PROBLEM NO. SIE-5

Title: Crack Growth and Residual Strength Analyses of Cracks Under and Beyond a Main Cargo Surround Doubler at a Lap Joint

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 skin lap joints underneath a main cargo door surround doubler for the purpose of determining multiple crack link up and establishing inspection intervals for a long crack growing from underneath the doubler. The critical area includes the main cargo door surround doubler and the existing fuselage skin. The stresses acting at the doubler attachments to the lap splices are derived from a conservative loading spectrum based on pressure loading. The critical area was modeled using Franc2DL for the long crack case to propagate the crack to obtain 'K' vs. 'a' values and NASGRO3.0 to compute the life of the cracked structure for both cases.

Topics Covered: Damage tolerance assessment, stress intensity solutions using finite element analysis, crack growth analysis, residual strength calculation, inspection intervals

Type of Structure: fuselage skin

Relevant Sections of Handbook: Section 2, 4, 5, 11

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Overview of Problem Description

This problem focuses on the fuselage skin lap joints in transport aircraft when a main cargo door surround doubler is present. The doubler covers parts of the lap splices adjacent to the main cargo door cutout. The lap splices that are covered are 4L, 10L, 14L, and 19L. The doublers consist of patches of rectangular sheets butt spliced together. This problem addresses the potential for skin crack initiation at multiple locations and crack growth underneath the doubler.

