

Quantifying sources of experimental and numerical variability using 3D FE representations in fatigue crack growth modeling validation process

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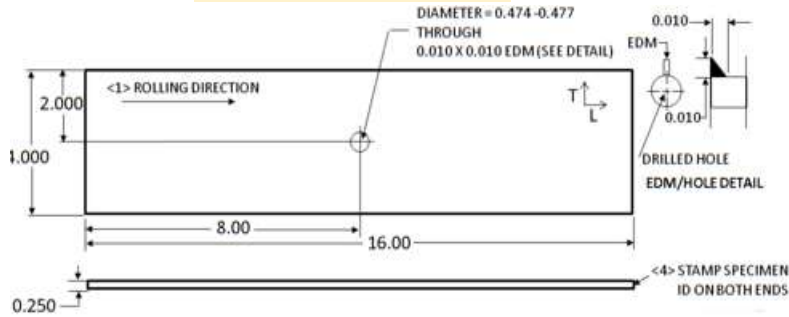
- Fatigue crack growth round robin challenges can provide very useful V&V benchmarks for the damage tolerance design community.
- Modeling solutions from different submissions show large scatter. Assumptions associated with each modeling technique are usually not addressed (i.e. impact of elliptical crack shape constraint in the remaining useful life solution).
- Sources of uncertainty (experimental or modeling process related) are many times neglected leaving unanswered questions related to accuracy of the numerical solutions presented in the Round Robin reports.

- Experimental datasets from two round robin challenges are used in this study:
 - AFGROW Round Robin
 - Reference: Tom Mills, Scott Fawaz, “AFGROW Round Robin: Corner Crack at Center and Offset Hole”, AFGROW User Workshop, 2017
 - Interference Fit Round Robin
 - Reference: Jake Warner, “Interference Fit Fastener Analytical Round Robin”, AFGROW User Workshop, 2020.
- Experimental dataset: three center hole specimens from AFGROW round robin
 - Nominal configuration solution using 3D modeling techniques (SimModeler Crack)
 - Sources of uncertainty in the numerical solution:
 - Fatigue Crack Growth Rate Data
 - Initial crack shape
- Experimental dataset: five interference fit center hole specimens
 - Nominal configuration solution using 3D modeling techniques (SimModeler Crack)
 - Sources of uncertainty in the numerical solution:
 - Interference fit variation along the bore
- Conclusions

AFGROW - Corner Crack - Round Robin Challenge

Problem Description

Specimen Geometry



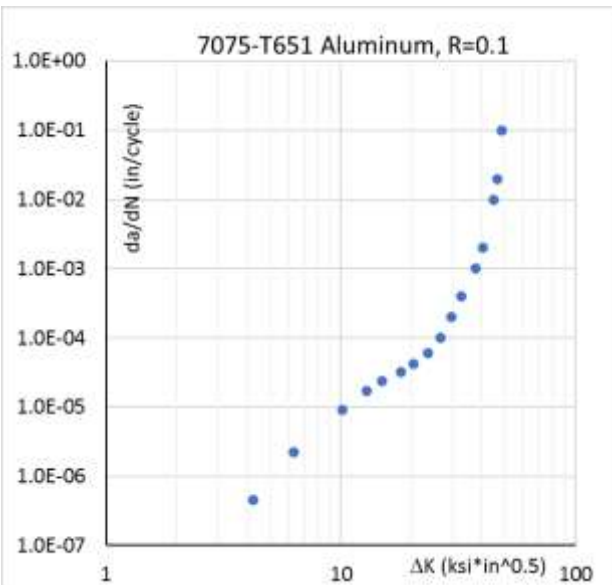
Material Properties

| Property | Value |
|---------------|-----------------|
| Material | 7075-T651 plate |
| Modulus (ksi) | 10400 |
| Poisson | 0.33 |

AFGROW Loading Mission

| | | |
|-----|------|------|
| 1 | 40 | |
| 1 | 0.1 | 2500 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 2500 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |
| 1 | 0.1 | 10 |
| 0.8 | 0.08 | 100 |

Fatigue Crack Growth Rate: Table Look-up



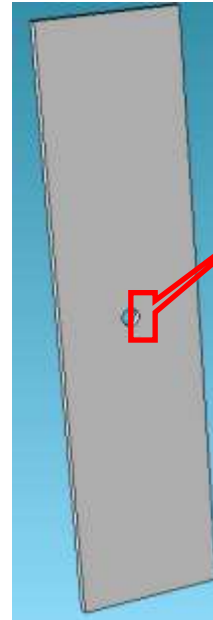
| da/dN | ΔK |
|----------|--------|
| 4.50E-07 | 4.236 |
| 2.20E-06 | 6.281 |
| 9.00E-06 | 10.148 |
| 1.70E-05 | 12.900 |
| 2.40E-05 | 15.000 |
| 3.25E-05 | 18.000 |
| 4.25E-05 | 20.500 |
| 6.00E-05 | 23.500 |
| 1.00E-04 | 26.600 |
| 2.00E-04 | 29.500 |
| 4.00E-04 | 32.750 |
| 1.00E-03 | 37.500 |
| 2.00E-03 | 40.250 |
| 1.00E-02 | 45.000 |
| 2.00E-02 | 46.500 |
| 1.00E-01 | 48.500 |

Reference

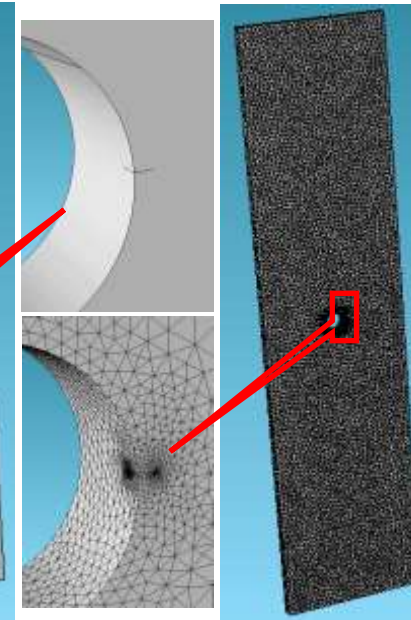
Tom Mills, Scott Fawaz, "AFGROW Round Robin: Corner Crack at Center and Offset Hole", AFGROW User Workshop, 2017

3D Model resembles experimental conditions

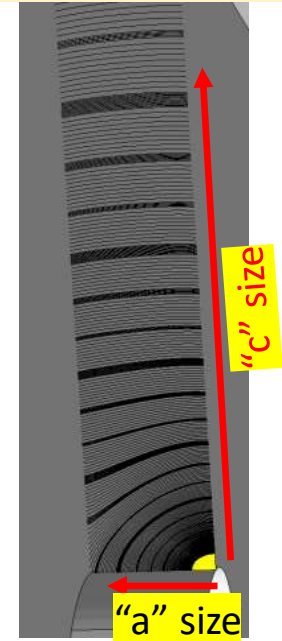
3D Central Hole Geometry



3D Central Hole Mesh



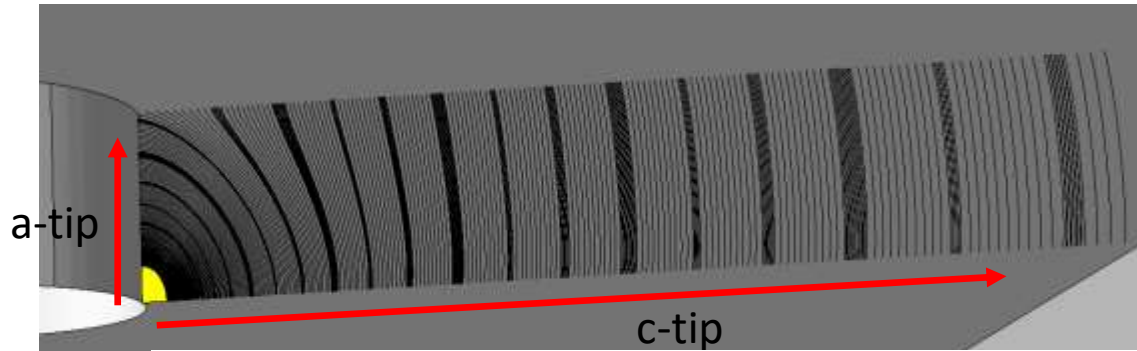
Crack Propagation Simulation



- Model resembles a "nominal" test configuration: nominal specimen geometry, elliptically shaped initial crack, no loading misalignment or misorientation of the specimen in the rig, basically following round robin's problem description.
- The challenge is to perform the 3D simulation using the same loading 40 step mission and use the R=0.1 FCGR table look-up
- Crack shape is not constrained to an elliptical shape during propagation. All simulations performed with SimModeler Crack capabilities.

