3.3 Proof Test Determinations

Tiffany and Masters [1965] first suggested that the conventional structural proof test could be used to inspect for crack damage that would eventually lead to catastrophic failure. These techniques were first applied to rocket motor cases and tankage as a result of numerous missile launch failure at Cape Canaveral. Air Force acceptance of this proof test philosophy has been stimulated by the inability of alternate non-destructive inspection tools to reliably detect cracks of near-critical size. The Air Force in the recent past has employed the proof test as a means of determining the maximum possible initial flaw that could exist in the structural subsystems identified in Table 3.3.1. Note that almost all of the examples cited represent the application of the proof stress techniques as an In-service Inspection. Buntin [1971], Cowie [1975], Horsley, et al. [1976], Gunderson [1974] and Albrectsen & Aitken-Case [1976] document the Table 3.3.1 and other Air Force uses of the crack-inspection proof test. White, et al. [1979] documents the recent Navy proof test of an A-7 arresting hook; this proof test is periodically repeated to ensure the continuing structural integrity of the component.

The proof test concept for all applications has been to size or eliminate the life degrading damage so that the structure would maintain its required level of structural integrity throughout a defined period of usage. However, due to substantially different technical requirements, the proof testing techniques employed in each case were different. The technical requirements that establish the type of tests conducted have been structural geometry, material properties, type of crack damage present in the structure, as well as the crack growth mechanism.

Table 3.3.1. Proof Testing of Aircraft Structures

System	Subsystem	Damage	Special Techniques
F-111	Lower surface of inner wings and pivot fittings	Potential forging defects propagated due to fatigue in D6AC steel	Upwing bending at -40° F after every 1,000 hours of flight
B-1A	F-101 (Development) engine combustor case	Pores and inclusion stringers in circumferential butt welds in Inconel 901 alloy	Internal pressure to 200% operating pressure
B-52D	Center and inner wing structure	Fatigue and stress corrosion cracks nucleated during southeast Asia service in 7075-T6 and 7079-T6 aluminum alloy structure	Down and up-wing bending at ambient temperature
C-141	Main Landing gear (cylinder)	Hydrogen entrapped during refurbishment	500 hours of continuous static loading to initiate and propagate cracks to failure
A-7	Carrier arresting hook (Navy)	Fatigue cracking initiated during service	Repeat periodically

3.3.1 Description of the Proof Test Method

Tiffany and Masters [1965] utilized the proof test as a means of guaranteeing that a potentially cracked structure would not fail during a defined period of operation. This guarantee results from the fact that all the cracks remaining in a proof-loaded structure must be smaller than those cracks which would have failed the structure during the proof test. Since the proof test loadings are typically larger than the maximum operating conditions, the post proof-tested structure's cracks are also expected to be substantially smaller than the cracks which would cause failure under operating loads.

Figure 3.3.1 schematically illustrates a stress-crack length diagram that defined the levels of loading (proof stress and operational maximum stress) and the corresponding crack lengths associated with structural failure by fracture. It can be noted from Figure 3.3.1 that all cracks larger than a_i will cause the structure to fail during the proof test loading, thus guaranteeing a "minimum" safe crack growth interval between a_i and the crack size (a_{op}) at which the operating conditions will cause failure. The interval established is the minimum safe interval because the structure may initially have cracks that are substantially smaller than the guaranteed initial size (a_i).

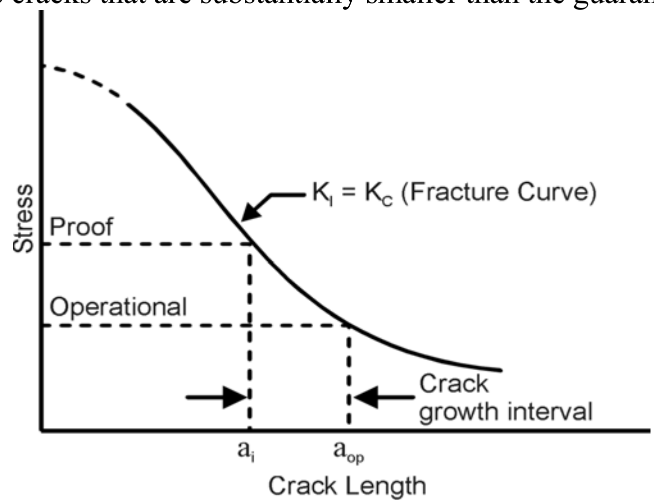


Figure 3.3.1. Fracture Critical Curve Defining Relationship Between Stress and Crack Length Associated with Fracture

Tiffany and Masters [1965] designed the proof test conditions so that all cracks initially present in the structure and of sufficient size that they could grow to failure during the planned service operating period would fail the structure during the proof test. If the operating conditions and the crack growth mechanisms are known, then a crack growth life calculation can be performed to establish the minimum safe crack growth interval during which failure will not occur during service. The minimum safe crack growth interval extends from the largest allowable initial crack size (a^*_i) and the crack size (a_{op}).

Figure 3.3.2 describes the interrelationship between the crack growth life and residual strength behavior of a structure and the stress-crack size diagram. As indicated in Figure 3.3.2 (right-hand side), the life limit associated with the crack growth process and the decay of the residual strength capability is lower than the service life requirement. An increase in the proof stress if required, therefore, to decrease the corresponding crack size (a_i) to the maximum allowable crack size (a^*_i) and thus ensure a safe period of operation. Note that the stress-crack size diagram indicates that all cracks greater than a_i, present at the time of the proof test, will cause structure failure. Thus, the proof test ensures that when the structure enters service, its initial cracks will be no larger than the size associated with the proof test conditions.

