



Providing Structural Integrity Technology to the Aerospace Community

SOLR Correlation Methodology

AFGROW Model Study

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Overview



USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

In 2019 in “Durability and Damage Tolerance Analysis Updates” (M. Wilcox 2019) the changes to the T-38 durability and damage tolerance analysis were discussed. SOLR correlation methodology was one of the topics discussed and changed for T-38.

- Updated SOLR correlations with new material crack growth curves
- Automated the SOLR correlation
- Choose the most conservative SOLR Value

Here we are looking at the different AFGROW model options for the SOLR Correlation and durability and damage tolerance analysis

- Two focuses
 - Using the Advanced model for SOLR Correlation
 - Using the classic model vs StressCheck Betas for unique geometry
- Methods are kept consistent through all steps



AFGROW Models



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User Defined Betas

- This method has been historically used in the DTA with StressCheck created betas

Historically in SOLR Correlation

- Betas inputted manually, using betas from StressCheck , or
- the betas and aspect ratio as measured from the coupon tests.

Classic Models

- This method has started to be used for newer SOLR correlations. Has been used for DTA other than a few exceptions
- Betas calculated using the Newman-Raju Model

Advanced Model

- This method is used for Phase III of continuing damage
- Fawaz-Anderson Model

Determination of SOLR

◆ Coupon spectrum test

■ Test coupon design

- Material matching actual structure
- Geometry similar to actual structure
- Geometry simple to analyze
- Boundary conditions known

■ Spectrum test loads

- Comparable to actual structure
- Simple to determine and analyze

◆ Correlation analysis

- Simulate test as closely as possible
- Use different SOLR values until analysis matches test



“The Generalized Willenborg shutoff overload ratio and its sensitivity to analytical parameters and techniques” (L. Smith 2012)



Background (cont.)



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- Generalized Willenborg Model
 - Adjusts da/dN by reducing R to R_{eff}

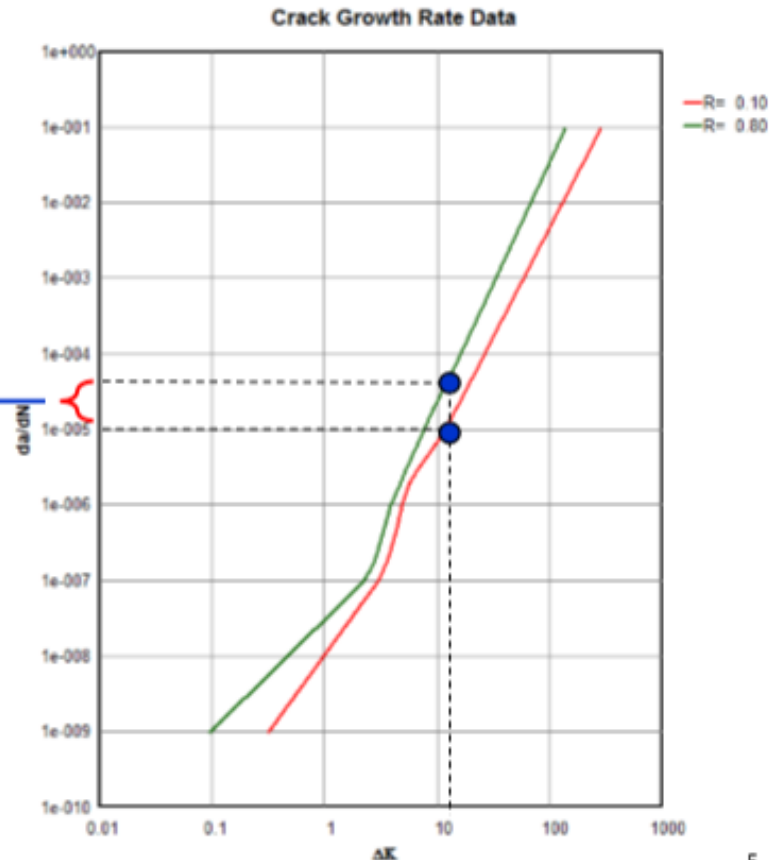
$$K_r = \frac{1 - \frac{\Delta K_{th}}{K_{max}}}{(SOLR - 1)} \left[K_{OL} \sqrt{1 - \frac{x - x_{OL}}{r_{OL}}} - K_{max} \right]$$

$$K_{min,eff} = K_{min} - K_r$$

$$K_{max,eff} = K_{max} - K_r$$

$$R_{eff} = \frac{K_{min,eff}}{K_{max,eff}}$$

Retardation Effect:
Reduction in da/dN



Note: For $R < 0.0$, K_{max} is used instead of Delta K

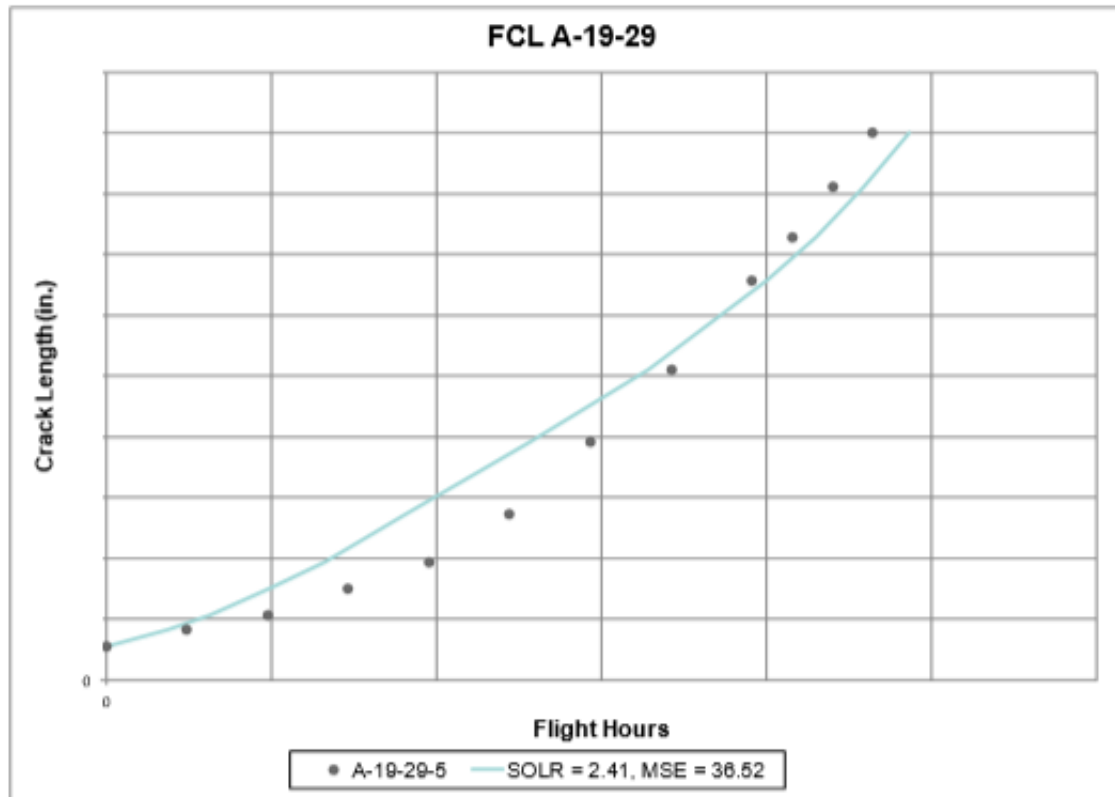
“Durability and Damage Tolerance Analysis Updates” (M. Wilcox 2019)



