# A-10 damage tolerance analysis ground rules refinement studies

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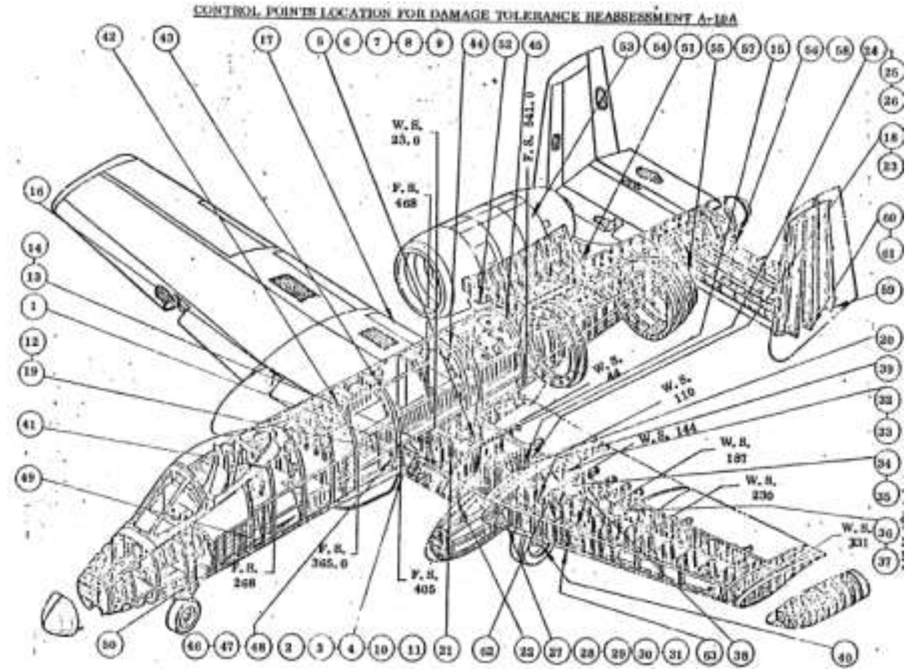
# Background

- First A-10 DTA was in 1982
  - Fairchild Republic software

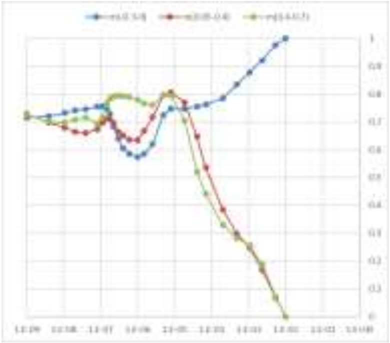



- Periodically updated by Fairchild and Grumman through the 80s and 90s
- Transitioned to AFGROW in 2003
  - Increased capability and flexibility
  - Analysis capability across the A-10 ASIP team (USAF and contractors)

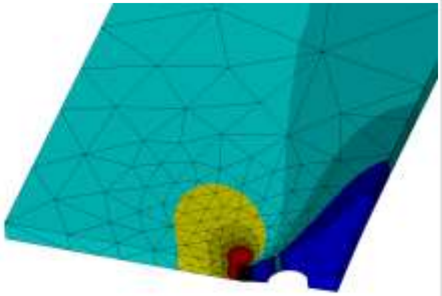
# Introduction

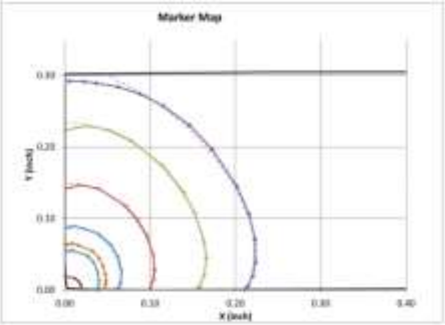
- In recent years, the A-10 ASIP team has continued to modernize DTA processes and inputs