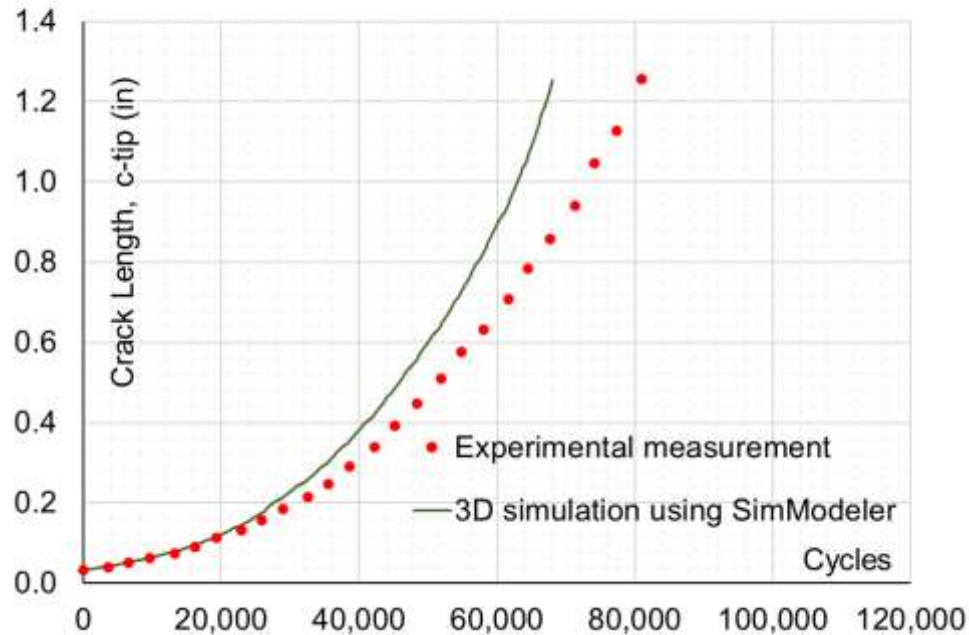
AFGROW - Corner Crack - Round Robin Challenge

PC-CX-7075-1 specimen, nominal configuration

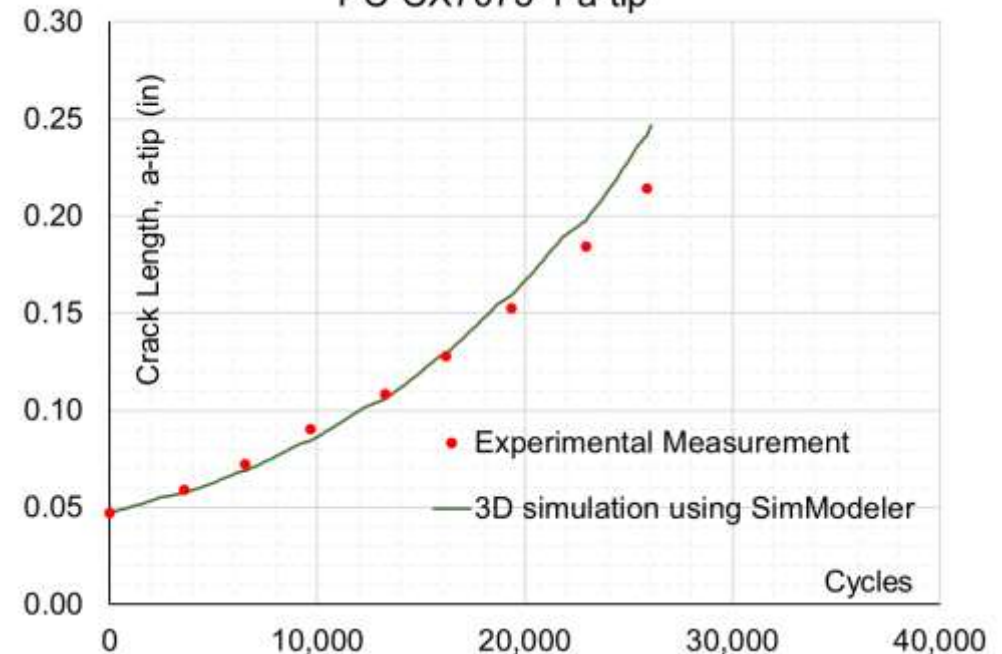


| PC-CX-7075 | Max Spectrum Stress | 12 ksi | | | | | |
|------------|---------------------|-------------------------|--------------|--------------|-------|---------------------------|--|
| Serial | Feature | Description | SwRI Measure | SAFE Measure | Pass? | SAFE Tool Used | |
| -1 | 1 | Width | 4.0070 | 4.0040 | Yes | SAFE Caliper 500-196-30 | |
| -1 | 2 | Thickness | 0.2515 | 0.2511 | Yes | SAFE Mike 59/30032 | |
| -1 | 3 | Hole Diameter | 0.4757 | 0.4756 | Yes | SAFE Inside Mike 13-576-4 | |
| -1 | 4 | Length | - | 16.0250 | - | 24" Mito Caliper | |
| -1 | 7 | Notch Width | | | | Microscope (W/ DRO) | |
| -1 | 8 | Notch Length | | | | Microscope (W/ DRO) | |
| -1 | | Initial crack (bore) | - | 0.0472 | | Nikon MM-60 (APES) | |
| -1 | | Initial crack (surface) | - | 0.0319 | | Nikon MM-60 (APES) | |

