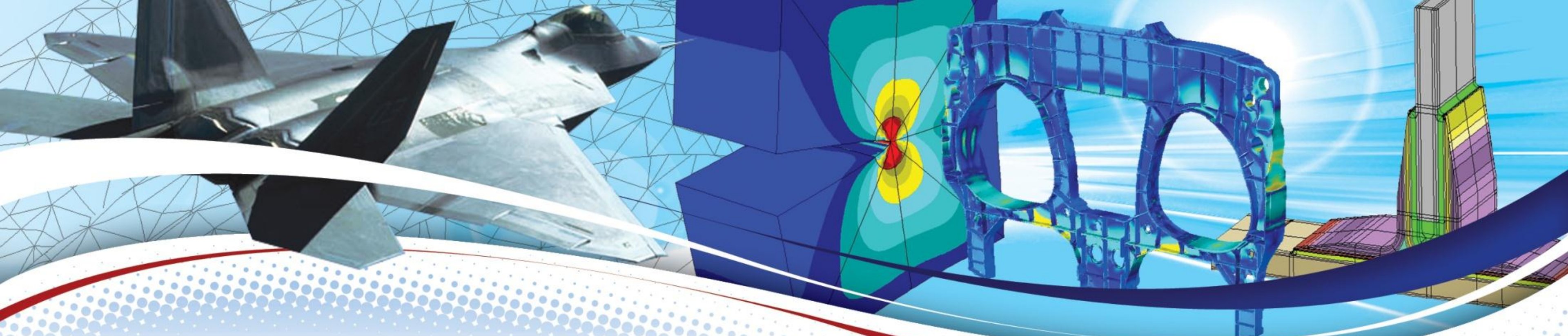

AFGROW User's Workshop 2014

Prediction of Fatigue Crack Propagation from Cold-Expanded Holes

Matt Watkins & Ricardo Actis

ESRD, Inc.

9 Sept 2014

esrd

StressCheck®

Outline

- Model of crack propagation
  - Simulation
  - Modeling assumptions
  - Sources of error
- Crack propagation tool
  - Input/output
  - Predictions
  - Effect of uncertainties in the predictions
- Summary and Conclusions

Simulation

STRESSCHECK®

- Simulation: The imitative representation of the functioning of one system by means of the functioning of another
  - Functioning of structural systems and the imitative representation by mathematical models
  - Transformation of one set of data **D** into another set **F** using the available background information **I**

$$(\mathbf{D}, \mathbf{I}) \rightarrow \mathbf{F}$$

Crack Propagation Model
Background Information

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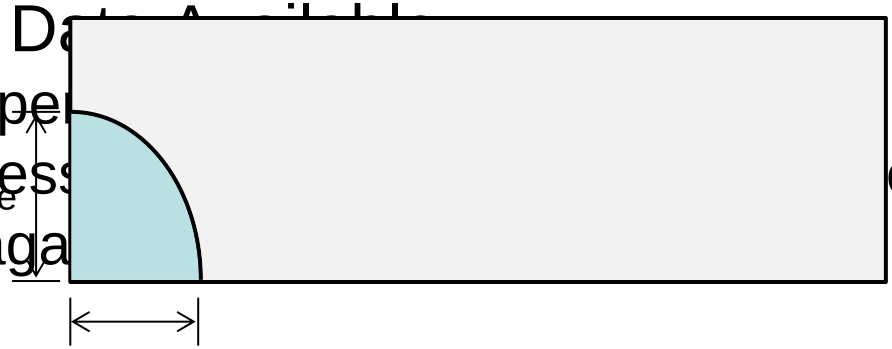
- Cold expansion (CX) of fastener holes have been shown to provide substantial increase in fatigue life
  - Compressive residual stresses (RS) due to cold expansion slow down crack propagation of corner flaws around CX holes
- How to account for the beneficial effect of RS-CX in the computation of fatigue crack propagation life?

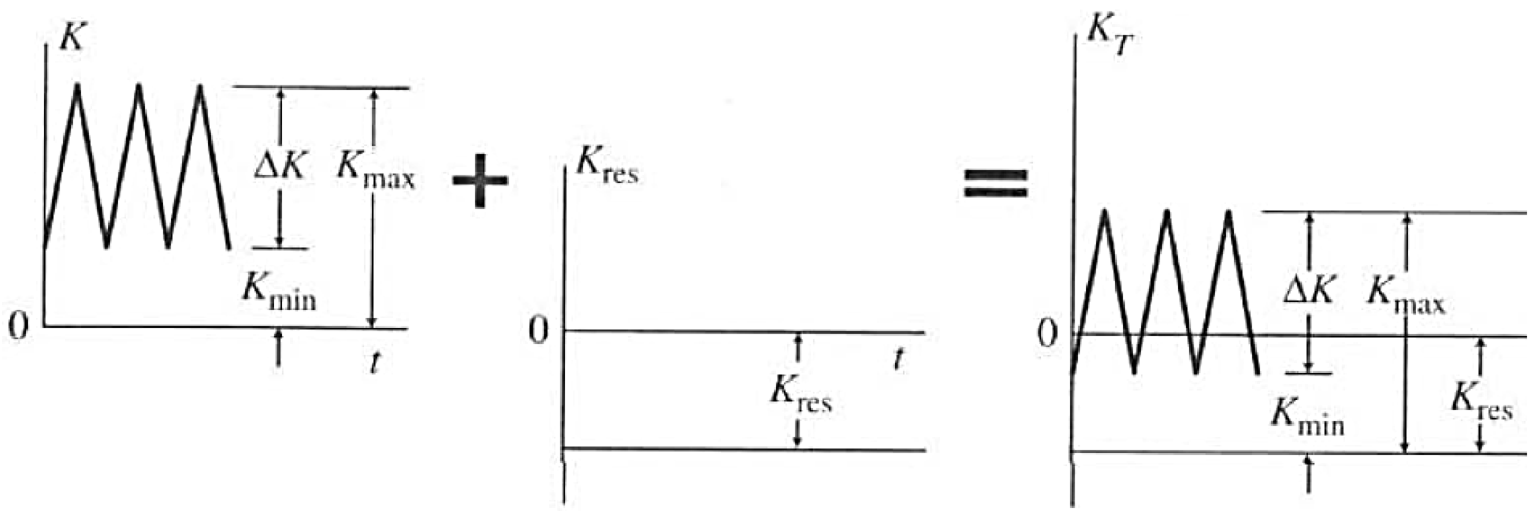
Crack Propagation Model
Background Information

- Given
  - Specimen with a cold-worked (CX) hole
  - Initial crack size in the hole
  - Constant amplitude or variable amplitude remote loading
- Compute
  - The crack trajectory from the initial pre-crack to final failure
  - The crack length vs. number of cycles curve
  - The expected life of the specimen
- Experimental Da
  - Material prope
  - Residual stress … crack (RS)
  - Crack propaga



Crack Propagation Model
Modeling Assumptions

- The driver of fatigue crack propagation is the stress intensity factor amplitude ΔK_I (LEFM)
  - The principle of superposition is applicable
  - Residual stresses only affect the R-ratio of the load cycle



