Structures Bulletin

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Subject: Requirements to Establish the Beneficial Effects of Cold Expanded Holes in Development of Damage Tolerance Initial and Recurring Inspection Intervals

References:

1. JSSG-2006, "Joint Service Specification Guide Aircraft Structures," 30 Oct 1998
2. MIL-A-83444, "Airplane Damage Tolerance Requirements", 2 Jul 1974
3. AFI 20-106, "Management of Aviation Critical Safety Items", Department of the Navy, Air Force, Army, Defense Logistics Agency, and Defense Contract Management Agency, 27 January 2020
4. MIL-STD-1530D, "Aircraft Structural Integrity Program (ASIP)", Department of Defense Standard Practice, 31 Aug 2016
5. EN-SB-08-012 Rev. D, "In-Service Inspection Flaw Assumptions for Metallic Structures", Apr 2018
6. EZ-SB-14-003, "Durability Test Programs to Validate Aircraft Structure Service Life Capability for Repairs, Modifications, and Materials & Processes Changes", 9 Apr 2014
7. Barter, S.A., et al., "Marker Loads for Quantitative Fractography of Fatigue Cracks in Aerospace Alloys", 25th ICAF Symposium, May 2009
8. EZ-SB-13-002, "Correlating Durability Analysis to Unanticipated Fatigue Cracks in Metallic Structure", 26 Feb 2013
9. ASTM E 647, "Standard Test Method for Measurement of Fatigue Crack Growth Rates", AD1070087

Background:

The effect of hole cold expansion in metallic structures is to increase service life. This effect is due to the fact that cold expansion introduces beneficial, compressive residual stresses around the perimeter of the hole. Many test programs have been completed for various materials and loads spectra and demonstrated significant improvements in the crack growth lives. In general, the USAF does not account for beneficial residual stresses during design, with exceptions as approved by the program office and documented in the Aircraft Structural Integrity Program (ASIP) Master Plan. For approved exceptions, the USAF typically only takes partial benefit during design to potentially mitigate the impacts of unanticipated damage. However, the USAF increases benefit during the aircraft sustainment phase to reduce the maintenance burden while still maintaining aircraft safety.

Reference 1 provides guidance for the initial damage types and sizes to be used in damage tolerance analyses and states that it should be a goal to achieve compliance with the requirements, "…without considering the beneficial effects of specific joint design and assembly procedures such as interference fasteners, cold expanded holes, or joint clamp-up." It then states that when exceptions are made, "the beneficial effects to be used in design should be no greater than the benefit derived by assuming a 0.005 inch radius corner flaw". Reference 2 adds that "…these beneficial effects shall be demonstrated by laboratory tests". The historical basis for inclusion of the 0.005 inch limit was to provide protection against the possibility that not all critical locations were properly processed, with the damage size based on approximate average equivalent initial flaw sizes characterized when damage tolerance methods were initially established for the USAF in the early 1970s. Additionally, References 1 and 2 were written when validated analysis methods to properly account for beneficial residual stresses in damage tolerance analyses did not exist.

Since then, analysis methods have been developed, and validated, to account for the presence of residual stresses. As neither Reference 1 nor 2 provide the testing requirements to validate cold expansion benefits for a given application, this Structures Bulletin (SB) establishes the testing and evaluation requirements to establish the beneficial effects of cold expanded holes for the damage tolerance initial and recurring inspection intervals for a range of possible applications.

Scope:

This Structures Bulletin (SB) establishes a tiered approach to account for the beneficial effects of cold expanded holes during the sustainment phase. Included are the testing and analysis requirements, durability and damage tolerance testing acceptance criteria, and descriptions of benefit determination for setting initial and recurring inspection intervals.