Correlation Approach



- **Goal: Iterate on SOLR values until the analytical crack growth resembles the tested growth as closely as possible**



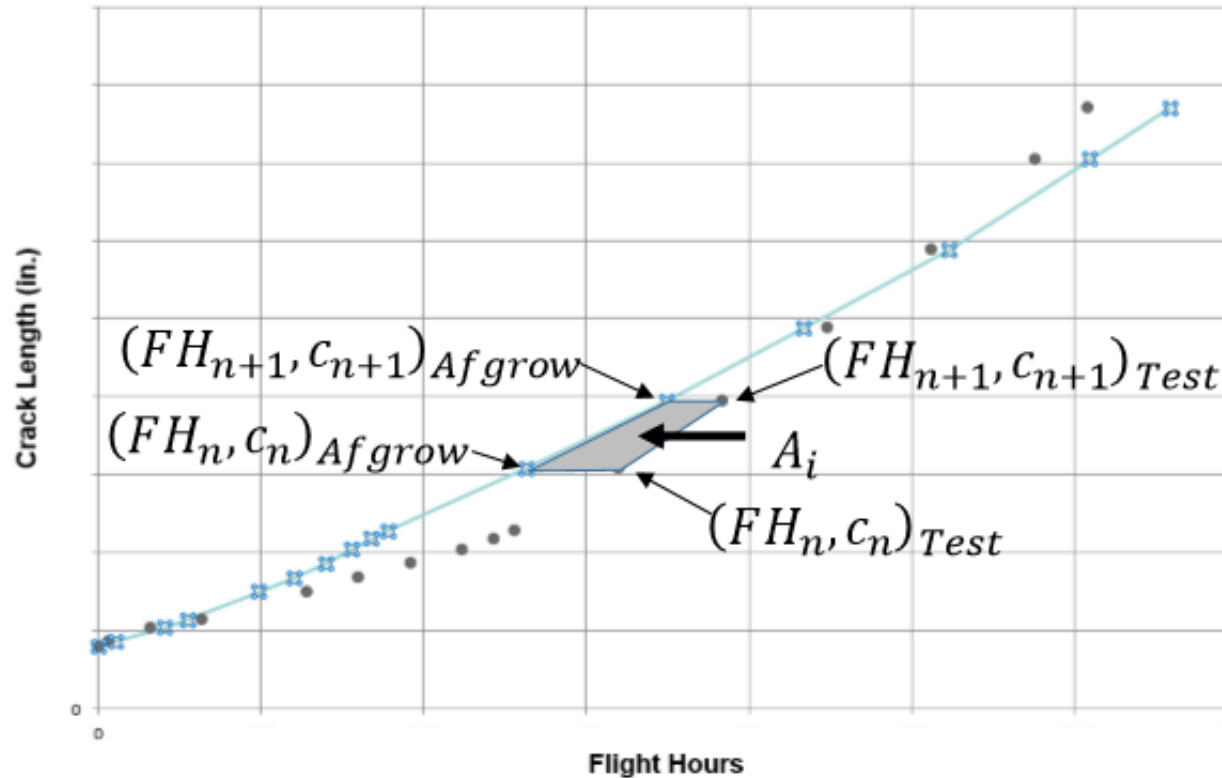
“Durability and Damage Tolerance Analysis Updates” (M. Wilcox 2019)



Correlation Approach



- Strategy: Minimize the difference between the two curves



“Durability and Damage Tolerance Analysis Updates” (M. Wilcox 2019)



Correlation Approach



■ Mean Squared Error

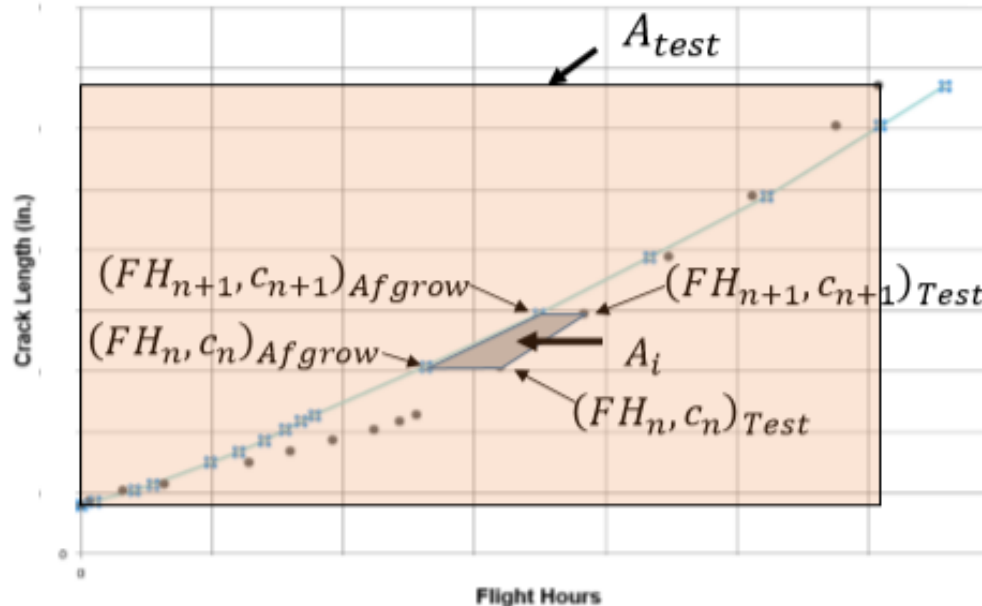
$$A_{Error} = \sum_{i=1}^{N-1} A_i$$

$$A_{test} = (c_{final} - c_{initial})(L_{final} - L_{initial})$$

$$MSE = \left(100 * \frac{A_{Error}}{A_{test}} \right)^2$$

■ Usefulness of

$$\sqrt{MSE}$$

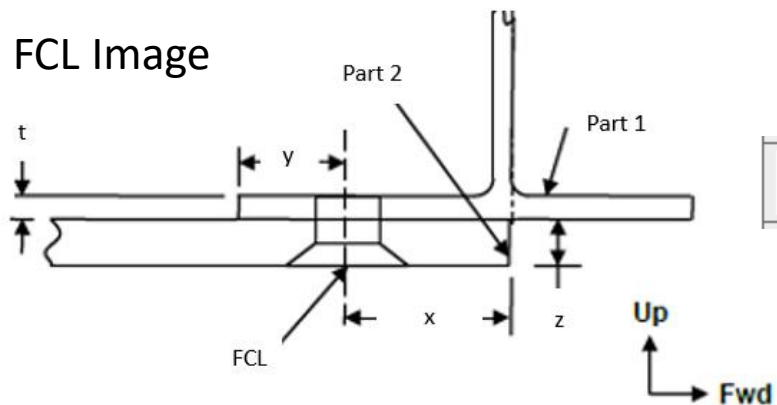


“Durability and Damage Tolerance Analysis Updates” (M. Wilcox 2019)