Crack Propagation Model
Modeling Assumptions

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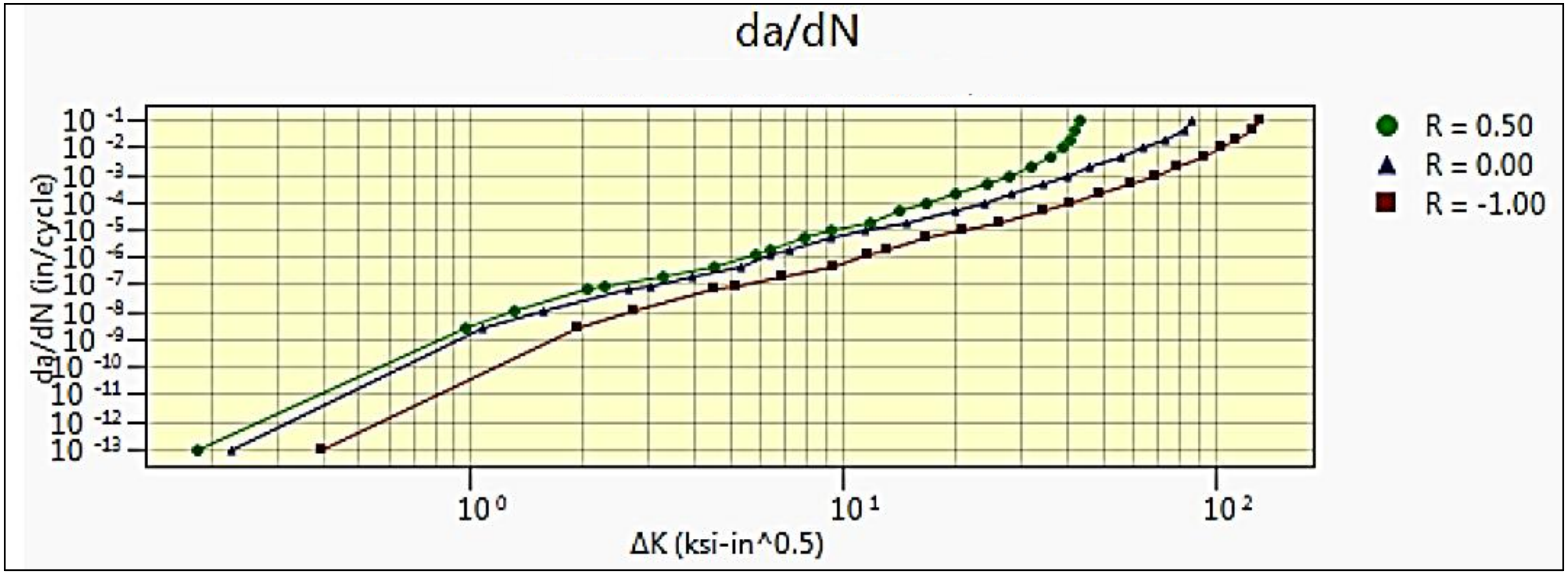
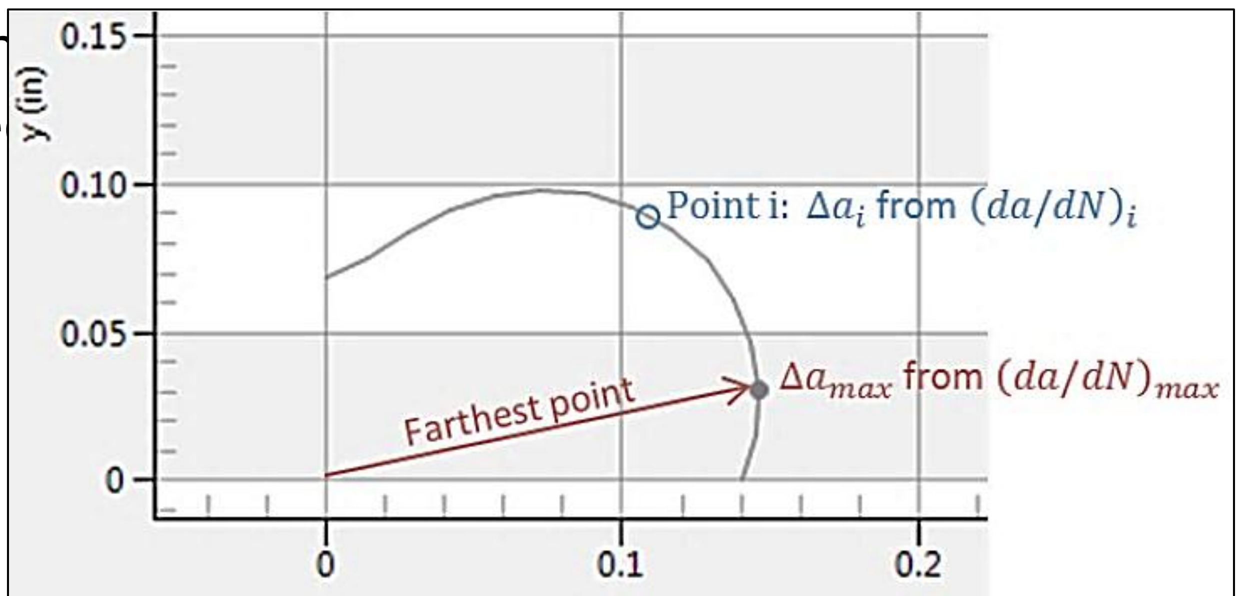
- The relation between the rate of crack growth and Δ*K* is obtained from experimentally-derived da/dN – Δ*K* curves at fixed R-ratios



Crack Propagation Model
Modeling Assumptions

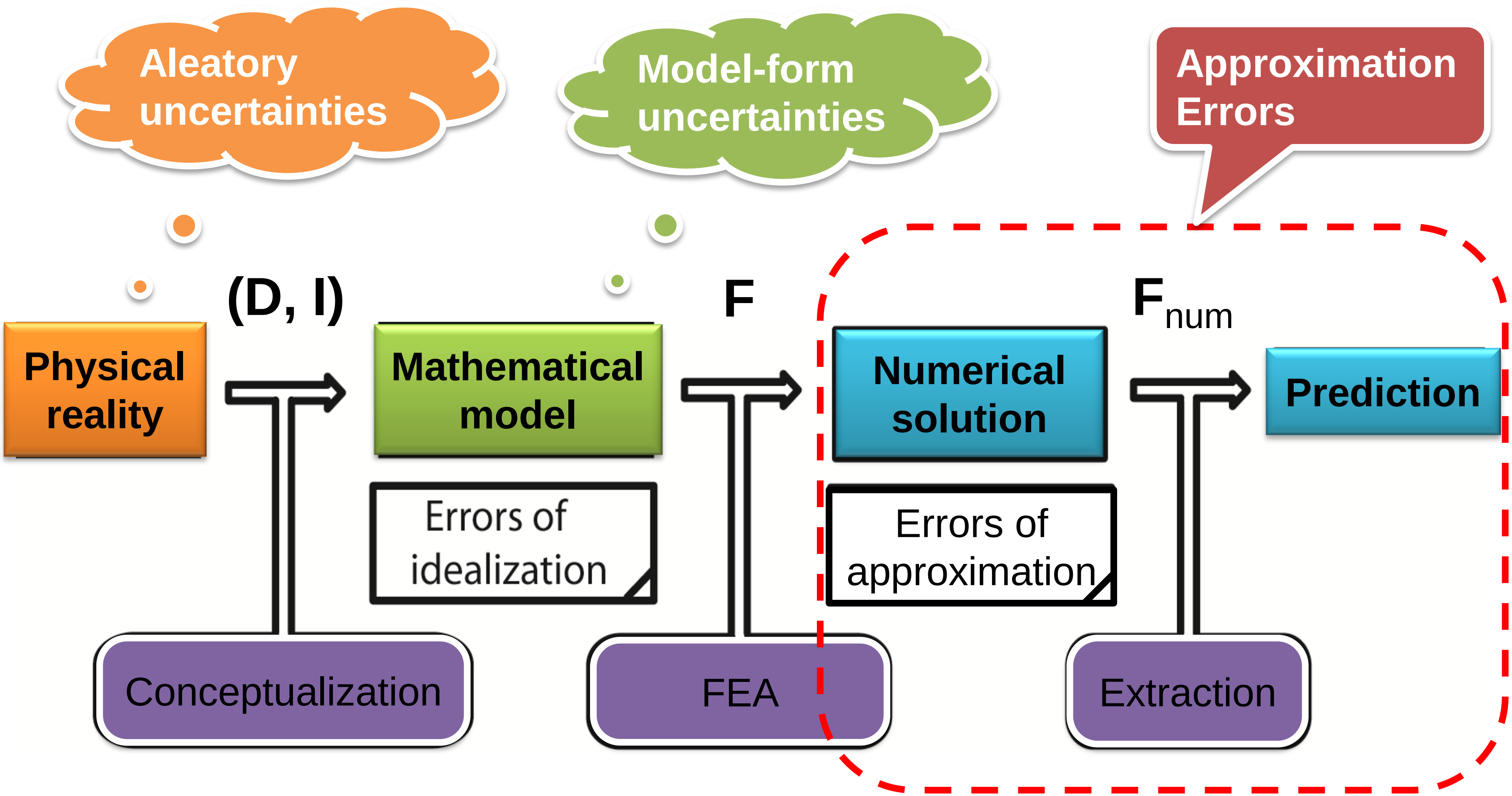
- The direction of crack growth is normal to the crack front
  - The crack grows in the plane of the initial flaw
  - Each point along the crack front has an R-ratio which depends on the RS at the point
  - On … are ne…



