HILL ENGINEERING

Predict. Test. Perform.

What's in a Filled Hole?

Joshua Hodges, Dallen Andrew

Hill Engineering

Dr. Tom Mills

APES

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analytical processes / engineered solutions

Agenda

- ❑ Summary of test data for filled vs unfilled holes
- ❑ How does AFGROW deal with a filled hole?
- ❑ What does FEA tell us about a filled hole?
- ❑ Continuing damage in a filled hole
- ❑ Secondary cracks and continuing damage
- ❑ How does interference effect hole fill?
- ❑ Residual stress in open vs filled holes
- ❑ How do we go forward with analytical comparisons?

Summary of Test Data

- **Test Program 1: Interference Fit Fastener Testing (Steel)**
  - Purpose was to evaluate reduced IFS for DTA for interference fit fasteners
  - Two geometries (e/D = 2.0, e/D = 1.5)
  - Three loading conditions (2 spectra & 1 constant amplitude)
  - Four hole conditions (open, neat fit, 0.002”, and 0.004” interference)

Loading Type	Geometry Configuration	Mean Life, Neat Fit to Open (cycles or hours)	Improvement Factor
Constant Amplitude	#1 (e/D = 2.0)	488,163 / 302,484	1.6
	#2 (e/D =1.5)	1,130,881 / 276,304	4.1
Spectrum 1	#1 (e/D = 2.0)	7,749 / 3,516	2.2
	#2 (e/D =1.5)	8,881 / 3,978	2.2
Spectrum 2	#1 (e/D = 2.0)	37,331 / 16,479	2.3
	#2 (e/D =1.5)	40,211 / 15,115	2.7

[SwRI Project 18-20411 FSIS Testing]

Summary of Test Data

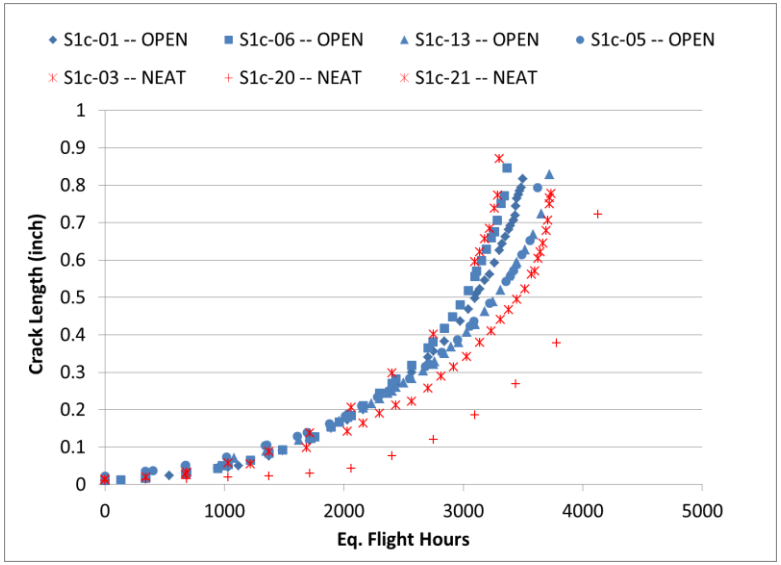
- **Test Program 1: Interference Fit Fastener Testing (Steel)**
  - AFGROW used to correlate with open hole test from previous slide for Spectrum #1, e/D = 2.0

Source	Mean Life, Neat Fit to Open (hours)	Improvement Factor
Test Data	7,749 / 3,516	2.2
AFGROW *Filled to Open*	3,303 / 2,991	1.1
AFGROW *Filled to Open with Beta Correction*	7,630 / 2,991	2.6

Summary of Test Data

- **Test Program 2: Interference Fit Fastener Testing (Aluminum)**
  - Purpose was to evaluate reduced IFS for DTA for interference fit fasteners
  - One geometry
  - One loading condition (1 spectrum)
  - Three hole conditions (open, neat fit, 0.0025” interference)