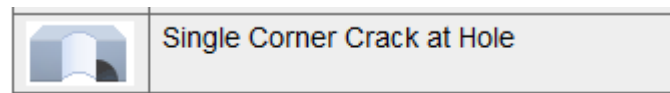


Wing FCL

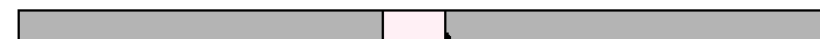
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Classic Crack Model



Advanced Model



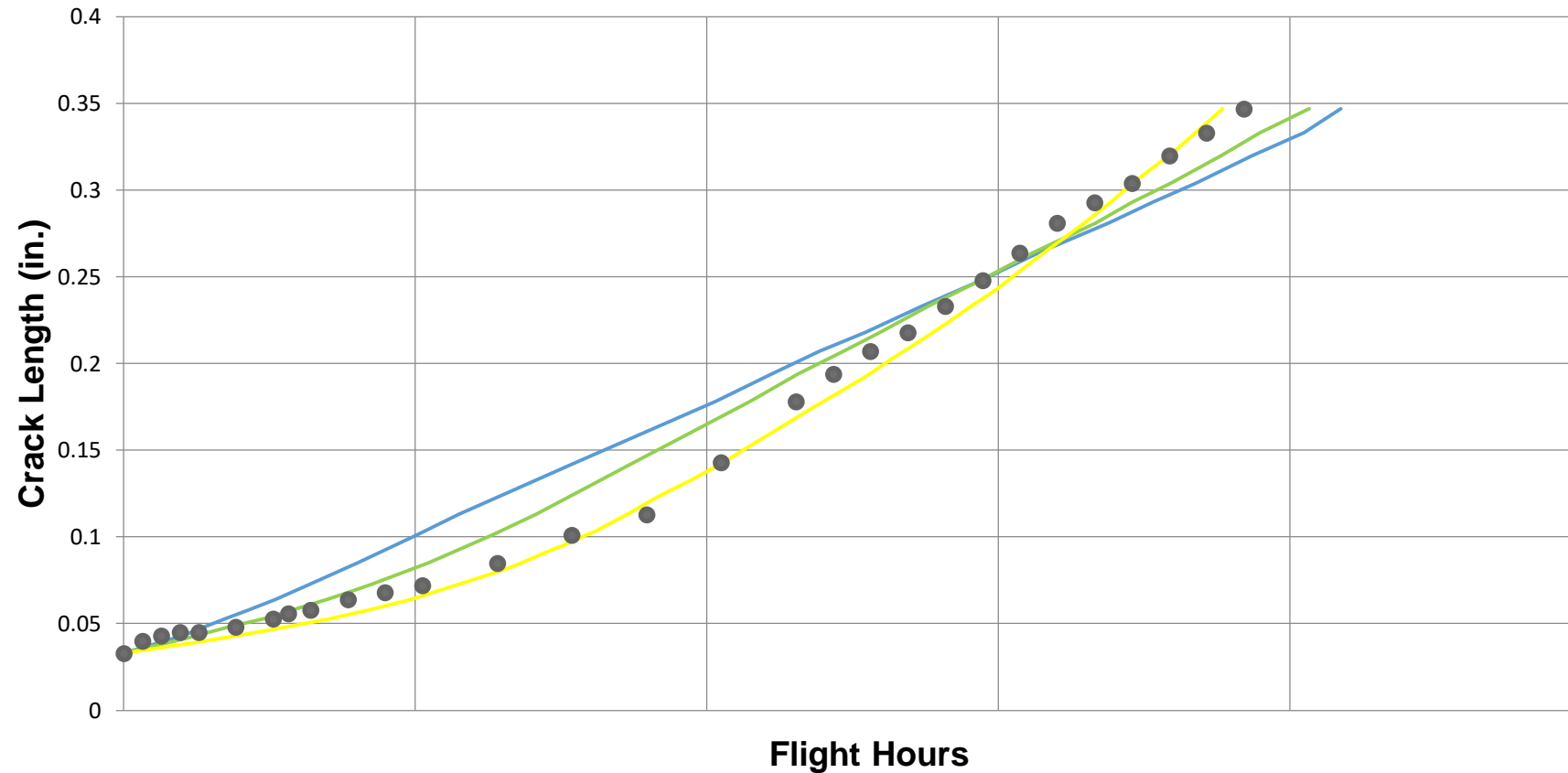
Both Classic Corner Crack and Advanced Model used the countersink beta correction factors

Test Coupon	User-Defined Betas SOLR*	User-Defined Beta MSE	Classic Crack Model SOLR	Classic Crack Model MSE	Advanced Model SOLR	Advanced Model MSE
Wing Test-1	2.45	53.2109	2.03	17.4183	2.7	2.02
Wing Test-2	2.18	61.4389	1.91	24.9346	2.48	2.12
Wing Test-3	2.6	27.0893	2.14	32.9114	2.5	3.48
Highest SOLR	2.6	27.0893	2.14	32.9114	2.7	2.02

