

AFGROW User's Workshop 2014

Prediction of Fatigue Crack Propagation from Cold-Expanded Holes

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- 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



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- 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**

$$(D, I) \rightarrow F$$

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



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- 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

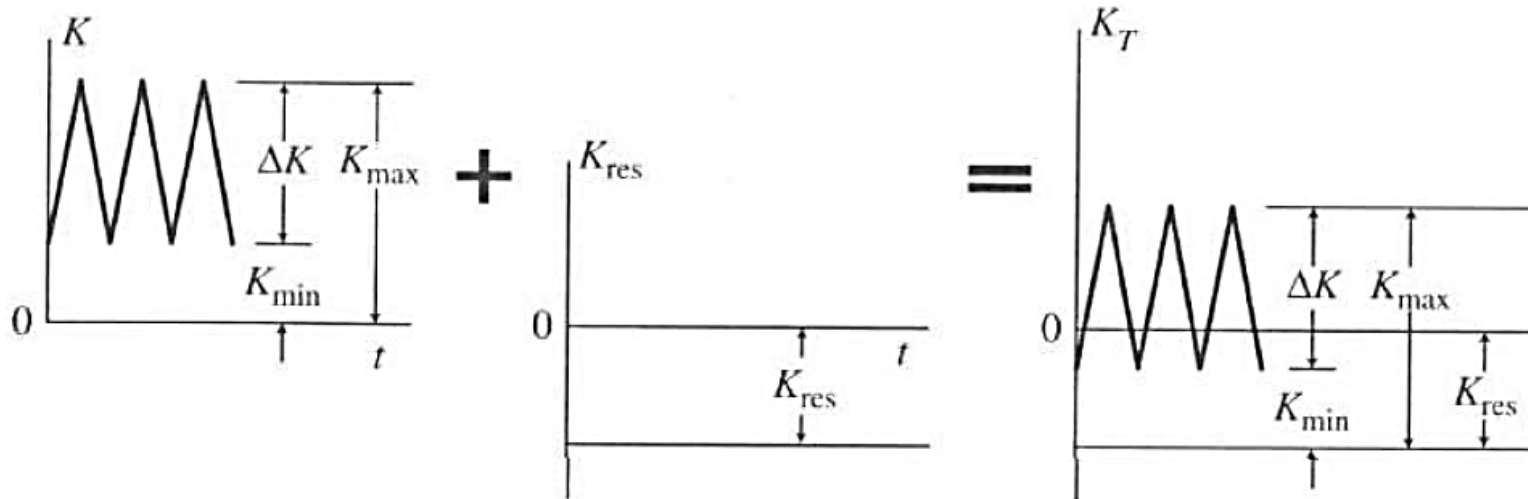
- Experimental Data
 - Material properties
 - Residual stress
 - Crack propagation
-
- Crack length bore
- Crack length surface
- crack (RS)

Crack Propagation Model Modeling Assumptions



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- 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