**Note: The neat fit coupons were later found to have 0.02% to 0.3 % clearance which would impact results stated here*



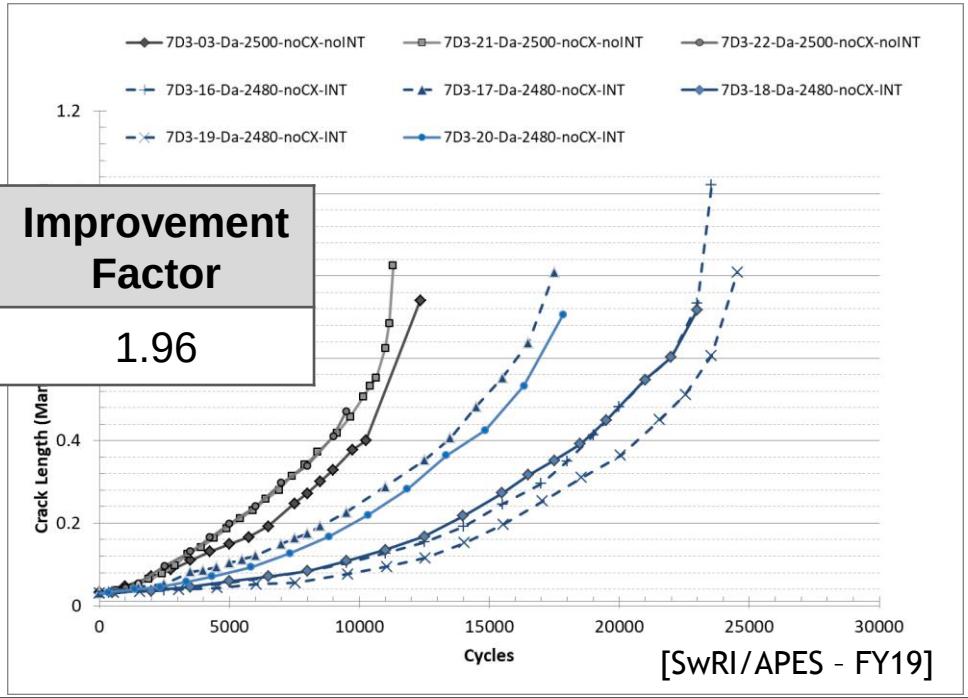
Loading Type	Mean Life, Neat Fit to Open (hours)	Improvement Factor
Spectrum 1	3,724 / 3,563	1.05

[SwRI-18-22334-006]

Summary of Test Data

- **Test Program 3: Interference Fit Fastener Testing (Aluminum)**
  - Purpose was to evaluate modeling techniques for interference effects
  - One geometry
  - One loading condition (1 constant amplitude)
  - Two hole conditions in non-Cx baseline (open, 0.4% interference)

Loading Type	Mean Life, Filled to Open (cycles)	Improvement Factor
CA	21,645 / 11,048	1.96



[SwRI/APES - FY19]

Summary of Test Data

- **Test Data Conclusions**
  - Test Programs 1 & 2
    - Neat fit and Interference level test specimens difficult to manufacture
    - Interference effectively shut down crack growth completely
    - Interference tests that progressed to fracture had various factors at play
      - Test Program 1: initial cracks were quite large (through cracks in many cases)
      - Test Program 2: initial batch had holes improperly sized (either clearance or interference that was about half of target)
  - Test Program 3*
    - Residual stress redistribution and life predictions at interference fastener holes
    - 24 specimens for fatigue test and residual stress measurements
      - Open Hole, neat fit, interference fit, CX and non-CX
    - Observations:
      - Interference pin at non-CX hole doubles life over non-CX open hole
      - Interference pin at CX hole outperforms open CX hole by factor of two, but there is scatter and even some overlap.