*Betas are from coupon test data



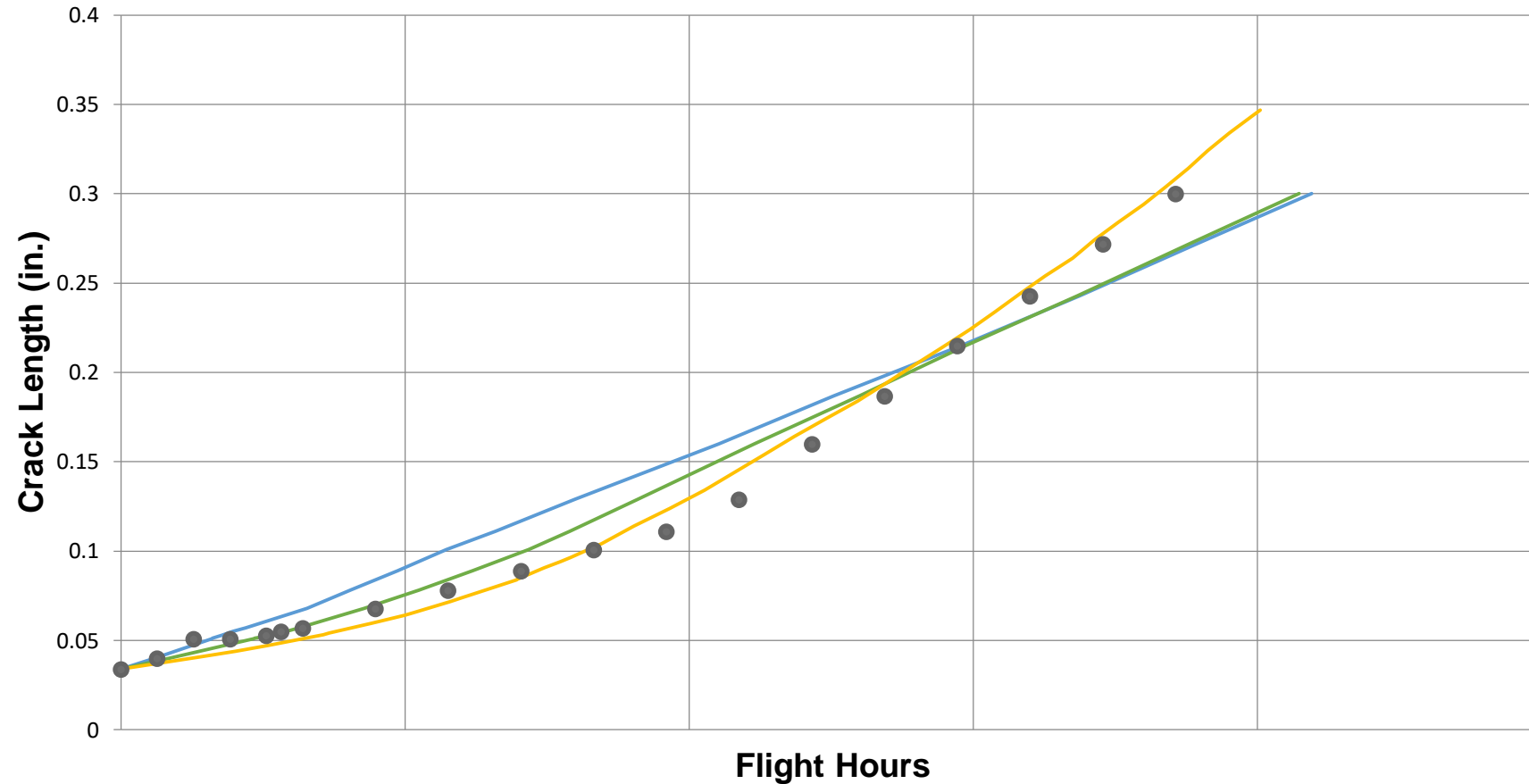
Wing FCL – Coupon 1



- Test 1
- SOLR = 2.45, MSE = 53.2109, User Defined Betas
- SOLR = 2.03, MSE = 17.4183, Classic Corner Crack
- SOLR = 2.7, Advanced Model



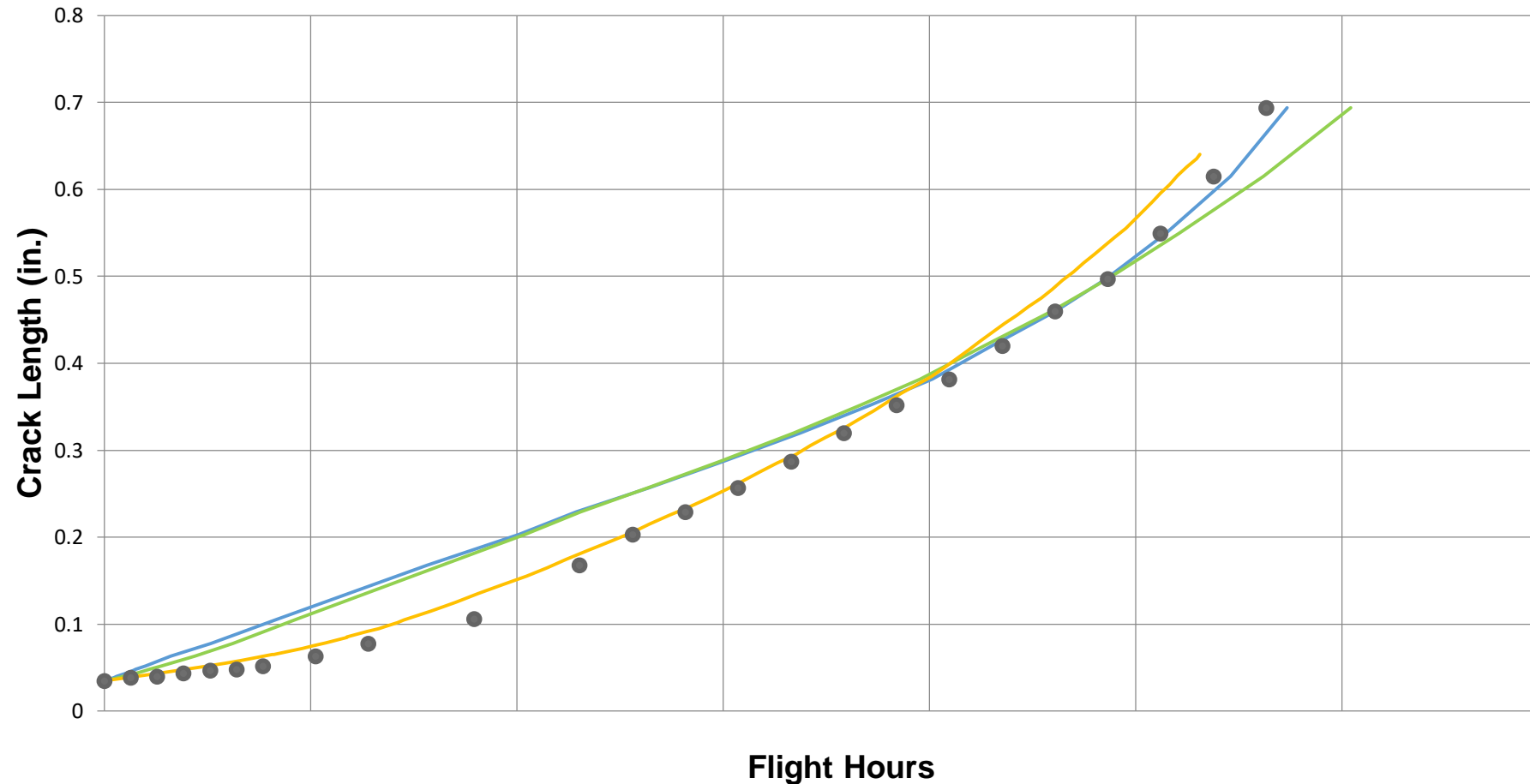
Wing FCL – Coupon 2



- Test 2
- SOLR = 2.18, MSE = 61.4389, User Defined Betas
- SOLR = 1.91, MSE = 24.9346, Classic Corner Crack
- SOLR = 2.48, MSE = 2.12, Advanced Model



Wing FCL – Coupon 3



- Test 3
- SOLR = 2.6, MSE = 27.0893, User Defined Betas
- SOLR = 2.14, MSE = 32.9114, Classic Corner Crack
- SOLR = 2.5, MSE = 3.48, Advanced Model