Crack Propagation Model
Sources of Error

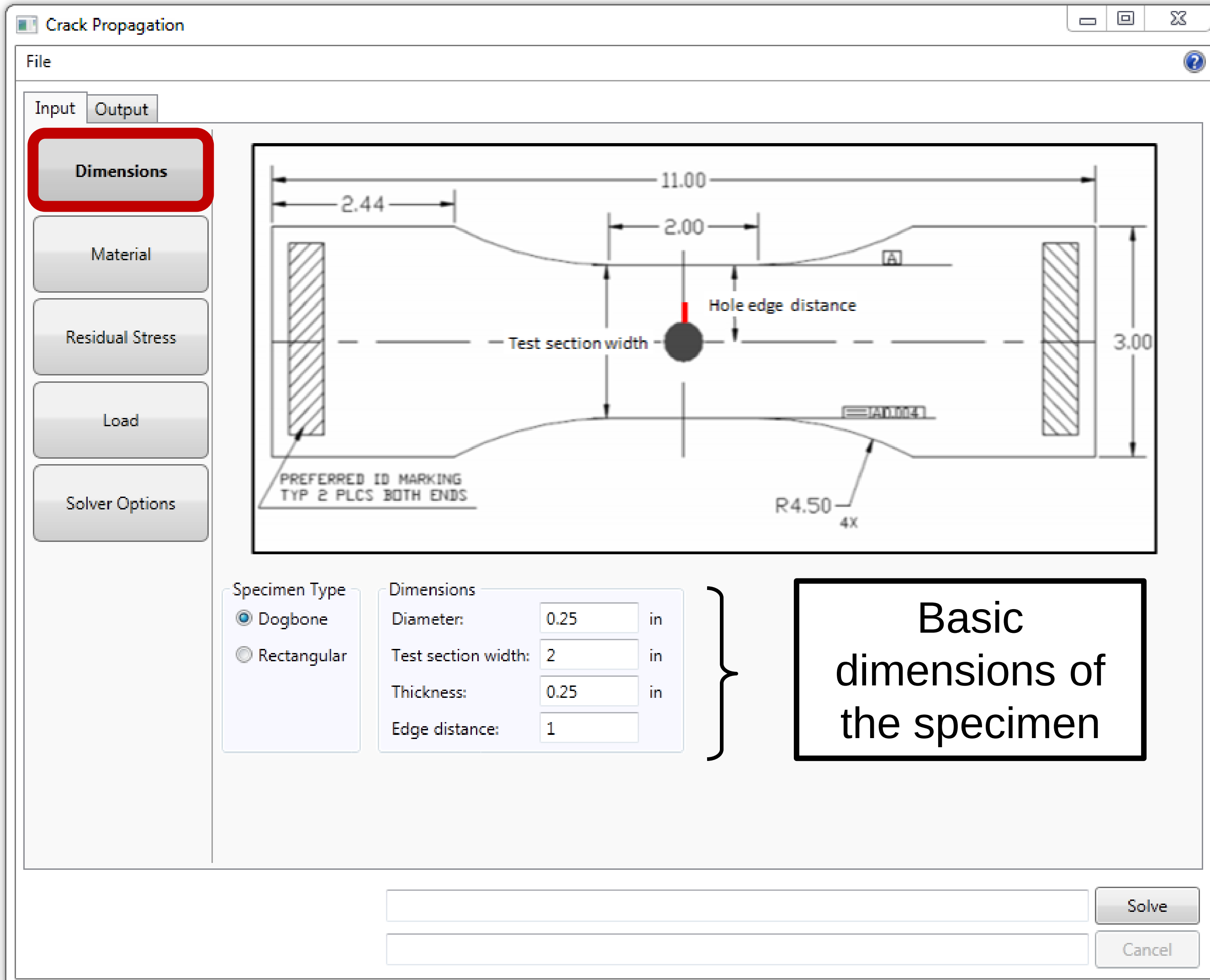
Sources of Error – Crack Propagation Model		
Aleatory (random)	**Epistemic (model-form)**	**Numerical Approximation**
Initial stresses before CX	Driver of crack propagation	Computation of SIFs with RS
Residual stresses after CX	Direction of crack extension	Computation of SIFs remote load
da/dN-ΔK data	Interpolation and fitting of test data	Numerical Integration to find ΔN
		Number of control points to define the crack shape