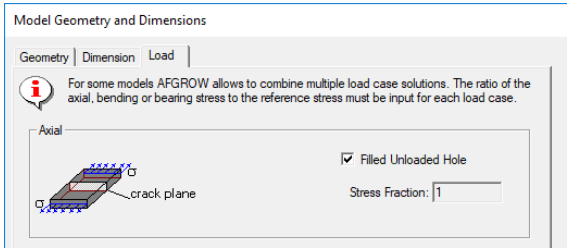
***Results and experimental design discussed at A-10 summit, Dr. Tom Mills, 7 May 2019**

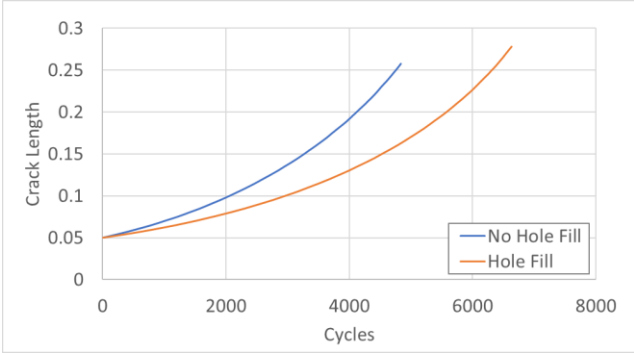
AFGROW & Filled Holes

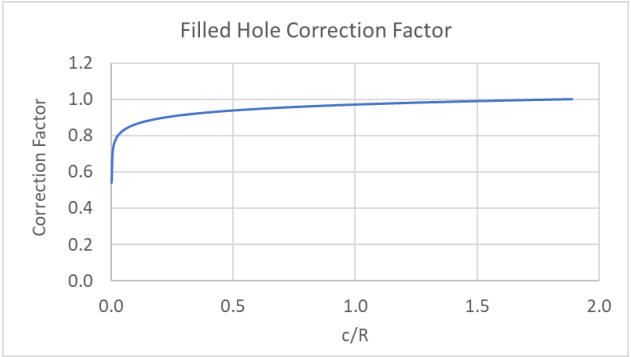
- AFGROW utilizes equation from Lincoln* to adjust Beta factor
- No hole fill capability with advanced model
- AFGROW remains linear with negative loads
- Corrections for 'c' and 'a' utilize the same factor:

$$Correction(c,R) = 0.969831 + 0.10763\frac{ln\left(\frac{c}{R} + 0.01\right)}{ln\,10}$$

where c = surface crack length and R= radius
if Correction(c,R) > 1.0 then Correction(c,R) = 1.0