PC-CX7075-1 c-tip



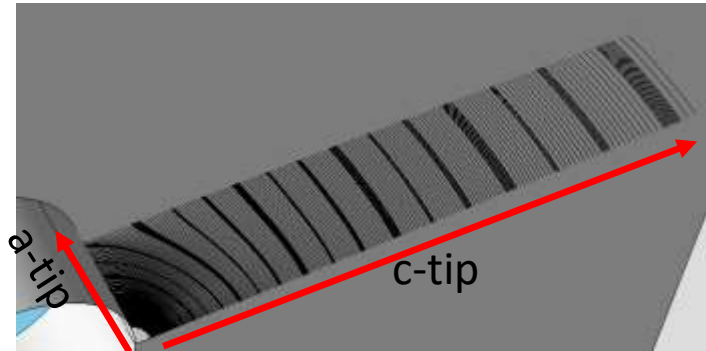
PC-CX7075-1 a-tip



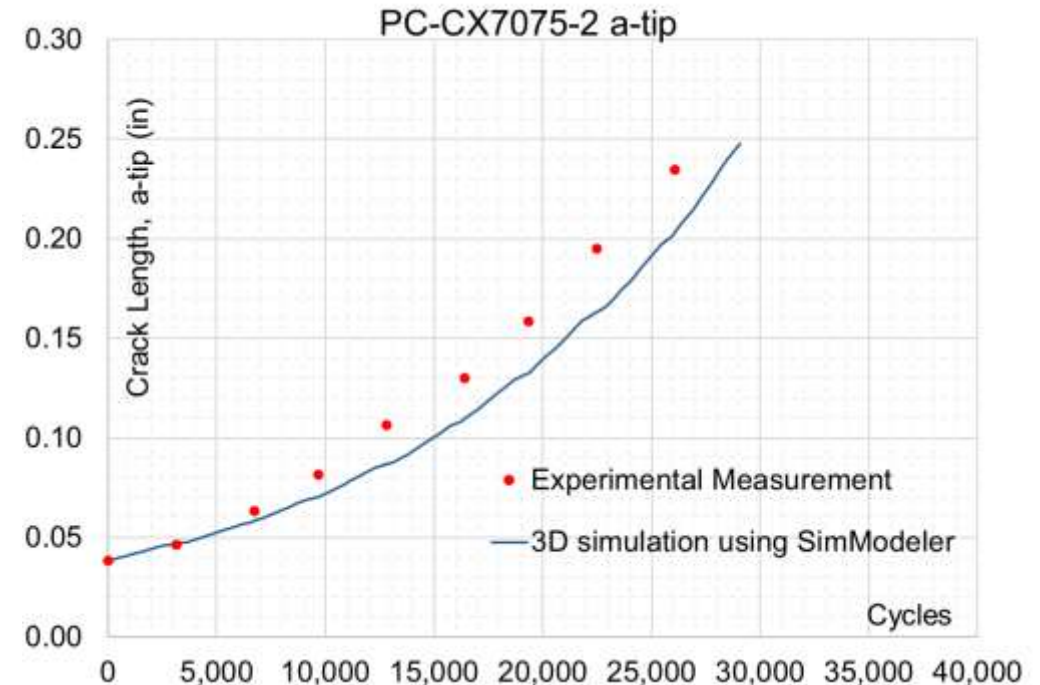
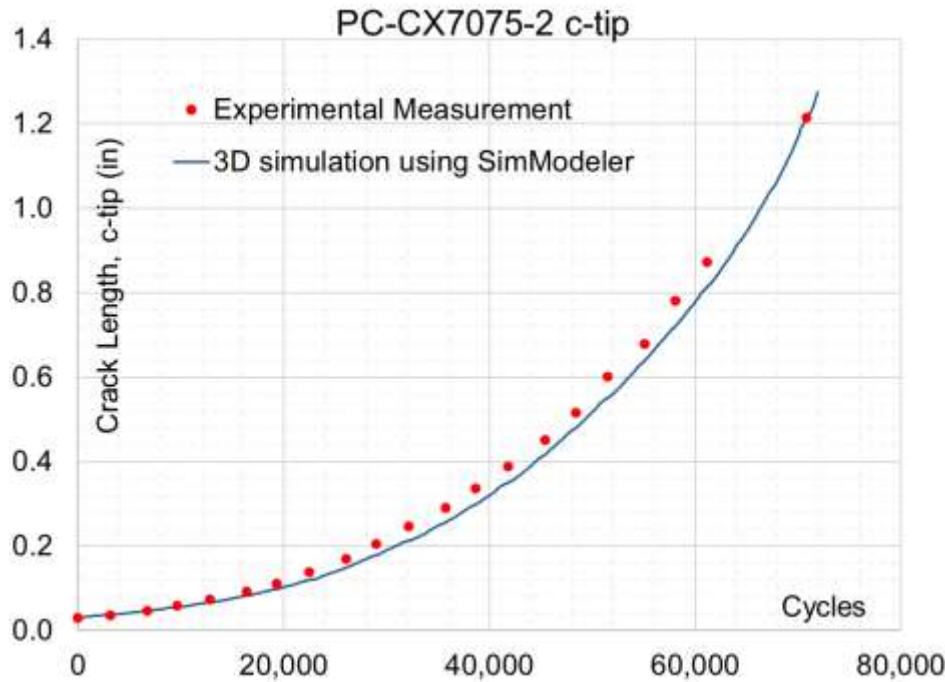
Good modeling solution – experimental measurement comparison using nominal configuration.

AFGROW - Corner Crack - Round Robin Challenge

PC-CX-7075-2 specimen, nominal configuration



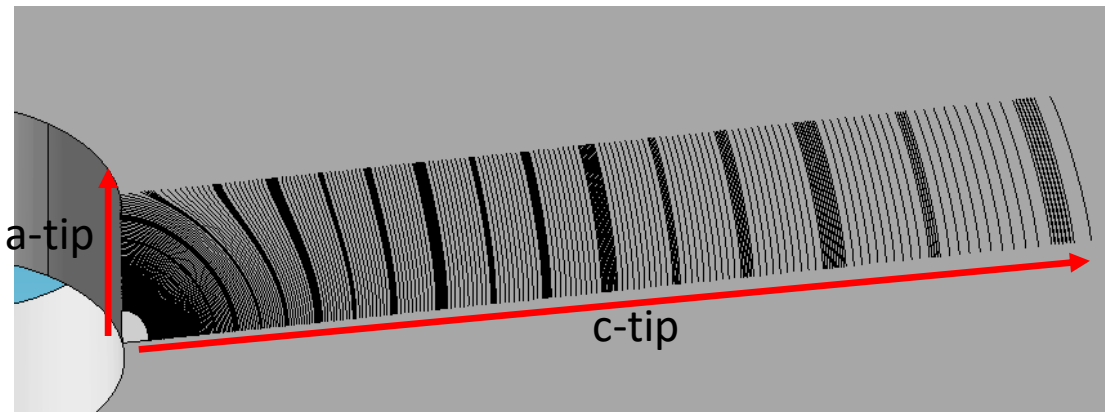
| Max Spectrum Stress | | 12 ksi | | | | |
|---------------------|---------|-------------------------|--------------|--------------|--------|---------------------------|
| Serial | Feature | Description | SwRI Measure | SAFE Measure | Pass? | SAFE Tool Used |
| -2 | 1 | Width | 4.0070 | 4.0040 | Yes | SAFE Caliper 500-196-30 |
| -2 | 2 | Thickness | 0.2515 | 0.2511 | Yes | SAFE Mike 59/30032 |
| -2 | 3 | Hole Diameter | 0.4757 | 0.4755 | Yes | SAFE Inside Mike 13-576-4 |
| -2 | 4 | Length | - | 16.0330 | - | 24" Mito Caliper |
| -2 | 7 | Notch Width | | | | on Microscope (W/ DRO) |
| -2 | 8 | Notch Length | | | | on Microscope (W/ DRO) |
| -2 | | Initial crack (bore) | | | 0.0384 | Nikon MM-60 (APES) |
| -2 | | Initial crack (surface) | | | 0.0307 | Nikon MM-60 (APES) |