Updated da/dN testing and fitting methods

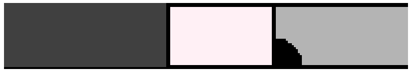


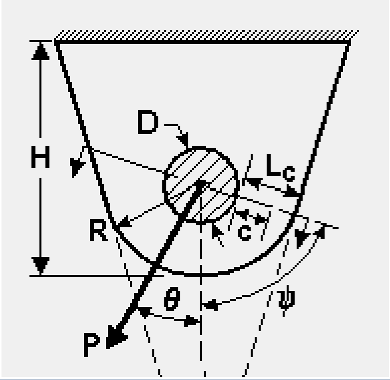
Incorporation of FE-based analysis



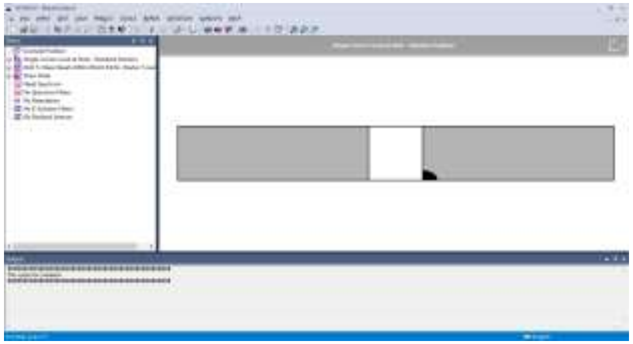



New fracture mechanics models






Updating AFGROW options



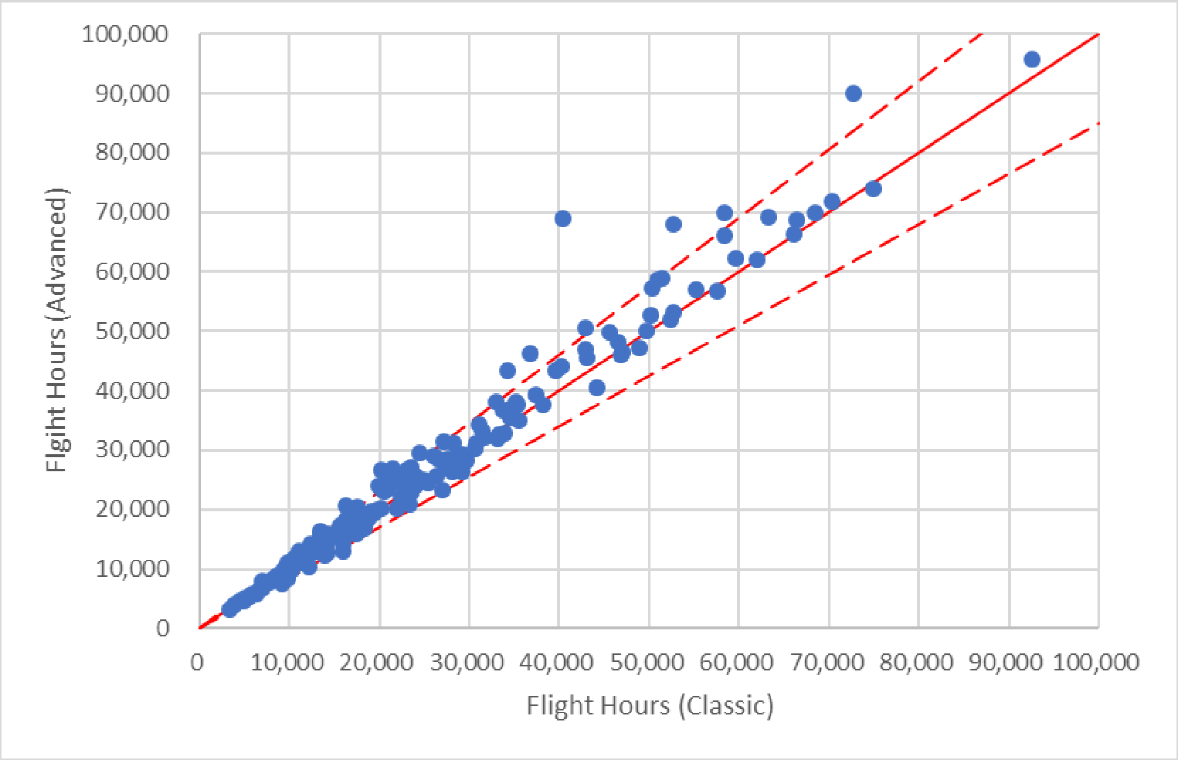
# Standard vs advanced hole models

- Looking into transitioning from standard to advanced models

- AFGROW standard corner-cracked hole model:
  - Developed by Newman and Raju in 1986
  - Valid limits:
    - 0.0 < a/t <= 1.0
    - 0.2 <= a/c <= 2.0
- AFGROW advanced corner-cracked hole model:
  - Developed by Fawaz and Andersson in 2004
  - Valid limits:
    - 0.1 < a/t <= 1.0
      - LexTech developed approach to handle smaller cracks
    - 0.1 <= a/c <= 10.0

