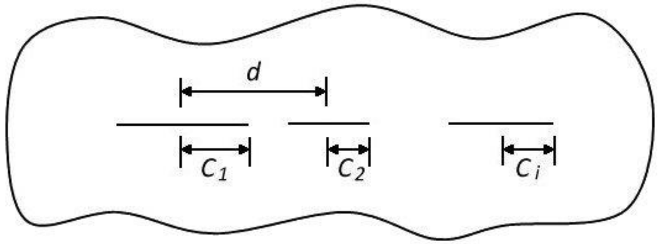
AFGROW Workshop 2023

MSD Implementation in AFGROW

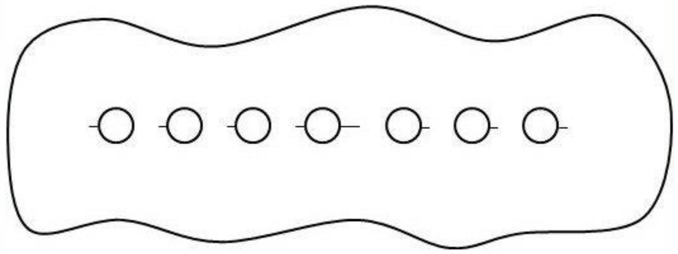
James Harter, Alexander Litvinov

LexTech, Inc .

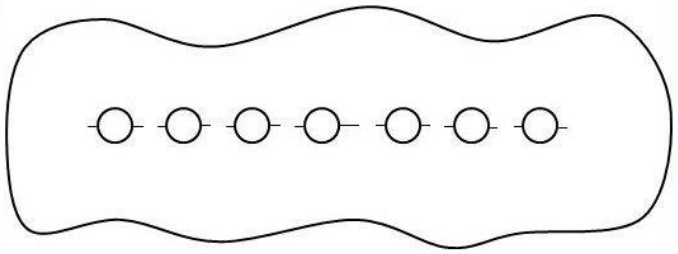
Through Crack Cases
(Infinite Plate)



Multiple Through Cracks



Multiple Holes, Continuing Damage



Multiple Holes, Full MSD Scenario

Baseline Reference

AFRL-RQ-WP-TR-2014-0233

IMPROVED STRESS INTENSITY SOLUTIONS DEVELOPED FOR THE MULTIPLE SITE DAMAGE SCENARIO

Two Unequal Through Cracks on Either Side of an Open Hole, Multiple Through Cracks, and Through Cracks Approaching an Open Hole

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OCTOBER 2014
Interim Report

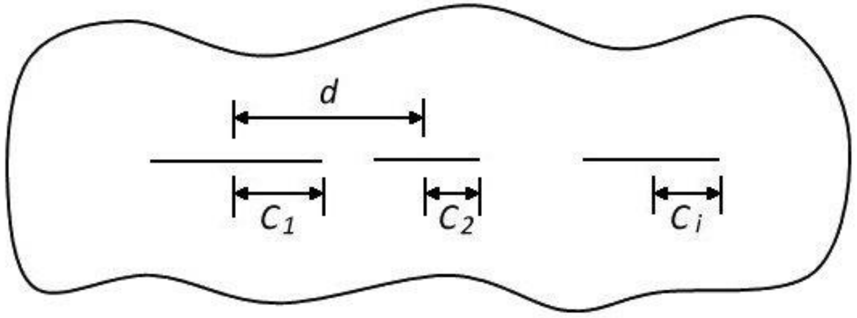
Approved for public release; distribution unlimited.

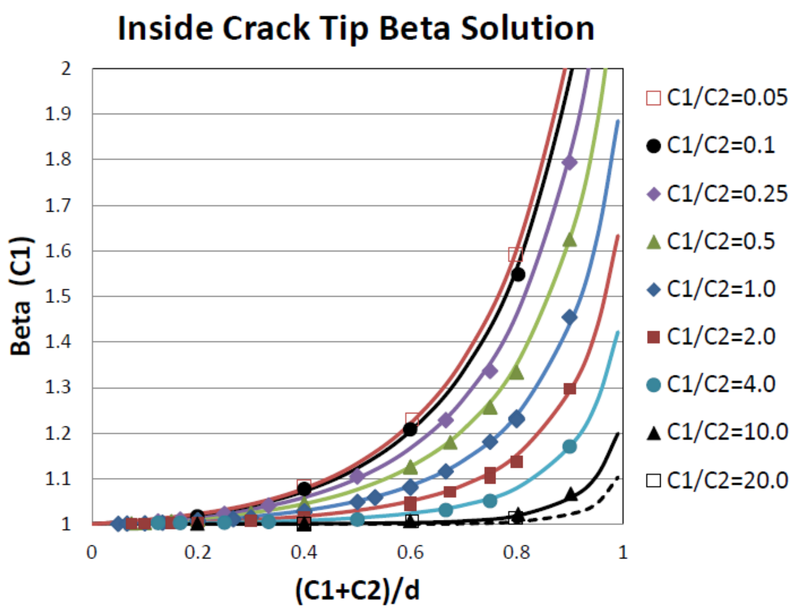
See additional restrictions described on inside pages

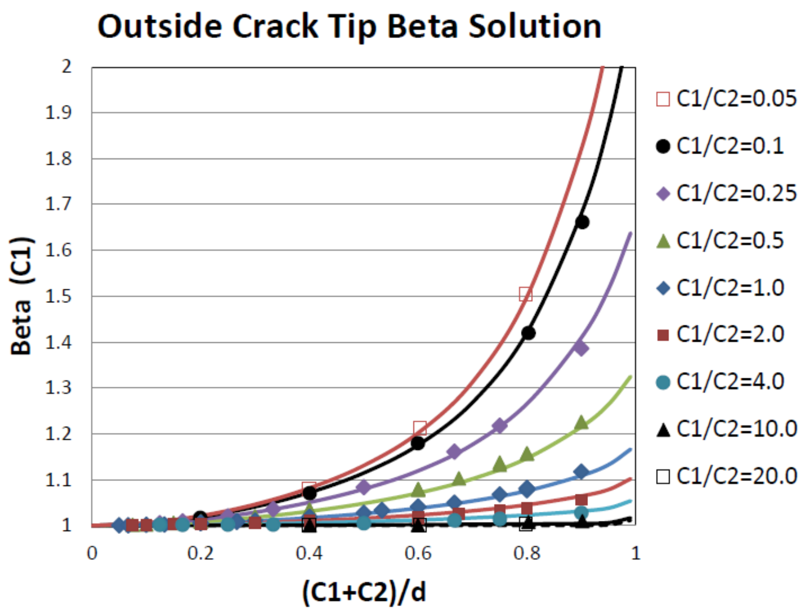
Multiple Through Crack Case

First, consider the two-crack case

Four crack tips (2 inside crack tips and 2 outside crack tips)
Two Parameters: C1/C2, and (C1 + C2)/d





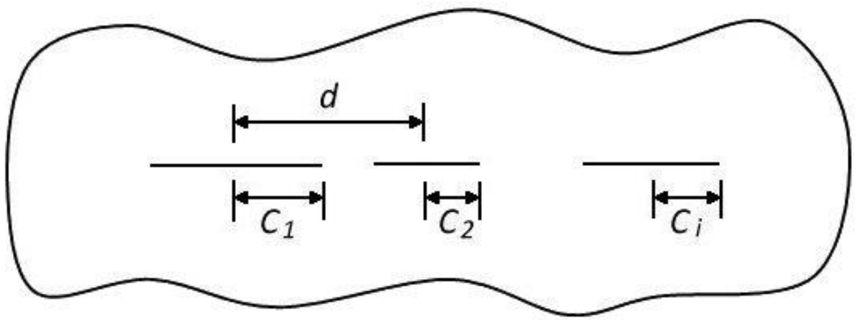


Curve fit solutions available in the baseline reference

Multiple Through Crack Case

Solution Procedure

- To solve for any number of through cracks, consider the crack of interest to be C_1 and calculate the beta value for each crack tip using the appropriate curve fit equation for each crack from 2 through i (total number of cracks).
- The inside crack tip is toward the adjacent crack and the outside crack tip is on the opposite side of the adjacent crack.
- AFGROW will allow 3 <= i <= 9 since the two crack solution is available in the Advanced Interface
- The method of compounding is used to calculate the final beta solution for each crack tip. $Beta_{total} = Beta_1 * Beta_2 * \ldots * Beta_{(i-1)}$