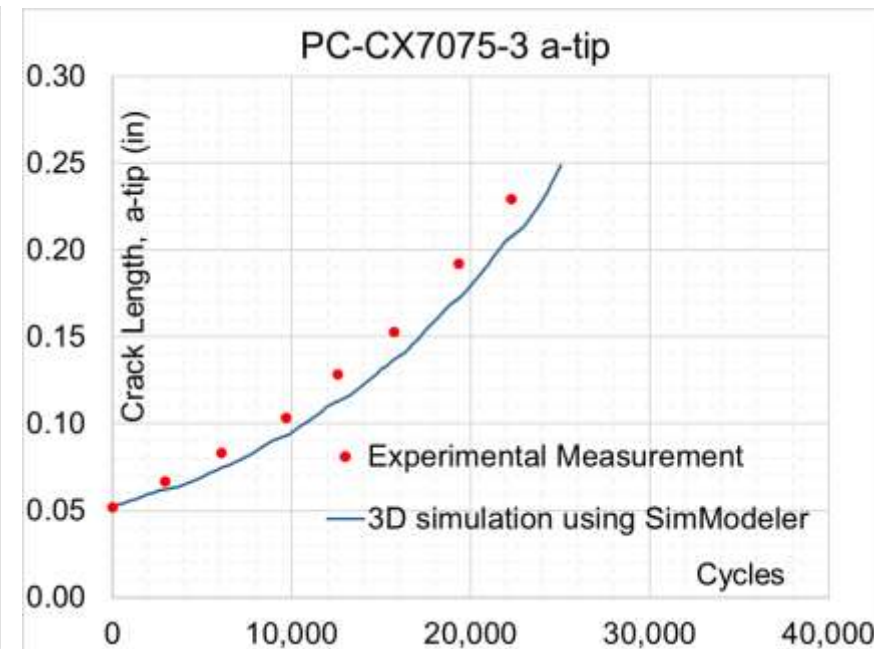
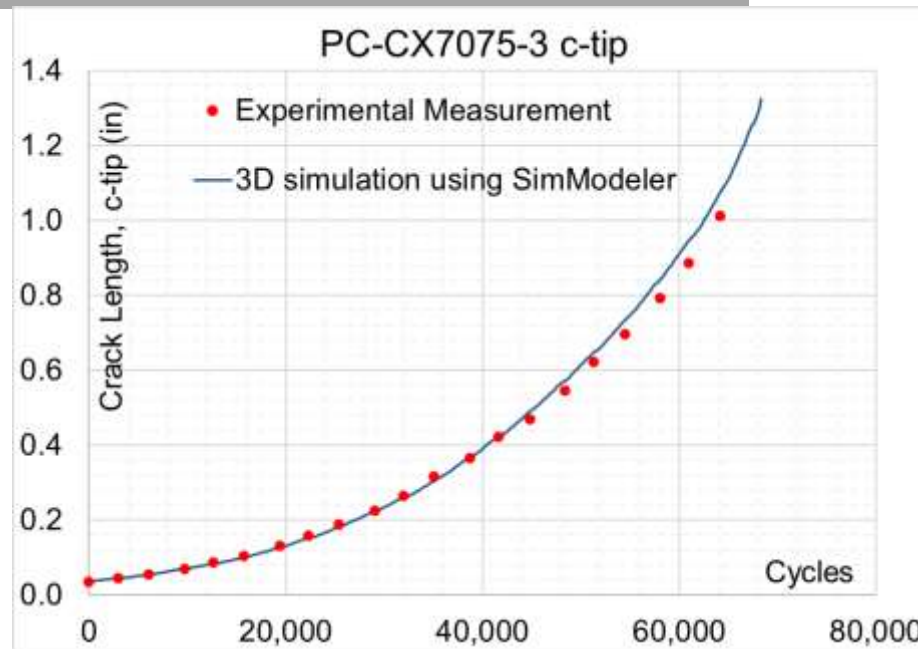
Good modeling solution – experimental measurement comparison using nominal configuration.

AFGROW - Corner Crack - Round Robin Challenge

PC-CX-7075-3 specimen, nominal configuration



| Max Spectrum Stress | | 12 ksi | | | | |
|---------------------|---------|-------------------------|--------------|--------------|-------|---------------------------|
| Serial | Feature | Description | SwRI Measure | SAFE Measure | Pass? | SAFE Tool Used |
| -3 | 1 | Width | 4.0030 | 4.0030 | Yes | SAFE Caliper 500-196-30 |
| -3 | 2 | Thickness | 0.2510 | 0.2511 | Yes | SAFE Mike 59/30032 |
| -3 | 3 | Hole Diameter | 0.4758 | 0.4751 | Yes | SAFE Inside Mike 13-576-4 |
| -3 | 4 | Length | - | 16.0310 | - | 24" Mito Caliper |
| -3 | 7 | Notch Width | | | | n Microscope (W/ DRO) |
| -3 | 8 | Notch Length | | | | n Microscope (W/ DRO) |
| -3 | | Initial crack (bore) | | 0.0313 | | Nikon MM-60 (APES) |
| -3 | | Initial crack (surface) | | 0.0255 | | Nikon MM-60 (APES) |

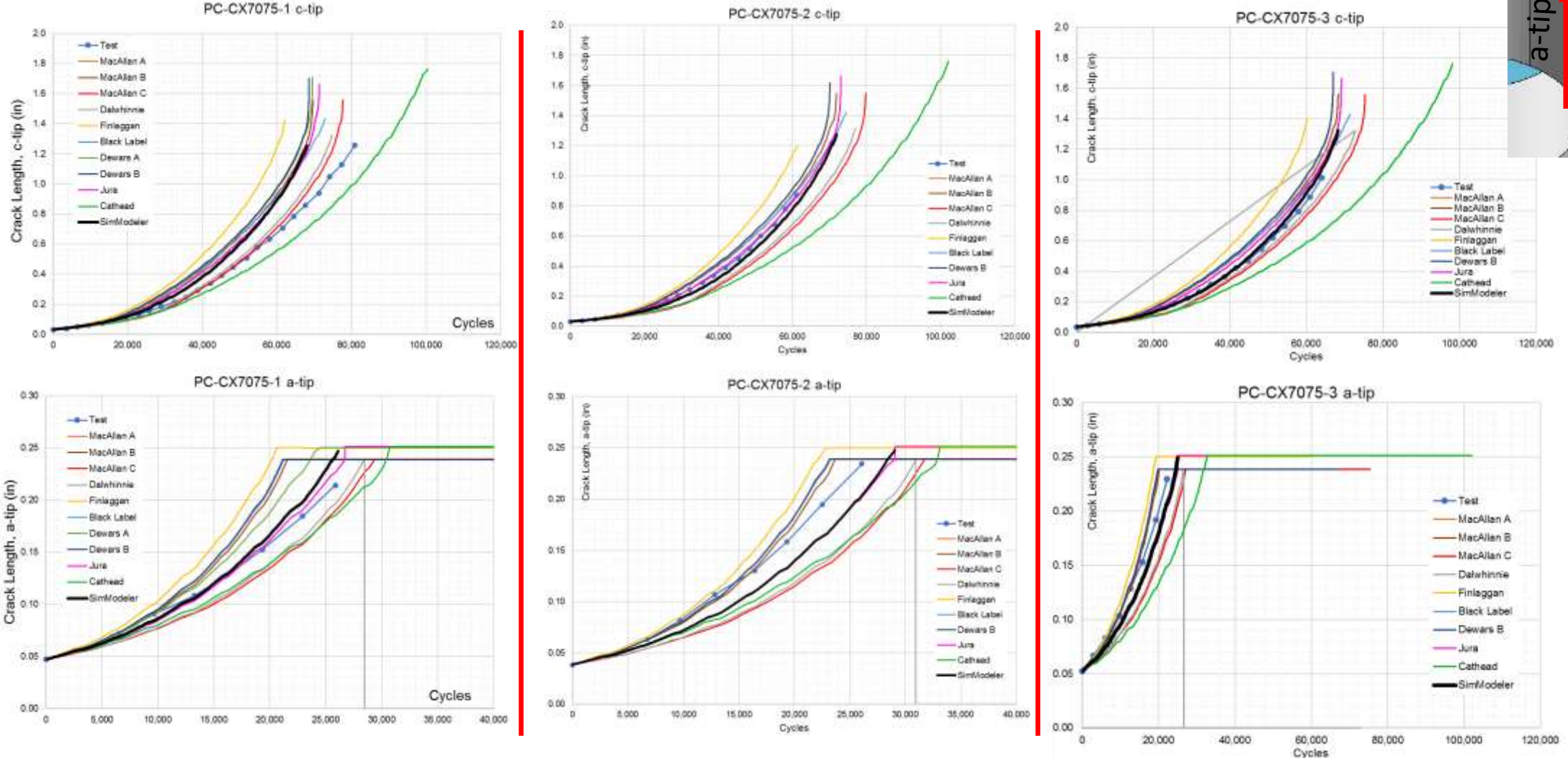
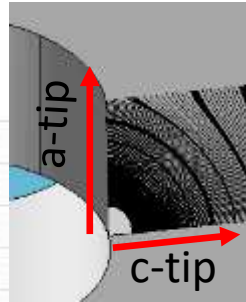


Very good modeling solution – experimental measurement comparison using nominal configuration.