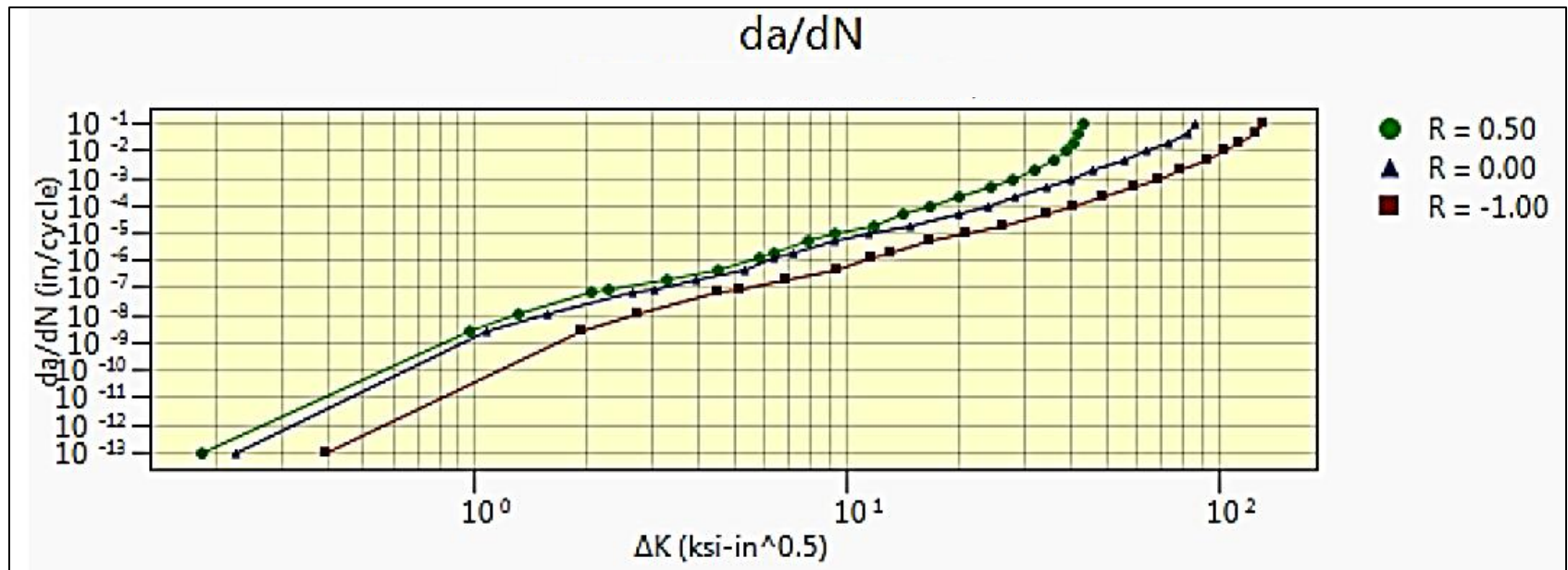


Crack Propagation Model Modeling Assumptions



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

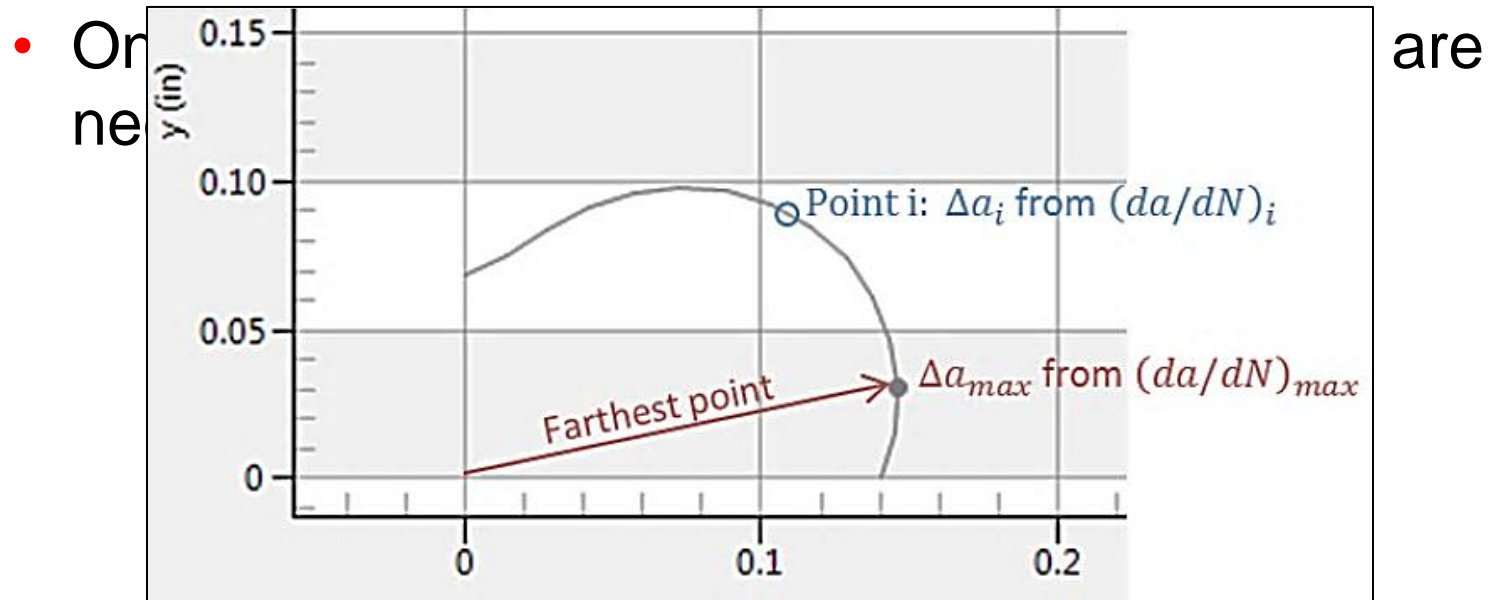


Crack Propagation Model Modeling Assumptions



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- 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