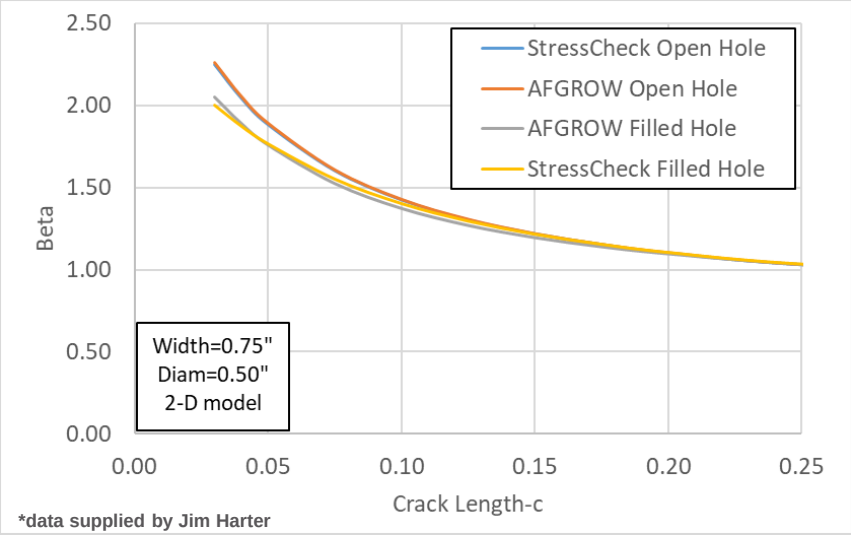




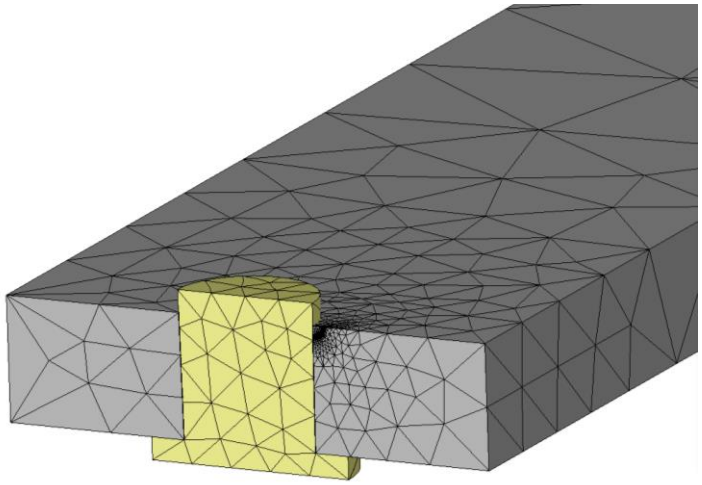
*Personal Communication, Dr. Lincoln and James Harter

FEA & Filled Holes

- **StressCheck can model hole fill with:**
  - Compression springs
  - Non-linear multibody contact
  - ~~Pressure distribution~~
- **How do they compare to AFGROW?**

