Engineered residual stress implementation workshop 2016
Ogden UT

Engineered Residual Stress in Military Aircraft Structure

15 September, 2016

Dale L. Ball

LOCKHEED MARTIN
Aeronautics Company

Engineered Residual Stress in Military Aircraft Structure

- **STRUCTURES POLICY**
  - *Shot Peening*
  - *Laser Peening*
  - *Hole Cold-working*
- **Cold-Worked Hole R&D**
  - *Residual Stress Analysis*
  - *Fatigue Crack Initiation Analysis*
  - *Fatigue Crack Growth Analysis*
- **Conclusions**

GENERAL POLICY

- Compressive engineered residual stresses in metallic materials are known to be beneficial:
  - *Increase time for fatigue crack initiation*
  - *Decrease fatigue crack growth rate*

- General structures policy is:
  - *Don't take credit for beneficial residual stresses during design, with exceptions as approved by the procuring agency*
  - *For approved exceptions, don't take full credit*
    - Typically allow one half of test demonstrated Life Improvement Factor (LIF/2)
    - This helps mitigate impact of issues discovered later
  - *Take full advantage of beneficial residual stresses during sustainment.*

STRUCTURES POLICY: SHOT PEENING

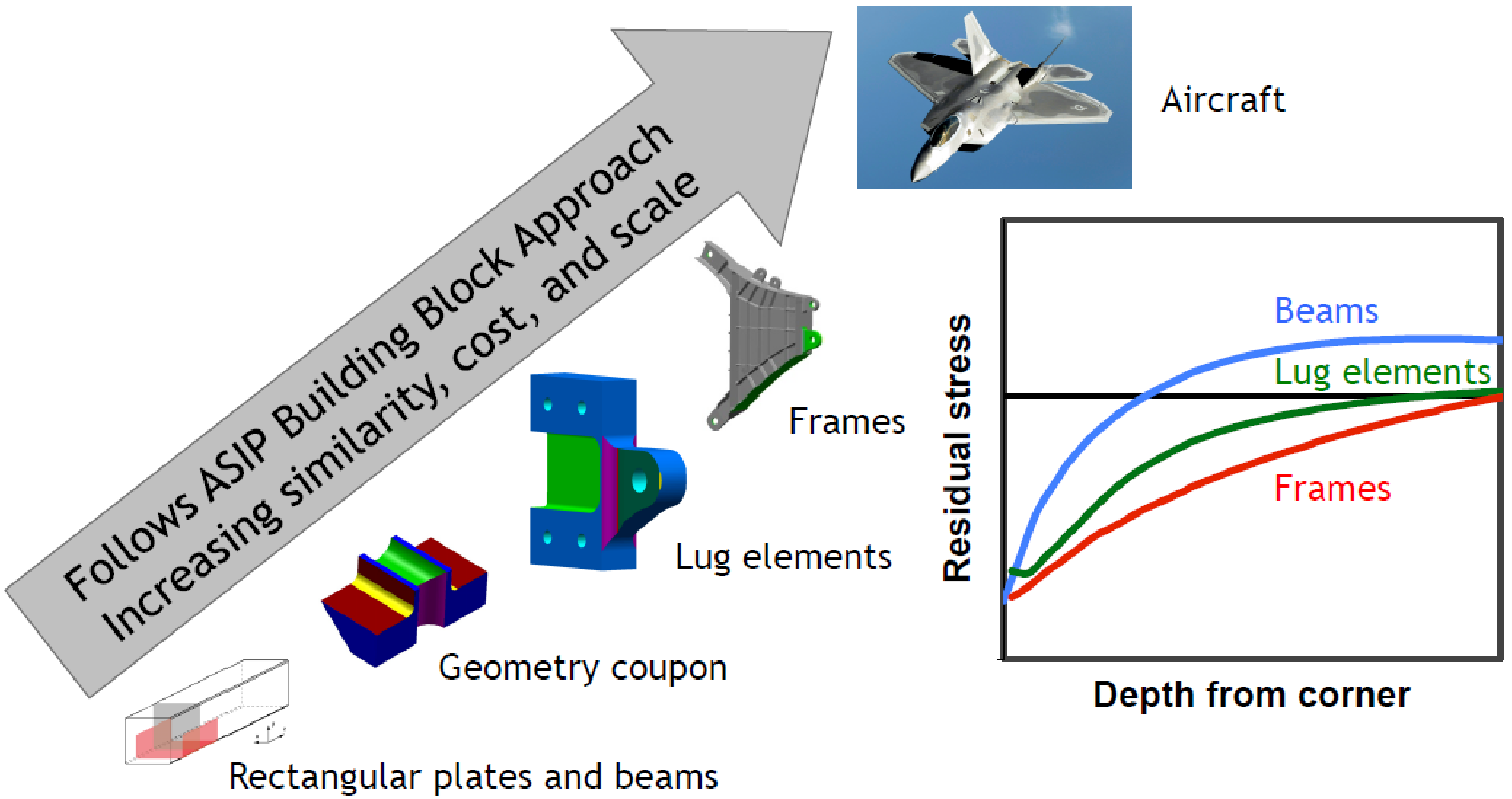
- Shot peening (SP) often applied to mitigate adverse effects of other manufacturing processes:
  - *Welding*
  - *Grinding*
  - *Plating*
  - *Anodizing*
  - *etc.*
- Standard practice is to apply SP at manufacture
  - *No credit (for beneficial residual stresses) is taken in design or sustainment analyses*

STRUCTURES POLICY: LASER PEENING

- Laser peening (LP) has been (or is being) developed and applied on two major LM airframes
- F-22 wing attach lugs
  - *Significant investment in process development, building block test program and methods development*
  - *Mod of in-service aircraft*
  - *Full credit taken for test demonstrated life extension*
- F-35 bulkheads and spars
  - *VERY significant investment in process development, building block test program and methods development*
  - *Mod of in-service aircraft*
  - *Full credit taken for test demonstrated life extension*

STRUCTURES POLICY: LASER PEENING

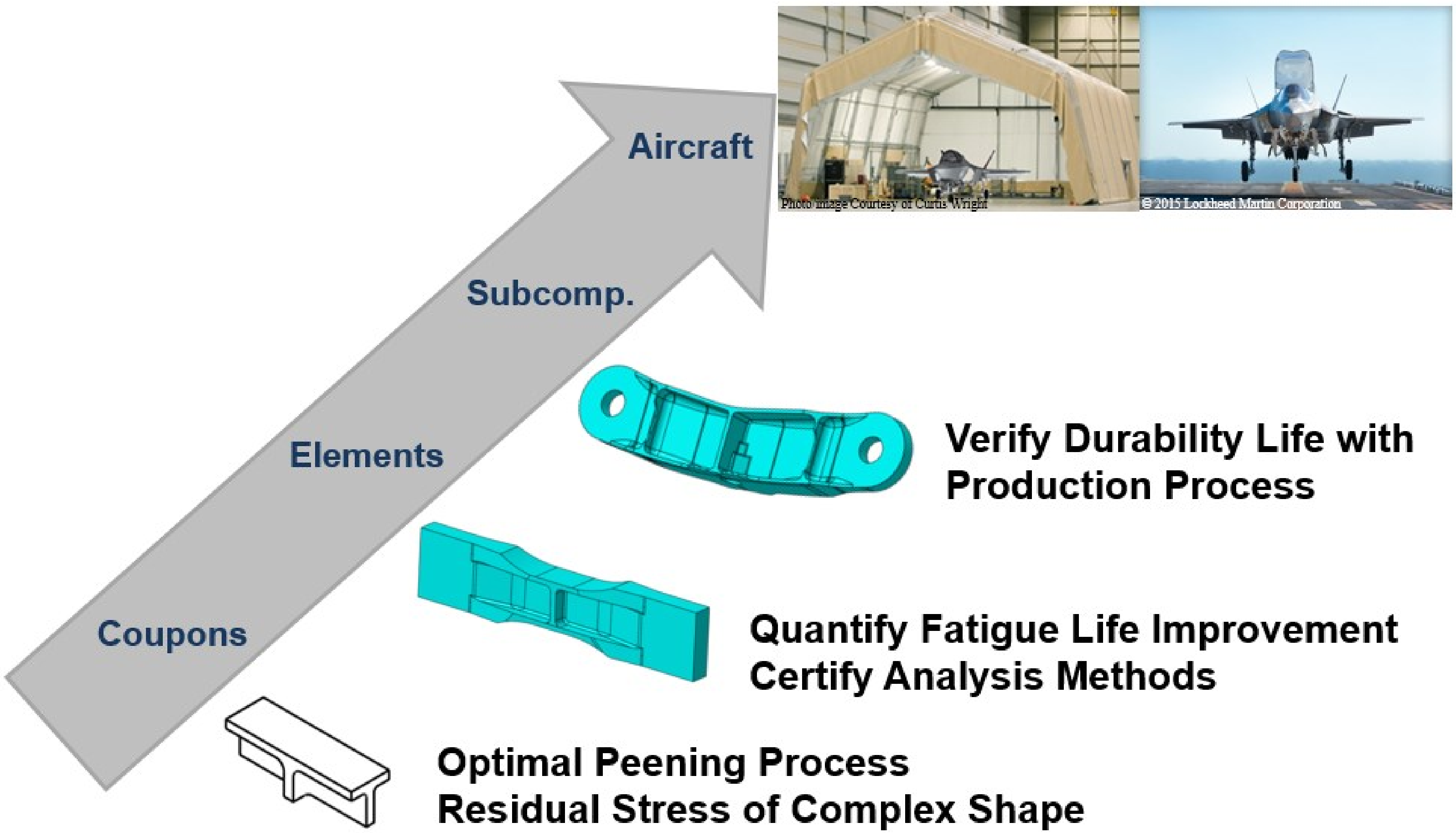
- F-22 wing attach lugs



Ref: M.Hill, et.al., USAF ASIP 2012

STRUCTURES POLICY: LASER PEENING

- F-35 bulkheads and spars
  - **Building Block Approach Reduces Risk during Qualification**