When identifying potential applications for this SB, particular attention must be given to:

- Compression loading effects – compression loads (i.e., – underloads) are known to reduce or even eliminate the beneficial compressive residual stress field by locally modifying the stress-strain response of the material
- Fastener fit – If the critical location relies on a neat-fit, interference fit fastener, or pin to mitigate compression loading effects, then the tests described in the subsequent sections must replicate the actual aircraft installation. Loose-fit or clearance-fit holes must be considered open holes.
- Edge margin – edge margin (e/D) < 1.2 may result in edge bulging and/or cracking
- Hole configuration – straight shank and/or countersunk holes and the associated Cx process (e.g., Cx straight hole then countersink, countersunk hole Cx using standard tooling, etc.) create variation in the residual stress that must be considered

Benefit Levels:

Variations in the amount of benefit needed for the range of aircraft structure applications, their associated complexity, and the cost to substantiate each, has prompted the need to establish different benefit levels as follows:

Level I: Initial inspection interval benefit, using the method described in References 1 and 2 and further defined below, with no recurring inspection interval benefit.

Level II. Level I initial inspection interval benefit and limited recurring inspection interval benefit through explicit incorporation of the non-verified residual stress field in the crack growth analysis.

General Requirements:

The following caveats must be satisfied:

1. The cold expansion process is used as a critical safety process [3] to treat fracture-critical components [4].

2. The cold expansion process specification is approved by the procuring agency and establishes detailed cold expansion process requirements (i.e. – hole measurements, tool selection, tolerances, verification check gage usage, etc.).

3. Quality assurance requirements are approved by the procuring agency.

4. NDI probability of detection values per Reference 5 or other source as approved by the cognizant engineering authority, are used to establish subsequent inspection intervals.

1 Level I Benefit

Initial inspection interval benefit using the method described in References 1 and 2 with no recurring inspection interval benefit.

1.1 Level I Analysis Requirements:

Review the existing damage tolerance analysis for the hole location(s) to be cold expanded and ensure that all sources of variability (e.g., loads, spectra, crack growth rate data) are understood and accounted for as needed.

1.2 Level I Test Requirements:

Test and evaluation requirements to establish the beneficial effects of cold expanded holes for development of the damage tolerance initial inspection interval consistent with References 1 and 2 are described in the following steps:

1.2.1 Establish the test specimen design, fixture, load application, load spectrum, etc. that is predicted to replicate the actual cracking scenario (cracks experienced in service or during testing) or predicted cracking scenario (analysis predictions only, no cracks discovered in service or during testing).

1.2.2 Conduct baseline testing of 3 specimens to validate Section 1.2.1. The purpose of baseline testing is to validate that the test configuration adequately represents the complex geometry and stress state in the actual component. Replicate all important parameters of the configuration such as hole drilling/reaming, hole surface finish, pre-penetrant etch, etc. (see Reference 6). Obtain enough crack growth measurements during testing to accurately characterize the crack growth curve, a minimum of 10 measurements are typically needed. The use of marker bands (see Reference 7) should be considered to support crack growth measurements, especially for specimens that contain fasteners, so that fastener removal is not required to obtain the crack growth data necessary for test-to-model correlation.

a. Baseline durability testing: If the specimen is attempting to replicate test or service cracks, the baseline tests should neither be notched nor contain pre-cracks.

b. Baseline damage tolerance testing: If the baseline tests are attempting to match damage tolerance analysis (DTA) shortfalls with no prior cracking data (i.e. – cracking seen in-service or from coupon/full-scale test), the baseline tests may be notched and contain pre-cracks, if desired.

If the test results satisfy the applicable acceptance criteria described in Section 1.3, proceed to Section 1.2.3. If the criteria are not satisfied, determine the root cause [8] and repeat this step and potentially Section 1.2.1 until an acceptable match is obtained. Note that manufacturing test specimens for Sections 1.2.3 and 1.2.4 before completing this step may lead to increased costs.

