PROBLEM NO. SIE-1

Title: Crack Growth Analysis of Main Cargo Door Surround Doubler Attachment to Fuselage Skin with MSD Cracks

Objective:

To illustrate the process of estimating crack growth behavior to set inspection limits.

General Description:

This problem focuses on a damage tolerance assessment of a main cargo door surround doubler attachment to fuselage structure for the purpose of establishing inspection intervals for multi-site damage, MSD, conditions. The critical area includes the main cargo door surround doubler and the existing fuselage skin. The stresses acting at the doubler attachment at the upper edge are derived from a conservative loading spectrum based on pressure loading. The critical area was modeled using a standard NASGRO 3.0 stress intensity factor solution and crack growth model.

Topics Covered: Damage tolerance assessment, crack growth analysis, inspection intervals

Type of Structure: fuselage skin, main cargo door surround doubler

Relevant Sections of Handbook: Section 2, 5, 11

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Overview of Problem Description

This problem focuses on the main cargo surround doubler attachment to the existing fuselage skin at stringers 2R and 26L. The skin is considered to be a single load path structure under the total hoop stress before the doubler attachment. The critical location is in the skin at the first row of fasteners because the skin sees both bypass and bearing stresses at this row, where as, at the other fastener rows the load is in both the doubler and the skin with each row having lower load transfer.

The fuselage skin was fabricated from 2024-T3 aluminum. The fasteners are 0.188 in diameter, and join the skin and surround doubler.

The specific area is shown in View A of Figure SIE-1.1, with the specific details and MSD crack path shown in Figure SIE-1.3. Note that the skin at this first row of fasteners is a single load path as shown in Figure SIE-1.2.