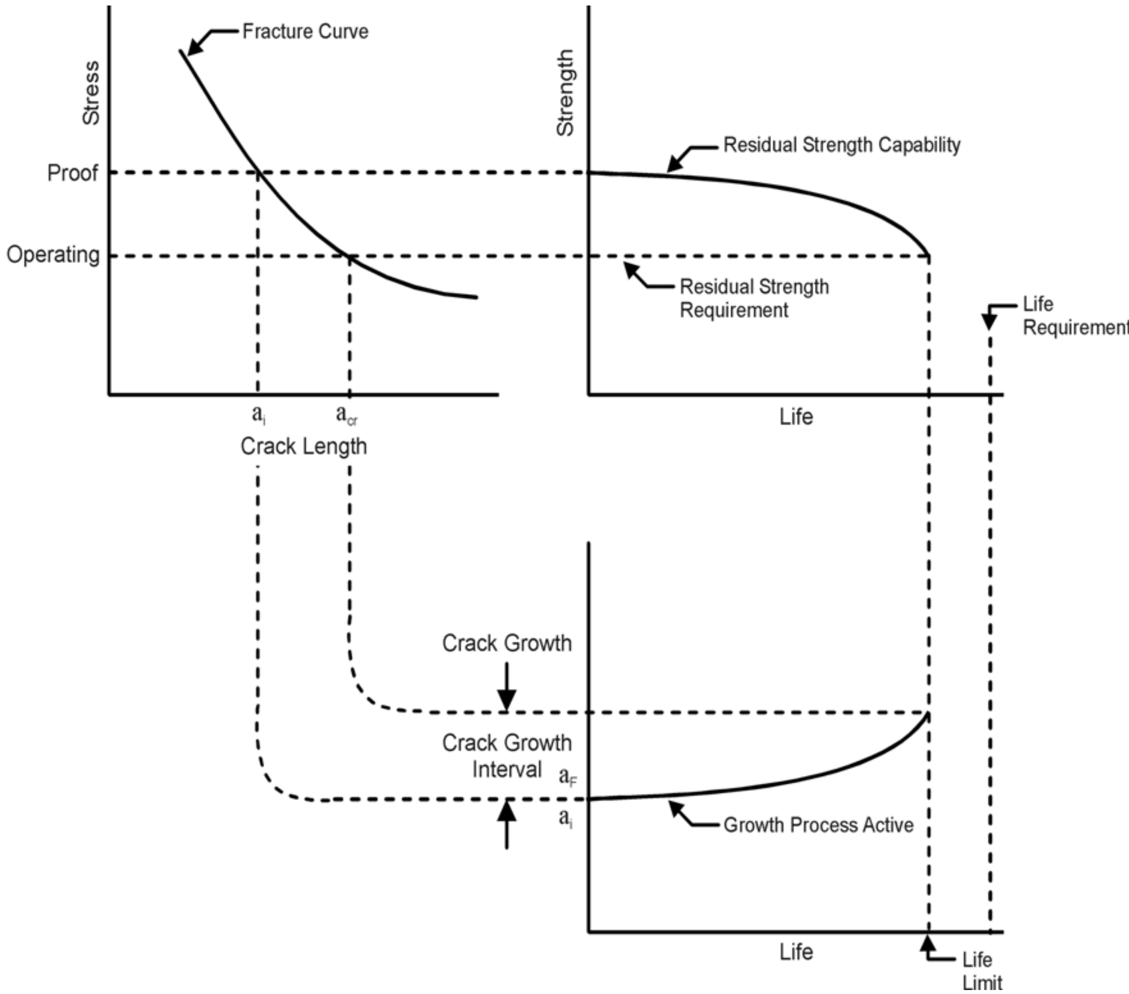


Figure 3.3.2. Schematic Illustrating the Relationship Between the Proof Test Diagram, the Residual Strength Capability and Crack Growth Life Interval

The levels of proof test stress and the material's fracture toughness combine to establish the maximum initial crack size guaranteed by the proof test. Because material and stress variations will exist throughout any proof loaded structure, the designer of a proof test must be aware of several important material variations which could significantly affect the post-proof test crack size distribution. These important material variations are caused by changes in temperature, loading rate, thickness, and yield strength. Figure 3.3.3 schematically describes how fracture toughness varies as a function of these parameters. Note that temperature and loading rate can affect some materials (some steels and titanium alloys are particularly susceptible) while other materials are unaffected. Aluminum alloys and many nickel-bases alloys exhibit almost no variation in fracture toughness as a function of temperature and strain rate).

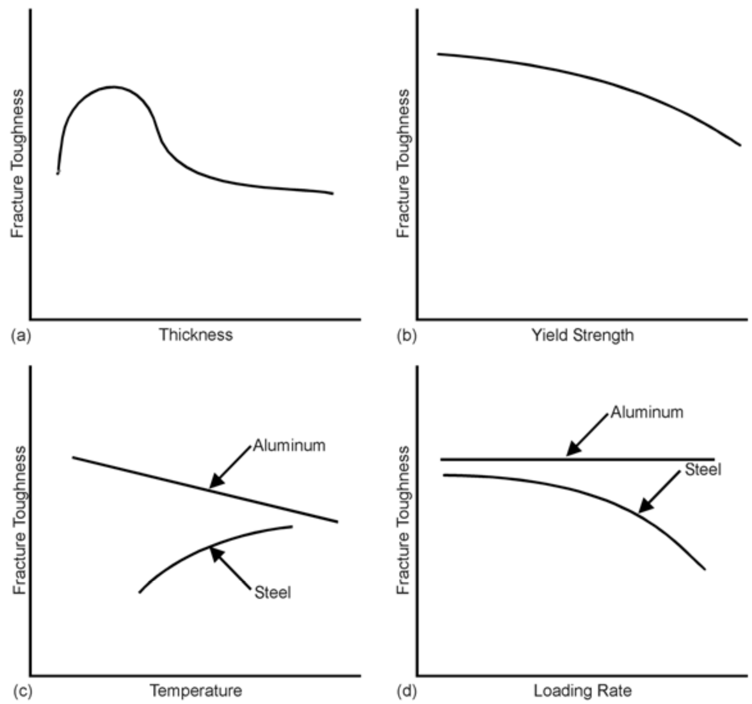


Figure 3.3.3. Fracture Toughness Varies as a Function of (a) Thickness, (b) Yield Strength, (c) Temperature, and (d) Loading Rate

Figure 3.3.4 provides an example of how a material's response to external stimuli can be utilized to increase the minimum safe crack growth interval. In Figure 3.3.4, a material's known response to temperature is utilized to select a low temperature condition for conducting the proof test. The lower fracture toughness exhibited at the low temperature is shown to extend the minimum safe crack growth interval substantially beyond what would have been expected for the same proof stress at the operating temperature conditions.

