Migrating to Afgrow

Afgrow workshop

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A GENERAL DYNAMICS COMPANY

Overview

- Why change over to new DT analysis software
  - No updates for current software (Cracks2K)
  - Goals
- What is required to continue current DT-analysis capabilities
  - Proven historical data
  - Integration of new methods with previous test correlation
- Logistics of Roll-Out
- Plug-in additional features
- Conclusions

WHY CHANGE?

Goals

- Increase efficiency in conducting DTA.
- Increase accuracy of analysis.
- Increase reliability of analysis process.
- Increase efficiency in generating report ready DT results.

Why is it not easy to switch to a new DT tool

- Proven Methods:

§ 25.571 Damage—tolerance and fatigue evaluation of structure.

(a) *General.* An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage, will be avoided throughout the operational life of the airplane. This evaluation must be conducted in accordance with the provisions of paragraphs (b) and (e) of this section, except as specified in paragraph (c) of this section, for each part of the structure that could contribute to a catastrophic failure (such as wing, empennage, control surfaces and their systems, the fuselage, engine mounting, landing gear, and their related primary attachments). For turbojet powered airplanes, those parts that could contribute to a catastrophic failure must also be evaluated under paragraph (d) of this section. In addition, the following apply:

(1) Each evaluation required by this section must include—

(i) The typical loading spectra, temperatures, and humidities expected in service;

(ii) The identification of principal structural elements and detail design points, the failure of which could cause catastrophic failure of the airplane; and

(iii) An analysis, supported by test evidence, of the principal structural elements and detail design points identified in paragraph (a)(1)(ii) of this section.

- Gulfstream analyses are supported by historically proven test evidence. A new DT tool should be able to implement these established methods. Afgrow is accepted by the FAA, but its use must be consistent with in-house test data.

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Requirements

- New DT software should produce similar analysis results.
- Gulfstream in-house solutions should be available.

- Stable software package.
- Continues product improvement.
- Continues helpdesk support.
- Potential for user specific capability enhancements.
- Cost?

LOGISTICS

Logistics

- Compare Gulfstream in-house solutions to external solutions.
  - How well do the same solutions compare?
  - If differences exist: What is the cause of the differences?
- Determine any missing DT solutions.
  - Can solutions be added to new DT tool?
  - Adding solutions internal or external?
- Availability of crack growth models.
- Crack growth data.
  - Material data checking in external software.
- Post-processing of DTA.

Compare in-house DTA and Afgrow

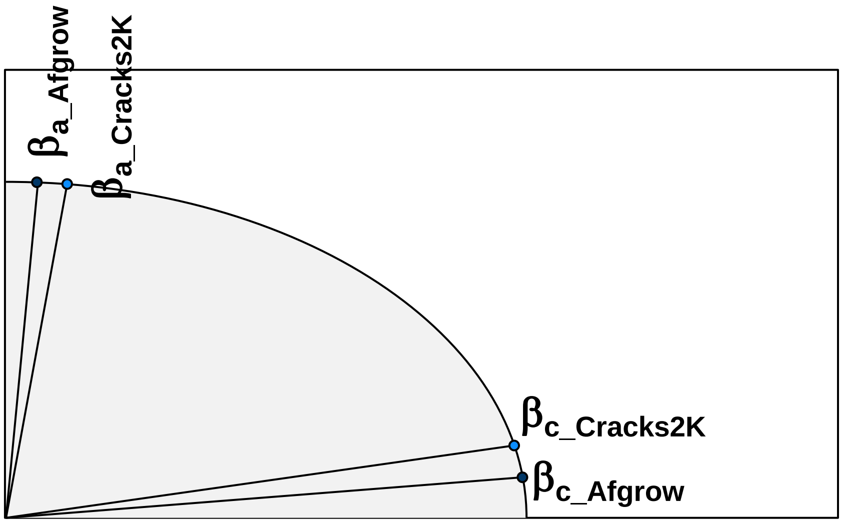
– In-house corner crack β solution differs from Afgrow solution, implement Afgrow β in beta table (Angle of β in a- and c-direction differs).