The curve fit solution is very good for each compounded case, but since the error is also compounded, it can increase somewhat as the number of cracks increase. However, this is mitigated since the distance between cracks also increases so that the solution for several compounded cases will eventually converge toward 1.0. Typical error will be << 3%

Multiple Through Crack Case

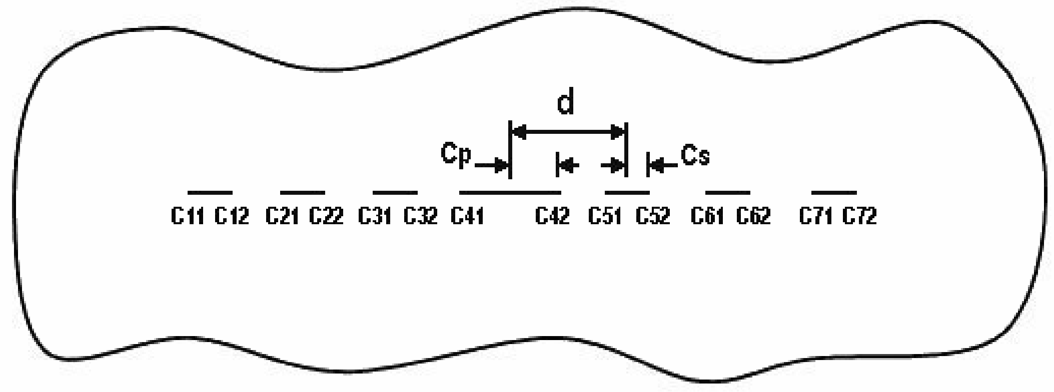
FEM Validation

Width	Spacing	Cp	Cs
75	0.5	0.1	0.05

	K	Beta	Eqn Beta	% Diff
C11	0.3991	1.006982	1.01012	0.3116
C12	0.3998	1.008748	1.02192	1.3057
C21	0.4027	1.016065	1.02043	0.4296
C22	0.4029	1.01657	1.02781	1.1057
C31	0.4074	1.027924	1.03343	0.5356
C32	0.4088	1.031457	1.03941	0.7711
C41	0.5687	1.014631	1.02394	0.9174
C42	0.5687	1.014631	1.02394	0.9174
C51	0.4088	1.031457	1.03941	0.7711
C52	0.4074	1.027924	1.03343	0.5356
C61	0.4029	1.01657	1.02781	1.1057
C62	0.4027	1.016065	1.02043	0.4296
C71	0.3998	1.008748	1.02192	1.3057
C72	0.3991	1.006982	1.01012	0.3116

Width	Spacing	Cp	Cs
150	1	0.1	0.05

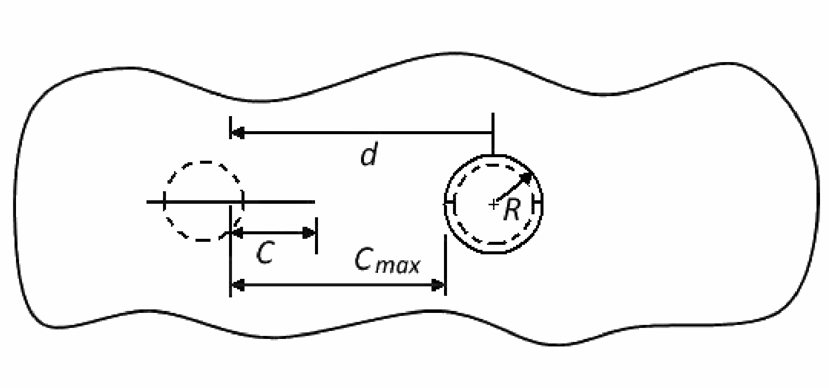
K	Beta	Eqn Beta	% Diff
0.3963	0.999917	1.00336	0.3443
0.3965	1.000422	1.00993	0.9504
0.3978	1.003702	1.00735	0.3634
0.3978	1.003702	1.01167	0.7938
0.399	1.00673	1.01148	0.4718
0.3991	1.006982	1.01448	0.7446
0.5623	1.003213	1.00841	0.5180
0.5623	1.003213	1.00841	0.5180
0.3991	1.006982	1.01448	0.7446
0.399	1.00673	1.01148	0.4718
0.3978	1.003702	1.01167	0.7938
0.3978	1.003702	1.00735	0.3634
0.3965	1.000422	1.00993	0.9504
0.3963	0.999917	1.0036	0.3683



FEM width set as 150 * d to approximate an infinite plate

Multiple Cracked Holes
Axial Load Case

We use the current AFGROW Advanced Model solution for two unequal through cracks at a hole and apply corrections for cracked, adjacent holes using the method of compounding.

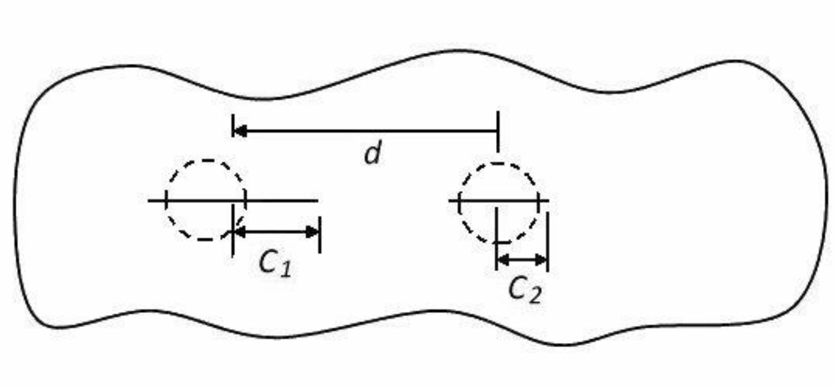


Crack Approaching a Hole

Two Possible Corrections

If the crack(s) at an adjacent hole are small (<= R/3), then we use the correction from the baseline reference for a through crack approaching a hole.

If the crack(s) at an adjacent hole are larger (> R/3) , we use the correction for a crack approaching another crack. This correction was explained in previous slides.