Sources of Error



Crack Propagation Tool
Input – Dimensions

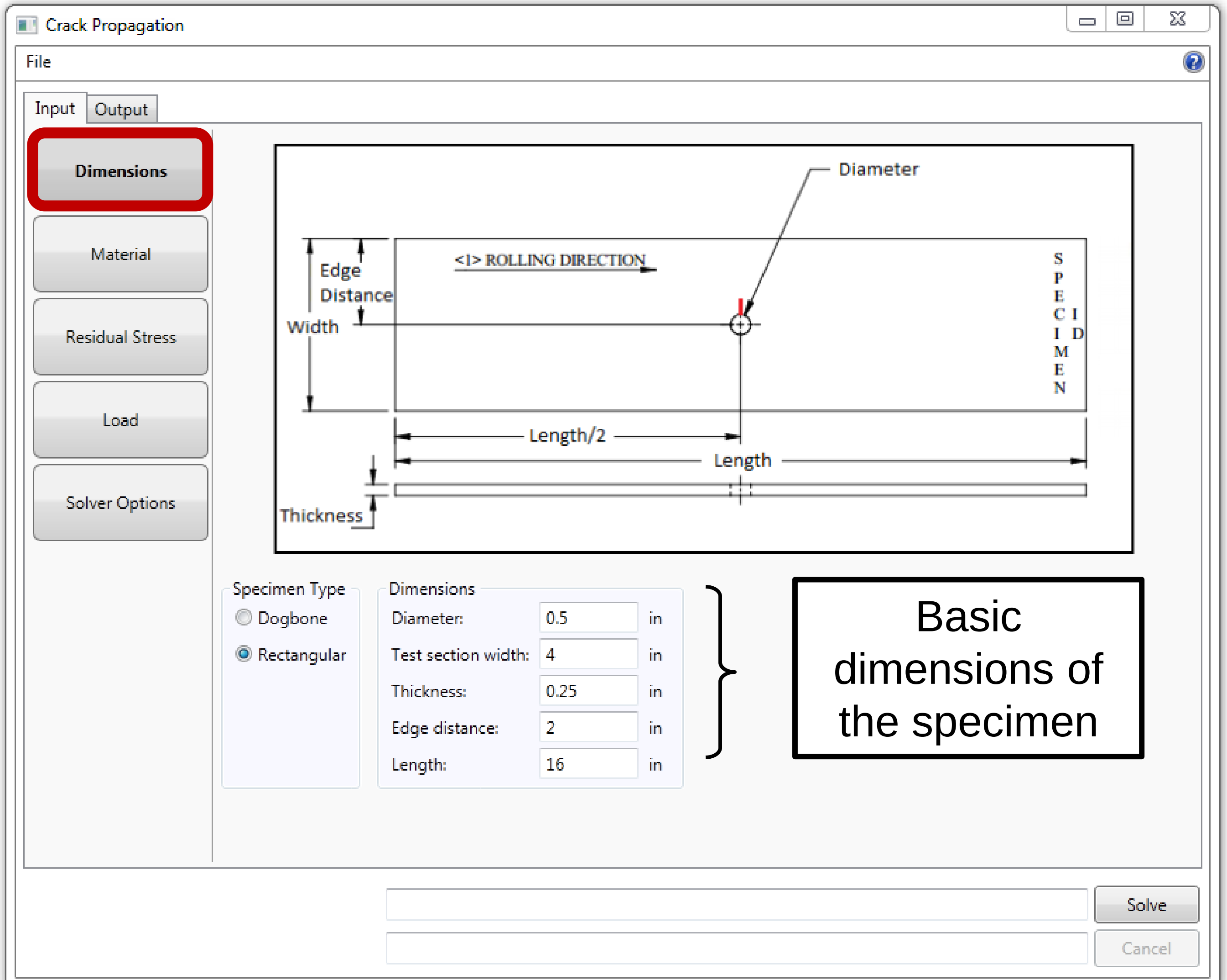
Input options



Basic dimensions of the specimen

Crack Propagation Tool
Input – Dimensions

Input options

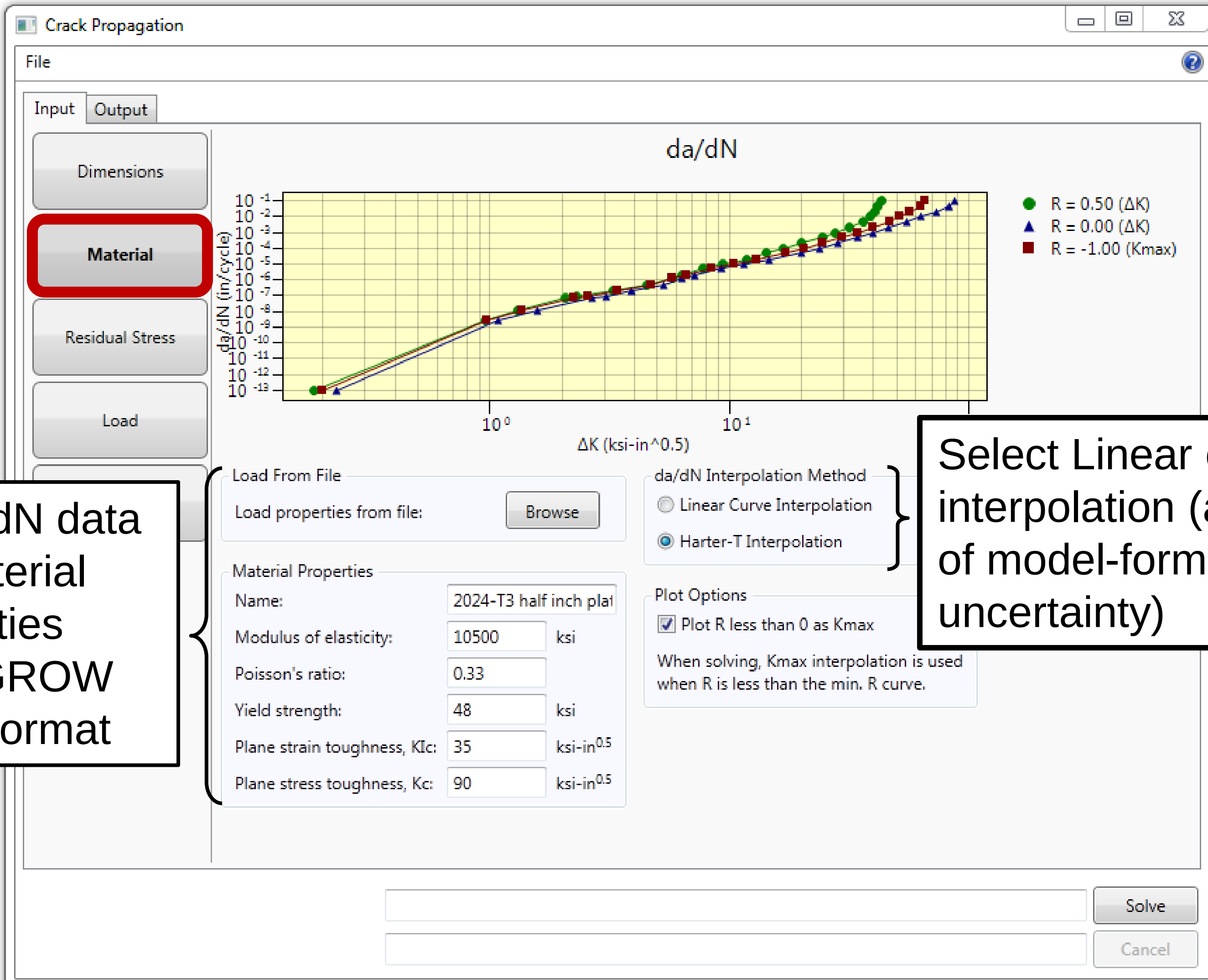


Basic dimensions of the specimen

Crack Propagation Tool

Input – Material

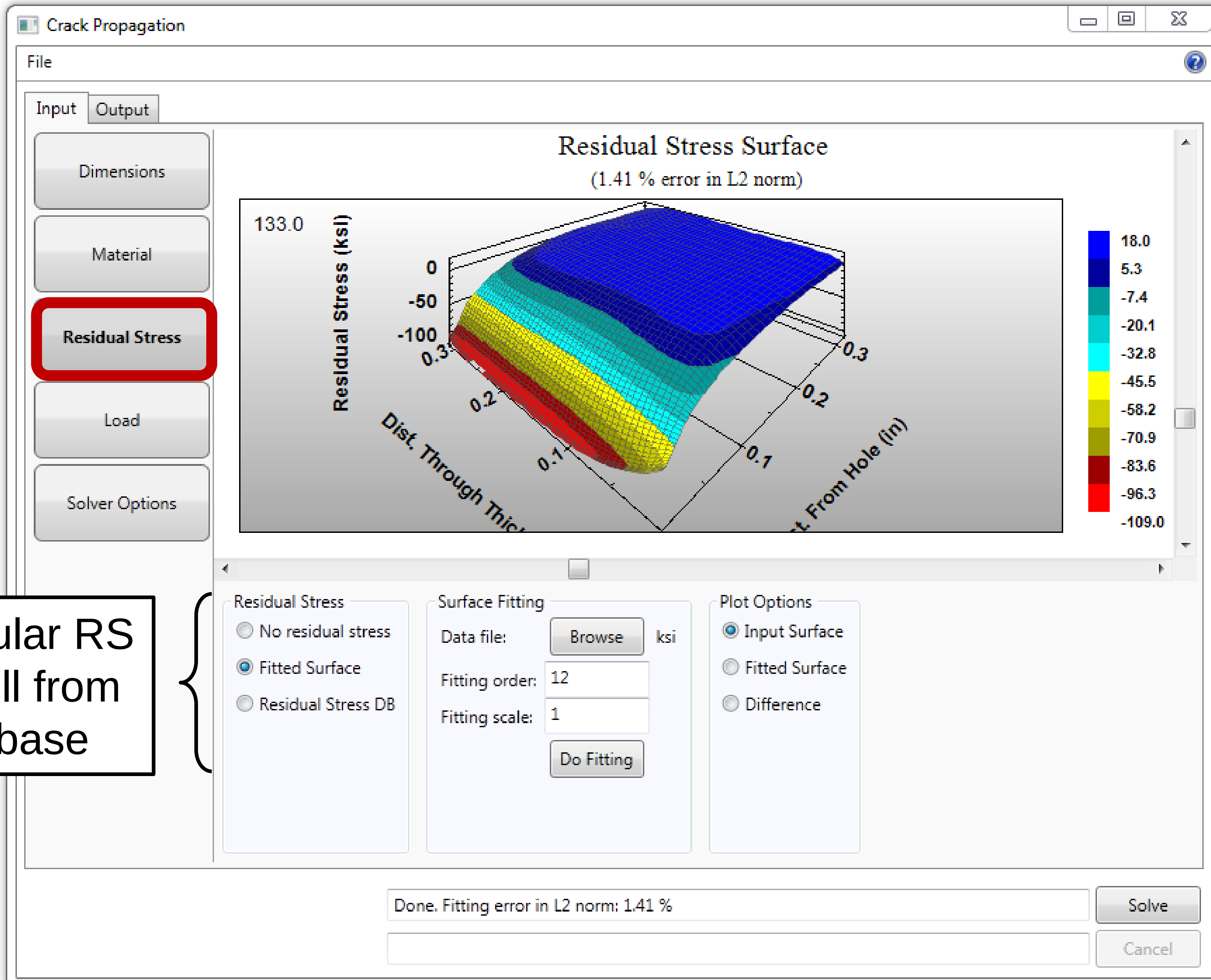
STRESSCHECK



Import da/dN data and material properties from AFGROW *.lkp file format

Select Linear or Harter-T interpolation (assessment of model-form uncertainty)

Crack Propagation Tool
Input – Residual Stresses



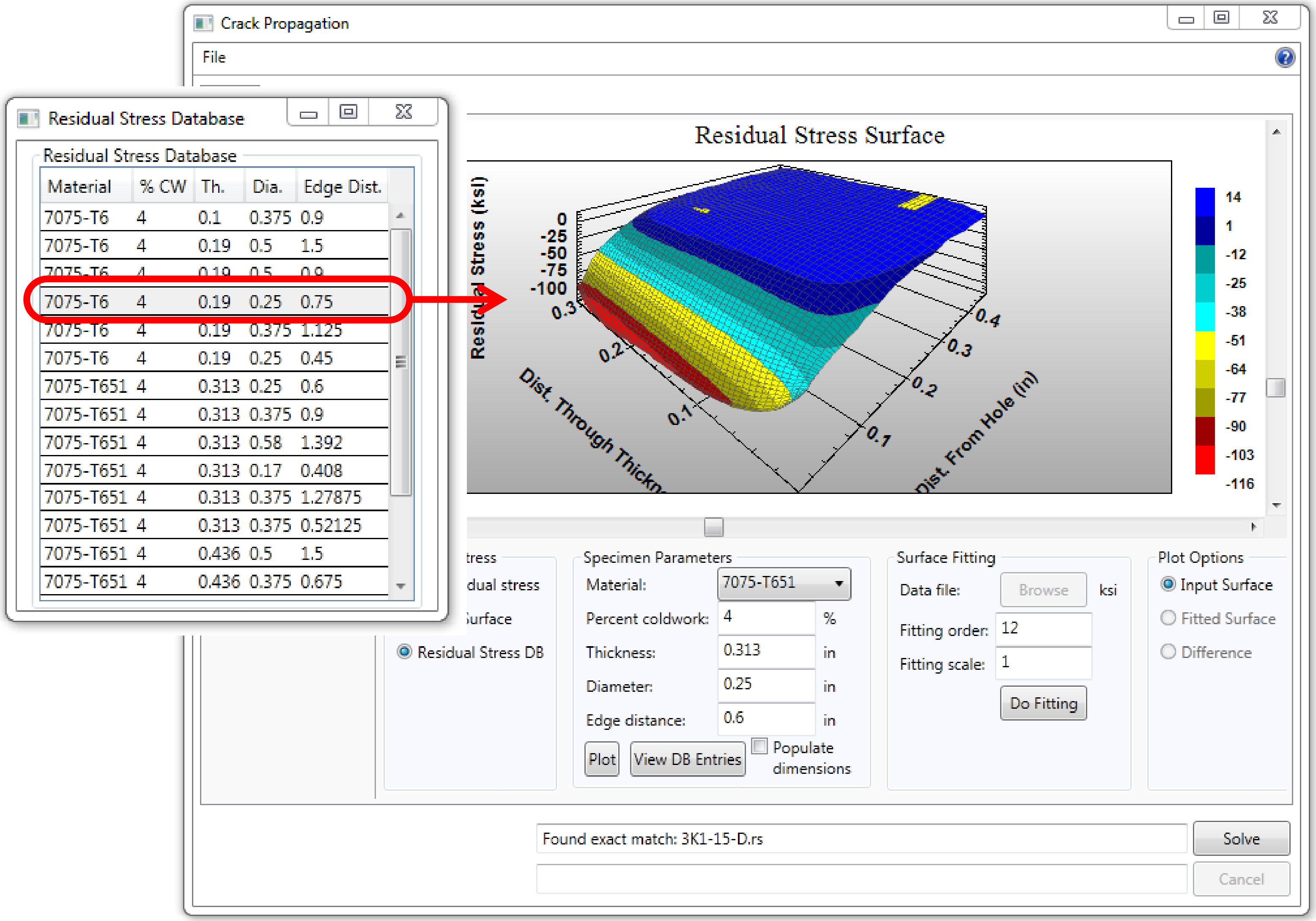
Import tabular RS data or pull from RS database