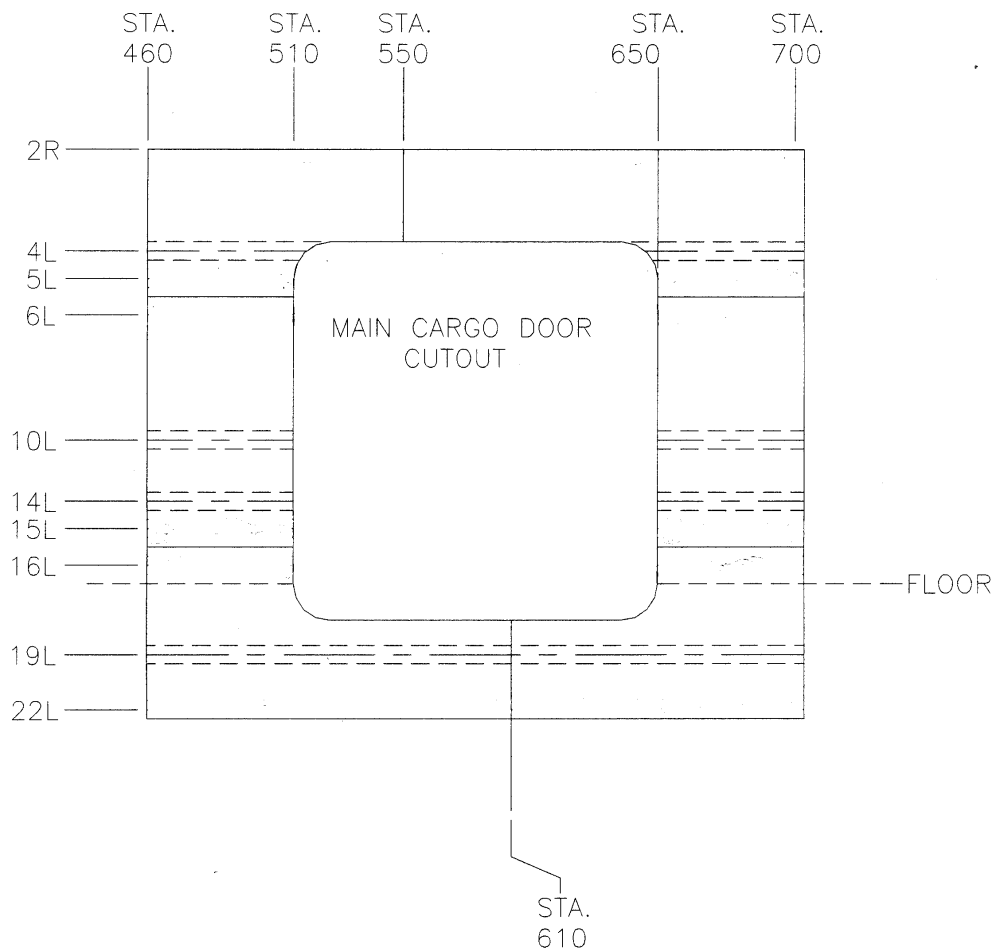

Figure SIE-5.1. Main Cargo Door Doubler Installation

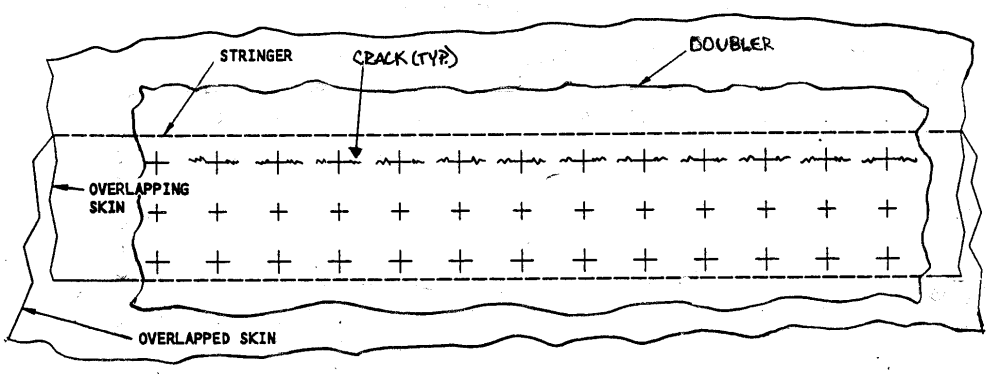

Figure SIE-5.2. Multiple Crack Linking Case.

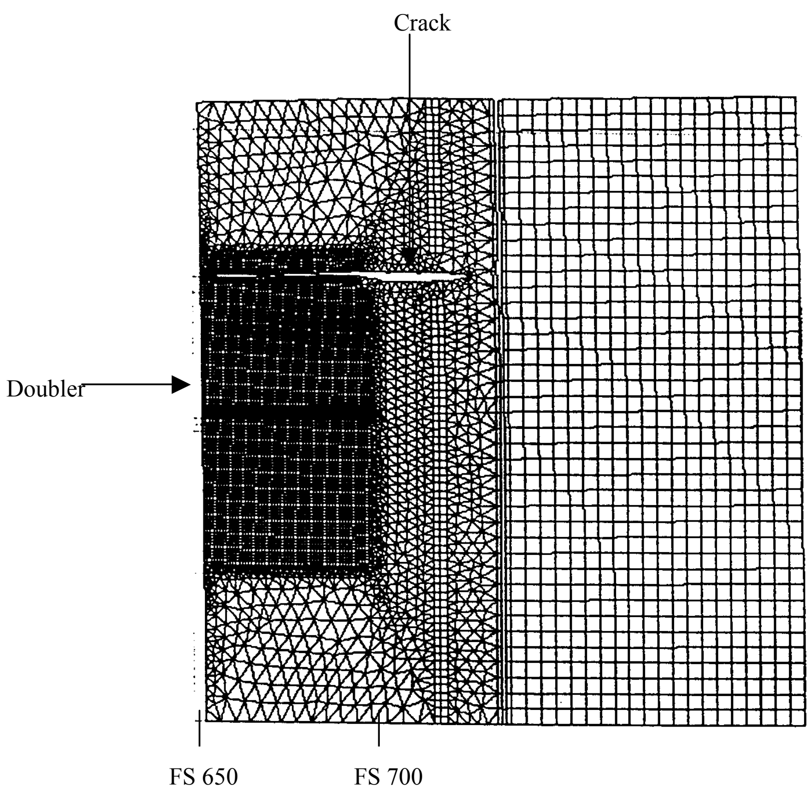

Figure SIE-5.3. Long Crack Case.

Structural Model

Franc2DL models two-dimensional geometries with multiple layers fastened together. Therefore, the geometry of the Franc2DL finite element model involves the creation of multiple layers, each with equivalent areas as that of the structure being modeled. These layers and geometry are created in a meshing program, 'Casca', which are then incorporated via a conversion program, 'Casca to Franc', into Franc2DL.

The basic model is as shown in Figure SIE-5.4. The layers include the 0.04 inch skin, 0.07 inch surround doubler, 0.05 inch tear strap, 0.07 inch doubler splice back up plate, and 0.07 inch skin circumferential splice. The fastener pitch in a row is 1.0 inch. The skin residual strength stress was used in the models.