AFGROW - Corner Crack - Round Robin Challenge

Comparison with other submissions: PC-CX-7075-1, PC-CX-7075-2, PC-CX-7075-3 nominal configuration

Reference: Tom Mills, Scott Fawaz, "AFGROW Round Robin: Corner Crack at Center and Offset Hole", AFGROW User Workshop, 2017

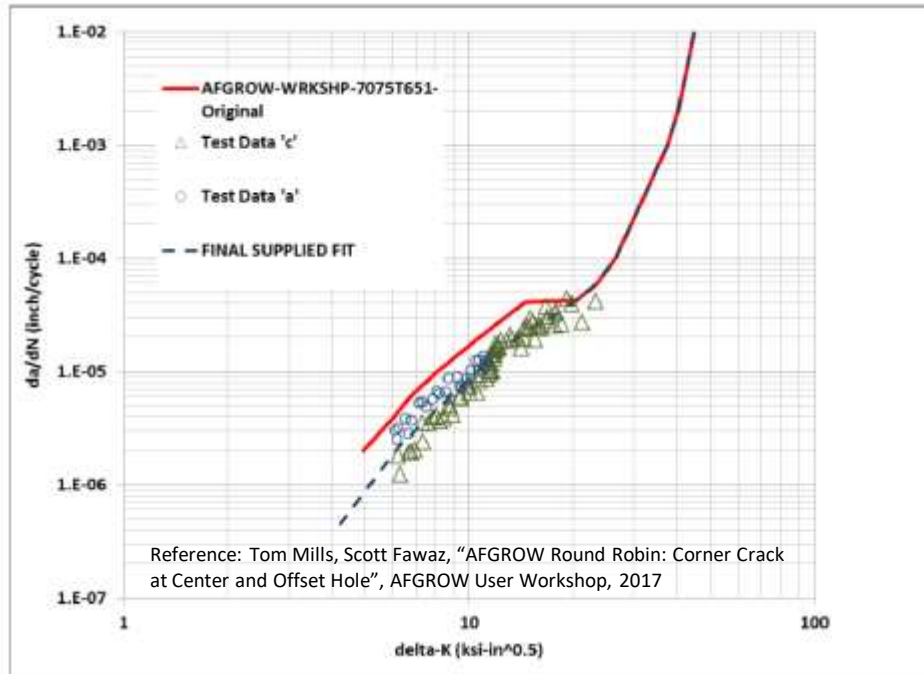


Overall, large variation in numerical solutions. Gap between experimental measurement and each submitted solution.

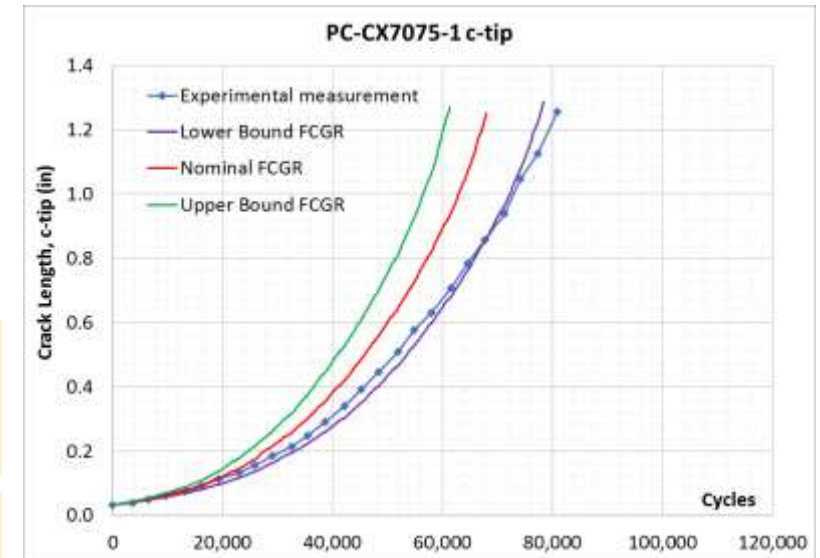
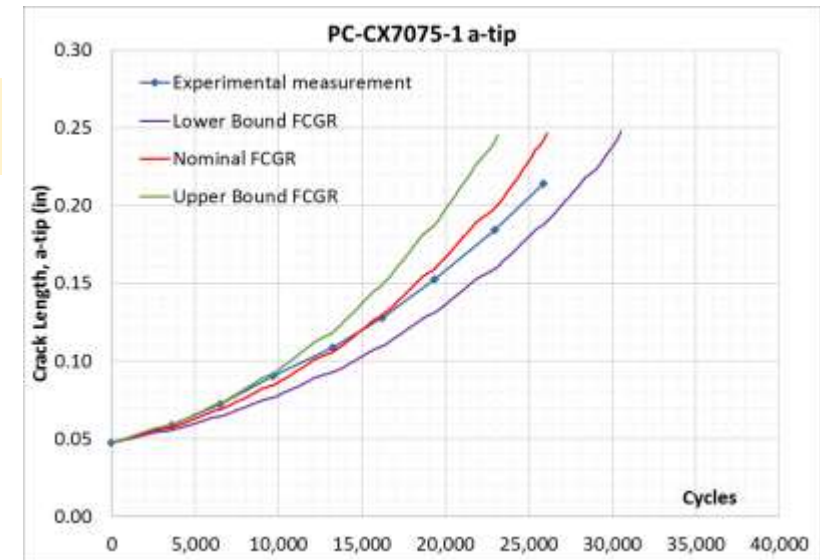
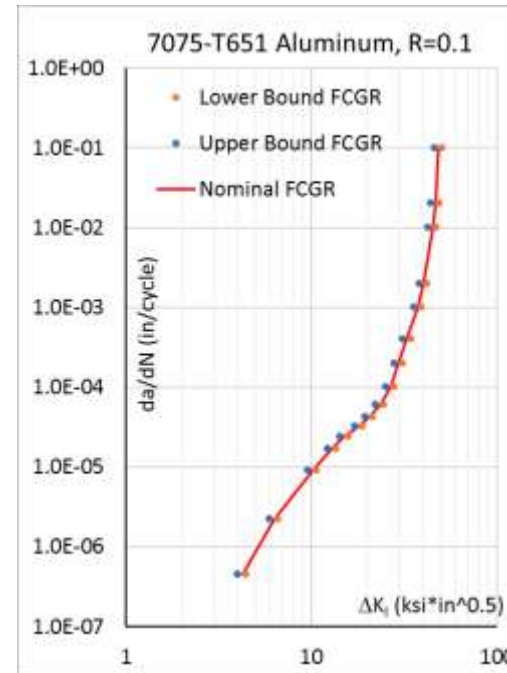
AFGROW - Corner Crack - Round Robin Challenge

