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Continuing Damage Case Study

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Content

INTRODUCTION

Motivation and Objective

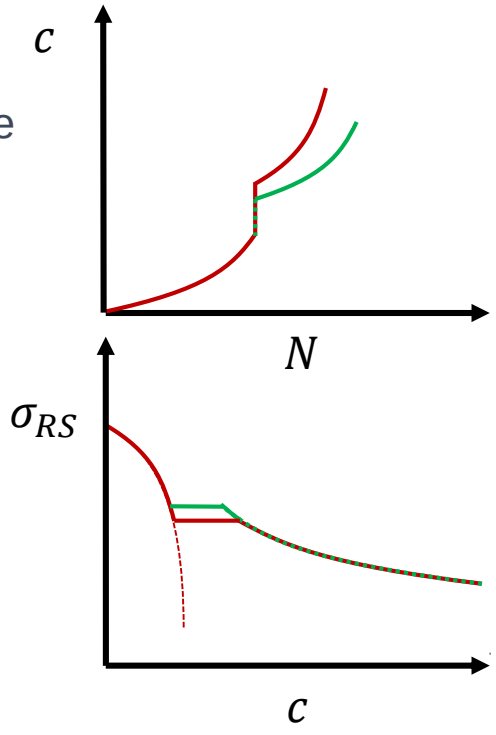
Introduction
Motivation and Objective

Life and Residual Strength for a Ligament Failure Scenario

- The life and residual strength after ligament failure depends on the continuing damage size.
- Traditional damage tolerance practices may underestimate the continuing damage size for some scenarios.

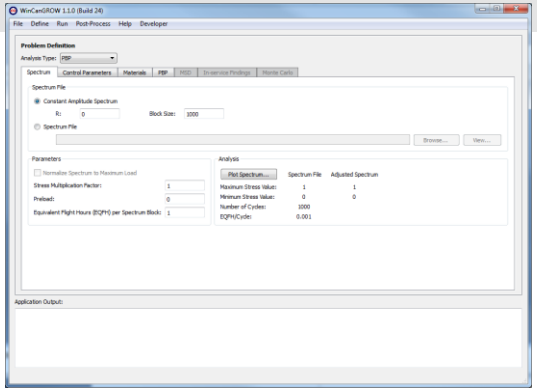
Objective

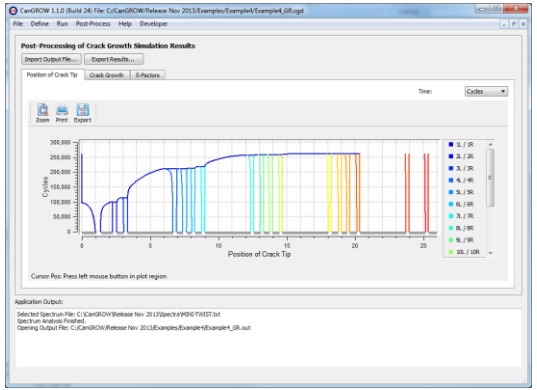
- Using CanGROW, compare crack growth characteristics resulting from independent (sequential) and simultaneous crack growth for a demonstration problem provided by USAF A-10 ASIP.
  - Compare Cangrow sequential analysis to AFGROW sequential analysis
  - Compare Cangrow sequential analysis with Cangrow simultaneous analysis



Introduction
CanGROW

- NRC in-house code developed to analyze multiple hole/crack scenarios
  - Phase-by-phase (**PBP**) (sequential crack growth)
  - Multi-Site Damage (**MSD**) (simultaneous crack growth)
- Many built-in K-solutions
- MSD analysis based on compounding method
- Regression of in-service findings for EIFS calculations
- Monte Carlo simulations
- NDI/Repair simulations





PROBLEM DEFINITION

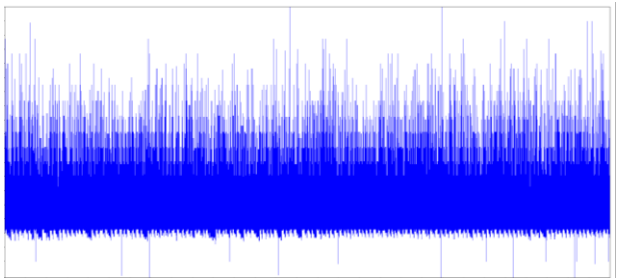
Provided by USAF A-10 ASIP

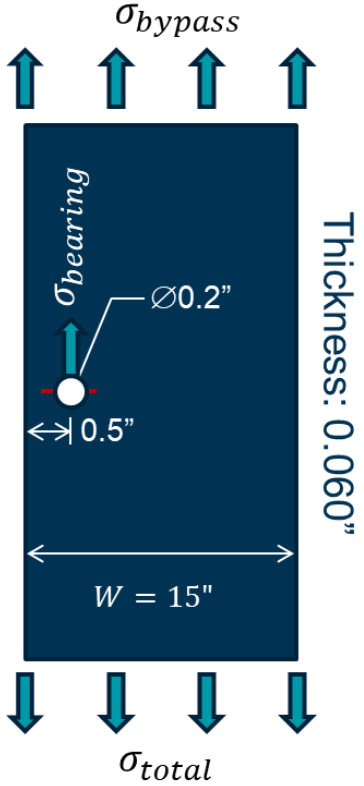
Problem Definition

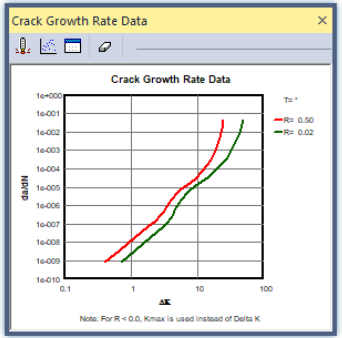
Geometry, Loading, Material

Offset hole in a plate

- Material: 7075-T6, Tabular Lookup (R = 0.02, R = 0.5)
- Retardation: Willenborg (SOLR = 1.7)
- Spectrum: Variable amplitude (A-10)



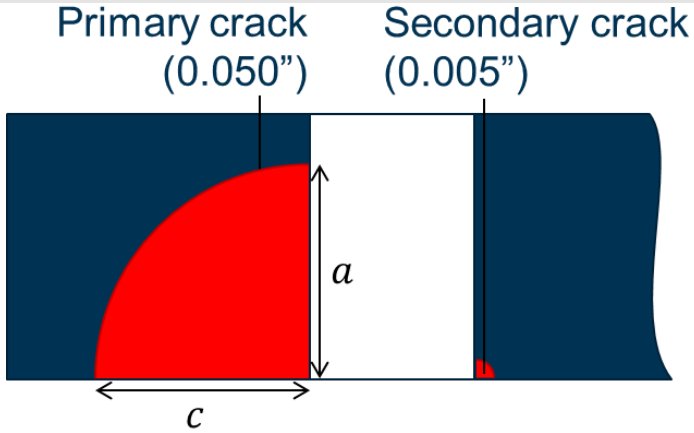




Problem Definition

Crack Size, Shape, Sequence

- Quarter-circular cracks (fixed a/c ratio)
  - Primary crack: c_o = 0.050”
  - Secondary crack: c_o = 0.005”
  - Bearing load lost after ligament failure
  - Transition to through crack: 95% of thickness[1]
- Three AFGROW files provided by USAF:
  - File 1: Primary crack
  - File 2: Secondary crack
  - File 3: Edge crack



Model	Bypass stress fraction	Bearing stress fraction
Diametrical crack	0.90	1.969
Edge crack	1.00	0.000

[1] Current CanGROW implementation: 100% of thickness. It is planned to be updated (e.g. transition when plasma zone reached the surface).

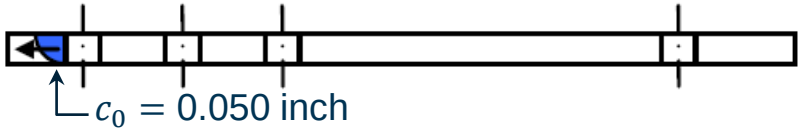
SEQUENTIAL CRACK GROWTH

Simulations conducted with CanGROW and AFGROW

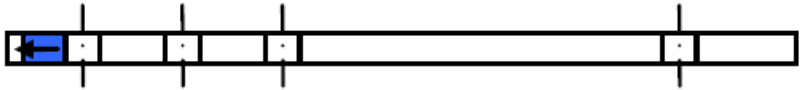
Sequential Crack Growth

Definition of Growth Phases

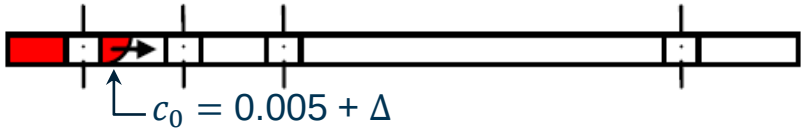
Phase 1: Corner crack from hole #1



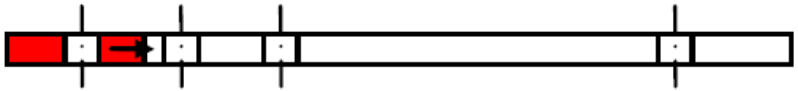
Phase 2: Through crack from hole #1



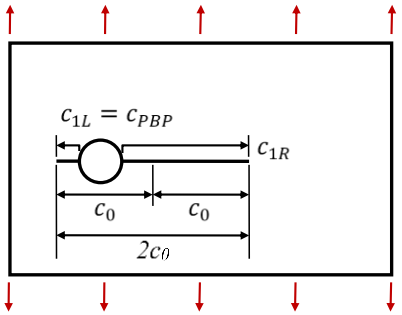
Phase 3: Edge corner crack from hole #1



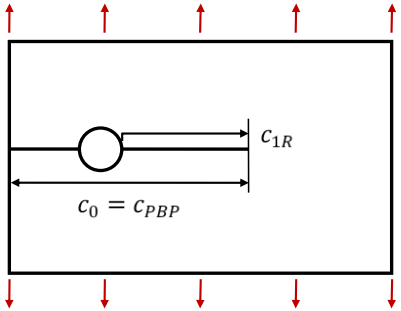
Phase 4: Edge through crack from hole #1



Crack Size Definition:

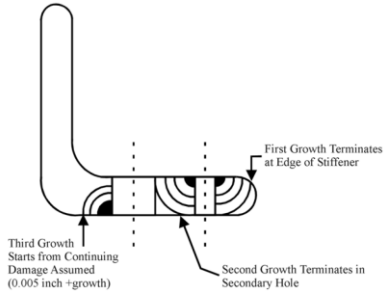


a) Radial/diametrical cracks



b) Edge crack

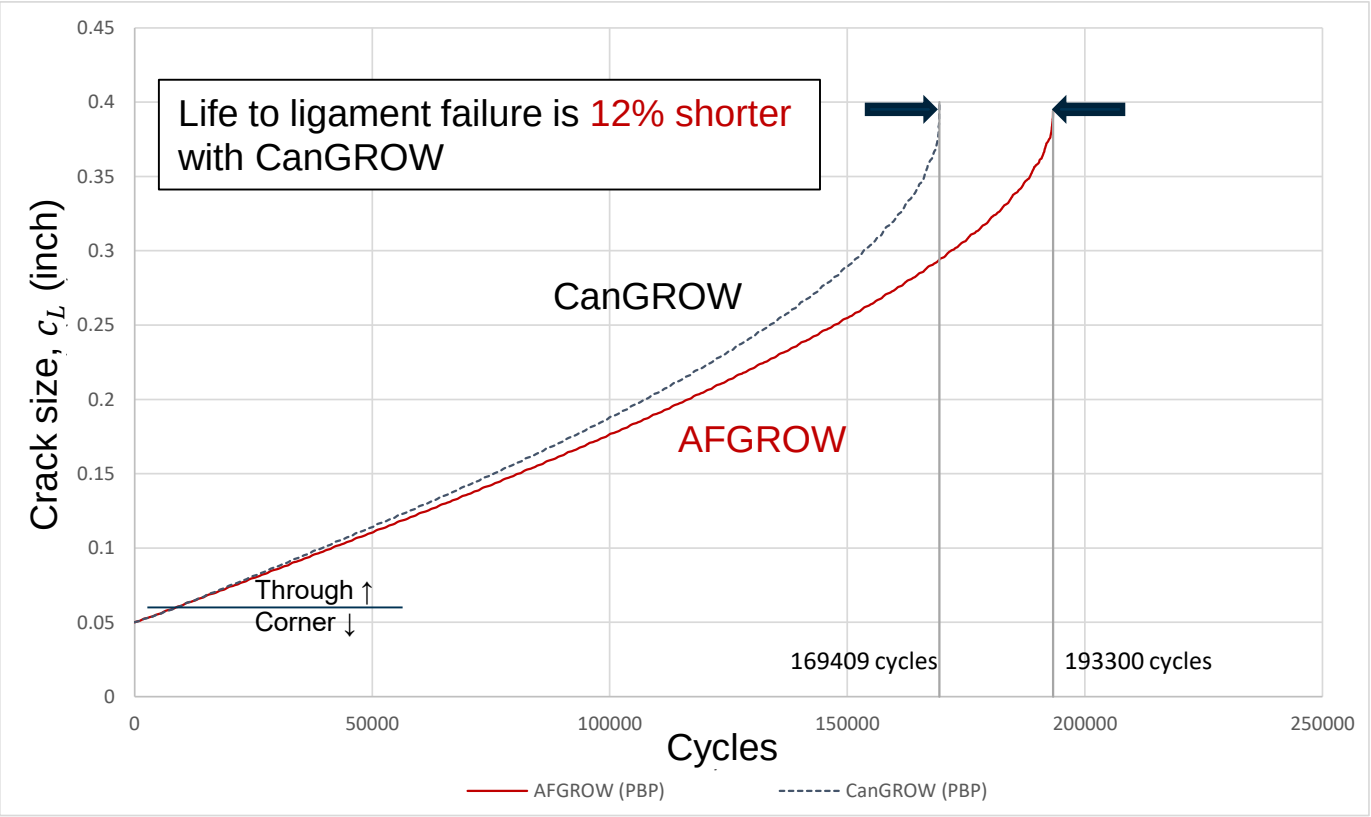
USAF Damage Tolerant Design Handbook



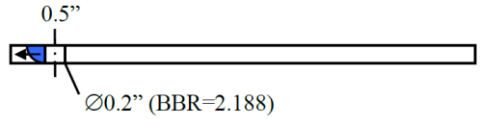
"When the crack growth from the assumed initial flaw enters into and terminates at a fastener hole, continuing damage should be an .005 inch radius corner flaw + Δa emanating from the diametrically opposite side of the fastener hole at which the primary damage initiated or terminated, whichever is more critical".