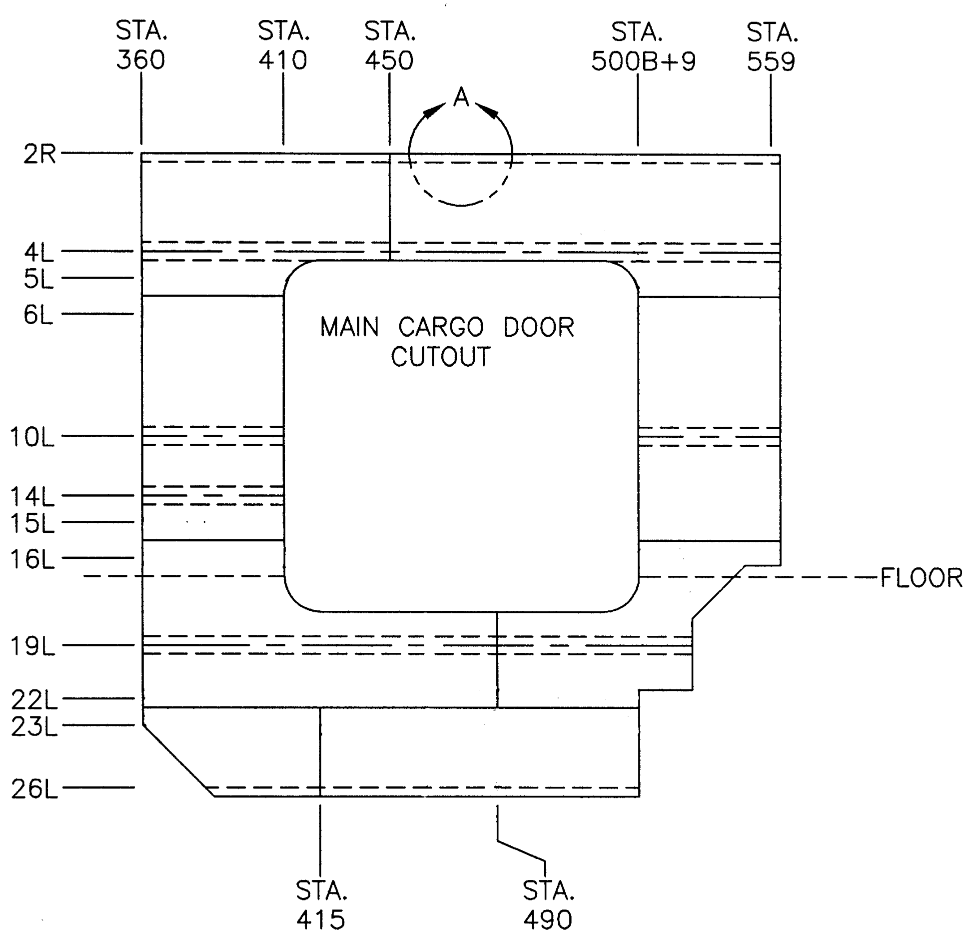

Figure SIE-1.1. Main Cargo Door Doubler Installation

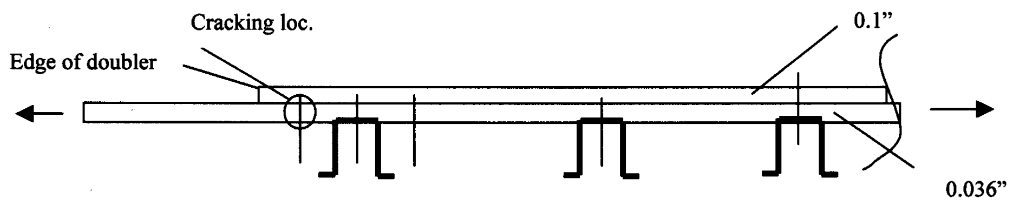

Figure SIE-1.2. Structural Detail for Critical Area

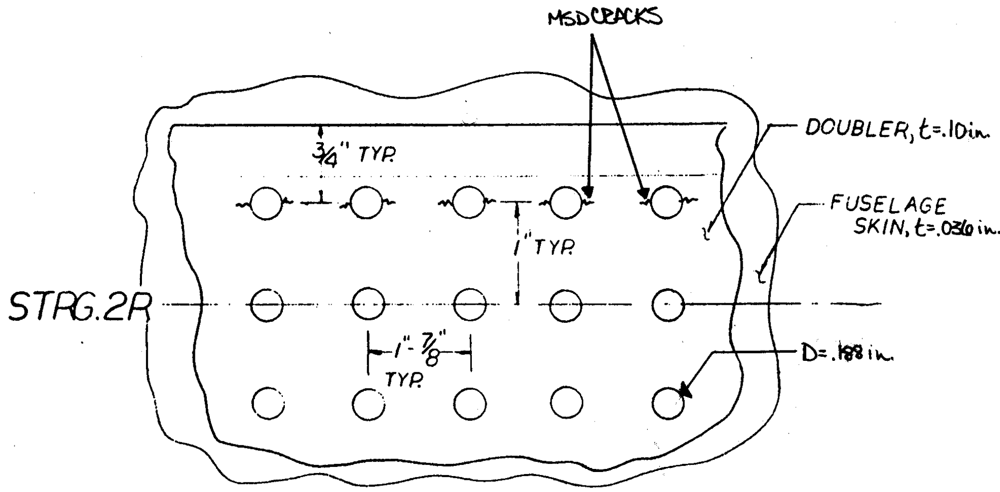

Figure SIE-1.3. Detail Geometry of Critical Location, View A.

Model Geometry Description

The crack growth analysis is based on the Fatigue Crack Growth Computer Program NASGRO3.0. This computer program calculates crack growth for a single crack for several standard crack cases. Crack growth rate calculations use the “NASGRO” equation with elements developed by Forman, Newman, de Koning, and Henriksen (see NASGRO reference manual). This is a modified Paris equation to account for fatigue crack closure, stress ratio effects, and upper and lower fatigue crack growth rate asymptotes for threshold and critical crack growth.

The analysis uses the NASGRO3.0 material libraries for the crack growth rate equation constants. Non-interaction of loads and constants for the Forman crack growth rate equation are used.

Since the standard crack models in NASGRO3.0 are for crack growth of single cracks, no influence of one crack upon another is calculated in NASGRO3.0 for these standard cases. MSD scenarios involve fatigue damage at multiple locations. This causes the potential of crack interactions. The analysis presented here includes these crack interaction effects by iterating though a series of NASGRO3.0 computer runs tracking the growth of multiple cracks and modifying the stress intensity factors appropriately. The increased stress intensity factors are based on the crack sizes of the interacting cracks from the previous iteration and correction factors based on the compounding of analytical stress intensity solutions.

This iteration procedure is accomplished in an Excel® Spreadsheet utilizing Visual Basic Programming to submit a NASGRO3.0 computer run for each crack at each iteration. The spreadsheet reads the NASGRO3.0 output files for cycles and current crack lengths. Based on these crack lengths, correction factors are calculated and input into the NASGRO3.0 input file for the next iteration, which is automatically submitted by the spreadsheet.