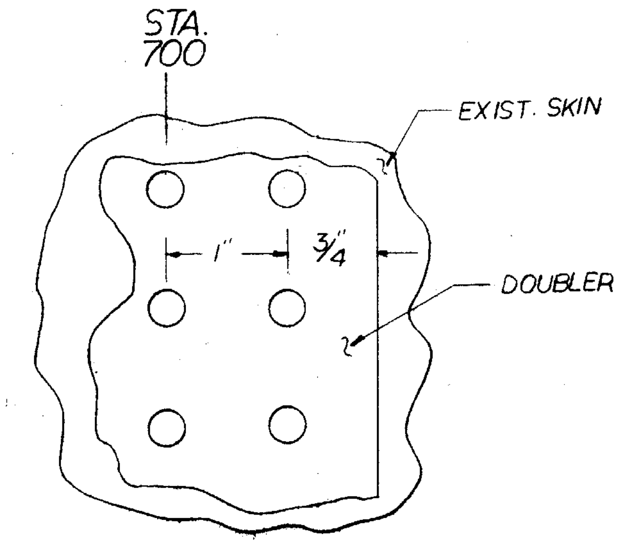

Figure SIE-5.4. Close Up View of Aft Doubler Edge

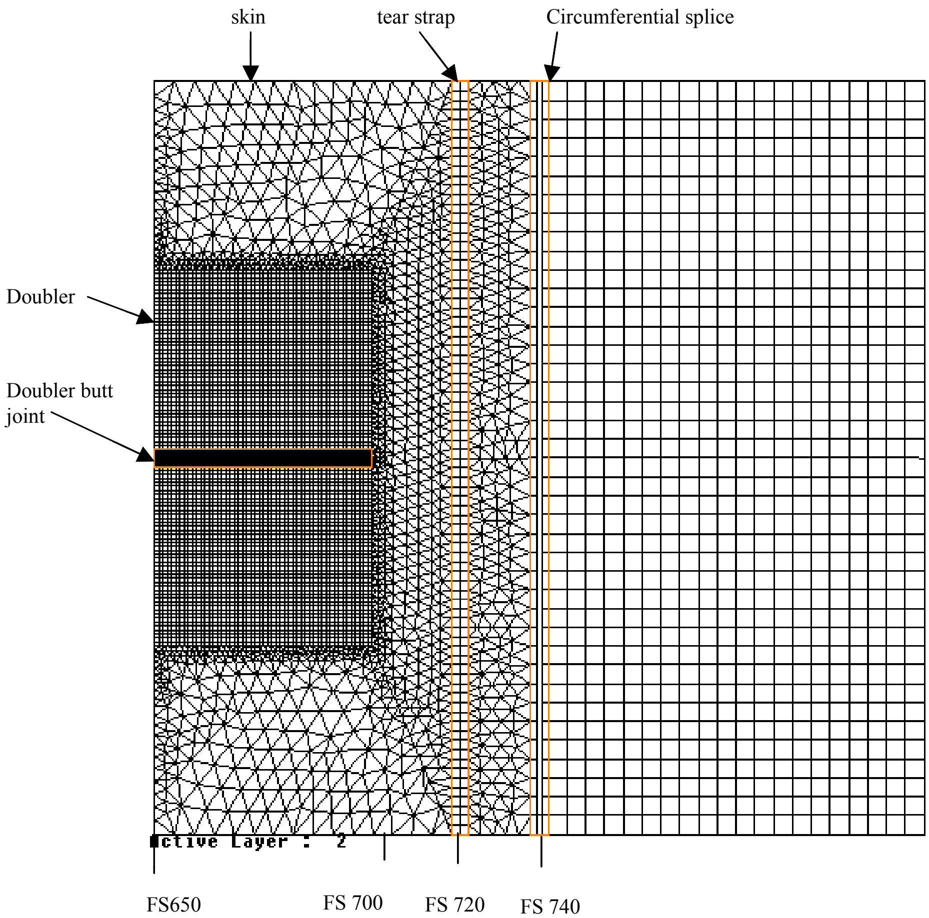

Figure SIE-5.5. Basic Franc2DL Model.

The material properties for each element within a layer are defined individually to account for changes in material type and thickness. Layers are fastened together with rivets, which are treated as finite element springs for which the user must define the stiffness.

If the skin cracks at the upper row of fasteners in a lap joint link underneath the doubler, a long crack completely covered by the doubler could be formed. Since the crack is covered, it is necessary to determine if the doubler can help maintain the residual strength of the skin lap splices. This is done by using a cracked element in Franc2DL as shown below.