Beta Comparisons

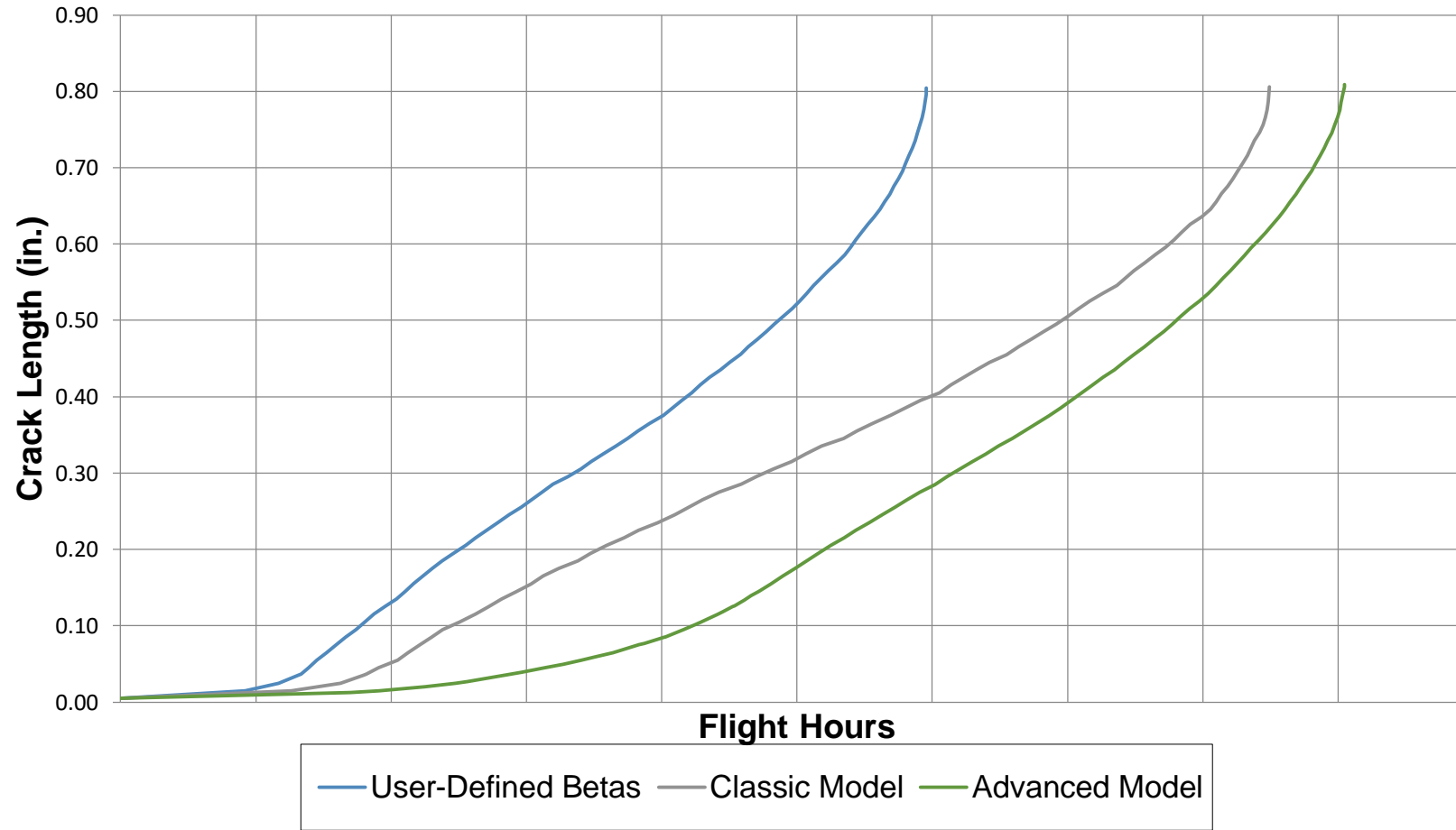


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Model	Advanced Model			User-Defined Betas			Classic Corner Crack		
SOLR	2.7			2.6			2.14		
Wing FCL	C Length	Beta C	Beta A	C Length	Beta C	Beta A	C Length	Beta C	Beta A
	0.01	2.71	2.84	0.01	3.00	3.09	0.01	3.00	3.09
	0.02	2.50	2.46	0.03	2.88	3.07	0.03	2.88	3.07
	0.05	2.01	1.86	0.05	2.90	2.60	0.03	2.88	3.07
	0.08	1.78	1.79	0.08	2.31	2.60	0.05	2.90	2.60
	0.10	1.72	1.72	0.11	1.94	2.60	0.08	2.31	2.60
	0.13	1.67	1.71	0.13	1.77	2.60	0.11	1.94	2.60
	0.15	1.65	1.90	0.15	1.62	2.60	0.13	1.77	2.60
	0.16	1.57	1.90	0.16	1.56	2.60	0.15	1.62	2.60
	0.19	1.45	1.90	0.19	1.41	2.60	0.16	1.56	2.60
	0.23	1.30	1.90	0.23	1.26	2.60	0.19	1.41	2.60
	0.27	1.17	1.90	0.27	1.14	2.60	0.21	1.33	2.60
	0.30	1.10	1.90	0.30	1.06	2.60	0.26	1.17	2.60
	0.31	1.10	1.90	0.31	1.05	2.60	0.31	1.05	2.60
	0.35	1.05	1.90	0.35	1.01	2.60	0.36	1.00	2.60
	0.35	1.05	1.90	0.41	0.96	2.60	0.41	0.96	2.60
	0.41	1.01	1.90	0.46	0.94	2.60	0.46	0.94	2.60
	0.46	0.97	1.90	0.51	0.92	2.60	0.51	0.92	2.60
	0.51	0.95	1.90	0.56	0.92	2.60	0.56	0.92	2.60
	0.56	0.93	1.90	0.61	0.93	2.60	0.61	0.93	2.60
0.61	0.91	1.90	0.66	0.96	2.60	0.66	0.96	2.60	
0.66	0.91	1.90	0.71	1.02	2.60	0.71	1.02	2.60	
0.71	0.89	1.90	0.76	1.17	2.60	0.76	1.17	2.60	
0.76	0.89	1.90	0.80	1.82	2.60	0.81	1.88	2.60	
0.81	0.88	1.90							