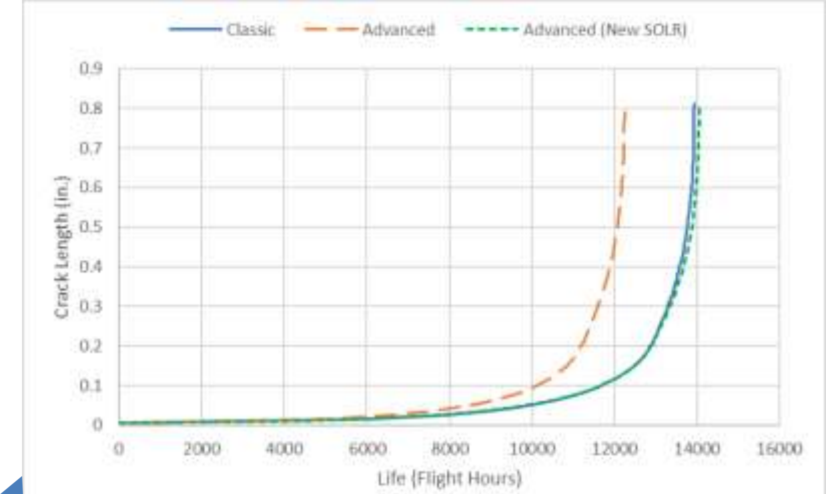
# Standard vs advanced hole models

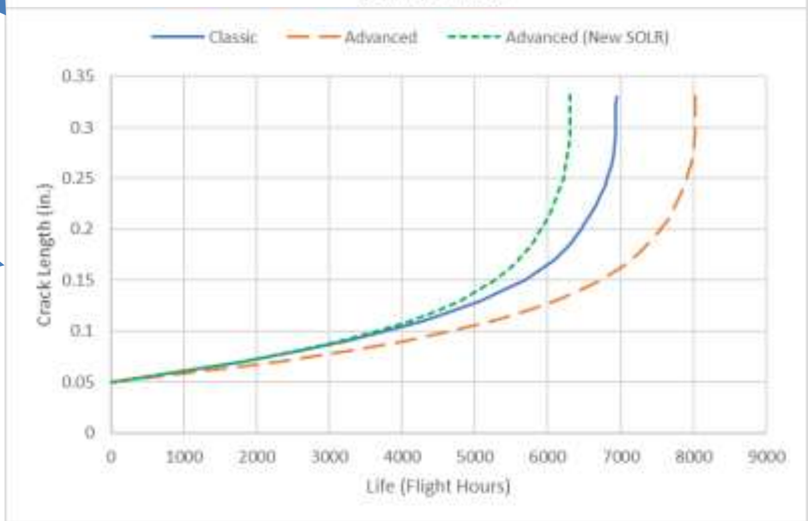
- All corner crack CPs run through COM using both classic (Newman-Raju) and advanced (Fawaz-Andersson) models
  - Good agreement in most cases
  - Median 2.4% increase in life



# Standard vs advanced hole models

- Highest correlations with life difference:
  - Thickness and IFS: Thicker CPs with smaller IFS have more opportunity for difference
  - Tension and bearing stress fraction: Lower tension/ higher bearing gives longer lives




- New SOLR correlation leads to even better agreement

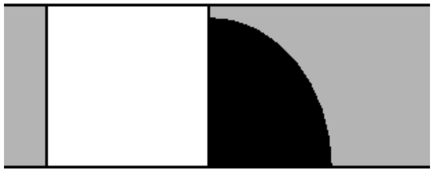
# Standard vs advanced hole models

- Factors to consider:
    1. Impact on maintenance – Very good agreement in analytical results, so impact will be minor
    2. Accuracy – We expect the advanced models to be more accurate where they do disagree
    3. Difficulty of change
        - Fully implemented in AFGROW and our A-10 DTA COM
        - Requires new retardation parameters

➢ Switch to advanced model with next usage update

# Corner crack aspect ratios

- Crack aspect ratio investigation
  - Current DTA ground rules call for using constant corner crack aspect ratios
  - Looked into whether we should consider changing the ground rules to allow AFGROW to vary the aspect ratio



# Corner crack aspect ratios

- Impact:

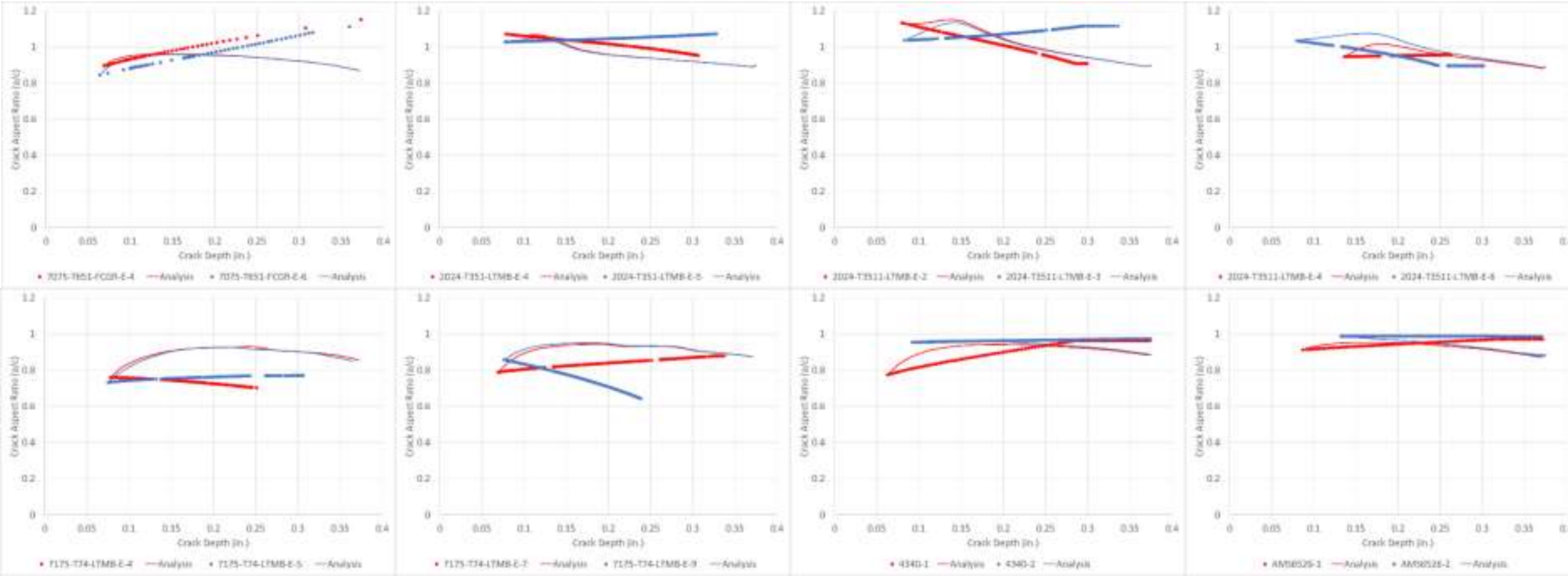
| Analytical interval less than | Control Points | |
|---|---|---|
| | Current | Advanced and varying a/c |
| **Every phase inspection** | 5 | 4 |
| **Every depot inspection** | 14 | 16 |
| **Every second depot inspection** | 33 | 52 |
| **Total** | 140 | 140 |