Ref: P.Caruso, 5th Intl.Conf. on Laser Peening, May 2015

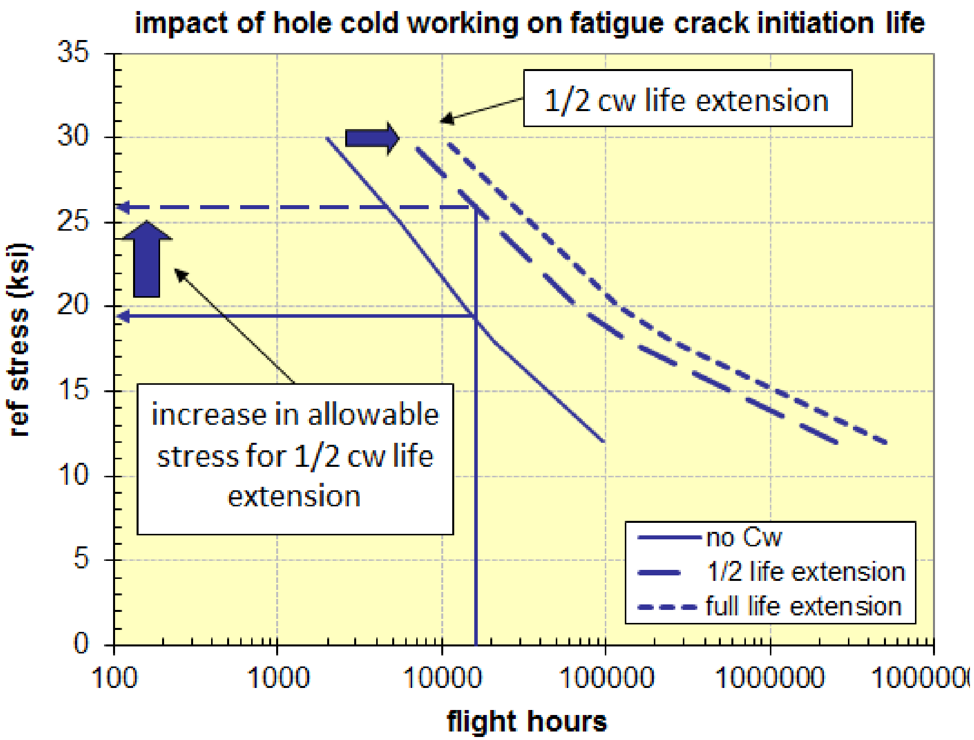
STRUCTURES POLICY: HOLE COLD-WORKING

- Hole Cold-working (CW) is applied extensively on all LM airframes
- General policy is the same as stated above:
  - *No credit during design (with exceptions as approved by the procuring agency)*
  - *Half credit for approved exceptions during design*
  - *Full credit during sustainment*
- However, each program has its own policy (especially true for legacy programs)

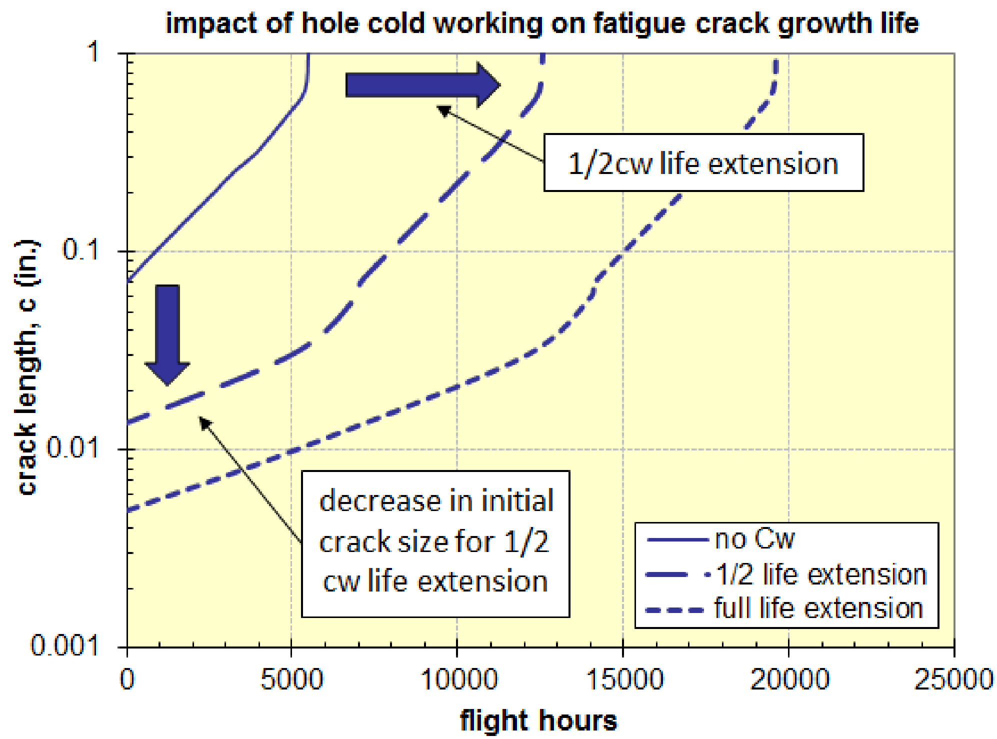
Engineered Residual Stress in Military Aircraft Structure

STRUCTURES POLICY: HOLE COLD-WORKING

- ½ cold work life extension for design exceptions



fatigue crack initiation analysis



fatigue crack growth analysis

STRUCTURES POLICY: HOLE COLD-WORKING

- C-130 program:
  - *Cold-working is being used:*
    - Half credit taken for DT flaw (ci reduced from 0.05 to 0.03 inch)
    - No credit taken for continuing damage flaw (ci=0.005).

- C-5 program:
  - *Cold-working is being used for RERP and selected mod programs*
    - No credit is being taken for sustainment DaDT analyses.
  - *C-5 program currently coordinating with AFLCMC, experimental program to define appropriate LIF*

STRUCTURES POLICY: HOLE COLD-WORKING

- F-16 program:
  - *Cold-working is being used extensively for sustainment*
    - No FCI analysis
    - No credit taken for FCG-based durability analysis: ci=0.005 inch
    - Full credit taken for FCG-based damage tolerance analysis: ci reduced from 0.05 to 0.005 inch (typically corresponds to 3x to 5x extension in life)
    - No credit taken for continuing damage flaw: ci=0.005 inch
    - No credit allowed for compression dominated spectra
  - *Has been very successful for both mitigation of design deficiency and for life extension beyond initial design life*
  - *Selected investigations of explicit use of cold-work-induced residual stress fields have been performed*

STRUCTURES POLICY: HOLE COLD-WORKING

- F-22 program:
  - *For approved exceptions during design, half credit was taken*
    - For FCI analysis of durability critical parts, life improvement incorporated via a local stress reduction factor for selected critical holes – C_{LI}=0.87 stress reduction factor corresponds to approximately 15% increase in design allowable stress
    - For FCG analysis of durability critical parts, no credit taken, ci=0.005 inch
    - For FCG analysis of fracture critical parts, half credit taken, ci=0.03 inch
    - No credit if Kt*DLS<1.2*Fcy
  - *Cold-working is being used for sustainment*
    - Full credit taken for DT flaw (ci reduced from 0.05 to 0.005 inch)
    - No credit taken for continuing damage flaw (ci=0.005).
    - No credit if Kt*DLS<1.2*Fcy

STRUCTURES POLICY: HOLE COLD-WORKING

- F-35 program:
  - *For approved exceptions during design, half credit being taken to mitigate impact of issues discovered during FSDT*
    - For FCI analysis, reduction factor applied
    - For FCG analysis of durability critical parts, no credit taken, ci=0.005 inch
    - For FCG analysis of fracture critical parts, half credit taken, ci=0.03 inch

Coldworked hole stress reduction factors for FCIA[1]	
Material	**Stress Reduction Factor**
2124 and 7050 Aluminum	0.87
Ti 6Al-4V beta Annealed and Ti 6-2222	0.85
All other materials	0.90

[1] Applicable when $\sigma_{max} * K_t \leq 1.2 * F_{cy}$

Coldworked hole initial flaw size assumptions for FCGA	
Material	**Ci, ai**
Ti 6Al-4V HIPped casting	0.03
All other materials	0.015

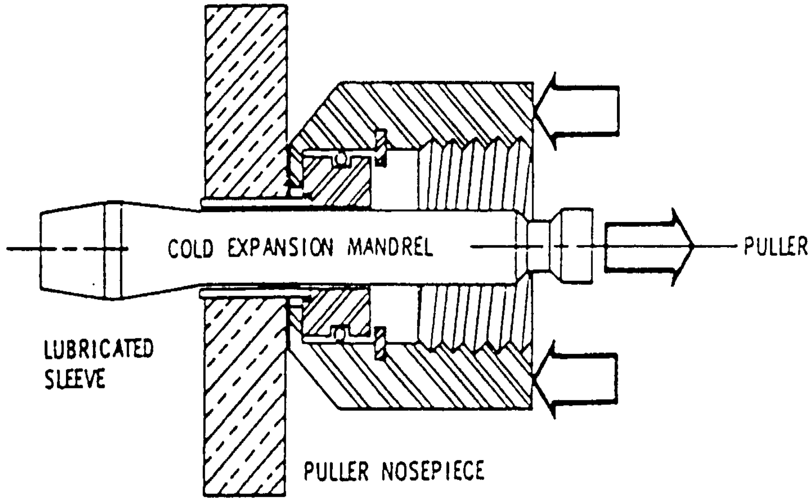
Engineered Residual Stress in Military Aircraft Structure