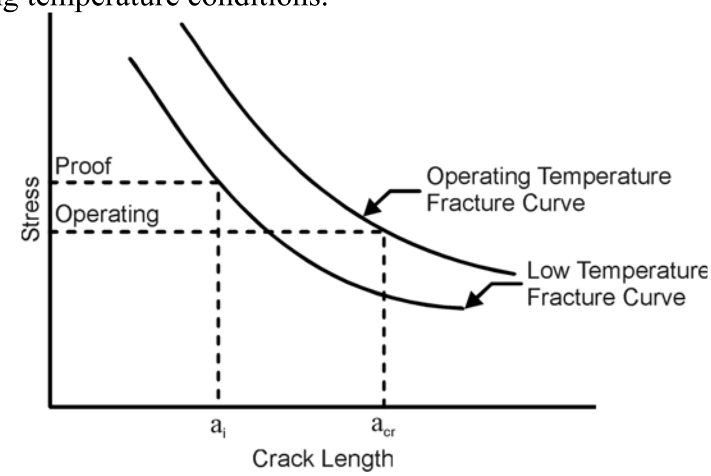


Figure 3.3.4. Using a Material's Low Temperature Fracture Sensitivity to Decrease Initial Crack Size and thus Increase the Minimum Safe Crack Growth Interval for a Given Proof Stressing Condition

As stated by JSSG-2006 A.3.12.1, "the minimum assumed initial flaw size shall be the calculated critical size at the proof test stress level and temperature using procuring activity approved upper-bound of the material fracture toughness data." The concept of using an approved upper-bound for the fracture toughness ensures a worst case assumption for the maximum allowable initial crack size (see Figure 3.3.5) and the minimum safe crack growth interval (see Figure 3.3.6). Figure 3.3.6 summarizes the JSSG-2006 requirements for establishing the minimum safe crack growth interval for the NDE proof test conditions.

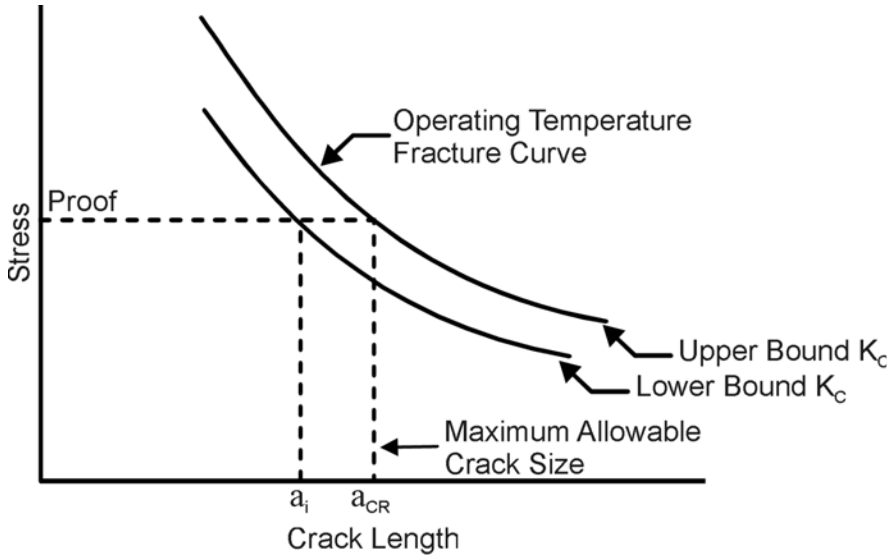


Figure 3.3.5. Influence of Fracture Toughness Variation on the Maximum Allowable Crack Size

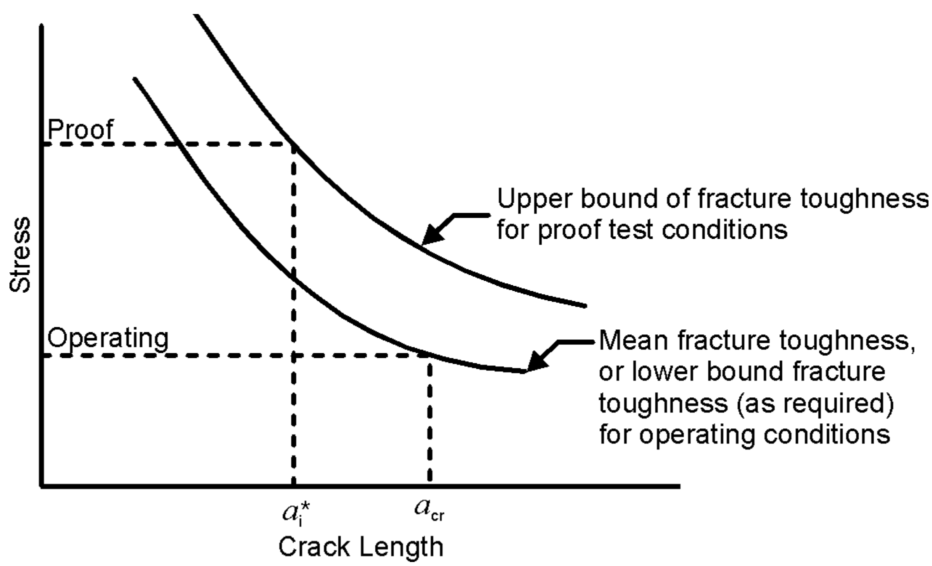


Figure 3.3.6. Description of Procedure Used to Establish Initial Crack Size and the Minimum Safe Crack Growth Interval According to JSSG-2006, A.3.12.1

