].

In the interest of improving analytical accuracy, the A-10 ASIP team has been actively researching Cx benefits and analytical methods to include those benefits in damage tolerance analyses for at least 15 years [6, 7]. The result has converged on the current approach being utilized in the damage tolerance analysis update. This approach and the lessons learned along the way are summarized, followed by example cases and correlations that demonstrate the effectiveness of the current approach at increasing safety while simultaneously improving aircraft availability.

As a note, all references to Cx in this paper are referring to the Fatigue Technology Inc. Split Sleeve Cx process [8].

HISTORICAL REVIEW

Crack Growth Rates at Cold Expanded Holes

A historical review for residual stresses could date back to initial development and utilization of engineered residual stress on aerospace structure. However, this brief review will focus on more recent events specific to the A-10 in an effort to highlight the advancements leading up to the current analytical approach. As a result, this review begins in the year 2009 with a USAF Small Business Innovative Research (SBIR) effort that sought to quantify the residual stress state present at cold expanded holes and to develop an analytical method to reliably predict crack growth through that residual stress field [9]. One unique aspect of the mentioned SBIR effort is that the validation test samples used naturally occurring cracks and a series of marker band sequences to track crack growth rates smaller than typical damage tolerance assumptions such as 1.27 mm (0.05 inch). This test approach empowered the evaluation of crack growth rates across the entire life of a crack, shedding light on the range of crack sizes for which Cx has the greatest influence on crack growth rate. The findings are summarized in a plot of crack growth rate as a function of crack size (Figure 1) where a significant dip in crack growth rate is shown to start at approximately 0.5 mm (~0.02 inch) and doesn't accelerate again until approximately 2 mm (~0.08 inch). Indicating that the greatest damage tolerance benefits from Cx occur when the crack is between 0.5 mm (~0.02 inch) and 2 mm (~0.08 inch).

In addition to the damage tolerance benefit observations from the previously mentioned SBIR effort, a significant durability observation was also made. For US military structure, the durability life (often also referred to as the initiation life) is defined as the life from a pristine part to the existence of a 0.254 mm (0.01 inch) crack [2]. The fractography work for this test effort successfully found the first marker band for both the cold expanded and non-cold expanded specimens (Figure 2). For both specimens the first marker band was applied at only 4,470 load cycles. While these cracks were relatively small, 0.01 mm (0.0004 inch) for the cold expanded specimen and 0.07 mm (0.0026 inch) for the non-cold expanded, the fact that both specimens were cracked after so few cycles is an indication that Cx doesn't inhibit the crack formation process. Rather, Cx only slows the rate of crack growth. This finding is significant as it demonstrates that while Cx can extend the number of loading cycles until a crack reaches 0.254 mm (0.01 inch), the written definition of durability life, Cx doesn't have any significant influence on cycles to crack formation which is the intent behind a durability analysis.

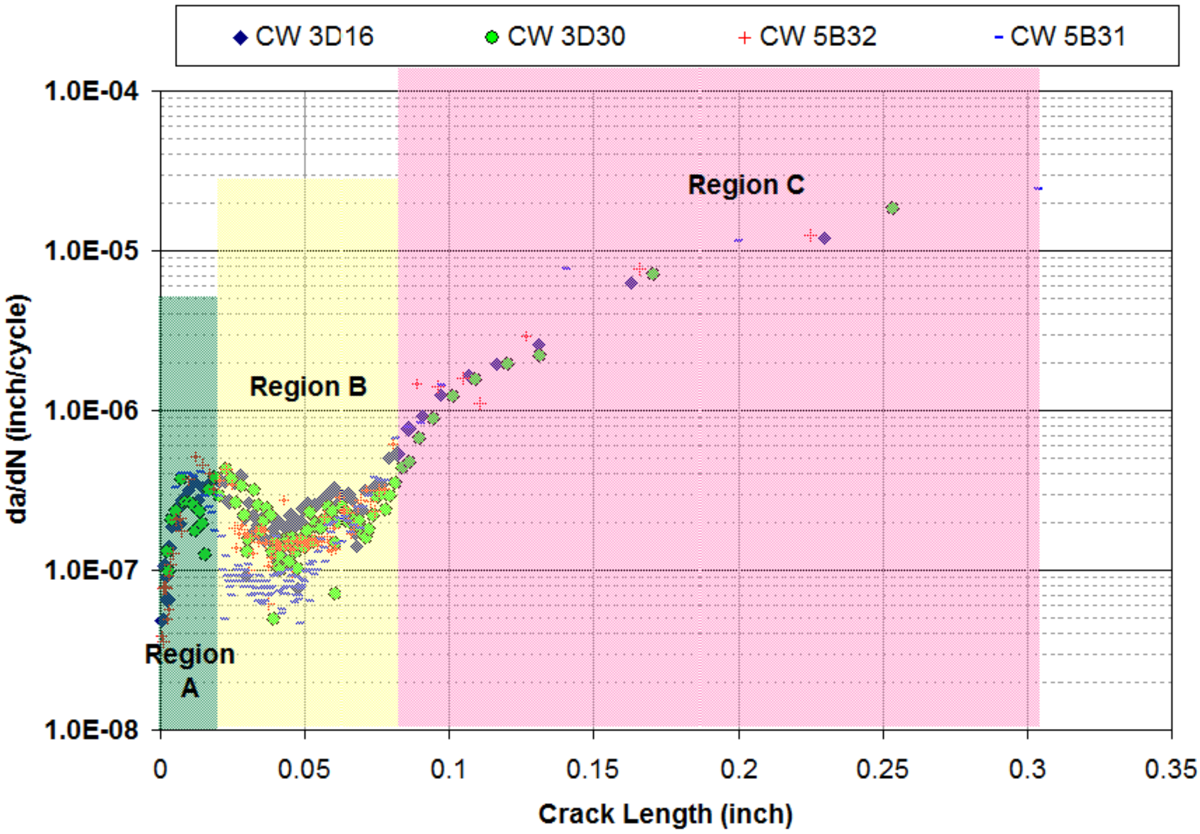

Figure 1: Fatigue crack growth rate regions at a cold expanded hole [9].