Sequential Crack Growth

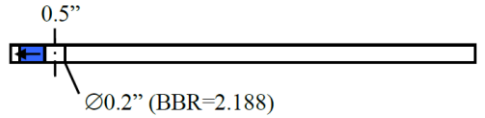
Phases 1 & 2: Primary Crack Growth Towards the Edge



Phase 1: Corner crack (primary)



Phase 2: Through crack (primary)

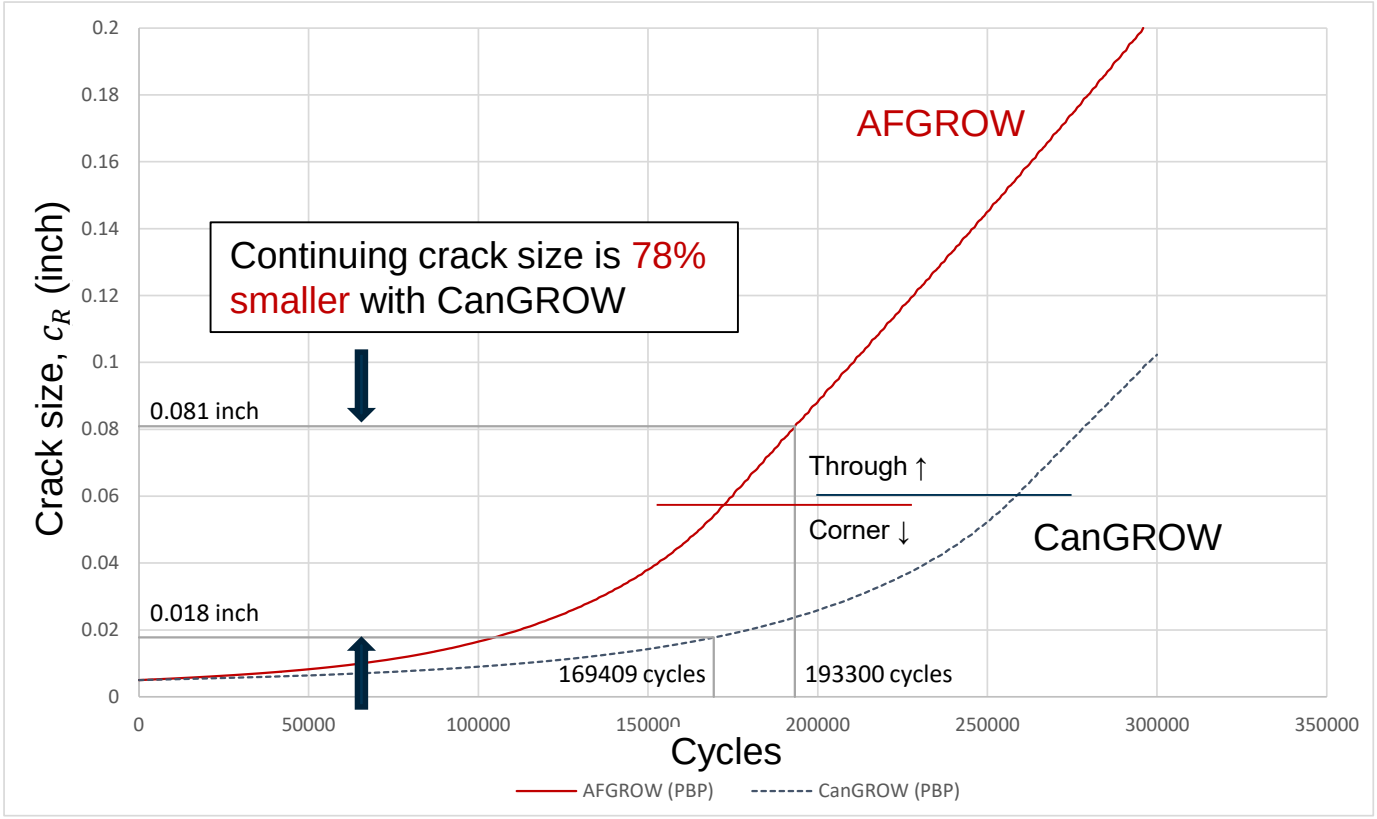


CanGROW and AFGROW seem to use different boundary conditions for the K-solutions. Refer to section “Verification of the Stress Intensity Factor (K) Solutions” for more details.

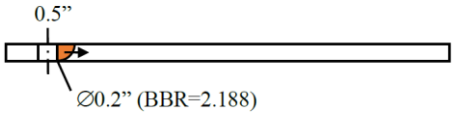
Canada

Sequential Crack Growth

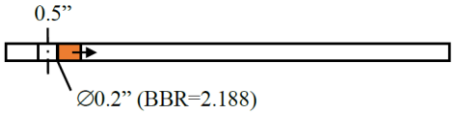
Calculation of Continuing Crack Size



Corner crack (continuing damage)



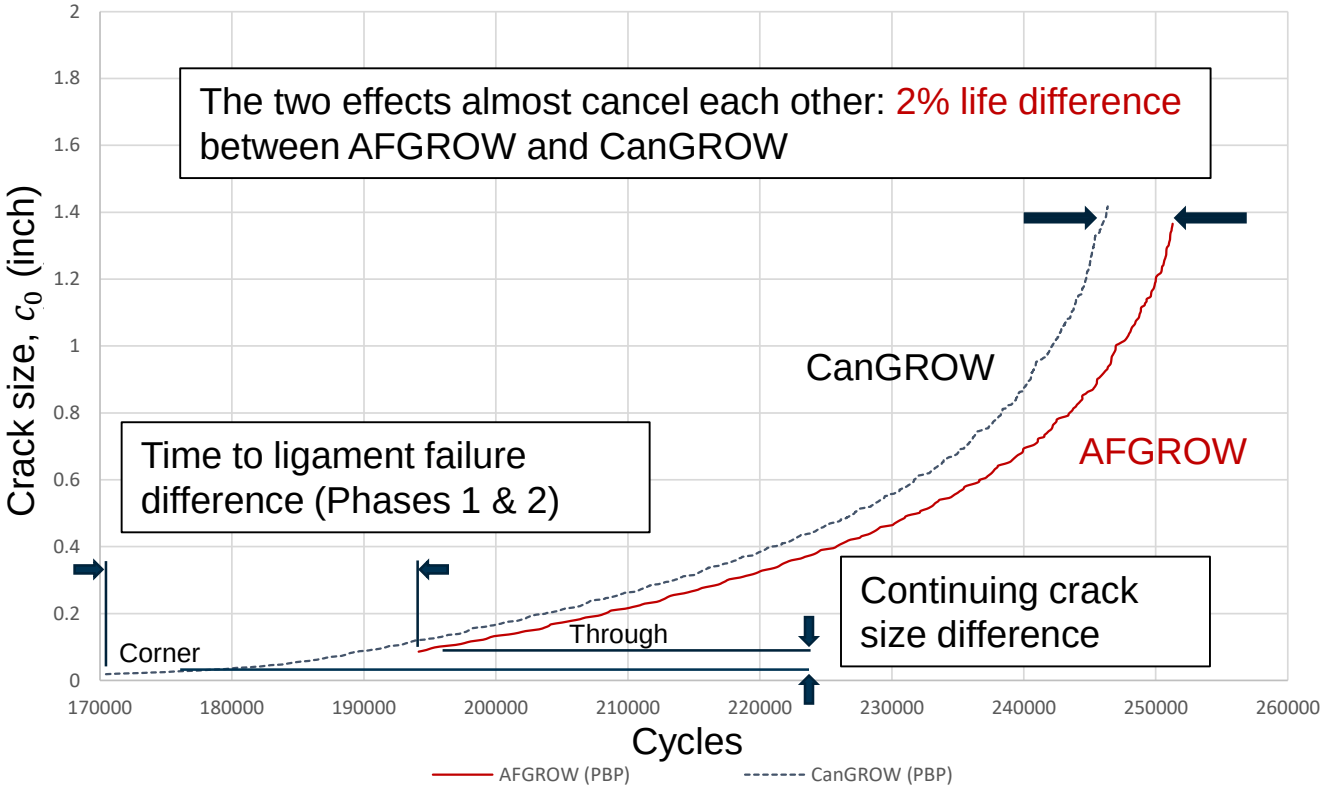
Through crack (continuing damage)



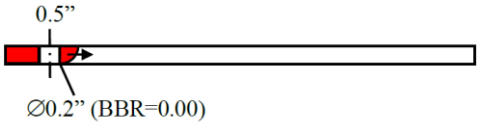
The CanGROW and AFGROW curves differ mainly because of their corner crack K-solutions ($a \leq 0.6$ in). Refer to backup slides (p. 41) for more details. Crack growth is similar for through cracks ($a \geq 0.6$ in).

Sequential Crack Growth

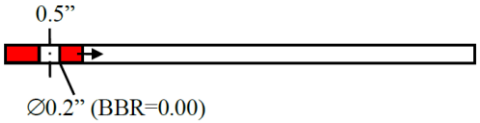
Phases 3 & 4: Edge Crack from Continuing Crack