RS Database

StressCheck

- Residual stress database **rs_database.dll**
  - Accessible from any .Net or COM-enabled software
  - Includes stand alone RS Visualizer for visualization and interpolation
  - Select from measured RS distributions
  - Interpolate between measured RS distributions
    - Interpolation parameters: CW%, thickness, edge distance, hole diameter
  - Populate the database with your own proprietary data in ASCII file format

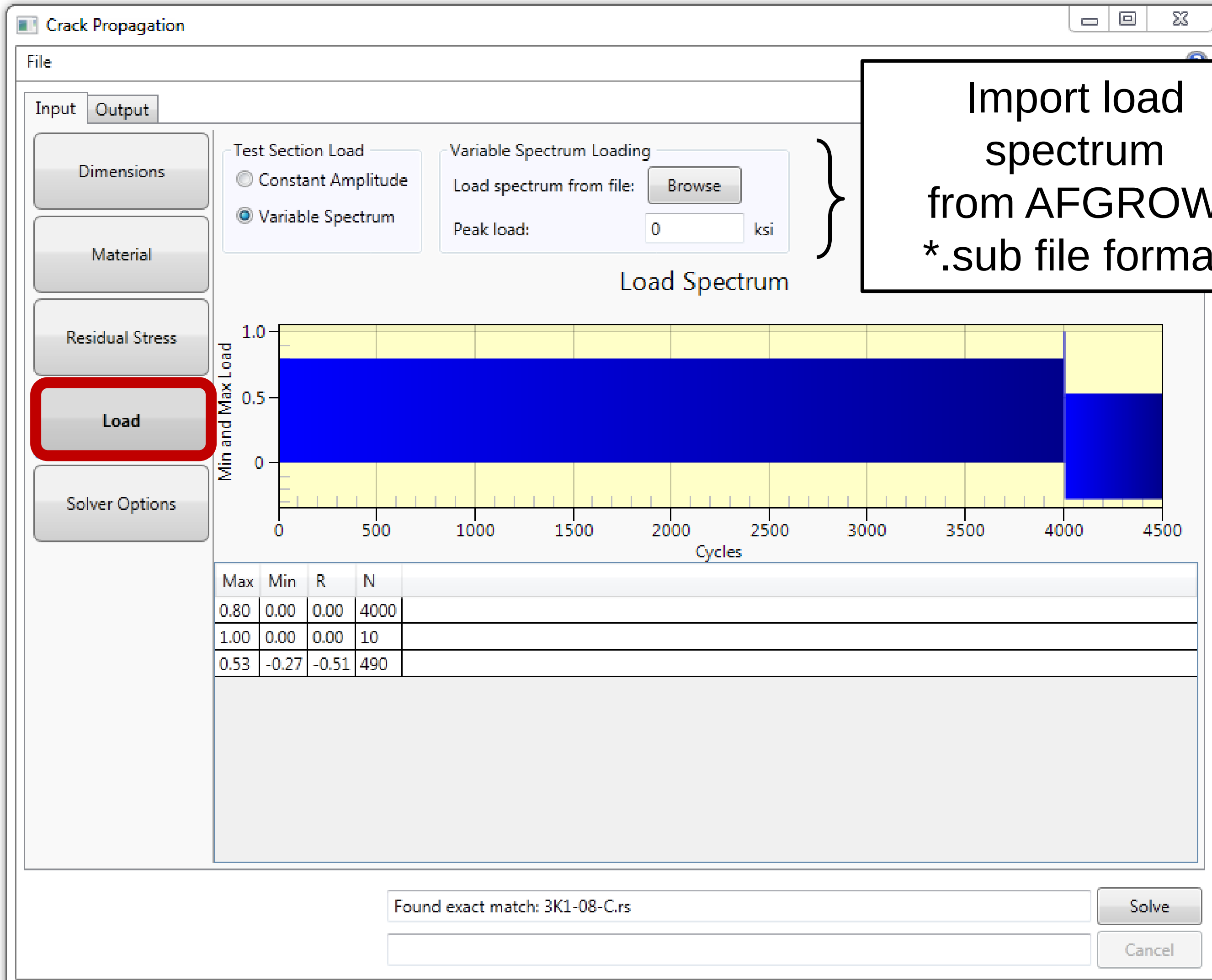
RS Database



Crack Propagation
File
Residual Stress Database
Residual Stress Database
Material | % CW | Th. | Dia. | Edge Dist.
7075-T6 4 0.1 0.375 0.9
7075-T6 4 0.19 0.5 1.5
7075-T6 4 0.19 0.5 0.9
7075-T6 4 0.19 0.25 0.75
7075-T6 4 0.19 0.375 1.125
7075-T6 4 0.19 0.25 0.45
7075-T651 4 0.313 0.25 0.6
7075-T651 4 0.313 0.375 0.9
7075-T651 4 0.313 0.58 1.392
7075-T651 4 0.313 0.17 0.408
7075-T651 4 0.313 0.375 1.27875
7075-T651 4 0.313 0.375 0.52125
7075-T651 4 0.436 0.5 1.5
7075-T651 4 0.436 0.375 0.675
Residual Stress Surface
Residual Stress (ksi)
Dist. Through Thickn
Dist. From Hole (in)
14
1
-12
-25
-38
-51
-64
-77
-90
-103
-116
Residual Stress DB
Specimen Parameters
Material: 7075-T651
Percent coldwork: 4 %
Thickness: 0.313 in
Diameter: 0.25 in
Edge distance: 0.6 in
Plot
View DB Entries
Populate dimensions
Surface Fitting
Data file: Browse ksi
Fitting order: 12
Fitting scale: 1
Do Fitting
Plot Options
Input Surface
Fitted Surface
Difference
Found exact match: 3K1-15-D.rs
Solve
Cancel