Crack Propagation Model

Sources of Error



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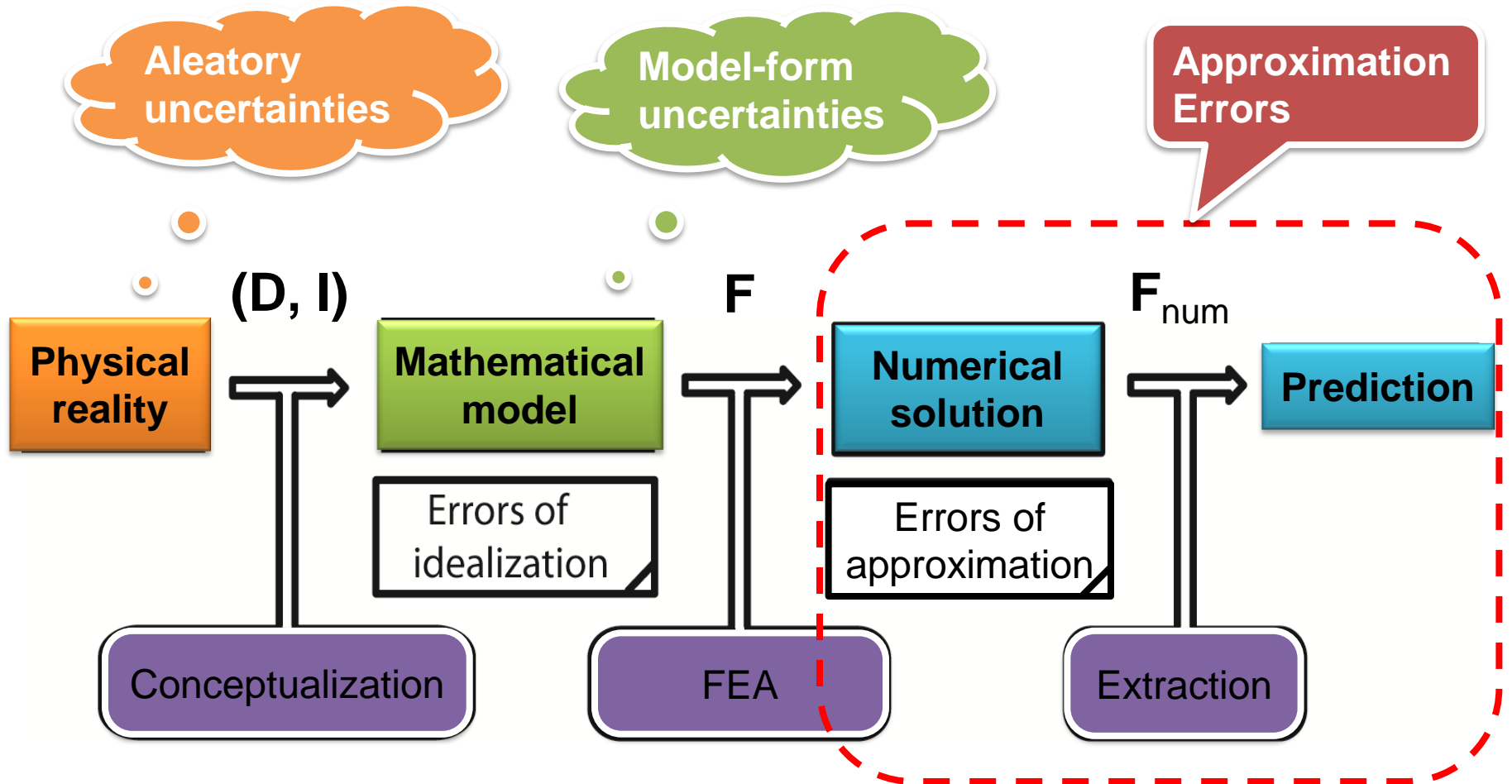
Sources of Error – Crack Propagation Model

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



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Crack Propagation Tool Input – Dimensions



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Input options

Crack Propagation

File

Input Output

Dimensions

Material

Residual Stress

Load

Solver Options

Specimen Type

Dogbone

Rectangular

Dimensions

Diameter: 0.25 in

Test section width: 2 in

Thickness: 0.25 in

Edge distance: 1

Solve

Cancel

Basic dimensions of the specimen

Crack Propagation Tool

Input – Dimensions



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The screenshot shows the 'Crack Propagation' software window. On the left, there is a sidebar with 'Input' and 'Output' tabs. Under 'Input', there are five buttons: 'Dimensions' (highlighted with a red box), 'Material', 'Residual Stress', 'Load', and 'Solver Options'. A bracket on the left side of the sidebar is labeled 'Input options'. The main area contains a diagram of a specimen with various dimensions labeled: 'Edge Distance', 'Width', 'Thickness', 'Length/2', 'Length', and 'Diameter'. The diagram also shows '<1> ROLLING DIRECTION' and 'SPECIMEN'. Below the diagram, there is a 'Specimen Type' section with radio buttons for 'Dogbone' and 'Rectangular' (selected). To the right of this is a 'Dimensions' table with input fields for Diameter, Test section width, Thickness, Edge distance, and Length, each with a unit of 'in'. A bracket on the right side of this table is labeled 'Basic dimensions of the specimen'. At the bottom right, there are 'Solve' and 'Cancel' buttons.