Phase 3: Edge corner crack

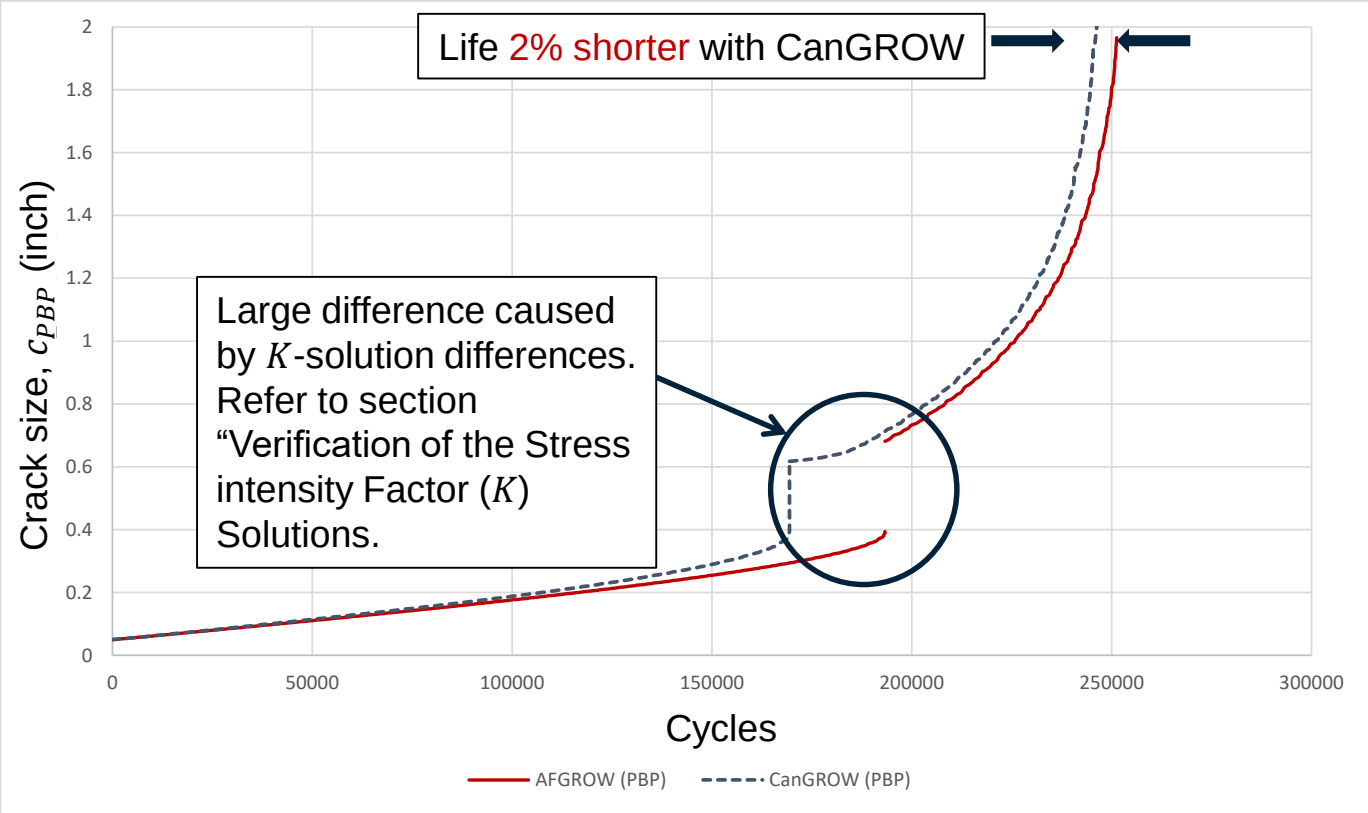


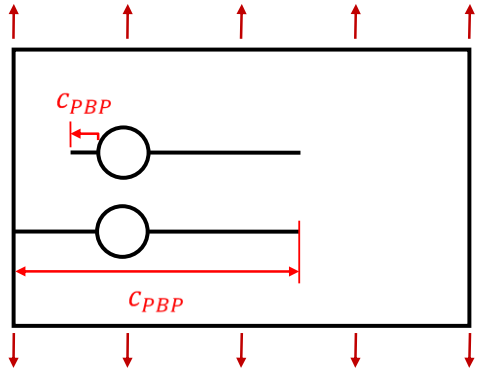
Phase 4: Edge through crack



Sequential Crack Growth Approach

Phases 1-4: Comparison between AFGROW and CanGROW





Time to ligament failure is 12% shorter with CanGROW. This results in a shorter continuing damage size for Phase 3, thus a longer Phase 3-4 life. When combined, these two effects almost cancel each other over the total life to failure.

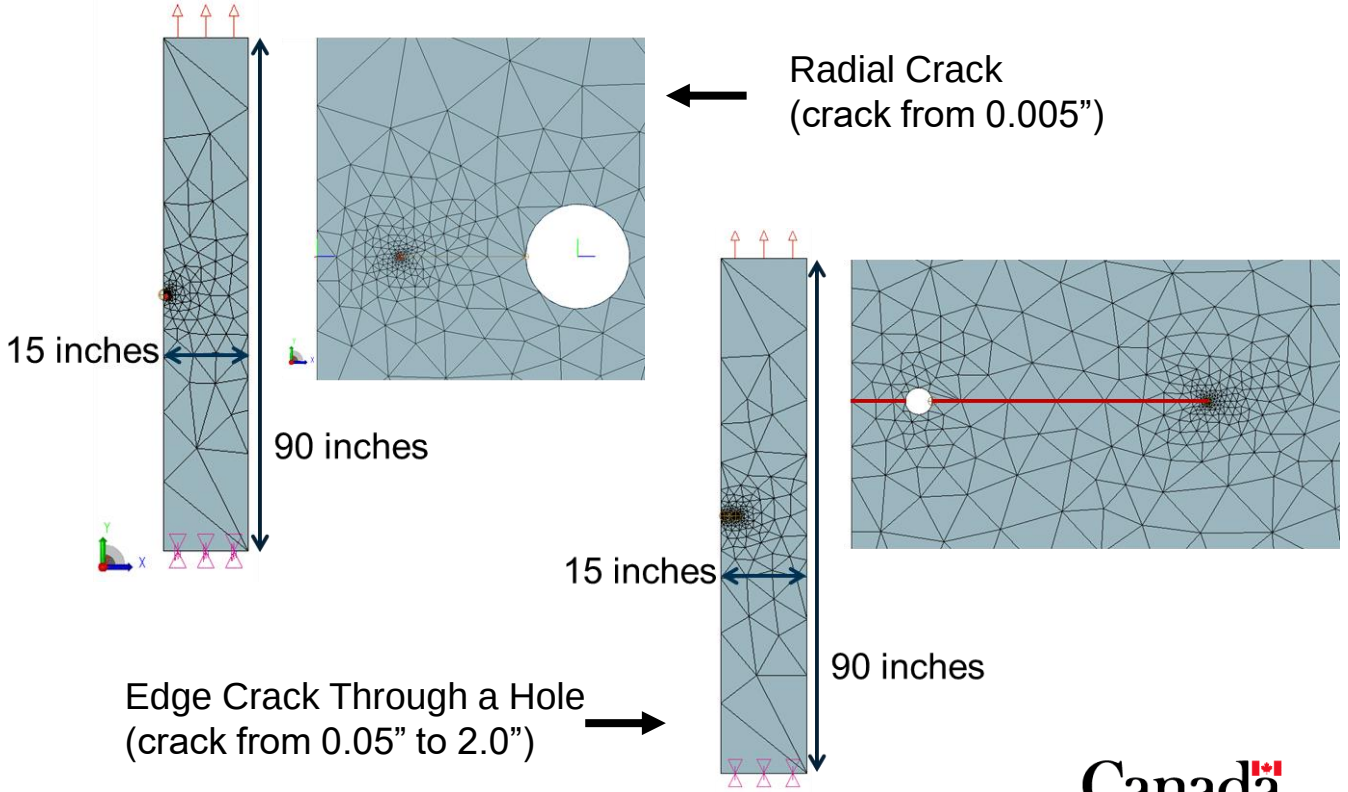
VERIFICATION OF THE STRESS INTENSITY FACTOR (K) SOLUTIONS

Verification of the K-Solutions

StressCheck Verification

StressCheck Model:

- Planar FEA (through cracks only)
- Crack path analyses with automesh
- Open hole
- Sinusoidal bearing load distribution (radial crack)



Verification of the K-Solutions

Verification Tests

Case	Crack	Type	Load	Result
1	Left	Through	Bypass	A ≠ C ≈ S
2	Left	Through	Bypass + Bearing	A ≠ C ≈ S
3	Right	Through	Bypass	A ≈ C ≈ S
4	Right	Through	Bypass + Bearing	A ≈ C ≠ S
5	Left	Corner	Bypass	A ≈ C
6	Left	Corner	Bypass + Bearing	A ≈ C
7	Right	Corner	Bypass	A ≈ C
8	Right	Corner	Bypass + Bearing	A ≠ C
9	Edge	Through	Bypass	A ≈ C ≈ S

⟵ Further investigation next

Left: Towards near edge
Right: Towards far edge

A: AFGROW
C: CanGROW
S: StressCheck

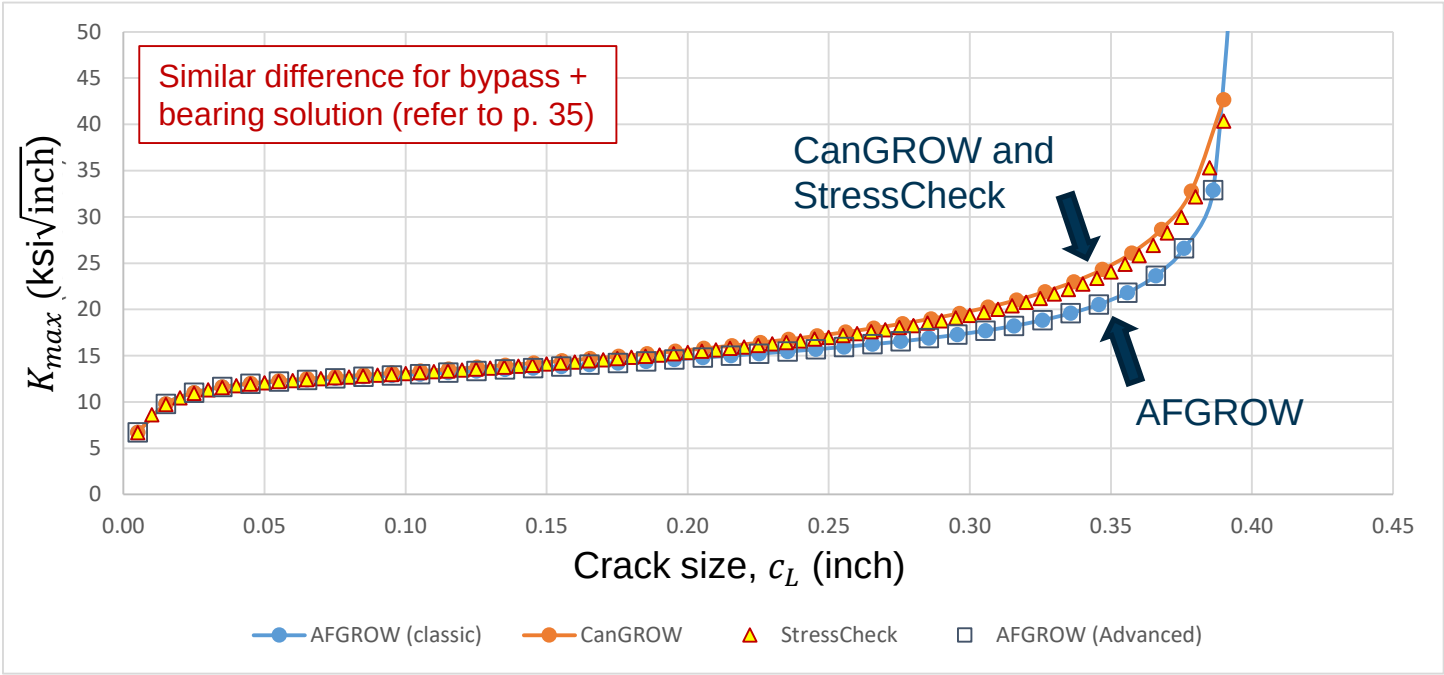
Note: All comparison plots are presented in the backup slides at the end of the deck

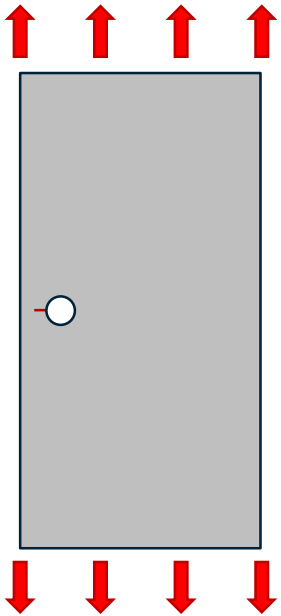
⟵ Further investigation next

Note: All tests were conducted using constant amplitude loading with $R = 0$, such that $\boldsymbol{K}_{max} = \boldsymbol{\Delta K}$

Verification

Through Crack – Left Side - Bypass Load

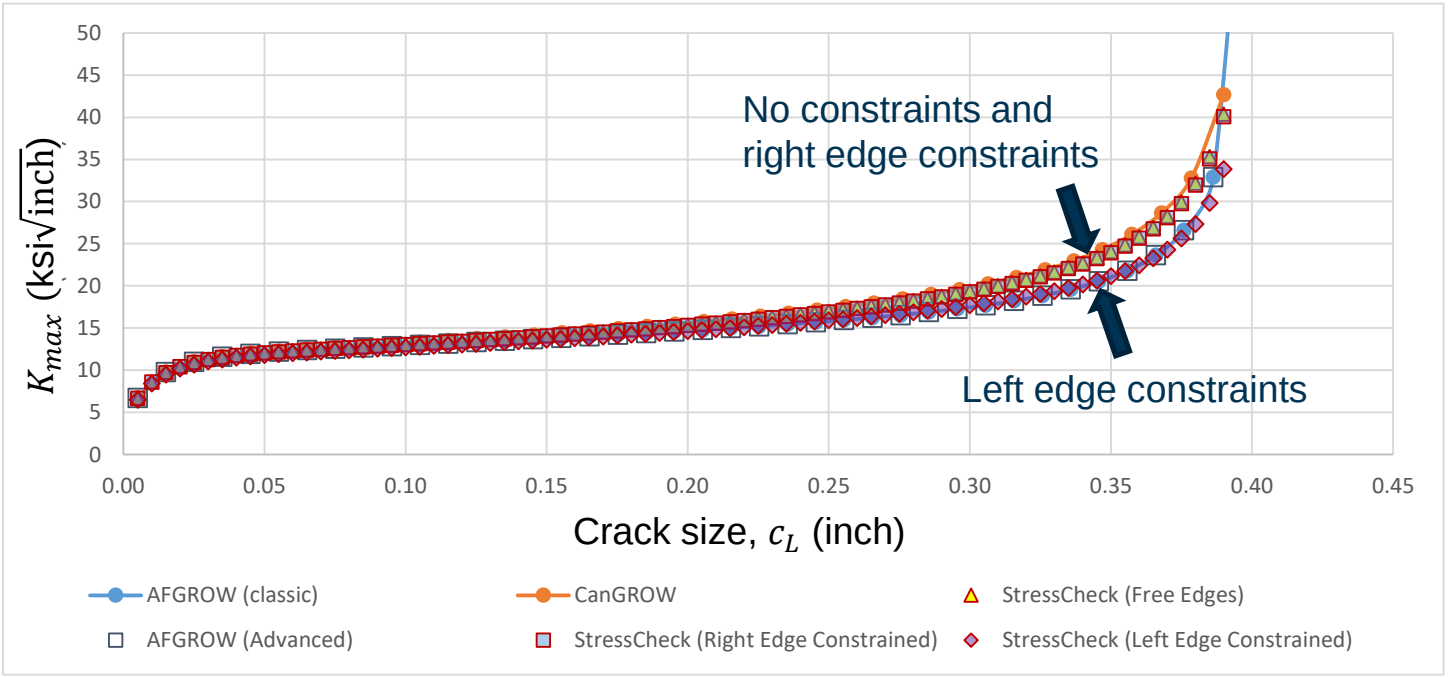


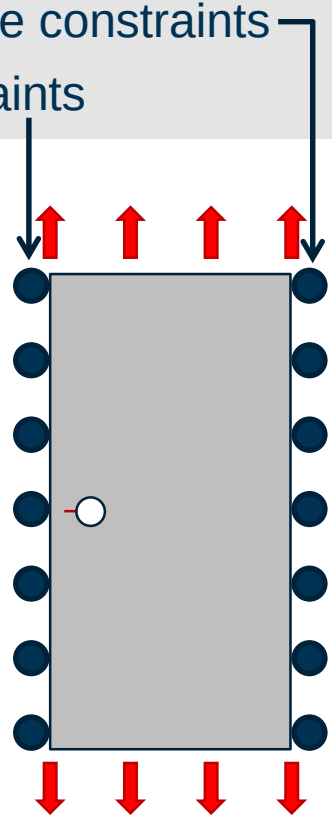


All solutions are similar, except that the CanGROW and StressCheck K-solutions diverge from the AFGROW solutions when the crack approaches the edge (different boundary conditions?).