  - Thicker components have largest differences

- Potential impacts to phase inspections:
  - The single edge corner crack analyses show an increase in life with the change to varying aspect ratios. The interval for one CP increased above the phase inspection frequency.
  - Two CPs decreased below the depot inspection frequency

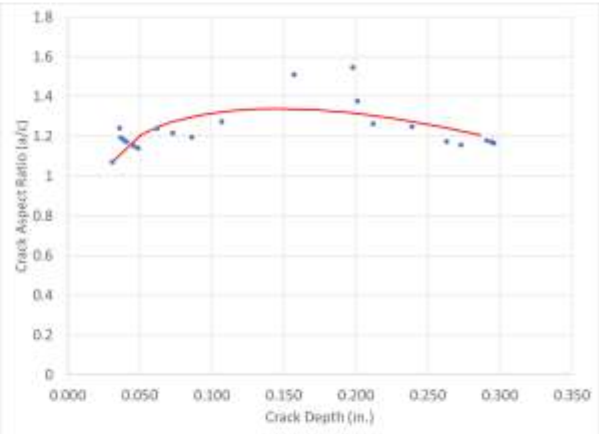
# Corner crack aspect ratios

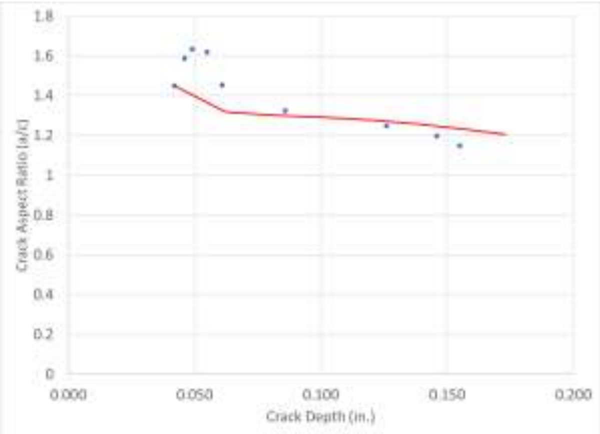
- Accuracy: Comparison to constant amplitude tests

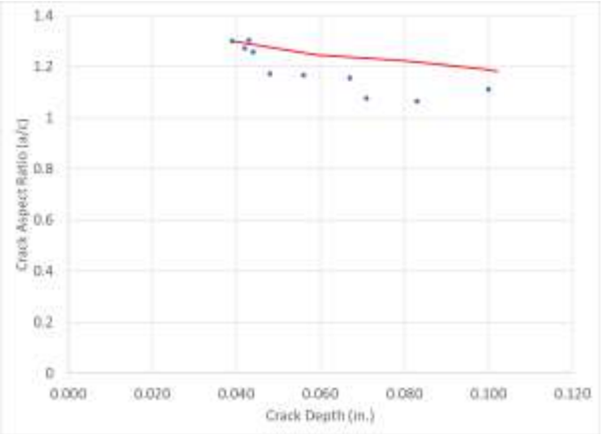


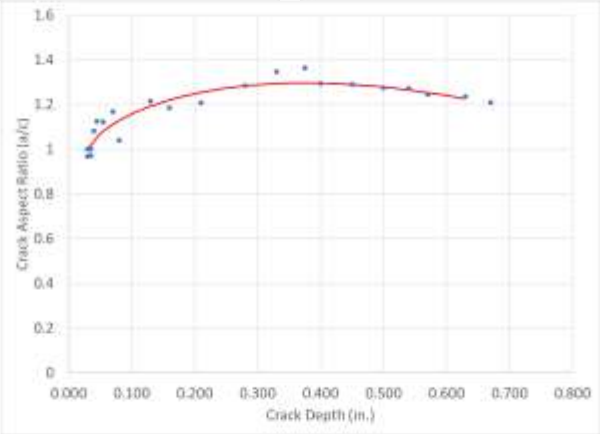
# Corner crack aspect ratios

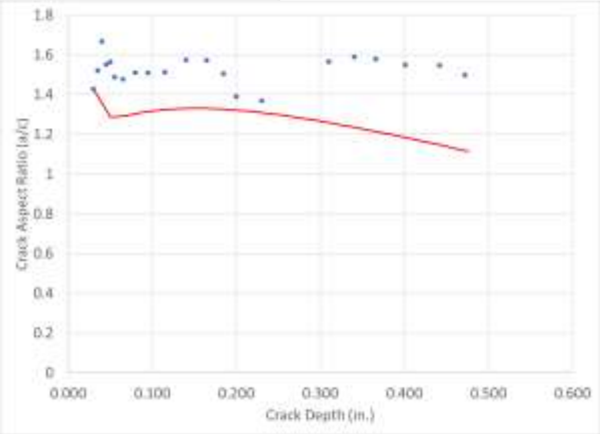
- Accuracy: Comparison to spectrum tests