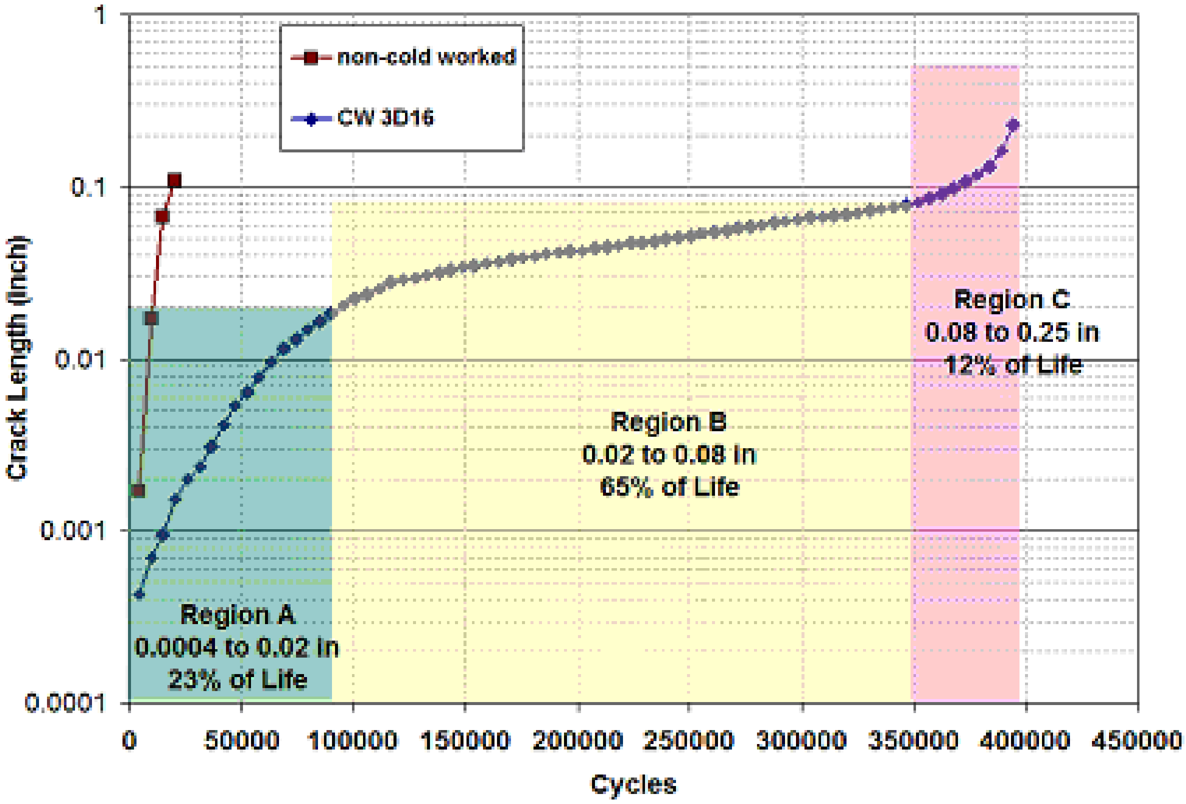

Figure 2: Crack growth of cold expanded and non-cold expanded samples [9].

A subsequent SBIR was funded that investigated multiple loading and cracking scenarios at cold expanded holes [10]. Specifically, the effort evaluated: overload/underload effect, load transfer influence, retardation model use, material models, crack interaction effects, and crack length influence on relaxation/redistribution of the residual stress state. The investigation identified high sensitivity to overloads/underloads, but little influence from load transfer. Retardation models were found to negatively impact the fit of the overall crack growth curve shape and were therefore not recommended. The findings from a study of material models identified some potential discrepancies between through crack growth rate data and corner crack growth rate data at equivalent stress intensities. This topic requires further study and investigation. Crack interaction effects (the influence of multiple cracks at the same hole) were found to have a trivial impact on the overall crack growth life and shape for cracks from cold expanded holes. Finally, while some changes to the residual stress state were observed from the crack growth into the residual stress field, the observed differences didn't significantly impact crack growth predictions.

Software Development

Multiple research efforts have shown unique crack front morphology at cold expanded holes due to residual stresses. In an effort to capture that morphology analytically a multi-point fracture mechanics code currently known as the Broad Application for Multi-point Fatigue (BAMpF) was developed for initial use in 2011 [11]. The code utilizes StressCheck for the stress intensity solution and AFGROW for the crack growth engine. With a capable tool for capturing detailed crack front shapes, a finite element approach to include residual stresses in the stress intensity solution was needed. This was accomplished by Engineering Software Research and Development Inc. (ESRD) by demonstrating that an accurate solution could be obtained if the residual stress field was applied to the crack face as a traction load [12].