Verification

Through Crack – Left Side - Bypass Load



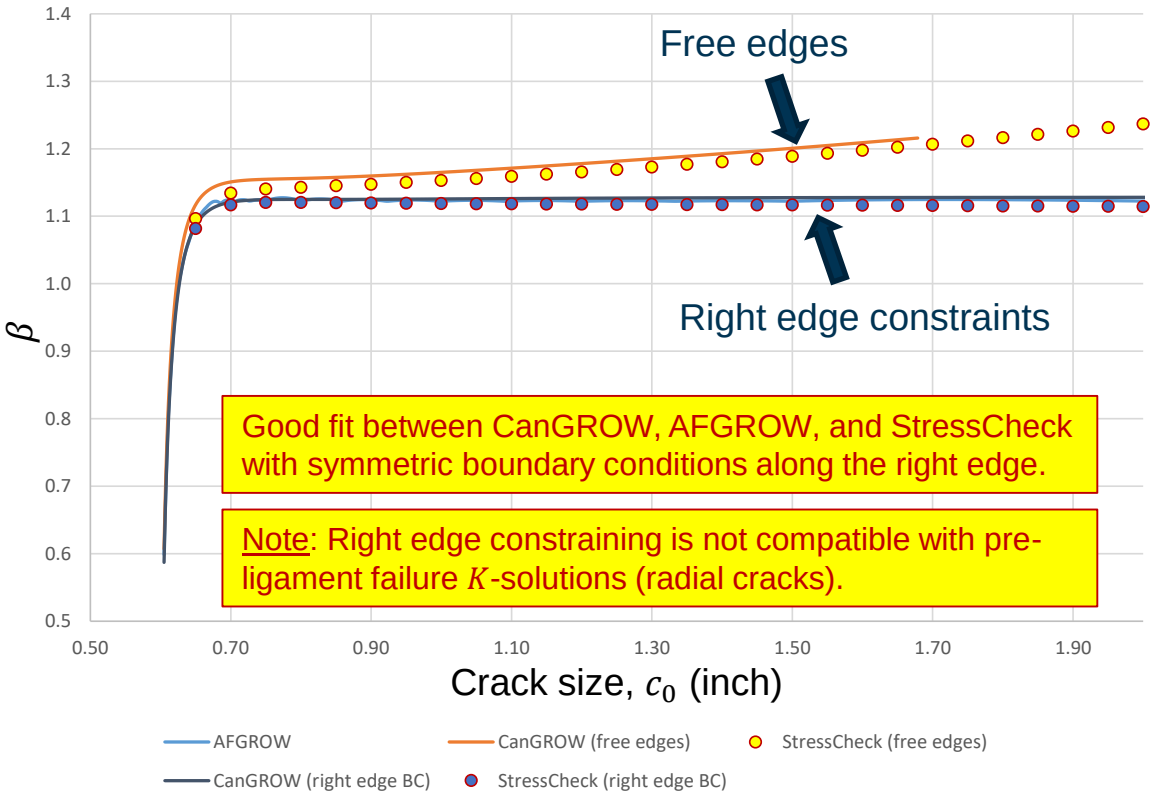


AFGROW classic and advanced solutions agree with the StressCheck results with constraints on left edge. These edge constraints may not work well for coupon level testing.

Canada

Verification

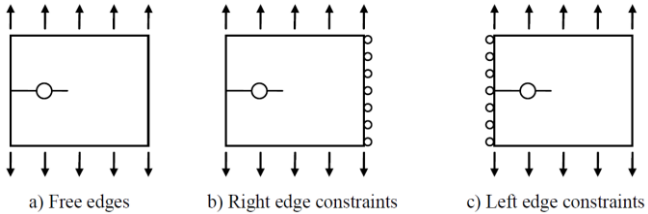
Edge Edge Crack Through a Hole



Good fit between CanGROW, AFGROW, and StressCheck with symmetric boundary conditions along the right edge.

Note: Right edge constraining is not compatible with pre-ligament failure K-solutions (radial cracks).

Three types of constraints can be selected for an edge crack in CanGROW:



The AFGROW solution agrees with the right edge constraints solution (b)). NRC used this solution for the CanGROW simulations presented herein.

SIMULTANEOUS CRACK GROWTH

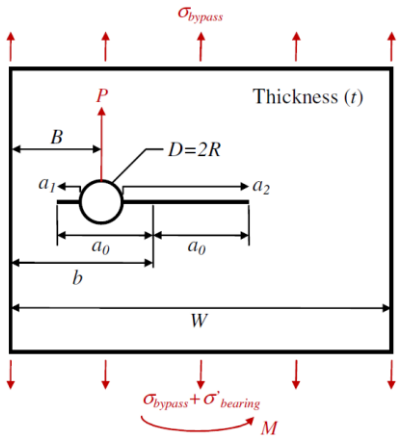
“MSD” simulations conducted with CanGROW (single hole)

Simultaneous Crack Growth

CanGROW's Core β-Solution

- Offset hole in a finite plate
- Crack(s):
  - Radial (single crack)
  - Diametrical (double cracks)
- Loads:
  - Bypass remote stress
  - Bearing stress (fastener loads)
- Assumptions:
  - Mode I only
  - Uniform bypass stress
  - Empty hole

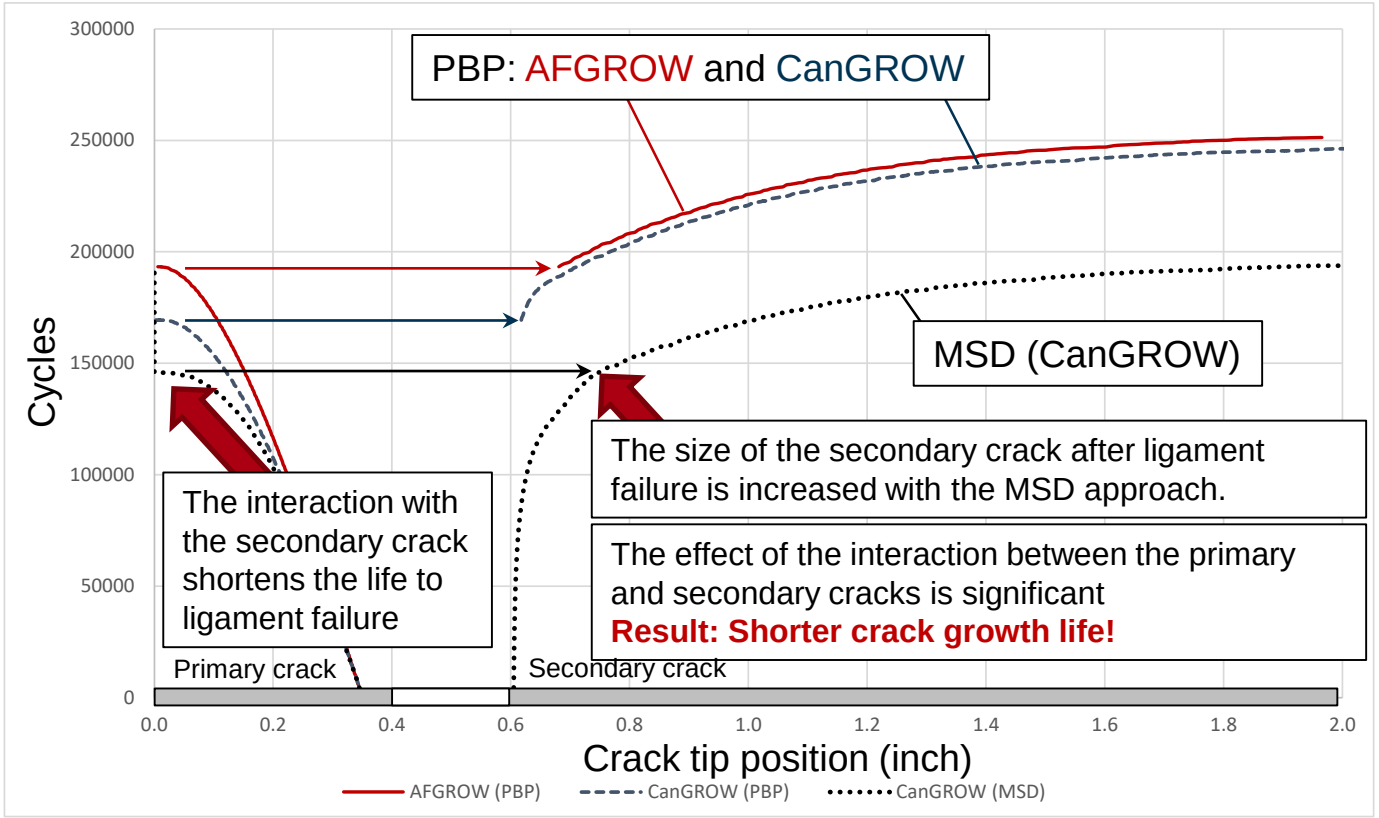
Crack Size Definition:

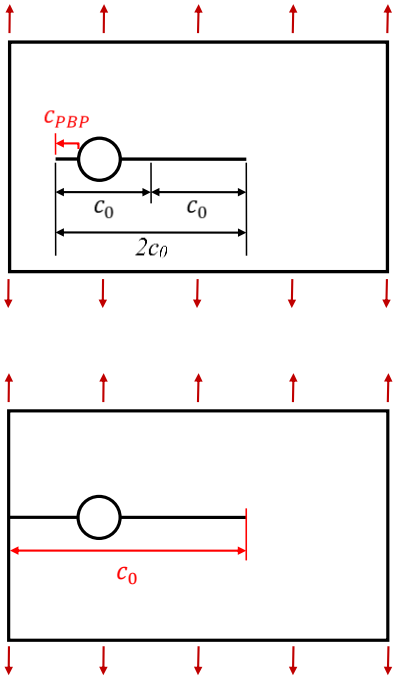


Reference: Bombardier, Y., Liao, M. (2010) *A New Stress Intensity Factor Solution for Cracks at an Offset Loaded Fastener Hole*, 51th AIAA SDM Conference Proceedings, Orlando, April 12-15 2010.