The correction factors are accounted for by increasing the stress scaling factors input into NASGRO3.0. These correction factors for crack interaction account for the condition of interactions of cracks in parts that are analyzed for multiple site damage. These increased stress scaling factors can be input based on the following:

$$K = S\beta_{CF}\beta_N\sqrt{\pi a} = S'\beta_N\sqrt{\pi a}$$

where,

$\beta_N =$ Beta for the standard NASGRO crack model

$\beta_{CF} =$ Beta calculated from the correction factor

$S' = S\beta_{CF} =$ increased stress scaling factor input into NASGRO

The correction factors for crack interaction are based on compounding of analytical stress intensity solutions. Two correction factors are used in this analysis. The first correction factor is termed "Bowie" and is for equal length cracks growing from opposite sides of a hole. The second correction factor is termed "Periodic" and is used for equal length cracks emanating from holes approaching one another.

Compounding of the first and second correction factors is done, and is termed "Bo + Bp'. This product of the "Bowie" and the "Periodic" correction factors is what is used for typical MSD situations where there are multiple fastener holes in a row and assumed imperfection flaws equal in size growing from opposite sides of each hole towards one another.

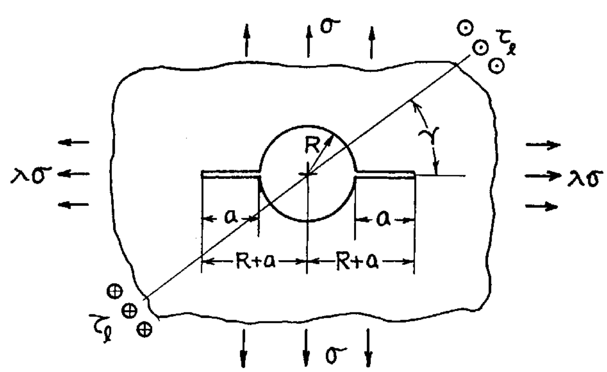

Figure SIE-1.4. Bowie Correction Factor

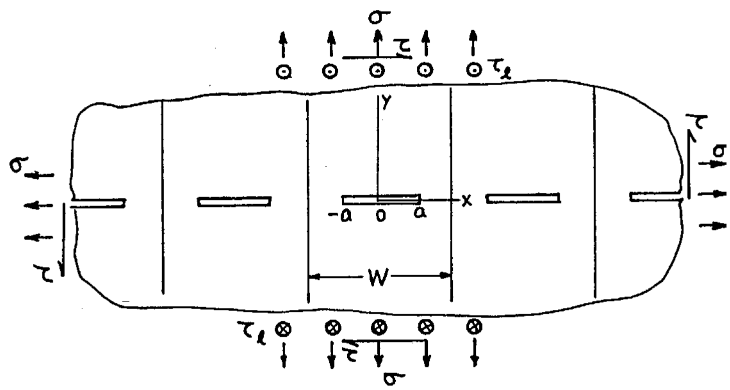

Figure SIE-1.5. Periodic Correction Factor

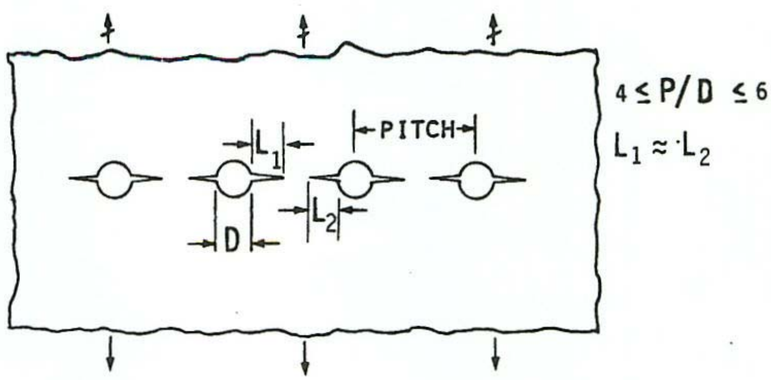

Figure SIE-1.6. Bowie + Periodic Correction Factor

These correction factors are based on through the thickness cracks. They are used for part through cracks when defined with an equivalent crack length. The equivalent crack length is based on equating the area of a part through crack as a quarter ellipse to that of an equivalent through crack as a rectangular area with thickness, t:

$$A_{pc} = A_{eq} = \frac{\pi ac}{4} = a_{eq}t \Rightarrow a_{eq} = \frac{\pi ac}{4t}$$

Note the correction factors are used in conjunction with standard crack models in NASGRO3.0. Therefore, to obtain a correction factor, the ratio of an analytical solution for a specific crack problem to a solution approximating the standard crack model is calculated. The analytical solutions used in deriving these correction factors are taken from H. Tada, P Paris, and G. Irwin, "The Stress Analysis of Cracks Handbook", Third Edition.