Dimensions	Value	Unit
Diameter:	0.5	in
Test section width:	4	in
Thickness:	0.25	in
Edge distance:	2	in
Length:	16	in

Crack Propagation Tool

Input – Material



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The screenshot shows the 'Crack Propagation' software interface. The 'Material' tab is selected in the left-hand menu. The main window displays a log-log plot of crack growth rate da/dN (in/cycle) versus stress intensity range ΔK (ksi-in^{0.5}). The plot shows three data series: $R = 0.50$ (ΔK) represented by green circles, $R = 0.00$ (ΔK) represented by blue triangles, and $R = -1.00$ (Kmax) represented by red squares. Below the plot, the 'Material Properties' section is filled out for '2024-T3 half inch plai'. The 'da/dN Interpolation Method' is set to 'Harter-T Interpolation'. The 'Plot Options' section has 'Plot R less than 0 as Kmax' checked.

Property	Value	Units
Name	2024-T3 half inch plai	
Modulus of elasticity	10500	ksi
Poisson's ratio	0.33	
Yield strength	48	ksi
Plane strain toughness, K _{Ic}	35	ksi-in ^{0.5}
Plane stress toughness, K _c	90	ksi-in ^{0.5}

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



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Crack Propagation

File

Input Output

Dimensions

Material

Residual Stress

Load

Solver Options

Residual Stress Surface
(1.41 % error in L2 norm)

133.0

Residual Stress (ksi)

Dist. Through Thickness (in)

Dist. From Hole (in)

18.0
5.3
-7.4
-20.1
-32.8
-45.5
-58.2
-70.9
-83.6
-96.3
-109.0

Residual Stress

No residual stress

Fitted Surface

Residual Stress DB

Surface Fitting

Data file: ksi

Fitting order: 12

Fitting scale: 1

Plot Options

Input Surface

Fitted Surface

Difference

Done. Fitting error in L2 norm: 1.41 %

Import tabular RS data or pull from RS database



- 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



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Crack Propagation

File

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 Thickness (in)

Dist. From Hole (in)

Material: 7075-T651

Percent coldwork: 4 %

Thickness: 0.313 in

Diameter: 0.25 in

Edge distance: 0.6 in

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



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Crack Propagation

File

Input Output

Dimensions

Material

Residual Stress

Load

Solver Options

Test Section Load

Constant Amplitude

Variable Spectrum

Variable Spectrum Loading

Load spectrum from file:

Peak load: ksi

Load Spectrum

Max	Min	R	N
0.80	0.00	0.00	4000
1.00	0.00	0.00	10
0.53	-0.27	-0.51	490

Found exact match: 3K1-08-C.rs

Import load spectrum from AFGROW *.sub file format

Crack Propagation Tool – CPT Input – Solver Options



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The screenshot shows the 'Crack Propagation' software window. The 'Input' tab is selected. On the left, there are buttons for 'Dimensions', 'Material', 'Residual Stress', 'Load', and 'Solver Options'. The 'Solver Options' button is highlighted with a red border. The main area contains the following settings:

- Crack Parameters:**
 - Init. Surf. Length: 0.025 in
 - Init. Bore Length: 0.025 in
 - Spline points: 15
- Crack Growth:**
 - Max. Δa percent: 5 %
 - Max. steps: 3
- Compute SIF errors with multiple solver runs
- Save solved StressCheck project files
- Output folder: C:\Users\mwatkins\Documents

Annotations with brackets point to specific sections:

- A bracket groups the 'Crack Parameters' fields with the text 'Initial crack parameters'.
- A bracket groups the 'Crack Growth' fields with the text 'Size of Δa for integration'.
- A bracket groups the 'Compute SIF errors with multiple solver runs' checkbox with the text 'Multiple solution runs to check errors in SIFs'.

At the bottom, there is a search bar containing 'Found exact match: 3K1-08-C.rs' and 'Solve' and 'Cancel' buttons.

Crack Propagation Tool – CPT Output



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The screenshot displays the 'Crack Fronts' window. On the left is a 'Crack step selection list' with steps 0 through 30. The main plot shows 'Crack front display' with x and y axes in inches. Below the plot are radio buttons for 'All crack fronts' (selected) and 'Length vs cycles'. A table below shows crack data for steps 42 to 52. A callout 'Details for each crack step' points to the table. At the bottom, 'Failure indicators' are shown as colored boxes: red for 'K_{Ic} exceeded for corner crack', yellow for 'K_{Ic} exceeded for thru crack', and purple for 'Net section yield'. The 'Solve' button is highlighted.