Simultaneous Crack Growth

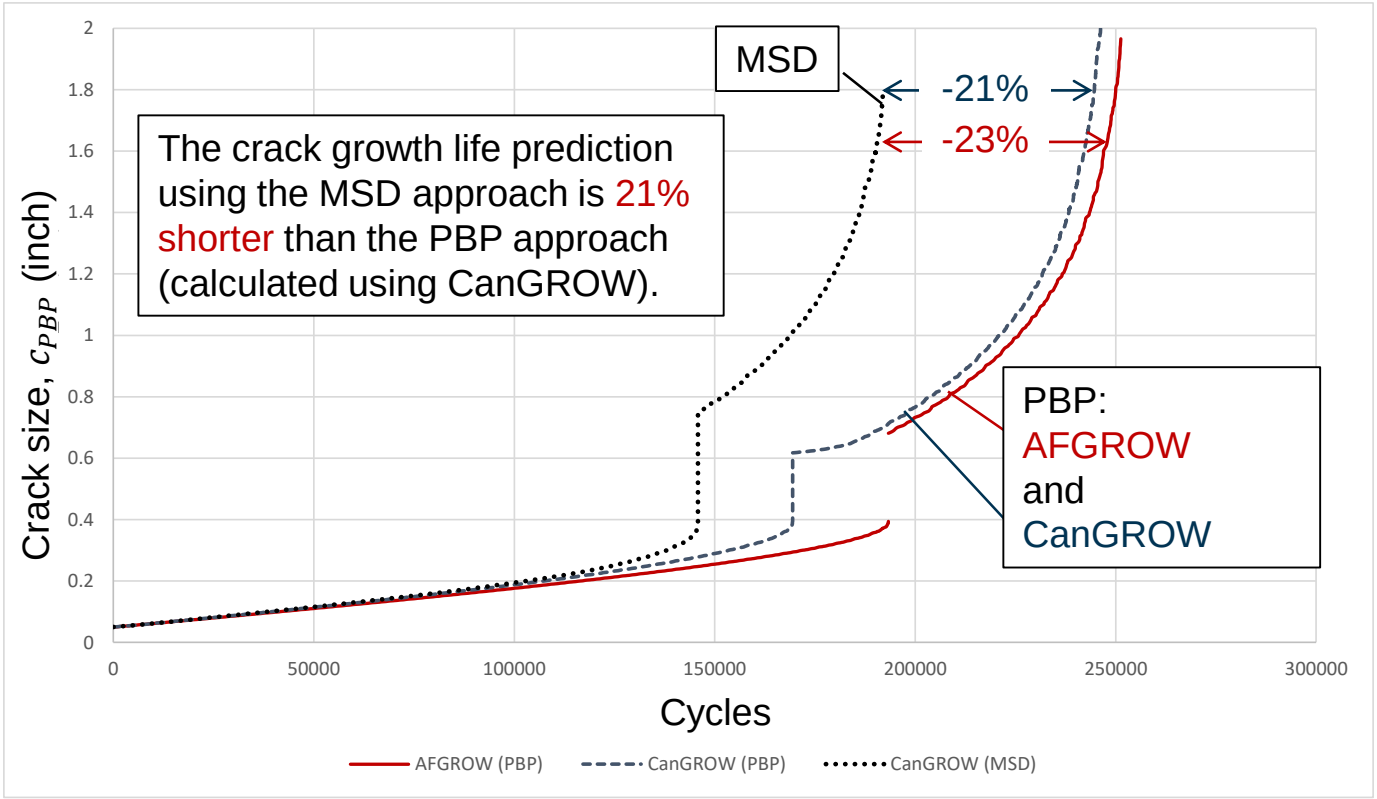
Crack Growth Results – Crack Tip Positions vs. Cycles





Simultaneous Crack Growth

Crack Growth Results – Lead Crack



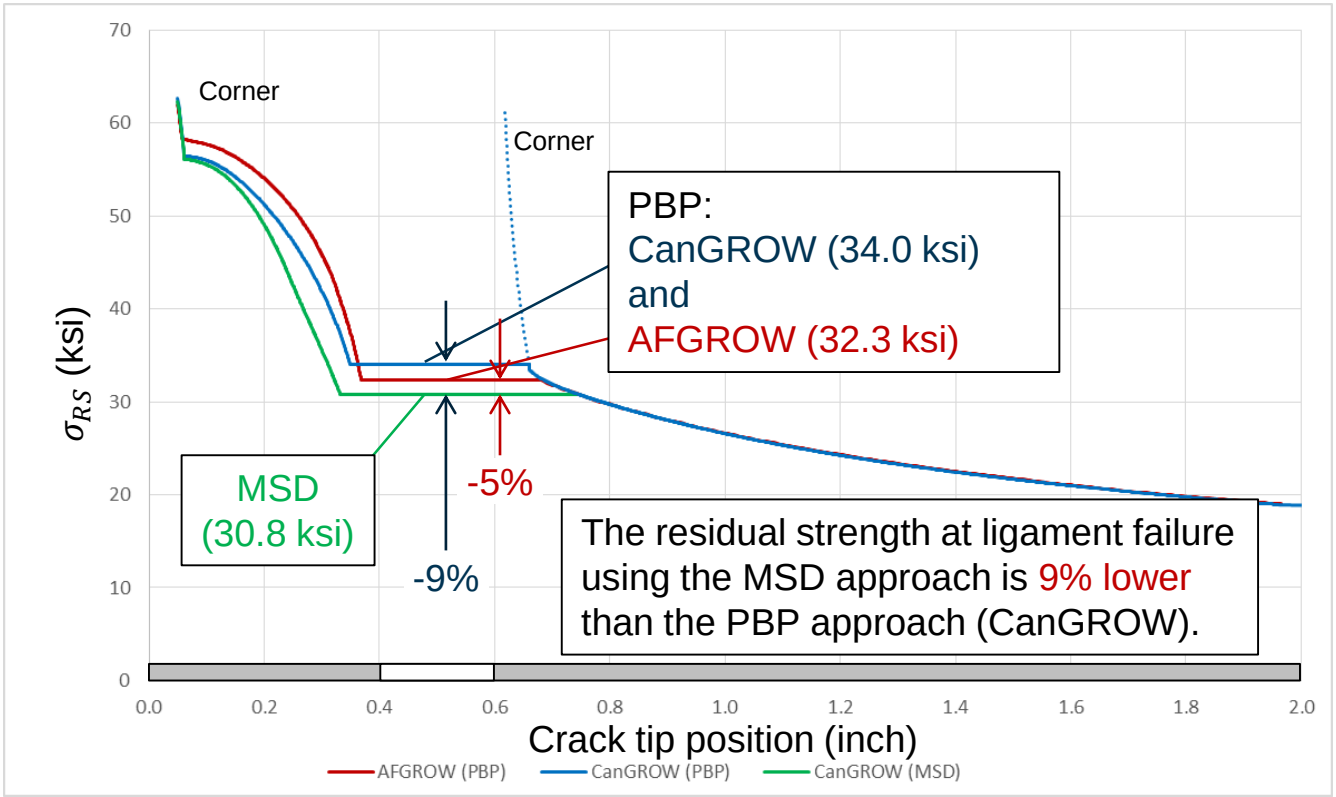
Approach	Life (cycles)
PBP/AFGROW	251,279
PBP/CanGROW	246,357
MSD/CanGROW	193,797

Approach	Cont. Crack
PBP/AFGROW	0.681”
PBP/CanGROW	0.618”
MSD/CanGROW	0.746”

Canada

Simultaneous Crack Growth

Residual Strength Results – Lead Crack



Approach	σ_{RS} at lig. failure
PBP/AFGROW	32.3 ksi
PBP/CanGROW	34.0 ksi
MSD/CanGROW	30.8 ksi

Note: Residual strength from PBP CanGROW Phase 3 corner crack was neglected

CONCLUDING REMARKS

Observations and Philosophical Questions

Concluding Remarks

Observations

- Simultaneous crack growth (MSD approach) made the crack growth life 21% shorter and the residual strength after ligament failure 9% lower compared to sequential crack growth (PBP approach).
- The crack growth rate of the secondary crack was highly influenced by the presence of the larger primary crack. Neglecting this effect leads to longer lives.
- The K-solution developed by NRC can correctly model the continuing damage scenarios because it includes crack interaction.

Concluding Remarks

Philosophical Questions…

- If simultaneous crack growth (MSD approach) is more representative of the target scenario, is the legacy approach un-conservative?
- Is there un-conservativism built in the traditionally assumed initial crack sizes (0.050” for the primary crack and 0.005” for the secondary crack)?
- If simultaneous growth is used, should the secondary initial crack size assumption be modified (reduced) to be made more representative of initial material discontinuity states?
- The way forward for modelling continuing damage using simultaneous growth (e.g. MSD scenarios) needs to be addressed as the legacy PBP approach leads to longer lives if the same initial crack size assumptions are used.

Acknowledgements

Thanks to Dallen Andrew for proposing and initiating this study.

Thanks to Jake Warner for assembling and providing the benchmark case.

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THANK YOU

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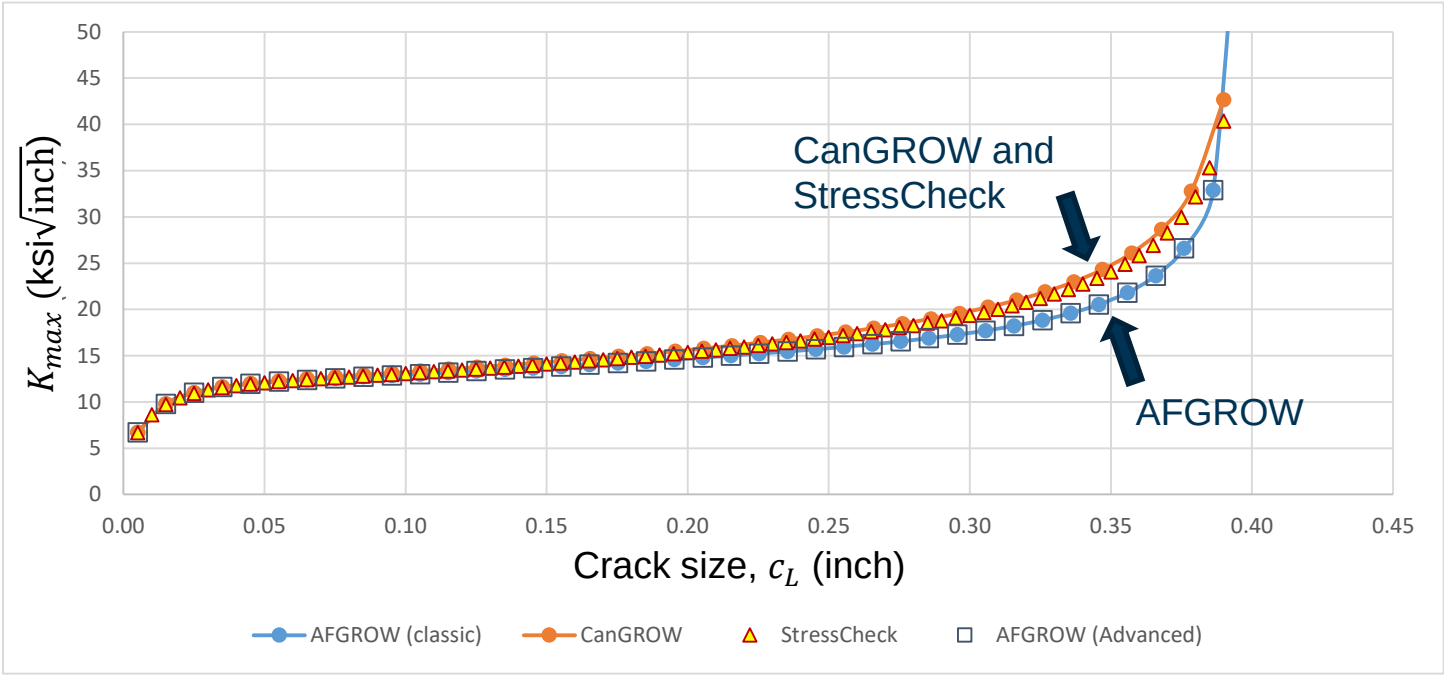
Yan Bombardier • Research Officer • Yan.Bombardier@nrc-cnrc.gc.ca