# Corner crack aspect ratios

- Conclusions:

  1. What is the impact on inspection intervals of making the change?
     - Most decrease slightly, but practical impact is minor
     - Potential for two more phase inspections
     - Potential for a few more SSIs happening more frequently

  2. How accurate is the model when allowing aspect ratios to vary?
     - Accuracy is mixed and hard to assess because of test variability
     - At least as accurate as keeping aspect ratios constant

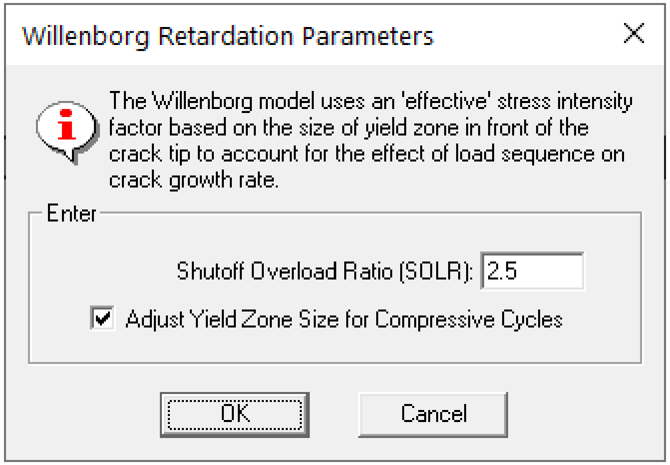
- Recommend to allow AFGROW to vary corner crack aspect ratios

# Generalized Willenborg correction

- Evidence shows that compressive loads cause a reduction in crack growth retardation due to reduction in the near-tip yield zone size
- AFGROW allows the user to reduce the overload yield zone size in the Generalized Willenborg model, reducing retardation when encountering compressive loads

$$r^{y}_{OL} = r^{y}_{OL}(1\text{-}0.9\left|\frac{\sigma_{compression}}{\sigma_{OL}}\right|)$$

- A-10 analyses do not currently use it
- Investigating the impact of turning it on



# Generalized Willenborg correction

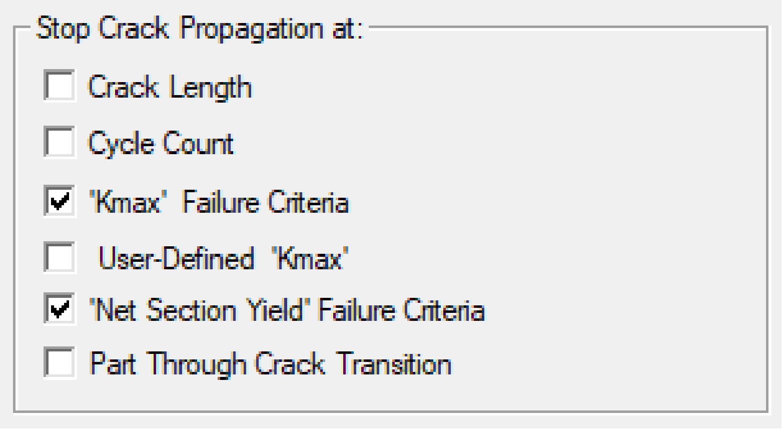
- Spectra were reviewed for compressive content
  - Ten calculation methods are used for A-10 spectra
  - Representative CPs were selected and reviewed
- SOLR values were correlated from test with and without the option selected
  - CPs without significant compression had no meaningful impact
  - CPs with compression gave unrealistic results – SOLRs below 1.10

➢ Recommended not using the compression correction

| Calculation Method | Spectrum | Minimum stress | Compressive cycles | Total cycles | % cycles with compression |
|---|---|---|---|---|---|
| 101 | 7 | -0.060 | 8 | 7,368 | 0.1% |
| 101 | 26.1 | -0.077 | 18 | 7,371 | 0.2% |
| 101 | 62 | -0.087 | 18 | 7,366 | 0.2% |
| 102 | 9 | 0.243 | 0 | 7,368 | 0.0% |
| 102 | 45 | 0.082 | 0 | 8,258 | 0.0% |
| 102 | 57 | -1.134 | 642 | 8,114 | 7.9% |
| 103 | 42 | -0.125 | 13 | 8,229 | 0.2% |
| 104 | 45.1 | 0.032 | 0 | 8,926 | 0.0% |
| 105 | 51L | 0.056 | 0 | 8,816 | 0.0% |
| 106 | 53.1 | 0.294 | 0 | 6,883 | 0.0% |
| 107 | 59L | -0.815 | 8,120 | 8,961 | → 90.6% |
| 108 | 50 | -0.062 | 147 | 4,177 | 3.5% |
| 109 | 82 | -0.626 | 7,369 | 7,369 | → 100.0% |
| 110 | 75 | 0.597 | 0 | 6,891 | 0.0% |