In conjunction with software development of multi-point analytical methods, traditional 2-point predictions were also being improved and advanced. In 2017 the Engineered Residual Stress Implementation (ERSI) working group completed a round robin prediction effort of predicting damage tolerance crack growth from a cold expanded hole. One of the findings from that round robin effort was that the 2-point AFGROW predictions often resulted in significant overpredictions relative to both test and other analytical methods [13]. AFGROW then updated and enhanced their residual stress calculation routine and much better correlations were observed with 2-point analyses using the advanced solutions in AFGROW [14, 15]. Subsequent studies with 2-point predictions were also successful at accurately replicating predictions from multi-point analysis tools [16]. This finding is significant as it empowers the inclusion of residual stresses for rapid analysis response times required for many practical application scenarios where prompt engineering dispositions are required.

Residual Stress Database

With the software tools updated to include residual stresses in a damage tolerance analysis, the next step was to obtain residual stress fields with sufficient accuracy to include them in analytical models and execute life predictions. To that end, a Rapid Innovation Fund (RIF) was utilized to obtain residual stresses using the Contour Method [17]. The RIF compiled contour results from 47 samples (two materials and varying geometries) into a database for ease of use and collaboration. The database has since been added to, increasing the number of cases for which direct residual stresses are available to well over 300. The database was used to successfully produce blind predictions of damage tolerance cracks in an academic research effort, replicating attack aircraft structure and loading [5].

Policy Guidance

In December of 2021 formal USAF guidance on applying residual stresses to damage tolerance analyses and the associated test validation was released [18]. This guidance empowered the use of residual stresses for recurring inspection intervals provided analytical efforts are validated by physical test samples. As airworthiness is the top priority for any structural engineering action, the potential benefit described by the structures bulletin is currently limited to the reduced IFS prediction. Although an update is planned to extend that benefit provided certain quality processes are adhered to.

LOWER WING SKIN EXAMPLE

The discussion in this section is based on test and prediction efforts included in a research effort mentioned in the previous sections that is representative of a lower wing skin control point located near the wing root [5]. For convenience, the basic details are outlined and repeated herein.

Consider a lower wing skin that can be physically represented for test and validation purposes as 6.35 mm (0.25 inch) rolled 2024-T351 plate with the geometry shown below (Figure 3). The assumed loading is tension dominated with a maximum spectrum stress of 228 MPa (33 ksi). The hole remains unfilled in test to facilitate crack length measurements in the hole. Multiple tests were completed of both the non-cold expanded and the cold expanded hole cases.

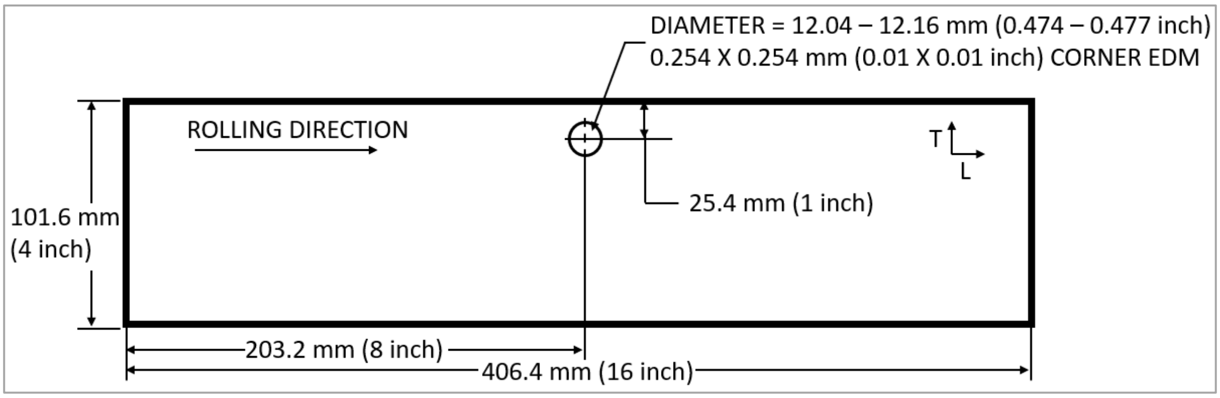

Figure 3: Lower wing skin example geometry.

Predictions of the crack growth life were completed prior to generation of test results to ensure no correlation work was done to improve the accuracy of the analytical approach. The residual stress field used for the predictions was obtained from the database created as part of the RIF mentioned previously. The residual stresses were included as a crack face traction load in a 3D finite element model of the part using the StressCheck software [12]. The BAMpF code was used to pull stress intensities from the StressCheck model and feed them into AFGROW for crack growth predictions. The resulting prediction is shown below (Figure 4) and shows that the “blind” (meaning the prediction was completed with no knowledge of the test results) prediction was far more accurate than the reduced initial flaw size approach, yet still under predicted the test results. Thereby yielding a conservative solution, ensuring airworthiness. It is likely that the disparity between the prediction with residual stresses and the cold expanded test result is a result of neglecting spectrum effects in the analysis with residual stresses [10].