1.2.3 Conduct durability tests on 5 specimens without cold expanded holes, notches, or pre-cracks. The purpose of the durability tests is to ensure crack growth predictions are sufficiently accurate. The specimens from Section 1.2.2 may be used as partial fulfillment of this step if the specimen design, loading, etc. are identical. Obtain crack growth measurements during testing and compare them to the durability crack growth analysis predictions using an initial crack size that is considered to represent near-typical material and manufacturing quality (e.g. – 0.005 inch to 0.01 inch for many legacy aerospace materials). Marker bands should be considered to aid in post-mortem crack growth measurements, especially for specimens that contain fasteners, to ensure the necessary crack growth data for test-to-model correlation is collected. If the test-to-analysis comparison satisfies the acceptance criteria in Section 1.3, use the durability crack growth analysis prediction for Section 1.2.4. If the criteria are not satisfied, determine the root cause [6] and re-evaluate the test specimen, fixture design, loading, and the crack growth analysis.

1.2.4 Conduct damage tolerance testing of 5 specimens with cold expanded holes following the same test approach as Section 1.2.3. The steps to notch, pre-crack, cold expand the hole, and cycle the specimens are listed below:

a. Start with a hole that has a diameter that is smaller than design.

b. Install initial notch (see Reference 9 for notch preparation procedures).

c. Cycle specimen until a natural fatigue crack forms and grows to a size such that a 0.05 inch fatigue crack, measured along either the surface or bore, whichever is longest, remains after reaming the hole to final size. The cyclic loading for this step should be constant amplitude tension-tension with a peak load approximately 40-60% of the peak spectrum load.

d. Ream hole to initial size per cold expansion specification.

e. Cold expand the hole using specified tooling and process, including controlling sleeve split orientation if required by the cold expansion process specification (and if a split sleeve is part of the applied cold expansion process). If cold expansion causes >0.005 inch extension of the installed crack, the effected specimen is invalid.

f. Ream to final diameter after cold expansion to remove ridge, if required per cold expansion process specification.

g. Cycle specimens using the same spectrum as Sections 1.2.2 and 1.2.3 to a pre-defined failure criteria and obtain incremental crack growth measurements.

Use the average of the 5 specimen results to estimate the damage tolerance life (see Section 1.4) unless the scatter in the test results is judged to be too high.

If the durability life of the cold expanded configuration is desired to be estimated, conduct durability tests of 5 specimens with cold expanded holes and obtain crack growth measurements (no notches, pre-cracking, etc.). Use the average of the 5 specimen results to estimate the durability life unless the scatter in the test results is judged to be too high.

1.3 Level I Acceptance Criteria:

Evaluate the scatter in the test results using the acceptance criteria below. If the test data does not meet the criteria, determine the root cause and modify and re-accomplish the tests or analysis as necessary. These acceptance criteria should be used to determine when to re-evaluate the adequacy of the test specimen design, loading, etc. Some flexibility in applying the acceptance criteria is required. It is possible that the test program is determined to be adequate if one or more criteria are not satisfied after the evaluation is completed. In other words, engineering judgment should be applied.

1.3.1 Acceptance criteria for durability tests:

a. Crack location and orientation are as predicted.

b. Analysis prediction matches average total life of all test results to within 20%, excluding runout tests.

c. Analysis prediction matches each test total life result to within 50%, excluding runout tests.

d. Weibull shape parameter for the test results is reasonable (engineering judgement required) such as the values cited in Reference 9 which are: ~3.5 for aluminum, ~2.5 for titanium, ~3.0 for steel with ultimate strength less than 200 ksi and ~2.0 for steel with ultimate strength greater than 200 ksi.

1.3.2 Acceptance criteria for damage tolerance tests:

a. Cold expansion does not cause detrimental extension (≤ 0.005 inch) of the installed crack (not applicable to baseline non-Cx tests).

b. The damage tolerance life of each test result is within 50% of the average of all test results, excluding runout tests, and cracks initiate and grow as expected.

c. The crack growth curve shapes for the test results are reasonably consistent (engineering judgment required).

1.4 Level I Benefit Determination

Compare the durability crack growth analysis prediction from Section 1.2.4 (excludes the beneficial residual stresses) with the average of the damage tolerance test results from Section 0. Determine the initial crack size to be used in the damage tolerance analysis by comparing the test demonstrated damage tolerance life to the durability crack growth analysis result. Two scenarios are possible, as stated below and illustrated in the figures that follow.