# Net section yield

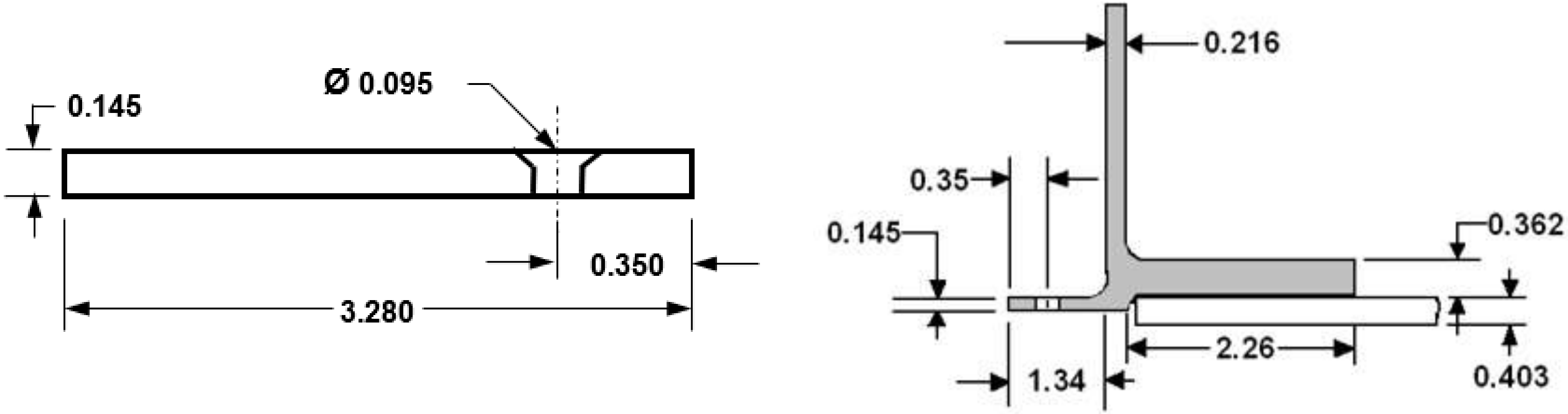
- Investigating the impact of using net section yield as a failure criterion
  - Historically not used on A-10 analyses because of the typical redundancy in load paths that leads to stress redistribution as cracks grow




- Ran all A-10 CPs through the COM with and without NSY
  - 30 failed due to NSY
  - 14 of those caused by the design of the analytical model

# Net section yield

- Causes of 14 unrealistic NSY failures
  - Fracture model uses a smaller cross section (thickness, width, or neglected secondary flange) than the structure
    - Ensure model has accurate cross sectional area




  - Reference stress includes a stress concentration
    - Ensure reference stress is the far field (average cross section) stress

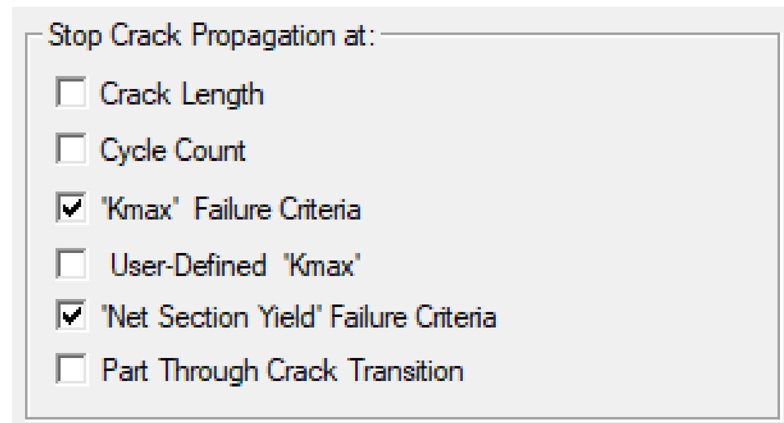
# Net section yield

- After correction:
  - Sixteen CPs have reduction in life from NSY
  - Only two of them have a practical impact on maintenance intervals
  - Both locations undergoing fleetwide modification

| CP | Title | Critical crack size | | Life | | Recurring interval | |
|---|---|---|---|---|---|---|---|
| | | No NSY | NSY | No NSY | NSY | No NSY | NSY |
| 17BR | Rear Spar Repair, WS 45 | 0.432 | 0.173 | 11,047 | 9,131 | 3,682 | 3,044 |
| 19 | Thin Skin Wing Lower Aux Spar Cap, WS 34 - 44.5 | 0.436 | 0.370 | 26,526 | 26,509 | 5,087 | 5,079 |
| 35 | Thin Skin Pylon Stud Hole in Mid Spar Cap, WS 144 | 0.456 | 0.456 | 7,069 | 6,990 | 2,198 | 2,172 |
| 41.1 | Turtledeck Support Radius, FS 268 | 1.769 | 0.867 | 18,013 | 17,584 | 3,206 | 3,063 |
| 41.1S | Turtledeck Support Radius Repair, FS 268 | 4.030 | 1.832 | 70,603 | 69,429 | 13,886 | 13,494 |
| 42.1 | Turtledeck Angle, FS 314 | 1.469 | 0.246 | 7,605 | 5,899 | 557 | 0 |
| 42.1S | Forward Fuselage Turtle Deck Angle, FS 314, SLEP | 2.495 | 1.489 | 74,978 | 74,311 | 5,001 | 4,779 |
| 45A | Fuselage Upper Longeron Strap, FS 541 | 0.432 | 0.432 | 31,666 | 31,579 | 10,555 | 10,526 |
| 45BW | Upper Longeron J-Extrusion Web, FS 531 | 2.630 | 1.529 | 20,295 | 18,536 | 5,384 | 4,798 |
| 45BWR | Repaired Upper Longeron J-Extrusion Web, FS 531 | 2.530 | 1.470 | 21,159 | 19,331 | 5,491 | 4,585 |
| 47A | Lower Auxiliary Longeron Inboard Flange, FS 405 | 0.286 | 0.158 | 5,897 | 3,588 | 1,966 | 1,196 |
| 47B | Lower Auxiliary Longeron Outboard Flange, FS 405 | 0.286 | 0.286 | 4,449 | 4,219 | 1,483 | 1,406 |
| 60B | Upper Mid Spar Horizontal Stabilizer, BL 109 | 0.489 | 0.244 | 54,824 | 53,831 | N/A | N/A |
| 62E | Thin Skin Wing Typical Stringer, WS 135 | 1.032 | 0.580 | 11,939 | 11,360 | 3,979 | 3,787 |
| 107 | Upper Aux Longeron, FS 524 | 0.285 | 0.089 | 10,304 | 5,014 | 3,435 | 1,763 |
| 62AT | Thick Skin Wing Typical Stringer, WS 135 | 1.059 | 0.585 | 33,766 | 33,176 | N/A | N/A |

