

## 9.6 Blend-Out Repairs

One of the accepted procedures for removing a small amount of crack damage in the field is through the use of blend-out repairs. These repairs are efficiently accomplished and for the most part, return the structure close to its original static strength and design crack growth life interval. This subsection addresses the type of fatigue crack growth life analysis one might conduct to ensure that a blend-out repair has not significantly degraded the anticipated service life of the structure.

There are two basic conditions that might degrade the life of the structure as a result of blend-out: (1) the accidental gouging, scraping, or otherwise damaging of the material during the repair and (2) the development of a stress concentration site. Both conditions must be actively avoided since both tend to accelerate the development of new cracks which could cause safety-of-flight problems.

As discussed in Section 9.5, one of the more difficult aspects of repair analysis is the definition of initial crack size utilized for life calculations. If the initial crack size assumed after repair is greater than or equal to the initial crack size assumed during design, then the structure life after repair is less than or equal to the initial design life. To determine the fractional loss (FL) in structural life, an engineer could utilize the ratio

$$FL = 1 - \frac{\textit{Life (Repair)}}{\textit{Life (Blueprint)}} \quad (9.6.1)$$

Alternately, the engineer could evaluate the loss in blueprint life by forming the life ratio:

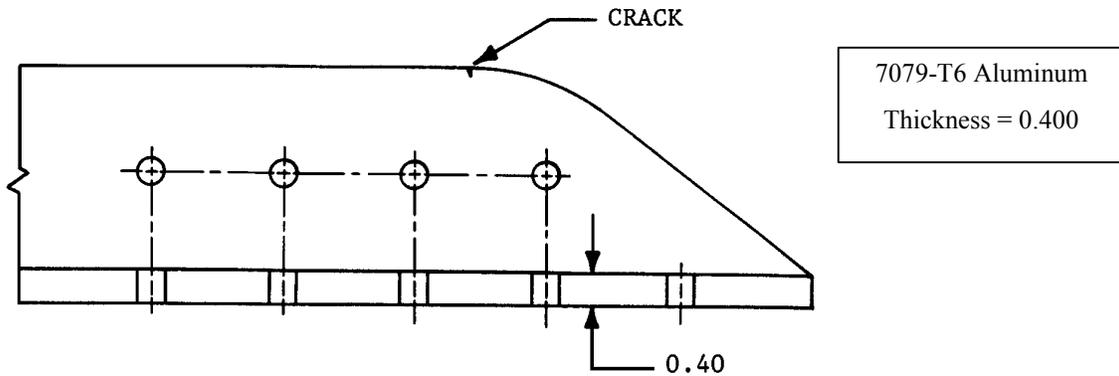
$$LR = \frac{\textit{Life (Repair)}}{\textit{Life (Blueprint)}} \quad (9.6.2)$$

For comparison purposes, it would probably be advisable to calculate both the repair life and blueprint life based on the same initial crack length and thereby assess the effects of stress concentration introduced by the blend-out operation. To establish the crack growth life of the repair in an absolute sense would require that the choice of initial crack length be given careful engineering consideration.

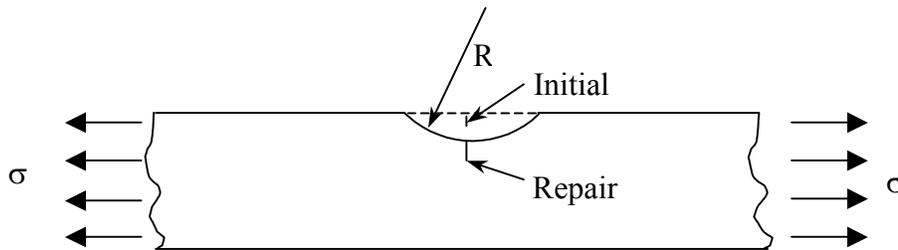
Two examples have been prepared to illustrate the types of analyses that could be conducted to evaluate the damage tolerance of blend-out type repairs. [Example 9.6.1](#) presents the calculations where the initial crack size for the repair is assumed to be equal to the crack size in as-manufactured structure. A sensitivity study is presented to demonstrate the impact that blend-out shape has on repair life. In [Example 9.6.2](#), the crack size after repair is assumed to be smaller than that in the as-manufactured structure, and a sensitivity study is presented to illustrate the effect of crack size.