1.4.1 Level I Example Scenario A

The 0.005 inch crack growth analysis life is less than or equal to the test demonstrated damage tolerance life.

If the damage tolerance test results demonstrate equal or longer time to failure than the analysis (see Figure 1), the use of 0.005 inch initial crack size in the damage tolerance analysis is allowed, subject to the general requirements at the beginning of this SB. This scenario demonstrates that the beneficial effect allowable for sustainment applications is limited to the 0.005 inch analysis result despite a demonstrated longer damage tolerance test life.

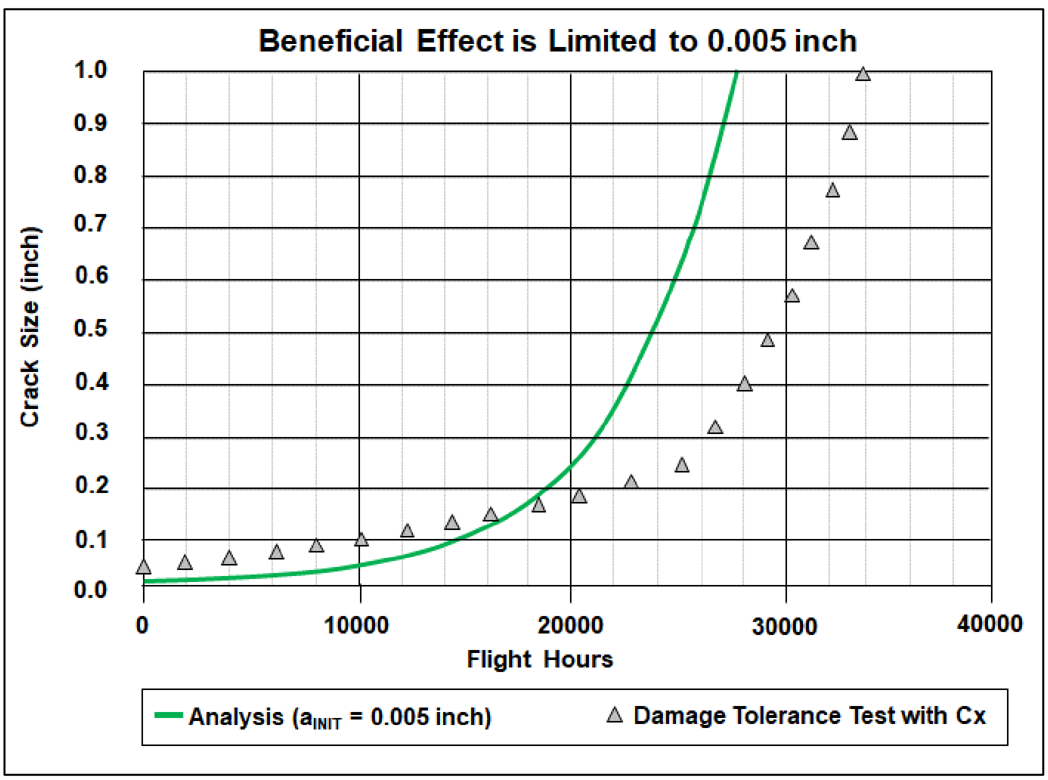

Figure 1. Beneficial Effect is Limited to Initial Crack Size = 0.005 inch

1.4.2 Level I Example Scenario B

The 0.005 inch crack growth analysis life is greater than the test demonstrated damage tolerance life.

If the damage tolerance test results demonstrate less time to failure than the analysis (see Figure 2), then a larger initial crack size must be used. The required size is found by iterating the initial crack size used in the crack growth analysis until a match is achieved between analysis and test. Use that initial crack size in the damage tolerance analysis for the cold expanded hole, subject to the caveats stated below. Figure 2 shows an example in which an initial crack size of 0.015 inch is required to match the damage tolerance test life.