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

Crack step selection list

Crack front display

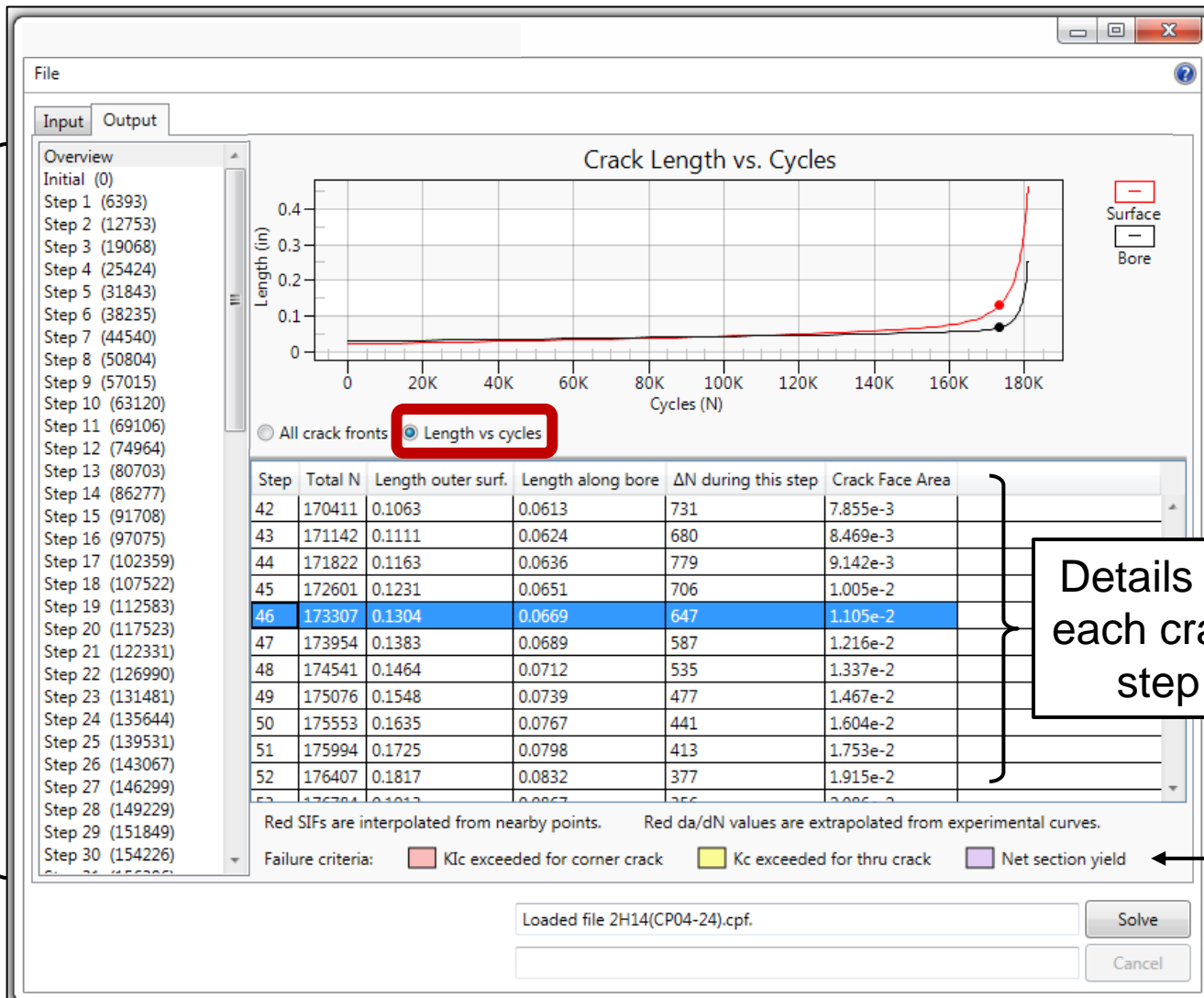
Details for each crack step

Failure indicators

Crack Propagation Tool – CPT Output