### EXAMPLE 9.6.1 Blend-Out Repair - Effect of Shape

The angle transition component shown below periodically exhibits evidence of cracking in the location identified and the engineer has recommended a blend-out repair to remove all evidence of cracking. Based on the manufacturer's stress report, the tensile stress in the angle transition component is 27 ksi for the critical load condition. Evaluate the damage tolerance of the component assuming that the initial crack size in the repair and the as-manufactured structure are the same ( $a_o = 0.050$  inch).



Geometry of Structure with Small Crack



Geometry of Blend-Out Repair Assumed for Analysis

#### SOLUTION:

The damage tolerance evaluation will be based on an assessment of both the change in crack growth lives and the change in critical crack size. Based on a lack of both a stress history and a wide area crack growth rate equation (discussed in paragraph 9.3.3), an engineer might choose a worst case loading environment to conduct the evaluation. Since the stress condition is known ( $\sigma_{max} = 27$  ksi), the engineer could approximate the loading with a once per flight maximum stress of 27 ksi applied in a constant amplitude manner. For simplicity, the minimum stress per flight is presumed to be zero so that the assumed loading is zero-tension ( $R = 0$ ) constant amplitude with a stress maximum of 27 ksi.

To conduct the life analysis, the life equation based on continuous crack growth (consistent with the constant amplitude loading assumption) will be utilized, i.e., life will be calculated using

$$Life = \int_{a_o}^{a_f} \frac{da}{f(K)}$$

The function  $f(K)$  describes the crack growth rate for the material and loading condition;  $a_o$  and  $a_f$  are the initial and critical crack sizes, respectively. Three elements are necessary for the life calculation: (1) the function  $f(K)$ , (2) the stress-intensity factor relationship for the geometry, and (3) the critical crack size ( $a_f$ ). Each element will be separated determined in the paragraphs below; subsequently, LIFE will be determined.

### **Function $f(K)$ Established**

The function  $f(K)$  describes crack growth rate as a function of a stress-intensity factor parameter (such as  $\Delta K$ ). As a result of the constant amplitude loading condition, the engineer would consult the Damage Tolerant Design (Data) Handbook [Skinn, et al., 1994] to find data consistent with the material and stress ratio conditions. The data in Figure 8.11.3.1 of the DTDH are considered representative of the 7079-T6 aluminum alloy. While it is possible to utilize the mean trend data given in tabular form, as presented in the figure, in conjunction with computer codes that employ table look-up schemes, it is instructive to plot the mean trend data and determine if a simple (power law) crack growth rate equation, i.e.

$$\frac{da}{dN} = C\Delta K^n$$

describes the behavior. Both the mean trend data for the  $R = 0.05$  data set and a power law equation that describes these data are presented. The power law equation was determined (graphically evaluated) to be

$$\frac{da}{dN} = 5.84 \times 10^{-10} \Delta K^{4.09}$$

Because the stress ratio ( $R$ ) for the assumed loading ( $R = 0$ ) and the data set ( $R = 0.05$ ) are relatively close, no stress ratio correction factor is applied to Equation 9.6.5. If a stress ratio correction must be applied to a handbook data set, it is suggested that a Walker type correction be considered. The suggested Walker correction factor for aluminum alloys is given by

$$\frac{da}{dN}_{R=R_{desired}} = C_{dataset} \left[ \left[ \frac{1-R_{dataset}}{1-R_{desired}} \right]^{\frac{1}{2}} \Delta K \right]^n$$

where  $R_{data\ set}$  and  $R_{desired}$  are the stress ratios associated with the Handbook data set and the assumed loading, respectively, and where  $n$  is the power law exponent for the data set ( $n = 4.09$  for the 7079-T6 aluminum data set). A quick evaluation of the Walker equation with the appropriate constants shows that the crack growth rate expression given by the power law equation is approximately 10 percent higher than a corresponding stress ratio corrected expression, and thus not overly conservative for a first order approximation.