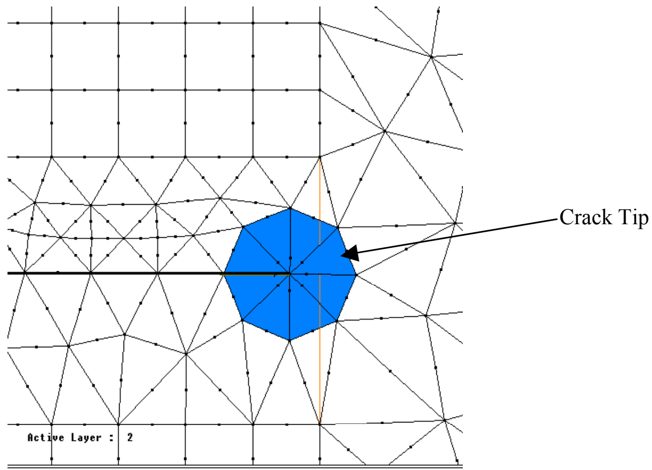

Figure SIE-5.6. Franc2DL Cracked Element.

The most critical location for a long crack is a crack growing from the edge of the door cutout towards the adjacent doubler edge (FS650-FS700). At lap splices 10L and 14L, a crack is located within one row of fasteners from the doubler edge.

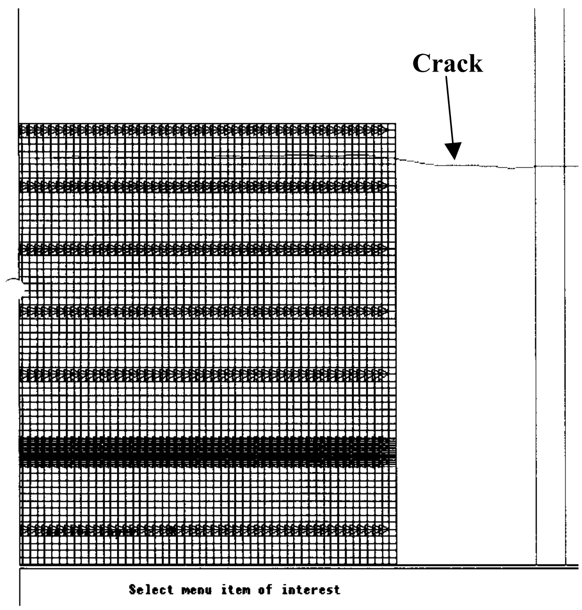

Figure SIE-5.7. Long Crack Model.

Note that Franc2DL is used to propagate the crack(s) to obtain 'K' vs. 'a' values. This is input as tabulated data into NASGRO3.0 to compute crack growth life.

Model Geometry Description

It is conceivable that cracks could have been present at most fastener holes in the top row of the lap splice at the time of the surround doubler installation. Since there were no inspections for cracks at the existing fastener holes prior to installation, it is necessary to establish the maximum crack size that could have been present. The largest multiple cracks that could have been present would have had crack lengths not quite long enough to cause failure under the standard operating loads. An ultimate strength failure criterion will be used for the ligament between two cracks emanating from adjacent holes and approaching each other (the applied K for the resulting crack size will be much smaller than the K_c for 2024-T3 thin sheet). For an applied cyclic stress of 16.8 ksi and a nominal ultimate strength of 66 ksi for 2024-T3, this will create a crack configuration as shown in Figure SIE-5.8 (L_i = (1-16.8/66)/2 = 0.373 in.).

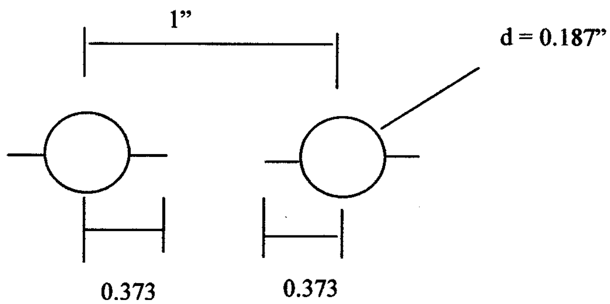

Figure SIE-5.8. Initial MSD Crack Length.

The cyclic stress for fatigue crack propagation after the 0.07 inch doubler installation on the 0.04 inch skin is (0.04/0.11)*16.8 = 6.11 ksi. For a 3/16 inch diameter hole, the initial crack length for crack growth is a_i = 0.373-3/32 = 0.279 inches. Note that this method of establishing the possible crack size of any cracks present is conservative since it assumes that the largest possible crack is present at all holes simultaneously.

The stress intensity factors for the case of cracks at adjacent holes, as shown in Figure SIE-5.9, were derived by combining several existing standard solutions.