The "Bowie" correction factor is derived by comparing Bowie's solution for equal length cracks from both sides of a hole to the solution of a single crack from one side of a hole. The ratio of these solutions, from pages 19.1 and 19.2 of the Handbook, respectively yield the "Bowie" correction factor:

for,

$$\lambda = 0$$

$$s = \frac{a}{R+a}$$

$$\beta_{bowie} = \frac{K_{19.1}}{K_{19.2}} = \frac{\sigma F_{19.1}(\lambda,s)\sqrt{\pi a}}{\sigma F_{19.2}(\lambda,s)\sqrt{\pi a}} = \frac{F_{19.1}(0,s)}{F_{19.2}(0,s)} = \frac{F_{0,19.1}(s)}{F_{0,19.2}(s)}$$

$$\beta_{bowie} = \frac{0.5(3-s)[1+1.243(1-s)^3]}{[1+.2(1-s)+.3(1-s)^6](2.243-2.64s+1.352s^2-.248s^3)}$$

The "Periodic" correction factor is derived from the ratio of the beta factor for a periodic array of cracks from page 7.1 of the Handbook to the solution of a crack in an infinite width plate. Note the solution for a periodic array of cracks is an exact solution. Including the diameter of the hole in the crack length and defining the pitch of the hole spacing to be the pitch of the crack spacing yields the "Periodic" correction factor:

$$a_{7.1} = D/2 + a$$

$$W = pitch = P$$

$$\beta_{periodic} = \frac{K_{7.1}}{\sigma\sqrt{\pi a}} = \sqrt{\frac{W}{\pi a_{7.1}}\tan\frac{\pi a_{7.1}}{W}} = \sqrt{\frac{P}{\pi(D/2+a)}\tan\frac{\pi(D/2+a)}{P}}$$

Note the periodic correction factor is based on the solution of an infinite width plate, while the standard crack model in NASGRO3.0 is for a finite width plate. The use of this correction factor is conservative based on the following calculations.

A comparison of the stress intensity factor calculated for a finite width plate with that of a periodic array of cracks in an infinite plate is made to estimate the effects on crack growth as cracks approach one another. Note that the cracks are analyzed with a finite width plate using the width equal to the pitch of the fastener spacing. Solutions for both problems are taken from H. Tada, P Paris, and G. Irwin, "The Stress Analysis of Cracks Handbook", Third Edition.

Koiter found the exact limit for the beta factor for the finite width plate at a/b=1 as:

$$\beta_{fw} = \frac{2}{\sqrt{\pi^2 - 4}}\frac{1}{\sqrt{1-a/b}}$$

For the periodic array of cracks in an infinite plate, the beta factor is:

$$\beta_P = \sqrt{\frac{2b}{\pi a}\tan\frac{\pi a}{2b}}$$

Using the following expansion on the tan(x) , taking the limit of a/b →1 and representing the second and higher terms of the series as the constant C_1:

$$\tan x = 8x\left[\frac{1}{\pi^2-4x^2}+\frac{1}{9\pi^2-4x^2}+\frac{1}{25\pi^2-4x^2}+\frac{1}{49\pi^2-4x^2}+...\right] = 8x\left[\frac{1}{\pi^2-4x^2}+C_1\right]$$

$$\lim_{a/b\to 1}\tan\frac{\pi a}{2b} = \frac{8\pi a}{2b}\left[\frac{1}{\pi^2-4(\frac{\pi a}{2b})^2}+C_1\right] = \frac{4a}{\pi b}\left[\frac{1}{1-\frac{a^2}{b^2}}+C_2\right]$$

$\therefore$

$$\beta_P = \sqrt{\frac{2b}{\pi a}\frac{4a}{\pi b}\left[\frac{1}{1-\frac{a^2}{b^2}}+C_2\right]} = \frac{2}{\pi}\sqrt{\frac{2}{(1-\frac{a}{b})(1+\frac{a}{b})}+C_3}$$