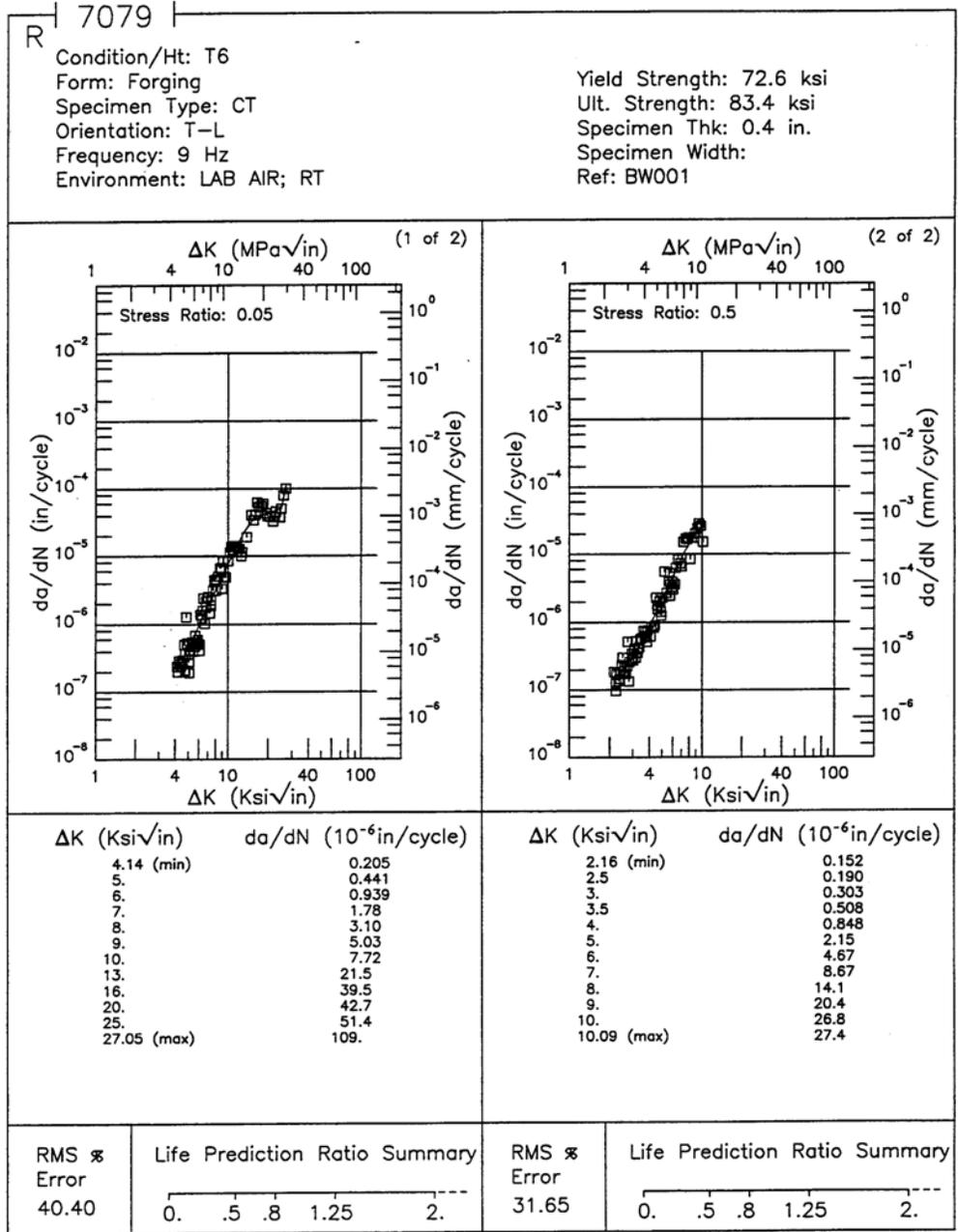
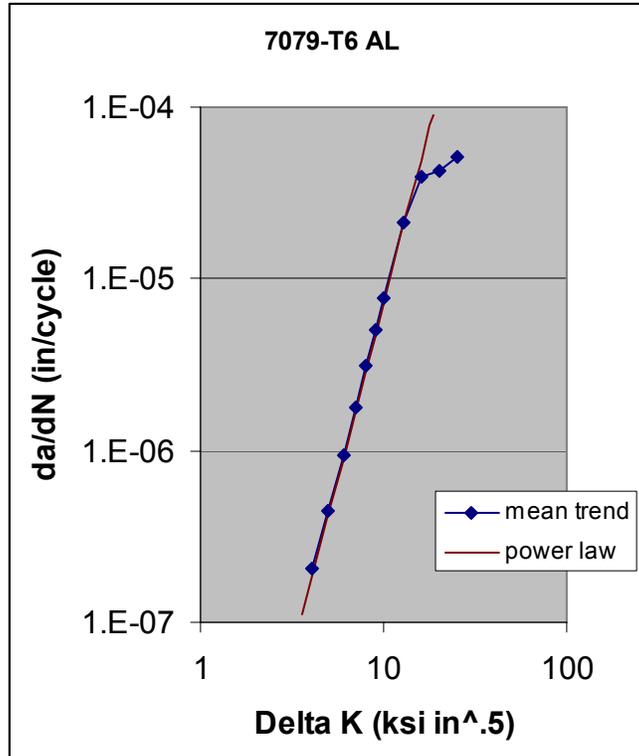