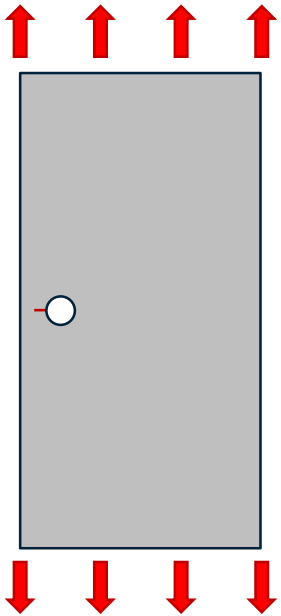
BACKUP SLIDES

K-solutions comparison plots

Verification

Through Crack – Left Side - Bypass Load





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Verification

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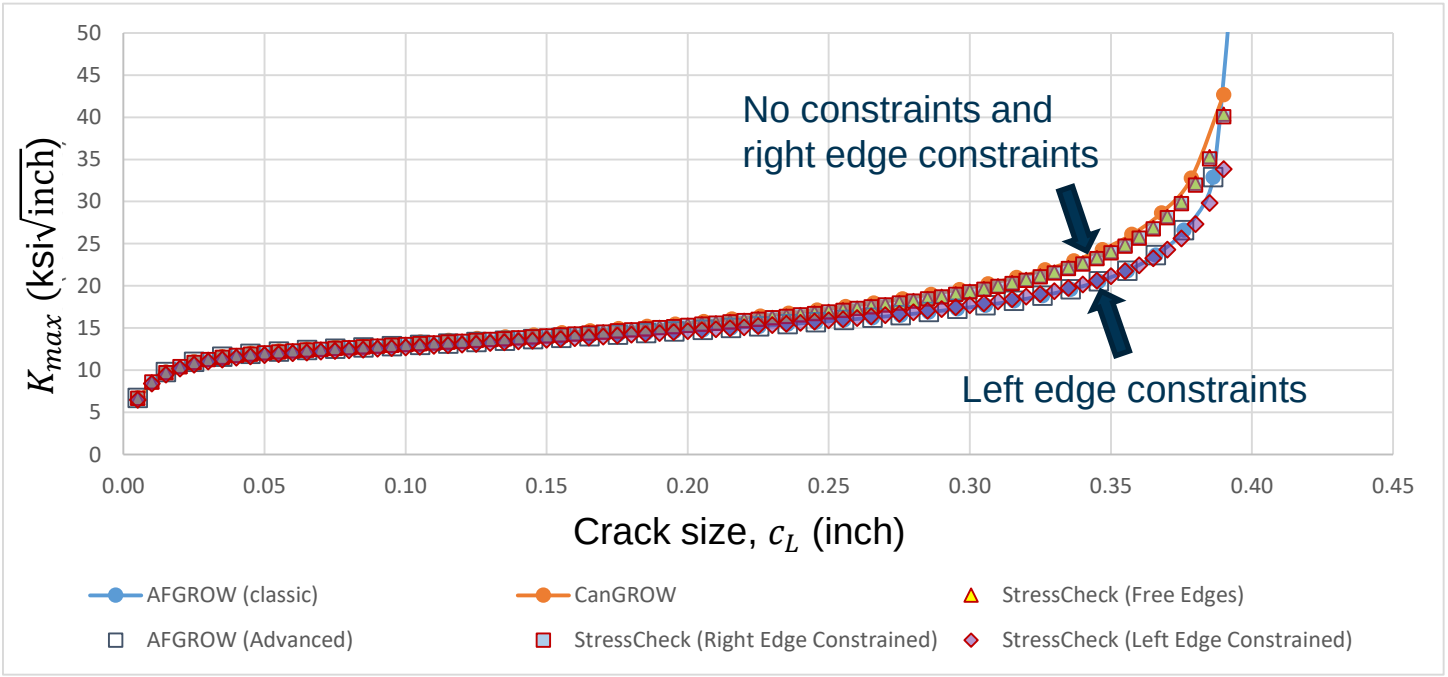

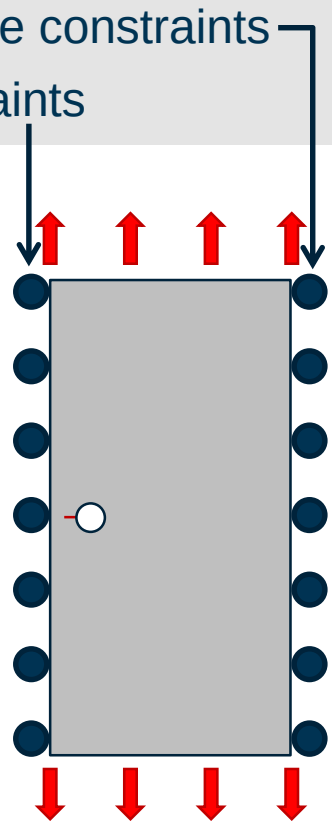

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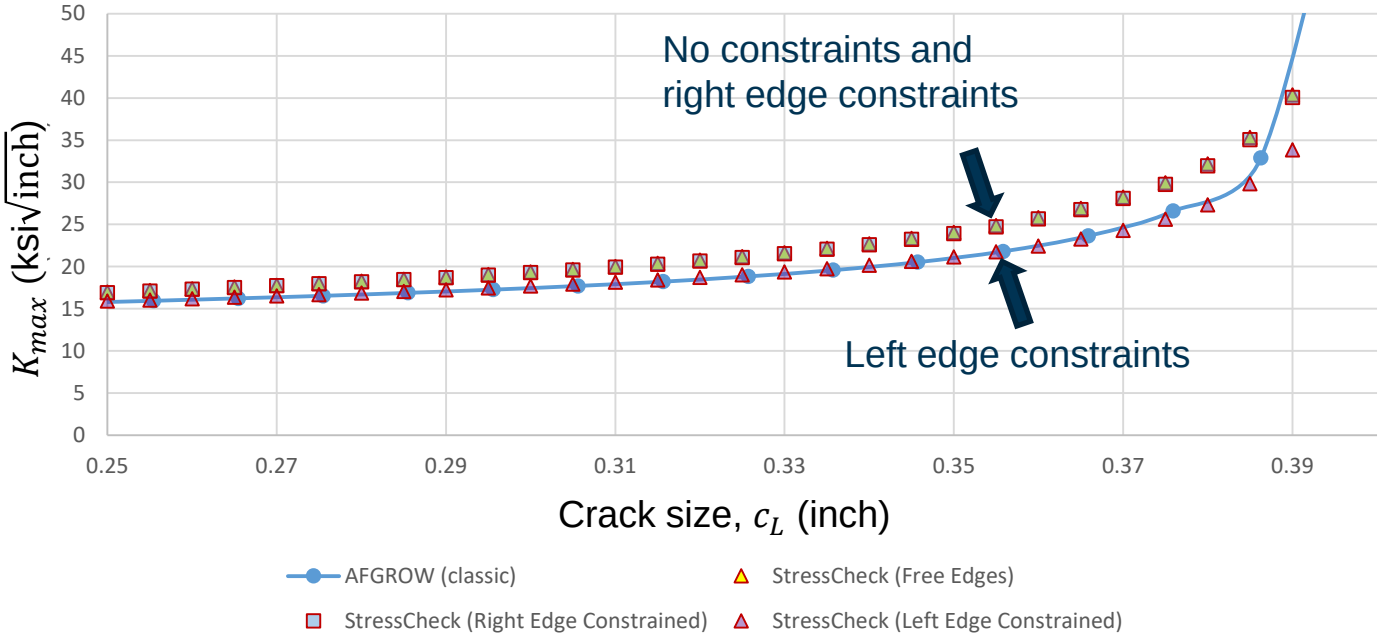
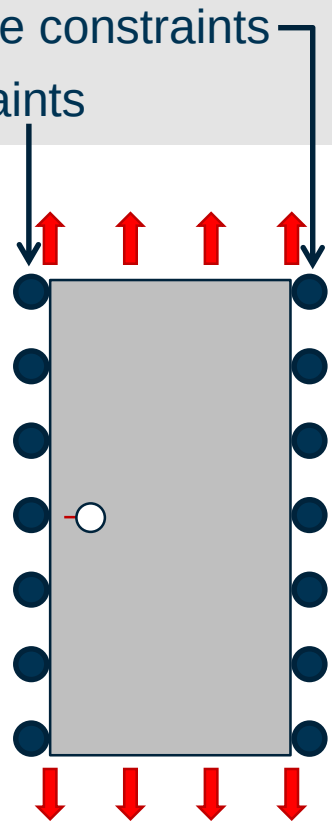
Through Crack – Left Side - Bypass Load

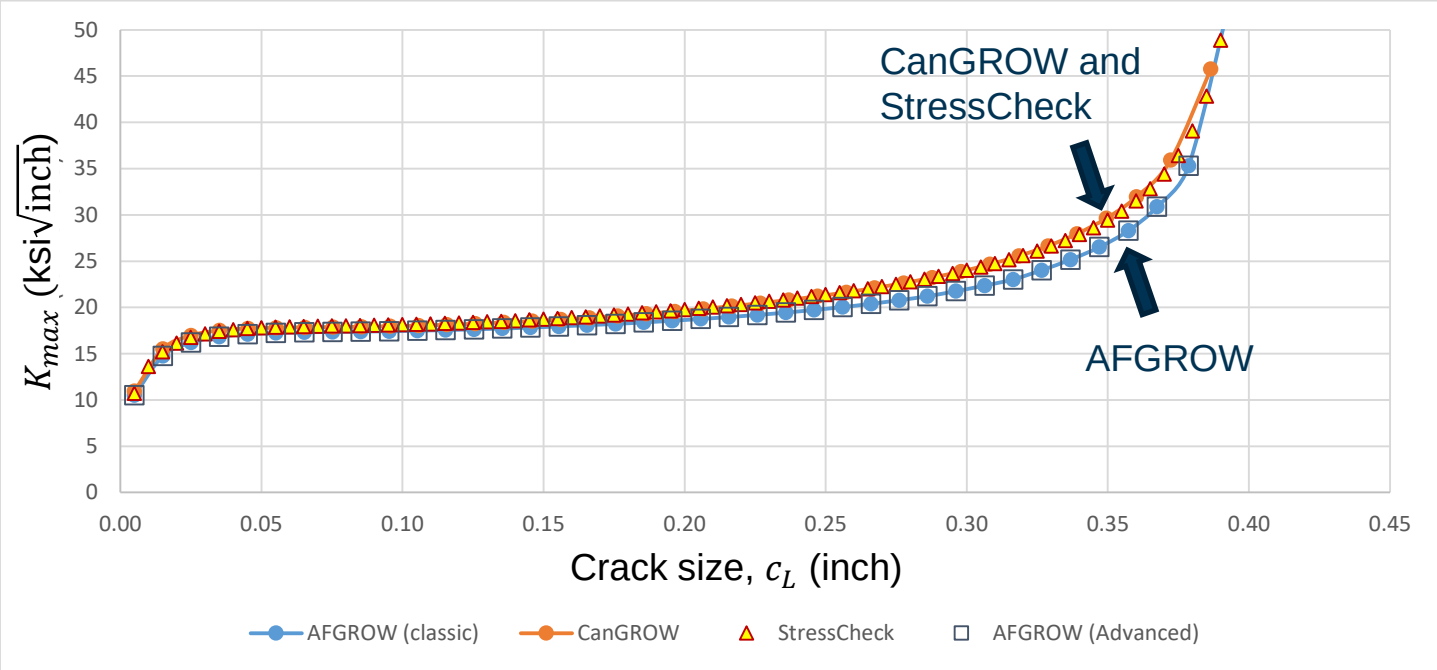


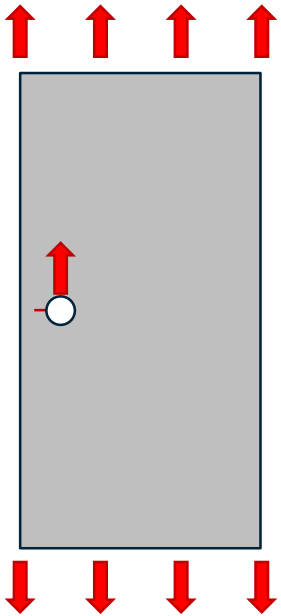


AFGROW classic and advanced solutions agree with the StressCheck results with constraints on left edge. These edge constraints may not work well for coupon level testing.

Verification

Through Crack – Left Side – Bypass and Bearing Load



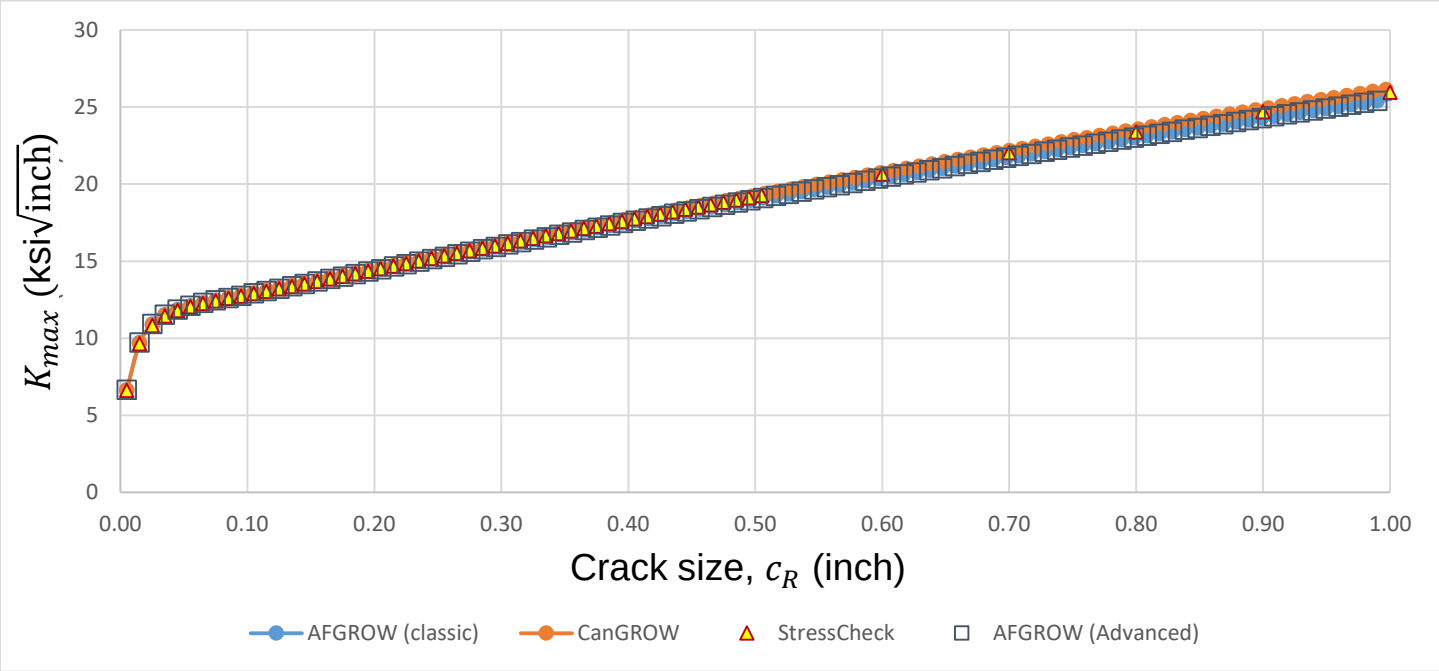


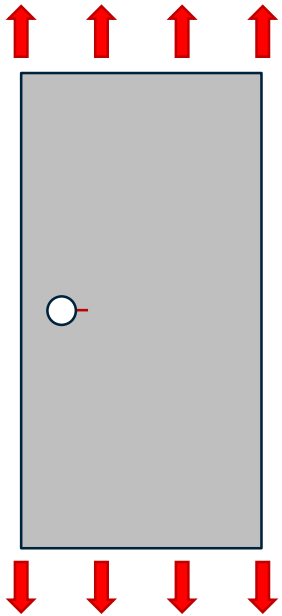
All solutions are similar, except that the CanGROW and StressCheck K-solutions diverge from the AFGROW solutions when the crack approaches the edge (different boundary conditions?).