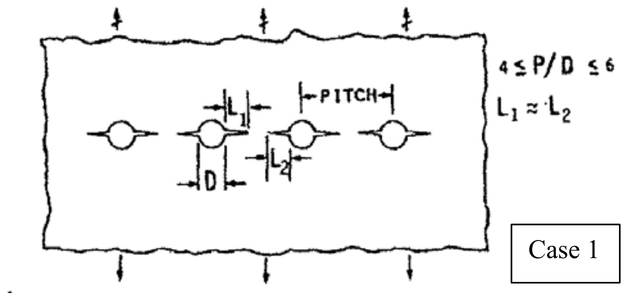

Figure SIE-5.9. Multi-Site Damage Crack Growth.

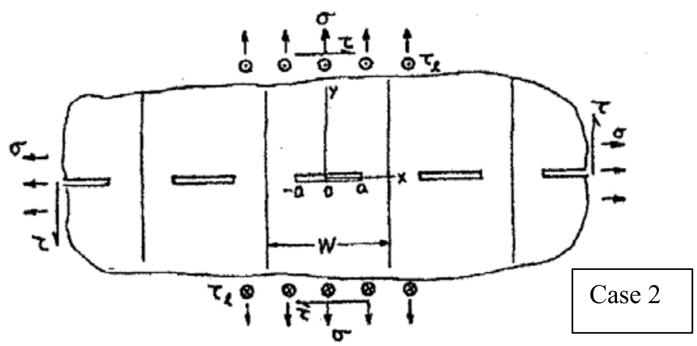

Figure SIE-5.10. Equally Spaced Cracks, Tada Case 7.1.

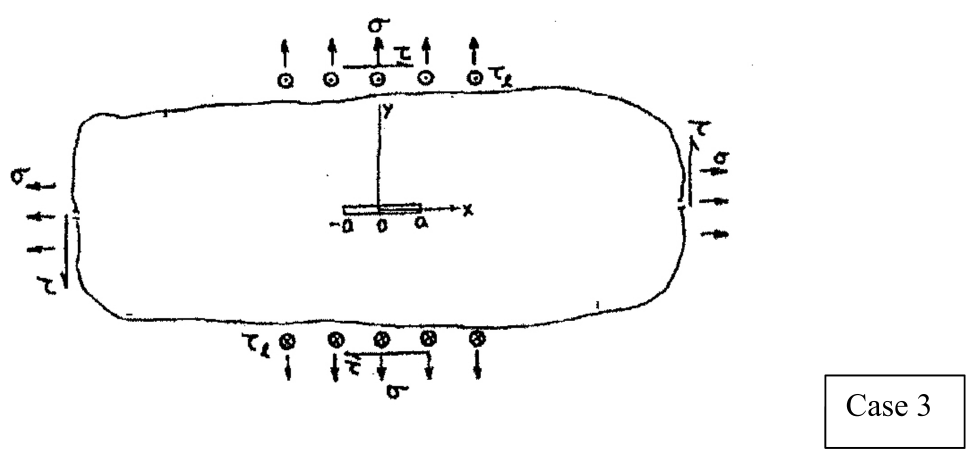

Figure SIE-5.11. Single Crack Solution, Tada case 5.1.

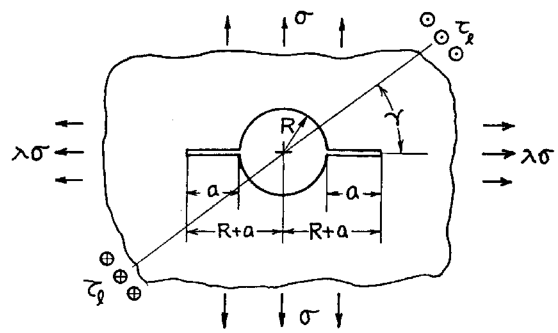

Figure SIE-5.12. Two Equal Cracks from a Hole, Tada case 19.1.