Crack Approaching a Crack

Through Crack Approaching a Hole

Correction

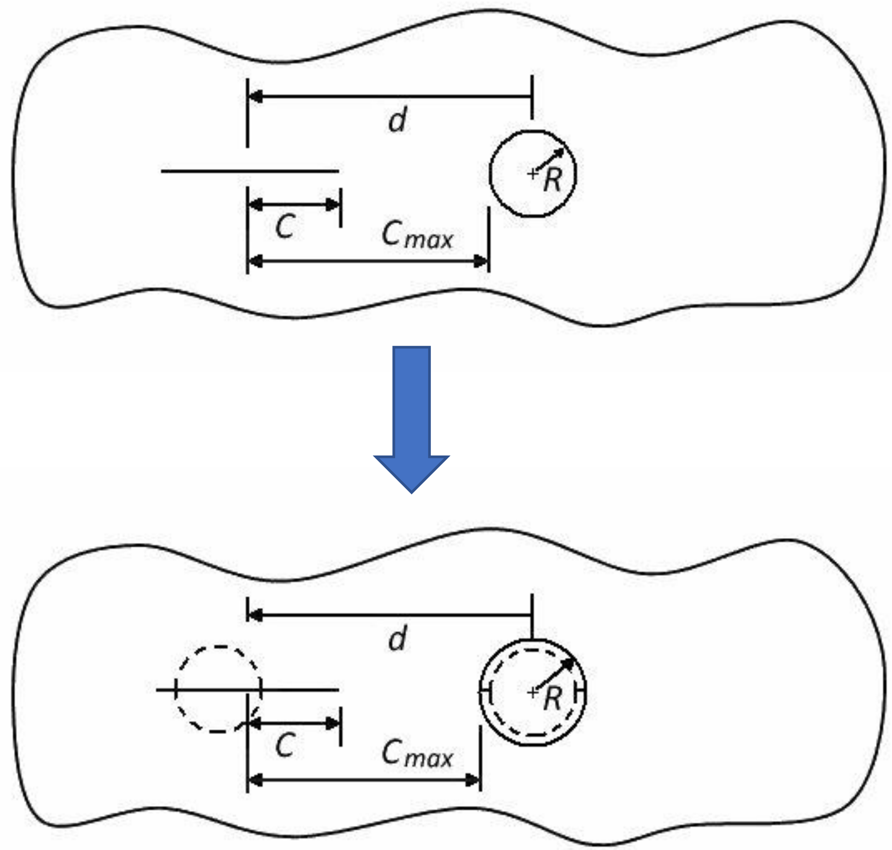
The hole of interest is assumed to be a through crack extending across the hole where the total length includes the crack(s) and the hole diameter. The new crack length and center is calculated.

The radius and center of the adjacent cracked hole is modified as required to create a new hole radius that extends to the edge of the crack(s).

Two possible crack tips

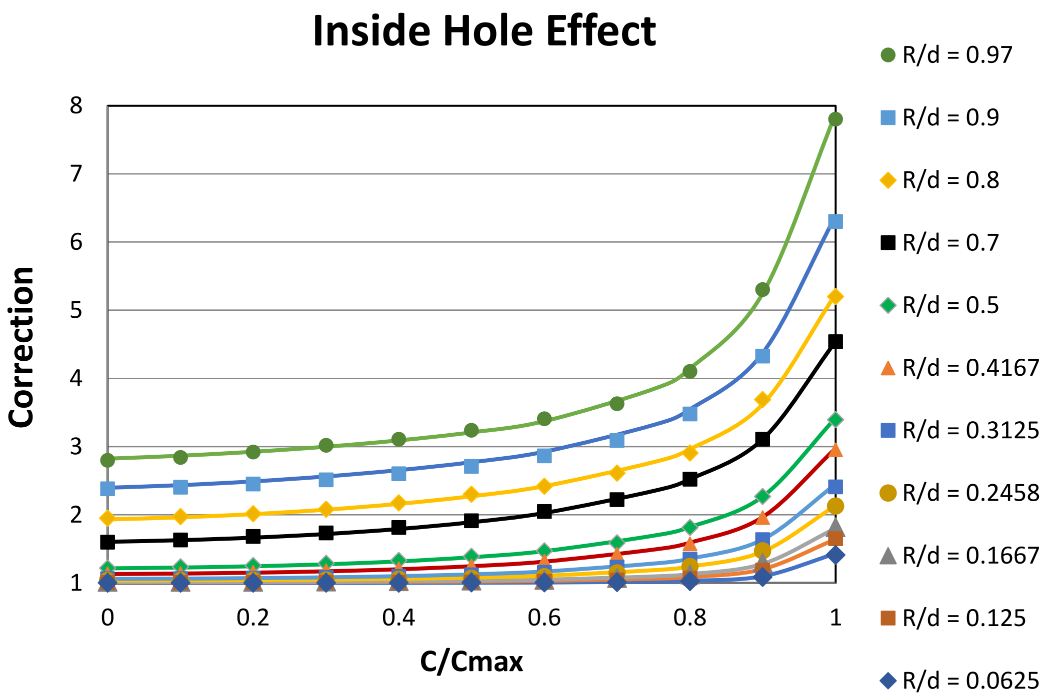
1 inside crack tip (toward the hole) and 1 outside crack tip (away from the hole)

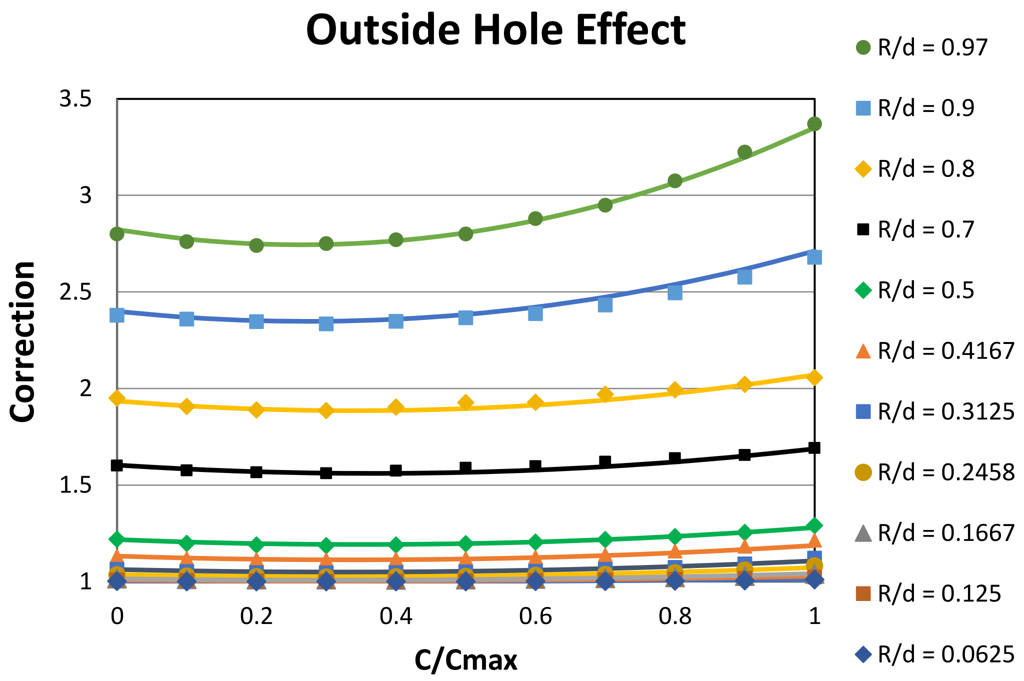
Two Parameters: R/d, and C/C_{max}



Through Crack Approaching a Hole

Correction

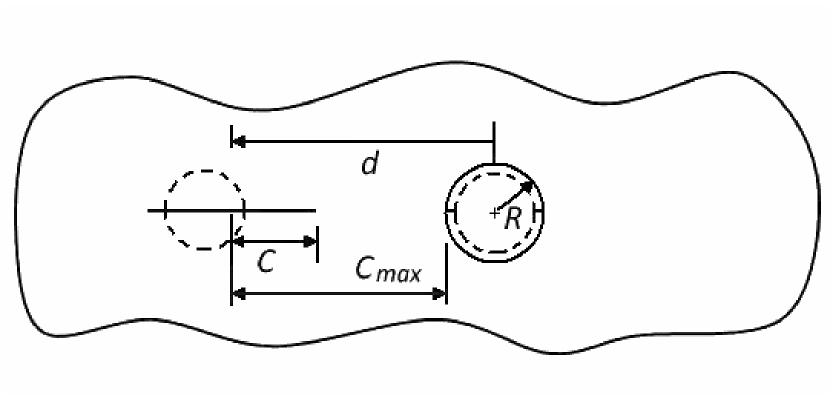




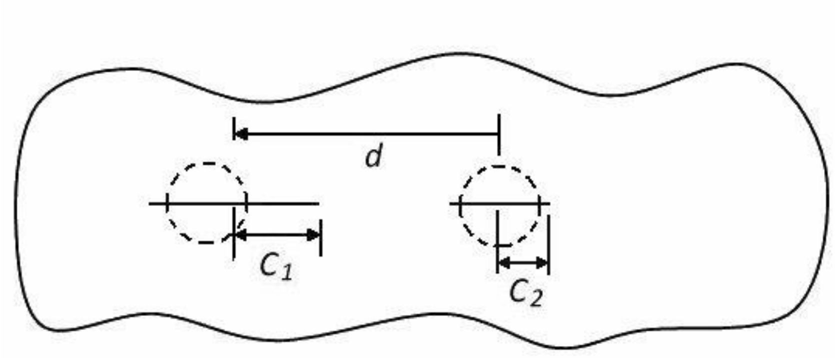
Curve fit solutions available in the baseline reference