WING FCL Life Curves



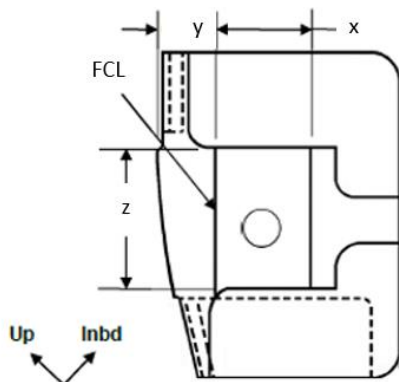


Fuselage FCL

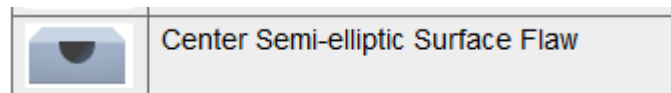


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FCL Image



Classic Crack Model



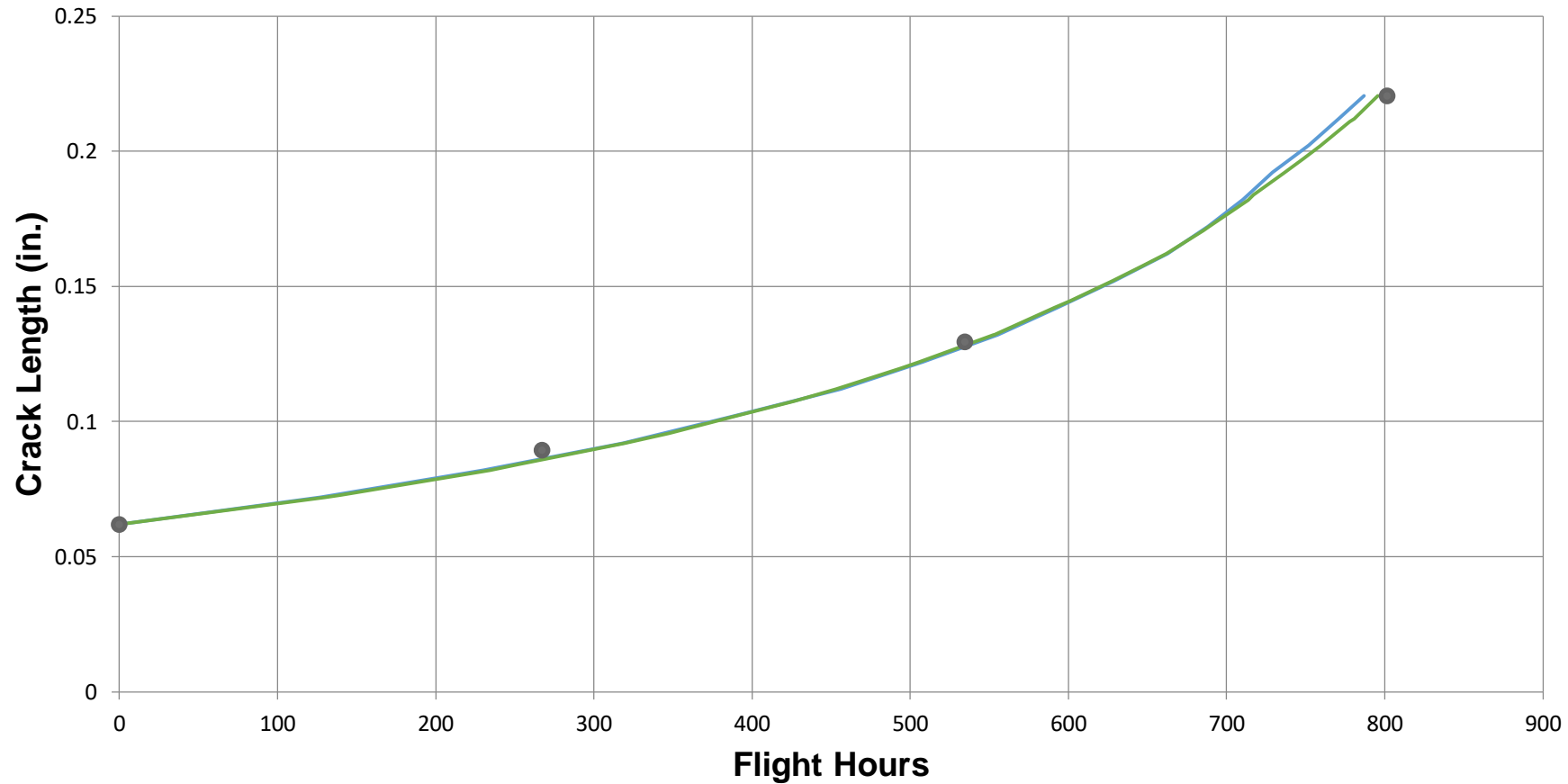
Advanced Model

No advanced model option for surface flaws

Test Coupon	StressCheck Beta SOLR	StressCheck Beta MSE	Classic Crack Model SOLR	Classic Crack Model MSE
Fuselage Test-1	1.72	1.86	2.13	1.29
Fuselage Test-2	1.7	5.11	1.93	0.05
Fuselage Test-3	1.67	4.46	1.87	0.13
Highest SOLR	1.72	1.86	2.13	1.29