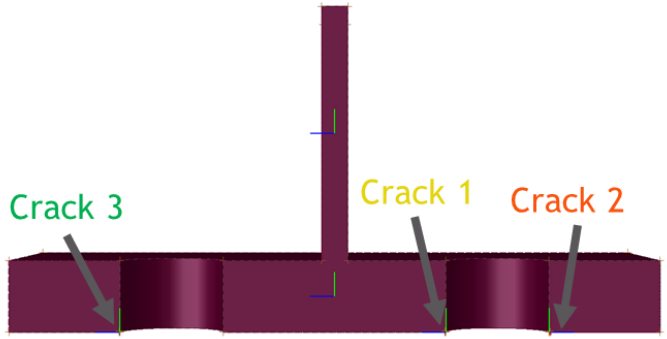


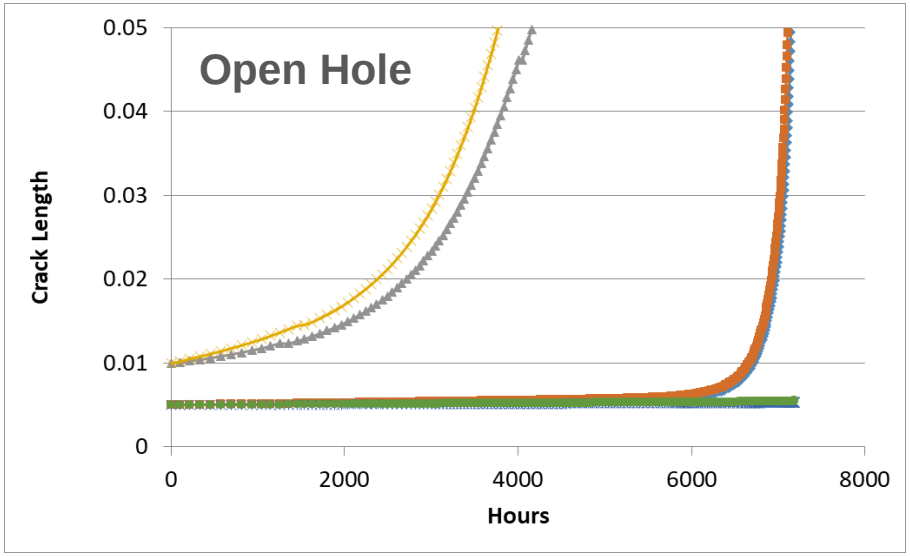
*data supplied by Jim Harter

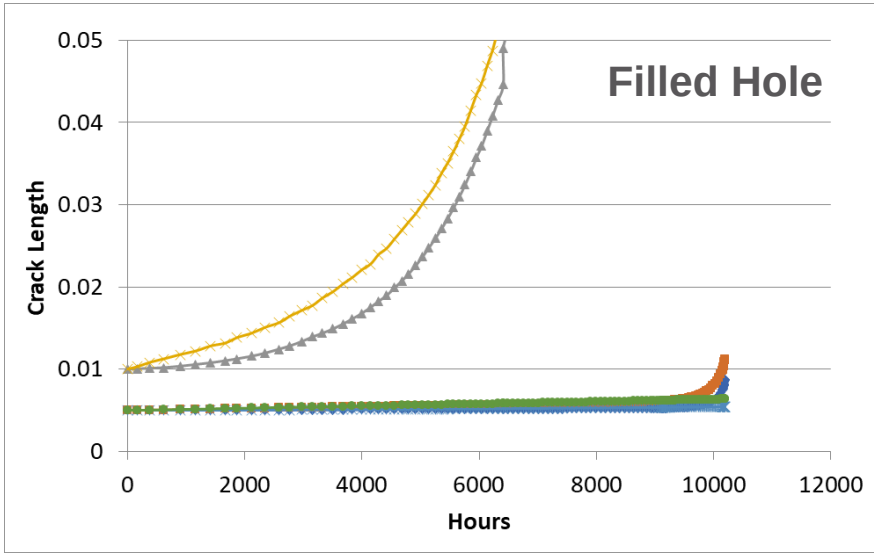


Continuing Damage in Filled Holes

- Project looking at multi-crack growth with continuing damage
- Open hole: Primary crack interacts with the secondary crack
- Filled hole: Secondary crack is not affected by primary crack







Shake Down of Residual Stress in an Open Hole

- What does cycling an open hole CX coupon do?

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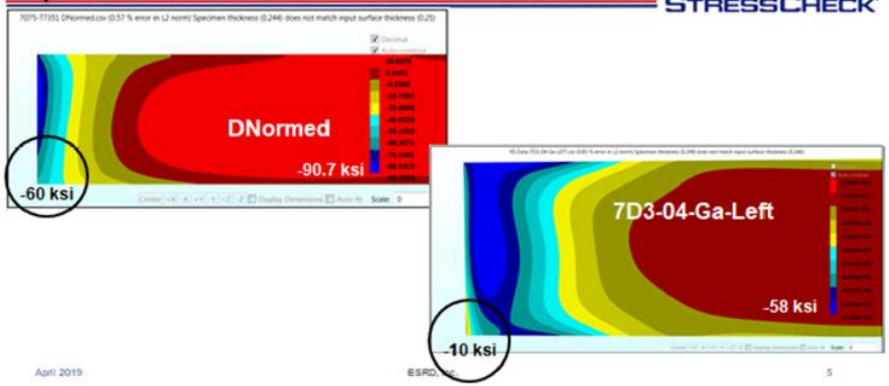
Residual Stress Comparison

- Original stresses ("DNormed" -- from a residual stress database) were deeply compressive.
- The new pre-cycled specimens have vastly different residual stresses

