Interference Fit Fastener Prediction Challenge

Analysis Methods Subcommittee

Round-Robin Life Prediction Invitation for Interference Fit Holes

Purpose:

Early discussions within the Engineered Residual Stress Implementation (ERSI) Analysis Methods Committee identified a need to perform a series of round-robin exercises. The primary focus of these round-robin exercises is to identify the random and systematic uncertainties associated with Damage Tolerance Analyses (DTA) related to residual stresses. Many factors influencing the total uncertainty have been discussed and are currently under investigation by various members of the ERSI team.

This is the second such round-robin exercise and focuses on the incorporation of an Interference Fit Fastener (IFF) into crack growth analysis. The first round-robin focused on open cold expanded holes. The focus of this (and the first) round-robin will be on systematic uncertainties, or the uncertainty associated with the system or process used by the analyst (also known as epistemic uncertainties or model-form uncertainties).

Overview:

To ensure that the systematic uncertainties are accurately identified by this effort, analysts are encouraged to collaborate as they normally would in responding to a real world scenario, but not to share prediction results with other individuals submitting predictions until after the submission period ends. The intent being to prevent a bias in predictions toward one analyst's submission.

Specific input data (defined below) will be provided to each analyst participating in the exercise to minimize the random uncertainties. The analyst is free to use any means to incorporate the IFF into the crack growth analysis, however it's important that the analyst adheres closely to the guidance in this document so that the variability in the predictions will be limited to the aspects left to analyst's discretion. Analysts are not to adjust any of the provided input data in any way. Analysts are permitted to provide multiple predictions if they desire, but it is required that the analyst identify a single prediction as the prediction they feel would best match the test data.

Fatigue test data for the scenarios involved in this round-robin will be provided to each participant at the conclusion of the round robin. Submissions results will be made anonymous and compared to test data to identify analytical approaches that worked well and to define best practices for future efforts. It is planned that the results of this round-robin will be submitted to a mutually agreed upon journal in a manner that will not identify the analyst who performed each prediction, but participants will be provided a key to know their results as they compare to the group.

Interference Fit Fastener Prediction Challenge

Conditions:

Specific conditions were selected to target existing datasets as well as the most basic conditions to predict. For all conditions, sufficient fatigue test and crack growth rate data exists to provide a sound foundation for comparison. As shown in Table 1, three conditions are identified with similar geometry, the baseline condition is an open hole test. The second and third conditions incorporate an IFF. The second condition, 0.4% interference, was the target interference for the test program that will be compared to. However, typical final hole tolerances permit a 0.6% interference condition, condition 3, so predictions at both interference levels are of interest.

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		

Input Data:

Provided input data for analyses:

- Test specimen geometry is defined by the drawings contained in Appendix B
- Material properties are contained in Appendix C
- Initial flaw size, shape, location, and orientation
  - Coupons were manufactured to a precrack hole diameter and jeweler's saw notches were cut on one corner of the hole. The jeweler's saw cut was ~0.007" wide and extended ~0.01" up the bore and along the face of the specimen.
  - Precracking was accomplished to 0.030" along the specimen face for all coupons at the test stress. Precracking was performed without the fastener installed and prior to final ream. Final ream removed the jeweler's saw notch.
  - The fastener was installed with the nut on the precracked specimen face. After installation the nut was removed to permit surface crack length measurements.
  - The fasteners were Hi-Loks (HL18BP-8-4) matched within 0.0001" to specimen hole diameters for a 0.4% interference at the mid-bore. It was noted that fastener diameters were consistently larger near the fastener head radius.
- Loading Spectrum
  - All loading is constant amplitude with a stress ratio (R) of 0.1
  - Gauge section applied stress was 27.9 ksi (high stress was used because the test program included specimens with cold expanded holes)
- Constraints
  - All coupons were tested in a servo-hydraulic fatigue machine with hydraulic wedge grips.