There are no design allowables for fracture toughness of aerospace materials. Figure 3.3.7 presents a portion of MIL-HDBK-5G data that define typical plane strain fracture toughness for aluminum alloys. The fracture toughness values presented are averages, coefficients of variation and the minimum and maximum values obtained from the test data collected for the individual alloys and heat temperature conditions shown. The supporting text in MIL-HDBK-5G notes that the fracture toughness values given do not have the statistical reliability of the typical mechanical properties (yield strength, elastic modulus, etc.) that are usually present in MIL-HDBK-5 properties. The lack of a definition of the fracture toughness upper-bound required by JSSG-2006 would be overcome if the upper-bound is estimated by a statistical definition that is agreed to by the procuring agency. An example of such a bound might be a tolerance limit on the distribution of fracture toughness values.

TABLE 3.1.2.1.6. ***Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys***[a]

Alloy/Temper	Product Form	Orientation[b]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{Ic}, ksi $\sqrt{in.}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
2014-T651	Plate	L-T	$\geq$0.5	1	24	0.5-1.0	25	22	19	8.4	
2014-T651	Plate	T-L	$\geq$0.5	2	34	0.5-1.0	23	21	18	6.5	
2014-T652	Hand Forging	L-T	$\geq$0.5	2	15	0.8-2.0	48	31	24	21.8	
2014-T652	Hand Forging	T-L	$\geq$0.8	2	15	0.8-2.0	30	21	18	14.4	
2024-T351	Plate	L-T	$\geq$1.0	2	11	0.8-2.0	43	31	27	16.5	
2024-T851	Plate	L-S	1.4-3.0	4	11	0.5-0.8	32	25	20	17.8	
2024-T851	Plate	L-T	$\geq$0.5	11	102	0.4-1.4	32	23	15	10.1	
2024-T851	Plate	T-L	0.4-4.0	9	80	0.4-1.4	25	20	18	8.8	
2024-T852	Forging	T-L	2.0-7.0	3	20	0.7-2.0	25	19	15	15.5	
2024-T852	Hand Forging	L-T	-----	4	35	0.8-2.0	38	28	19	18.4	
2024-T852	Hand Forging	T-L	-----	2	17	0.7-2.0	22	18	14	14.4	
2124-T851	Plate	L-T	$\geq$0.8	13	497	0.5-2.5	38	29	18	10.4	24
2124-T851	Plate	T-L	0.6-6.0	10	509	0.5-2.0	32	25	19	9.7	20
2124-T851	Plate	S-L	$\geq$0.5	6	489	0.3-1.5	27	21	16	9.8	18
2219-T851	Plate	L-T	-----	4	67	1.0-2.5	38	33	30	7.2	
2219-T851	Plate	T-L	$\geq$1.0	6	108	0.8-2.5	37	29	20	10.1	
2219-T851	Plate	S-L	$\geq$0.8	3	24	0.5-1.5	26	22	20	9.6	
2219-T851	Forging	S-L	-----	1	85	1.0-1.5	34	25	19	12.1	
2219-T8511	Extrusion	T-L	-----	1	19	1.8-2.0	34	29	23	12.3	
2219-T852	Forging	S-L	-----	2	60	0.8-2.0	35	25	20	12.1	
2219-T852	Hand Forging	L-T	-----	2	32	1.5-2.5	46	38	30	9.7	
2219-T852	Hand Forging	T-L	$\geq$1.5	2	28	1.5-2.5	30	27	22	8.4	
2219-T87	Plate	L-T	$\geq$1.5	3	11	0.8-2.0	34	27	25	9.3	
2219-T87	Plate	T-L	-----	1	11	1.0	22	22	19	3.9	
7049-T73	Die Forging	L-T	1.4	3	21	0.5-1.0	34	30	27	7.4	
7049-T73	Die Forging	S-L	$\geq$0.5	3	46	0.5-1.0	26	22	18	9.7	
7049-T73	Hand Forging	L-T	$\geq$0.5	2	28	0.5-1.0	37	30	23	12.1	
7049-T73	Hand Forging	T-L	2.0-7.1	2	27	1.0	28	22	18	12.5	
7049-T73	Hand Forging	S-L	1.0	2	24	0.8-1.0	22	19	14	14.2	
7050-T7351	Plate	L-T	1.0-6.0	2	31	1.0-2.0	43	35	28	11.3	
7050-T7351	Plate	T-L	2.0-6.0	1	29	1.5-2.0	35	30	25	8.5	
7050-T7351	Plate	S-L	2.0-6.0	1	30	0.8-1.5	30	28	25	4.6	
7050-T74	Die Forging	S-L	0.6-7.1	3	12	0.6-2.0	27	24	21	8.8	

Figure 3.3.7. Table of Fracture Toughness Data from MIL-HDBK-5G

3.3.2 Examples

Two examples are now presented to illustrate how the proof test might be used. The first example describes how a proof stress condition might be chosen to find specific crack sizes. The second example describes a typical situation whereby the proof test must be designed to guarantee a service life interval.