$$\beta_{c\_Afgrow} = \frac{K}{\sqrt{\pi c}}$$

$$\beta_{a\_Afgrow} = \frac{K}{\sqrt{\pi a}}$$

$$\beta_{c\_Cracks2K} = \sqrt{\frac{a}{c}}\left(\frac{K}{\sqrt{\pi a}}\right)_{Newman-raju}$$

$$\beta_{a\_Cracks2K} = \frac{K}{\sqrt{\pi a}}$$



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Compare in-house DTA and Afgrow

- Use same basis, plate with central hole and 100% bypass loading, through the thickness crack at the hole of 0.15 in length.

- Results are compared with $\mathrm{abs}\left[\frac{\log(N_{\mathrm{Cracks}}) - \log(N_{\mathrm{Afgrow}})}{\log(N_{\mathrm{Afgrow}})} \cdot 100\%\right] < 2\%$ is OK!

Compare in-house DTA and Afgrow

- In-house DTA corner crack solutions differ from Afgrow standard corner crack solutions. Angle of β in a- and c-direction differs and β is normalized differently (Plug-in models solved this issue as the Gulfstream in-house solutions are available).
  - All corner crack solutions therefor produced different results.
- Using either Cracks-β in Afgrow or Afgrow-β in Cracks allowed for a direct comparison of the crack growth methodology.
  - Constant amplitude comparison provided no problems for any solution.
- Spectrum driven DT analysis showed differences.
  - These differences are contributed to the retardation methodology and the R^- and R^+ cut-off between Afgrow and Cracks.

Compare in-house DTA and Afgrow

- Interaction Models:

Cracks2K	Afgrow
Basic Willenborg	
Generalized Willenborg	**Generalized Willenborg**
Willenborg/Chang	**Modified Willenborg**
Hsu	Hsu
Wheeler	Wheeler
	Fastran

Compare in-house DTA and Afgrow

Basic Willenborg

$$K_{MAX(eff)} = K_{MAX} - K_{RED}$$

$$K_{MIN(eff)} = K_{MIN} - K_{RED}$$

$$R_{(eff)} = \frac{K_{MIN(eff)}}{K_{MAX(eff)}}$$

$$K_{RED} = \Phi\left(K_{MAX(OL)}\left(\frac{1-(X-X_{(OL)})}{YieldZone_{(OL)}}\right)^{0.5} - K_{MAX}\right)$$

Generalized Willenborg

$$\Phi = \frac{\left(1-\frac{\Delta K_{Threshold}}{K_{MAX}}\right)}{(SOR-1)} \qquad YieldZone = \left(\frac{K_{MAX}}{o_{YS}}\right)^2\left(\frac{1}{\pi P_{sx}}\right)$$

X : *Crack Length*

$X_{(OL)}$: *Crack Length at Overload*

SOR : *Overload Shut – off Ratio*

P_{SX} : *Stress State for a given crack* (2.0 – *Plane Stress to* 6.0 – *Plane Strain*)

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Compare in-house DTA and Afgrow

- Cracks2K uses the Chang acceleration model with the Willenborg retardation model to account for the effect of compressive stress (or load) cycles. The Chang model introduces a change in the overload interaction zone to account for compressive underload effects. AFGROW does not consider negative stress intensity factors to be valid (in general). In place of the Chang acceleration model, AFGROW uses the following method to account for the effect of compressive stresses (or loads):
- **Ry(ol) = (1.0 - 0.9*ABS(Compressive Stress (or load)/Overload Stress (or load))) * Ry(ol)**
- Using the absolute value of the ratio of the compressive stress (or load) to the overload stress (or load) reduces the size of the current overload yield zone size. The result of this is to simply reduce the effect of the previous overload. Therefore, the Willenborg model used in AFGROW can NEVER result in a life prediction that is less than the life prediction with no retardation.