Figure 8.11.3.1.3

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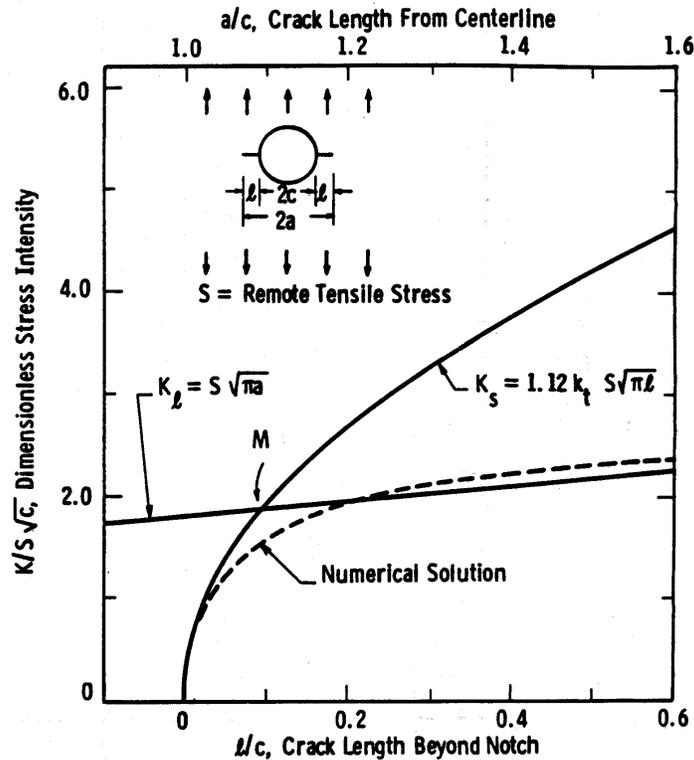
Data Page From the Damage Tolerant Design (Data) Handbook [Skinn, et al., 1994]  
 Used in [Example 9.6.1](#)



Data From Damage Tolerant Design (Data) Handbook Plotted and Compared to Graphically Established Power Law Equation

### Stress-Intensity Factor Establishment

The stress-intensity factor for the blend-out cracking problem can be solved without access to exact finite element stress analyses through the use of some work of Dowling [1979]. For the purpose of providing a methodology for estimating total fatigue life (crack initiation plus crack propagation lives) of notched structures, Dowling needed a transition crack length that separated the initiation life analysis from the crack propagation life analysis. His studies of the conditions controlling small crack growth behavior led him to the stress-intensity factor evaluation shown below. The point *M* identifies the condition where the short crack stress-intensity factor ( $K_s$ ) is equal to the long crack solution ( $K_\ell$ ). Dowling noted that these two crack solutions provided reasonably accurate estimates of the finite element solution in their respective crack length regions. For crack initiation life analysis, Dowling restricted crack length size measured in smooth fatigue samples to sizes less than the crack length associated with the point *M* in the figure. This is because the stress concentration effect dominates in this region.