Comparing the beta factors for both solutions as a/b $\to$1 and noting that the constant term is multiplied by zero:

$$\lim_{a\to b}\frac{\beta_P}{\beta_{fw}} = \lim_{a\to b}\frac{2}{\pi}\sqrt{\frac{2}{(1-\frac{a}{b})(1+\frac{a}{b})}}\frac{\sqrt{\pi^2-4}}{2}\sqrt{1-\frac{a}{b}}+C_4\frac{\sqrt{\pi^2-4}}{2}\sqrt{1-\frac{a}{b}}$$

$$\lim_{a\to b}\frac{\beta_P}{\beta_{fw}} = \lim_{a\to b}\frac{2}{\pi}\sqrt{\frac{2}{(1+1)}}\frac{\sqrt{\pi^2-4}}{2} = \frac{\sqrt{\pi^2-4}}{\pi} = 0.771$$

Based on this comparison, it is conservative to approximate the beta factor of a periodic array of cracks in an infinite plate with that of a finite width plate of the same dimension. Note that this comparison is at the limit as a/b $\to$1. This ratio increases to 1.0 as a/b $\to$0.

Therefore, the crack growth model for the main cargo door surround doubler attachment to the fuselage skin at stringer 2R employs the NASGRO3.0 corner crack from a hole centered in a plate, CC02, with the correction factors for both the influence of cracks growing from opposite sides of a hole , “Bowie”, and the influence of a periodic array of cracks approaching one another, “Periodic”.

These correction factors are used along with the NASGRO3.0 standard crack growth model CC02. The following dimensional values are used for the CC02 crack growth model.

$t = 0.036\ in.$

$W_{typ} = 5.0\ in.$

$D = 0.188\ in.$

$B_{typ} = 2.50\ in.$

$Pitch_{typ} = 0.94\ in.$

$a_C = 0.005\ in.,$ multi-site damage crack

$$\beta_P = \sqrt{\frac{W}{\pi a}\tan\frac{\pi a}{W}} = \sqrt{\frac{p}{\pi(D/2+L1)}\tan\frac{\pi(D/2+L1)}{p}}$$

for,

$p = 0.94\ in.$

$D = 0.19\ in.$

$a_A = a_B = L1 = L2 = 0.005\ in.$

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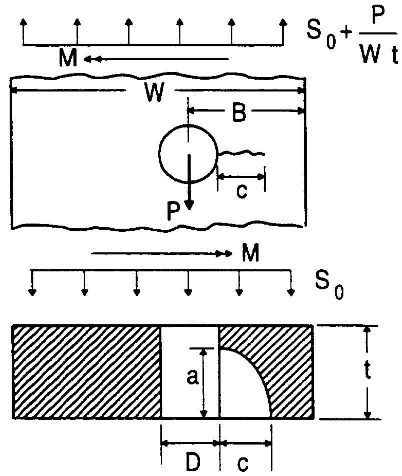


Figure SIE-1.7. NASGRO3.0 Crack Model, CC02.

Two identical NASGRO files are created for the multiple site damage cracks and submitted to the Excel interaction spreadsheet. The spreadsheet accesses NASGRO and grows both cracks for 100 flights. The β correction factors are calculated for the crack lengths at that time and the resulting increased stress scaling factors are plugged back into the NASGRO files. The interaction spreadsheet grows the two cracks until there is a 10% change in crack length (this could also be done in increments of flights), recalculates the β correction and stress scaling factors, and continues to grow the cracks until they become critical or the edge of the plate is reached, whichever occurs first.

Inspection Capabilities and Crack Limits

The holes in the fuselage skin at the attachment of the first row of the surround doubler attachment at 2R (and 26L) are directly accessible from the inside. Therefore, these areas are inspected by HFEC surface probe. With a HFEC inspection, the minimum detectable crack size in the field is assumed to be a 0.0625 inch crack past the fastener head.

Structural Loading and Stress History Description

The stress spectrum is considered to have a remote stress due to cabin pressurization. Cabin pressurization primarily causes hoop tension in the fuselage. The GAG pressurization load is based on FAR25.571. The pressure condition is comprised of a 7.8 psi normal operating differential pressure and an additional 0.5 psi external aerodynamic pressure. A factor of 1.1 is only applied to the normal operating pressure for residual strength.

$$P = 7.8 + 0.5 = 8.3 \ psi$$

$$R = 74 \ in. \text{ (radius of fuselage)}$$

$$S_r = \frac{PR}{t_{skin}} = \frac{8.3(74)}{0.036} = 17.061 \ ksi$$

The bypass and bearing load at the critical fastener row is calculated using a displacement compatibility analysis as described by Swift ("Repairs to Damage Tolerant Aircraft," presented to the International Symposium on Structural Integrity of Aging Airplanes, Atlanta, Georgia, USA, 1990). Layer "a" is the fuselage skin and an existing bonded doubler. Layer "b" is the main cargo door surround doubler. The surround doubler becomes fully effective after the first three rows. This analysis shows the most critical fastener location is the first row of fasteners.