Combining the solutions and solving for K_1 gives:

$$K_1 = \frac{K_2}{K_3} K_4$$

$$K_2 = \sigma \sqrt{w \tan \frac{\pi (R+a)}{w}},\ w = 1.0\,in. \text{ pitch}$$

$$K_3 = \sigma \sqrt{\pi (R+a)}$$

$$K_4 = \sigma \sqrt{\pi a} F_\lambda (s)$$

$$F_\lambda (s) = (1-\lambda) F_0 (s) + \lambda F_1 (s)$$

$$\lambda = 0,\ s = \frac{a}{R+a}$$

$$F_0 (s) = 0.5(3-s)\left[1 + 1.243(1-s)^3\right]$$

After obtaining K_1, the crack growth analysis can be performed using the NASGRO3.0 data table option for a one-dimensional data table for through cracks, DT01, with a unit stress. The crack lengths and corresponding β values are shown below.

$$\beta = \frac{K_1}{\sqrt{\pi a}}$$

Table SIE-5.1. NASGRO Input Values for MSD DT01.

a (in.)	K_2	K_3	K_4	K_1	β
0.05	0.6964	0.6720	0.7068	0.7325	1.8481
0.1	0.8348	0.7802	0.7941	0.8498	1.5161
0.2	1.1494	0.9606	0.9563	1.1442	1.4434
0.25	1.3678	1.0392	1.0325	1.3589	1.5334
0.275	1.5120	1.0763	1.0690	1.5018	1.6157
0.28	1.5452	1.0836	1.0762	1.5347	1.6363
0.285	1.5802	1.0908	1.0834	1.5694	1.6586
0.29	1.6172	1.0980	1.0905	1.6062	1.6827
0.295	1.6564	1.1051	1.0976	1.6451	1.7089
0.3	1.6982	1.1122	1.1046	1.6866	1.7373
0.305	1.7427	1.1192	1.1116	1.7308	1.7682
0.31	1.7904	1.1262	1.1186	1.7783	1.8019
0.315	1.8418	1.1332	1.1255	1.8293	1.8389
0.32	1.8973	1.1401	1.1324	1.8845	1.8795
0.325	1.9576	1.1470	1.1392	1.9444	1.9243
0.33	2.0235	1.1538	1.1461	2.0099	1.9740
0.335	2.0959	1.1606	1.1528	2.0819	2.0293
0.34	2.1760	1.1673	1.1596	2.1616	2.0915
0.345	2.2655	1.1740	1.1663	2.2505	2.1617
0.35	2.3664	1.1807	1.1730	2.3508	2.2419
0.355	2.4814	1.1873	1.1796	2.4652	2.3343
0.36	2.6142	1.1939	1.1862	2.5972	2.4422
0.37	2.9569	1.2070	1.1993	2.9379	2.7250
0.38	3.4783	1.2200	1.2123	3.4564	3.1634
0.4	7.1360	1.2455	1.2379	7.0925	6.3270

The stress intensity factors, K, and corresponding crack lengths for the long crack case are taken from the Franc2DL model. This model was run with the skin residual strength stress of 18.426 ksi. The K values are converted into betas for a unit stress using the equation:

$$\beta = \frac{\left(\frac{K}{\sqrt{\pi a}}\right)}{18.246}$$

The β and crack length values are input into NASGRO3.0 using the same data table option as for the MSD case. Table SIE-5.2 shows the crack lengths, K values, and calculated β values for the long crack case.

Table SIE-5.2. NASGRO Input Values for Long Crack DT01.

a (in.)	K	β
48.066	35.49	0.1567
53.066	44.58	0.1874
58.066	58.57	0.2353
63.066	71.35	0.2751
68.066	81.82	0.3037
73.066	88.29	0.3163
78.066	93.84	0.3252
83.066	105.2	0.3534

Inspection Capabilities and Crack Limits

The long crack will be detectable once it grows out from underneath the surround doubler. The crack will be directly accessible externally and inspected for by using either HFEC or detailed visual techniques. With a HFEC inspection, the minimum detectable crack size in the field is assumed to be a 0.125 inch crack away from a fastener hole. With a detailed visual inspection, the minimum detectable crack size in the field is assumed to be a 3.0 inch uncovered crack.

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 8.6 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.

$$P = 8.6 + 0.5 = 9.1 \ psi$$

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

$$S_r = \frac{PR}{t_{skin}} = \frac{9.1(74)}{0.04} = 16.835 \ ksi$$

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

$$P = 1.1 * 8.6 + 0.5 = 9.96 \ psi$$

$$R = 74 \ in.$$

$$S_r = \frac{PR}{t_{skin}} = \frac{9.96(74)}{0.04} = 18.426 \ ksi$$

Material Property Description

In Franc2DL, materials can be assigned to each element individually. Material properties that are user defined for the models in this analysis are as follows; Young's modulus, Poisson's Ratio, and thickness. The values used for the long crack case are shown in Table SIE-5.3.

Table SIE-5.3. Material Properties and Growth Rate Data.