Multiple Cracked Open Holes
Solution Procedure

- To solve for any number of holes, start from the hole of interest, calculate the beta solution for a given crack tip using the Advanced Model Solution for one or two non-symmetric cracks with no adjacent holes. Calculate the beta correction value for each adjacent cracked hole using the appropriate correction model for each hole from 3 through i (total number of holes).
- The inside crack tip is toward the adjacent hole and the outside crack tip is on the opposite side of the adjacent hole.
- AFGROW will allow 3 <= i <= 9 (odd number)
- The method of compounding is used to calculate the final beta correction for each crack tip. $Correction_{total} = Correction_1 * Correction_2 * \ldots * Correction_{(i-1)}$



Crack Approaching a Hole



Crack Approaching a Crack

Multiple Cracked Open Holes
FEM Validation

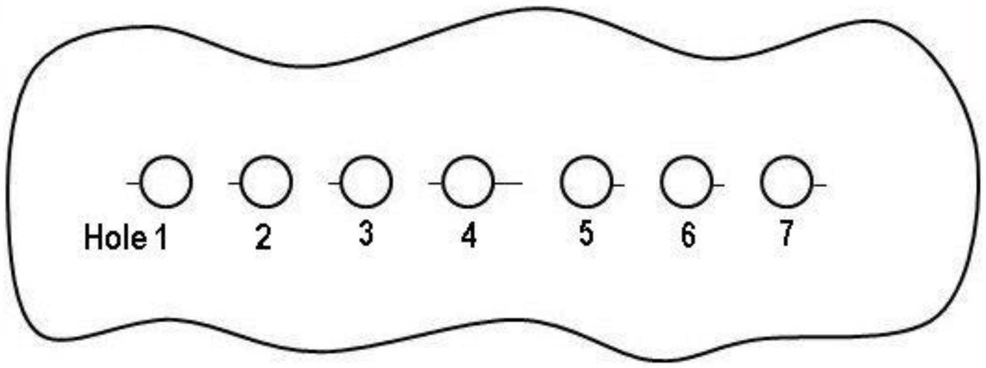
Hole Dia.	Spacing	Pin Load	ByPass	Thickness	Width	Height
0.25	4D	0	10	0.04	50	250

Cp	Cs
0.05	0.005

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	3.165	3.201	3.213	3.291	7.228	3.215	3.201	3.165
	Beta							
Beta	2.525	2.554	2.564	2.626	1.824	2.565	2.554	2.525
Equation	2.494	2.517	2.521	2.624	1.784	2.521	2.516	2.494
Diff (%)	-1.231	-1.466	-1.645	-0.084	-2.202	-1.715	-1.474	-1.234

Cp	Cs
0.25	0.1

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	8.080	8.270	8.401	10.380	10.410	8.495	8.284	8.084
	Beta							
Beta	1.442	1.475	1.499	1.852	1.175	1.516	1.478	1.442
Equation	1.406	1.440	1.466	1.849	1.183	1.480	1.442	1.407
Diff (%)	-2.471	-2.376	-2.221	-0.154	0.670	-2.380	-2.413	-2.479



Why Haven’t These Solutions Been Released Sooner?

The multiple hole case isn’t practical without a bearing load option

Bearing Load Effect on Adjacent Holes

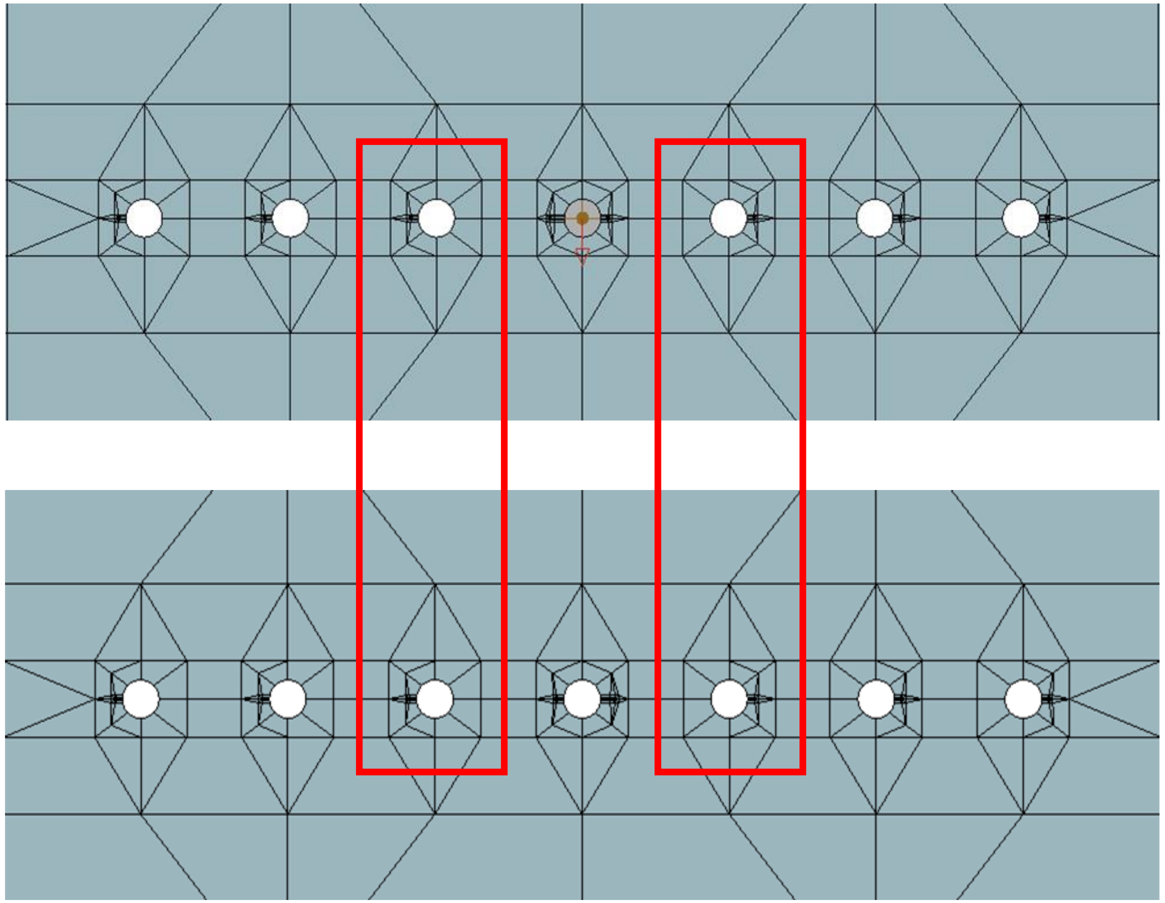
Width (in)	Total Height (in)	Thickness (in)	Hole Dia (in)	Spacing (hole dia)	ByPass (Ksi)	Pin Load (Kip)	Fastener Material
50	250	0.04	0.25	4	10	0.2	Steel

Pin Load in Center Hole Only			
Cp	Cs	Kp	Ks
0.1	0.05	10.96	11.16

Adjacent Holes	
K Left	K Right
7.819	7.832

No Bearing Load (all open holes)			
Cp	Cs	Kp	Ks
0.1	0.05	8.562	8.46

Adjacent Holes	
K Left	K Right
7.652	7.661



New Bearing Load Solution for Multiple Holes

We have developed a bearing solution for the multiple hole geometry that accounts for the following effects:

- Different bearing loads at each hole
- Influence of bearing load on adjacent holes

The current solution in AFGROW allows the bearing load in the primary hole to be different than the bearing load at the secondary holes.