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Compare in-house DTA and Afgrow

- Spectrum driven DT analysis showed differences.
  - These differences are contributed to the retardation methodology and the R^- and R^+ cut-off between Afgrow and Cracks:

Cracks2K	Afgrow
If $R > R^+_{cut}$ then $R = R^+_{cut}$	If $R > R^+_{cut}$ then $R = R^+_{cut}$
If $R < R^-_{cut}$ then $R = R^-_{cut}$	If $R < R^-_{cut}$ then $R = R^-_{cut}$
The K_{max} and K_{min} are calculated using $R^-_{cut} < R < R^+_{cut}$	The K_{max} and K_{min} are calculated using the actual R-ratio. The da/dN is then selected based on $R^-_{cut} < R < R^+_{cut}$

Crack Growth Material Models

- Afgrow has Forman equation, Harter-T, Nasgro, Table Lookup and the Walker equation.
- Commonly used in-house are Walker/Chang, Nasgro and Tabular data.
- In-House data must be converted before use in Afgrow.

Material data

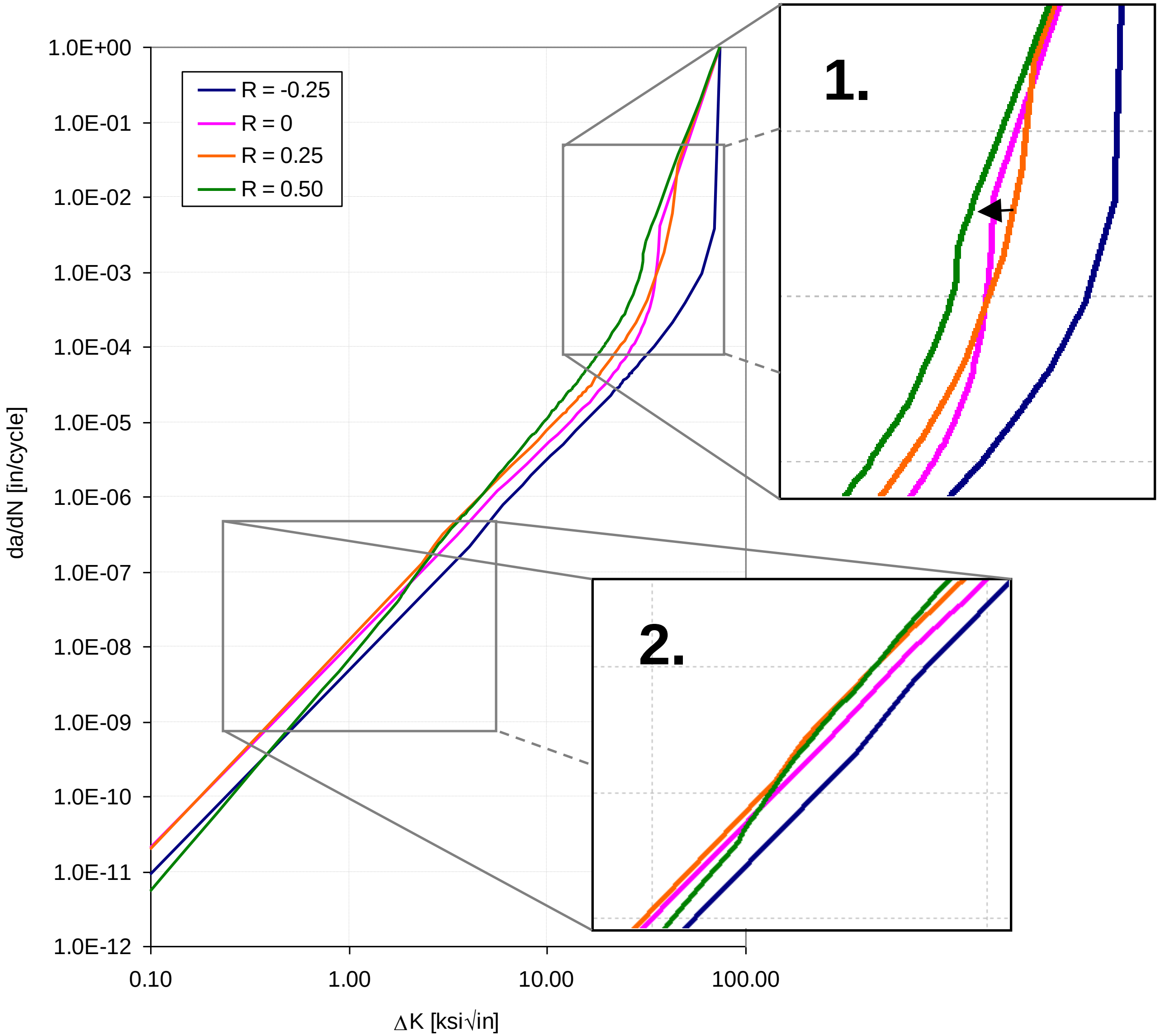
- Materials using Nasgro equations are directly available in Afgrow.
- In-House Tabular data will have to be converted to Afgrow format.
- Walker/Chang material models will be modified and transferred into tabular format.
- All materials will have to be checked for validity.
- Afgrow Material database (Afgrow website) is used to complement in-house material test data.