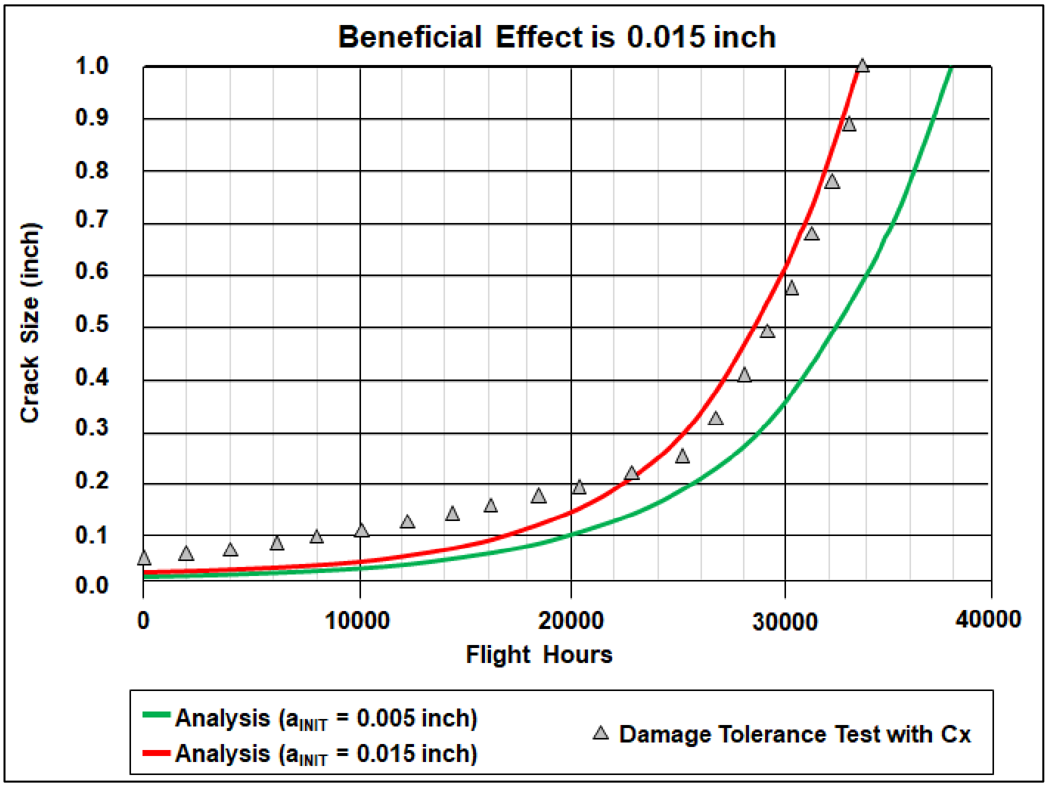

Figure 2. Beneficial Effect Requires Use of Initial Crack Size > 0.005 inch

2 Level II Benefit

Level II initial inspection interval benefit and limited recurring inspection interval benefit through explicit incorporation of non-verified residual stress field in the crack growth analysis.

2.1 Level II Analysis Requirements:

Residual stresses incorporated in the damage tolerance analysis shall be consistent with the geometry, material, and cold expansion process utilized at the critical location of interest. Determination of the residual stress field for use in the damage tolerance analysis shall be approved by the cognizant engineering authority.

Note: Crack growth predictions that explicitly incorporate residual stresses often are influenced by data in the "low" crack growth rate regime. Improved crack growth life correlation can result from developing rate data in this regime.

2.2 Level II Test Requirements:

The Level II test requirements are identical to those given in Section 1.2.

2.3 Level II Acceptance Criteria:

The Level II acceptance criteria are identical to those given in Section 1.3.

2.4 Level II Benefit Determination:

For this benefit level, two analyses must be performed:

Analysis 1: Damage tolerance analysis (as defined in Section 1.4 for a Level 1 benefit)), using the appropriate starting crack size: no smaller than a_{INIT} = 0.005 inch for initial intervals and a_{NDI} [5] of the inspection method being used for recurring intervals. (No RS may be included in this analysis)

Analysis 2: Damage tolerance analysis with residual stresses incorporated and the appropriate starting crack size: a_{INIT} = 0.050 inch for initial intervals and a_{NDI} [5] of the inspection method being used for recurring intervals.