- **STRUCTURES POLICY**
  - *Shot Peening*
  - *Laser Peening*
  - *Hole Cold-working*
- **COLD-WORKED HOLE R&D**
  - *Residual Stress Analysis*
  - *Fatigue Crack Initiation Analysis*
  - *Fatigue Crack Growth Analysis*
- **Conclusions**

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

COLD WORK PROCESS:

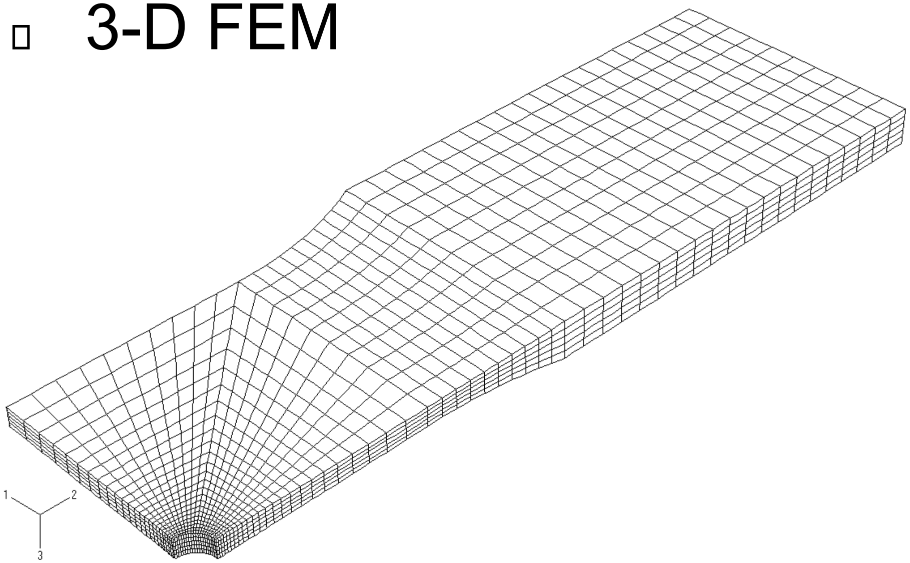
- Radially expand hole by drawing oversized mandrel though
- Radial expansion causes permanent plastic deformation
- Beneficial compressive residual stress field formed around hole upon unloading (removal of mandrel), **provided have sufficient surrounding elastic material**



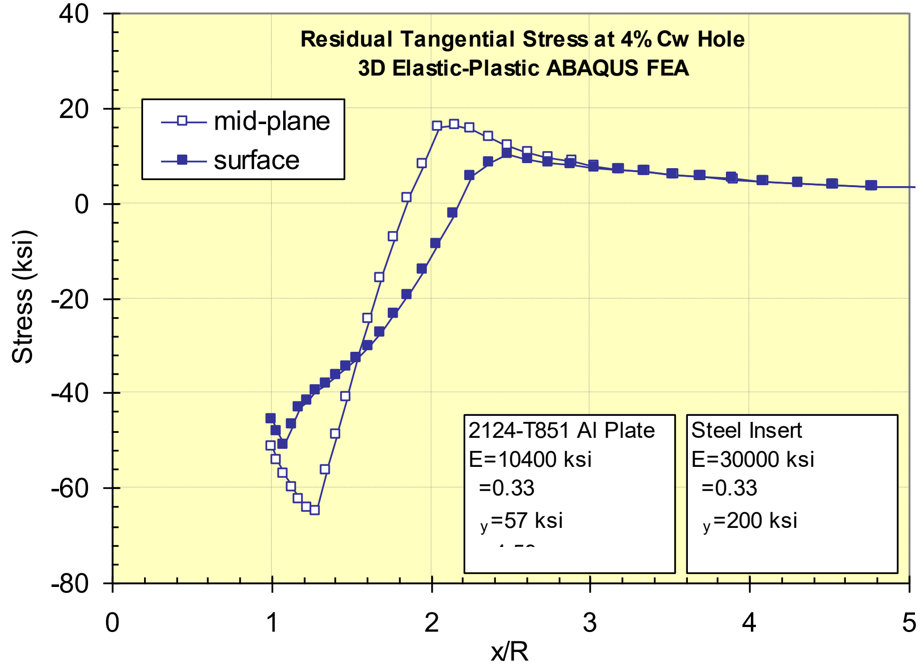
CW HOLE R&D: RESIDUAL STRESS ANALYSIS

STRESS ANALYSIS OF UNCRACKED HOLE - FEA (ABAQUS):

- Elastic-plastic analysis, kinematic hardening, bi-linear s-e curve
- Cold work process modeled as radial displacement (2-D) and release at hole perimeter
- 3-D FEM



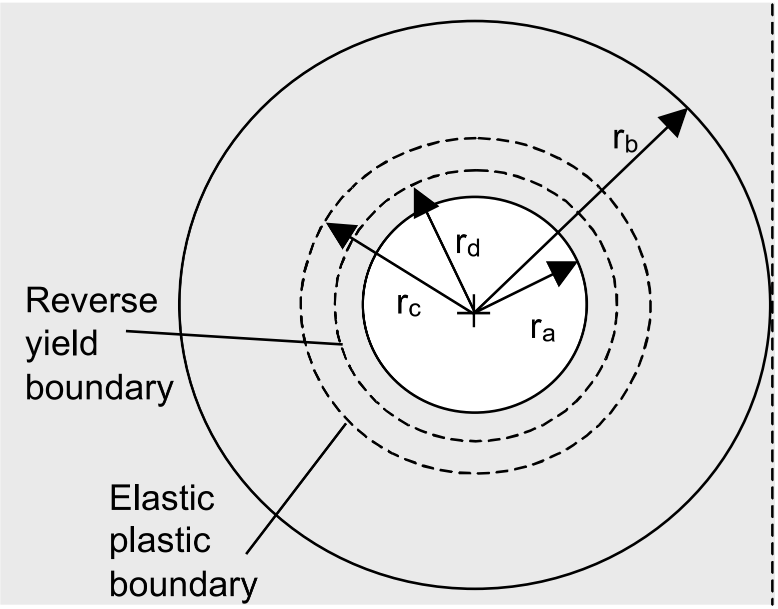
ABAQUS V6.3-2 3D FEA model of dogbone specimen (xy, xz, & yz symmetry



CW HOLE R&D: RESIDUAL STRESS ANALYSIS

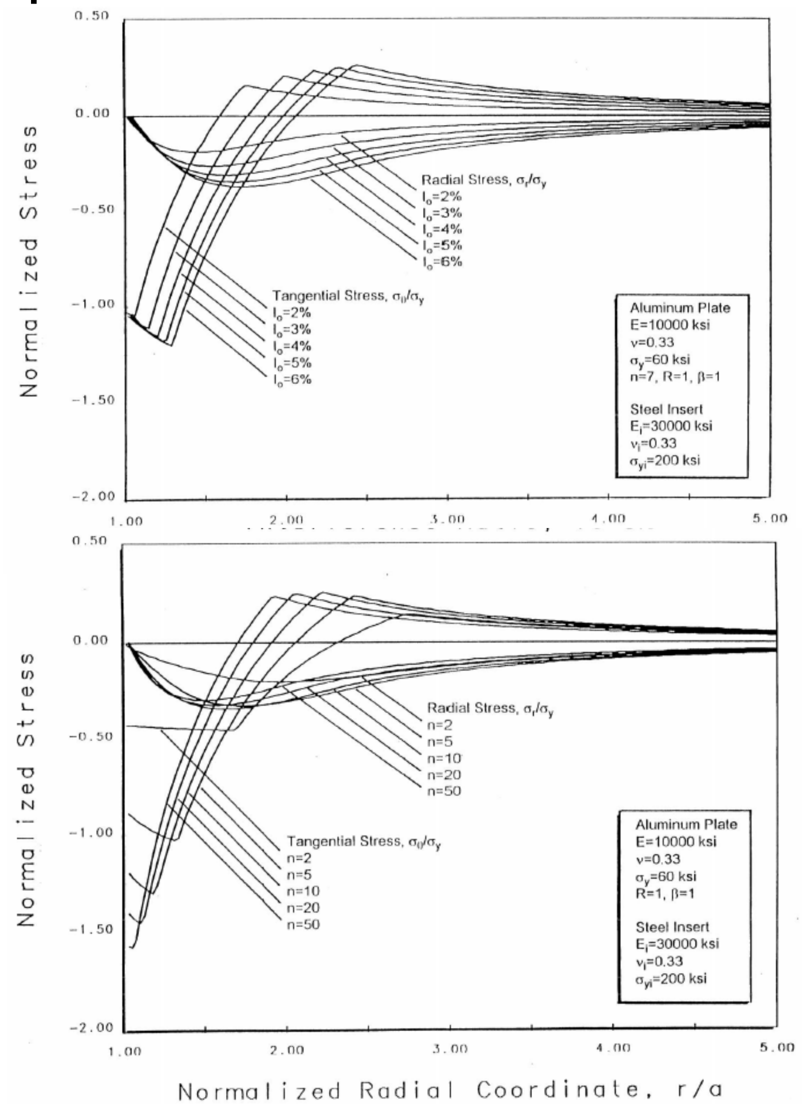
STRESS ANALYSIS OF UNCRACKED HOLES - CLOSED FORM SOLUTIONS:

- Assume axisymmetric thick walled cylinder (for eccentric holes, assume edge distance defines outer radius)
- 2D analysis (applied displacements are radial only)
- J_2 plasticity with kinematic hardening
- Plane stress solution due to G. Wanlin
- Plane strain solution due to G.S. Wang