Life Predictions

Input RS DNormed & 7D3-04-Ga-Left

STRESSCHECK



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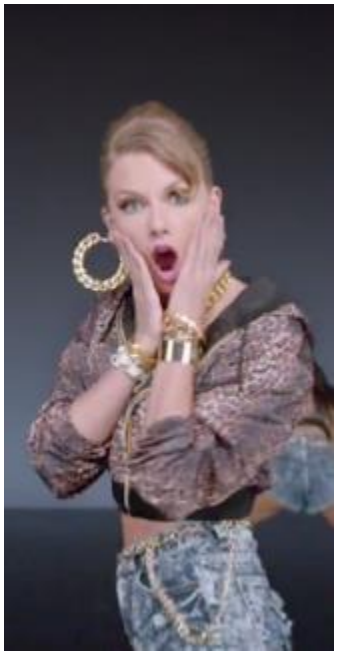
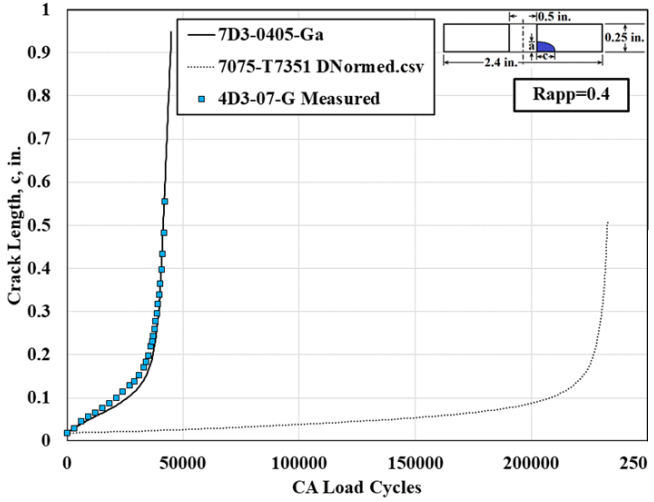
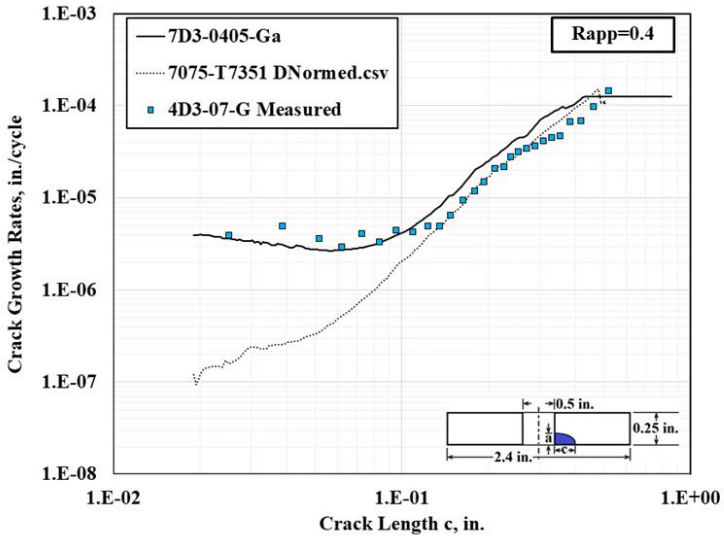


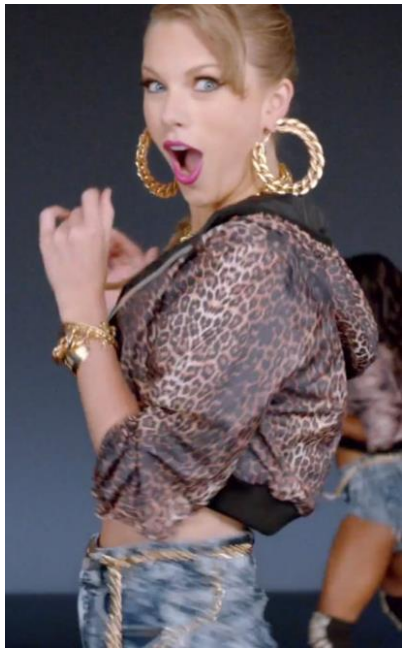
Swift, Taylor. (2014), "Shake It Off"

Shake Down of Residual Stress in an Open Hole

- What effect does this have on fatigue life and crack shape?