Table SIE-1.1. Fastener Transfer Calculations.

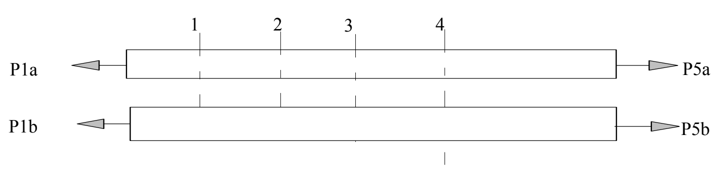
DISPLACEMENT COMPATIBILITY ANALYSIS USING SWIFT'S FASTENER STIFFNESSES

(Note: If there are n fastener rows, there are n+1 segments. However, stiffnesses of last segment do not affect solution)

INPUT — See bottom for sketch (expand view for clarity)

Copy last two columns for additional fastener rows

SEGMENT	1	2	3	4	5	6	7	8	9	10
FASTENER										
STEEL? 1=yes, 0 = no	0	0	0	0	0	0	0	0	0	
ALUMINUM? 1= yes, 0= no	1	1	1	1	1	1	1	1	1	
D	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	
ta	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	
tb	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Esheet	10000000	10000000	10000000	10000000	10000000	10000000	10000000	10000000	10000000	
PLATES										
L	1	1	1	9.5	9.5	9.5	9.5	9.5	9.5	
Aa	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	
Ea	10000000	10000000	10000000	10000000	10000000	10000000	10000000	10000000	10000000	
Ab	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Eb	10000000	10000000	10000000	10000000	10000000	10000000	10000000	10000000	10000000	
CALCULATIONS										
Ca		1.389E-06	1.389E-06	1.319E-05	1.319E-05	1.319E-05	1.319E-05	1.319E-05	1.319E-05	
Cb	0.000001	0.000001	0.000001	0.0000095	0.0000095	0.0000095	0.0000095	0.0000095	0.0000095	
Cf	4.5707E-06	4.571E-06	4.571E-06	4.571E-06	4.571E-06	4.571E-06	4.571E-06	4.571E-06	4.571E-06	
Cf*Pf		7.322E-07	4.541E-07	6.663E-08	1.001E-08	3.067E-09	1.136E-08	7.605E-08	5.183E-07	
Pa	1	0.6952251	0.5350271	0.4356777	0.4210997	0.4189104	0.4182393	0.4157542	0.3991162	0.285714
Pb	0	0.3047749	0.4649729	0.5643223	0.5789003	0.5810896	0.5817607	0.5842458	0.6008838	0.714286
Pf	0.30477492	0.160198	0.0993494	0.014578	0.0021893	0.0006711	0.0024851	0.016638	0.1134022	
Cumulative load transfer a to b	0.30477492	0.4649729	0.5643223	0.5789003	0.5810896	0.5817607	0.5842458	0.6008838	0.714286	0.714286
% Pf load transfer of segment 1 Pa	30.48%	16.02%	9.93%	1.46%	0.22%	0.07%	0.25%	1.66%	11.34%	0.00%



Based on these results, 30% of the load is taken through bearing in the first row of fasteners. This first row of fasteners therefore has 30% as a bearing load and the remaining 70% as a bypass load.

The axial stress and bearing stress acting on this section are:

$$\sigma_{bypass} = S_0 = (1-0.305)S_r = 0.695S_r = 0.695(17.061) = 11.857\ ksi$$

$$\sigma_{brg} = S_3 = \frac{P}{Dt} = \frac{0.305S_rWt}{Dt} = \frac{0.305S_rW}{D} = \frac{0.305(17.061)0.94}{.188} = 26.018\ ksi$$

The limit stress used for residual strength purposes in this scenario is calculated as stated earlier according to FAR25.571.