Multiple Cracked Bearing Loaded Holes

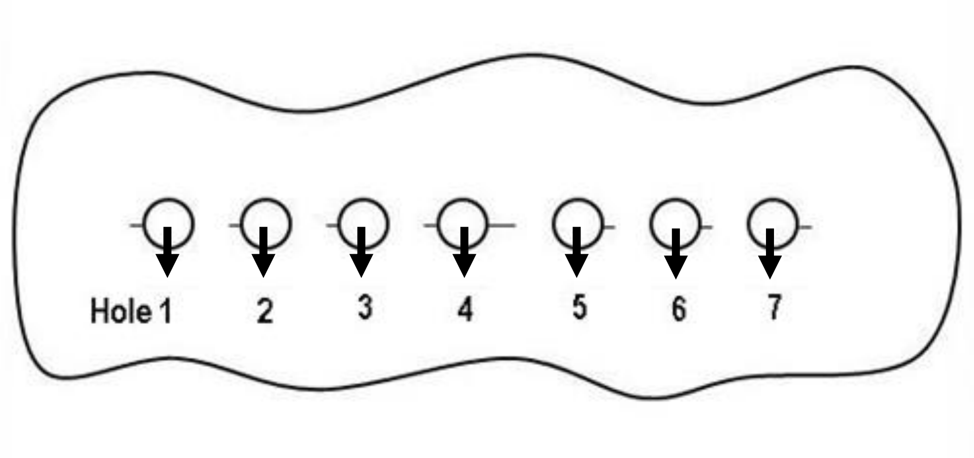
FEM Validation

Hole Spacing = 2.25 D

Hole Dia.	Spacing (D)	Pin Load	ByPass	Thickness	Width	Height
0.25	2.25	0.5	0	0.04	28.125	140.63

Cp	Cs
0.05	0.05

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	9.758	11.05	11.25	11.69	11.69	11.25	11.05	9.758
AFGROW	9.519	10.796	10.968	11.566	11.566	10.968	10.796	9.519
Diff (%)	-2.452	-2.299	-2.507	-1.061	-1.061	-2.507	-2.299	-2.452



Multiple Cracked Bearing Loaded Holes

FEM Validation

Hole Spacing = 3 D

Hole Dia.	Spacing (D)	Pin Load	ByPass	Thickness	Width	Height
0.25	3	0.5	0	0.04	50	250

Cp	Cs
0.05	0.05

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	8.867	9.396	9.462	9.87	9.87	9.462	9.396	8.867
AFGROW	8.813	9.350887	9.44607	9.996244	9.996244	9.44607	9.350887	8.813
Diff (%)	-0.607	-0.045	-0.016	0.126	0.126	-0.016	-0.045	-0.054

Cp	Cs
0.1	0.1

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	8.045	8.904	9.104	10.07	10.07	9.104	8.904	8.045
AFGROW	8.273	8.966	9.104	9.775	9.775	9.104	8.966	8.273
Diff (%)	2.829	0.693	0.002	-2.931	-2.931	0.002	0.693	2.829

Cp	Cs
0.1	0.05

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	8.874	9.41	9.508	10.46	9.285	9.542	9.416	8.876
AFGROW	8.820	9.365	9.490	10.594	9.135	9.522	9.369	8.821
Diff (%)	-0.613	-0.482	-0.195	1.281	-1.614	-0.215	-0.500	-0.621

Cp	Cs
0.25	0.25

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	7.462	8.932	9.569	11.41	11.41	9.569	8.932	7.462
AFGROW	7.421	8.879	9.212	10.991	10.991	9.212	8.879	7.421
Diff (%)	-0.549	-0.590	-3.736	-3.672	-3.672	-3.736	-0.590	-0.549

Multiple Cracked Bearing Loaded Holes

FEM Validation

Hole Spacing = 4 D

Spacing	Hole Dia.	Spacing (D)	Pin Load	ByPass	Thickness	Width	Height
4D	0.25	4	0.5	0	0.04	50	250

Cp	Cs
0.05	0.05

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	8.325	8.552	8.567	8.963	8.963	8.567	8.552	8.325
AFGROW	8.423	8.562	8.621	9.142	9.142	8.621	8.562	8.423
Diff (%)	1.172	0.120	0.626	1.993	1.993	0.626	0.120	1.172

Cp	Cs
0.1	0.1

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	7.644	7.833	7.925	8.832	8.832	7.925	7.833	7.644
AFGROW	7.764	7.940	8.020	8.628	8.628	8.020	7.940	7.764
Diff (%)	1.566	1.367	1.203	-2.309	-2.309	1.203	1.367	1.566

Cp	Cs
0.1	0.05

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	8.329	8.559	8.591	9.484	8.215	8.604	8.561	8.329
AFGROW	8.426	8.570	8.645	9.672	8.120	8.658	8.572	8.427
Diff (%)	1.169	0.129	0.633	1.985	-1.159	0.626	0.125	1.177

Cp	Cs
0.25	0.25

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	6.258	6.607	6.884	8.542	8.542	6.884	6.607	6.258
AFGROW	6.451	6.791	6.947	8.466	8.466	6.947	6.791	6.451
Diff (%)	3.090	2.789	0.908	-0.892	-0.892	0.908	2.789	3.090

Multiple Cracked Bearing Loaded Holes

FEM Validation

Hole Spacing = 6 D

Hole Dia.	Pin Load	Spacing (D)	ByPass	Thickness	Width	Height
0.25	0.5	6	0	0.04	50	250

Cp	Cs
0.05	0.05

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	7.867	7.931	7.923	8.311	8.311	7.923	7.931	7.867
AFGROW	7.896	7.963	7.996	8.493	8.493	7.996	7.963	7.896
Diff (%)	0.371	0.032	0.073	0.182	0.182	0.073	0.032	0.029

Cp	Cs
0.1	0.05

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	7.869	7.934	7.933	8.788	7.475	7.937	7.934	7.869
AFGROW	7.898	7.967	8.007	8.976	7.374	8.011	7.968	7.898
Diff (%)	0.369	0.416	0.938	2.143	-1.346	0.932	0.422	0.370

Cp	Cs
0.1	0.1

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	6.996	7.091	7.122	7.987	7.987	7.122	7.091	6.996
AFGROW	7.122	7.200	7.242	7.799	7.799	7.242	7.200	7.122
Diff (%)	1.797	1.536	1.679	-2.349	-2.349	1.679	1.536	1.797

Cp	Cs
0.25	0.25

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	5.232	5.375	5.484	7.036	7.036	5.484	5.375	5.232
AFGROW	5.441	5.557	5.627	6.960	6.960	5.627	5.557	5.441
Diff (%)	3.995	3.388	2.604	-1.080	-1.080	2.604	3.388	3.995

Cp	Cs
0.5	0.25

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	5.193	5.398	5.552	7.933	5.562	5.619	5.408	5.196
AFGROW	5.453	5.581	5.699	8.023	5.380	5.770	5.591	5.456
Diff (%)	5.007	3.394	2.651	1.132	-3.278	2.680	3.382	5.004

Multiple Cracked Bearing Loaded Holes

FEM Validation

Hole Spacing = 10 D

Hole Dia.	Spacing (D)	Pin Load	ByPass	Thickness	Width	Height
0.25	6	0.5	0	0.04	125	625