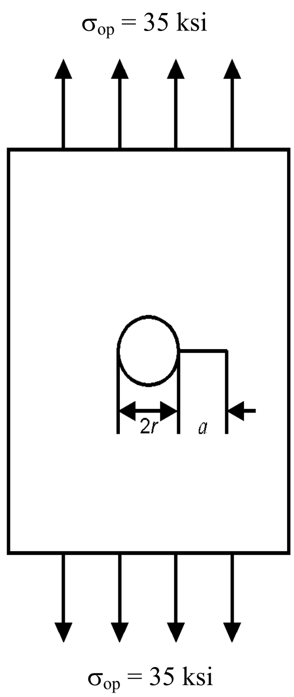
EXAMPLE 3.3.1 Proof Test Stress-Crack Length Relationships

For the radially-through-thickness cracked structure illustrated here, answer the following questions:

(a) What proof stress *(σ_p)* is required at room temperature to guarantee that the maximum crack size is less than 0.05 inches? Also, define the ratio of proof to operating stress conditions *($\alpha = \sigma_p/\sigma_{op}$)*.

(b) For a proof test conducted at -40°F, define the proof stress and proof stress ratio associated with finding a crack with a length 0.05 in.

(c) If the proof test ratio is 1.5, what is the minimum flaw size that will be detected at room temperature?



Material Properties

σ_{YS} = 70 ksi
K_{IC} = 40 ksi √in at 75°
K_{IC} = 35 ksi √in at -40°

STRESS INTENSITY FACTOR SOLUTION

$K = \sigma\sqrt{\pi a}\,F(a)$
where

$$F(a) = \frac{0.8734}{0.3246 + \frac{a}{r}} + 0.6762$$

SOLUTION:

The equation that governs the solution to all three questions is the Irwin fracture criterion, i.e.,

$$K = K_{IC}$$

where

$$K = \sigma\sqrt{\pi a}\cdot F(a/r)$$

with *F(a/r)* and the material properties defined above.

To address the questions parts a and b, the equations are solved for the proof stress σ_p, i.e.

$$\sigma_p = \frac{K_{IC}}{\sqrt{\pi a}\cdot F(a/r)}$$

for the given K_{IC} conditions at temperature and for a 0.05 inch long crack, i.e. *a* in this equation is 0.05 inch. So, for room temperature, the proof stress is

$$\sigma_p = \frac{40}{\sqrt{\pi(0.05)} \cdot (2.34)} = 43.1\,ksi$$

and for -40° F the proof stress is

$$\sigma_p = \frac{35}{\sqrt{\pi(0.05)} \cdot (2.34)} = 37.7\,ksi$$

In both cases, the proof stress is well below the yield strength; however, it might be noted that localized yielding at stress concentrations could occur at these levels. The proof stress ratios (α) are 1.23 and 1.08 for the room temperature and -40°F proof test conditions, respectively. To address the third part of the question, it is necessary to solve the equations for crack length (*a*), i.e.

$$a = \frac{1}{\pi}\left(\frac{K_{IC}}{\sigma_p}\right)^2 \left[\frac{1}{F(a/r)}\right]^2$$

Because this equation involves crack length in the function *F* in a complicated fashion, the equation is solved iteratively for the given material and stress conditions, i.e. K_{IC} = 40 ksi $\sqrt{\text{in}}$ and σ_p = 1.50 x (35) = 52.5 ksi. Thus,

$$a = \frac{1}{\pi}\left(\frac{40}{52.5}\right)^2 \left[\frac{1}{F\left(\frac{a}{r}\right)}\right]^2$$

A series of several trials are shown in the following table, where a match of the right and left side of the equation is achieved when $a \cong 0.0245$ inches. Thus, 0.049 inch long cracks can be found for a proof test ratio of 1.50.

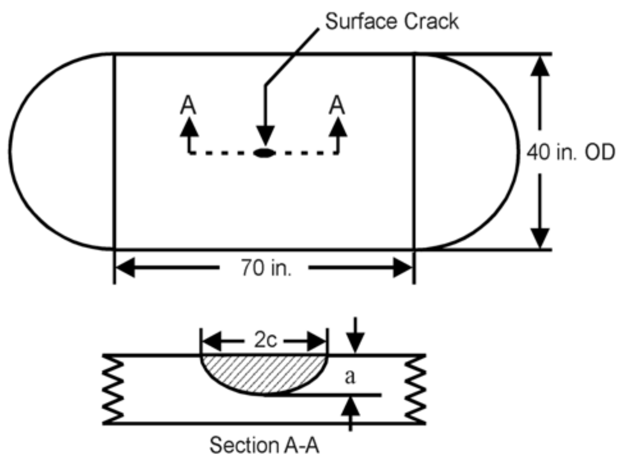
Trial And Error Solution

a **(left-hand side)**	***a/r***	***F(a/r)***	***a*** **(right-hand side)**
0.020	0.08	2.835	0.0230
0.025	0.10	2.733	0.0247
0.030	0.12	2.641	0.0265
0.0255	0.102	2.723	0.0249
0.0245	0.098	2.743	0.0246

In the above solutions, it is seen that in some cases the proof stress is sufficiently large such that yielding can be expected at the edge of the hole and other stress concentration sites. The reader is cautioned that linear elastic fracture mechanics (LEFM) techniques such as applied in these equations should not be utilized when extensive local yielding occurs except to obtain first-order estimates of the crack length. From a proof test standpoint, the LEFM estimates of the minimum crack length will be actually larger than those screened by loading the structure to the proof condition, assuming load control conditions, and thus conservative.