Crack Propagation Tool

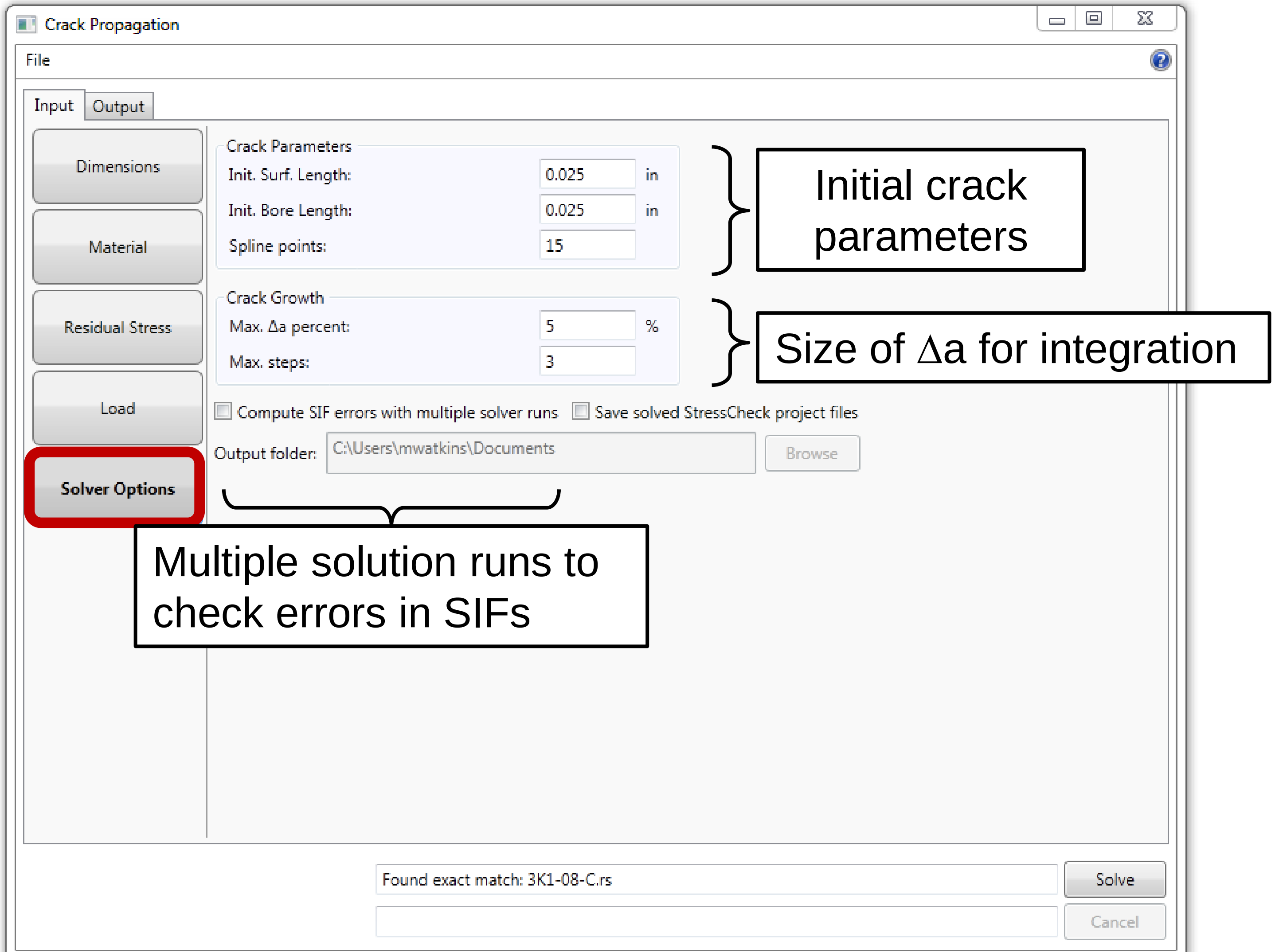
Input – Load



Import load spectrum from AFGROW *.sub file format

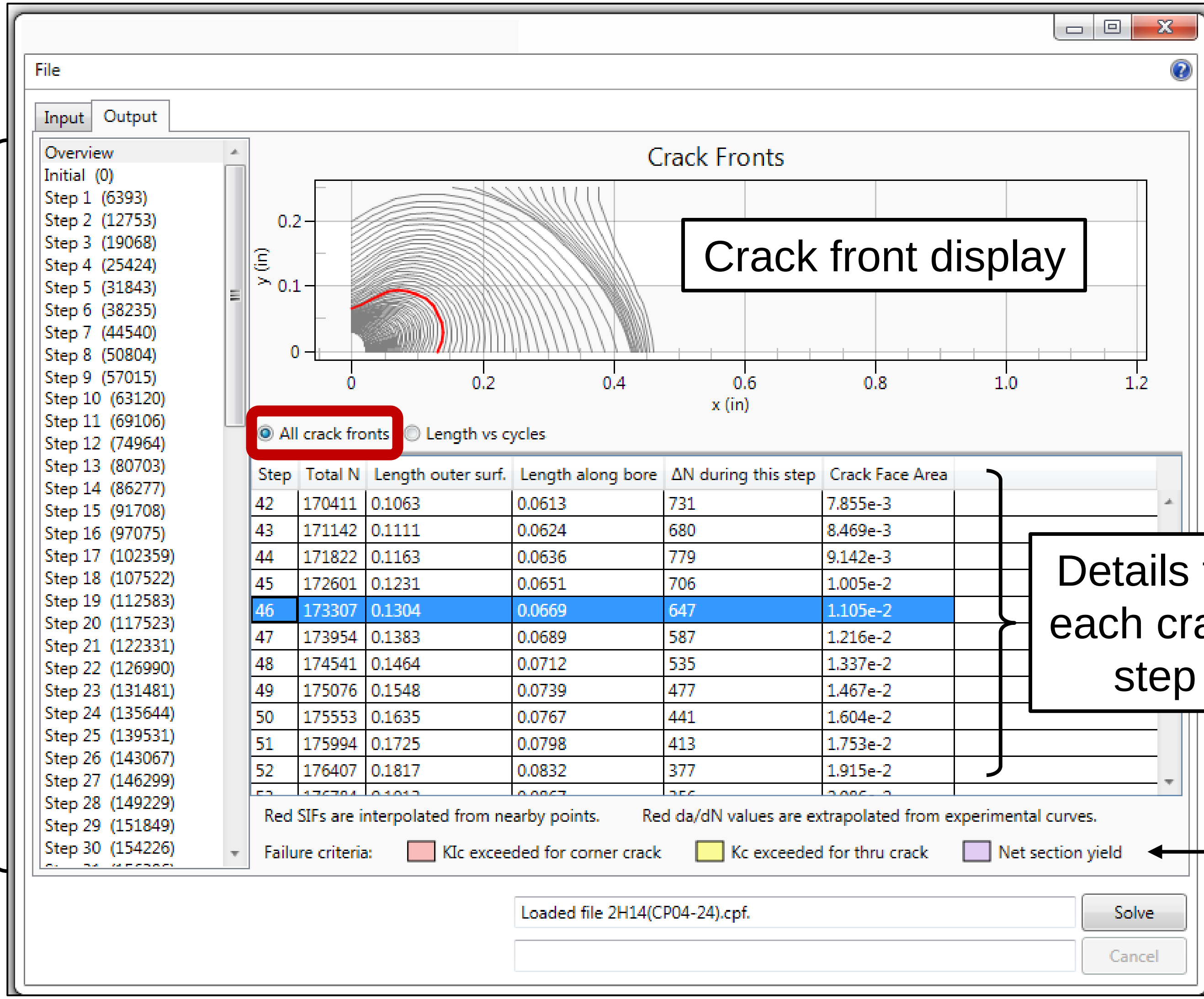
Crack Propagation Tool – CPT

Input – Solver Options



Crack Propagation Tool – CPT **Output**

Crack step selection list



Step	Total N	Length outer surf.	Length along bore	ΔN during this step	Crack Face Area
42	170411	0.1063	0.0613	731	7.855e-3
43	171142	0.1111	0.0624	680	8.469e-3
44	171822	0.1163	0.0636	779	9.142e-3
45	172601	0.1231	0.0651	706	1.005e-2
46	173307	0.1304	0.0669	647	1.105e-2
47	173954	0.1383	0.0689	587	1.216e-2
48	174541	0.1464	0.0712	535	1.337e-2
49	175076	0.1548	0.0739	477	1.467e-2
50	175553	0.1635	0.0767	441	1.604e-2
51	175994	0.1725	0.0798	413	1.753e-2
52	176407	0.1817	0.0832	377	1.915e-2

Details for each crack step

Failure indicators

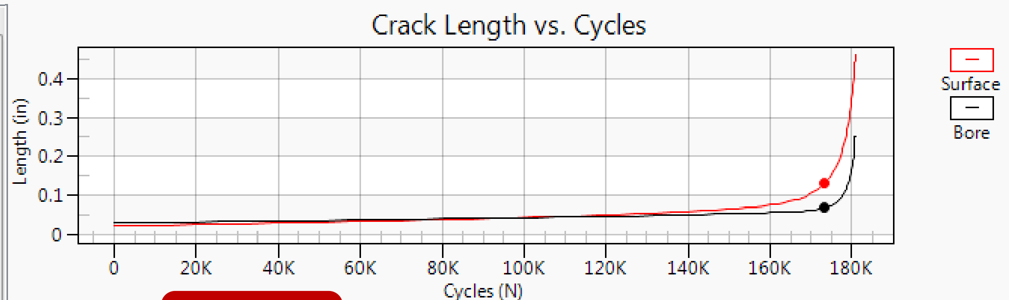
Crack Propagation Tool – CPT Output

File

Input | Output

Crack step selection list

- Overview
- Initial (0)
- Step 1 (6393)
- Step 2 (12753)
- Step 3 (19068)
- Step 4 (25424)
- Step 5 (31843)
- Step 6 (38235)
- Step 7 (44540)
- Step 8 (50804)
- Step 9 (57015)
- Step 10 (63120)
- Step 11 (69106)
- Step 12 (74964)
- Step 13 (80703)
- Step 14 (86277)
- Step 15 (91708)
- Step 16 (97075)
- Step 17 (102359)
- Step 18 (107522)
- Step 19 (112583)
- Step 20 (117523)
- Step 21 (122331)
- Step 22 (126990)
- Step 23 (131481)
- Step 24 (135644)
- Step 25 (139531)
- Step 26 (143067)
- Step 27 (146299)
- Step 28 (149229)
- Step 29 (151849)
- Step 30 (154226)