Short and Long Limiting Cases and Numerical Solution, for Crack Growing from a Circular Hole in an Infinite Plate (Newman)

For the purpose of analysis, the engineer could estimate the stress-intensity factor for the blend-out repair using a Dowling type approach where for small cracks, a short crack stress-intensity factor would apply, and for longer cracks, a long crack stress-intensity factor would apply. Thus, for the blend-out repair, the engineer could describe the stress-intensity factor as:

$$K = K_s \text{ if } a \leq a_M$$

$$K = K_l \text{ if } a > a_M$$

with the short and long crack stress-intensity factors given by:

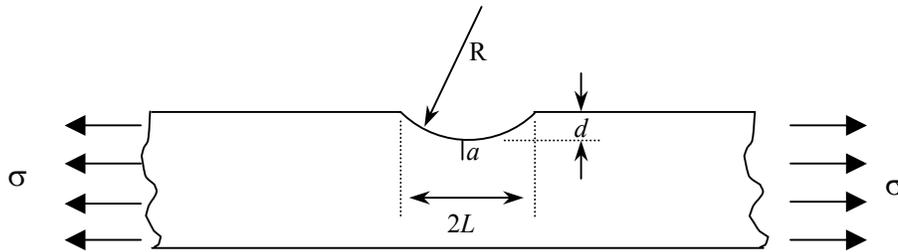
$$K_s = 1.12k_t\sigma\sqrt{\pi a}$$

and

$$K_l = 1.12\sigma\sqrt{\pi(a+d)}$$

where  $k_t$  is the stress concentration factor associated with the blend-out shape.

The equations are written in a form slightly different than those presented in the figure because (1) the geometry of the blend-out is more in line with an edge crack rather than a central crack (Dowling's solution) and (2) the crack length  $a$  is measured from the surface of the blend-out (see the figure for a definition of  $a$  and  $d$ ).



Geometry of Blend-Out with Edge Crack Present

Based on an analysis of these equations, one can see that the blend-out geometry affects the stress-intensity factor solutions through the stress concentration factor ( $k_t$ ) and blend-out depth ( $d$ ). An estimate of the stress concentration  $k_t$  for a blend-out repair is made using the solution of an elliptical cut out in a plate. For an ellipse oriented with the major axis in line with the direction of the stress axis, the stress concentration is given by [Mushhelishvili, 1954; Peterson, 1974]:

$$k_t = \frac{3 + 2M - M^2}{1 + 2M + M^2}$$

where

$$M = \frac{L - d}{L + d}$$

with  $L$  and  $d$  defined as the major and minor radii of the ellipse. As can be noted from the figure,  $L$  and  $d$  define a segment of a circle that we are approximating with a semi-ellipse. Thus, if one has a measure of  $L$  and  $d$  for a blend-out repair, one can estimate  $k_t$  and the corresponding short crack stress-intensity factor using the equations above.

### **Critical Crack Size, $a_f$**

The critical crack size for both as-manufactured (blueprint) and repaired structure will be based on the Irwin hypothesis for abrupt failure, i.e., when

$$K = K_{cr}$$

failure occurs. The critical stress-intensity factor is obtained by estimating the stress-intensity factor range required to achieve a growth rate of 1000 microinches/cycle. Solving the power law equation in an inverse manner, i.e., solving

$$\Delta K = \left[ \frac{1 \times 10^{-3}}{5.84 \times 10^{-10}} \right]^{\frac{1}{4.09}}$$

yields  $\Delta K = 33.34 \text{ ksi}\sqrt{\text{in}}$ . As a lower bound to this estimate, one might choose  $K_{cr} = 30 \text{ ksi}\sqrt{\text{in}}$  for convenience.  $K_{cr} = 30 \text{ ksi}\sqrt{\text{in}}$  corresponds to a crack growth rate of 642 microinches/cycle.

The stress-intensity factor for the blueprint structure is given by

$$K = 1.12\sqrt{\pi a}$$

whereas that for the repaired structure is given by

$$K = 1.12\sigma\sqrt{\pi(a+d)}$$

(Note that the long crack solution is being used for the repair). In both equations,  $a$  is measured from the surface. Solving for  $K_{cr} = 30 \text{ ksi}\sqrt{\text{in}}$  and the above stress-intensity factor solutions yields

$$a_f = 0.325 \text{ inch for the blueprint critical size and}$$

$$a_f = (0.325-d) \text{ inch for the repair critical size.}$$

### **Life Estimating**

While the LIFE equation could be used directly for life estimates of the as-manufactured (blueprint) structure, the stress-intensity factor analysis requires that the integral equation be broken into two intervals. For this repair analysis, LIFE is calculated using