With the recent successes of 2-point damage tolerance analyses including residual stresses [19], the test and prediction scenario outlined above was revisited to generate a 2-point prediction for this case. The result was fantastic agreement between the multi-point and the 2-point analyses (Figure 5). Unfortunately, the 2-point prediction was not done as a “blind” prediction. However, the ground rules used for correlating a 2-point prediction require correlating any 2-point prediction attempt to a multi-point prediction in the absence of test data [20, 21]. So, the agreement shown below is still the agreement that would have resulted from a “blind” 2-point prediction for the test case.

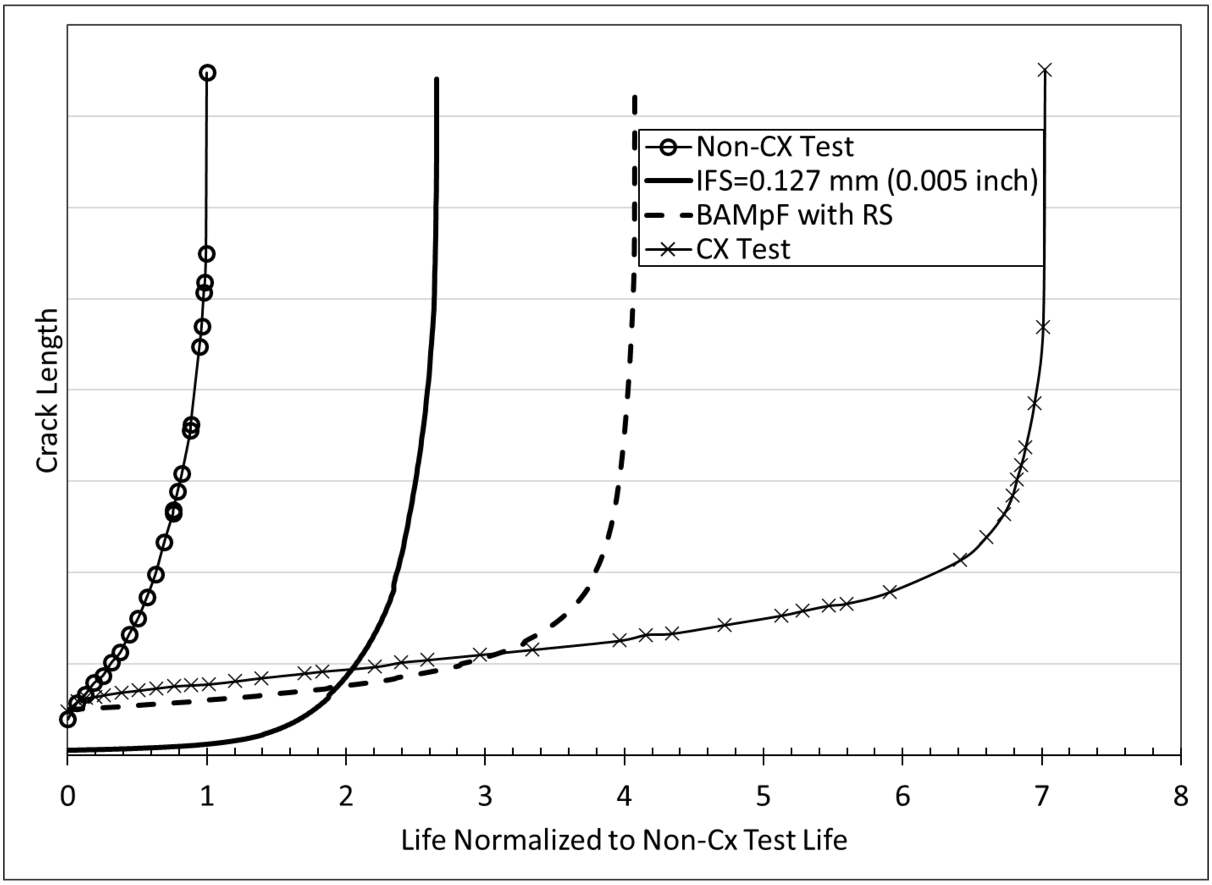

Figure 4: Lower wing skin example.