All crack fronts | Length vs cycles

Step	Total N	Length outer surf.	Length along bore	ΔN during this step	Crack Face Area
42	170411	0.1063	0.0613	731	7.855e-3
43	171142	0.1111	0.0624	680	8.469e-3
44	171822	0.1163	0.0636	779	9.142e-3
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49	175076	0.1548	0.0739	477	1.467e-2
50	175553	0.1635	0.0767	441	1.604e-2
51	175994	0.1725	0.0798	413	1.753e-2
52	176407	0.1817	0.0832	377	1.915e-2

Details for each crack step

Red SIFs are interpolated from nearby points. Red da/dN values are extrapolated from experimental curves.

Failure criteria: KIc exceeded for corner crack | Kc exceeded for thru crack | Net section yield

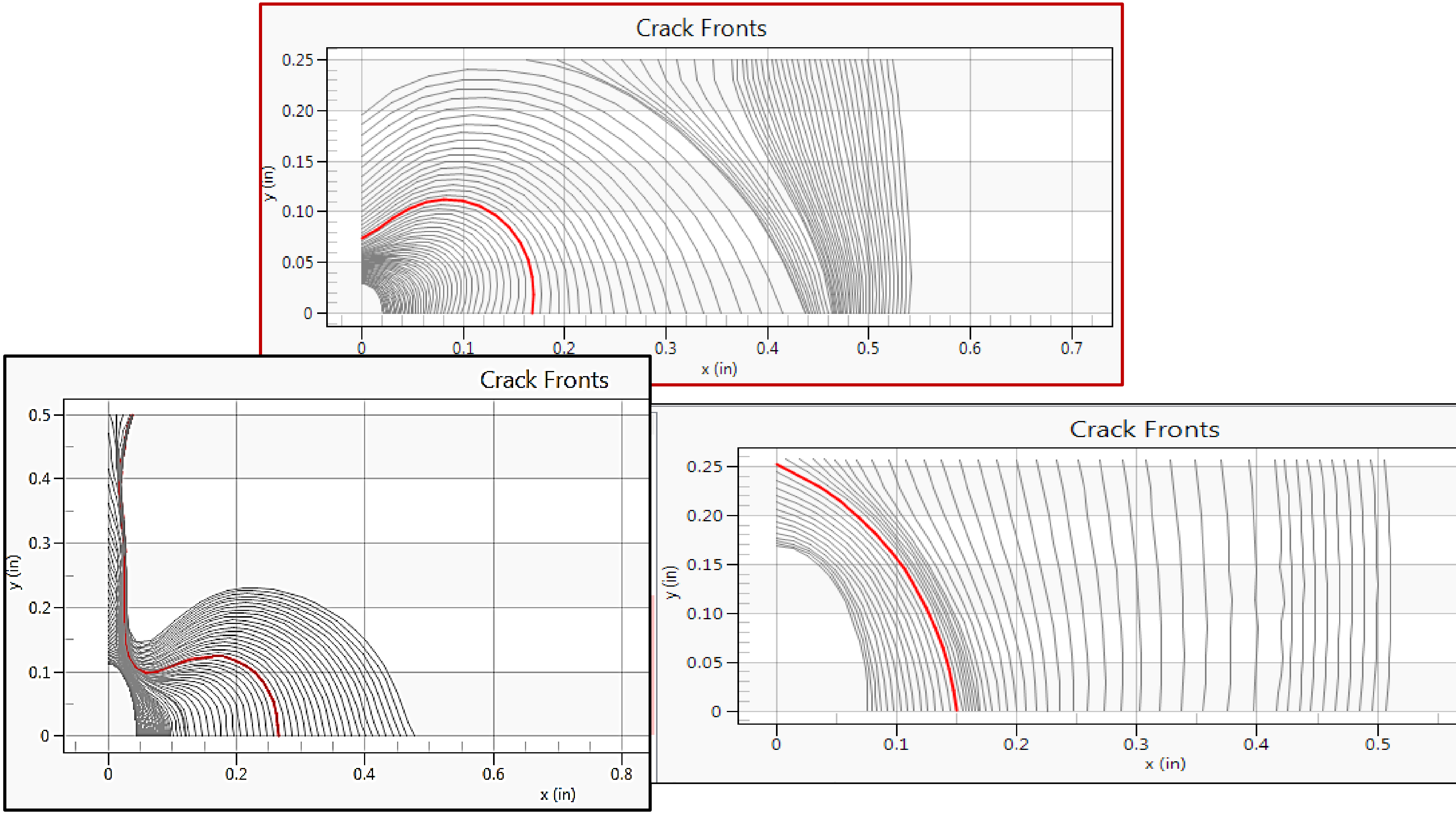
Failure indicators

Loaded file 2H14(CP04-24).cpf.