CW HOLE R&D: RESIDUAL STRESS ANALYSIS

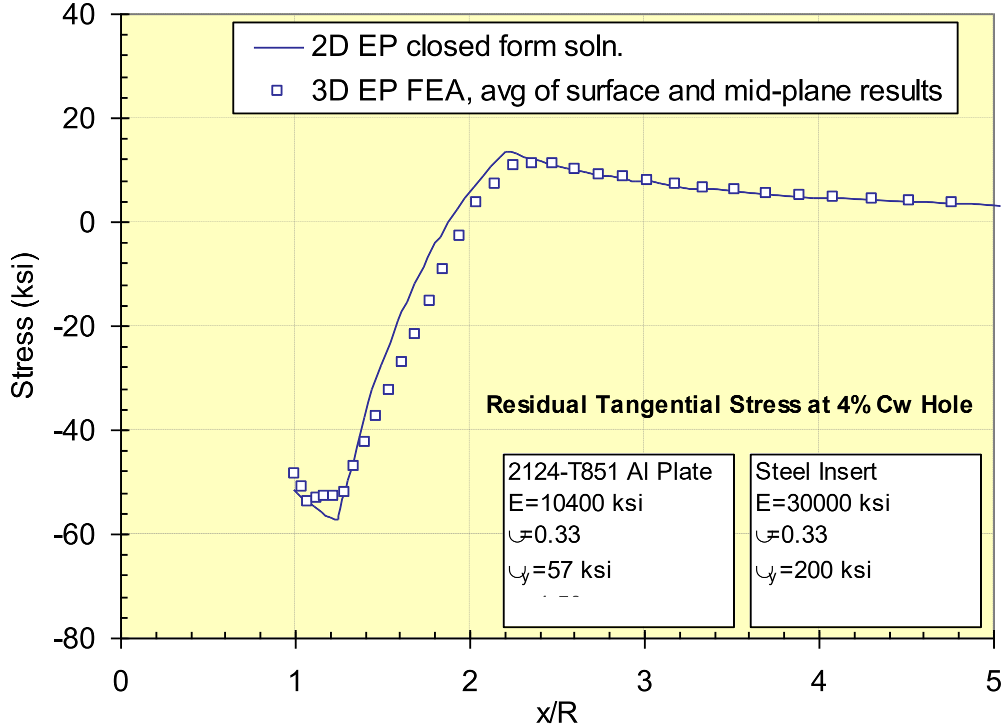
- Closed form solutions allow rapid, parametric evaluations of residual stress dependence on:
  - *Level of cold expansion*
  - *Mandrel and plate elastic constants*
  - *Plate material yield strength*
  - *Plate material strain hardening characteristics and cyclic plasticity behavior (isotropic, kinematic, mixed hardening)*
  - *Hole size and edge distance*
  - *Stress state (plane stress vs. plane strain)*



CW HOLE R&D: RESIDUAL STRESS ANALYSIS

STRESS ANALYSIS OF UNCRACKED HOLES:

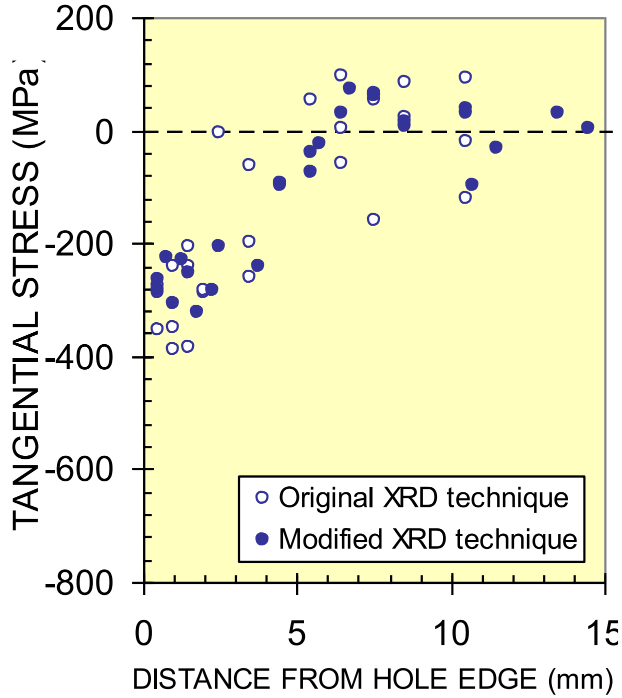
- Closed form solution for initial, cold work induced residual stress field compares favorably with FEA results



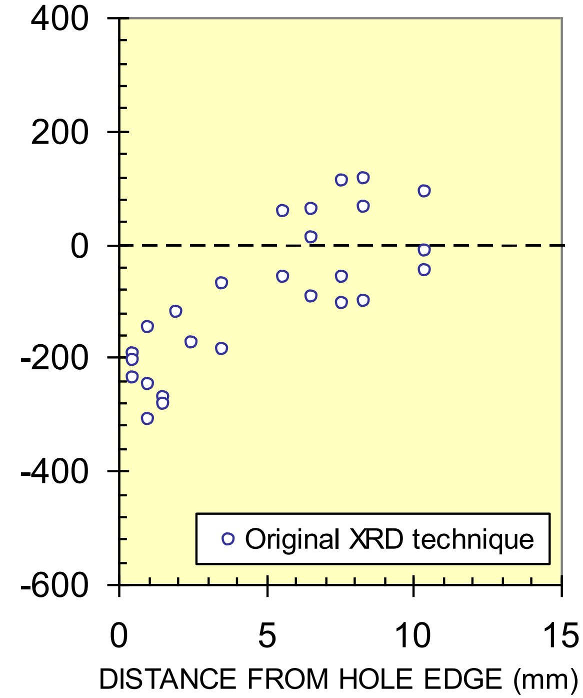
CW HOLE R&D: RESIDUAL STRESS ANALYSIS

EXPERIMENTAL VALIDATION

- X-Ray diffraction not suitable for quantitative analysis for most Al alloys under Cw conditions
  - Large grain size, texturing introduced large scatter in calculated residual stresses
  - Results do provide qualitative information regarding residual stress profiles



centered hole
e/D=5

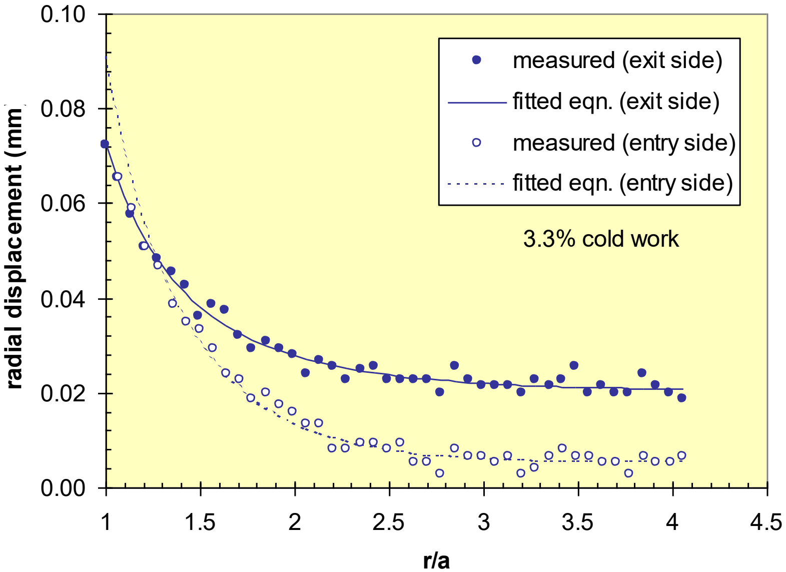


eccentric hole
e/D=2

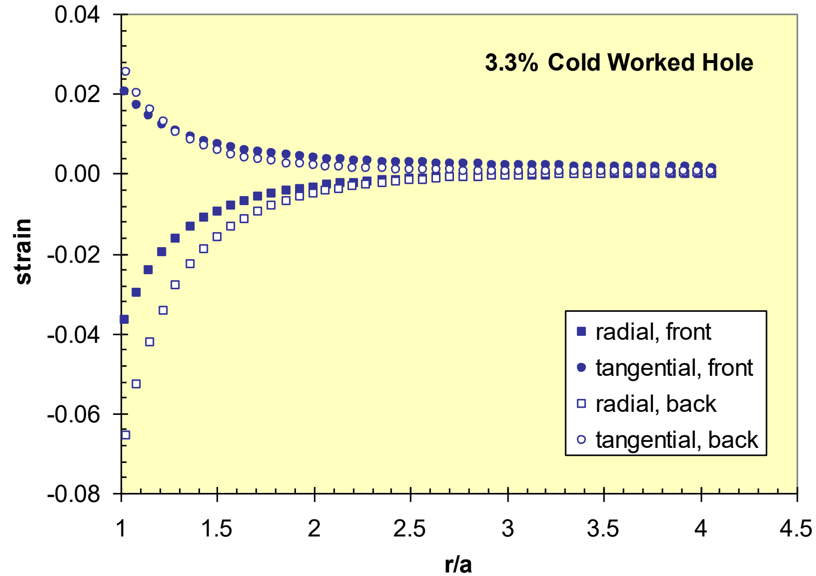
CW HOLE R&D: RESIDUAL STRESS ANALYSIS

EXPERIMENTAL VALIDATION (cont'd)

- Surface Displacement Mapping:
  - Rectangular grid painted on surface prior to Cw, positions of nodes (grid line intersections) measured before and after cold work
  - Strains calculated from displacements
  - Able to discriminate between entry and exit side residual strain profiles