Material	Young's Modulus	Poisson's Ratio
2024-T3 Aluminum	10.3E+06	0.35

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 crack growth rate properties. The material properties used are for 2024-T3; Clad, Plate and Sheet; T-L; LA & HHA NASGRO3.0 material code M2EA12AB1.

Table SIE-5.4. 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:
```

The K_c value is conservative for the long crack case. This value was changed to 108.9 ksi√in. (Department of Defense Damage Tolerant Design Handbook) in order to better calculate the actual crack growth in a large panel.

Solution Technique

The multiple cracks case is conveniently solved using NASGRO3.0 with the crack growth interactions previously discussed, while the long crack case is solved using Franc2DL and NASGRO3.0. The spectrum is the same for both cases and is included as a constant amplitude GAG cycle with 100 flights per block, with a single block applied per schedule.

Results

Critical crack size/Residual Strength

The residual strength stress for the multiple cracks is (0.04/0.11)*18.4 = 6.7 ksi. This stress results in a critical crack geometry as shown in Figure SIE-5.13 (L_f = (1-6.7/66)/2 = 0.449 in.). The final crack length is a_f = 0.449-3/32 = 0.355 inches.

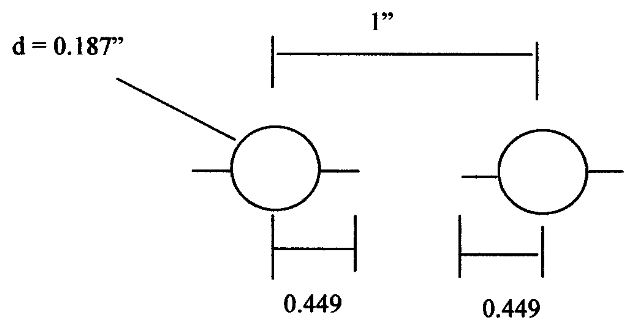

Figure SIE-5.13. MSD Critical Crack Length.

Life:

Based on the calculations for growing the crack in NASGRO3.0 and the MSD crack growth interactions, the life from initial crack size to failure is determined to be 16,868 flights. The results of crack length and crack depth versus life are shown in Figure SIE-5.14. The life is given in numbers of flights. These results show that there is ample time before multiple cracks present at the time of the surround doubler installation link up and become critical.