$$P = 1.1*7.8+0.5 = 9.1\ psi$$

$$R = 74\ in.$$

$$S_r = \frac{PR}{t} = \frac{9.1(74)}{0.036} = 18.706\ ksi$$

The residual strength axial stress and bearing stress acting on this section are:

$$\sigma_{bypass} = S_0 = (1-0.305)S_r = 0.695S_r = 0.695(18.706) = 13.0\ ksi$$

$$\sigma_{brg} = S_3 = \frac{P}{Dt} = \frac{0.305S_rWt}{Dt} = \frac{0.305S_rW}{D} = \frac{0.305(18.706)0.94}{.188} = 28.527\ ksi$$

Material Property Description

The outer skin and doubler are made from 2024-T3 IAW QQ-A-250/5. The material properties from the NASGRO3.0 libraries are used for the fracture toughness and the crack growth rate properties. The material properties used are for 2024-T3; Clad, Plate and Sheet; T-L; LA & HHA NASGRO material code M2EA12AB1.

Table SIE-1.2. Material Properties and Growth Rate Data.

```
MATL 1: 2024-T3
        Clad Plt & Sht; L-T; LA & HHA

Material Properties:

:Matl:  UTS :  YS  :  K1e :  K1c :  Ak :  Bk :  Thk  :  Kc  : Keac :
: No.:      :      :      :      :     :     :       :      :      :
:----:------:------:------:------:-----:-----:-------:------:------:
:  1 :  66.0:  53.0:  46.0:  33.0: 1.00: 1.00:  0.036:  66.0:      :

:Matl:--------------- Crack Growth Eqn Constants -------------------:
: No.:    C    :  n  :  p :  q :  DKo : Cth+ :Cth- : Rcl:Alpha:Smax/:
:    :         :     :    :    :      :      :     :    :     :SIGo :
:----:---------:-----:----:----:------:------:-----:----:-----:-----:
:  1 :0.829D-08:3.284:0.50:1.00:  2.90:  1.50: 0.10:0.70: 1.50: 0.30:
```

Solution Technique

This type of problem is conveniently solved using NASGRO3.0 with the crack growth interactions previously discussed. The input files for the equal length cracks growing from opposites sides of a hole are identical for the NASGRO3.0 analysis shown in Table SIE-1.3. The spectrum is included as a constant amplitude GAG cycle with 100 flights per block, with a single block applied per schedule.

Table SIE-1.3. NASGRO Input File for Problem SIE-1.

Data	Description
71fc1-2cout	Output file name
1	1=US units
D	D=direct
71fc1-2 skin at upper and lower doubler edges	Problem name
CC	Crack model type
2	Crack model no.
0.036	Thk, t
5	W
0.188	D
2.5	Hole center to edge
0.33	Poisson's Ratio
U	U=User defined crack
0.005	Initial a
1	Initial a/c
1	Number of materials
N	Non Interaction
1	Matl input choice
w	File input choice
M	Material Category
2	Material type
EA	Material alloy
1	Material heat treat information
Stress on skin at upper/lower edged	Spectrum name
N	Flag for identifying steps
100000	No. times to apply schedule
1	No. distinct blocks
N	Don't display spec blocks
1	Num steps/block
3	Schedule option
1	Load step number
100	Number of cycles
0	FMIN(1) t1 S_0
11.857	FMAX(1) t2 S_0
0	FMIN(2) t1 S_1
0	FMAX(2) t2 S_1
0	FMIN(3) t1 S_3
26.018	FMAX(3) t2 S_3
0	End manual input
1	Scaling Factor S_0
1	Scaling Factor S_1
1	Scaling Factor S_3
Y	Reference stress input
13	REFACT(1,1,1) S_0
2	Ref Stress at t2
0	REFACT(2,1,1) S_1
2	Ref Stress at t2

28.527	REFACT(4,1,1) S_3
2	Ref Stress at t2
N	Do not enter schedule from file
1	Sblock case
1	Number of times to apply
0	End Spectrum input

Results

Critical crack size/Residual Strength

This case is considered to address an MSD case where 0.005 inch cracks are grown from both sides of a fastener hole over an effective width to represent multiple fastener holes with cracks growing from both sides. There is potential for these crack to link prior to failure. The following calculations estimate this potential.

The half distance between the edges of adjacent holes is:

$$e = \frac{H - D}{2} = \frac{0.94 - 0.188}{2} = 0.376 \ in.$$

The plastic zone size of the MSD type cracks is estimated to be:

$$r_p = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_{ys}}\right)^2 = \frac{1}{2\pi}\left(\frac{30}{54}\right)^2 = 0.049 \ in.$$

If fast fracture failure does not occur first, the two MSD type cracks approaching one another will link at a crack length of:

$$c_L = e - r_P = 0.376 - 0.049 = 0.327 \ in.$$

Life:

Based on the calculations for growing the crack in NASGRO and the MSD crack growth interactions, the life from initial crack size to failure is determined to be 52,161 flights. The results of crack length and crack depth versus life are shown in Figure SIE-1.8. The life is given in numbers of flights.