Measured Residual Displacement Profiles



Calculated Residual Strain Profiles

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

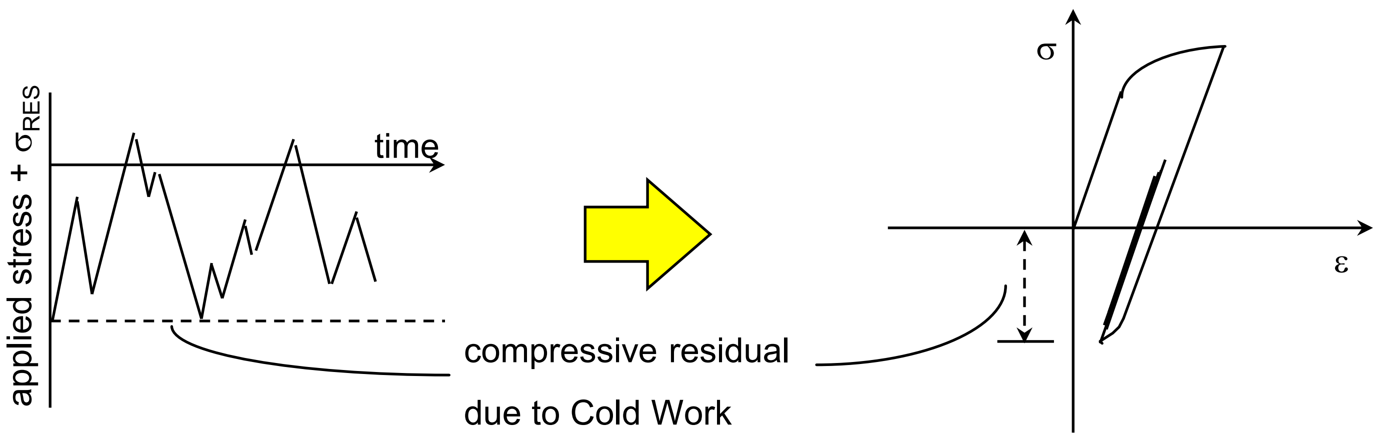
EVOLUTION OF RESIDUAL STRESS AND STRAIN FIELDS DURING FATIGUE LOADING:

- Initial, cold-work-induced residual stress and strain fields can be modified by tensile and compressive overloads experienced during subsequent fatigue loading.
- Tensile overload tends to reinforce compressive residual, beneficial impact on fatigue life
- Compressive overload can cause reverse yielding, reduction or elimination of compressive residual stress. This causes reduction in fatigue life benefit.

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

STRESS ANALYSIS OF UNCRACKED HOLES – NOTCH PLASTICITY:

- Residual stress field evolution under tension dominated loading



Applied stress history

(R_{avg}>0)

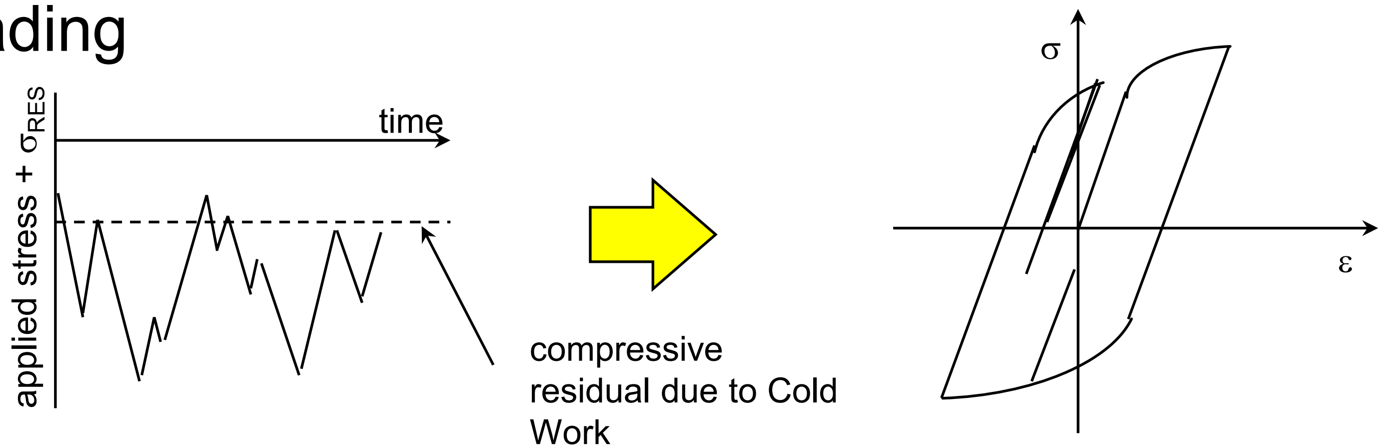
Response stresses and strains:

- Due to compressive residual, response cycles have lower mean than applied cycles
- Absence of compressive applied stresses minimizes chance of reverse yielding

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

STRESS ANALYSIS OF UNCRACKED HOLES – NOTCH PLASTICITY (cont'd):

- Residual stress field evolution under compression dominated loading



Applied stress history

(R_{avg}<0)

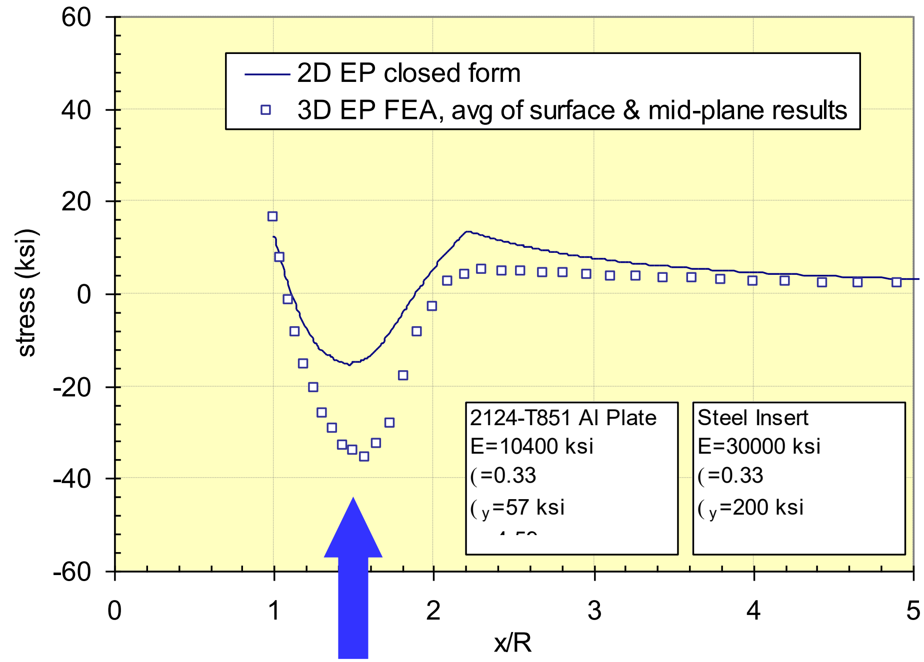
Response stresses and strains:

– Compressive underloads cause reverse yielding and eventual loss of compressive residual stress field

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

RS FIELD EVOLUTION:

- Cyclic, elastic-plastic response in vicinity of cold worked hole estimated using both FEA and notch plasticity algorithm with cold work induced residual stresses and strains as initial condition



After removal of compression overload, much of Cw induced residual stress has been lost

CW HOLE R&D: FCI ANALYSIS

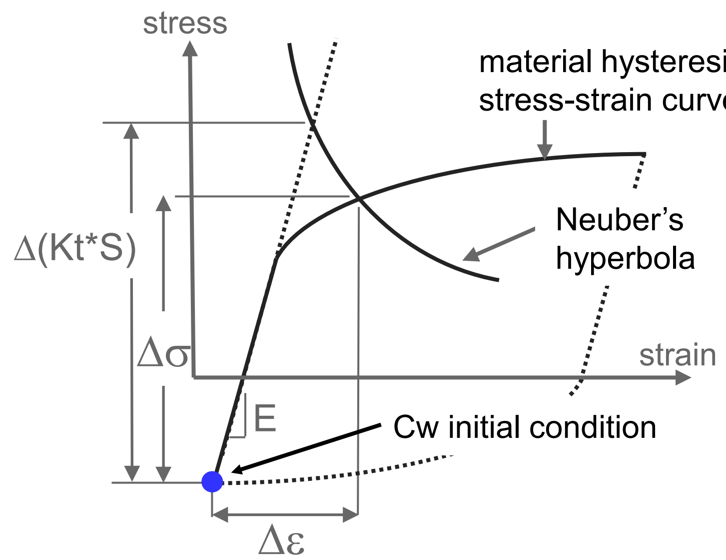
FATIGE CRACK INITIATION ANALYSIS WITH COLD WORK INDUCED RESIDUAL STRESS FIELDS:

- Adaptation of industry standard stress-strain hysteresis loop tracking (LOOPIN)
- Calculate local stress-strain history
  - *Determine stress and strain at hole edge due to Cw*
  - *Hysteresis loop tracking starting from Cw initial condition*
- Calculate incremental damage
  - *Mean stress reduction at analysis point produces increase in crack initiation life*
- Sum damage, compute life

CW HOLE R&D: FCI ANALYSIS

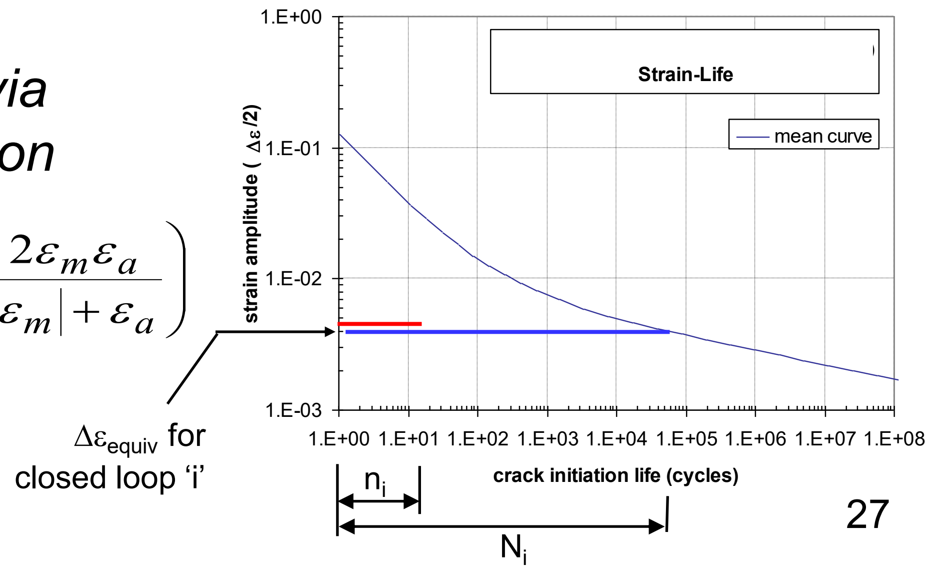
- Local stress-strain history
  - *Initial condition found from stress analysis of Cw process*
  - *Neuber's rule used for subsequent, cyclic stress-strain analysis*

$$\Delta\sigma\Delta\varepsilon = \frac{(SSF_{max}S_{max} - SSF_{min}S_{min})^2}{E}$$