Sources of uncertainty in the numerical solution: Fatigue Crack Growth Rate Data

Supplied fatigue crack growth rate dataset for the round robin challenge (marked "final supplied fit")



Lower and an upper bound FCGR curves used in the assessment

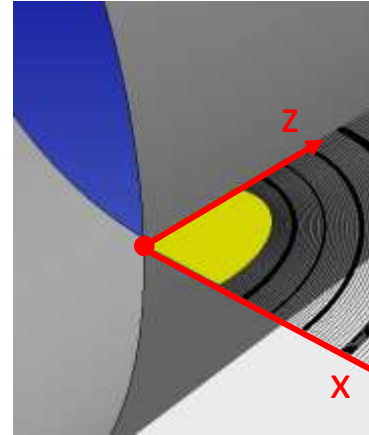
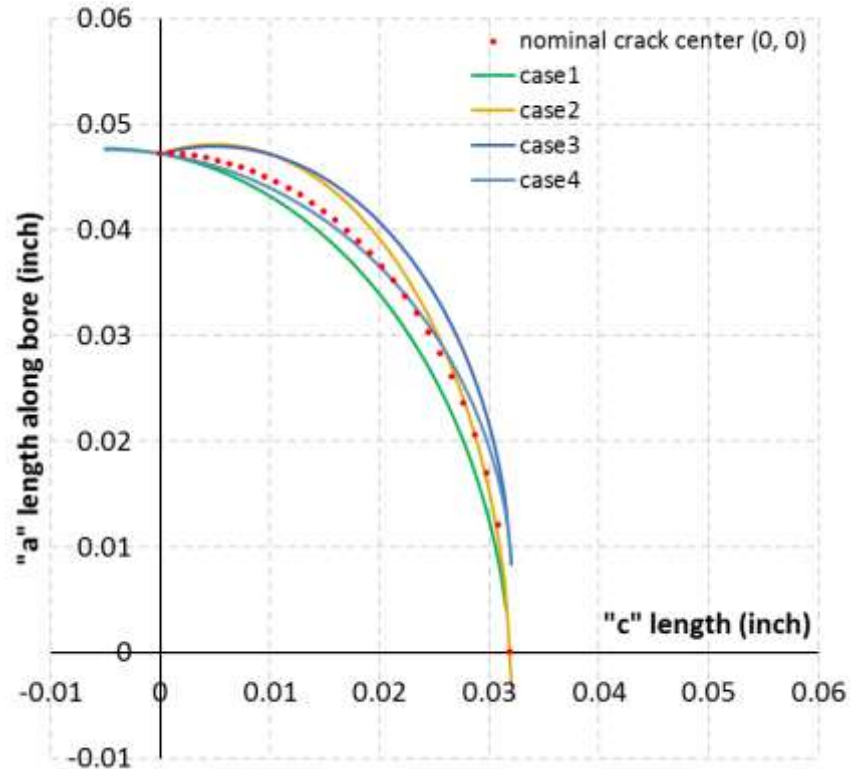


- A lower and an upper bound ($\pm 5\% \Delta K_1$ for a given "nominal" da/dN point) FCGR datasets are defined to simply assess the impact of FCGR scatter onto the predicted remaining useful life
- In this assessment, about $\mp 10\%$ in remaining useful life from the "nominal" reference is recorded

Low (assumed) FCGR deviation from a "nominal" curve can produce a significant RUL modeling solution variability.

AFGROW - Corner Crack - Round Robin Challenge

Sources of uncertainty: initial crack shape

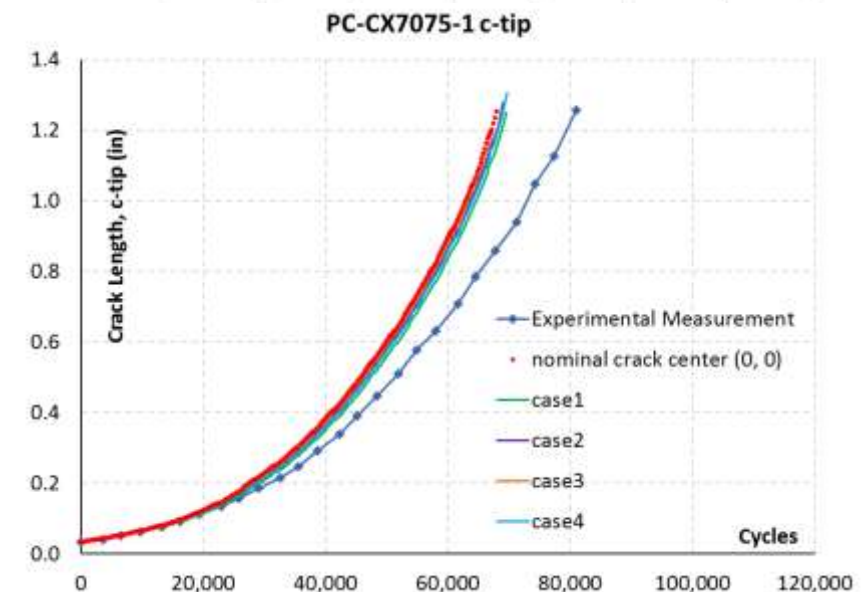
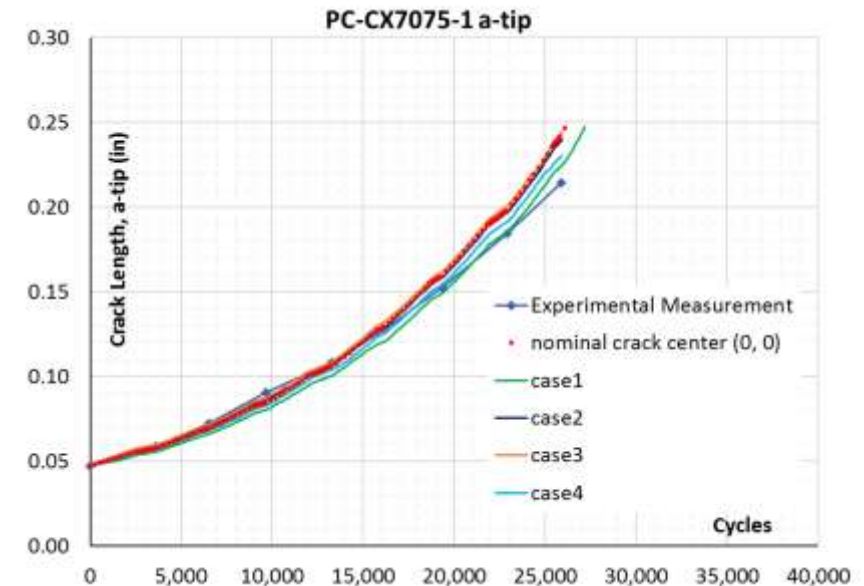


Location of the ellipse center that defines initial crack

| | shiftX (inch) | shiftZ (inch) |
|-------|---------------|---------------|
| case1 | -0.005 | -0.005 |
| case2 | 0.005 | -0.005 |
| case3 | 0.005 | 0.005 |
| case4 | -0.005 | 0.005 |

- Initial elliptical crack shape is defined by shifting the center of the ellipse and maintain the “a” and “c” size (intersections with the free model boundaries)
- The crack propagation simulation does not constrain the crack front to be elliptical
- Initial assumed crack shape appears to have a lower impact on RUL than FCGR scatter.

Modeling validation assessment can benefit out of additional measurement data that can be collected post experimental procedure.