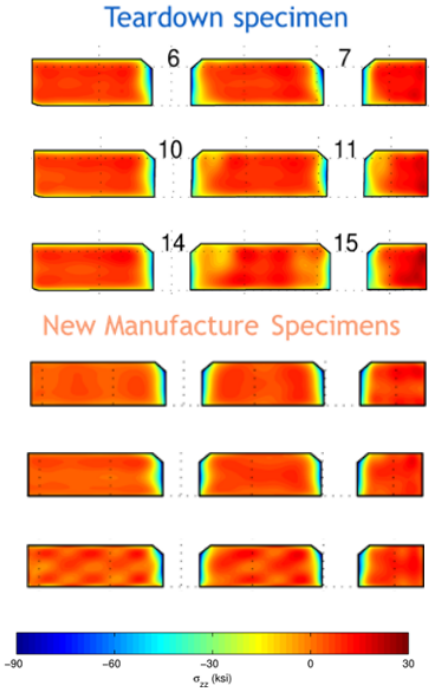


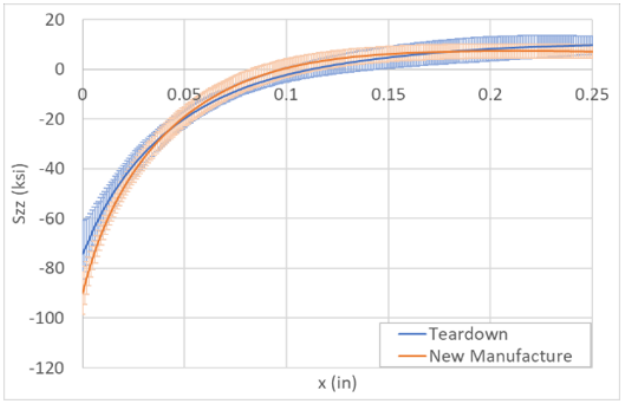
Swift, Taylor. (2014), "Shake It Off"

Residual Stress in Filled Holes from Legacy A/C

- What has a decade of service life done to the RS of a filled hole?

Level I Analysis - Comparison Results (A-10) Section R3.1P





Sample ID	Midthickness 0.125*rad (ksi)	Midthickness 0.25*rad (ksi)	Midthickness 0.5*rad (ksi)	Midthickness 0.75*rad (ksi)	Depth at crossover (midthickness) (in)	Point Value of Entrance (ksi)	Avg RS in 0.05" Radius Entrance (ksi)	Point Value CSK Knee (ksi)	Avg RS in 0.05" Radius CSK knee (ksi)
Mean	-47.15	-31.04	-12.29	-2.60	0.13	-51.30	-34.67	-77.92	-44.59
Stdev	5.17	4.10	2.71	2.99	0.04	21.61	6.68	16.67	10.37
Mean	-52.82	-32.95	-10.82	-0.19	0.10	-49.72	-31.57	-98.82	-55.33
Stdev	3.68	3.91	3.91	3.65	0.02	21.46	3.05	14.72	2.64
Residuals (Td-NM)	5.68	1.91	-1.46	-2.42	0.03	-1.58	-3.09	20.90	10.74
P Value	0.00	0.13	0.15	0.05	0.02	0.43	0.08	0.00	0.00
Significant	Yes	No	No	Yes	Yes	No	No	Yes	Yes