- Damage calculation
  - *Effect of mean stress introduced via equivalent strain amplitude equation*

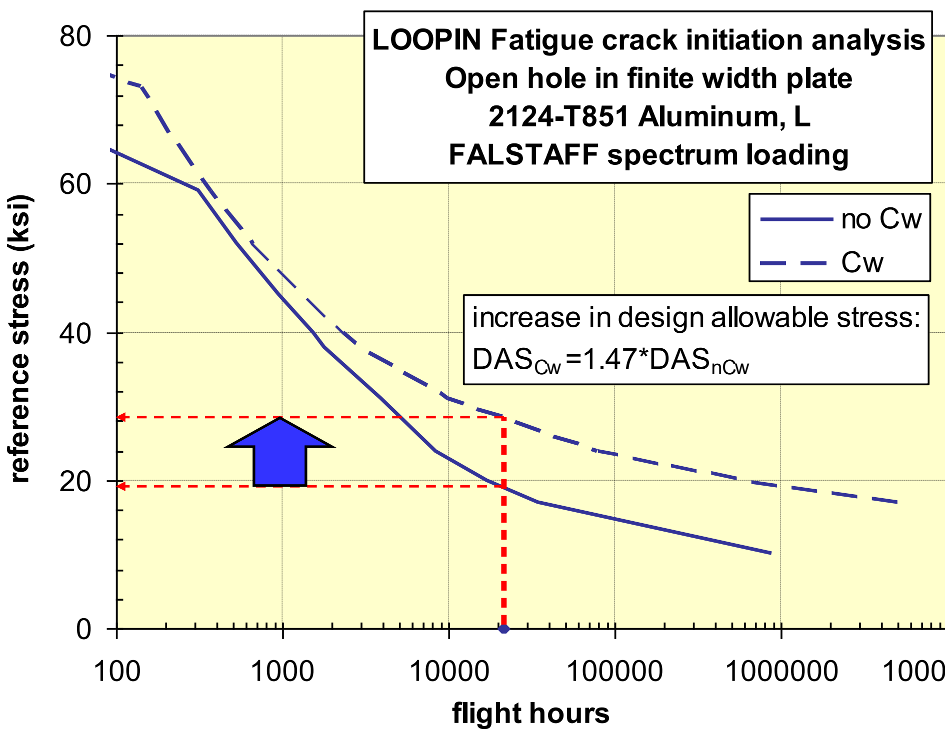
$$\left(\frac{\Delta\varepsilon}{2}\right)_{equiv,R=-1} = \left(\frac{\Delta\varepsilon}{2}\right) + A\left(\frac{2\sigma_m\sigma_a}{|\sigma_m| + \sigma_a}\right)\frac{1}{E} + B\left(\frac{2\varepsilon_m\varepsilon_a}{|\varepsilon_m| + \varepsilon_a}\right)$$

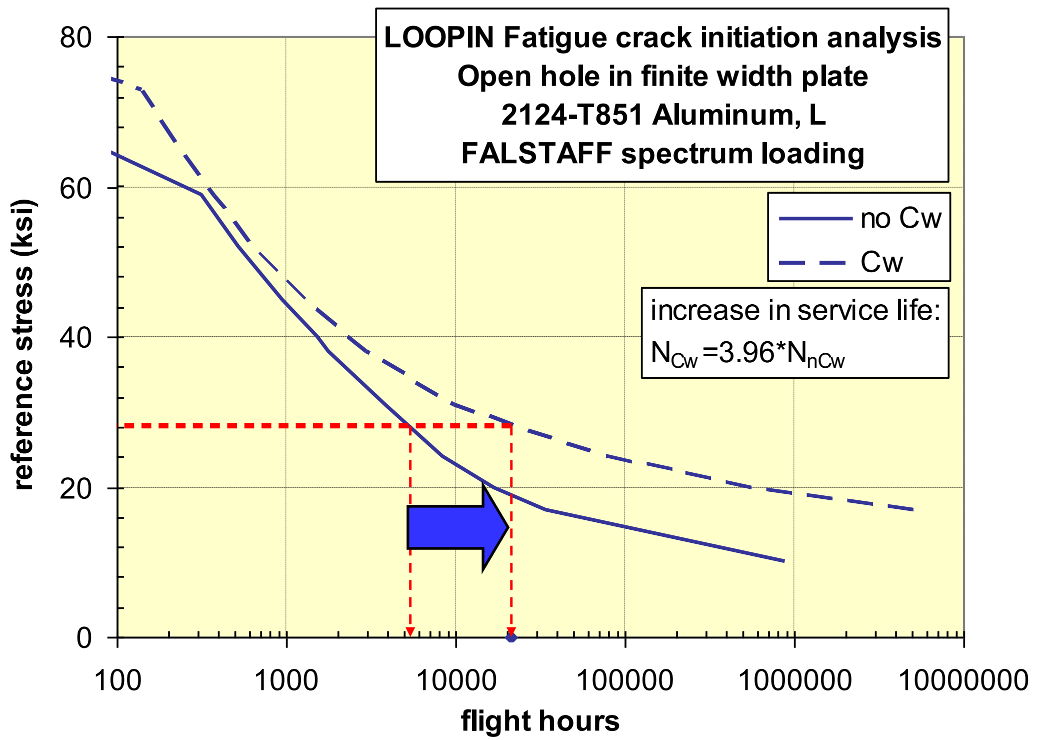


CW HOLE R&D: FCI ANALYSIS

FCI ANALYSIS ALLOWS CALCULATION OF Cw EFFECT:

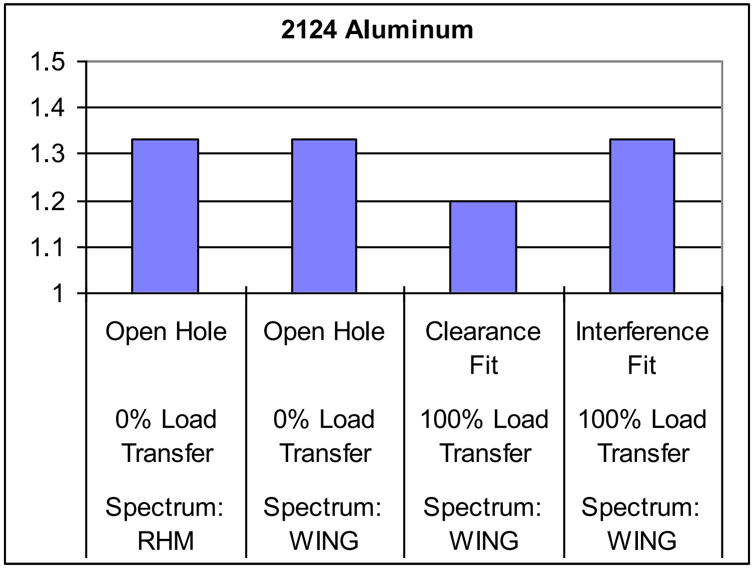
- For tension dominated loading, approx 50% increase in DAS (depending on nominal stress)
- For tension dominated loading, approx 4x increase in life

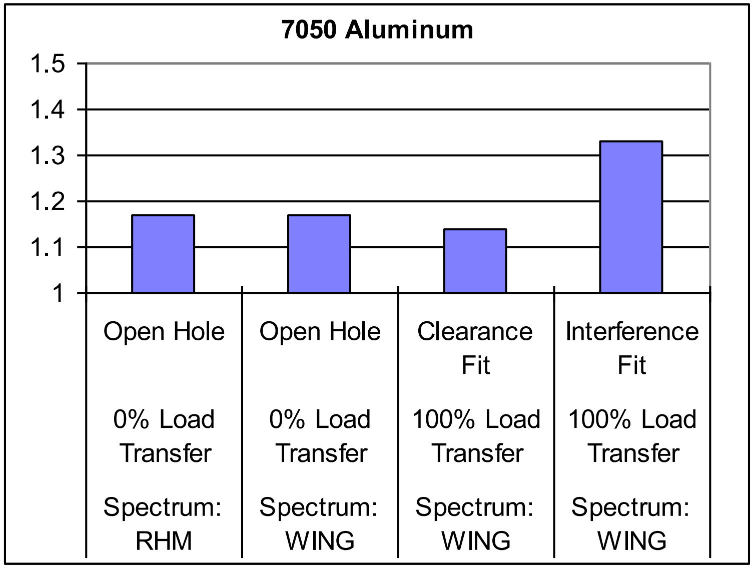




CW HOLE R&D: FCI ANALYSIS

- Test demonstrated life improvement factors for various geometry and spectrum types
  - Minimum 15% improvement in allowable stress obtainable with cold work





CW HOLE R&D: FCG ANALYSIS

FATIGE CRACK GROWTH ANALYSIS WITH COLD WORK INDUCED RESIDUAL STRESS FIELDS :