Interference Fit Fastener Prediction Challenge

Prediction Submission Requirements:

A summary of the results for each analysis case must include:

- For each point used to define the crack front at each growth increment:
    - Number of cycles for the current growth increment
    - X-dimension following coordinate system shown in Figure 1.
    - Y-dimension following coordinate system shown in Figure 1.
    - $R_{effective}$ (stress ratio actually referenced for crack growth rate data)
    - K_{max}
    - Delta K

An excel template has been provided to ensure consistency of the data submitted and minimize the collation effort. All results should be provided in English units (inch, ksi, ksi√inch). The number of points along the crack front and the number of output increments is at the analyst's discretion, and the template quantities can be adjusted accordingly.

A questionnaire, detailed in Appendix A, is provided to describe the general approach, software, and assumptions utilized in the analyses. The questionnaire must be submitted with the prediction results.

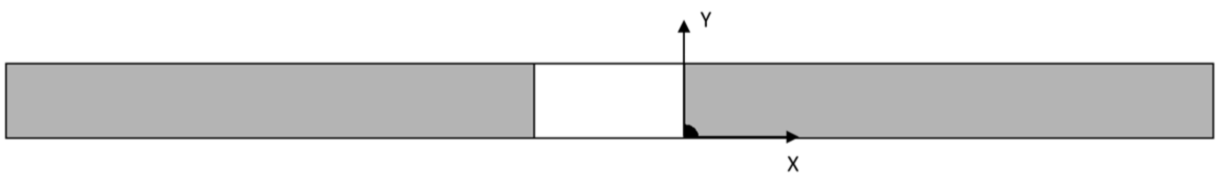


Figure 1. Crack Growth coordinate system

Deadline for Result Submittals:

Submissions must be submitted by the end of the day, June 1, 2020.

Contact Information:

All questions and final submissions should be submitted to: Jacob.Warner@us.af.mil

Interference Fit Fastener Prediction Challenge

APPENDIX A

QUESTIONNAIRE

Contact Name: Fighting Falcon

Please provide information about the analyses completed:

1. Analysis Software (name and version)
    a. FEA software (if applicable): StressCheck v10.5
    b. Crack growth software: LifeWorks (Boeing Internal)

2. FEA Model Setup (if applicable)
    a. Describe the boundary conditions utilized in the FEMs, to include applied loads and constraints

    Open Hole: N/A

    IFFs: 2D Plane stress model with steel fastener. Interference applied to fastener according to table provided. Bilinear material properties applied to plate with kinematic hardening law. NL sequence of events was insert IFF, peak load of 27.9ksi, min load of 2.79ksi. Yielding did not occur due to IFF insertion in either case but does occur with applied loading (including the open hole case).

    Traction was applied at the far end of the plate and rigid body constraints were used.

    b. Describe the methods to define and control the crack front shape and control meshing along the crack front

    StressCheck was only used to obtain stress information. Stress information was plugged into LifeWorks.

3. Interference Fit Modeling
    a. Describe the methods used to characterize and incorporate the effect of the IFF.
    No fit modeling was performed.

    b. If the fastener effect was derived from a closed form solution, what were the assumptions of the solution. Is the solution based on empirical data or FEM correlations?
    N/A

    c. If the fastener was modeled using FEA, does the model consider non-linear effects? Was multi-body contact used? If contact was used, what friction related assumptions were made?

    See #2

4. Stress Intensity Calculations
    a. Describe the methods used to extract and calculate the stress intensities for applied remote loads

    Stress intensities were internally calculated in LifeWorks based on the local stress state along the crack path. Chosen solution in LifeWorks uses StressCheck SIFs from a large array lookup based on flaw size and geometry.

    b. Describe the methods used to incorporate the stress intensities into the crack growth code (superposition, etc.)

    For open hole case the approach used was input geometry into LifeWorks along with the applied remote load and let LifeWorks calculate SIFs from a StressCheck based array lookup.