Canada

Verification

Through Crack – Right Side - Bypass Load

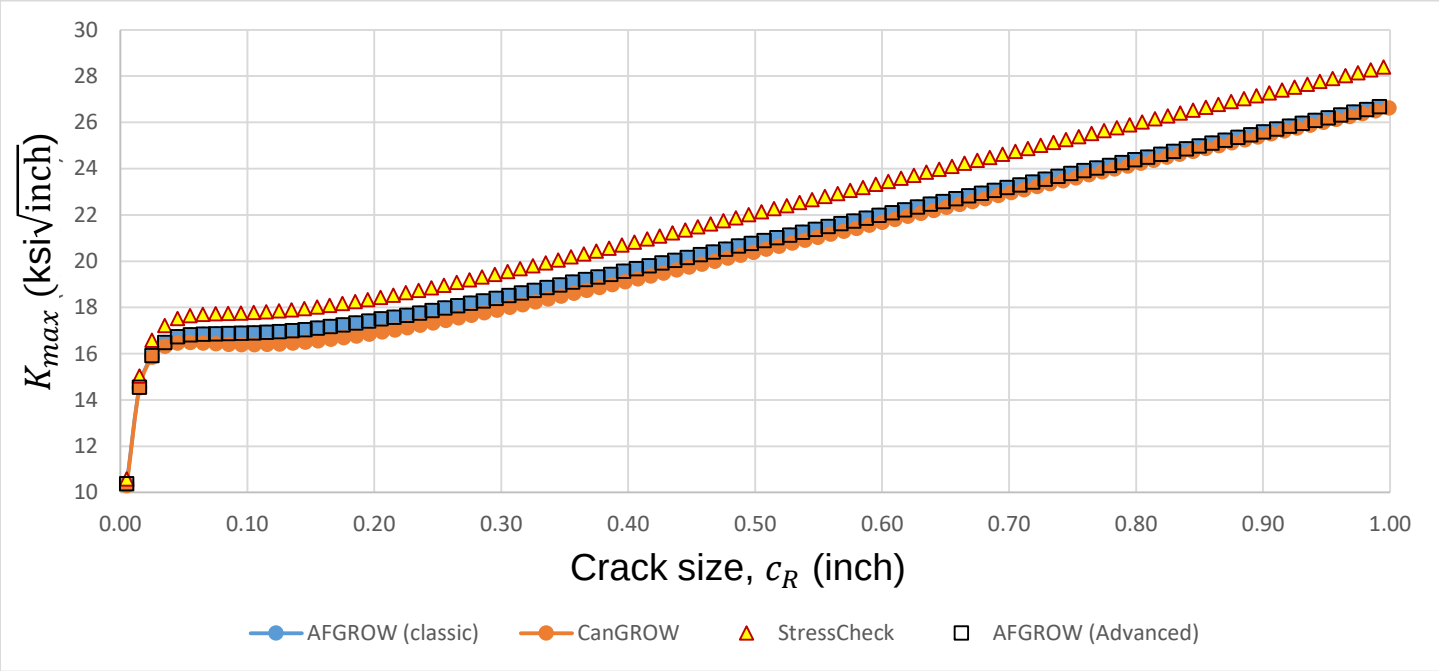


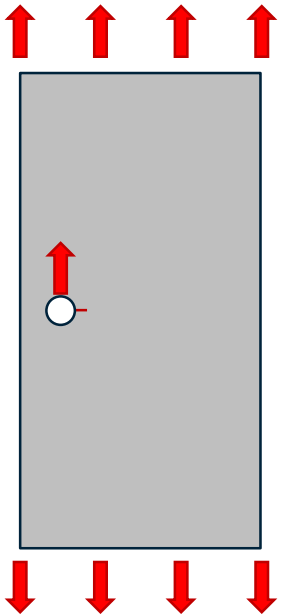


The AFGROW, CanGROW, and StressCheck K-solutions are very similar.

Verification

Through Crack – Right Side – Bypass and Bearing Load

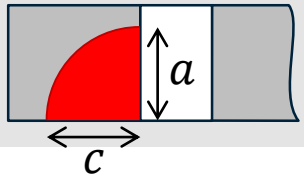


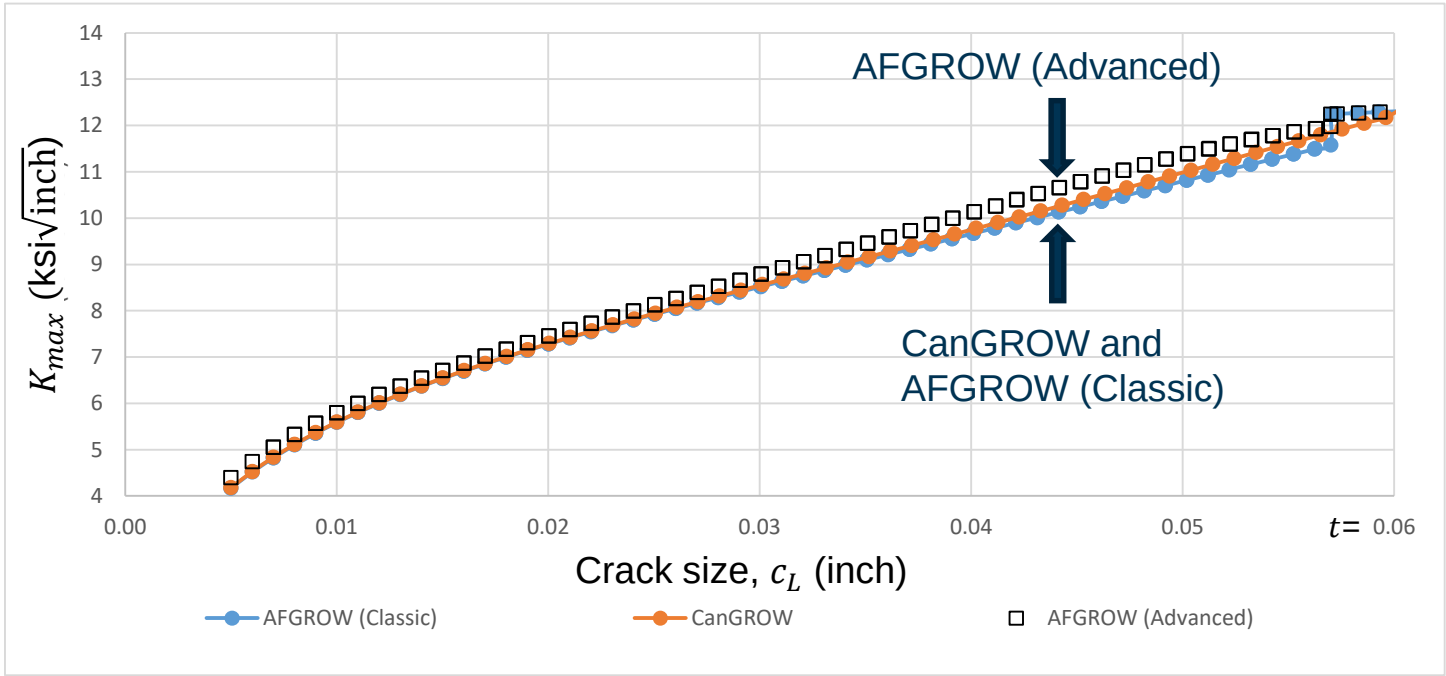


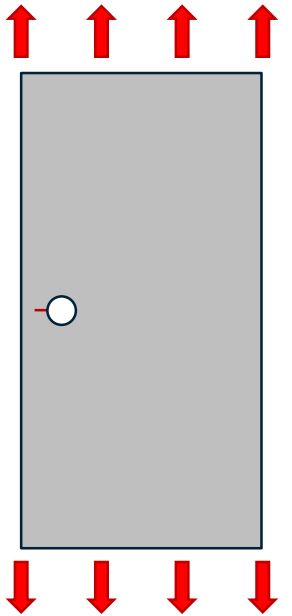
AFGROW and CanGROW underestimate the K-solution compared StressCheck. The CanGROW K-solution is slightly lower than AFGROW's. Further investigation is needed.

Verification

Corner Crack – Left Side - Bypass Load



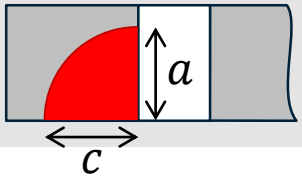


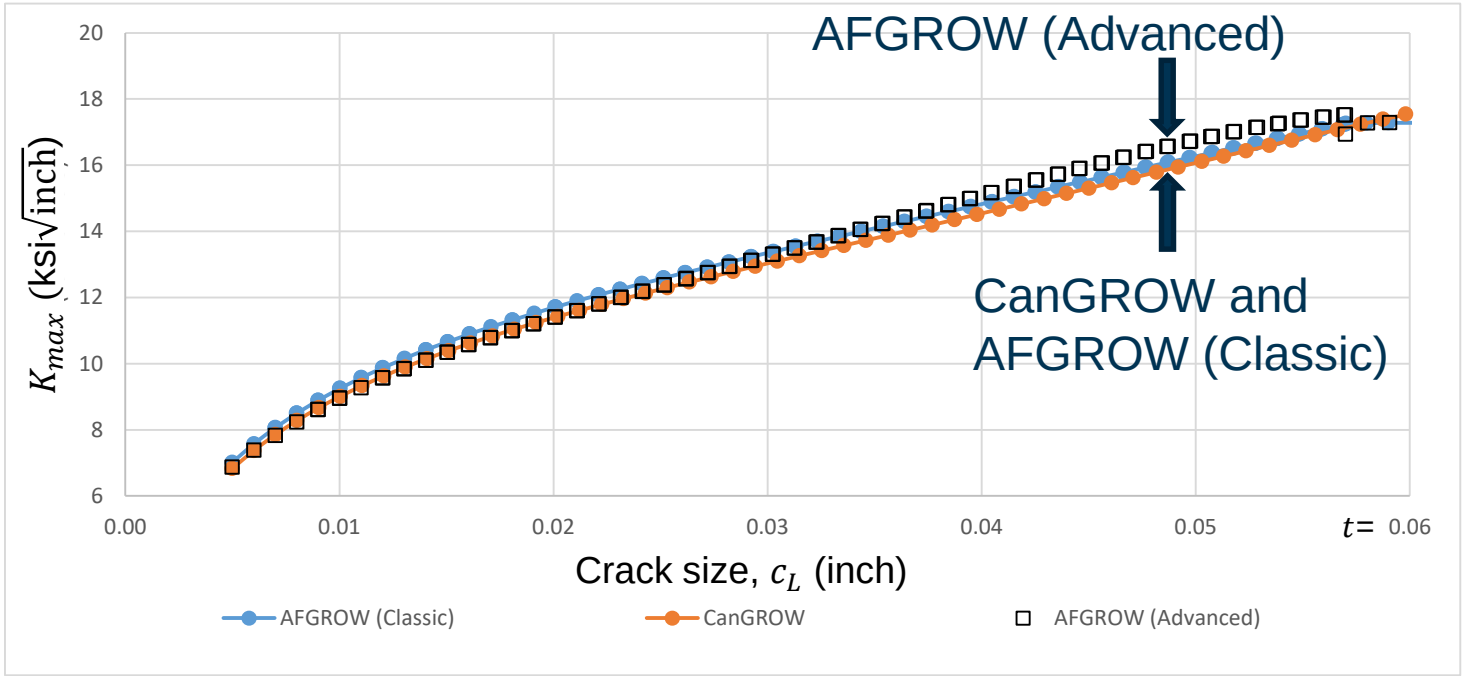


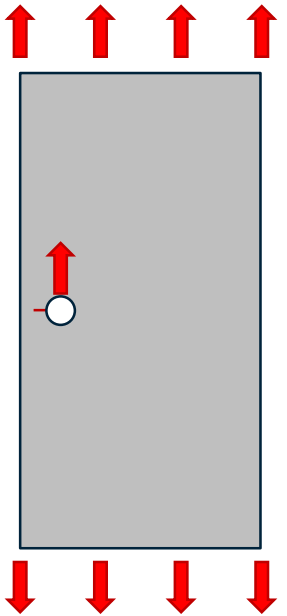
The AFGROW and CanGROW K-solutions are very similar. The advanced AFGROW solution appears to be slightly higher as c approaches t (near the corner to through crack transition).