- Standard LEFM approach
- Calculate stress intensity factors (SIF)
  - *Green's function approach*
  - *Compute applied SIF and residual SIF and sum*
  - *Adjust for load interaction, closure*
- Calculate fatigue crack growth rate
- Increment crack size
- Repeat until K>Kc or c>cmax

CW HOLE R&D: FCG ANALYSIS

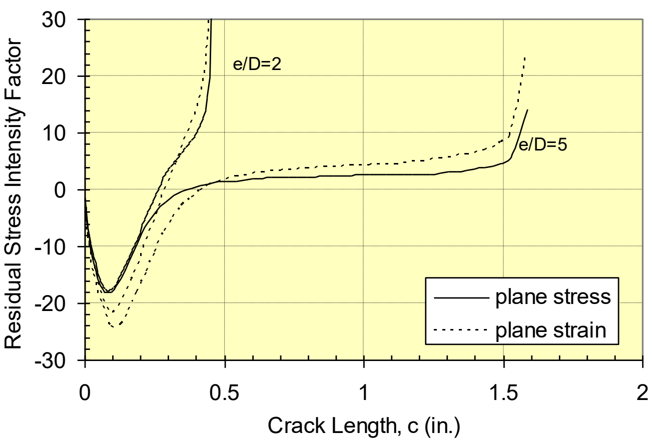
CALCULATION OF SIF – GREEN'S FUNCTION APPROACH:

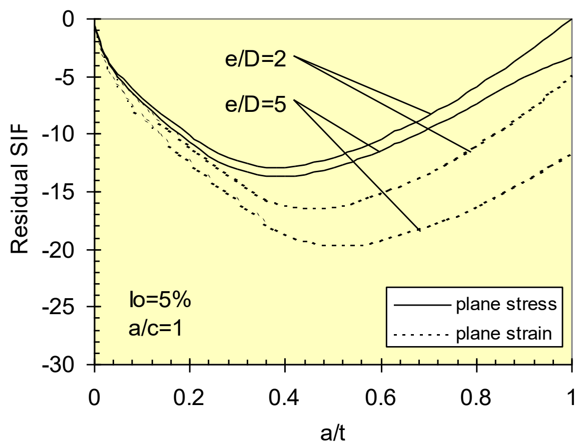
- For 1-D (thu thickness) crack at hole

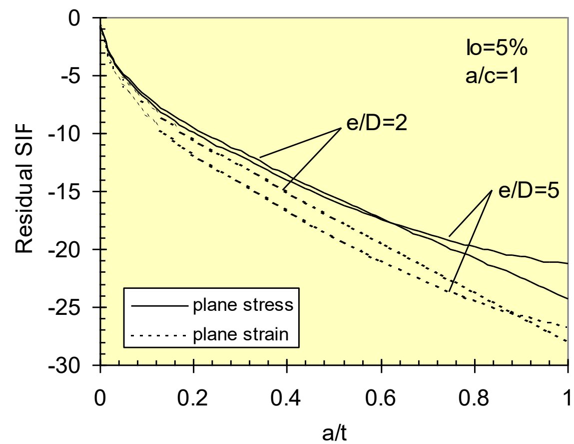
$$K_I = \int_c \sigma_y(x) G(x,c) t\,dx$$

- For 2-D (corner) crack at hole

$$K_I = \frac{1}{(\pi c)^{3/2}} \int_0^{\pi/2} \int_0^{r_f} \sigma(r,\theta) G(R,b,t,a,c) r_L\, dr_L\, d\theta_L$$



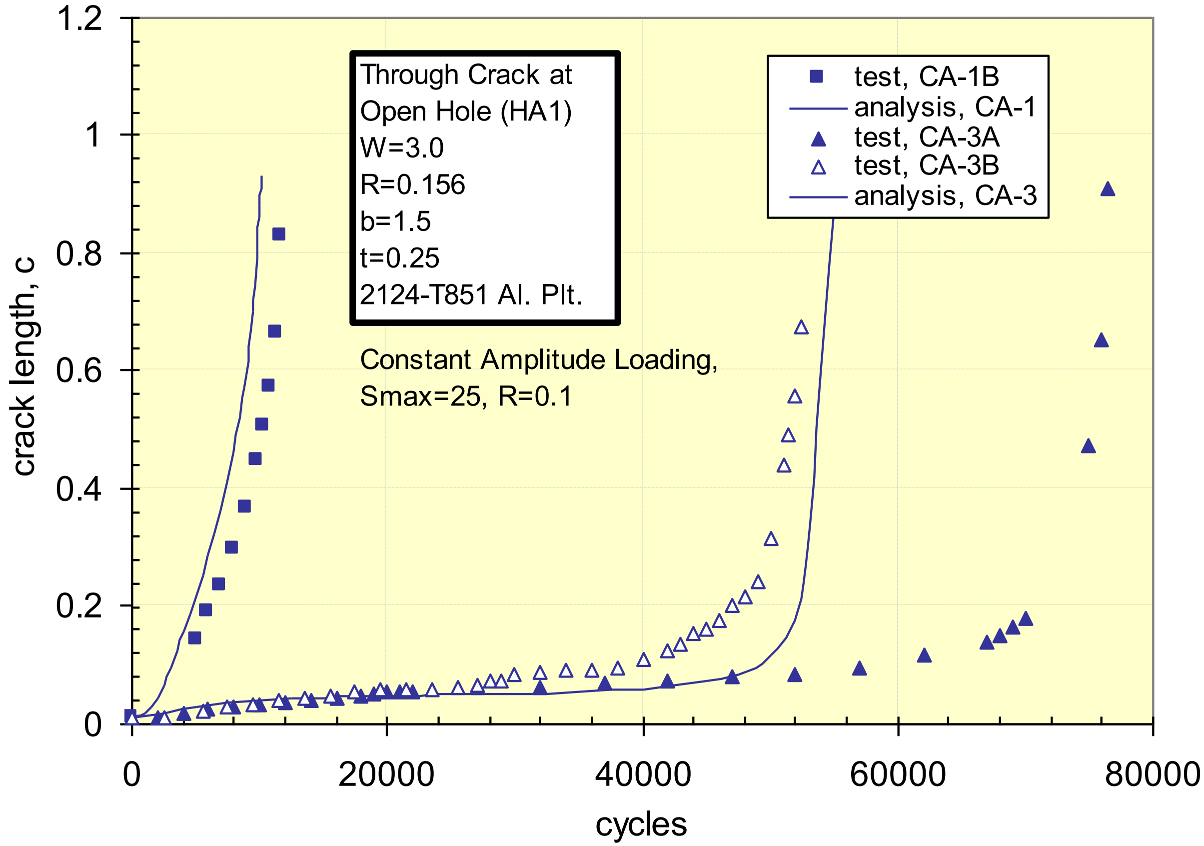




CW HOLE R&D: FCG ANALYSIS

COMPARISON WITH EXPERIMENT:

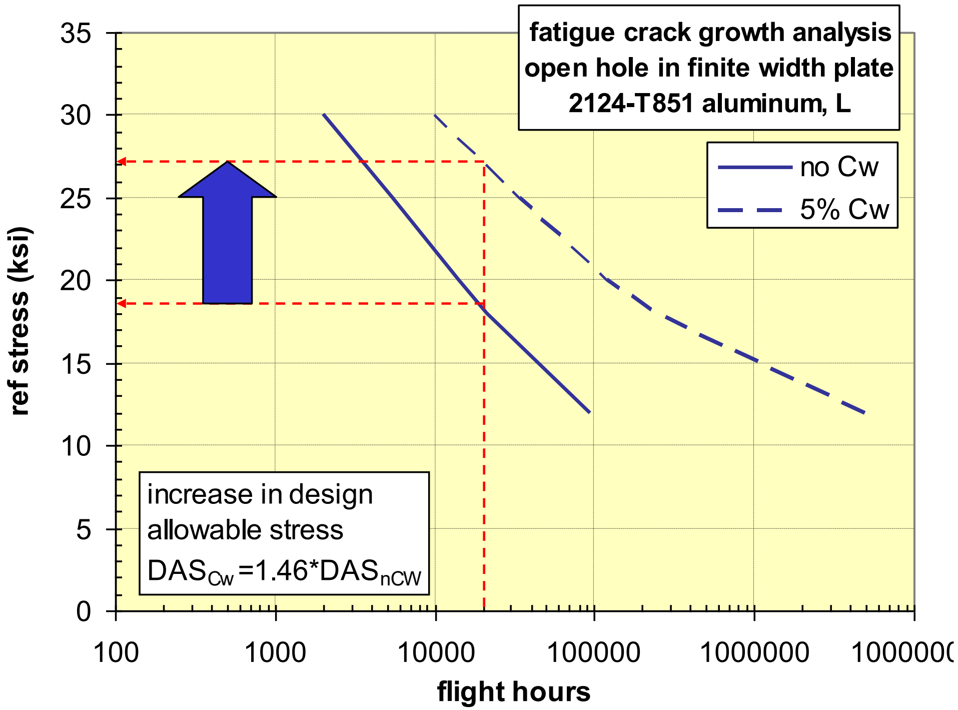
- R=0.1 CA loading after 4% cold expansion – 5x to 7x increase in life