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Crack step selection list

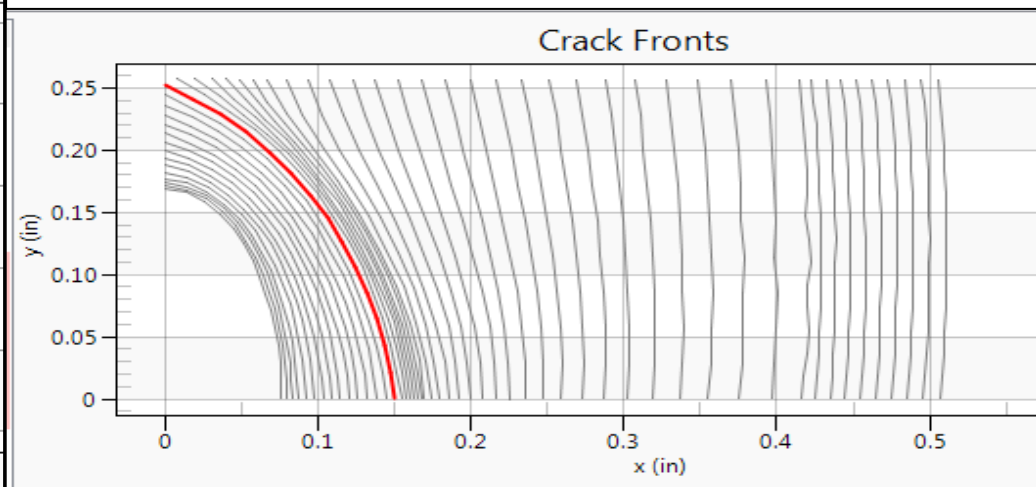
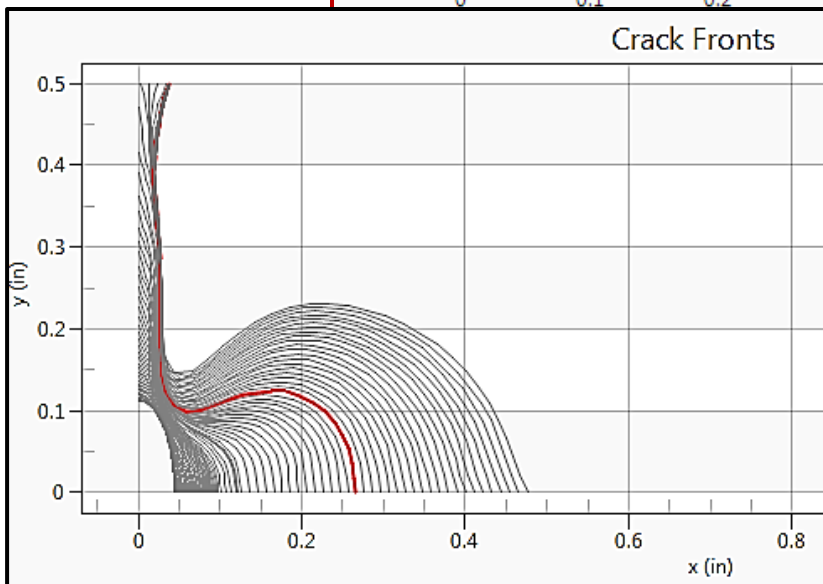
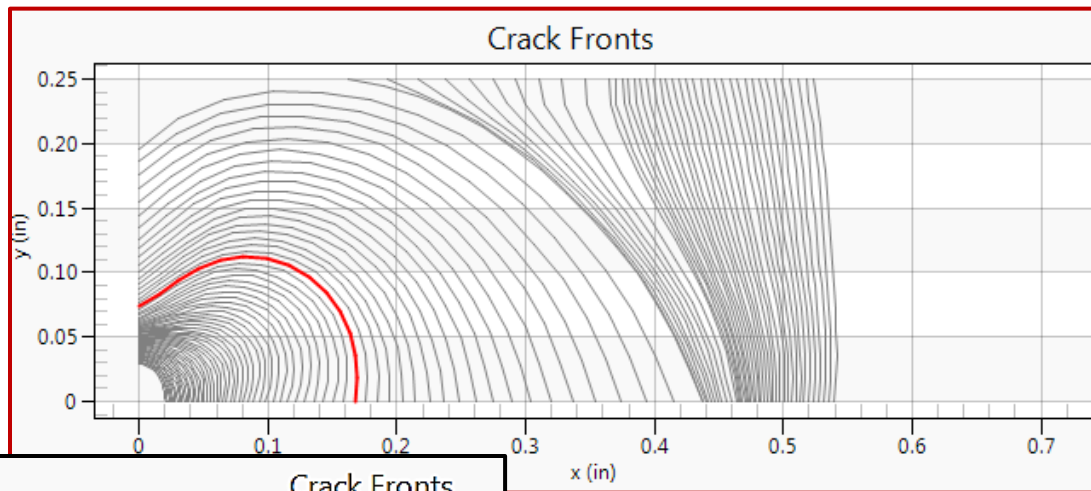
Details for each crack step