    For the IFF cases the stress state along the crack path was input for the peak and valley loading and tied to the those points in the spectrum. StressCheck derived SIFs were once again used by a LifeWorks array lookup.

Interference Fit Fastener Prediction Challenge

Crack Growth Predictions

c. Describe the material model approach used for the crack growth predictions (NASGRO, tabular, etc.) and the assumptions/approach used for “threshold”, stress ratio (R) shift, and negative R behavior.

   Provided data was input into LifeWorks as-is. LifeWorks uses a proprietary contact stress model and closure model to “shift” R-ratio data from R = 0 to the required R-ratio.

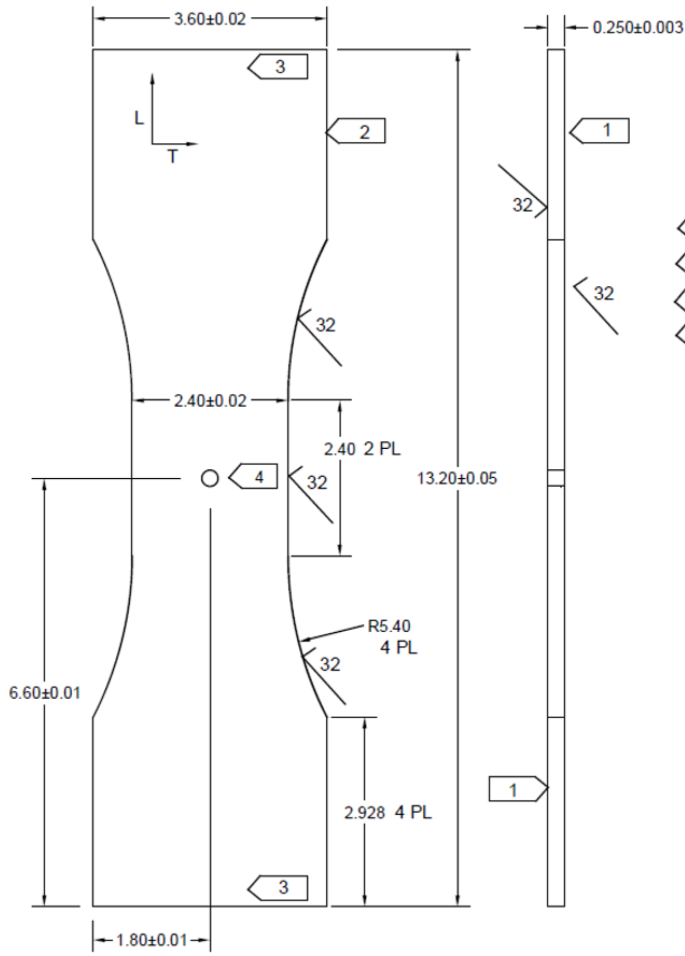
d. What growth increment was utilized between stress intensity calculations?

   Cycle by cycle.

5. Provide any additional details that may be pertinent to the analyses completed

I started this work rather late so I’m not expecting great results. The IFF cases appear to be fully plastic for at least 0.10” away from the hole edge once the IFF is inserted and the peak load applied. Not sure LEFM is going to provide something meaningful in this scenario. I also noticed that even from the industry standard 0.005” starting flaw the life was rather short (not much different than the 0.02-0.03” starting flaw in this test). I wish there was a bit more building-block approach to this challenge. I think it jumped quickly between the open hole and the IFF due to a number of factors.