# Net section yield

- Impact: Minimal
- Accuracy: Conservative because of structural redundancy
- Difficulty: Requires corrections to cross sectional areas and stresses (which should probably be done anyway if no negative impact on fracture results)

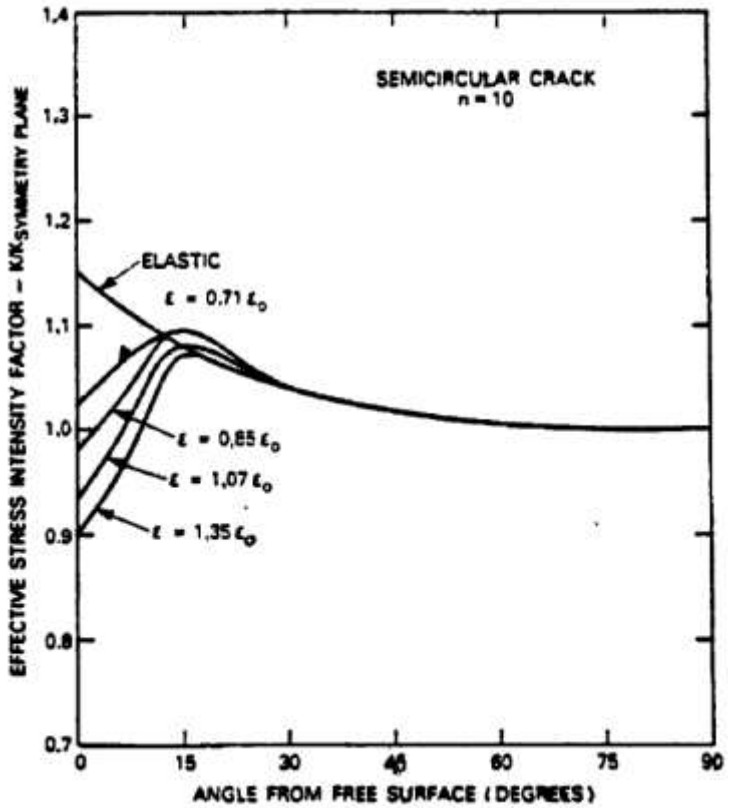



- Recommendation:
  - If using net section yield as a failure criterion, update analyses to reflect accurate cross sectional area and stress

# Crack closure factor

- The crack closure factor ($\beta_R$) was developed by Newman and Raju in 1984 to account for slowing of growth near surfaces
  - Lack of constraint near surfaces
    - Plane stress behavior
      - Increased plasticity
        - Lower effective K

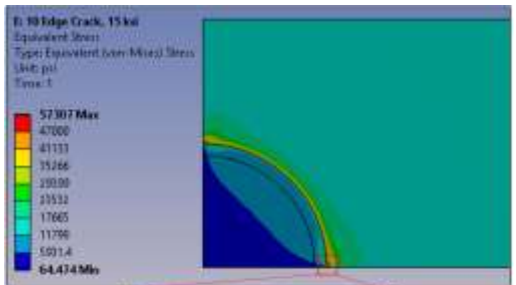
$$\beta_R = 0.9 + 0.2R^2 - 0.1R^4 \text{ (if } R > 0) \text{ or } 0.9 \text{ (if } R <= 0)$$