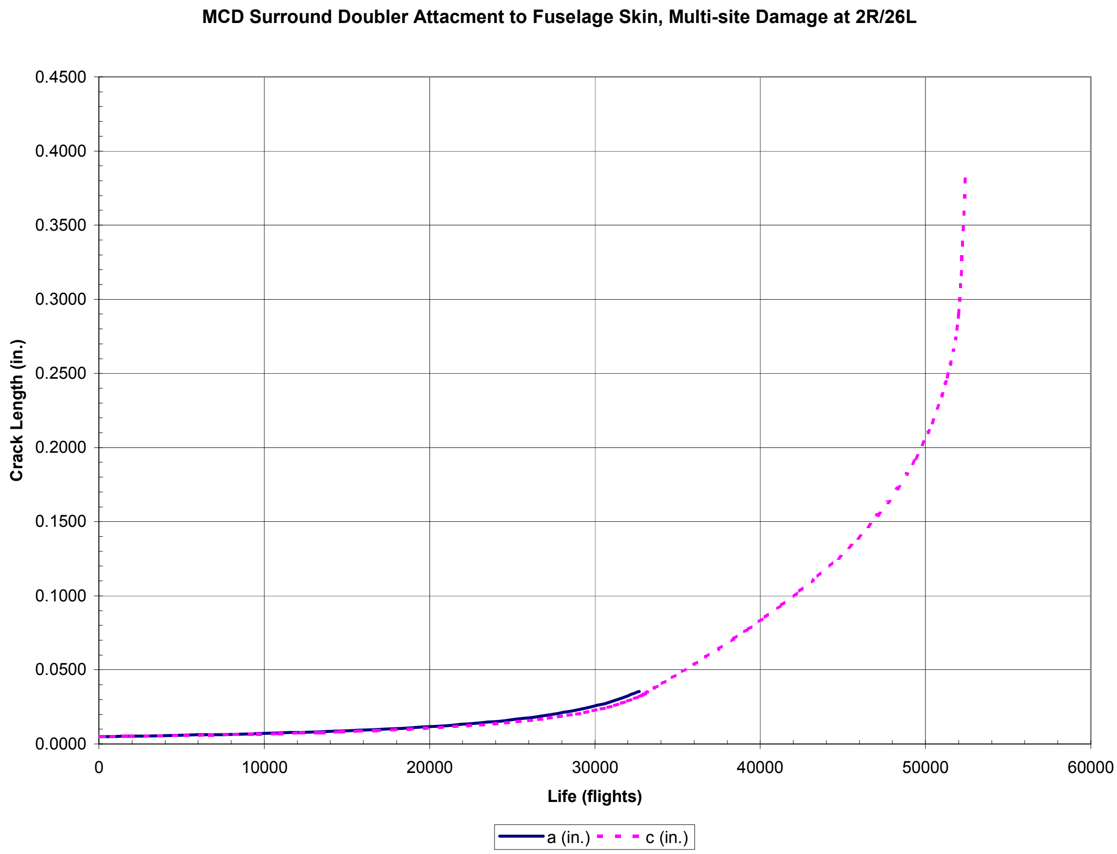


Figure SIE-1.8. Crack Growth Life for Problem SIE-1.

Inspection Intervals

The threshold and repeat intervals are calculated using the life reduction factors shown below.

Life Reduction Factors:

$K_1 = 2.0$
$K_2 = 3.0$, MSD crack scenario

Detectable crack length (HFEC around fastener head):

$$c_{\det} = a_{\det} = \frac{(D_{head} - D)}{2} + 0.0625 = \frac{(0.3016 - 0.188)}{2} + 0.0625 = 0.1193\,in.$$

Number of flights @ detectable crack length, N_{det} = 44,085 flights

Critical crack length: c = 0.327 in.
Number of flights @ critical crack length, N_{crit} = 52,161 flights

$$\text{Threshold Interval} = \frac{N_{crit}}{K_1} = \frac{52161}{2.0} = 26,081\,\text{flights}$$

$$\text{Repeat Interval} = \frac{N_{crit} - N_{\det}}{K_2} = \frac{52161 - 44085}{3.0} = 2,692\ \text{flights}$$