APPENDIX B
COUPON GEOMETRIES



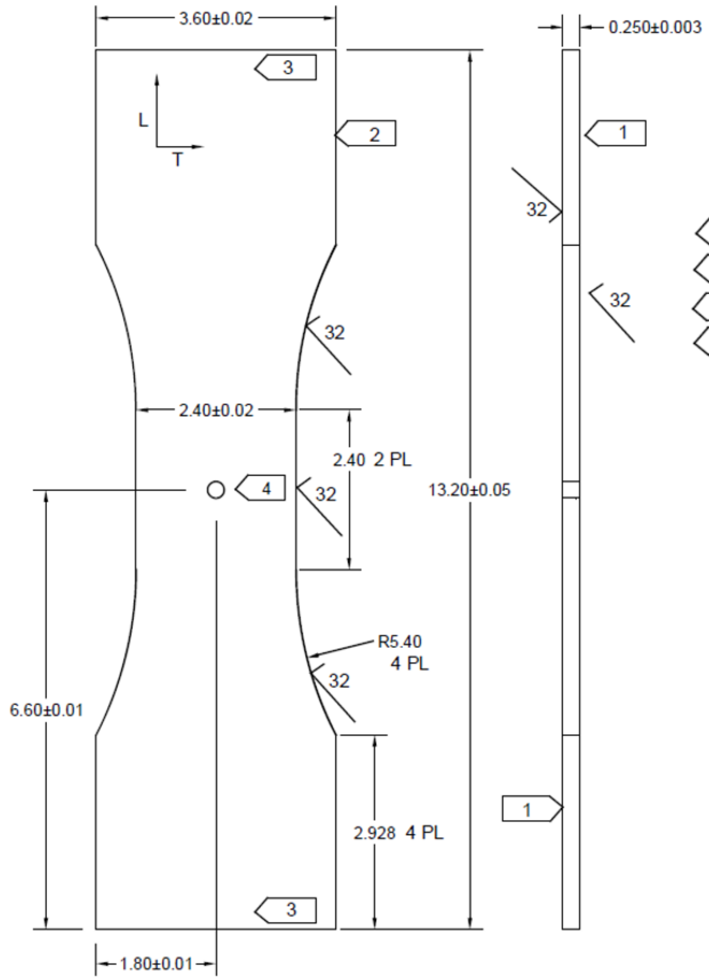
Dimensions in inches unless otherwise noted.

Stock thickness is approximately 0.250 inch. Use as-is.

1. Hand sand with emery cloth in longitudinal direction (each face) to remove mill scale
2. Last 0.020" removal on edges must be done in 0.005" passes.
3. Specimen ID will be engraving in format 7D3-xx-Da-2480, with xx ranging sequentially from 13 to 28
4. Hole preparation (drill & reamer entry face are on Specimen ID side)
   - A. Initial drill using FTI CBSD-8-0-N-1 (approx. 0.216" diameter)
   - B. Initial ream using FTI CBSR-8-0-N-1 (approx. 0.2355" diameter. Tolerance is +/- 0.0005)
   - C. Manually deburr hole without radiusing or chamfering edge.
   - D. Record straight bore hole diameter to X.XXXX precision
   - E. Holes will require final ream to 0. 25 inch +/- 0.0005
   - F. Deburr front and back side of hole using supplied Cogsdill Burraway Tool or similar method
   - G. Corner break on label face should be 0.025 inch + 0.005 / - 0.000 inch (radius or chamfer)
   - H. Corner break on opposite face should have corner break not exceeding 0.005 inch.

Material: 7075-T651 AL	QTY: 16	Condition: Type A CX	Finish: 64 RMS unless noted

Figure 2. Benchmark Condition 1 Geometry (Precracked at initial ream, final ream after precrack and removing notch)



Dimensions in inches unless otherwise noted.

Stock thickness is approximately 0.250 inch. Use as-is.