Regardless of the total predicted life from Analysis 2, the maximum benefit for a recurring inspection interval calculation for Level II is limited to the predicted life from Analysis 1 (see Figure 3) and requires that all analysis predictions must be less than or equal to the average of the cold expanded hole damage tolerance tests (excluding runout tests) in order to utilize any recurring interval benefit.

The following scenarios outline how these two analyses are used to determine both the initial and recurring inspection intervals.

2.4.1 Level II Example Scenario A

Analysis 1 life is less than or equal to the test demonstrated damage tolerance life and less than Analysis 2 – see Figure 3.

Initial Interval: Here Analysis 1, which satisfies an a_{INIT} = 0.005 inch assumption, has a total life less than Analysis 2, which uses an a_{INIT} = 0.05 inch prediction and includes residual stresses. Analysis 1 life shall be used for determining the initial inspection interval of 12,000 flight hours (24,000 / 2) for this example.

Recurring Interval: Assuming an appropriate NDI technique is used and the a_{NDI} = 0.1 inch, the life from Analysis 1 (24,000 flight hours) and the flight hours at a_{NDI} = 0.1 inch from Analysis 2 (10,000 flight hours) shall be used for determining the recurring inspection interval of 7,000 flight hours ((24,000-10,000) / 2) for this example. Note that this method increases the recurring inspection interval from Level I by 4,000 flight hours for this example.

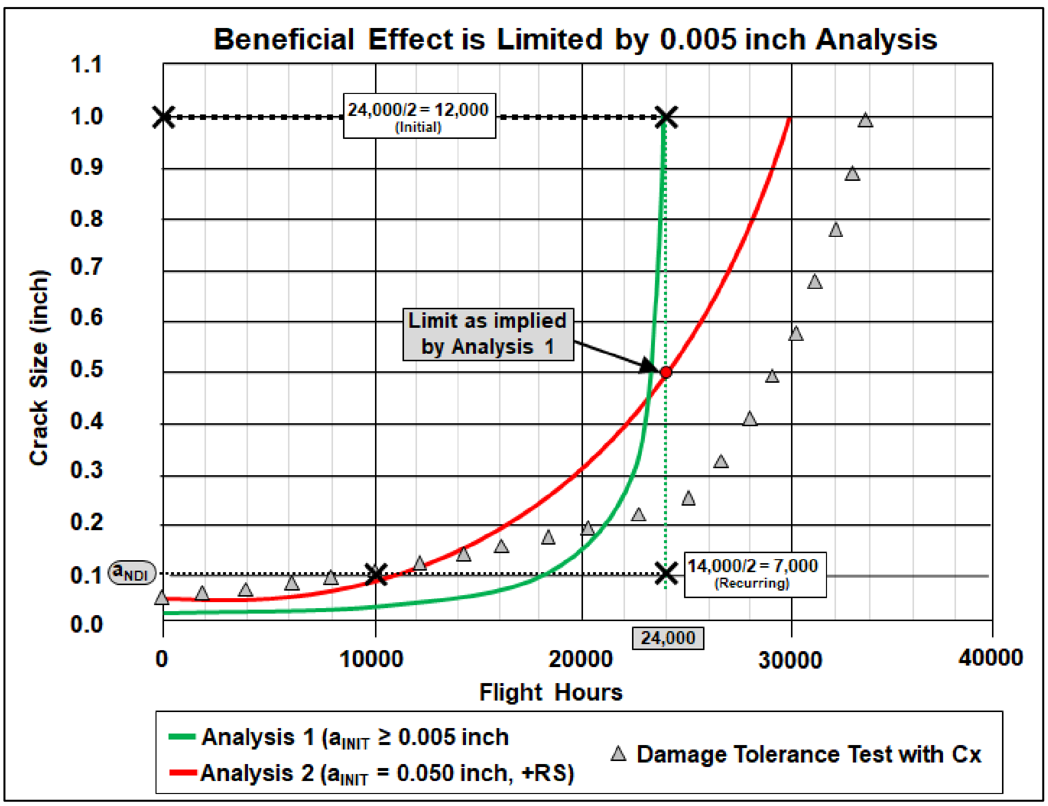

Figure 3. Incorporating Residual Stress Benefit for Inspection Interval Calculation (Both Analyses Shorter Than Test)

2.4.2 **Levell II Example Scenario B**

Analysis 1 is less than or equal to the test demonstrated damage tolerance life but greater than Analysis 2 – see Figure 4.