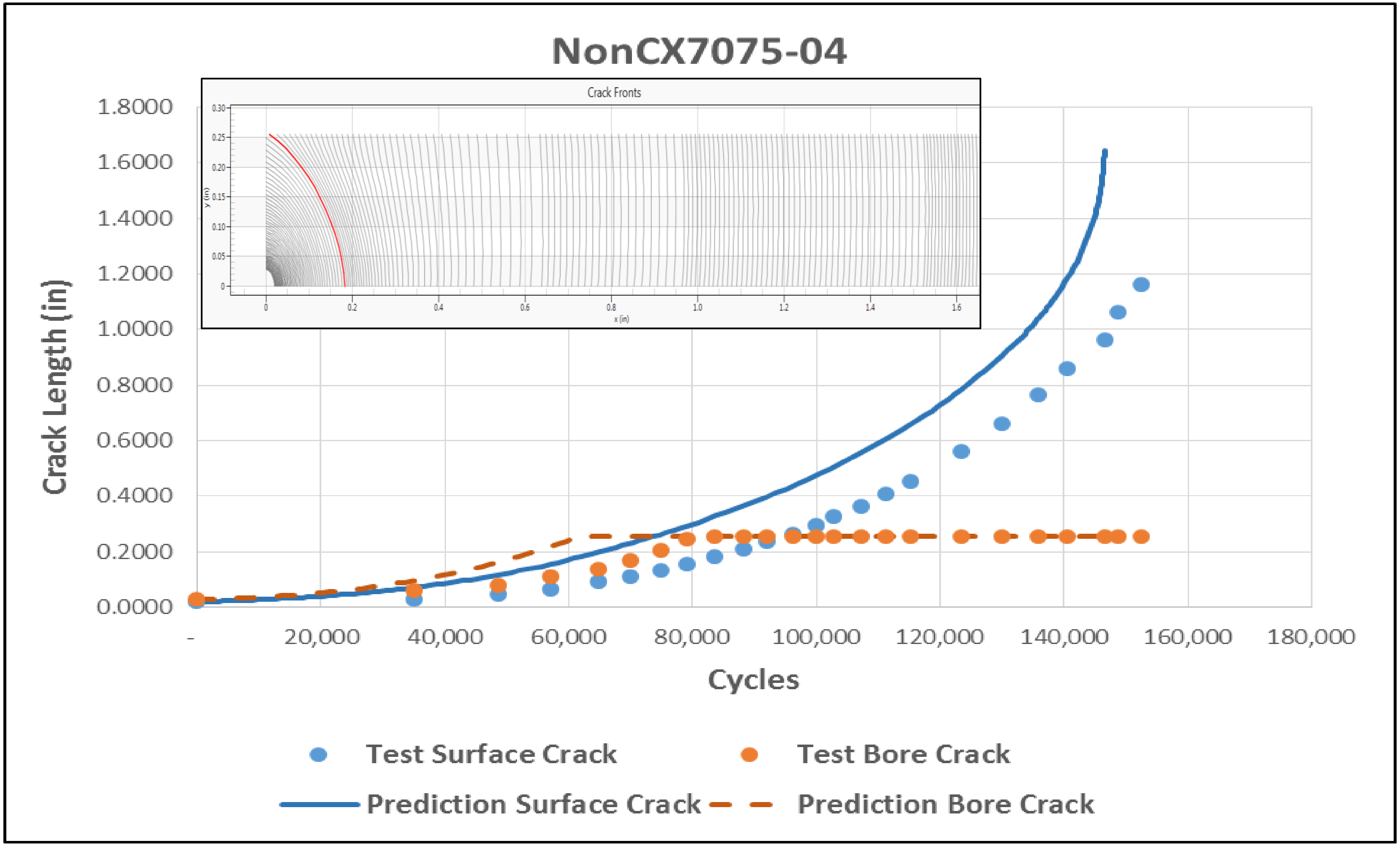
Solve

Cancel

Crack Propagation Tool – CPT
Sample Results



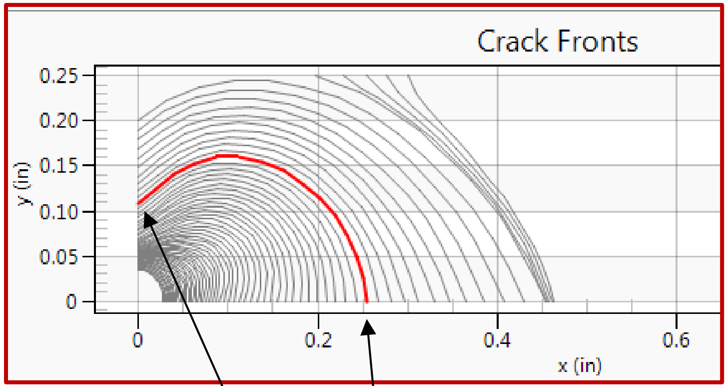
Experimental Comparisons
No RS (Not Coldworked)

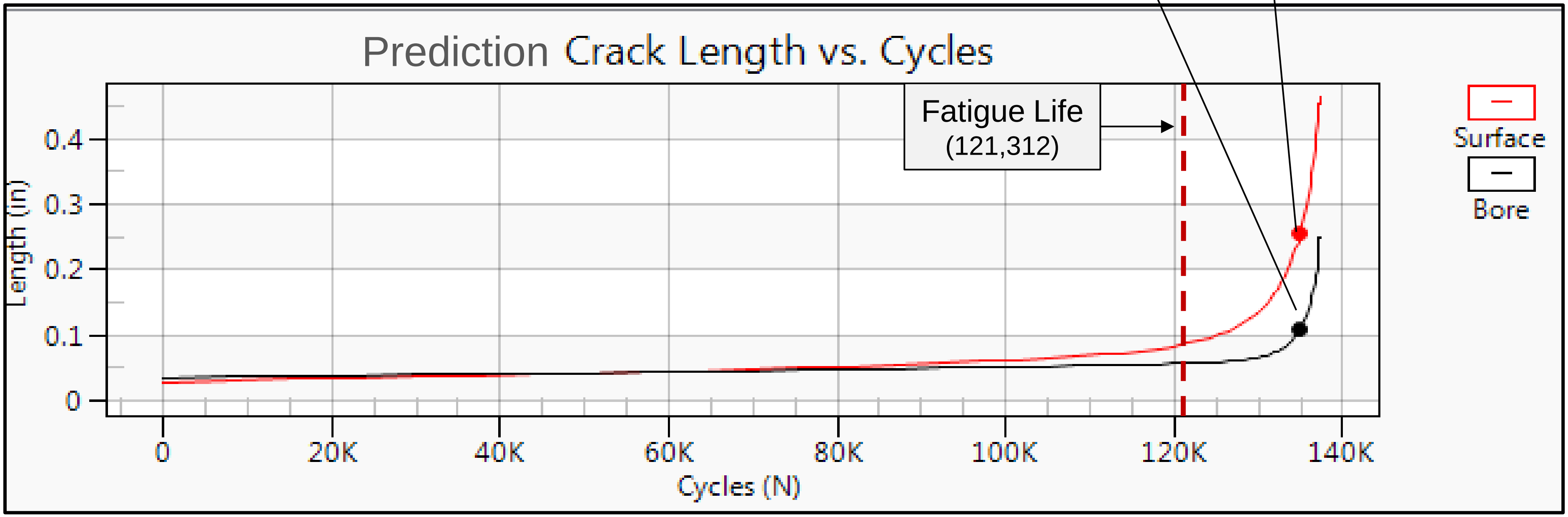


* Robert Pilarczyk, *Experimentally Derived Beta Corrections to Predict Fatigue Crack Growth at Cold Expanded Holes in 7075-T651*, Master Thesis, Department of Mechanical Engineering, University of Utah, May 2008

Experimental Comparisons
Cold-Worked & Pre-Cracked

Coupon	Surface Pre-crack, in.	Bore Pre-crack, in.	Fatigue Life, Cycles
1	0.02810	0.03486	121312
2	0.02166	0.04136	65890
3	0.02200	0.03204	126587
4	0.02032	0.02936	180066





Experimental Comparisons
Sensitivity to RS

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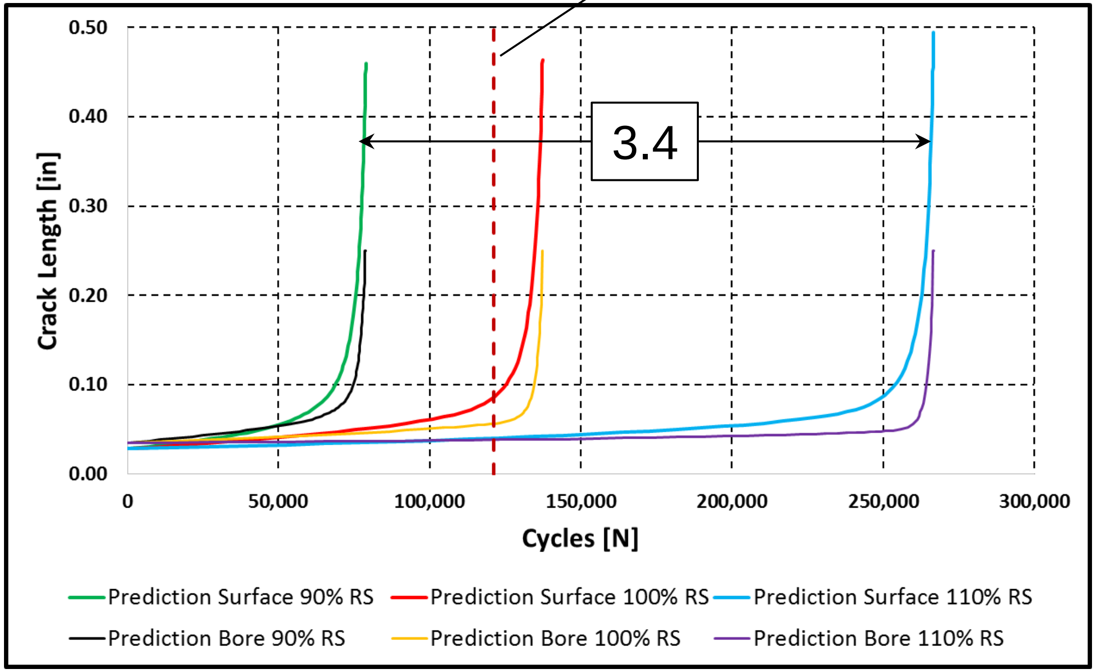
Predicted Life [Cycles]			Specimen Life [Cycles]
90% RS	100% RS	110% RS	
78,913	137,305	266,500	121,312

+/-10% variation in RS

Prediction → 137,305 { + 94% / – 43%



Summary & Conclusions

StressCheck

- The modeling assumption were clearly defined
  - For in-plane crack propagation only the component of the residual stress tensor normal to the plane is required
- K_{RES} is computed independently of K_{MECH}
  - K_{RES} and K_{MECH} are computed using the contour integral method
  - $K_{RES\text{-}NUM}$ and $K_{MECH\text{-}NUM}$ are obtained by the finite element method at each control point along the crack front using StressCheck

Summary & Conclusions

- The proposed model accounts for the beneficial effects of RS in the calculation of fatigue life of cracks in CX holes
  - Good estimates of crack propagation life
  - Crack propagation maps consistent with experimental observations
- Prediction of fatigue life is strongly affected by the statistical dispersion of the residual stresses
  - 10% in RS $\rightarrow$ a factor of 3 or more in fatigue life estimates

Acknowledgment

STRESSCHECK

- This work was performed in support of the project
  - *Integrating Residual Stress Analysis of Critical Fastener Holes into USAF Depot Maintenance*
    - Rapid Innovation Fund (RIF) program AFRL-PK-11-0001
    - Contract USAF AFRL/RVKVS FA9453-12-C-0218
    - TPOC: Robert Pilarczyk, AFLCMC/WWAEJ Hill AFB, UT
      - robert.pilarczyk@us.af.mil