Material database conversion

- Afgrow performs error checks on tabular input
  - Positive and Negative R curves may NOT cross each other in the domain of the crack growth rate and R limits input by user
  - ΔK (K_{max}) values for given R must increase with increasing da/dN
  - ΔK values for increasing positive R must decrease for increasing R
  - K_{max} values for decreasing negative R must decrease for decreasing R
  - K_{max} values for negative R values must be less then ΔK for R = 0.0
  - Threshold ΔK value at R = 0 must be in range of possible ΔK values for R = 0
  - K_{IC} must be less than K_C
  - RLO must be less than or equal to 0.0
  - RHI must be greater than 0.0 AND less then 1.0

- Since these checks are NOT performed by Cracks2K, *data manipulation is required.*

Material database conversion



Example of crossing curves:

1. Curve for R = 0.25 is shifted to the left not to cross the R = 0 curve. This is a conservative approach, same da/dN for lower ΔK
2. Curve for R = 0.50 needs to be shifted towards the left not to cross the R = 0.25 and the R = 0 curve.

Material database conversion

	$R < 0$				$R \geq 0$			
da/dN	K_{max}	K_{max}	K_{max}	K_{max}	ΔK	ΔK	ΔK	ΔK
da/dN_1	(1,1)	(1,2)	…					(10,1)
da/dN_2	(2,1)							⋮
⋮	⋮							
da/dN_{30}	(30,1)							(30,10)

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Post prosessing

- XML output contain all information regarding the analysis, geometry, material and DT analysis results.
- An external post-processing option is available that reads in the xml output from the plug-in models and generates a DT analysis output.
- This output generates:
  - Fracture toughness plot (residual strength)
  - Net section yield plot (residual strength)
  - Crack growth plots
  - Summary of the DT analysis
  - Complete output of tabular crack growth data

PLUG-IN FEATURE

Plug-in features Afgrow

- Plug-in capability allows the user to analyze common solutions needed for method conformity. Plug-in provides the β's for the DTA.
- New Afgrow release allows for more information exchange between plug-in module and Afgrow. Thus more analysis based on crack length can be performed, e.g. residual strength as Afgrow does not know what the 'geometry' is to asses the residual strength.
- Large data base of solutions available that can be incorporated easily using the plug-in models, e.g DAMGRO - "AFWAL-TR-86-3003 Assessment of Damage Tolerance Requirements and Analyses".