Initial Interval: If the Analysis 2 prediction (a_{INIT} = 0.05 inch crack with residual stress), has a shorter life than the Analysis 1 prediction (a_{INIT} = 0.005 inch assumption), the initial inspection interval can still be based on the Analysis 1 prediction and results in an initial inspection interval of 16,000 flight hours (32,000 / 2) for this example.

For this scenario, Analysis 2 could potentially be refined to better agree with the test demonstrated life. Any adjustments made to model inputs must be substantiated by physical tests/measurements. Per the acceptance criteria of this bulletin in Section 2.3, Analysis 2 must not exceed the average of the test results (excluding runout tests).

Recurring Interval: Assuming an appropriate NDI technique is used and an a_{NDI} = 0.125 inch, the recurring inspection interval is calculated based on the damage tolerance life from a_{NDI} to the critical crack size, resulting in a recurring interval of 7,000 flight hours ((24,000-10,000) / 2) for this example. Note that this method increases the recurring inspection interval from Level I by 4,000 flight hours for this example.

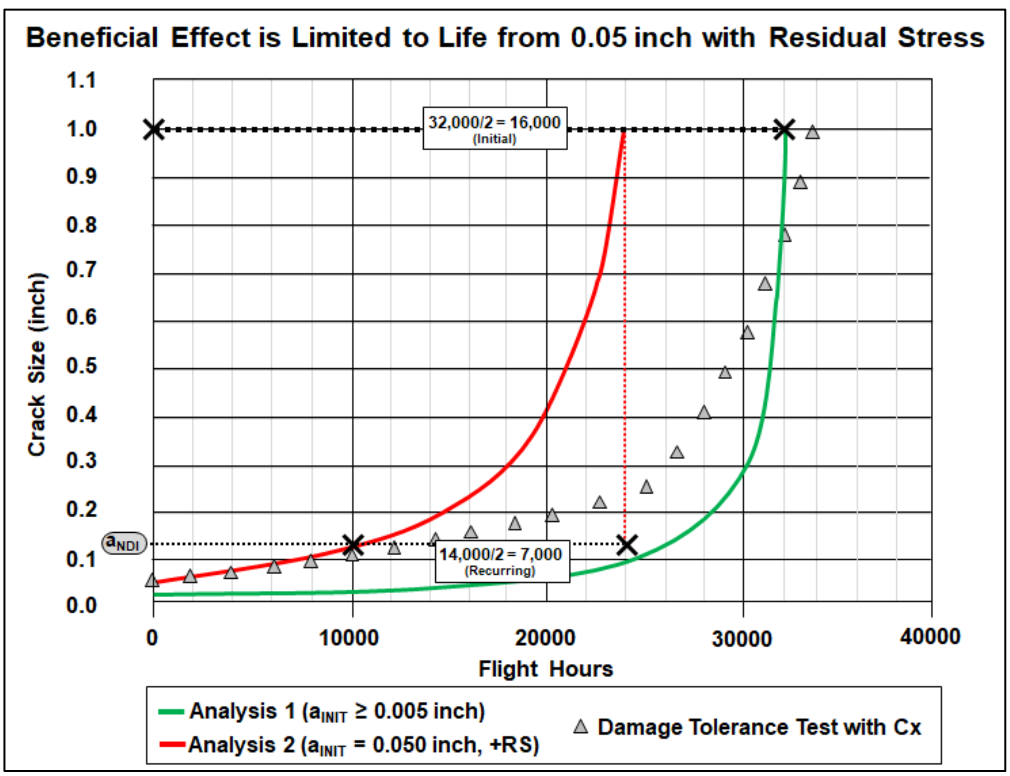

Figure 4. Incorporating Residual Stress Benefit for Inspection Interval Calculation (Analysis 2 Shorter than Analysis 1)

2.4.3 **Level II Example Scenario C**

Analysis 2 predicted lives are greater than the test demonstrated damage tolerance life – see Figure 5.