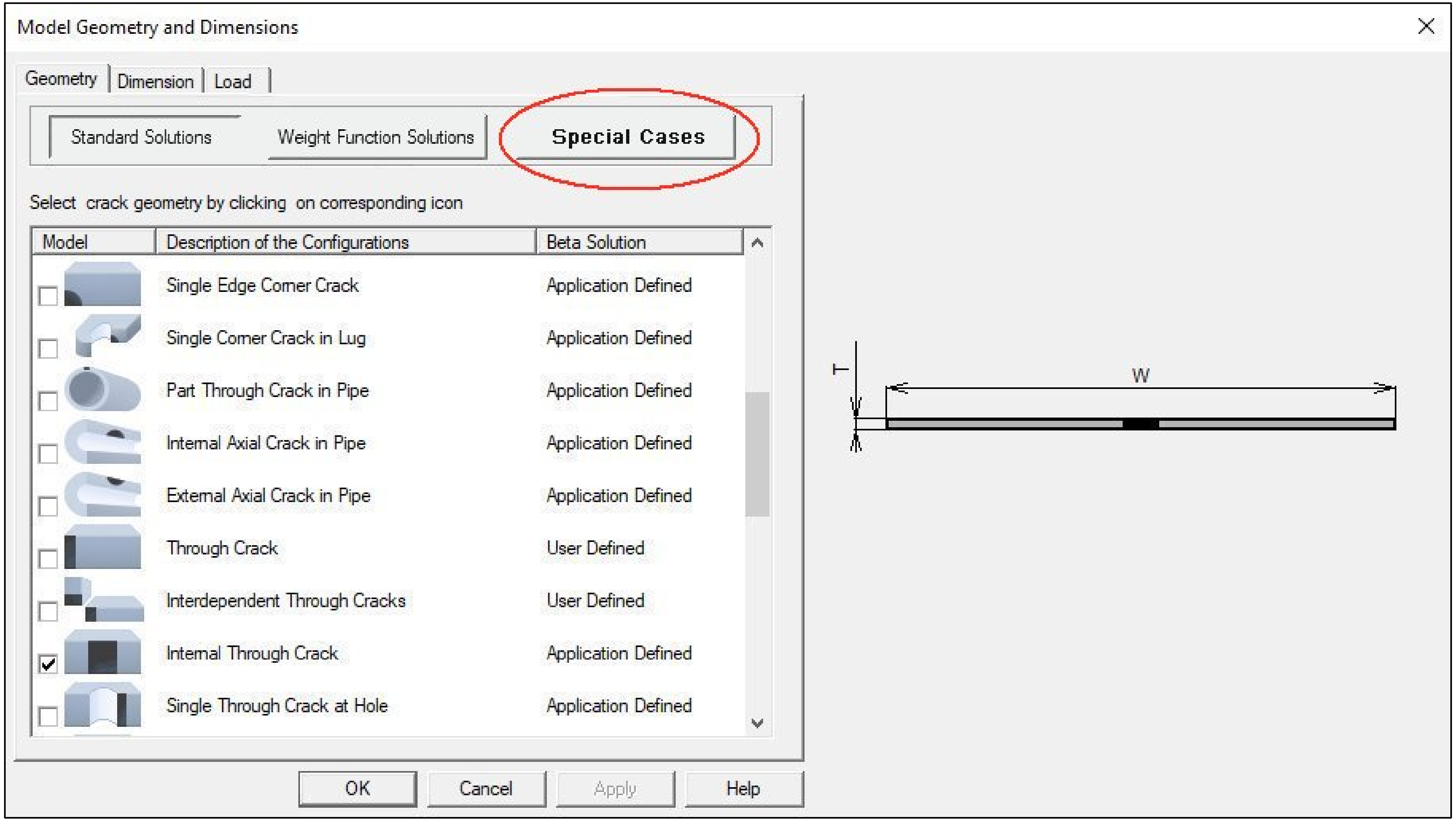
Cp	Cs
0.05	0.05

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	7.55	7.548	7.52	7.922	7.922	7.52	7.548	7.55
AFGROW	7.581	7.614	7.631	8.113	8.113	7.631	7.614	7.581
Diff (%)	0.412	0.875	1.475	2.415	2.415	1.475	0.875	0.412

Cp	Cs
0.25	0.25

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
FEM	4.735	4.769	4.788	6.296	6.296	4.788	4.769	4.735
AFGROW	4.982	5.027	5.058	6.307	6.307	5.058	5.027	4.982
Diff (%)	5.216	5.404	5.631	0.179	0.179	5.631	5.404	5.216

Implementation



Special Cases

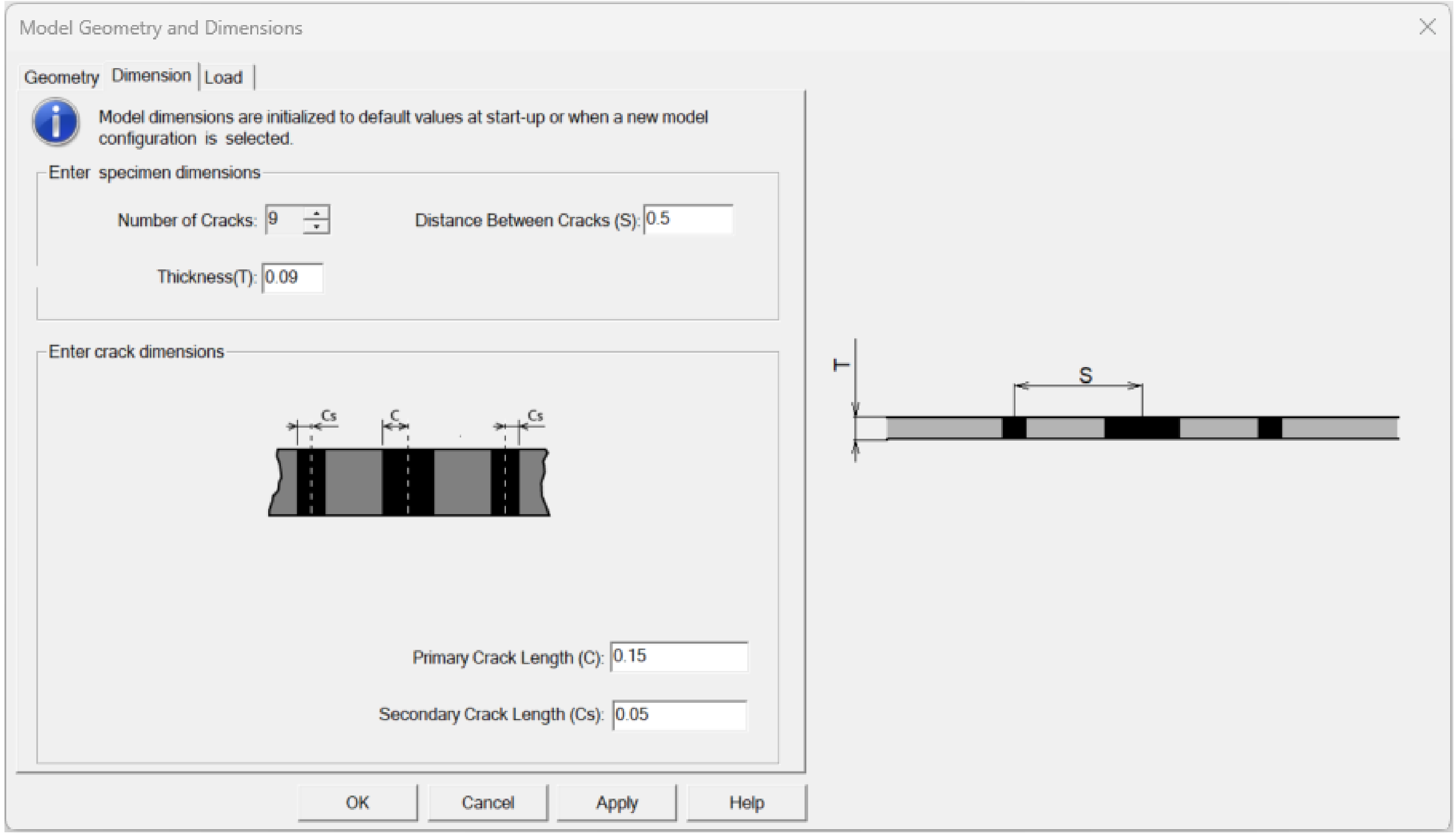
Multiple Through Cracks in an Infinite Plate