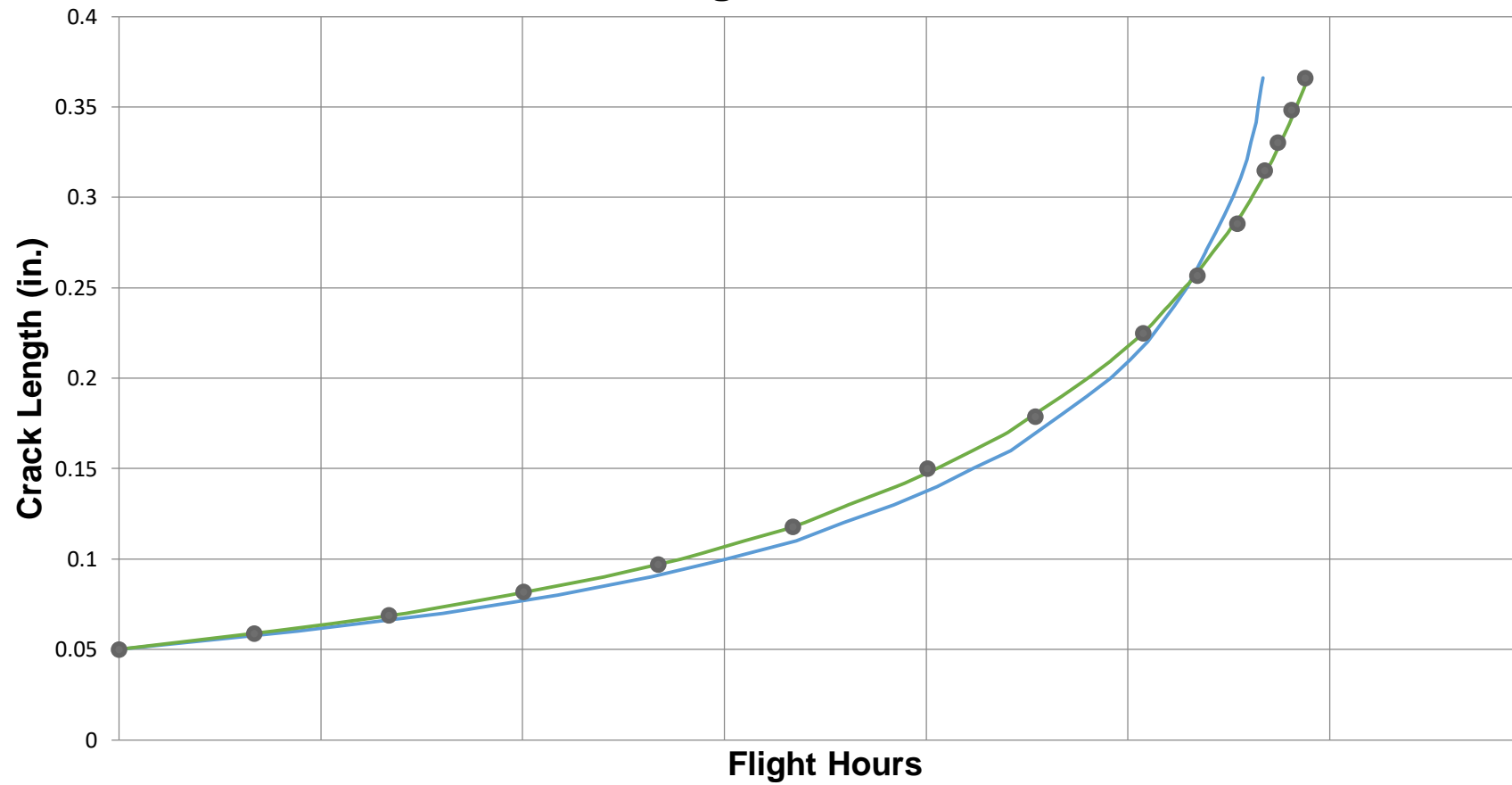
Fuselage FCL Test 1



● Test 1
— SOLR = 1.72, MSE = 1.86, Stess Check Betas
— SOLR = 2.13, MSE = 1.29, Classic Model



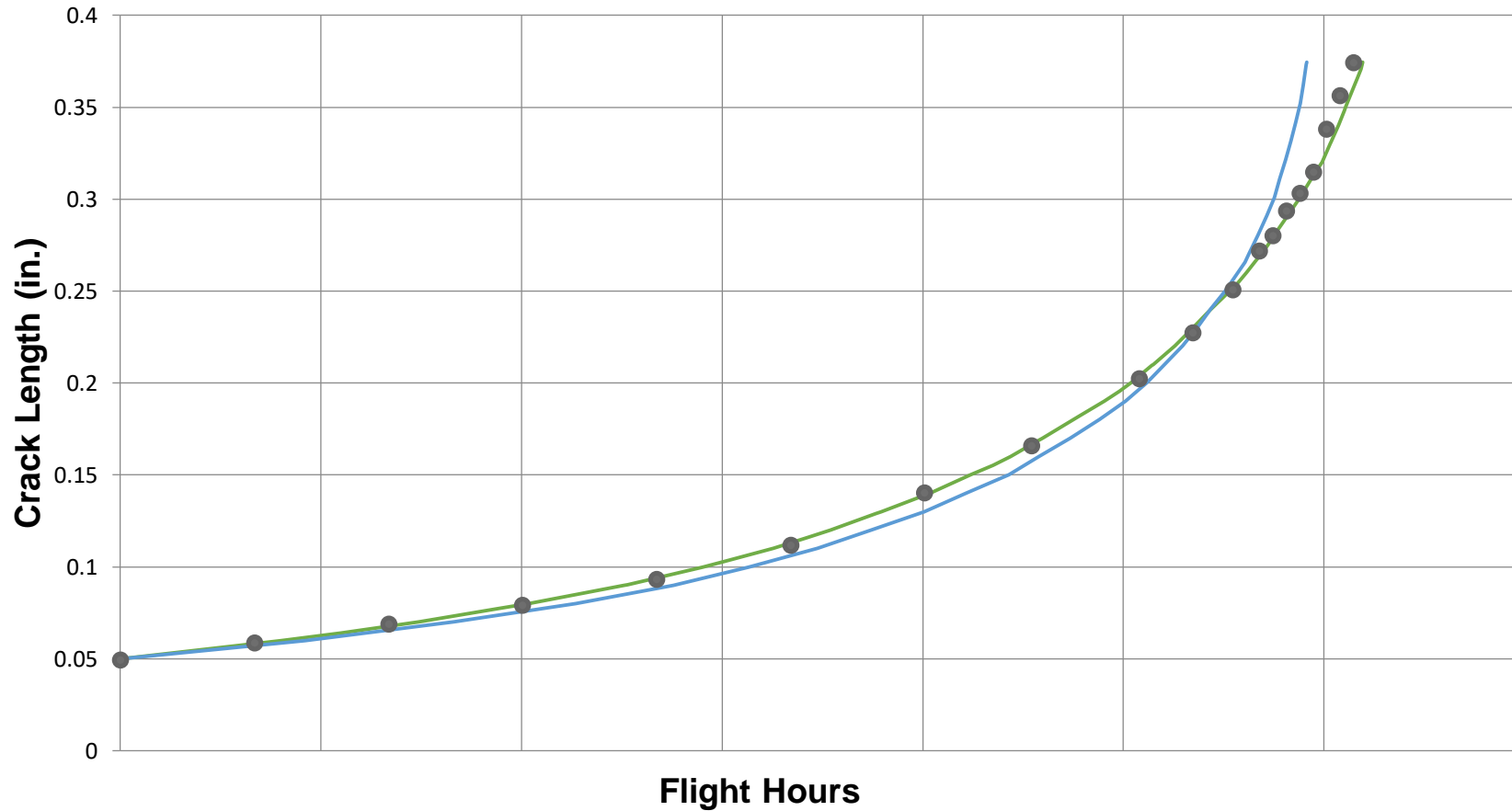
Fuselage FCL Test 2



● Test 2
— SOLR = 1.7, MSE = 5.11, Stress Check Betas
— SOLR = 1.93, MSE = 0.05, Classic Model



Fuselage FCL Test 3



● Fuselage Test 3
— SOLR = 1.87, MSE = 0.13, Classic Model
— SOLR = 1.67, MSE = 4.46, Stress Check Betas