Initial Interval: For this scenario, the initial inspection interval shall be based on the Analysis 1 prediction and results in an initial inspection interval of 13,000 flight hours (26,000 / 2) for this example.

Recurring Interval: Assuming an appropriate NDI technique is used and an a_{NDI} = 0.125 inch, the recurring inspection interval is limited to the Analysis 1 damage tolerance life from a_{NDI} to the critical crack size, resulting in a recurring interval of 5,750 flight hours (11,500 / 2) for this example. No credit can be taken for Analysis 2 because it overpredicts the test data, but could potentially be refined to better agree with the test demonstrated life. Any adjustments made to model inputs must be substantiated by physical tests/measurements. Re-evaluating analysis assumptions from Section 1.1 is also advised.

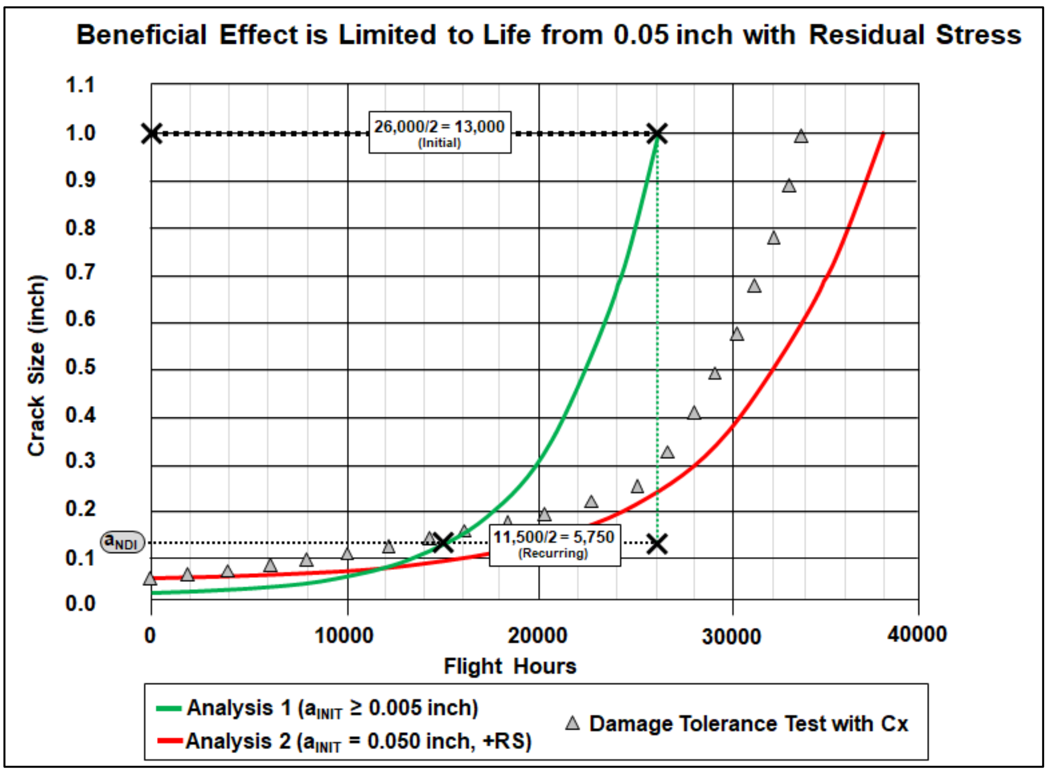

Figure 5. Incorporating Residual Stress Benefit for Inspection Interval Calculation (Analysis 2 Greater than Test)

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