Verification

Corner Crack – Left Side – Bypass and Bearing Load



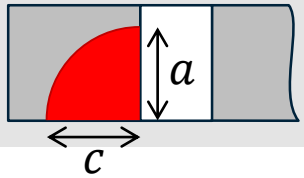


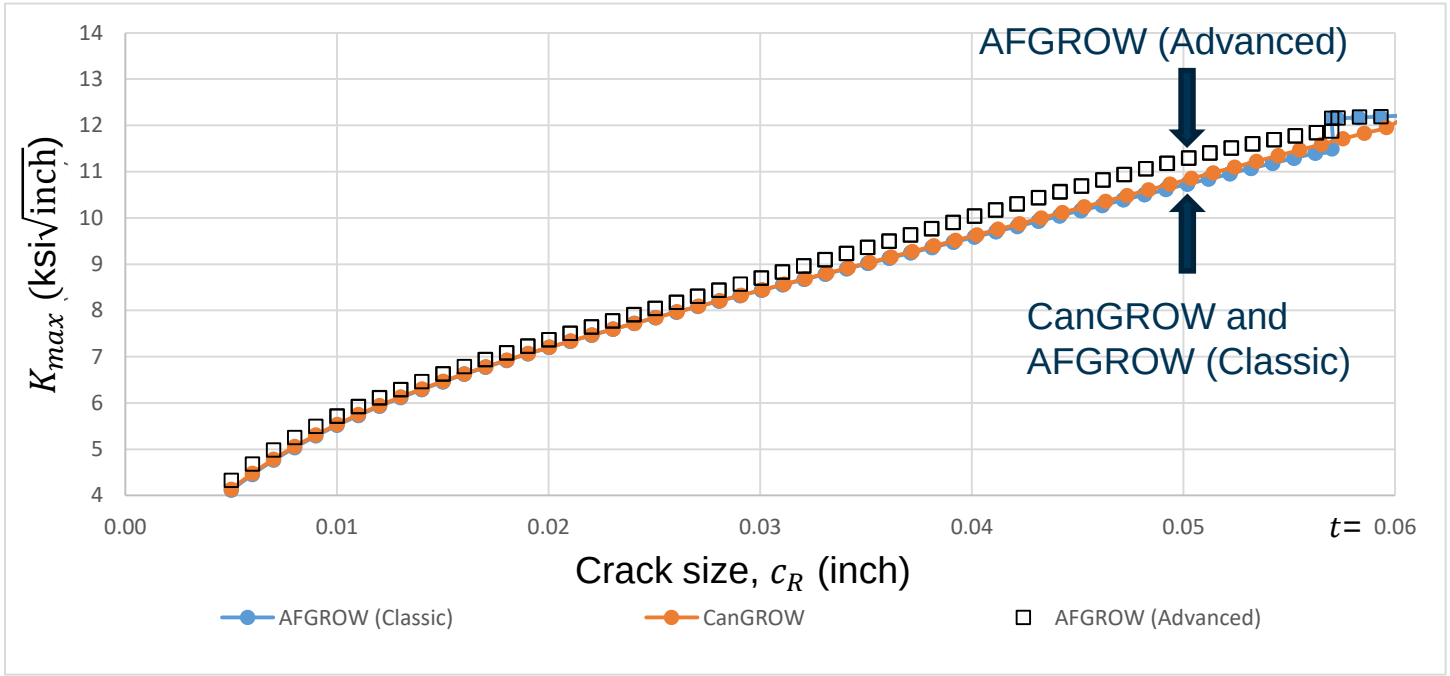


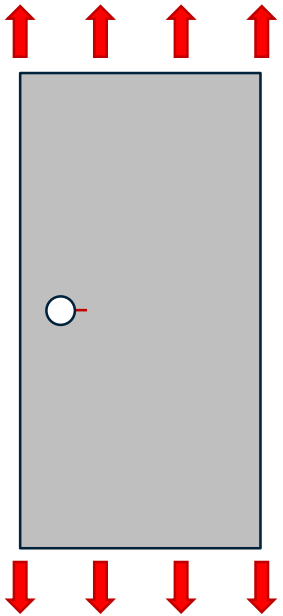
The AFGROW and CanGROW K-solutions are very similar. The advanced AFGROW solution appears to be slightly higher as c approaches t (near the corner to through crack transition).

Verification

Corner Crack – Right Side – Bypass Load



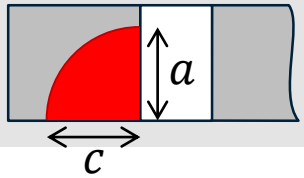


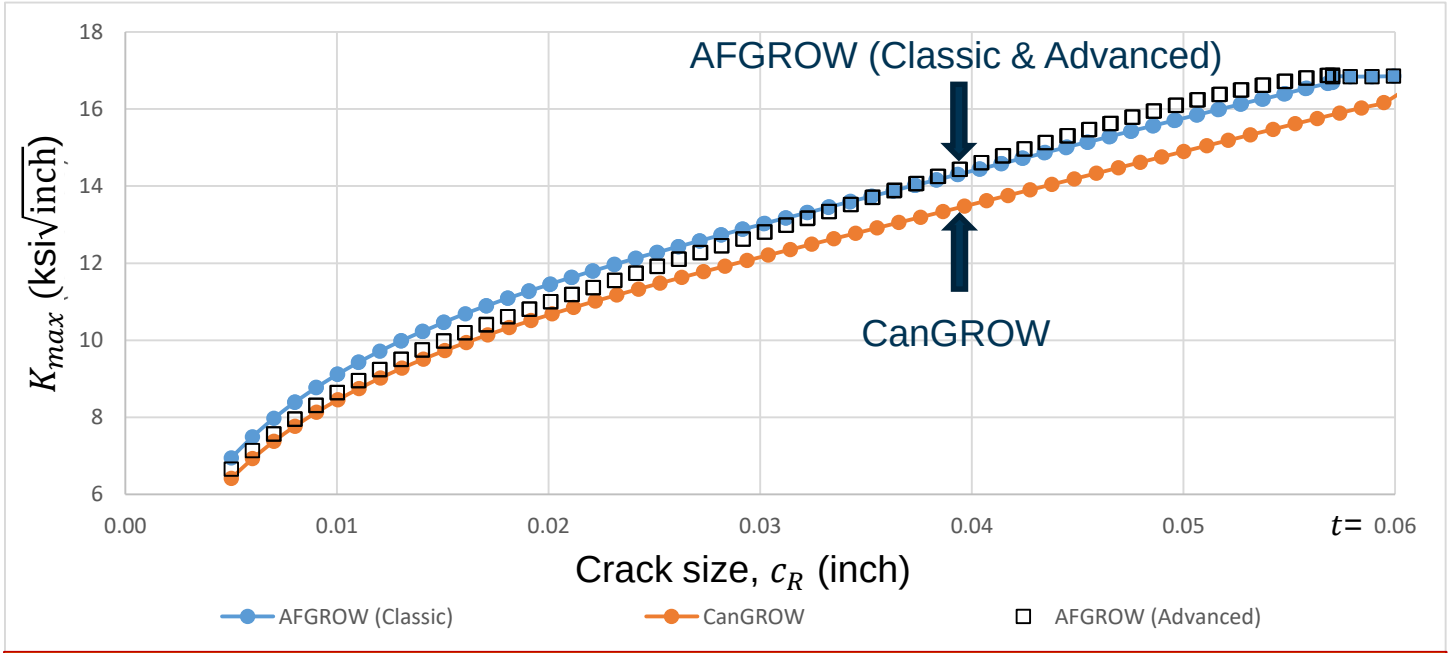


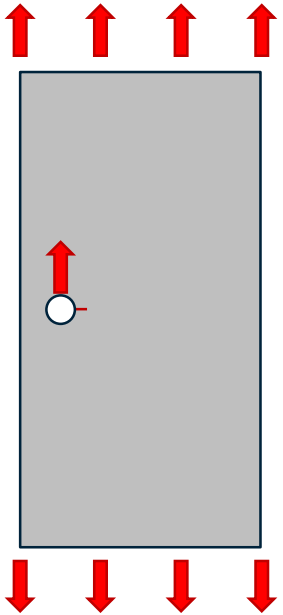
The AFGROW and CanGROW K-solutions are very similar. The advanced AFGROW solution appears to be slightly higher as c approaches t (near the corner to through crack transition).

Verification

Corner Crack – Right Side – Bypass and Bearing Load



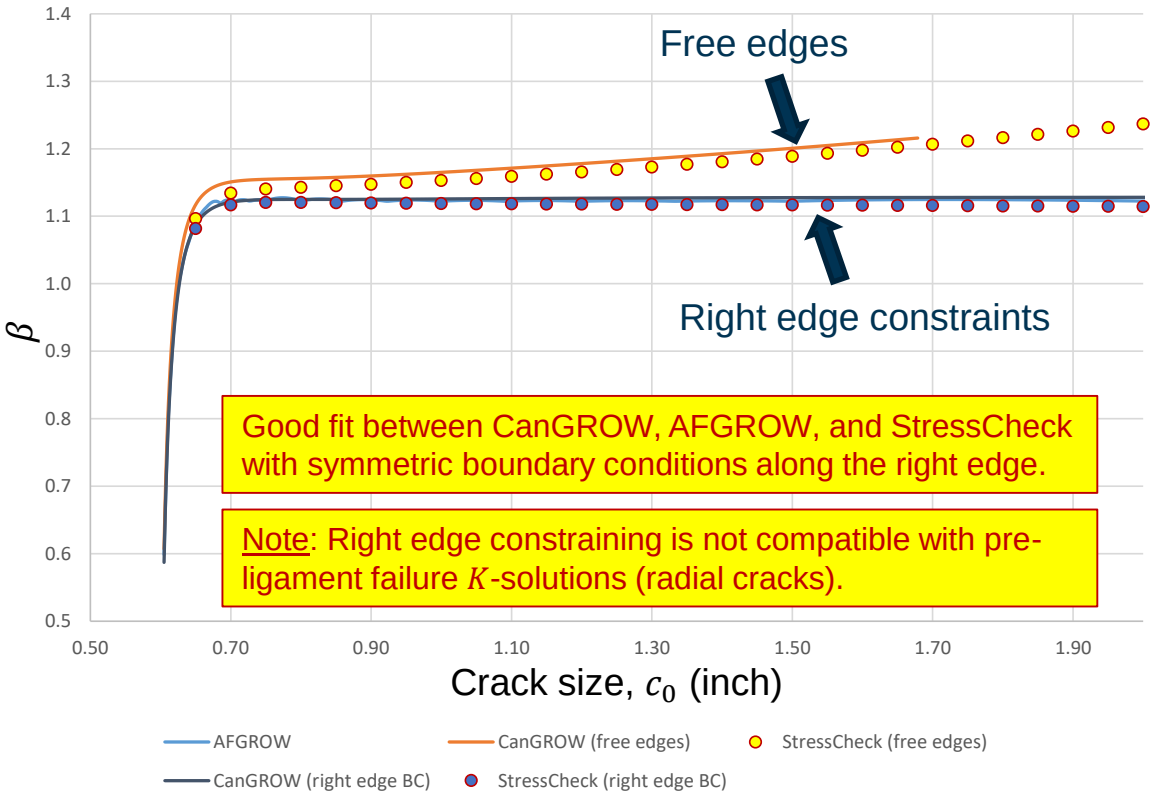




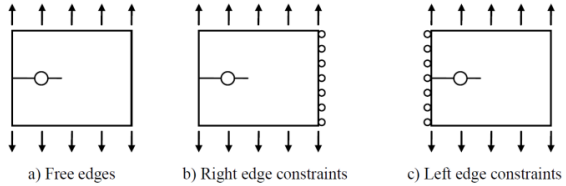
There is a small but obvious difference between the CanGROW and the AFGROW classic K-solutions. The advanced AFGROW solution migrates between the CanGROW and the AFGROW classic solutions. Further investigation is needed.

Verification

Edge Edge Crack Through a Hole



Three types of constraints can be selected for an edge crack in CanGROW:



The AFGROW solution agrees with the right edge constraints solution.
NRC used this solution BC for in the CanGROW simulations.

Verification

Notes on CanGROW corner crack solution

- Compounding approach used by CanGROW: $\beta_{total} = \beta_{through} \times \beta_{corner}$
- Corner crack correction taken from Newman-Raju solution at 5 degrees (default value in CanGROW is 10 degrees).
- CanGROW and AFGROW (classic and advanced) corner crack solutions provide similar but not identical K-solutions. It is recommended to re-assess available K-solutions for corner cracks and conduct independent verifications using finite element methods to increase confidence in current solution, especially for loaded holes.