Interference Fit - Corner Crack - Round Robin Challenge

Problem Description

Different 3D models were created based on different **nominal** dimensions

Table 1. Round-robin analysis conditions

| Condition | Specimen Type | Hole Diameter (in) | Fastener Diameter (in) | Surface Precrack Length (in) | Bore Precrack Length (in) | Loading | Max Stress (ksi) |
|-----------|---------------|--------------------|------------------------|------------------------------|---------------------------|------------|------------------|
| 1 | Open Hole | 0.25 | N/A | 0.027 | 0.0278 | CA (R=0.1) | 27.9 |
| 2 | 0.4% IFF | 0.2479 | 0.24885 | 0.0257 | 0.042 | | |
| 3 | 0.6% IFF | 0.2474 | 0.24885 | 0.0257 | 0.042 | | |

Experiment: Loading Conditions

Far field R ratio = 0.1
 Local field (near hole) R ratio needs to be identified
 Benchmark interference fit values = {0.4%, 0.6%}

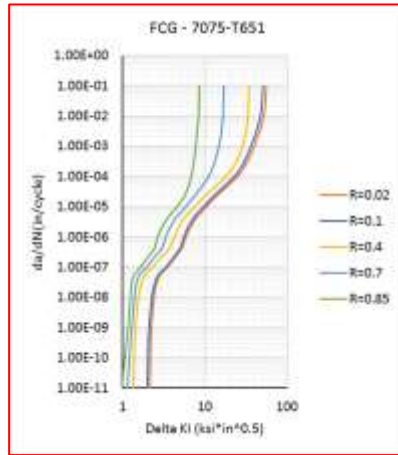
Material Model

| Property | Value |
|---------------|-----------------|
| Material | 7075-T651 plate |
| Modulus (ksi) | 10400 |
| Poisson | 0.33 |

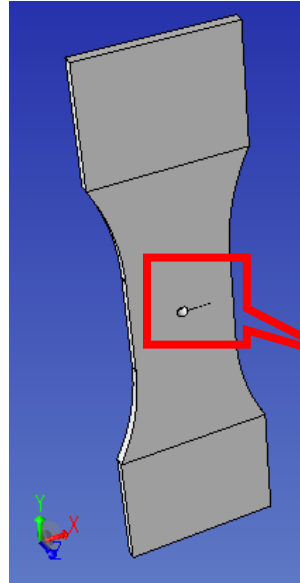
Reference:

Jake Warner, "Interference Fit Fastener Analytical Round Robin", AFGROW User Workshop, 2020.

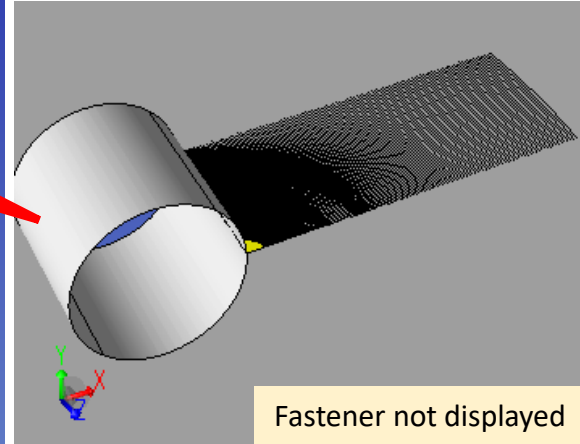
Fatigue Crack Growth Rate measurement data: Look-up Table



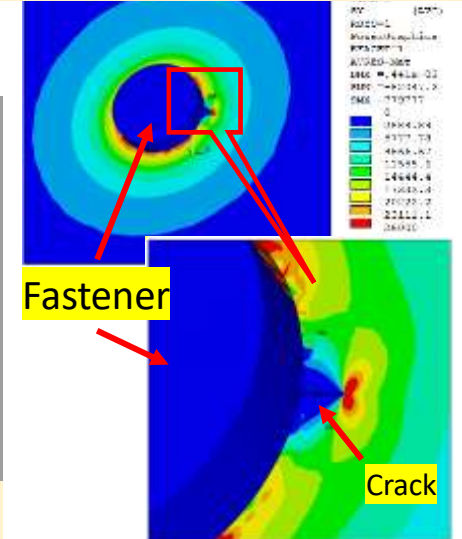
3D Model resembles experimental conditions



3D FEA procedure using SimModeler capabilities



σ_0 contour plot for initial crack, 0.4% IFF



- Explicit crack incrementation; each crack increment has a representative 3D model; the same model setup is used for each simulated crack front.
- Two load steps for the open hole (max load, min load); three load step solution for the interference fit cases (fastener-specimen contact, max load, min load).
- Stress intensity factors computed based on displacement correlation technique. LEFM framework.
- SimModeler Crack application is used in the 3D simulations. da/dN vs. ΔK_I table used for integration.
- No crack closure effects considered in the 3D simulations.

Reference: .

Adrian Loghin, Corner Crack Round Robins: Verification&Validation and UQ, AA&S 2021.

- Model resembles a "nominal" configuration: specimen geometry, initial (elliptical shape) crack size, uniform interference fit
- The challenge is to capture correctly the crack driving force ΔK_I , R ratio along the crack front and, to make use of fatigue crack growth rate specific to the R ratio at each location along the crack front

Interference Fit - Corner Crack - Round Robin Challenge

Sources of uncertainty: Interference Fit along the bore

Table 1. Round-robin analysis conditions

| Condition | Specimen Type | Hole Diameter (in) | Fastener Diameter (in) | Surface Pre-crack Length (in) | Bore Pre-crack Length (in) | Loading | Max Stress (ksi) |
|-----------|---------------|--------------------|------------------------|-------------------------------|----------------------------|---------------|------------------|
| 1 | Open Hole | 0.25 | N/A | 0.027 | 0.0278 | CA (R=0.1) | 27.9 |
| 2 | 0.4% IFF | 0.2479 | 0.24885 | 0.0257 | 0.042 | | |
| 3 | 0.6% IFF | 0.2474 | 0.24885 | 0.0257 | 0.042 | | |

- Constant interference fit was considered in the Round-Robin challenge: 0.4% and 0.6%
- An averaged initial crack size was considered