$$LIFE = \int_{a_o}^{a_M} \frac{da}{f(K_s)} + \int_{a_M}^{a_f} \frac{da}{f(K_\ell)}$$

where the crack size  $a_M$  is associated with the transition between the short and long crack stress-intensity factor solutions. This crack size is obtained by equating the two solutions and solving for  $a_M$ , thus

$$K_s = K_\ell$$

in conjunction with the stress intensity equations results in

$$a_m = \frac{d}{k_t^2 - 1}$$

Since for a blend-out repair  $k_t$  would be greater than 1.0 and hopefully less than 1.4,  $a_M$  will be greater than  $d$ .

### **Numerical Details of Blueprint Life**

For an edge crack problem with the material crack growth rate response given by a power law expression, i.e. the LIFE equation can be written as

$$LIFE = \frac{1}{C(1.12\sigma\sqrt{\pi})^n} \left[ \int_{a_o}^{a_f} \frac{da}{a^{\frac{n}{2}}} \right]$$

When integrated, this equation becomes

$$LIFE = \frac{1}{C(1.12\sigma\sqrt{\pi})^n} \left[ \frac{1}{\left(1 - \frac{n}{2}\right)} \cdot \left( a_f^{1 - \frac{n}{2}} - a_o^{1 - \frac{n}{2}} \right) \right]$$

Given the growth rate constants  $C$  and  $n$ , the critical crack size  $a_f$ , the given stress ( $\sigma = 27$  ksi) and the given initial crack size ( $a_o = 0.050$  inch), the crack growth life for the blueprint conditions is determined to be

$$LIFE = 2910 \text{ cycles}$$

of zero-tension loading.

### **Numerical Details of Repair Life**

For the blend-out repair with the material crack growth rate response given by a power law expression, the *LIFE* equation can be expressed as:

$$LIFE = \frac{1}{C(1.12\sigma\sqrt{\pi})^n} \left[ \frac{1}{k_t^2} \int_{a_o}^{a_M} \frac{da}{a^{\frac{n}{2}}} + \int_{a_M}^{a_f} \frac{da}{(a+d)^{\frac{n}{2}}} \right]$$

When integrated, this equation becomes

$$LIFE = \frac{1}{C(1.12\sigma\sqrt{\pi})^n} \left( \frac{1}{1-\frac{n}{2}} \right) \left[ \frac{1}{k_t^2} \cdot \left( a_M^{1-\frac{n}{2}} - a_o^{1-\frac{n}{2}} \right) + \left( (a_f+d)^{1-\frac{n}{2}} - (a_M+d)^{1-\frac{n}{2}} \right) \right]$$

Given the growth rate constants  $C (=5.84 \times 10^{-10})$  and  $n (=4.09)$ , the critical crack size, the given stress ( $\sigma = 27$  ksi), and the given initial crack size ( $a_o = 0.050$  inch), one can estimate the LIFE for defined values of  $k_t$  and  $d$ . For example, when  $d$  and  $L$  are 0.08 inch and 1.0 inch,  $k_t$  is 1.16,  $a_f = 0.245$  inch,  $a_M = 0.231$  inch, and LIFE = 2033 cycles of zero-tension loading. This is approximately 30 percent lower than that given for the blueprint life.

### **Comparative Analysis of Shape Effect**

To summarize the analysis for different blend-out shapes, the LIFE equation was repetitively solved for several different length ( $2L$ ) and depth ( $d$ ) conditions for  $a_o = 0.050$  inch. These results are presented in the following table in the form of life ratios and utilize the blueprint life obtained above. Focusing on three crack depths (0.050, 0.100 and 0.150 inches) as representative, one can immediately note from the table that even for the more gradual blend-out case, the life is substantially reduced (to approximately 80, 65, and 50 percent, respectively) of the original life estimate.

The life ratios presented in the table show the close correlation between life and the stress concentration factor. These results only reinforce common sense since they show that the more gradual the blend-out, the closer to initial life one achieves.