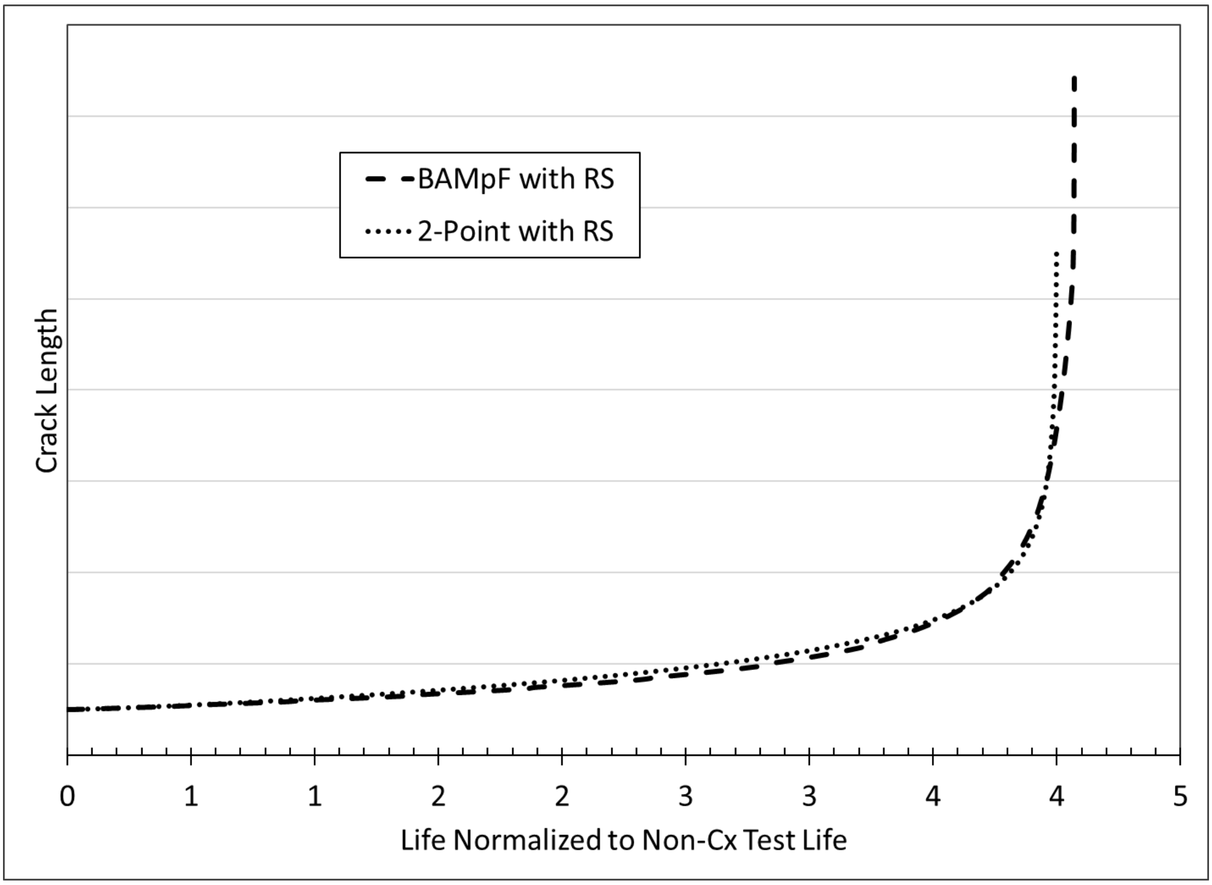

Figure 5: 2-Point analysis agreement with multi-point analysis.

MILD LOAD TRANSFER EXAMPLE

Now let us consider an outer lower wing skin case, under tension dominated loading with 8% load transfer at the fastener hole of interest. The basic geometry is very similar to, though slightly different from, the geometry shown above (Figure 3). A bearing load is applied to the StressCheck model as a bearing surface load to represent the load transfer at this joint. A fringe plot of the loaded model is shown below (Figure 6), the asymmetry above and below the hole is a result of the bearing load applied in the downward direction. It should be noted that the model width is much wider than what is shown on the left side of the fringe plot below, resulting in the stress eccentricities from left to right. The reader should also know that the course mesh shown is only acceptable because StressCheck is a P-element solver. A more traditional H-element solver would need a significantly finer mesh to converge.

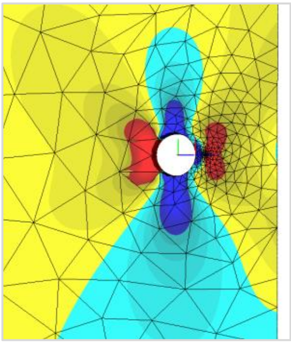

Figure 6: Fringe plot of bearing and bypass loading.

Damage tolerance analysis of this outer lower wing skin location was completed to evaluate the influence of residual stresses as compared to the reduced IFS approach. The resulting comparison is shown below (Figure 7), again with the life normalized to the non-Cx life. This example demonstrates the extremely large damage tolerance benefits that Cx has for many applications. Benefits from Cx less than a factor of 4 relative to the non-Cx life are typically only observed for high stress and/or short edge margin conditions (“short” is defined as an edge distance to diameter ratio of less than two) [3-5].