1. Hand sand with emery cloth in longitudinal direction (each face) to remove mill scale
2. Last 0.020" removal on edges must be done in 0.005" passes.
3. Specimen ID will be engraving in format 7D3-xx-Da-2480, with xx ranging sequentially from 1 to 3
4. Hole preparation (drill & reamer entry face are on Specimen ID side)
   - A. Initial drill using FTI CBSD-8-0-N-1 (approx. 0.216" diameter)
   - B. Initial ream using FTI CBSR-8-0-N-1 (approx. 0.2355" diameter. Tolerance is +/- 0.0005)
   - C. Manually deburr hole without radiusing or chamfering edge.
   - D. Record straight bore hole diameter to X.XXXX precision
   - E. Holes will require final ream to 0.2480 inch +/- 0.0005
   - F. Deburr front and back side of hole using supplied Cogsdill Burraway Tool or similar method
   - G. Corner break on label face should be 0.025 inch + 0.005 / - 0.000 inch (radius or chamfer)
   - H. Corner break on opposite face should have corner break not exceeding 0.005 inch.

Material: 7075-T651 AL	QTY: 16	Condition: Type A CX	Finish: 64 RMS unless noted

Figure 3. Benchmark Condition 2 and 3 Geometry (Precracked at initial ream, final ream after precrack and removing notch)

APPENDIX C
MATERIAL PROPERTIES

Property	Value
Material	7075-T651 plate
Modulus (ksi)	10400
Poisson	0.33
Ultimate Strength (ksi)	83
Yield Strength (ksi)	73
Plane Stress Fracture Toughness (ksi-root(inch))	58
Plane Strain Fracture Toughness (ksi-root(inch))	27
Rlo	-0.15
Rhi	0.85

Interference Fit Fastener Prediction Challenge

da/dN	Stress Ratios (R)					
	K_{max}	ΔK				
	-0.15	0.02	0.1	0.4	0.7	0.85
1.00E-11	1.957	2.15	2.010	1.36	1.150	0.972
1.00E-10	1.995	2.175	2.045	1.39	1.220	1.071
3.00E-10	2.015	2.193	2.065	1.408	1.255	1.119
1.00E-09	2.062	2.237	2.111	1.442	1.300	1.172
2.00E-09	2.103	2.278	2.152	1.473	1.330	1.201
1.00E-08	2.233	2.400	2.280	1.562	1.400	1.255
2.00E-08	2.336	2.492	2.380	1.634	1.440	1.269
4.00E-08	2.529	2.675	2.570	1.765	1.530	1.326
6.00E-08	2.744	2.897	2.787	1.919	1.645	1.410
1.00E-07	3.302	3.485	3.354	2.322	1.965	1.663
2.00E-07	4.052	4.275	4.115	2.890	2.400	1.993
4.00E-07	4.878	5.150	4.955	3.650	2.975	2.425
6.00E-07	5.191	5.490	5.275	3.950	3.175	2.552
1.00E-06	5.477	5.825	5.575	4.225	3.360	2.672
2.00E-06	6.064	6.550	6.200	4.750	3.765	2.984
4.00E-06	7.026	7.650	7.200	5.550	4.400	3.488
6.00E-06	7.895	8.630	8.100	6.260	4.950	3.914
1.00E-05	9.419	10.339	9.675	7.510	5.875	4.596
2.00E-05	11.885	13.110	12.225	9.530	7.250	5.515
4.00E-05	15.605	17.300	16.075	12.600	8.850	6.216
1.00E-04	22.061	24.550	22.750	17.925	11.100	6.874
2.00E-04	26.617	29.700	27.470	21.725	12.500	7.192
4.00E-04	30.493	34.100	31.490	24.885	13.650	7.487
6.00E-04	32.597	36.500	33.675	26.550	14.200	7.595
8.00E-04	34.115	38.225	35.250	27.690	14.625	7.724
1.00E-03	35.231	39.500	36.410	28.500	14.900	7.790
2.00E-03	38.526	43.250	39.830	30.500	15.600	7.979
4.00E-03	42.037	47.250	43.475	31.870	16.130	8.164
1.00E-02	45.770	51.500	47.350	33.000	16.650	8.401
2.00E-02	47.313	53.250	48.950	33.5	16.875	8.500
1.00E-01	49.287	55.500	51.000	34.1	17.100	8.575