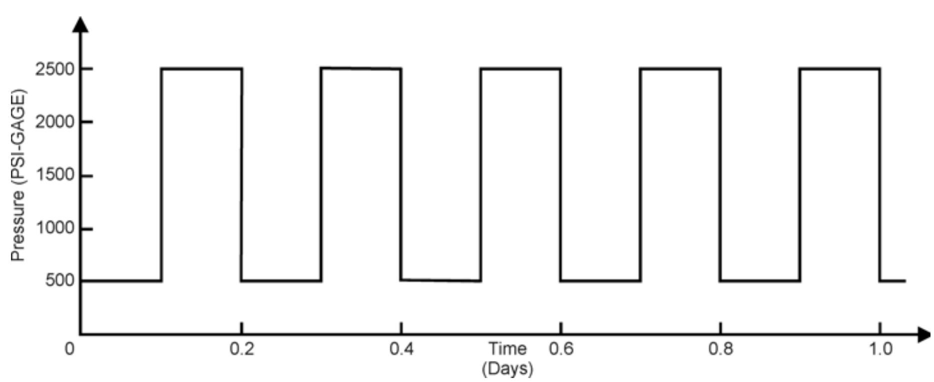
EXAMPLE 3.3.2 Proof Test Conditions to Guarantee Life

The pressure vessel shown here has a semicircular surface crack of unknown size located in the longitudinal direction. This vessel is subjected to an on-off pressure loading condition of the type illustrated below and is made of a structural steel with the mechanical properties shown.

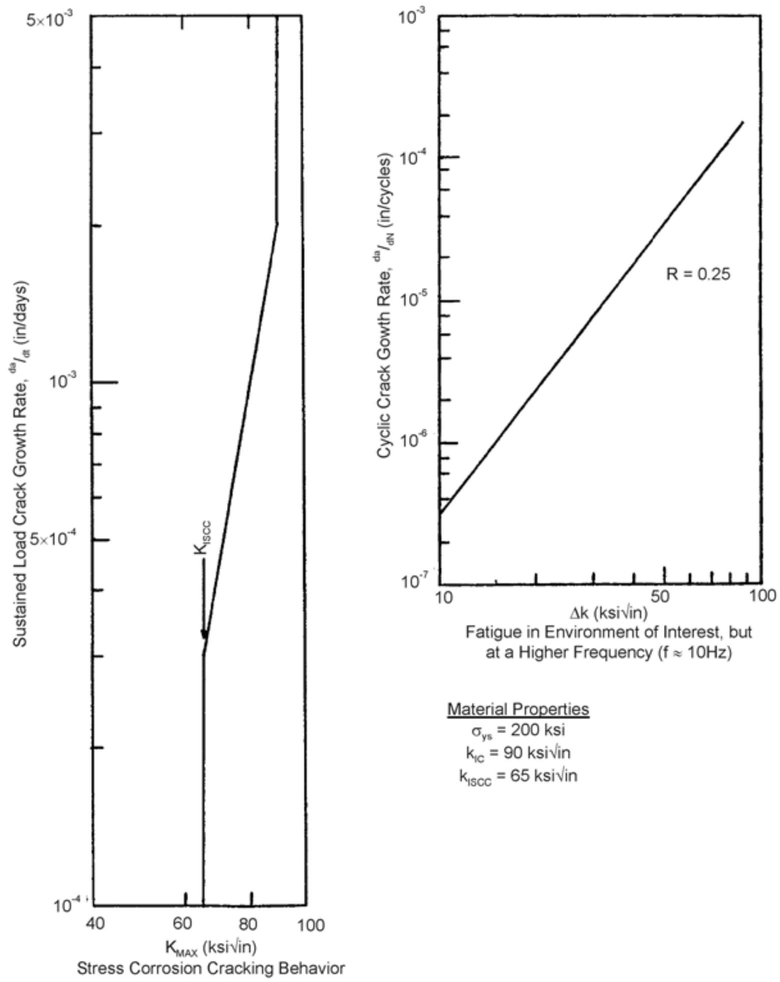


Pressure Vessel Structure with Semicircular Surface Crack

For economic purposes, it has been decided that the structure will only be inspected yearly and the inspection procedure has been chosen to be a proof test. You have been asked to select the proof pressure level that will guarantee that this vessel will not fail during the interval between proof test inspections subject to the crack/loading/material property assumptions.



Pressure/Time Loading Cycle



Material Properties for Steel Pressure Vessel

SOLUTION:

It is first necessary to calculate the gross stress in the section of the structure where the crack is located. From any standard strength of materials text, it is determined that for a pressure (p) of 2,000 psi, the maximum operating stress (σ) for the vessel with an outside diameter of 40 inch and a thickness (B) of 0.4 inch is given by

$$\sigma_{\max} = \frac{pD}{2B} = \frac{(2000)(40)}{2(0.4)} = 100{,}000\,psi$$

or 100 ksi, and the range of stress is

$$\Delta\sigma = 0.75\sigma_{max} = 75ksi$$

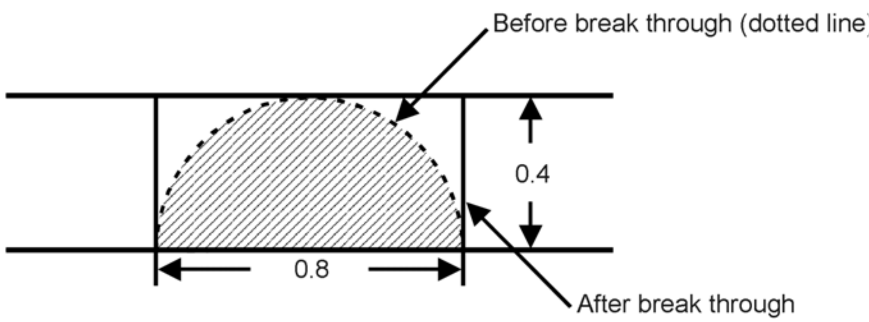
For the semicircular crack partly through the vessel wall, the stress-intensity factor is given by

$$K = 1.12\left(\frac{2}{\pi}\right)\sigma\sqrt{\pi a}$$

neglecting the back surface correction factor. Assume for illustrative purposes that the equation can be considered a reasonable estimate of the true stress-intensity factor at all depths through the thickness. As a first step, determine if the structure will leak before it breaks by calculating the stress-intensity factor for the condition where the crack depth is equal to the thickness. Thus, with σ = 100 ksi and a = 0.4 in.,

$$K = 1.12\left(\frac{2}{\pi}\right)(100)\sqrt{\pi(0.4)}$$
$$= 79.9 ksi\sqrt{in}$$

which is less than K_{IC} = 90 ksi√in and thus the vessel might leak before fracturing. Consider, however, the potential cracking situation that occurs if the semicircular crack penetrates the wall and immediately transitions to a through thickness crack as shown. An analysis indicates that $K \cong$ 112 ksi√in, which is greater than K_{IC}. Thus, given this situation, the vessel will fail catastrophically.