- Axial load case
- 3 to 9 cracks

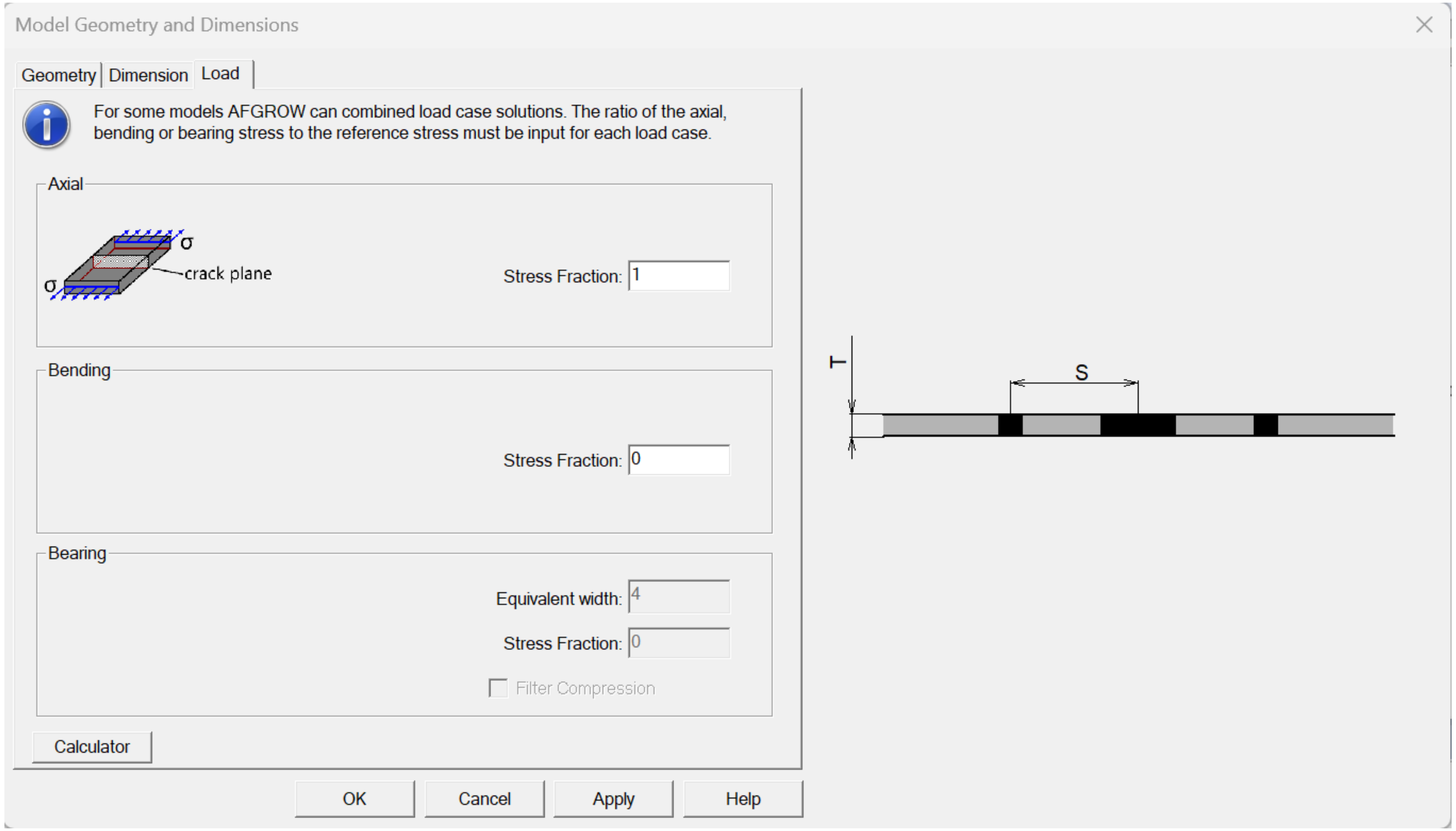
Through Cracks at Multiple Holes in an Infinite Plate (Continuing Damage)

- Axial and bearing load cases
- Primary and Secondary Crack at the Center Hole (primary hole)
- Single Secondary Crack on Outside of each adjacent hole (3, 5, 7, or 9 holes in total)
- Fastener load at the primary hole may be different than the fastener load at the secondary holes

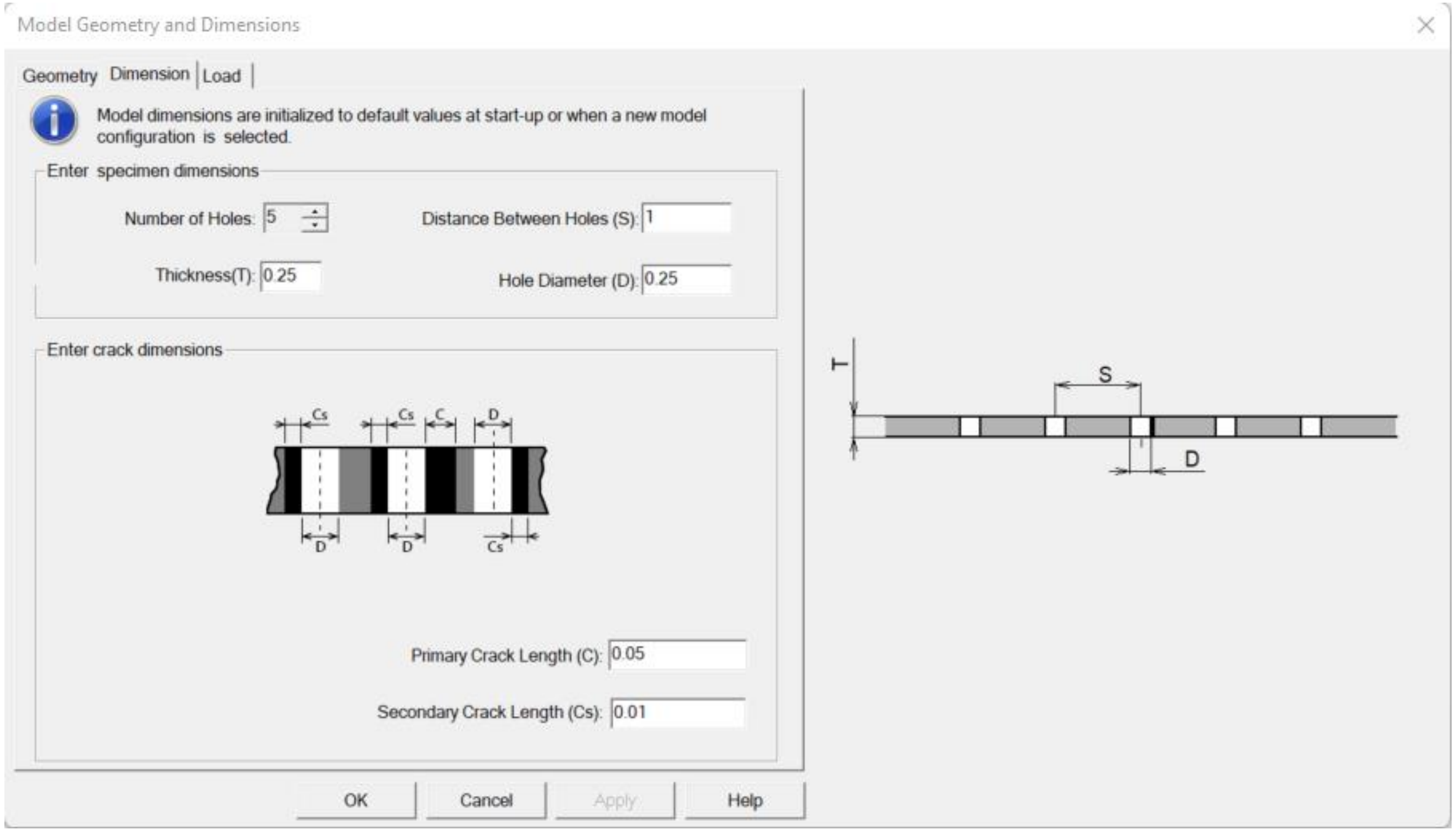
Multiple Through Cracks in an Infinite Plate (Geometry)