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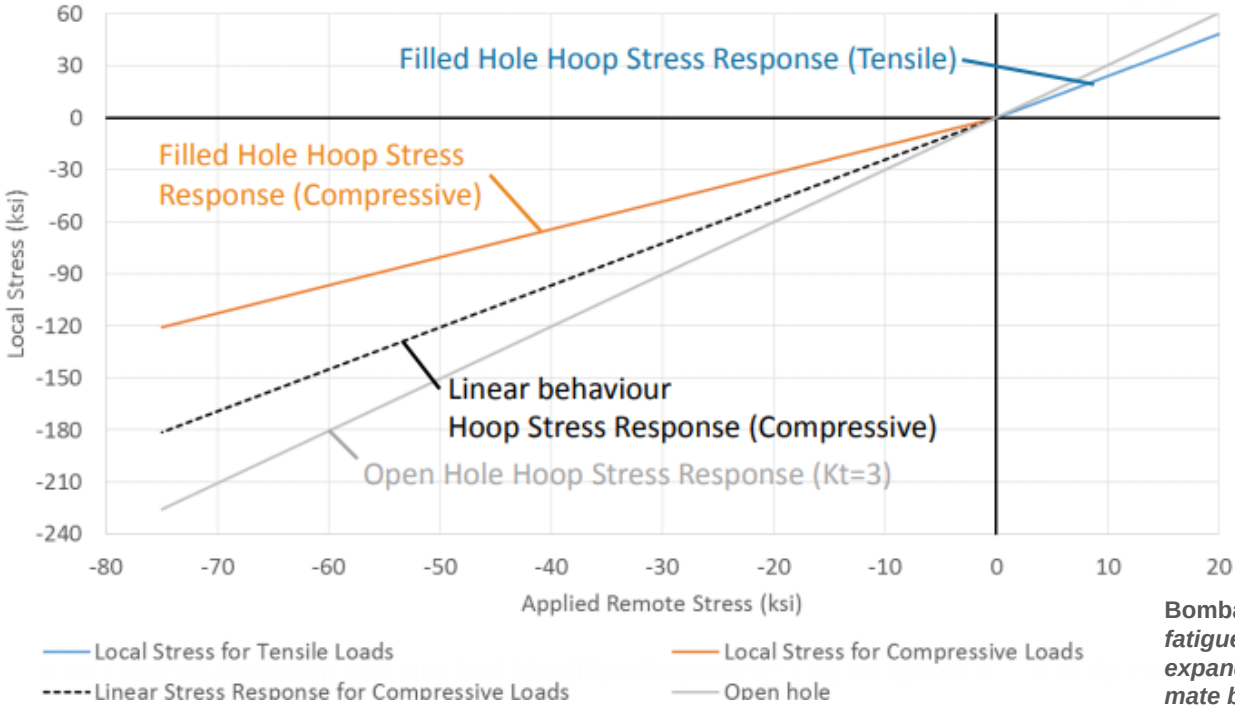
Swift, Taylor. (2014), "Shake It Off"

Advanced Fatigue Analysis and Filled Holes

- Current methodology solves for one load case and assumes stress intensities are linear
- Additionally, when interference is applied K's at zero applied remote stress are not positive, not taken into account in BAMF/CPT



Bombardier, Yan, *Prediction of fatigue crack growth at cold expanded fastener holes with force mate bushings,* AFGROW 2018 Users Workshop

Future of BAMF/CPAT Filled Holes

- **BAMF and AFGROW are currently developing a way to deal with this issue**
  - Work is being accomplished to pass a table of K's and stresses that will allow interpolation to occur between those points
  - With enough solutions, hole propping can be modeled correctly in a BAMF analysis
- **StressCheck (CPAT) and APES have been working on methods to handle interference fit**
  - Beta correction tables in AFGROW can be used to capture hole propping from hole fill
  - Does not capture "R shift" associated with interference at min load
  - CPAT interactive K-solver being used, but it is time consuming
  - Attempts to superimpose these models with residual stress (CX holes) has encountered difficulty
- **Utilizing Contact/Non-linear solutions and solving multiple load cases is time intensive**

Moving Forward

- Determining a way to handle neat fit and interference fit in an AFGROW type solution would be ideal
- Additional validation work of AFGROW / Lincoln neat fit correction
- What is the best way to approach this?