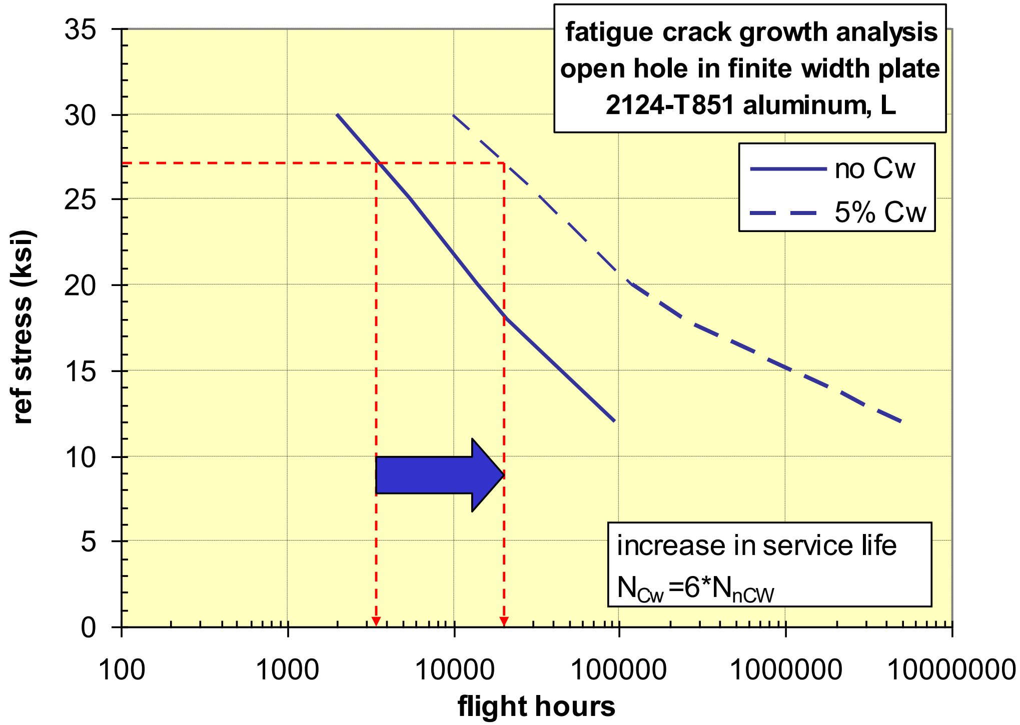


CW HOLE R&D: FCG ANALYSIS

FCG ANALYSIS ALLOWS CALCULATION OF Cw EFFECT:

- For tension dominated loading, approx 50% increase in DAS (depending on nominal stress)
- For tension dominated loading, approx 6x increase in life



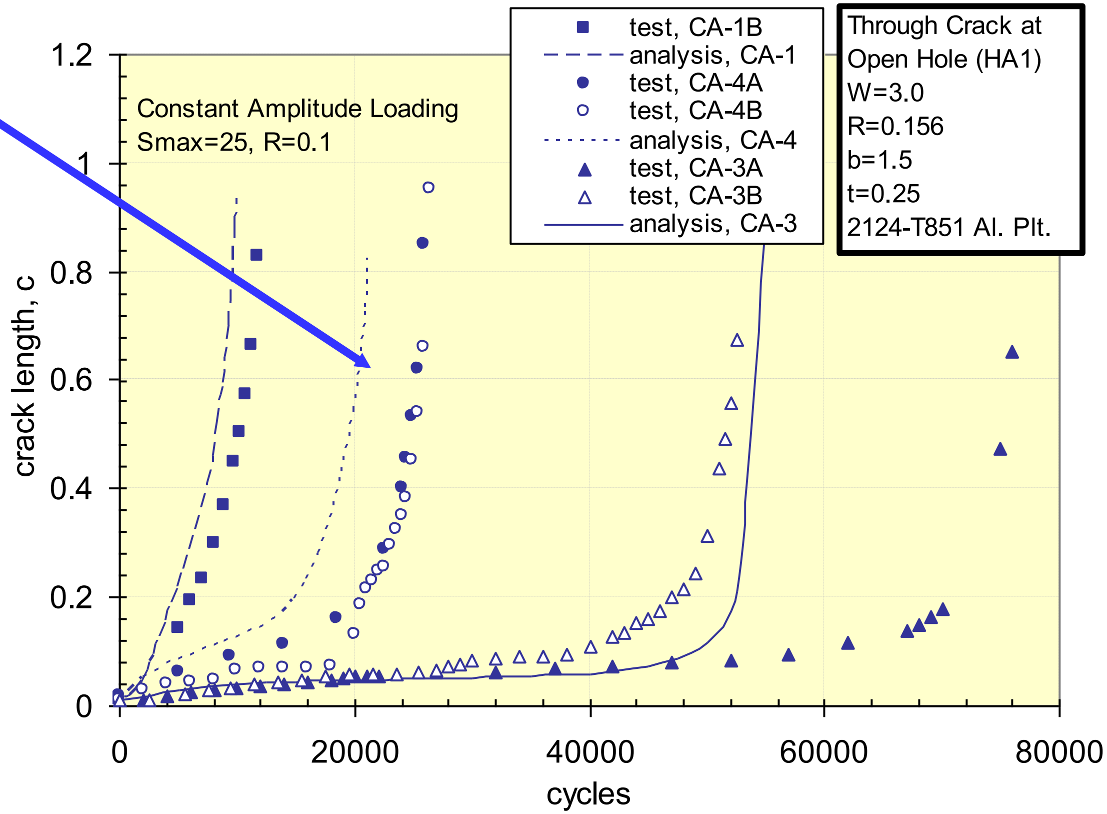


CW HOLE R&D: FCG ANALYSIS

ELASTIC-PLASTIC FCG REQUIRED TO SIMULATE LOSS OF CW RS FIELD DUE TO COMPRESSION OVERLOAD:

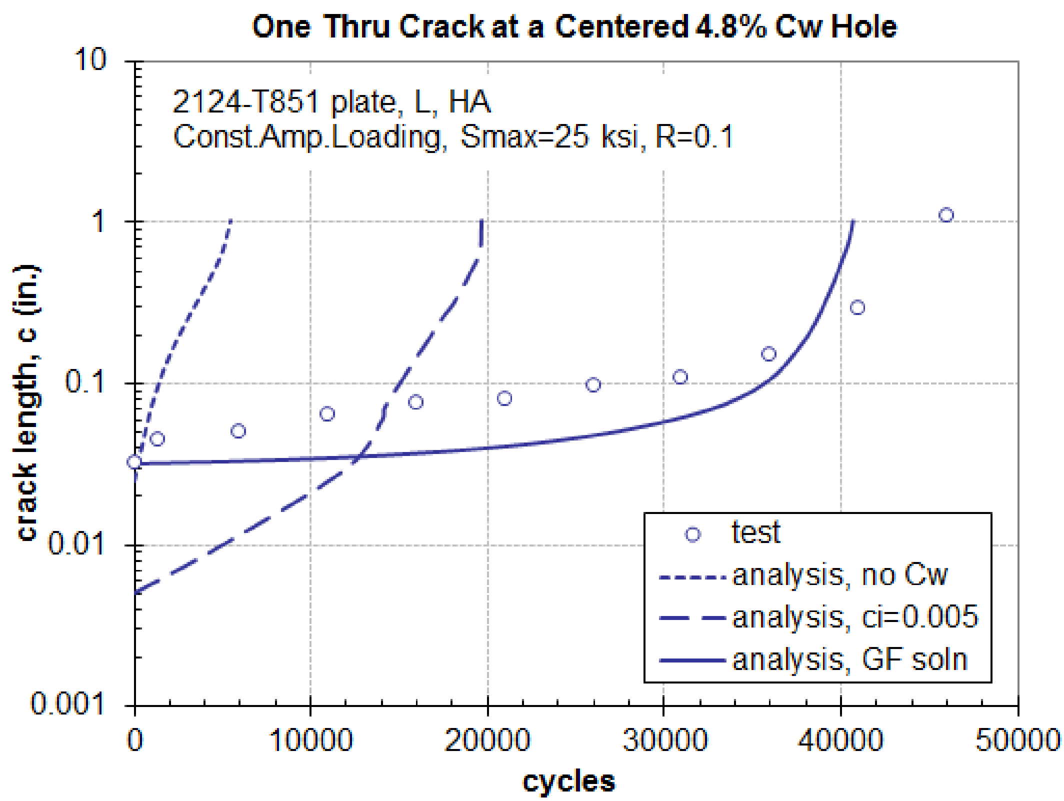
- 4% cold expansion, -25 ksi overload, R=0.1 CA loading – life improvement factor reduced from about 5 to 7 down to about 2

LOSS OF COMPRESSIVE RESIDUAL RESULTS IN REDUCED AMOUNT OF LIFE EXTENSION



CW HOLE R&D: FCG ANALYSIS

- Strong motivation for explicit inclusion of cold work induced residual stress field in FCG analysis
  - *EIFS approach does not address underlying mechanics of the problem*
  - *EIFS approach can be conservative (compared to test) in some cases*
  - *EIFS approach does not produce correct crack growth curve shape, which can be significant for IAT / maintenance planning*



Engineered Residual Stress in Military Aircraft Structure

- **STRUCTURES POLICY**
  - *Shot Peening*
  - *Laser Peening*
  - *Hole Cold-working*
- **Cold-worked hole r&d**
  - *Residual Stress Analysis*
  - *Fatigue Crack Initiation Analysis*
  - *Fatigue Crack Growth Analysis*
- **CONCLUSIONS**

CONCLUSIONS

- Very heavy reliance on engineered residual stresses for mitigation of life short-falls, and for service life extensions on almost all products
- Restrictions are imposed for large compression loads, short eoD etc.
- Extensive testing required to determine / validate design factors / life extension available
- Current standard analysis procedures (for cold worked holes) are based on reduction factors (FCI) or EIFS (FCG) – these methods do not address mechanics of Cw process and may not allow full utilization of Cw benefit

CONCLUSIONS

- Methods that do address appropriate mechanics are available and may improve use / optimization of Cw in design and service life extension
  - *Closed form solutions for residual stress / strain fields due to cold expansion, explicit dependence on most material, geometric and Cw process parameters*
  - *Notch plasticity algorithm gives estimated response stress distribution on critical plane*
  - *Green's function approach gives SIF based on response stress distribution*
  - *Model captures effects of both initial Cw induced residual stresses and subsequent modification of residual profiles due to notch plasticity*
  - *Effects of crack closure must be studied further, current treatment is inadequate*