Failure indicators

Crack Propagation Tool – CPT Sample Results



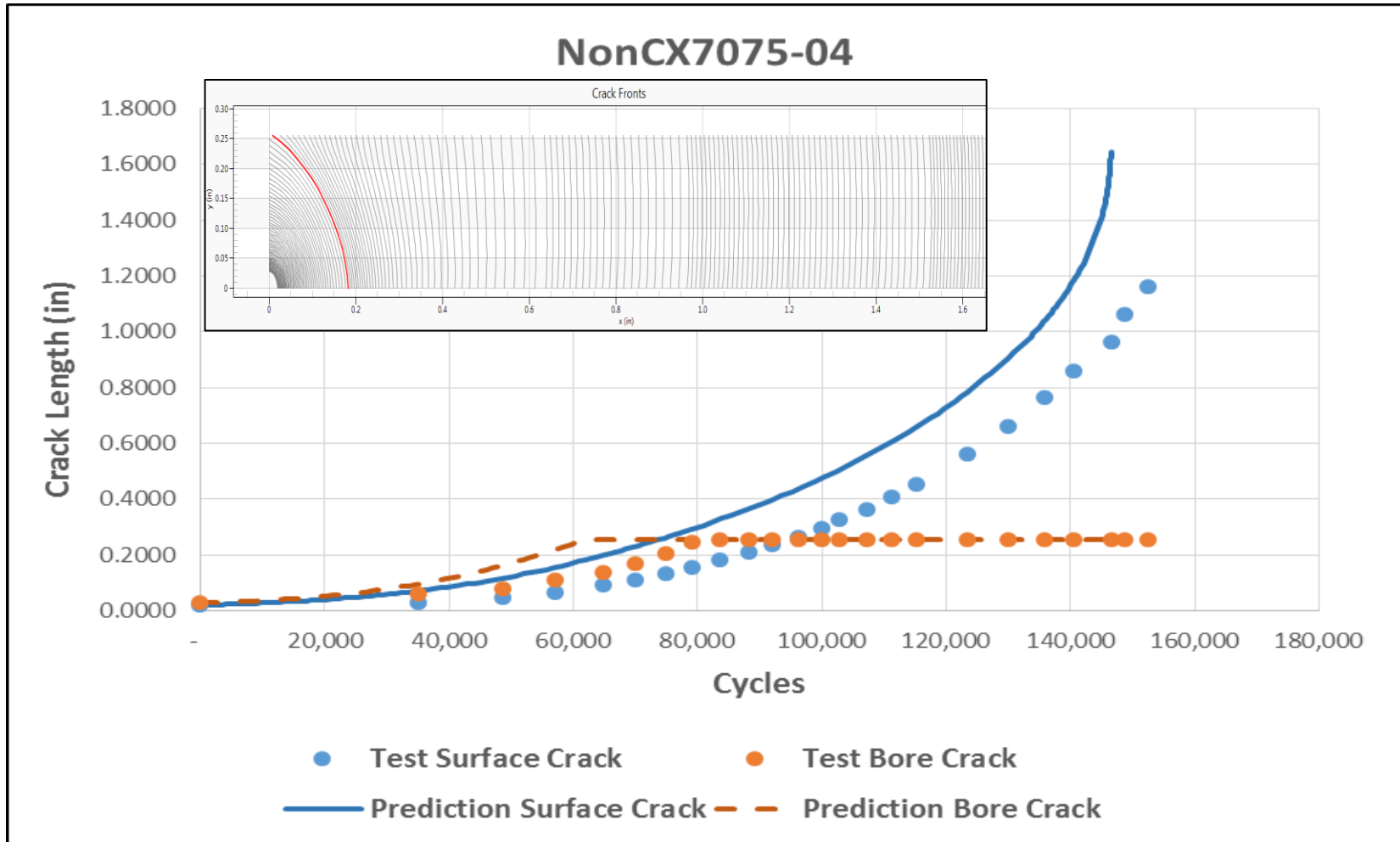
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Experimental Comparisons No RS (Not Coldworked)



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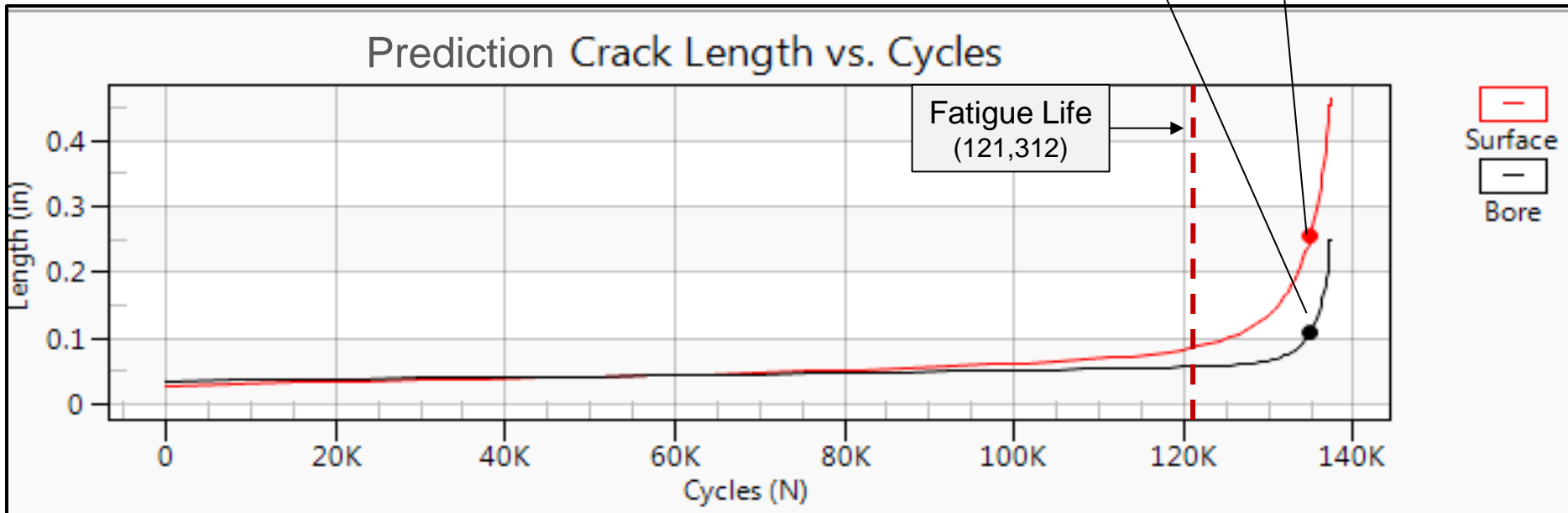
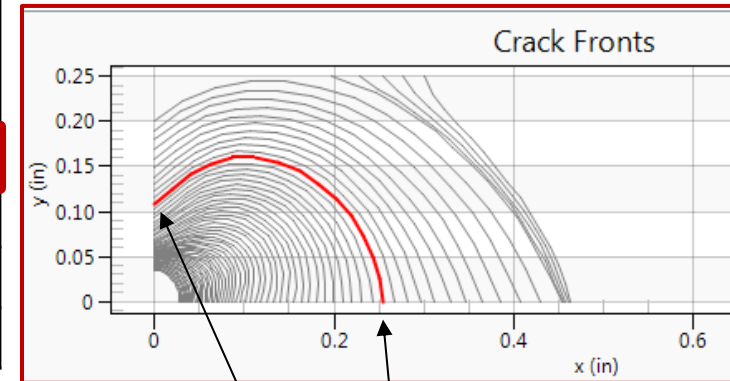
* Robert Pilarczyk, *Experimentally Derived Beta Corrections to Predict Fatigue Crack Growth at Cold Expanded Holes in 7075-T651*, Master Thesis, Department of Mechanical Engineering, University of Utah, May 2008