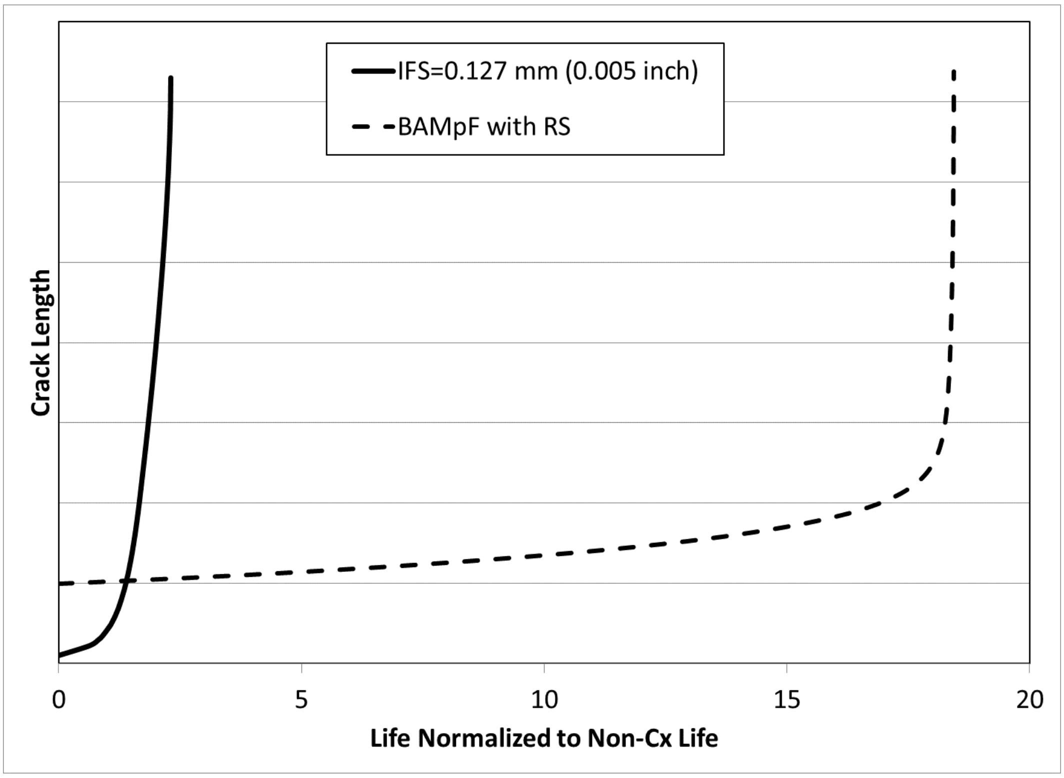

Figure 7: Life benefit of including RS compared to reduced IFS.

HIGH BEARING AND BYPASS STRESS EXAMPLE

While most Cx applications yield large improvements, aside from the high stress and short edge margin conditions stated previously, combined loading scenarios can create a high stress state that is not readily observed by a simple maximum stress comparison. This next example evaluates the scenario of a lower wing skin location that has approximately 10% higher max stress than the previous example, as well as greater load transfer (20% as opposed to 8%). The increase in bypass stress or bearing stress alone would have yielded appreciable benefits from Cx. However, the combined increase in bearing and bypass stresses resulted in a minimal benefit from Cx as shown below (Figure 8). This example is significant because it demonstrates that explicitly including residual stresses in the analysis can accurately predict scenarios where the reduced IFS approach would overpredict. This example paired next to the previous example where a life improvement of greater than 10 times was shown demonstrates the power afforded by including residual stress in analysis. Being capable of accurately predicting both extremes increases safety and airworthiness.

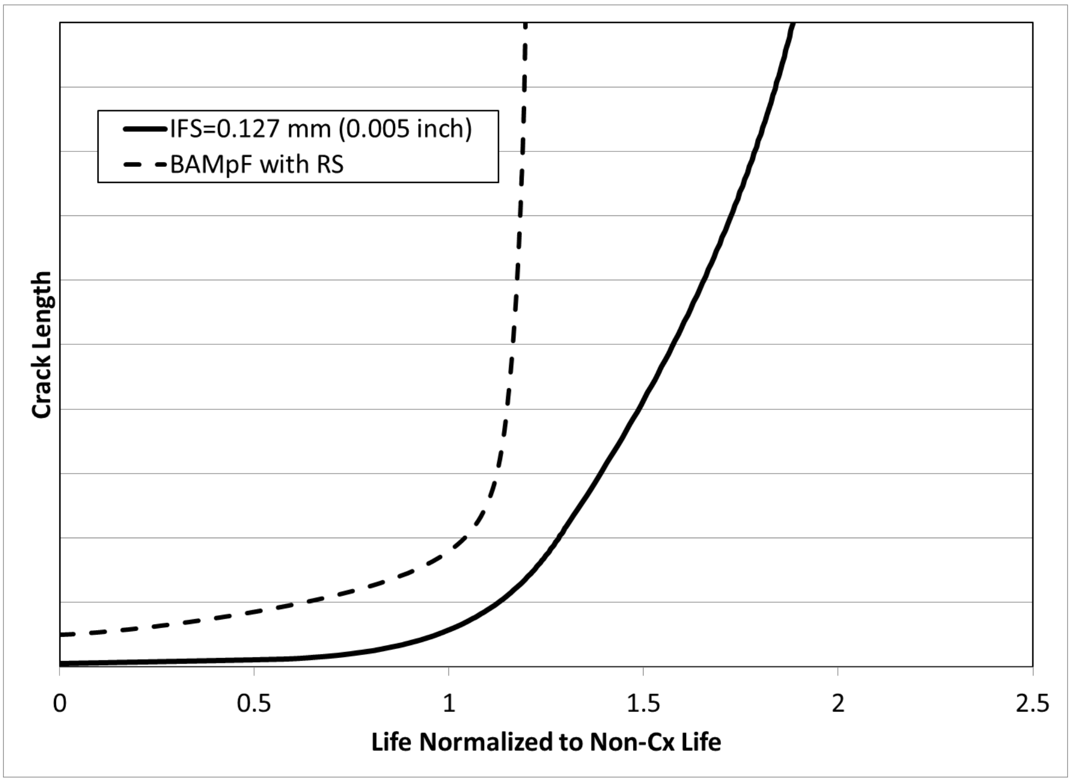

Figure 8: 2-Point analysis agreement with multi-point analysis.

ADVANTAGE OF MULTI-POINT EXAMPLE

It was previously shown (Figure 5) that multi-point and 2-point analyses can produce effectively equivalent damage tolerance predictions with residual stresses. That is true for most scenarios. However, there are situations in which a simplification of the geometry to a hole in a plate for a 2-point analysis results in a disparity between the 2-point and the multi-point solutions. This scenario is illustrated for a T-section spar cap, with the crack growing in the vertical leg of the T-section. Again, the loading spectrum is tension dominated, though the max spectrum stress is roughly 20% less than the first example shown here, and no load transfer. The thickness, diameter and edge distance dimensions are only mildly different from those shown previously (Figure 3). Surprisingly, the accurate representation of the cross section afforded by the multi-point approach results in a significant increase in predicted life compared to the flat plate approximation of the 2-point analysis. The 2-point analysis could have been adjusted with beta corrections to accurately account for the influence of the actual cross section on the stress intensities, but the point is to demonstrate that geometry influences directly accounted for in multi-point solutions can have a significant influence on the analysis.