Change in Crack Geometry to Through-Thickness Crack After the Semicircular Crack Grows to the Inside Wall

To establish the crack size associated with the proof test, one must conduct a life analysis which works from the final crack size (a = 0.4 inch) backwards until the one-year life interval (a two-year life interval with the factor of two life margin) is guaranteed. The life analysis that is conducted illustrates an incremental crack length method that uses the iterative equation

$$Life = \sum_{i=1}^{n}\left[\frac{\Delta a_i}{\left.\frac{da}{dt}\right|_i}\right](days)$$

where the increments of crack length (Δa_i) and crack growth rate values ($da/dt/_i$) are chosen to be compatible.

On the basis of the given material data, one must assume that both a fatigue and a stress-corrosion cracking mechanism are active (see Section 5 for discussion on these mechanisms). The fatigue crack growth rate behavior can be described using the power law

$$\frac{da}{dN} = 3.3x10^{-10}\Delta K^{2.959}(in/cycle)$$

On the basis of the material data, this equation is restricted to the range $10 \leq \Delta K \leq 90$ ksi $\sqrt{in}$, and to the stress ratio (*R*) of 0.25, which is compatible with the given loading cycle.

The stress-corrosion cracking rate data can be described with the power law:

$$\frac{da}{dt}\bigg|_{cor} = 9.24x10^{-15} K_{\max}{}^{5.798} (in / day)$$

which is valid for sustained loading conditions when K_{max} is between the threshold of stress corrosion cracking (K_{Iscc} = 65 ksi √in) and the fracture toughness level (K_{IC} = 90 ksi √in).

As a first approximation of the effect of combined stress corrosion action and fatigue crack growth, the linear summation hypothesis of Wei-Landes is suggested (see Section 5):

$$\frac{da}{dt}\bigg|_{total} = \frac{da}{dt}\bigg|_{cor} + \frac{da}{dt}\bigg|_{fat}$$

where the time based fatigue crack growth rate is obtained from

$$\frac{da}{dt}\bigg|_{fat} = f \cdot \frac{da}{dN}$$

whereby the cycle-dependent component from the power law equation is multiplied by the cyclic frequency (*f*). It is also to be noted that the stress-corrosion cracking rate contribution for a day in service is one-half that established by the *da/dt* equation since the vessel is only loaded to the maximum pressure only half the time.

There are a number of ways that the *Life* equation can be used to establish the crack length-life relationship. The method for this example will be to choose equal increments of K_{max} between the crack size at failure and the other crack lengths established to obtain the Δa_i values. The next table describes the relationships between the maximum stress-intensity factor and the crack length, the crack length increment, the average values of the maximum stress-intensity factor ($\overline{K}_{max}$) and stress-intensity factor range ($\overline{\Delta K}$).

Crack Interval Table

K_{max} (ksi √in)	55	60	65	70	75	80
a (inch)	0.189	0.225	0.264	0.307	0.352	0.400
Δa (inch)	0.036	0.039	0.043	0.045	0.048	
$\overline{K}^{*}_{\max} (ksi\sqrt{in.})$	57.5	62.5	67.5	72.5	77.5	
$\overline{\Delta K}^{*} (ksi\sqrt{in.})$	43.1	46.9	50.6	54.4	58.1	

*Average values for the interval

The calculations of crack length *a* in this table are directly related to K_{max} through the equation

$$a = \left[\frac{K_{\max}}{1.12\left(\frac{2}{\pi}\right)\sigma_{\max}\sqrt{\pi}} \right]^2$$

which when solved for a typical value of K_{max}, say 55 ksi √in, the crack length becomes

$$a = \left[\frac{55}{1.12\left(\frac{2}{\pi}\right)100\sqrt{\pi}} \right]^2 = 0.189\,inch$$

The difference in crack lengths *(Δa)* comes from subtracting the two corresponding crack lengths. The values of $\overline{K}_{max}$ are computed by averaging the two corresponding K_{max} values, e.g. 62.5 ksi √in = 0.5 (60 + 65). The values of $\overline{\Delta K}$ are computed from the relationship $\Delta K = (1-R) K_{max}$, where R is the stress ratio (0.75).

The next table presents the fatigue crack growth rate contribution and the following table presents the stress corrosion cracking contribution.

Fatigue Crack Growth Rate Contribution

$\overline{\Delta K}$ **(ksi √in)**	$\frac{da}{dN}$ **(in/cycle)**	$\left.\frac{da}{dt}\right\rvert_{fat} = \frac{5cycles}{day} x \frac{da}{dN}$
43.1	2.26 x 10 $^{-5}$	1.13 x 10 $^{-4}$
46.9	2.91 x 10 $^{-5}$	1.46 x 10 $^{-4}$
50.6	3.64 x 10 $^{-5}$	1.82 x 10 $^{-4}$
54.4	4.51 x 10 $^{-5}$	2.25 x 10 $^{-4}$
58.1	5.48 x 10 $^{-5}$	2.74 x 10 $^{-4}$

Stress-Corrosion Cracking Rate Contribution.