Experimental Comparisons Cold-Worked & Pre-Cracked



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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

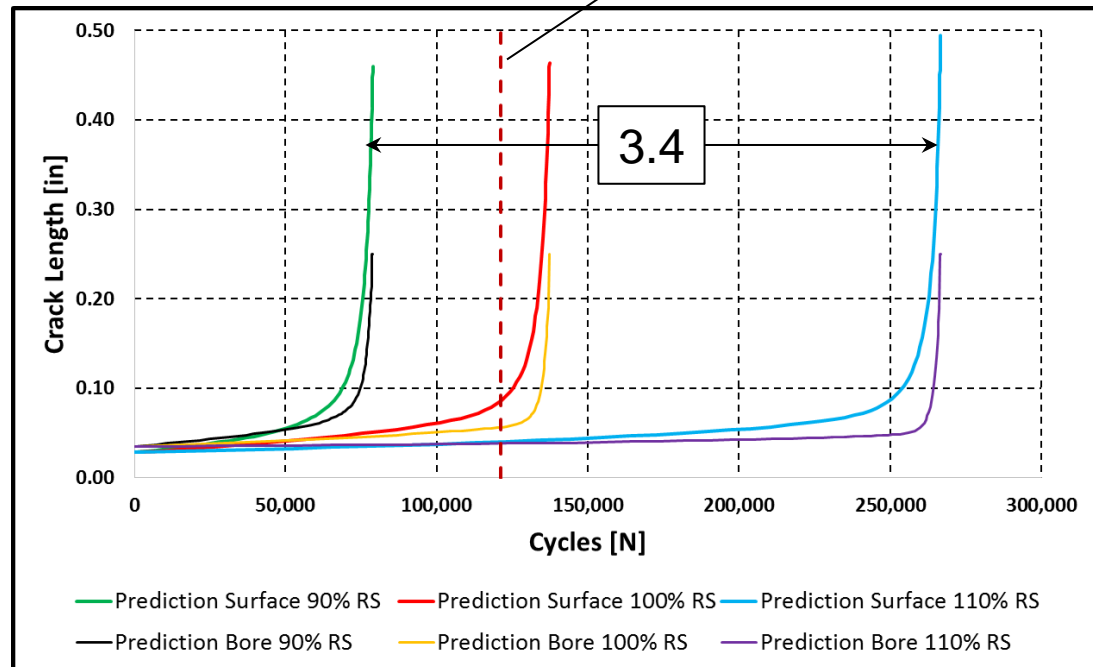


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Predicted Life [Cycles]			Specimen Life [Cycles]
90% RS	100% RS	110% RS	
78,913	137,305	266,500	121,312

+/-10% variation in RS

Prediction → 137,305 { + 94%
- 43%



Summary & Conclusions



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- 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
 - $K_{RES-NUM}$ and $K_{MECH-NUM}$ are obtained by the finite element method at each control point along the crack front using StressCheck

Summary & Conclusions



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- ❑ 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 → a factor of 3 or more in fatigue life estimates

Acknowledgment



STRESSCHECK™

- This work was performed in support of the project
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