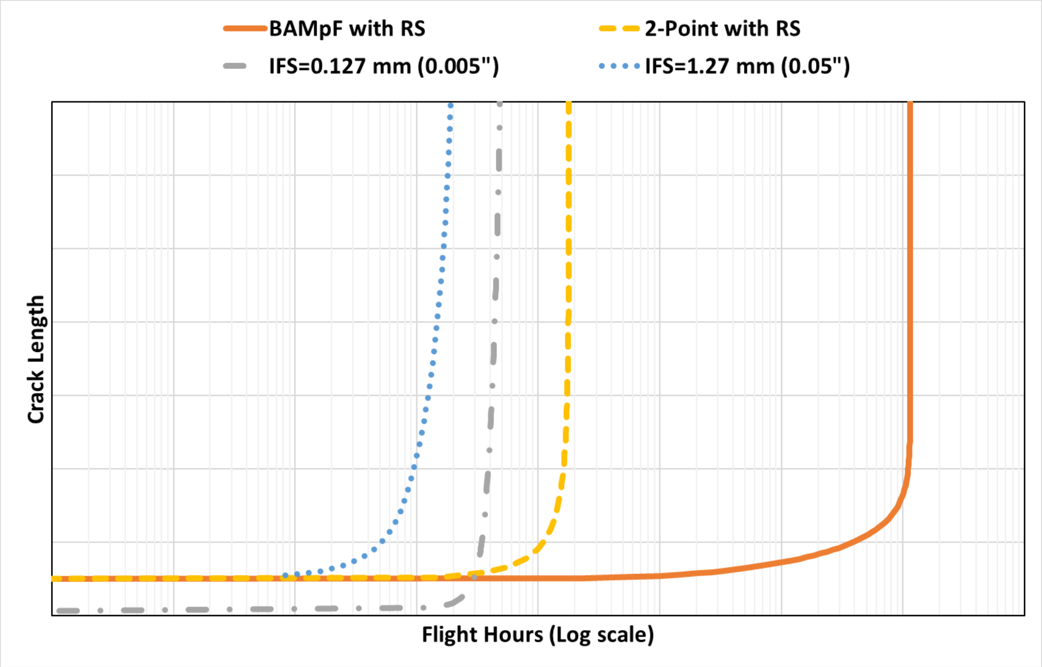

Figure 9: Multi-point analyses can more accurately predict complex geometries.

ANALYTICAL VALIDATION WITH LIMITED TEST DATA

Under ideal circumstances, each scenario would have it's own set of test data with coupons and stresses specific to each scenario. However, since it is often not practical to test every single scenario outright an approach has been developed in which only the most extreme cases are explicitly tested. The test results from those extreme cases are then used to validate analysis for all less severe stress states that experience the same loading spectrum with similar geometry. (The geometry is considered "similar" in accordance with some guidelines provided by the Engineered Residual Stress Implementation (ERSI) working group adopted by the A-10 [21].)

To illustrate this approach, consider a lower wing root attachment location that is "similar" to the geometry discussed (Figure 3), with a roughly 20% lower stress. Since it is known that a lower stress would result in an equal or greater benefit from Cx as compared to the higher stress scenario, the higher stress test results are used to clip the life benefit of the lower stress scenario. This clipping process is shown below, where the available test results are used to clip the life benefit of the less severe case (Figure 10).