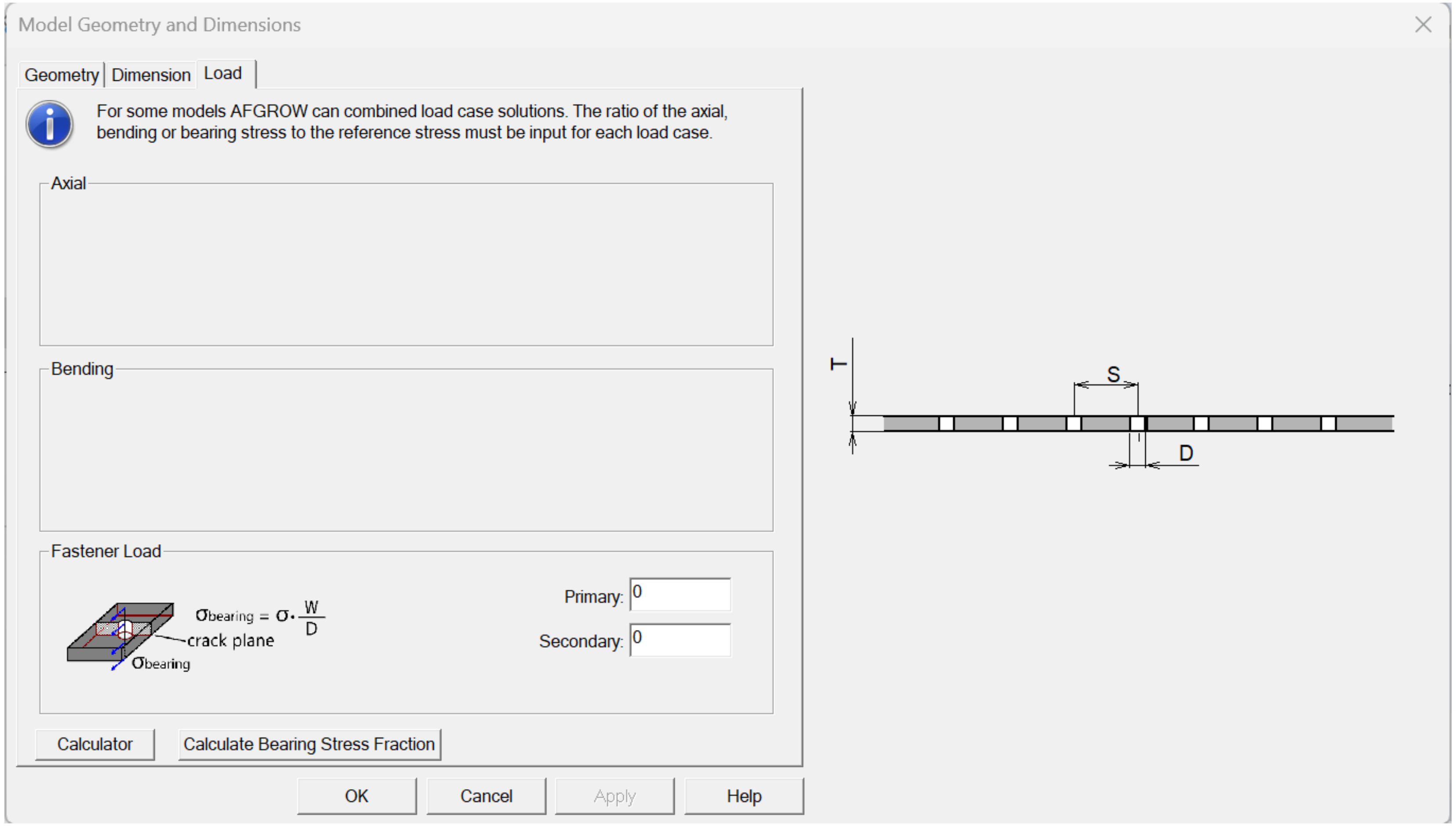
Multiple Through Cracks in an Infinite Plate (Load)



Through Cracks at Multiple Holes in an Infinite Plate (Geometry)



Through Cracks at Multiple Holes in an Infinite Plate (Load)



Multiple Holes in an Infinite Plate

- The axial and bearing stress fraction (SF) for each hole are calculated using the spectrum Stress Multiplication Factor (SMF) specified for the applied **normalized loading history**.
- The spectrum stress reference is the remote traction applied to the structure
- This solution does not include out-of-plane bending because the fasteners are assumed to constrain this type of bending due to fastener preload.
- The bypass and bearing stress components are *calculated internally* by AFGROW as shown below:

$$\sigma_{bypass} = \left(SMF - \frac{Fastener\ Load}{t*S}\right) + Effect\ of\ Adjacent\ Fastener\ Loads$$

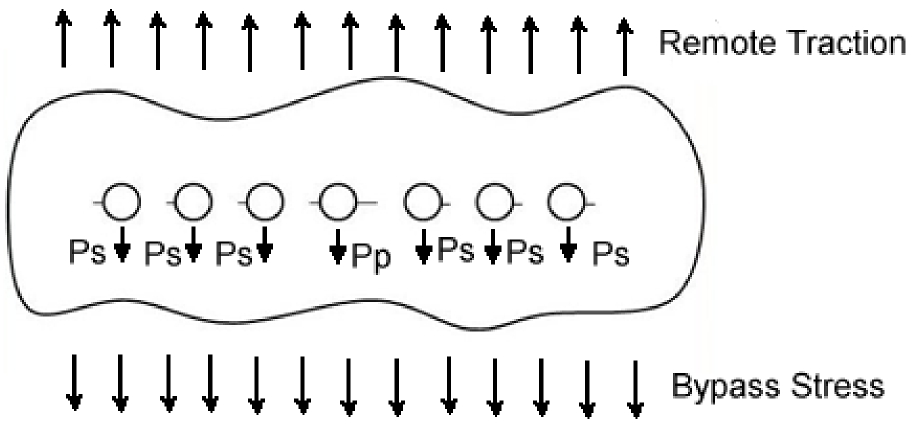
$$\sigma_{bearing} = \frac{Fastener\ Load}{t*D}$$

$$SF_{axial} = \frac{\sigma_{bypass}}{SMF}$$

$$SF_{bearing} = \frac{\sigma_{bearing}}{SMF}$$

Multiple Holes in an Infinite Plate

- The remote stress (traction) at this location is determined based on the maximum spectrum stress and the fastener loads at the primary and secondary holes in the doubler are estimated using some type of spring or fastener compliance method.
- The downstream bypass stress is equal to the stress required to make up the difference between the remote traction and the load carried by the row of fasteners.
- The applied remote traction loading spectrum is normalized so that the maximum spectrum stress corresponding to the reference load case is 1.0 and all other spectrum values are scaled accordingly.
- The SMF is then set equal to the reference remote traction in the skin.
- When using a single channel loading spectrum, we assume that the relationship between the remote traction and fastener loads are linearly proportional.



Questions/Comments