$\overline{K}_{max}$ *(ksi* $\sqrt{in}$*)*	$\frac{da}{dt}$ (in/day)	$\left.\frac{da}{dt}\right\rvert_{cor}$ (in/day)
57.5	0*	0
62.5	0*	0
67.5	3.73 x 10 $^{-4}$	1.86 x 10 $^{-4}$
72.5	5.65 x 10 $^{-4}$	2.82 x 10 $^{-4}$
77.5	8.3 x 10 $^{-4}$	4.16 x 10 $^{-4}$

* $\overline{K}_{max}$ is below K_{Iscc} and therefore no growth occurs

In the Fatigue Crack Growth Rate Table, the $\Delta\overline{K}$ values are taken from the Crack Interval Table and cover each of the consecutive intervals of crack length. From the *da/dN* equation the crack growth fatigue rate for a stress-intensity range of 43.1 is

$$\frac{da}{dN} = 3.3x10^{-10}(43.1)^{2.959} = 2.26x10^{-5}\,\frac{in}{cycle}$$

The calculations of $\left.\frac{da}{dt}\right|_{fat}$ follow directly from multiplying the fatigue crack growth rates by the frequency of load application (5 cycles/day).

In the Stress-Corrosion Cracking Rate Table, the $\overline{K}_{max}$ values are taken from Crack Interval Table and cover each of the consecutive intervals of crack length. From the *da/dt* equation, the sustained load stress corrosion cracking growth rate is

$$\frac{da}{dN} = 9.24x10^{-15}(67.5)^{5.798} = 3.73x10^{-4}\,in/day$$

The calculations of the corrosion contribution to the total *da/dt* equation are also given in the table. These come directly from the fact that the structure is only loaded into the range where stress corrosion cracking occurs for one-half of the time (on-off cycling) so the $\left.\frac{da}{dt}\right|_{cor}$ numbers are one-half those given in the middle column.

The total contribution to cracking behavior is calculated from the total *da/dt* equation, and the individual crack increments in the *Life* equation are used to establish the time that it takes to grow the crack through the successive intervals. The appropriate calculations are reported in the next table.

Estimating the Time To Growth Through Successive Intervals.

Δa (inch)	$\left.\frac{da}{dt}\right|_{total}$ (in/day)	Δt (days)	A (inch)	t = ΣΔt (days)
0.036	1.13 x 10 $^{-4}$	318.6	0.189	861.1
0.039	1.46 x 10 $^{-4}$	267.8	0.225	542.5
0.042	3.68 x 10 $^{-4}$	114.9	0.264	274.7
0.045	5.07 x 10 $^{-4}$	89.5	0.307	159.8
0.048	6.9 x 10 $^{-4}$	70.3	0.352	70.3
			0.400	0

The crack length increment (Δa) and the crack length (a) values given in this table come from the Crack Interval Table. The total crack growth rate $\left(\left.\frac{da}{dt}\right|_{total}\right)$ values come from the total *da/dt* equation, where the individual contributions come from the Fatigue Crack Growth Rate and Stress-Corrosion Cracking Rate Tables, e.g.

$$\left.\frac{da}{dt}\right|_{total} = 5.07x10^{-4}\,\frac{in}{day} = 2.25x10^{-4} + 2.82x10^{-4}$$

for Δa = 0.045 inch and a between 0.307 and 0.352 inch. The increment of time required to propagate the crack through this interval is obtained from

$$\Delta t = \left.\frac{\Delta a}{\frac{da}{dt}}\right|_{total} = \frac{0.045in}{5.07x10^{-4}\,\frac{in}{day}} = 89\,days$$

The total time that it takes to grow through successive intervals is obtained by summing the results from this equation for each interval using the *Life* equation.

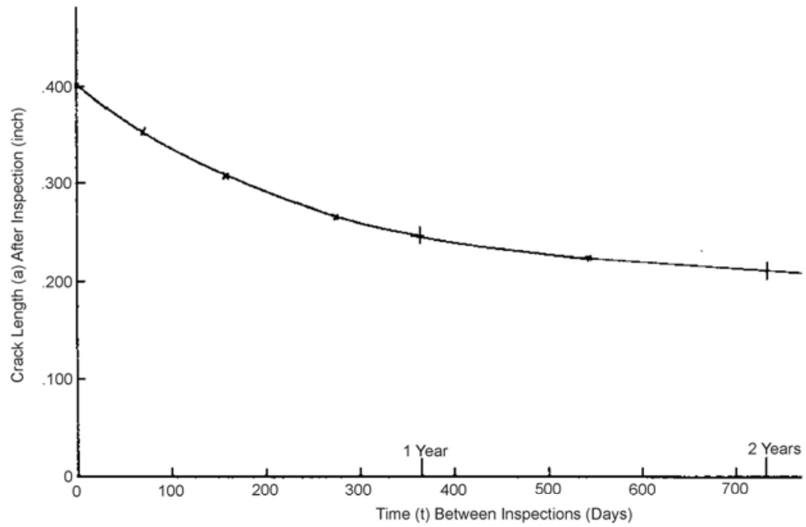
The data from the table that relates crack length (a) to the total time (t) to failure shows that the proof test must find a crack length between 0.189 and 0.225 inch to guarantee the integrity of the vessel with a factor of two life margin. The crack length versus total time to failure data have been graphically displayed in the next figure, where it can be seen that for one year of growth the crack length is 0.245 inch (and for a factor of two life margin the crack length is 0.20 inch). The required proof stress for the 0.20 inch long crack length is obtained from the Irwin criterion:

$$\sigma_p = \frac{K_{IC}}{1.12\left(\frac{2}{\pi}\right)\sqrt{\pi a}} = \frac{90}{1.264\sqrt{(0.2)}}$$

which is about 80 percent of the yield strength and therefore, the proof pressure (p_p) must be at least

$$p_p = \frac{2\sigma_p B}{D} = \frac{2(159{,}200)(0.4)}{40}$$

to ensure that all semicircular cracks longer than 0.2 inch are removed from the center section of the vessel prior to operation.



Graphical Procedure for Interpreting Crack Length