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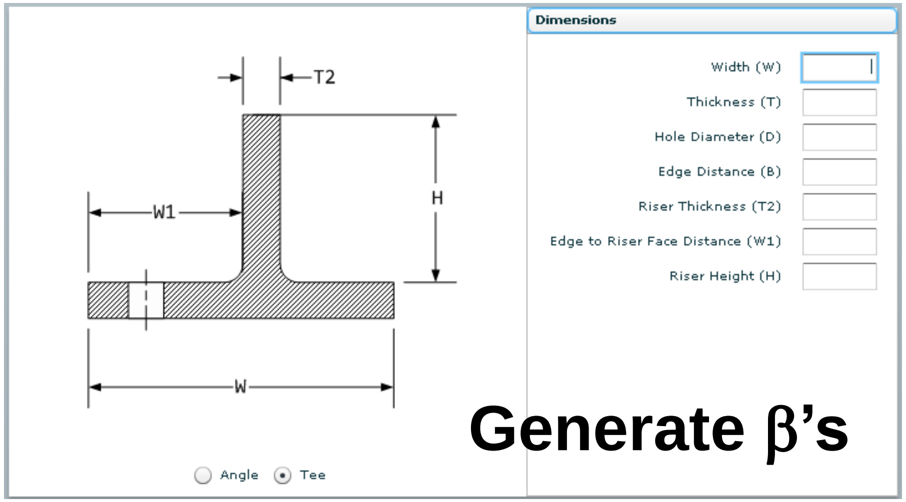
Plug-in features Afgrow

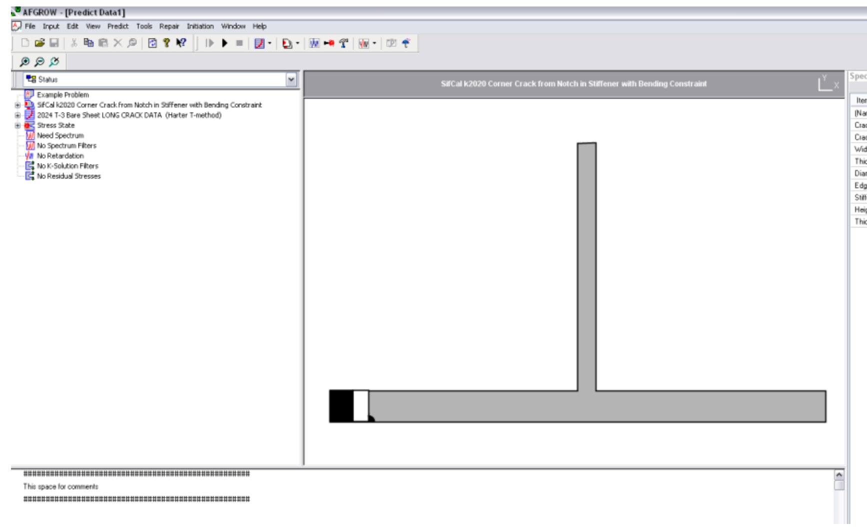
- Using the Plug-in option allows to calculate β's to run a DT analysis using Afgrow's material, spectrum and crack growth method.
- β's can be calculated for any possible analytical solution. If one has to generate β's for a commonly used problem outside the used DT tool and then import into the DT tool, Afgrow actually allows integration of the β–generation through the plug-in models.
- The solution is then hardcoded into Afgrow through the plug-in models and can be used directly, eliminating a step in which a user can make additional mistakes.

From 2-step to integrated approach



Generate β's

Integrated β's



Use external β's in Cracks2K

Integration of β's is achieved by using the plug-in model option in Afgrow. "How to" can be found on the Afgrow website.

CONCLUSIONS

Conclusions

- Increase efficiency in conducting DTA
  - Previously, beta generation and crack growth analysis were separated. Afgrow combines these steps.
- Increase accuracy of analysis
  - Larger community using Afgrow, user feed back will provide updates to improve.
- Increase reliability of analysis process
  - Less steps to analyze a structure increases reliability due to lower probability of user error.
- Increase efficiency in generating report-ready DT results
  - XML output of Afgrow allows for post-processing generating ready DT results including residual strength analysis for all plug-in models.