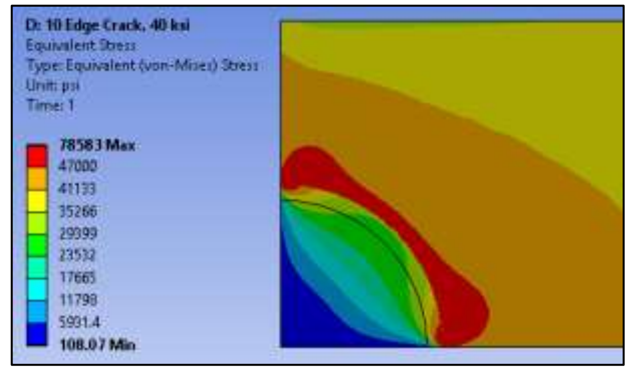



- Studied whether to use the factor in A-10 DTA

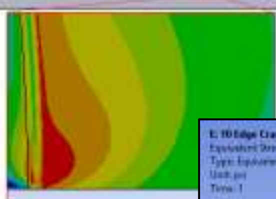
# Crack closure factor

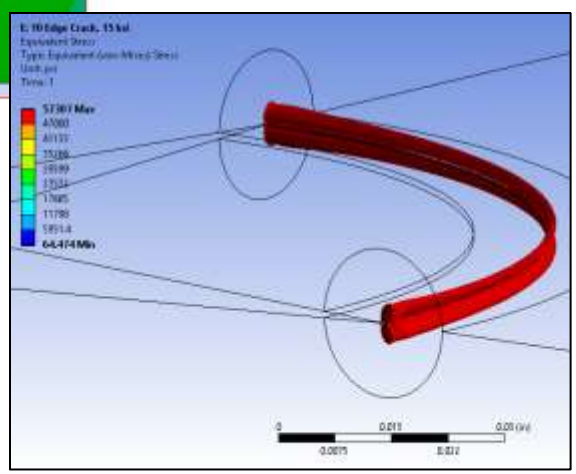
- Elastic-plastic models developed to see how plastic zone changes across the crack front at low and high stress

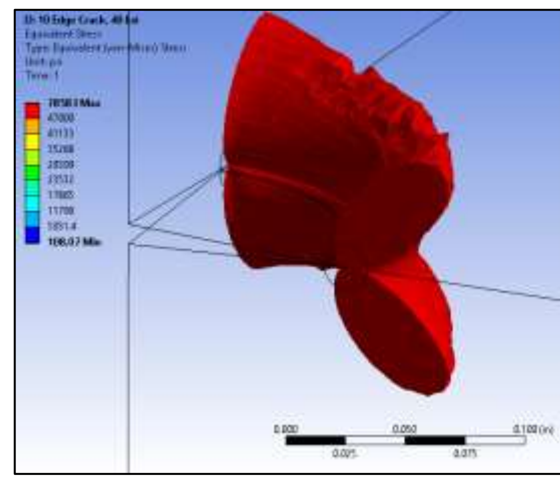








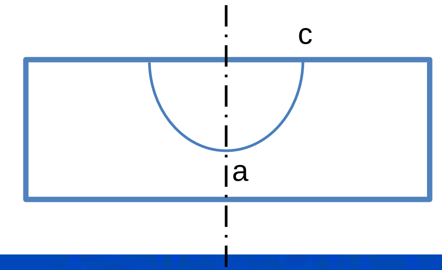




# Crack closure factor

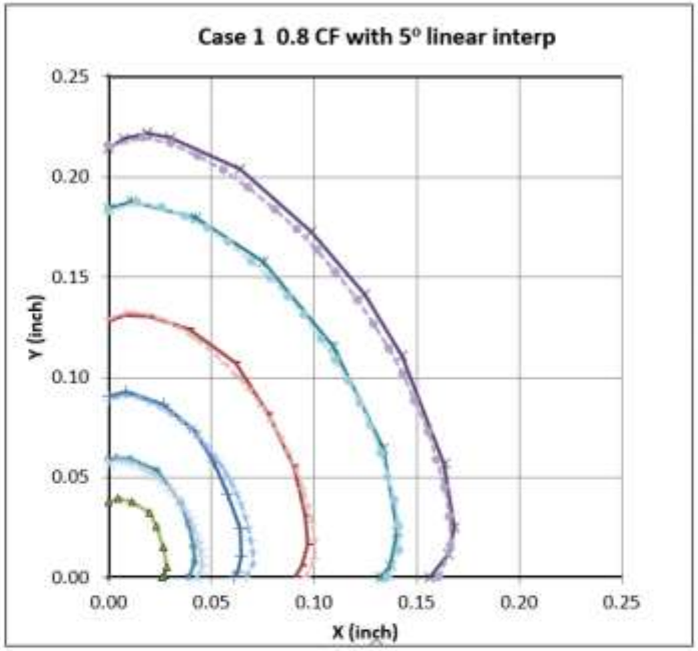
- 5 corner crack CPs analyzed in AFGROW with and without the factor (with varying aspect ratios)
  - Aspect ratios are negligibly different
  - Lives increase between 2 and 37%, which would be offset by recorrelated SOLRs


- All 5 surface crack CPs analyzed with and without the factor
  - Aspect ratios increase between 2 and 19%
  - Lives increase between 2 and 6%



# Crack closure factor

- Conclusions:
  - Until we move away from constant aspect ratio cracks, the factor will only decrease SOLR and have no practical impact
  - Investigate the use of the factor with multi-point analyses, comparing growth using nominal Ks against growth using decreased K near free surfaces
    - Hill Engineering 2020
  - Further investigate the appropriateness of the factor in spectrum loading analyses
    - Newman and Raju wrote that the factor "can only be used for constant-amplitude loading."



# Summary

- Advanced models: Make the transition when changing to a new usage so SOLR values have to be newly correlated anyway
- Corner crack aspect ratios: Allow AFGROW to vary, as part of the change to advanced models
- Generalized Willenborg compressive correction: Leave unchecked
- Net section yield: If using as a failure criterion, ensure models have accurate cross sectional areas and stresses
- Crack closure factor: Hold off on using the factor until other issues are considered