Beta Comparisons

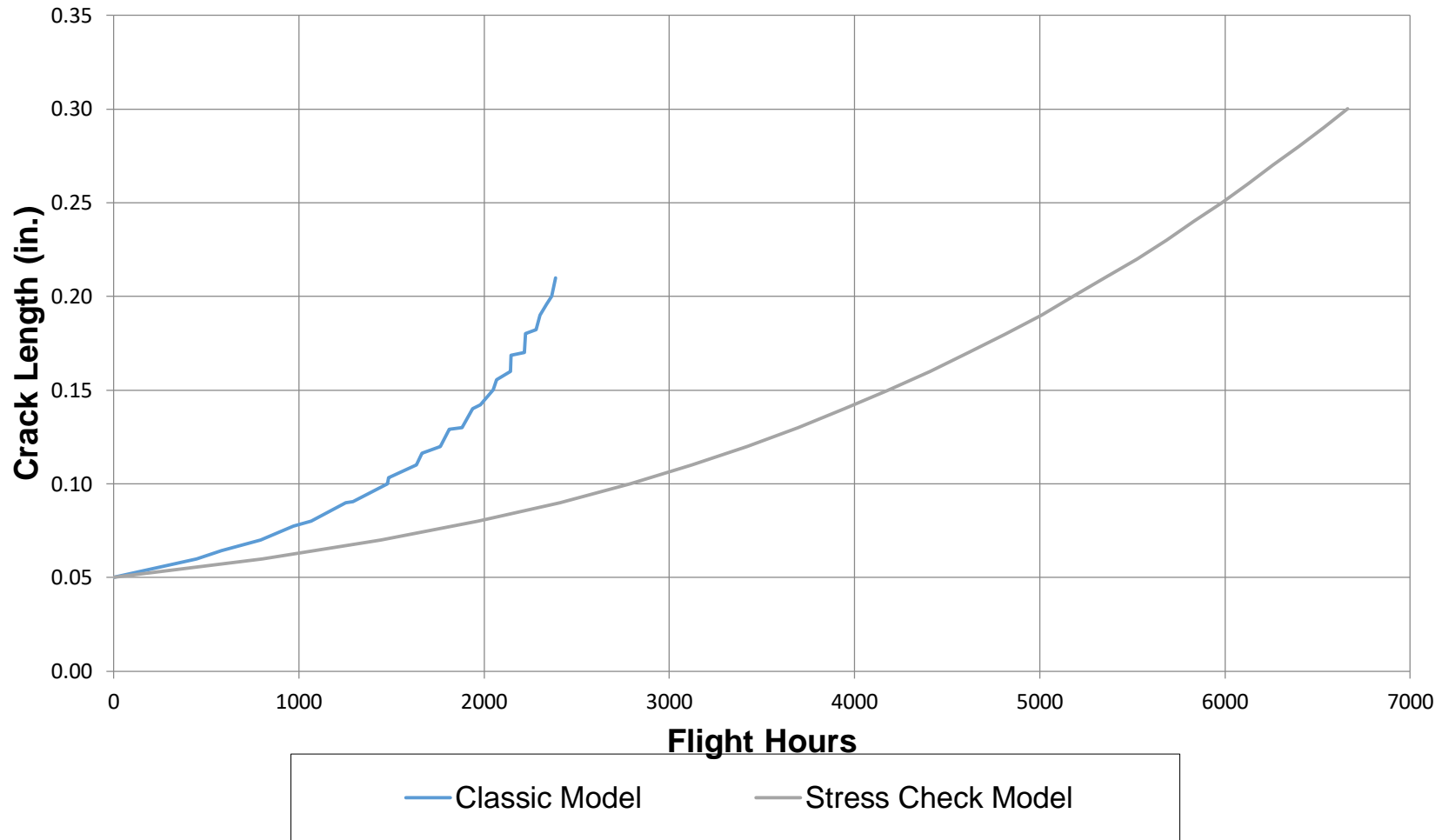


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Model	Stress Check Betas		Classic Corner Crack	
SOLR	1.79		1.87	
Fuselage FCL	C Length	Beta C	C Length	Beta C
	0.005	0.734	0.050	0.978
	0.050	0.683	0.080	0.935
	0.080	0.644	0.100	0.926
	0.100	0.627	0.120	0.922
	0.150	0.579	0.140	0.921
	0.200	0.543	0.150	0.922
	0.300	0.492	0.160	0.923
	0.400	0.459	0.190	0.929
	0.500	0.440	0.196	0.931
	0.501	0.533	0.200	0.932
	0.600	0.531	0.218	0.938
	0.700	0.562		
	0.760	0.713		



Fuselage FCL Life Curves





Conclusions



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- On the Wing FCL, classic models, user-defined models and advanced models were compared. This showed that the advanced model matched the correlation the best.
- On the Fuselage FCL, we compared the StressCheck beta models with the classic model. The classic model matched the SOLR correlation best.
- Using the StressCheck betas on the DTA is a less conservative approach, but is it more realistic?



Next Steps

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- Further investigate the use of the Advanced Model for corner cracks at a hole FCL in order to move all analysis in that direction
- Potentially remove all user defined betas that are not using StressCheck Beta solutions
- Create StressCheck Beta solutions for DTA that are using classic models with unique geometry



Acknowledgements



USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

T-38 Structural Integrity and Analysis Group
-Michael Wilcox and Chad King

Southwest Research
-Lucky Smith



Backup Slides

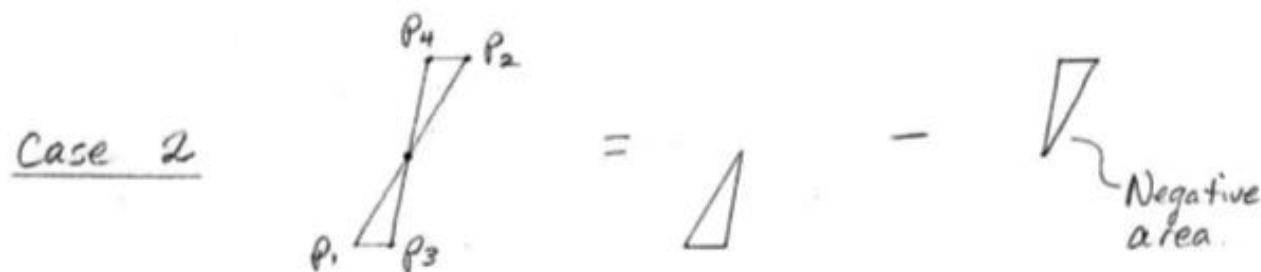
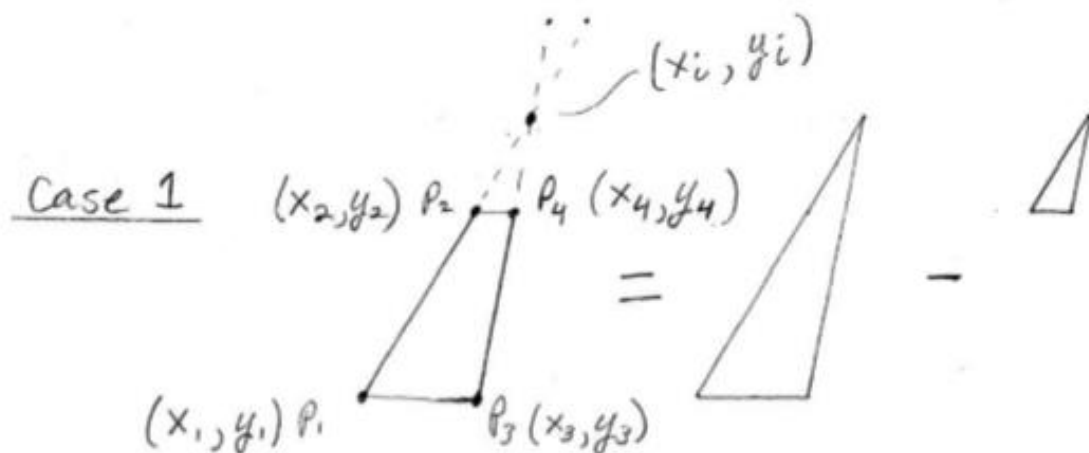


Correlation Approach



- Method of calculating an area segment:

$$A_i = A_1 - A_2$$





Correlation Approach



- Method of calculating an area segment:

$$A_i = A_1 - A_2$$