Effects Of Blend-Out Shape On Crack Growth Life Ratio

Depth ( $d$ ) inch	Length ( $2L$ ) inch	$k_t$	Life Ratio	Condition
0.005	2	1.01	0.977	Gradual Blend-Out
0.010		1.02	0.954	
0.015		1.03	0.933	
0.020		1.04	0.911	
0.025		1.05	0.891	
0.030		1.06	0.870	
0.040		1.08	0.833	
0.050		1.10	0.796	
0.060		1.12	0.762	
0.080		1.16	0.699	
0.100		1.20	0.640	
0.120		1.24	0.584	
0.150		1.30	0.503	
0.200		1.40	0.366	
0.250		1.50	0.179	
0.010	1	1.04	0.911	Less Gradual Blend-Out
0.020		1.08	0.831	
0.050		1.20	0.638	
0.080		1.32	0.496	
0.100		1.40	0.421	
0.150		1.60	0.282	

EXAMPLE 9.6.2 Effect of Repair Initial Crack Size

To justify removing shallow cracks with blend-out repair procedures, [Example 9.6.1](#) is extended by considering the effect of repair initial crack size. As a basis for comparison, the life ratio equation,

$$LR = \frac{\text{Life (Repair)}}{\text{Life (Blueprint)}}$$

will again be employed, and the blueprint (as-manufacturing) LIFE is calculated using

$$LIFE = \frac{1}{C(1.12\sigma\sqrt{\pi})^n} \left[ \frac{1}{k_t^2} \int_{a_o}^{a_M} \frac{da}{a^{\frac{n}{2}}} + \int_{a_M}^{a_f} \frac{da}{(a+d)^{\frac{n}{2}}} \right]$$

with  $a_o = 0.050$  inch. Thus, the blueprint LIFE is 2910 cycles, as calculated in [Example 9.6.1](#).

The purpose of this example is to show that if only part of the crack remains after blend-out there can be substantial life improvement over that calculated for the blueprint LIFE.

The effect of repair initial crack size on crack growth life was calculated using

$$LIFE = \frac{1}{C(1.12\sigma\sqrt{\pi})^n} \left( \frac{1}{1 - \frac{n}{2}} \right) \left[ \frac{1}{k_t^2} \cdot \left( a_M^{1 - \frac{n}{2}} - a_o^{1 - \frac{n}{2}} \right) + \left( (a_f + d)^{1 - \frac{n}{2}} - (a_M + d)^{1 - \frac{n}{2}} \right) \right]$$

whereas the initial crack size  $a_o$  was varied along with length ( $2L$ ) and depth ( $d$ ) of the blend-out.

The results are summarized in the following table as a function of the various geometric parameters considered. As expected, the table shows that initial repair crack size substantially affects the damage tolerant life of the blend-out. In fact, compared to the other parameters considered, it dominates. Based on this table, the importance of the variables on life is;

- $a_o$  - most significant,
- $k_t$  - significant, and
- $d$  - least significant.

Thus, during a blend-out repair, the objective is to remove as much of the damage as possible (and hopefully all) with a minimum amount of shape change.

Effect of Repair Initial Crack Size on Crack Growth Life Ratio

Repair Initial Crack Size ( $a_0$ ) inch	Depth ( $d$ ) inch	Length ( $2L$ ) inch	$k_r$	Life Ratio
0.005	0.02	2.0	1.04	11.81
0.005	0.05	2.0	1.10	10.55
0.005	0.10	2.0	1.20	8.83
0.005	0.15	2.0	1.30	7.49
0.010	0.02	2.0	1.04	5.63
0.010	0.05	2.0	1.10	5.02
0.010	0.10	2.0	1.20	4.19
0.010	0.15	2.0	1.30	3.52
0.010	0.02	1.0	1.08	5.21
0.010	0.05	1.0	1.20	4.20
0.010	0.10	1.0	1.40	3.02
0.010	0.15	1.0	1.60	2.28
0.020	0.02	2.0	1.04	2.64
0.020	0.05	2.0	1.10	2.34
0.020	0.10	2.0	1.20	1.94
0.020	0.15	2.0	1.30	1.61
0.050	0.02	2.0	1.04	0.91
0.050	0.05	2.0	1.10	0.80
0.050	0.10	2.0	1.20	0.64
0.050	0.15	2.0	1.30	0.50