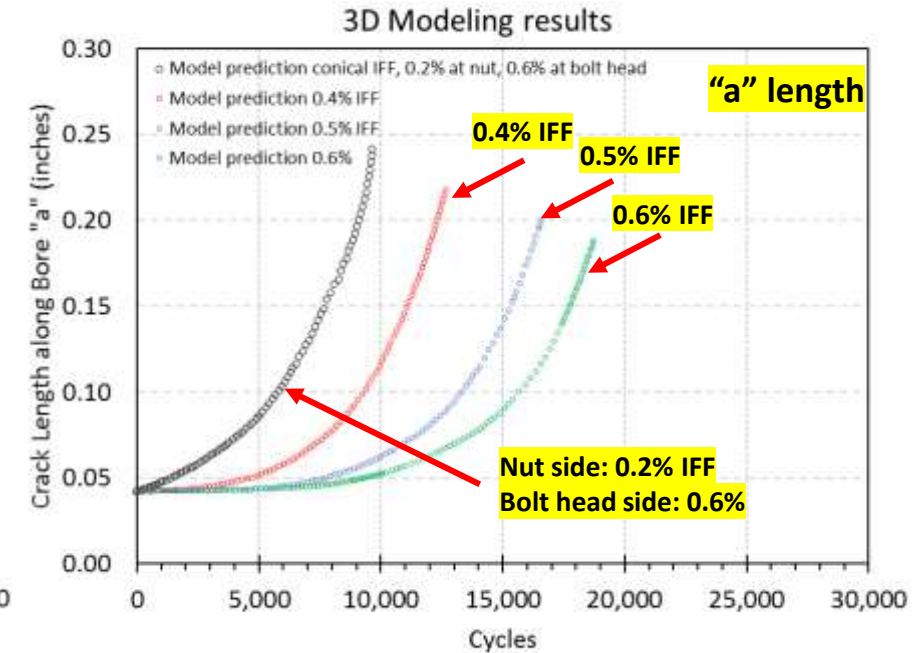
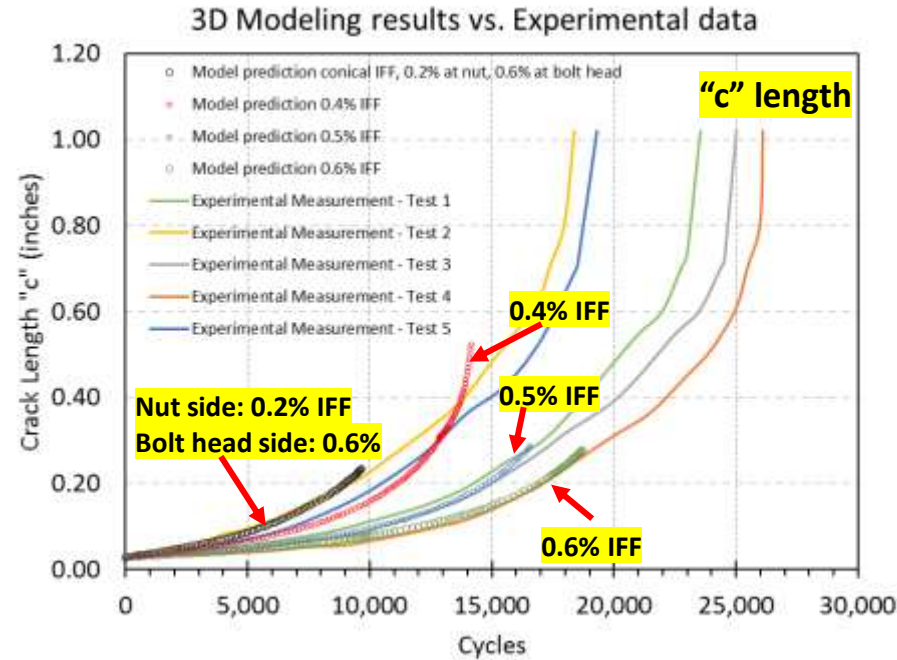
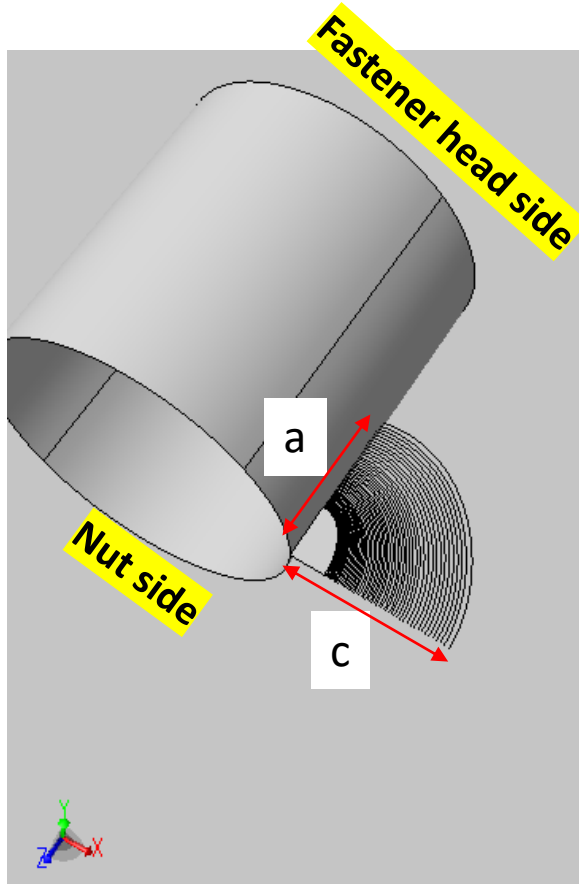
- The reality is different: there is a large IFF variation along the bore for each specimen.
- The IFF is larger at the bolt head side than the nut side where the precrack is introduced.
- A different initial crack size used in the model than the precrack size from the experiment can contribute to modeling uncertainty.
- Elliptical shape considered for the initial crack in the model can be another error source.

| FILLED HOLE | | | | | | | | | | | |
|----------------|----------------|-------------------|---------|---------|---------------|---------------|---------------|-----------------------|----------------|----------------|--------------|
| Specimen | Hole Diameter | Fastener Diameter | | | Interference | | | Fatigue Life Total | Initial Crack | | |
| | | MAX | AVE | MIN | MAX | AVE | MIN | | Surface | Bore | a/c |
| 7D3-16-Da-2480 | 0.24786 | 0.24932 | 0.24884 | 0.24841 | 0.589% | 0.397% | 0.222% | 23545 | 0.02978 | 0.04504 | 1.512 |
| 7D3-17-Da-2480 | 0.24784 | 0.24932 | 0.24884 | 0.24841 | 0.597% | 0.405% | 0.230% | 18390 | 0.02522 | 0.04144 | 1.643 |
| 7D3-18-Da-2480 | 0.24789 | 0.24932 | 0.24884 | 0.24841 | 0.577% | 0.385% | 0.210% | 24997 | 0.02252 | 0.04052 | 1.799 |
| 7D3-19-Da-2480 | 0.24788 | 0.24932 | 0.24884 | 0.24841 | 0.581% | 0.389% | 0.214% | 26107 | 0.02480 | 0.03648 | 1.471 |
| 7D3-20-Da-2480 | 0.24788 | 0.24932 | 0.24884 | 0.24841 | 0.581% | 0.389% | 0.214% | 19303 | 0.02616 | 0.04662 | 1.782 |
| AVERAGE | 0.24787 | | | | 0.585% | 0.393% | 0.218% | 22468 | 0.02570 | 0.04202 | 1.635 |

The deterministic model allows modeling of any IFF configuration if the geometry of the fastener and the bore are known.

Interference Fit - Corner Crack - Round Robin Challenge

IFF fatigue crack growth: 3D modeling solutions vs. measurement data



- The uncertainty in the IFF along the bore can introduce variability in the experimental measurements
- The conical IFF of 0.6% IFF at bolt head, 0.2% IFF at nut side seems to capture the lower bound of the recorded measurement data
- A uniform 0.6% IFF seems to capture the upper bound of the test measurements

Numerical modeling solutions are consistent. The RUL uncertainty related to IFF is captured well with the deterministic procedure.

Conclusions

- In a Round Robin challenge, most of the time, modeling solutions that capture nominal conditions (specimen geometry, initial elliptical crack size, perfect specimen alignment in the grip, loading mission, interference fit allowance) are solicited.
- Large variation in the numerical solutions provided by the participants is observed but not fully addressed. 3D FEA based fatigue crack growth simulations can be a reference to understand sources of numerical uncertainties in these submissions. Potential sources:
 - Accuracy of K_I values
 - Impact of elliptical crack shape constraint on remaining useful life
- 3D FEA provides modeling capabilities to relate experimental uncertainties to the remaining useful life modeling solutions
 - For the AFGROW Round Robin, initial assumed crack shape has a lower impact on RUL than FCGR scatter.
 - RUL modeling solutions are sensitive to FCGR scatter. A better model validation procedure should consider FCGR variability.
 - IFF allowance along the bore is a source of experimental variability.
- A future Round Robin challenge needs to provide additional measurement data (DIC, crack front shapes) which can be used to improve confidence in the modeling procedure. A solution that represents a “nominal” configuration is insufficient to quantify the accuracy of the modeling technique.

Questions?