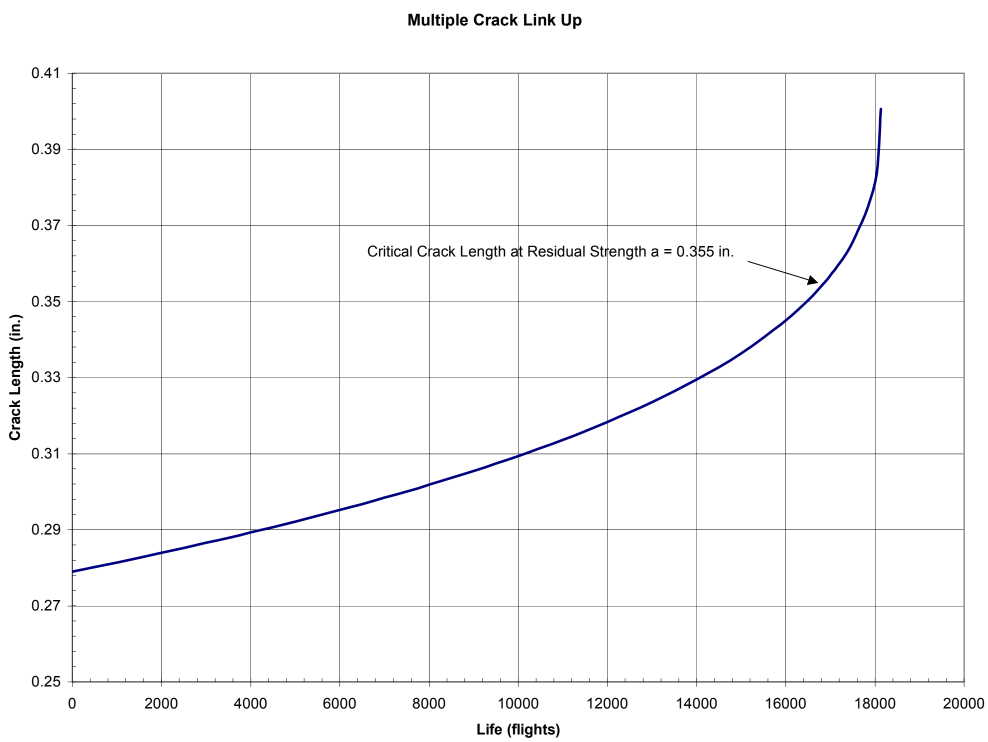

Figure SIE-5.14. Crack Growth Life for MSD Case.

Based on the calculations for growing the crack in NASGRO3.0 for the long crack case, the life from initial crack size to failure is determined to be 65,554 flights. The results of crack length and crack depth versus life are shown in Figure SIE-5.15.

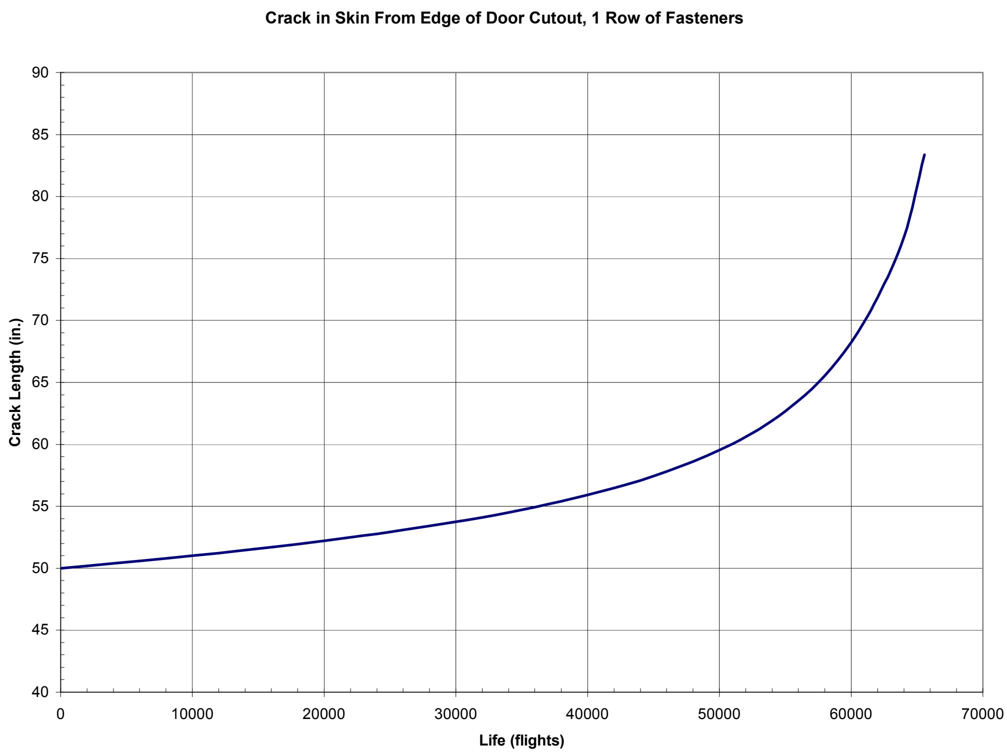

Figure SIE-5.15. Crack Growth Life for Long Crack Case.

Inspection Intervals

The threshold and repeat intervals for the long crack case are calculated using the life reduction factors shown below.

Life Reduction Factors:
$K_1 = 2.0$
$K_2 = 2.0$, Multiple load path structure

Detectable crack length (HFEC at edge of doubler):
$$c_{\text{det}} = c_{dblr} + 0.125 = FS700 - FS650 + 1.75 + 0.125 = 51.75 + 0.125 = 51.875\,in.$$
Number of flights @ detectable crack length, N_{det} = 17,400 flights

Detectable crack length (Detailed visual at edge of doubler):
$$c_{\text{det}} = c_{dblr} + 3.0 = FS700 - FS650 + 1.75 + 3.0 = 51.75 + 3.0 = 54.75\,in.$$
Number of flights @ detectable crack length, N_{det} = 35,200 flights

Critical crack length: c = 83.3659 in.
Number of flights @ critical crack length, N_{crit} = 65,554 flights

$$\text{Threshold Interval} = \frac{N_{crit}}{K_1} = \frac{65554}{2.0} = 32,777 \text{ flights}$$

$$\text{Repeat Interval, HFEC} = \frac{N_{crit} - N_{\det,HFEC}}{K_2} = \frac{65554 - 17400}{2.0} = 24,077 \text{ flights}$$

$$\text{Repeat Interval, Det. Visual} = \frac{N_{crit} - N_{\det,DV}}{K_2} = \frac{65554 - 35200}{2.0} = 15,177 \text{ flights}$$

References

Tada, H., P. Paris, and G. Irwin, "The Stress Analysis of Cracks Handbook," Third Edition.