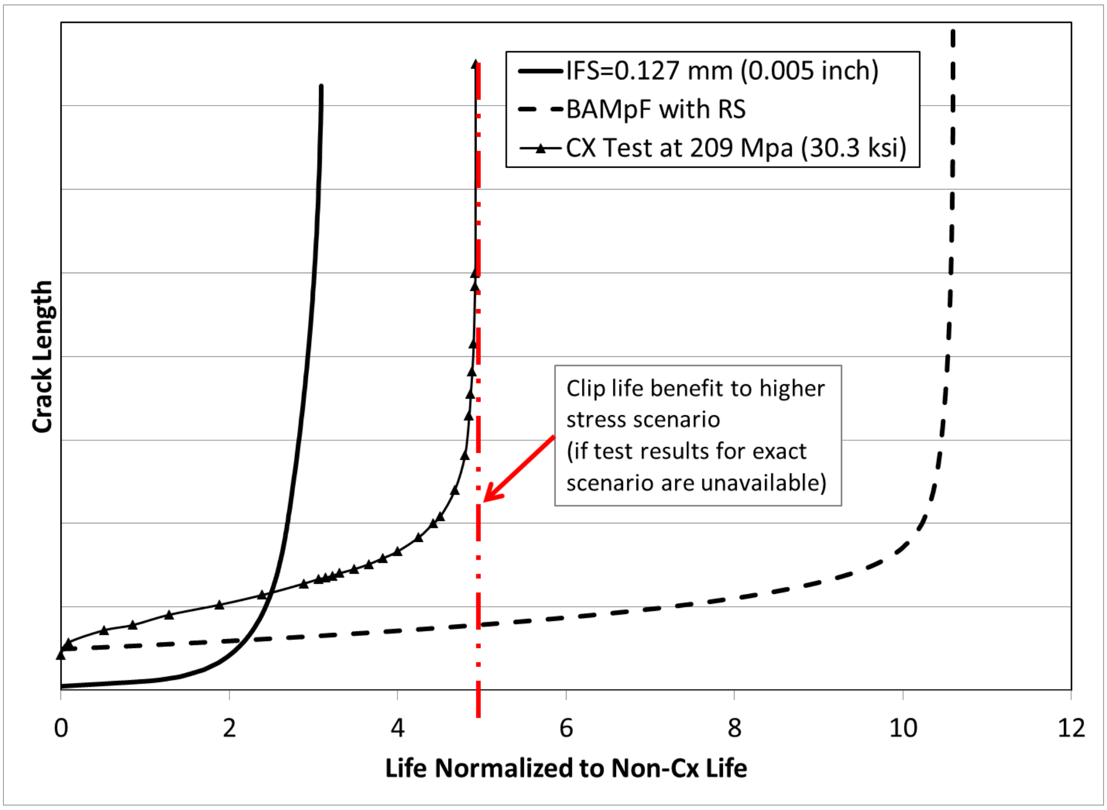

Figure 10: Clipping life benefit to available test results.

CONCLUSION

A final example of a stores hard point attachment hole in a spar cap is offered (Figure 11). This example highlights strong consistency between test replicates and the superior performance of explicitly including residual stresses in the analysis over the reduced IFS approach. Tremendous increases in analytical accuracy stand to be gained by explicitly including residual stresses in damage tolerance analyses.

Cx and the associated benefits have been investigated for decades. The A-10 program has expended significant research efforts over the last 15 years to arrive at an initial implementation of residual stresses in damage tolerance analyses. The lessons learned from many research efforts have culminated to a successful, robust, repeatable process for analyzing damage tolerance crack growth through residual stress fields.

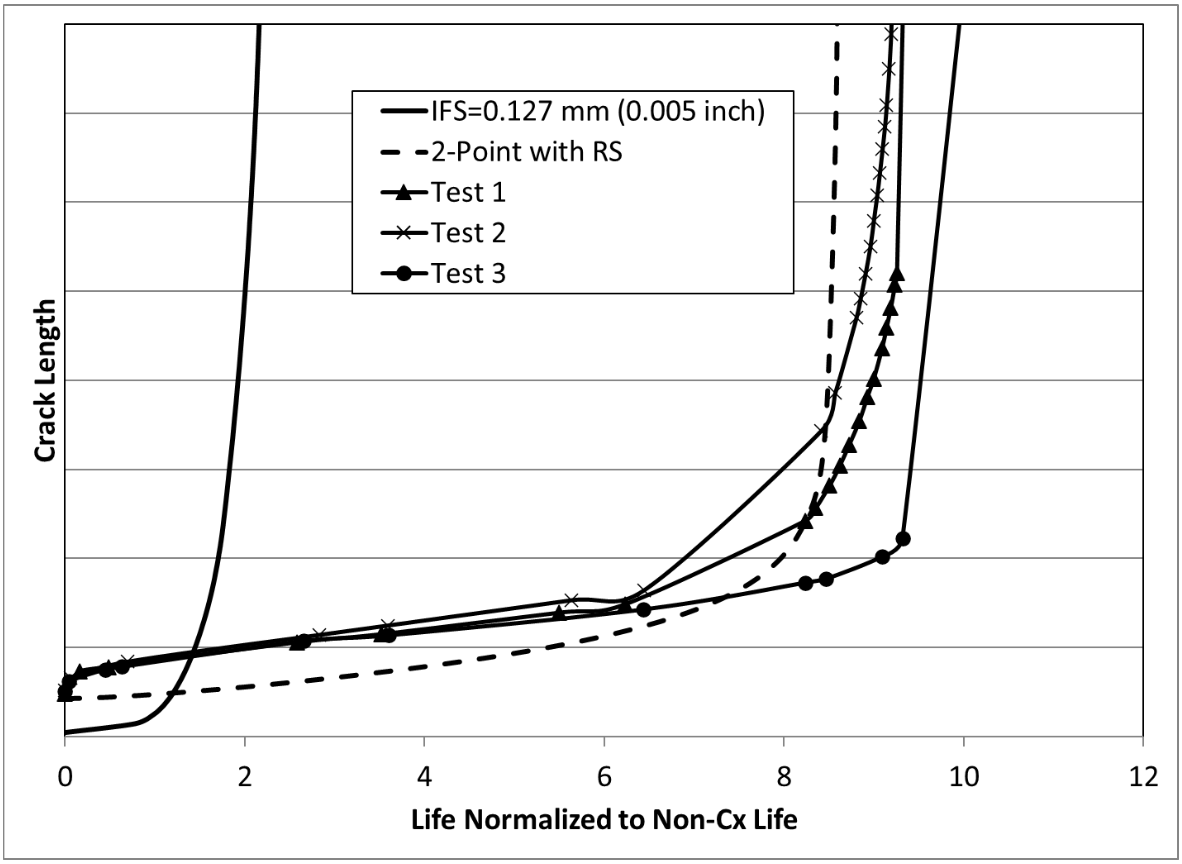

Figure 11: High analytical accuracy from including residual stresses.

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